Western Region Technical Attachment
No. 06-05
February 2, 2006

Unexpected Widespread Rain over South-Central Arizona on 4 December 2004

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Introduction

Widespread light to moderate rain occurred over southern and south-central Arizona, including the entire Greater Phoenix area, from early afternoon through early evening of 4 December 2004. Precipitation totals over metro Phoenix generally ranged from one quarter to one third inch (Figure 1), with around one half inch occurring over several locations in south-central Arizona, including the far southeast portion of the metropolitan area (0.47" at Globe, in southern Gila County; 0.49" at Coolidge, in eastern Pinal County). Phoenix Sky Harbor airport received just over one quarter inch of rain (0.28").

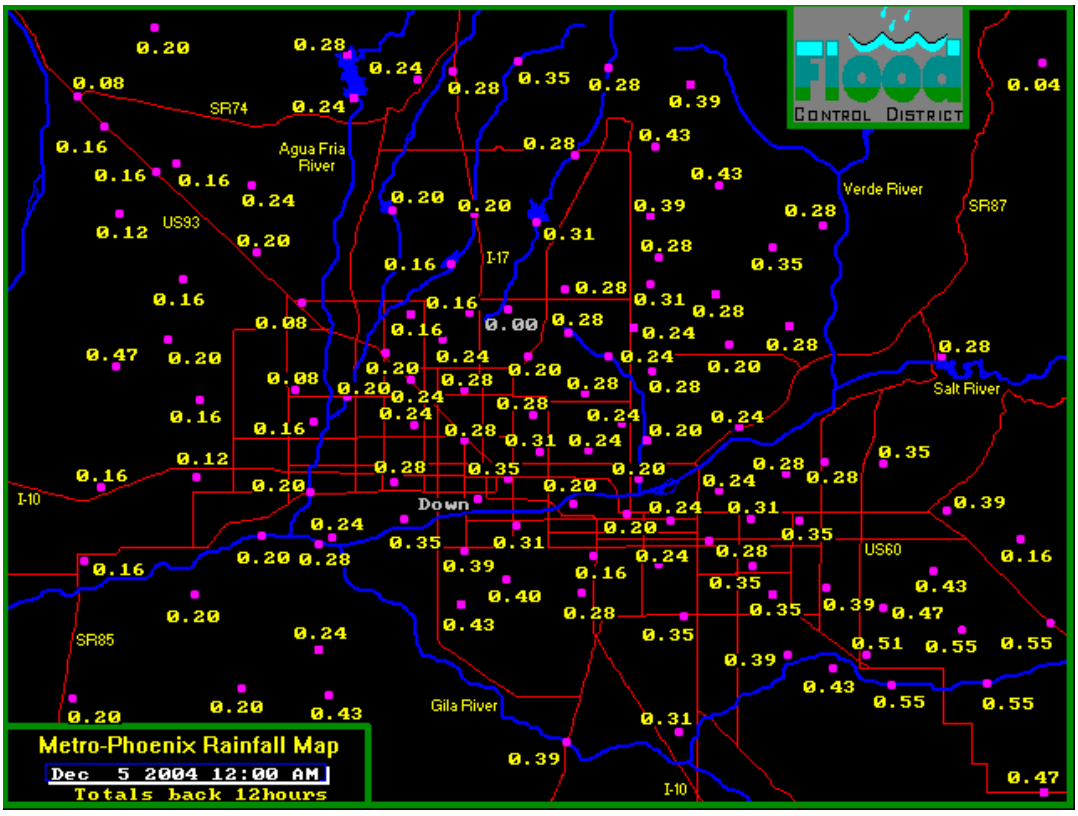


Figure 1. Storm Total Precipitation for the Greater Phoenix area, from the Maricopa County Flood Control District ALERT rain gauge network.

This precipitation event was not well-forecast. The first period of the Greater Phoenix metro zone forecast, issued at 345 am MST (1045 UTC) on Saturday, 4 December, called for partly sunny skies Saturday with highs in the mid to upper 60s, partly cloudy skies Saturday night, and no chance for precipitation during either period. Changes made via updates during the day on Saturday were: 1) at 905 am, sky condition was changed to "mostly cloudy", weather to "slight chance of showers" and probability of measurable precipitation (PoP) raised from 0% to 10% for "today"; 2) at 1221 pm, the daytime high was decreased from "the mid to upper 60s" F to "the lower 60s" F; 3) at 107 pm, PoP was increased to 30%, weather was changed to "scattered showers" and daytime high was cooled to "the mid to upper 50s" F (Sky Harbor max temp was 54 F). This note provides a brief review of the synoptic situation, a discussion as to why the forecast was so poor, and identifies several items that should enhance forecaster situational awareness.

Synoptic Situation

At 0000 UTC Saturday, 4 December (5 pm MST Friday, 3 December), an upper low was centered off the southern California coast, while a vigorous short wave trough was situated upstream from the upper low (Figure 2). A subtropical mid-upper level cloud deck extended from the east Pacific across northwest Mexico to southern Texas, with a baroclinic leaf associated with a 200 hPa jet streak situated over/south of Tucson, AZ.

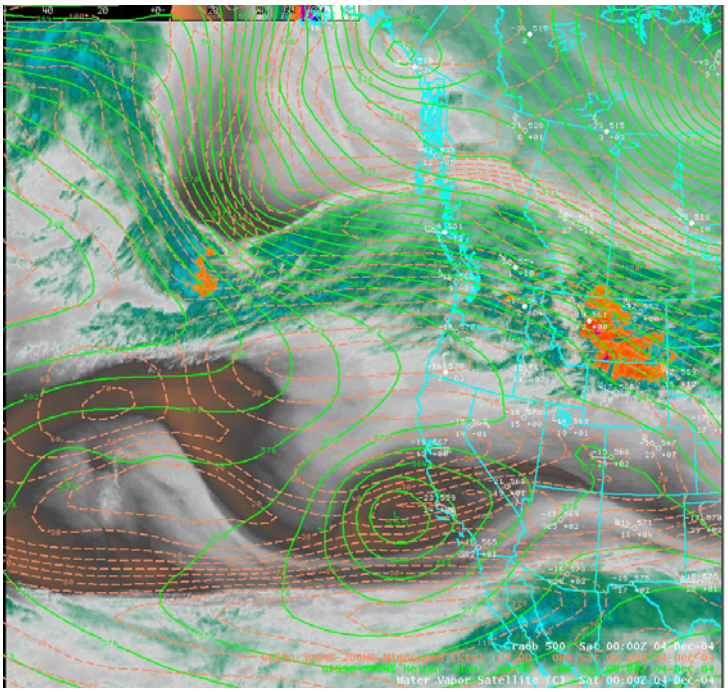


Figure 2. WV image with 500 hPa heights (green), 300-200 hPa wind speed (brown) and 500 hPa plot data (white) for 0000 UTC 4 Dec 2004.

Typically, showers would be a distinct possibility over portions of the Phoenix CWA as the upper low moved east across the forecast area. The smoothed frequency of occurrence of measurable rain for individual days in early December at Sky Harbor airport is approximately 10%. With a well-defined upper low to the west, and a plume of subtropical moisture as close as northwest Mexico, one could surmise that a reasonable "first-guess PoP" over south-central Arizona for this situation might be on the order of 20-30%. However, the ambient air mass over Arizona and far southeast California was very dry, with surface dew points 10-15 deg F below average, while precipitable water was quite low…less than 0.25" (Figure 3). Numerical models and associated MOS guidance forecast considerable mid-high level clouds, but little, if any, chance for rain over the Phoenix CWA (Table 1 and Figure 4).

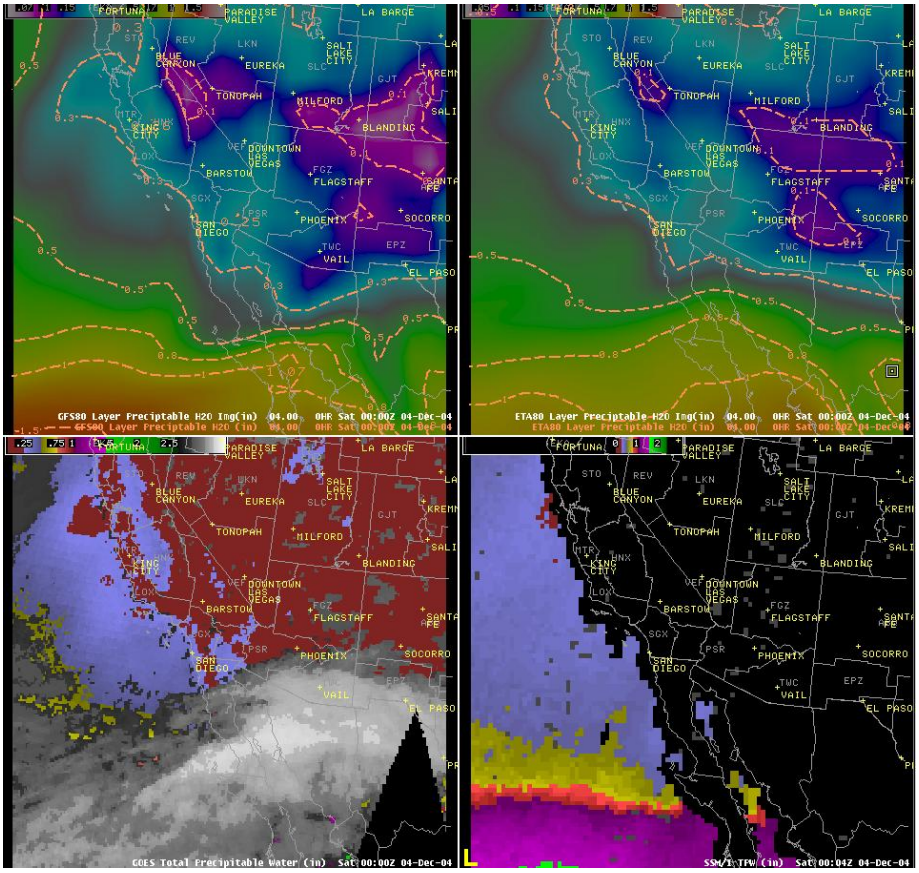
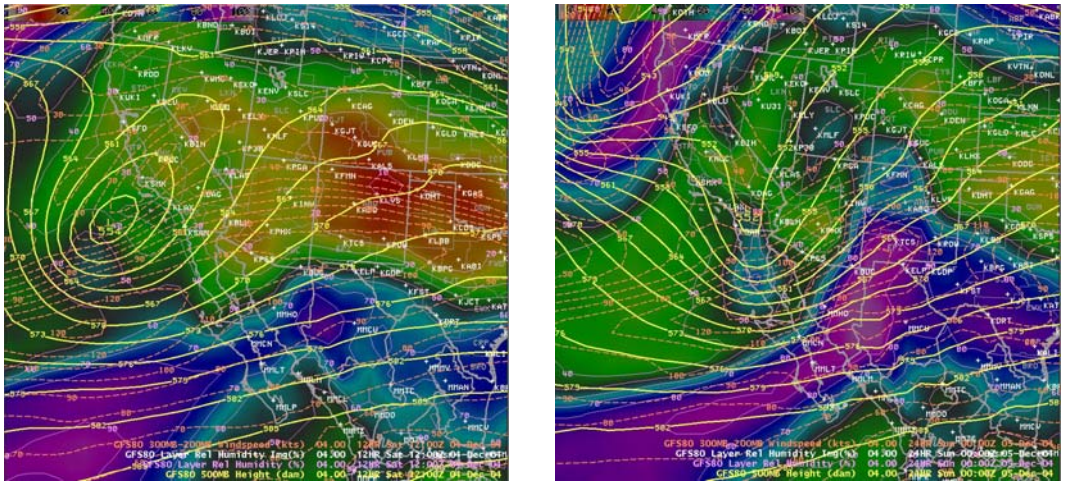


Figure 3. Layer precipitable water as of 0000 UTC 4 December 2004 from the GFS (upper left), NAM (upper right), GOES TPW image (lower left), and SSM/I TPW image (lower right).

Table 1. MOS PoP for Phoenix Sky Harbor based on 0000 UTC 4 December model runs.

	MAV	MET	FWC
1200-2400 UTC Sat	2	15	9
0000-1200 UTC Sun	2	13	2



(a) (b)

Figure 4. a) GFS 12-hr forecast valid at 1200 UTC 4 December 2004. b) GFS 24-hr forecast valid at 0000 UTC 5 December 2004 [Layer RH (image), 500 hPa heights (yellow), and 300-200 hPa wind speed (brown)].

At 0600 UTC 4 Dec 2004 (Figure 5), the upper low was still centered west-southwest of Los Angeles. Ridging associated with weak warm advection in advance of the upper low had increased over Arizona and western New Mexico, which caused the baroclinic leaf to the southeast of Tucson to assume more of an S-shape (weak cyclogenesis?). Comparison of GOES TPW images for 0000 and 0600 UTC 4 December 2004 (not shown) showed little change in atmospheric moisture over Arizona and Sonora, Mexico; however, extensive cloud cover precluded accurate determination of TPW over northwest Mexico.

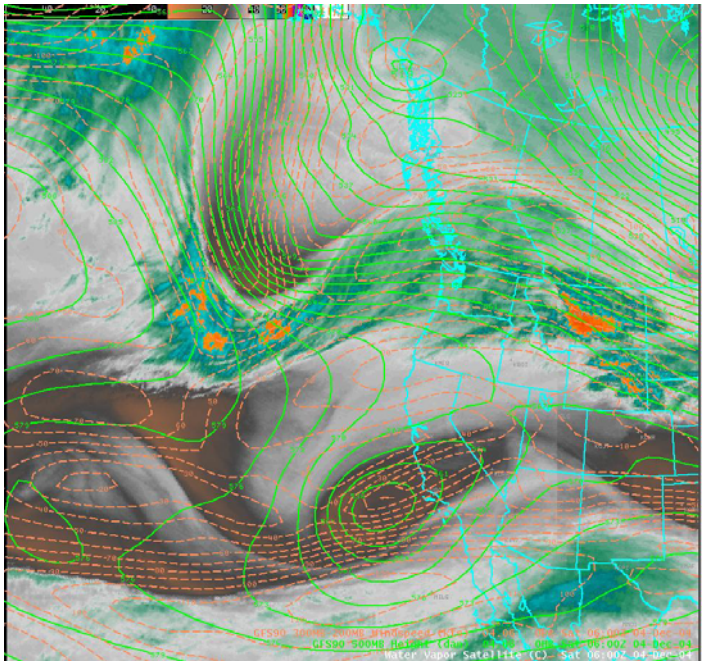
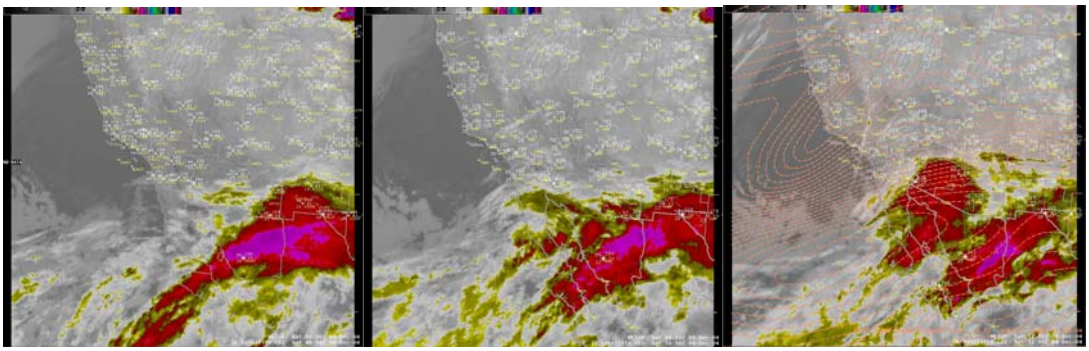


Figure 5. Same as Figure 2, except at 0600 UTC 4 December 2004. Between 0600 UTC and 1200 UTC, clouds expanded and cloud tops cooled over southwest and south-central Arizona, just west and north of the subtropical baroclinic leaf (Figure 6); by 1200 UTC 4 December, a new baroclinic leaf had developed. This feature was associated with the approach of a 130+ knot 300-200 hPa jet streak associated with the upper low.

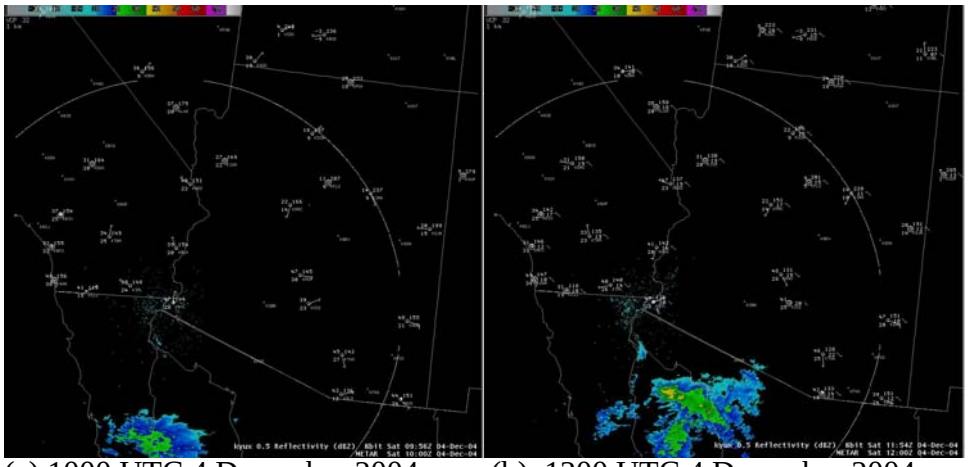


(a) (b) (c)

Figure 6. IR images at (a) 0600, (b) 0900 and (c) 1200 UTC 4 December 2004.

As the baroclinic leaf developed, the Yuma WSR-88D begin to detect light precipitation over far northwest Mexico; the area of precipitation expanded and moved northeast over northwest Sonora, Mexico, between 1000 and 1200 UTC, in conjunction with rapidly cooling and expanding cloud tops (Figure 7). While clouds were expected to increase

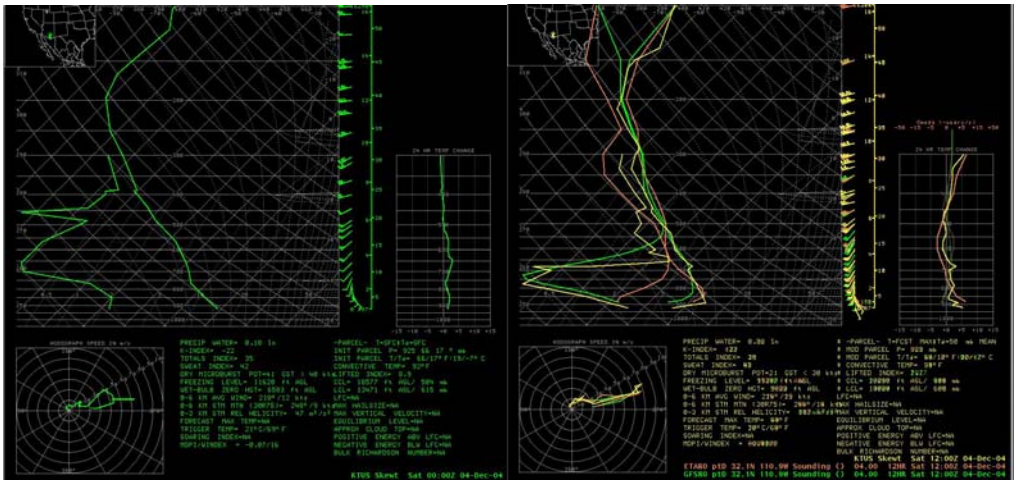
over south-central Arizona, the degree of cloud cover was unexpected. This, combined with the onset of precipitation over northwest Mexico, were harbingers of what was to occur over south-central Arizona later in the day.



(a) 1000 UTC 4 December 2004 (b) 1200 UTC 4 December 2004

Figure 7. KYUX (Yuma, Arizona WSR-88D) 0.5 degree base reflectivity.

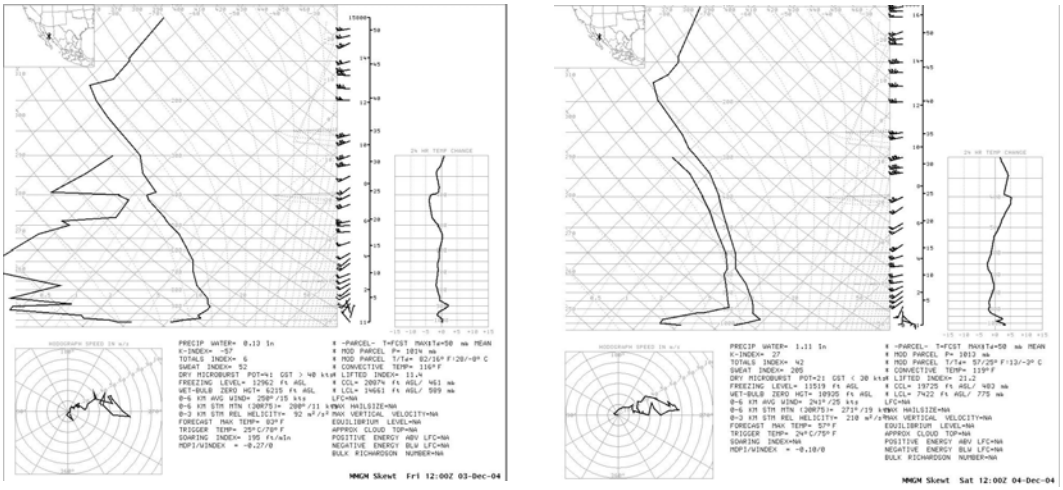
A comparison of the 0000 and 1200 UTC 4 December 2004 Tucson soundings revealed that moistening had occurred in the 650-350 hPa layer, with that layer close to saturation, but very dry conditions persisted below 650 hPa, and precipitable water had only risen from 0.18" to 0.32" (Figure 8). The GFS 12-hour forecast sounding was very similar to what was observed, while the NAM was too moist in the low levels (Figure 8).



(a) 0000 UTC 4 December 2004 (b) 1200 UTC 4 December 2004

Figure 8. Tucson, Arizona, soundings at 0000 UTC (green) and 1200 UTC (yellow) 4 December 2004. 12-hr GFS (green) and NAM (brown) forecast soundings valid at 1200 UTC are displayed with the 1200 UTC sounding.

Further south, the Guaymas, Mexico, 380 miles south of Phoenix, sounding had undergone remarkable moistening between 1200 UTC 3 December and 1200 UTC 4 December (Figure 9), with precipitable water rising from 0.13” to 1.11”.



(a) 1200 UTC 3 December 2004 (b) 1200 UTC 4 December 2004

Figure 9. Guaymas, Mexico, soundings.

Precipitable water information from numerical models and conventional satellite images was in line with what was observed via the Guaymas and Tucson soundings (Figure10).

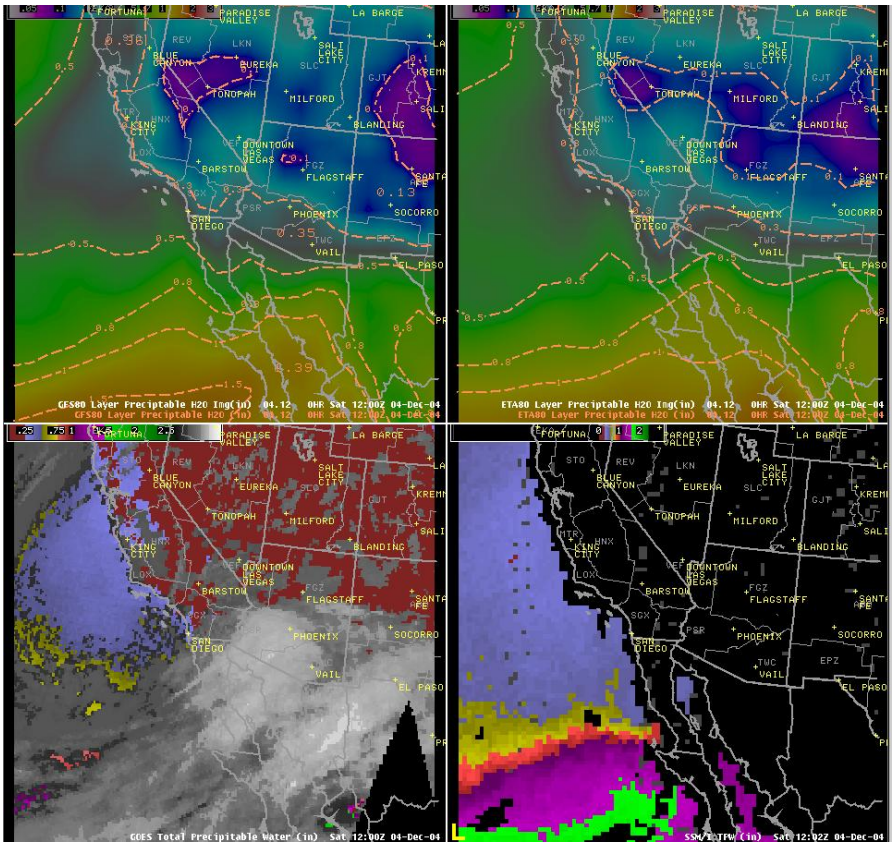


Figure 10. Layer precipitable water as of 1200 UTC 4 December 2004 from the GFS (upper left), NAM (upper right), GOES TPW image (lower left), and SSM/I TPW image (lower right).

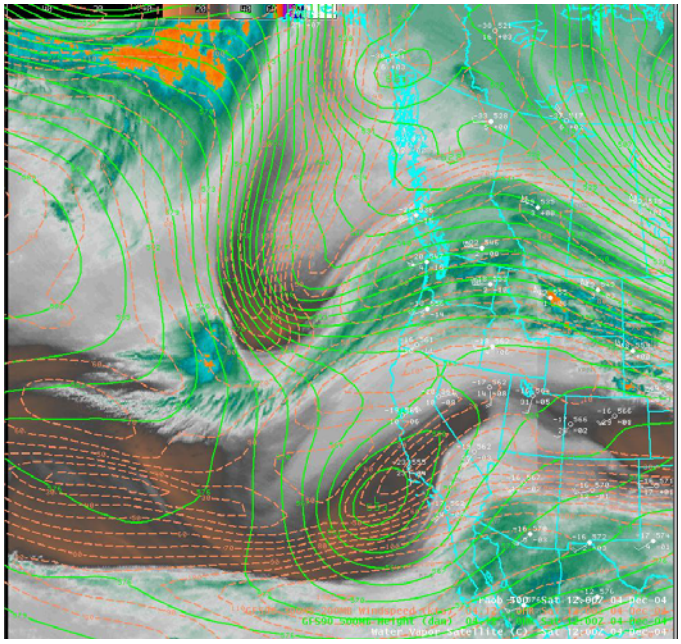
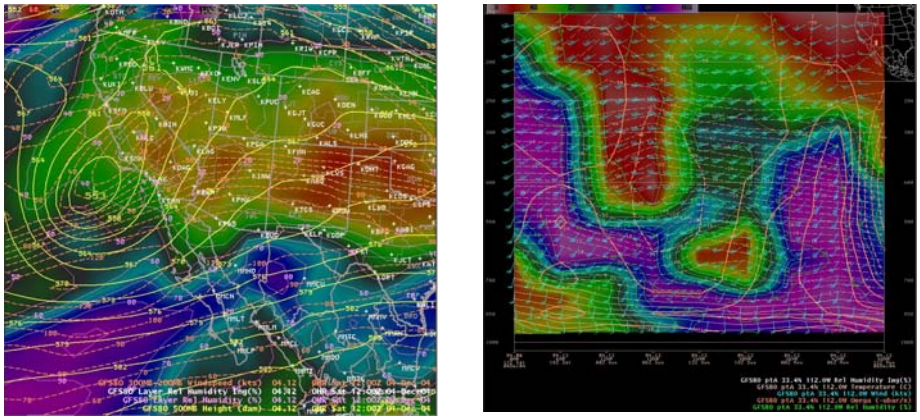


Figure 11. WV image with 500 hPa heights (green), 300-200 hPa wind speed (brown) and 500 hPa plot data (white) at 1200 UTC 4 December 2004.

WV imagery for 1200 UTC 4 December 2004 (Figure 11) showed that, while the center of the upper low was still just west and south of Los Angeles, the upstream trough off the Pacific Northwest Coast was much more amplified, possessed a 130+ knot jet streak on its backside, and would soon kick the upper low to the east.

The GFS run for 1200 UTC 4 December was very similar to what was generated from the previous couple of model runs. Relatively dry conditions continued to be forecast in the surface-700 hPa layer over Phoenix, while moist conditions and weak ascent were forecast in the mid-upper levels; typically, this results in mostly cloudy skies and, at best, some virga over the south-central Arizona desert (Figure 12). MOS PoP guidance for Phoenix based on the 1200 UTC model runs (Table 2) supported this idea.



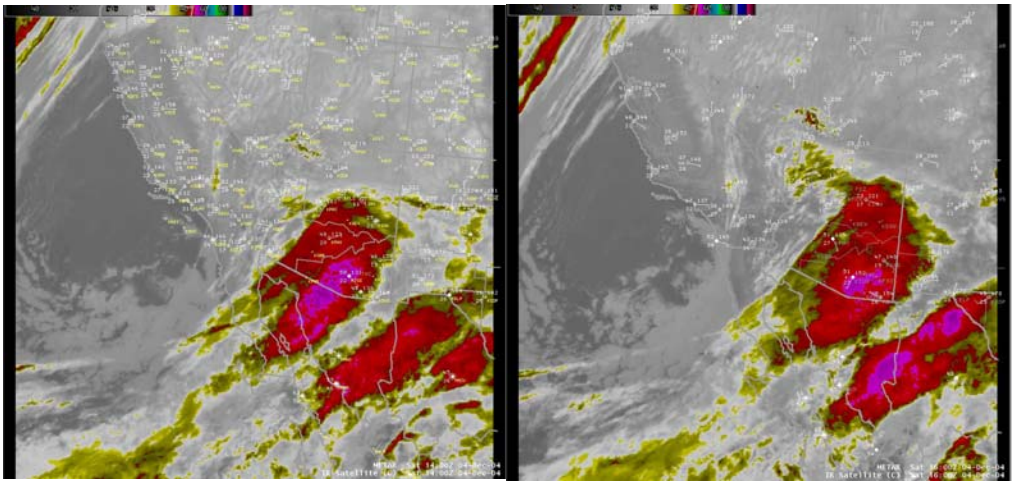
(a) (b)

Figure 12. (a) 1200 UTC 4 December GFS initial conditions (F00) plot of 500 hPa heights (yellow), layer RH (image) and 300-200 hPa wind speeds (dashed brown). (b) Two-day time-height display of RH (image), omega (brown), wind (blue), and temperature (degrees F, dashed beige) for Phoenix Sky Harbor airport, with initial conditions at left edge of image.

Table 2. MOS PoP for Phoenix Sky Harbor based on 1200 UTC 4 December model runs.

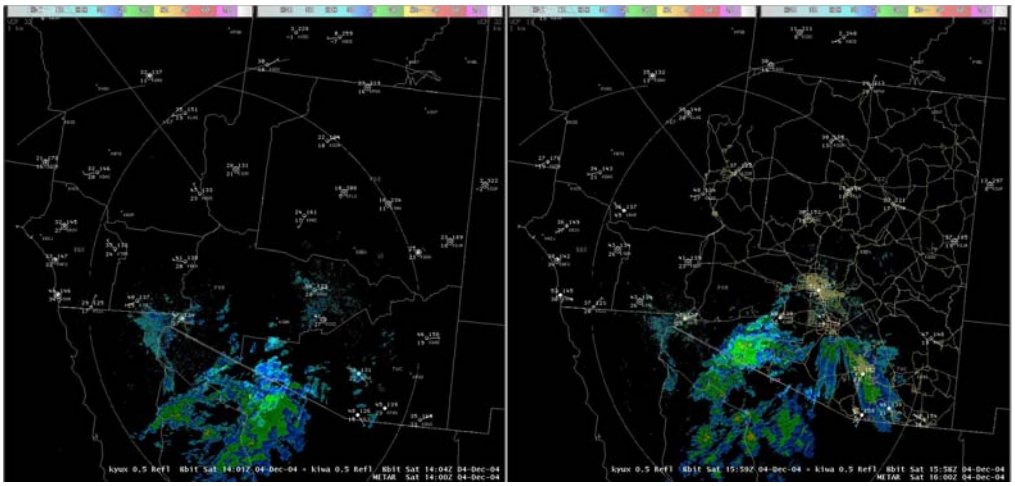
	MAV	MET	FWC
1200-2400 Sat	5	0	n/a
0000-1200 Sun	25	9	6

While the numerical models and associated MOS guidance suggested little if any precipitation would occur over south-central Arizona, morning satellite and radar images (Figures 13 and 14, respectively) suggested otherwise. IR satellite imagery showed a continued cooling and expanding of cloud tops, while radar detected an expanding area of light precipitation approaching from the southwest.



(a) 1400 UTC 4 December 2004 (b) 1600 UTC 4 December 2004

Figure 13. IR imagery.

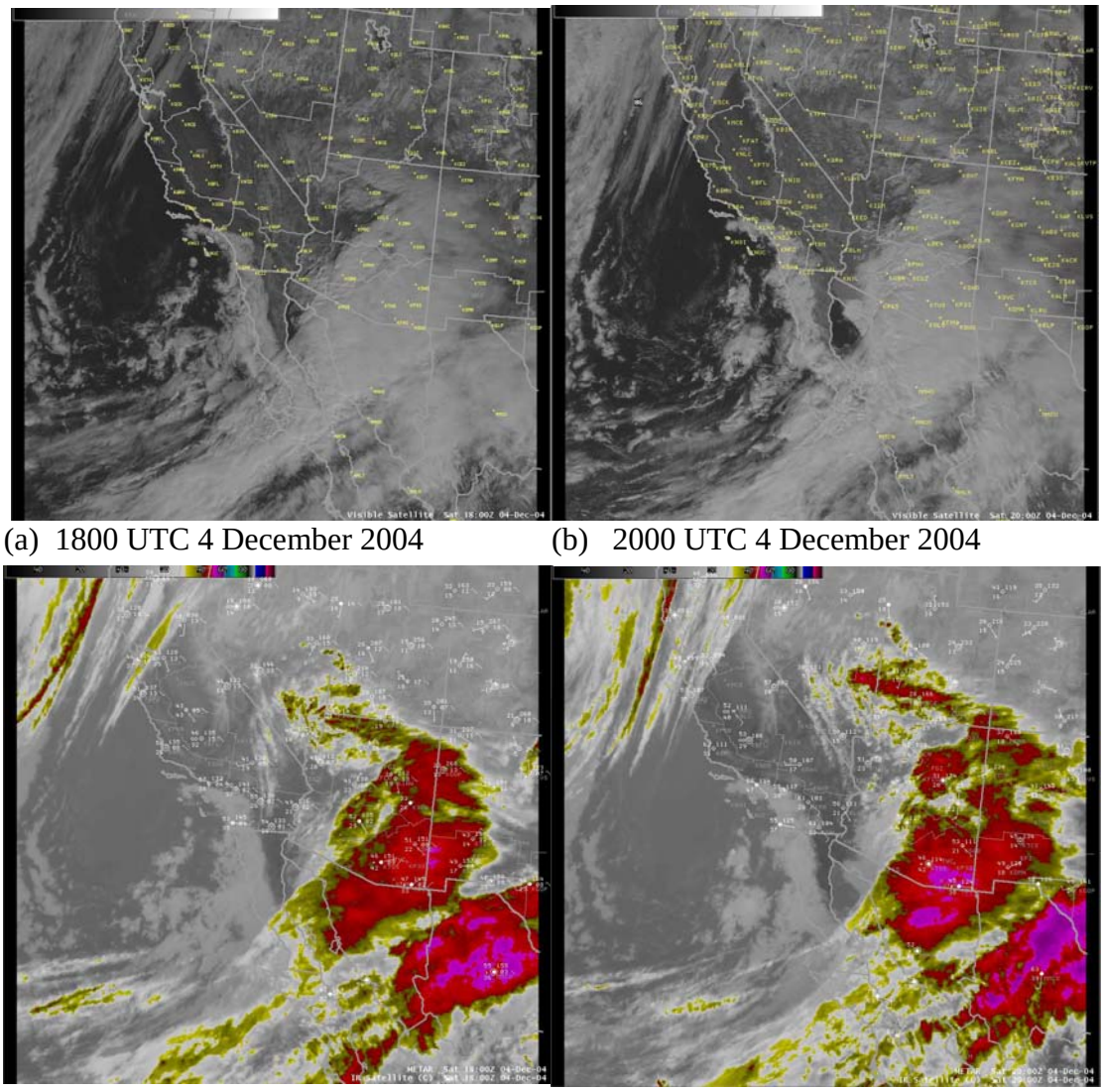


(a) 1400 UTC 4 December 2004 (b) 1600 UTC 4 December 2004

Figure 14. 0.5 degree base reflectivity composites from KYUX and KIWA.

WFO Phoenix forecasters pondered the following questions, amongst others: “How had the models handled the development/evolution of the baroclinic wave over Arizona and northwest Mexico?”, “How much moisture would advect over the forecast area during the day, especially in the surface-700 hPa layer?”, and, most importantly, “What changes, if any, needed to be made to the short term forecast for the today and tonight periods (gridded fields, such as sky, weather, PoP, temperatures, dew points, etc., as well as accompanying text products)”? As mentioned earlier, WFO Phoenix updated the forecast shortly after 1600 UTC to call for mostly cloudy skies, along with a 10% chance for a shower.

Late-morning and early afternoon satellite imagery (Figures 15 and 17) depicted rapid development of low-mid level clouds from the northern end of the Gulf of California to south-central Arizona, which occurred just west of the trailing edge of the mid-high level cloud deck, while radar imagery (Figure 16) showed continued development and northeast movement of an area of light to moderate rain, with rain occurring over nearly all of south-central Arizona by 2000 UTC.



(a) 1800 UTC 4 December 2004 (b) 2000 UTC 4 December 2004

Figure 15. Visible (top) and IR (bottom) satellite images. Note development of low-mid level cloud over extreme northern Gulf of California, as well as cooling cloud tops over north-central Arizona.

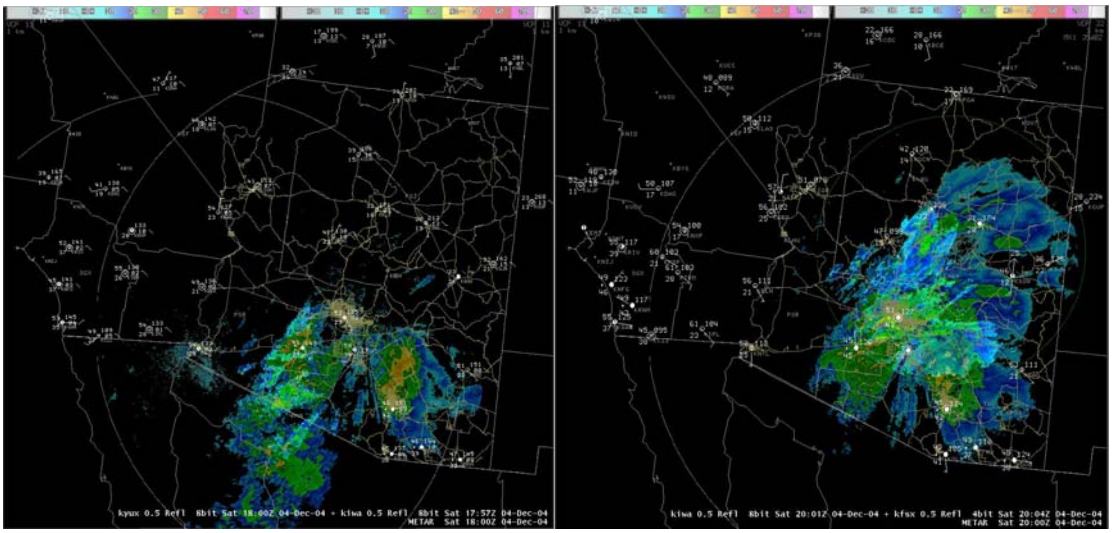


Figure 16. KYUX and KIWA 0.5 degree mosaic at 1800 UTC 4 December 2004 (left); KIWA and KFSX 0.5 degree base reflectivity mosaic at 2000 UTC 4 December 2004 (right). Measurable rain began to fall over the metropolitan Phoenix area shortly after 1900 UTC.

The last update to the forecast for south-central Arizona occurred at 2007 UTC: key changes included increasing precipitation probability to 30%, calling for "scattered showers" (since showers already existed), and lowering daytime highs from the lower 60s to the mid-upper 50s. In hindsight, this update, while showing proper PoP and temperature trends, continued to noticeably underplay this event.

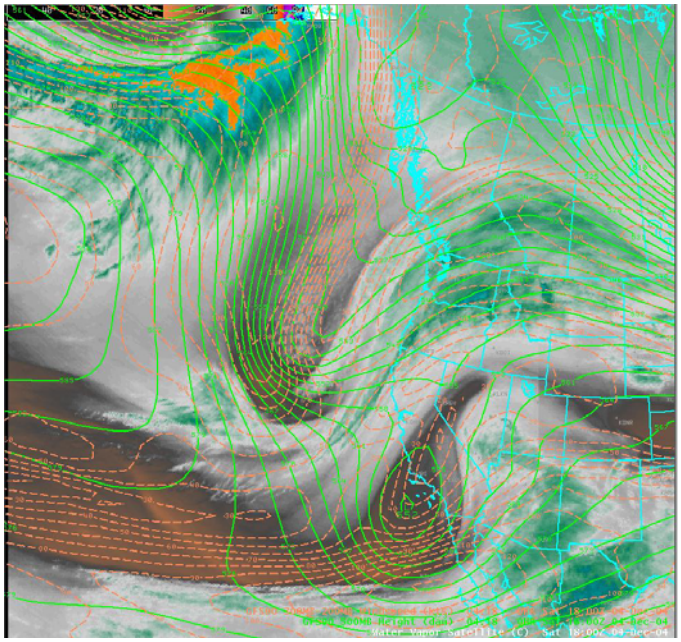


Figure 17. Same as Figure 2, except valid at 1800 UTC 4 December 2004.

As mentioned earlier, light to moderate precipitation continued over nearly all of south-central Arizona during the afternoon and early evening hours (Figure 18), with snow, heavy at times, commencing over the higher terrain of north-central Arizona, including Flagstaff and Winslow after 2200 UTC (4-6 inches of snow occurred at both locations between 2200 UTC 4 December and 0700 UTC 5 December). Precipitation gradually ended from south to north across the metropolitan Phoenix area between 0200 and 0400 UTC 5 December (not shown).

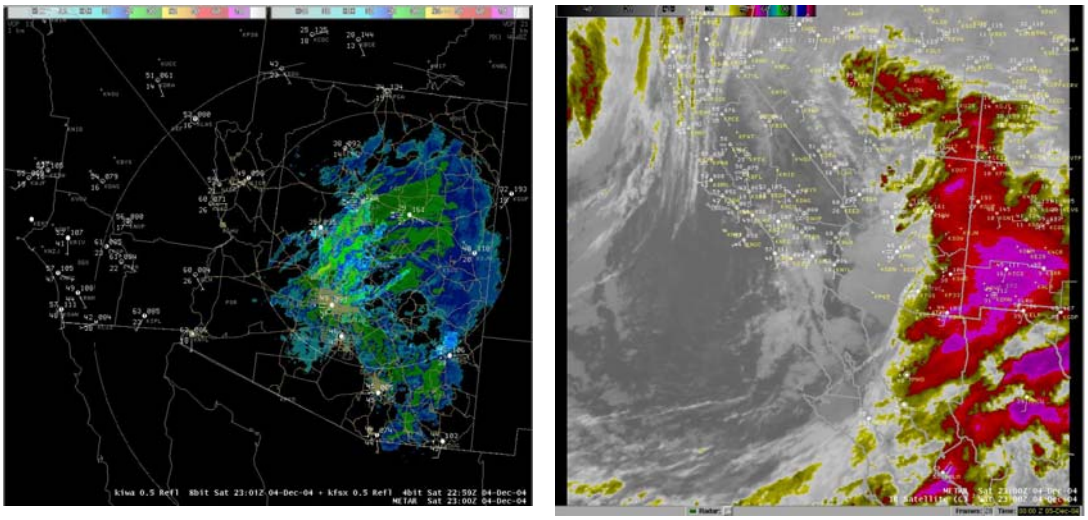


Figure 18. Radar and satellite images valid at 2300 UTC 4 December 2004.
(a) 0.5 degree base reflectivity mosaic from KIWA and KFSX.
(b) GOES IR image.

Discussion

Mass field forecasts from the GFS and NAM were reasonably good for this event. Both models called for upward vertical motion to increase on Saturday as the upper low began to approach the Phoenix CWA. Baroclinic leaf development and subsequent precipitation, however, were not well-forecast. Typically, moisture availability is the most challenging parameter Phoenix forecasters deal with during these situations, and that was clearly a challenging aspect of this case as well.

The KEY factor with regard to this forecast "bust" centered on a poor estimate of precipitable water over and southwest of the Phoenix CWA. For several days leading up to the event, numerical models consistently underestimated the amount of low-level moisture advection over extreme northwest Mexico, as well as central and eastern Arizona. Table 3 depicts precipitable water initial condition estimates (bold) and forecast values (6-hr intervals) from the GFS and NAM over Phoenix, beginning with the 0000 UTC 4 December model runs and concluding with the 1200 UTC 4 December model runs.

Table 3. Precipitable water forecast for Phoenix for given times from the model runs at 0000, 0600 (GFS only) and 1200 UTC 4 December 2004.

		4 Dec				5 Dec				6 Dec
	UTC	0000	0600	1200	1800	0000	0600	1200	1800	0000
GFS	0000	**0.19**	0.23	0.27	0.29	0.24	0.36	0.56	0.53	0.69
	0600	-----	**0.24**	0.29	0.39	0.31	0.40	0.56	0.52	0.66
	1200	-----	-----	**0.31**	0.45	0.39	0.56	0.56	0.46	0.61
NAM	0000	**0.16**	0.22	0.44	0.56	0.52	0.39	0.41	0.41	0.49
	1200	-----	-----	**0.24**	0.42	0.46	0.38	0.35	0.36	0.48

The GFS consistently forecast precipitable water to peak below 0.5”around 1800 UTC 4 December, then decrease during the afternoon; the NAM called for precipitable water to peak sometime during the day, at slightly above 0.5”, then lower during the night. A GPS-IPW plot for Scottsdale, Arizona, revealed that precipitable water actually increased from 0.38” at 1600 UTC to 0.93” by 2200 UTC (Figure 19)! The peak value was about one half inch greater than what was forecast.

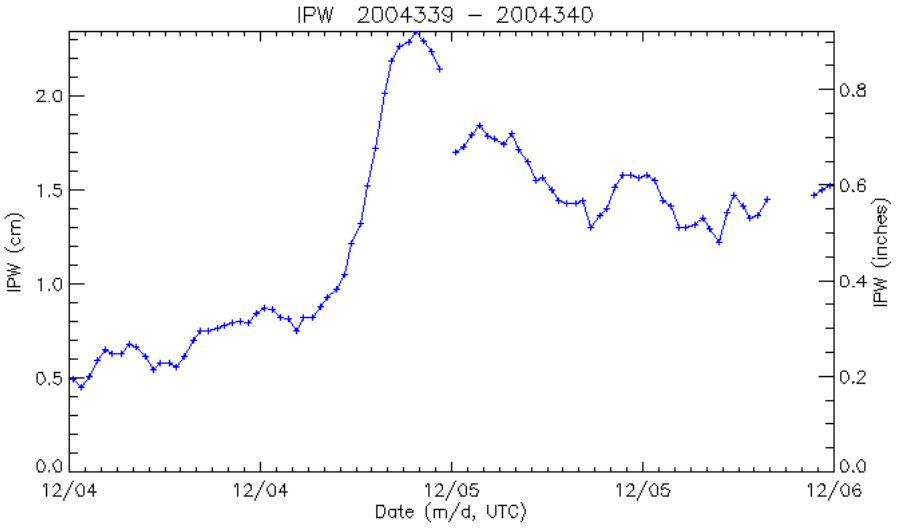


Figure 19. GPS-IPW plot derived from information collected at Scottsdale, Arizona, for the period 0000 UTC 4 December to 0000 UTC 6 December 2004 [image courtesy of Seth Gutman and Kirk Holub, FSL].

Although it appeared obvious that moist advection occurred as low level southerly flow developed over northwest Mexico in advance of the upper low, and that moisture was advected from the central and north-central Gulf of California, further examination of GPS-IPW data were needed, especially at sites over northwest Mexico. Two stations, Hermosillo and Puerto Penasco (Rocky Point), collected IPW before and during this event; their IPW plots, combined with Scottsdale’s, are shown in Figure 20.

An examination of the IPW plots indicates that rapid moistening began at Hermosillo, MX, (29 N latitude) at 0400 UTC 4 December, at Puerto Penasco (31.3 N) at 1000 UTC, and at Scottsdale (33.7 N) around 1400 UTC. So, a pronounced moisture gradient moved north at 25 knots across northern Sonora, Mexico, prior to reaching Puerto Penasco, then moved toward the north-northeast at a somewhat faster rate, approximately 35-40 knots, between Puerto Penasco and Scottsdale. Visible satellite imagery depicted rapid low-level cloud development along the northeast coast of the Gulf of California, over and east of Puerto Penasco, as the western edge of the newer baroclinic leaf edged east of that area. According to the KIWA VWP (not shown), 800-700 hPa winds increased from 25-30 knots at 1700 UTC to 35-40 knots at 2000 UTC 4 December, with south winds backing toward the southeast during the afternoon.

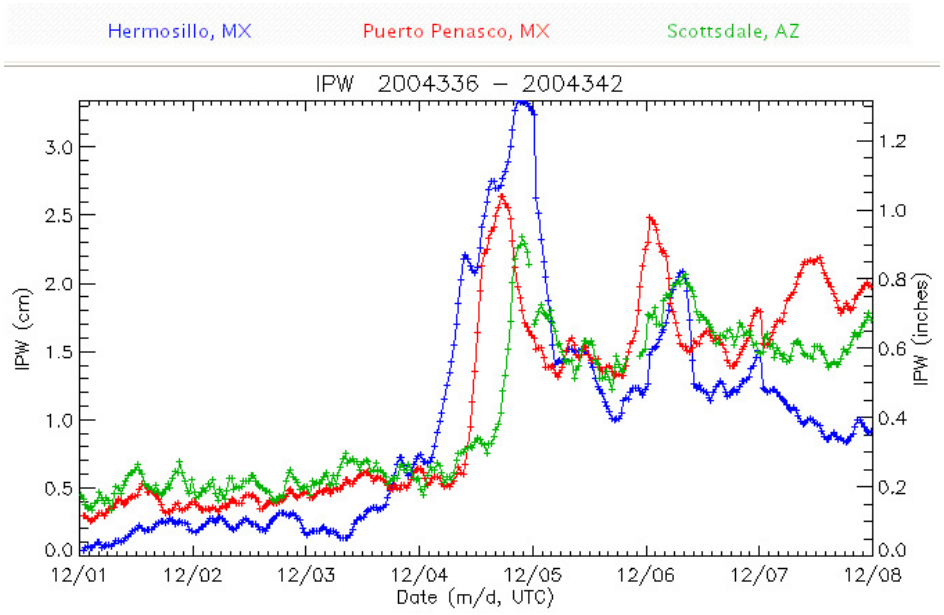


Figure 20. GPS-IPW plot for Dec 1-7 2004. Hermosillo, MX is located at approximately 29 N 111 W; Puerto Penasco, MX, is located at approximately 31.3 N 113. W; Scottsdale, AZ is located at approximately 33.7 N 111.9 W. [image courtesy of Seth Gutman and Kirk Holub, FSL].

The increase in wind was associated with a strengthening north-south pressure gradient, with 24-hr surface pressure falls (0000 UTC 4 December to 0000 UTC 5 December) of 15-18 mb across central-northern Nevada and western Utah, while falls of 5-7 mb were more typically observed over south-central Arizona. It is possible that a mesoscale low level jet developed from the northern end of the Gulf of California toward south-central Arizona during the early morning of 4 December, but this cannot be confirmed based solely on the observational evidence.

Satellite imagery suggested that atmospheric processes typically associated with an "instant occlusion" occurred over the southwest United States on 4 December 2004 (Young et.al., 1987, VisitView Cyclogenesis teletraining module; Figures 21 and 22). In this case, two well-defined baroclinic leafs (warm conveyor belts) existed, with the newer leaf developing in response to forcing associated with a strong upper level jet streak just south of the upper low. Visible and infrared satellite imagery hinted at the existence of a cold conveyor belt and associated cloud development across central and northern Arizona during the afternoon and early evening of 4 December, which may have served to enhance precipitation over northern Arizona, but upslope flow and local terrain effects make this determination much more difficult without further examination.

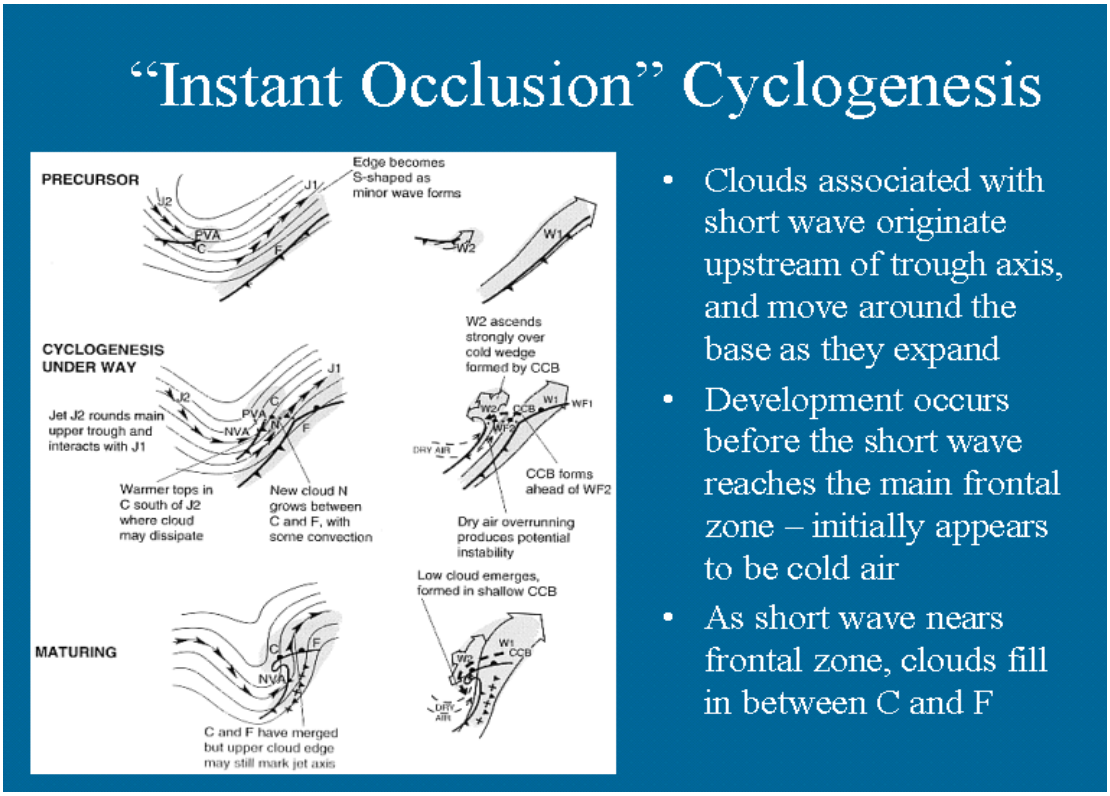


Figure 21. "Instant Occlusion" graphic/cartoon [source: VisitView "Cyclogenesis" module].

Interestingly, for several days prior to 4 December, precipitation and cool weather had been forecast over much of the Phoenix CWA on Sunday, 5 December, in association with the approach and passage of the vigorous short wave trough upstream from the upper low (Figure 17). A special weather statement issued late Friday afternoon, 3 December, addressed the expected impact from both weather systems (Appendix 1). Widespread rain did occur in association with the short wave trough, though most of the rainfall over south-central Arizona, including the Phoenix metro area, occurred overnight on 5-6 December 2004 (Appendix 2).

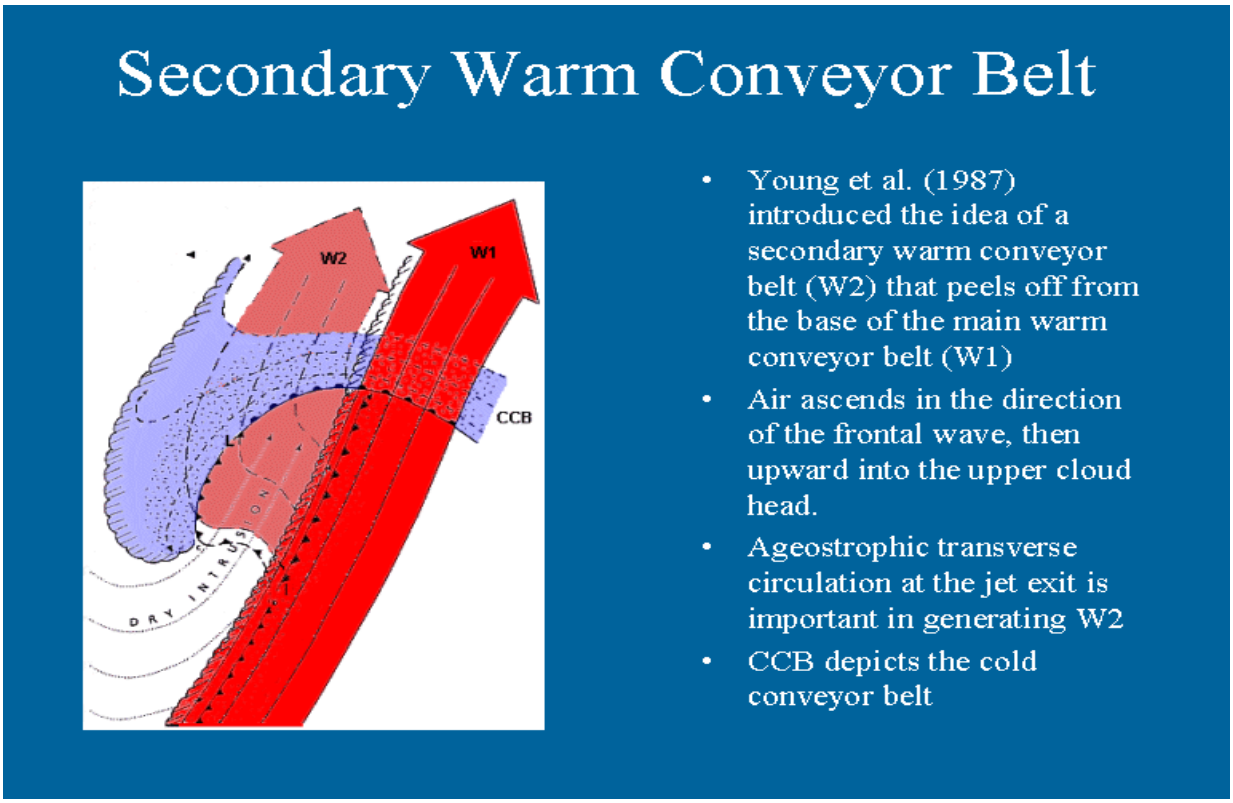


Figure 22. Secondary Warm Conveyor Belt graphic/cartoon [source: VisitView "Cyclogenesis" module].

Conclusions

An unexpected widespread rain event occurred over south-central Arizona on 4 December 2004. Forecasters were unable to accurately assess the degree of moist advection, which was a key detriment to correctly determining the potential for measurable rainfall. Model guidance, while doing reasonably well with regard to mass field forecasts, did not handle the moisture fields very well; consequently, MOS PoP guidance was very poor. This case highlighted the need to combine key observational information with the more trustworthy components of numerical model guidance in order to make the best possible short term forecast.

GPS-IPW data from sites over northwest Mexico and Arizona were found to be extremely useful with regard to making a more reliable assessment of moisture advection. The Guaymas, MX, sounding, available once/day during December 2004, provided "ground truth" that abundant, deep-layered moisture had overspread northwest Mexico; unfortunately, no Guaymas soundings have been available to WFO Phoenix since 1 February 2005. Proper satellite imagery interpretation, especially with regard to diagnosing the onset of cyclogenesis over and near the Phoenix CWA, would certainly

have helped the forecaster make a better short-term forecast (a review of the VISIT module “Cyclogenesis” was linked to forecaster completion of this WES case).

This case presented an excellent opportunity to highlight the value of isentropic analysis. Much of the upward motion forecast by the numerical models was associated with the adiabatic component of omega, best explained by viewing a combination of pressure, wind and relative humidity on the 300 K and 305 K isentropic surfaces (not shown). In this instance, warm, moist flow overspread the south-central desert and was lifted over the higher terrain as the parcels streamed toward the north-northeast, which led to development of widespread rain, with snow at higher elevations, over north-central and northeast Arizona.

Reference

Young, M.V., G.A. Monk and K.A. Browning, 1987: Interpretation of satellite imagery of a rapidly developing cyclone. *Q.J.R. Meteorol. Soc.*, **113**, 1089-1115.

Acknowledgment

Special thanks to Seth Gutman, Kirk Holub, and everyone at FSL involved with providing GPS-IPW data and graphics for this event. Seth, Kirk and others had to retrieve and process data that was not initially available via http://gpsmet.noaa.gov, and I’m grateful they were willing and able to fulfill my request.

Appendix 1. SPS issued by WFO Phoenix the afternoon of 3 December 2004.

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WWUS85 KPSR 032338
SPSPSR

SPECIAL WEATHER STATEMENT
NATIONAL WEATHER SERVICE PHOENIX AZ
422 PM MST FRI DEC 3 2004

AZZ020>028-041200-
GREATER PHOENIX AREA-LOWER COLORADO RIVER VALLEY AZ-
NORTHWEST AND NORTH CENTRAL PINAL COUNTY-NORTHWEST MARICOPA COUNTY-
SOUTHERN GILA/TONTO NF FOOTHILLS-SOUTHWEST DESERTS-
SOUTHWEST MARICOPA COUNTY-WEST CENTRAL DESERTS-
YUMA/MARTINEZ LAKE AND VICINITY-
422 PM MST FRI DEC 3 2004

...COLD WINDY AND POTENTIALLY WET WEATHER HEADED FOR SOUTHWEST AND
SOUTH CENTRAL ARIZONA SUNDAY...

A COUPLE OF WEATHER DISTURBANCES WILL BE MOVING INTO SOUTHWEST AND
SOUTH-CENTRAL ARIZONA SATURDAY AND SUNDAY. THE FIRST SYSTEM SATURDAY
WILL BE RELATIVELY DRY...WITH VARIABLE CLOUDS...BREEZY AND COOLER
WEATHER EXPECTED.  THE SECOND SYSTEM SUNDAY PROMISES TO BE MUCH
STRONGER...COLDER...AND WINDIER...WITH A CHANCE FOR SHOWERS OVER THE
DESERTS AND MOUNTAINS. SNOW LEVELS BY EARLY SUNDAY EVENING COULD FALL
TO NEAR 5000 FEET.

RESIDENTS AND THOSE PLANNING OUTDOOR ACTIVITIES SUNDAY SHOULD
CONTINUE TO LISTEN TO THE LATEST FORECASTS AND UPDATES CONCERNING
THIS APPROACHING WINTER STORM.
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Appendix 2. Storm Total Precipitation for the Greater Phoenix area, from the Maricopa County Flood Control District ALERT rain gauge network, for the storm of 5-6 December 2004. Sky Harbor airport received 0.44", mainly overnight on 5-6 December.