A CASE STUDY OF RAPID AIRMASS MODIFICATION OVER ARIZONA DUE TO LARGE-SCALE UPWARD MOTION

Ira S. Brenner

Weather Service Forecast Office
Phoenix, Arizona 85034

Abstract

The Arizona monsoon season is typically characterized by the rather persistent large-scale flow of moist air from the south and east. Once established, further airmass changes within the state are generally limited to occasional reinforcing surges of cooler tropical air from the Gulf of California and western Mexico. These surges have been found to occur about every week or ten days on the average; nevertheless, the occurrence, coverage and intensity of Arizona's thunderstorm activity varies considerably from day to day. Increases in thunderstorm activity can often be attributed to decreasing stability and increasing moisture content in association with upward motion. Emphasis has been directed to the fact that 'dry' air, undergoing only weak large-scale upward motion (with negligent horizontal advective influences), can easily become saturated at middle and upper levels in a relatively short period of time. A case study during which this process was actively engaged is presented.

1. INTRODUCTION

Arizona thunderstorms are almost a daily occurrence during the summer monsoon season (Sellers, 1974). These thunderstorms normally originate in the orographically favored regions of the state (Figure 1) by midday and spread toward the lower deserts by late afternoon or evening (Hales, 1972b).

During the period of the Arizona monsoon, large-scale moisture-laden easterly or southerly flow prevails over the state (Jurwitz, 1953; Ingram, 1972). Complimenting this generally light flow at middle and high levels are occasional reinforcing surges of very moist tropical maritime air at low levels (Gulf Surge) which move into Arizona from the Gulf of California and the west coast of Mexico regions (Hales, 1972a; Brenner, 1974).

Intense insolation prevails during the monsoon months and results in very unstable lapse rates over the state daily (Hales, 1972a). However, counterbalancing this otherwise explosive condition is the fact that, in general, large-scale airmass changes over the state are quite subtle (Brenner, 1974), since the main belt of the westerlies are so far removed to the north. Therefore, thermal advective patterns through the troposphere are very weak or nearly non-existent. However, the significant increases in thunderstorm occurrence, coverage, and intensity that do occur can frequently be a result of very small fluctuations of stability and moisture content.

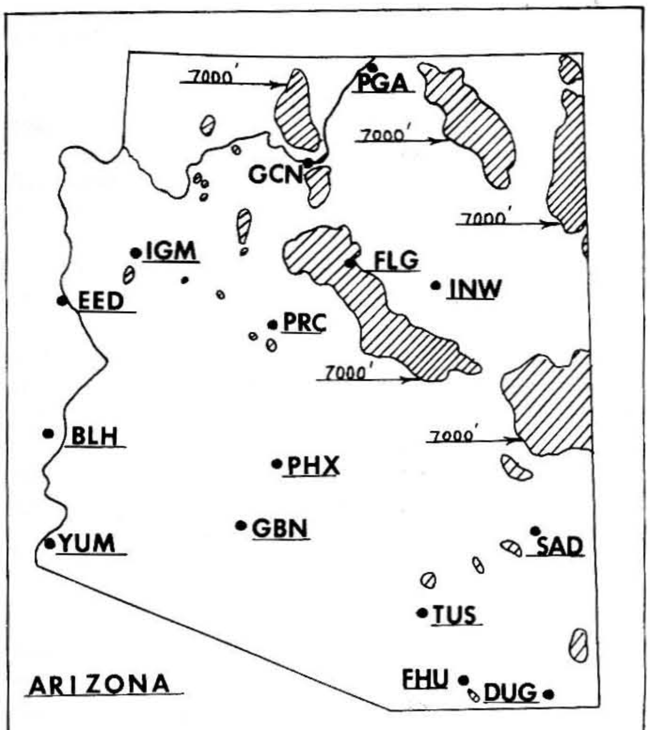


Figure 1. Schematic showing 7000 ft. elevation contour in Arizona

The most common processes by which this is accomplished are the Gulf Surges, upward motion associated with positive vorticity advection (PVA) and horizontal moisture and/or cold air advection at middle and high levels.

This paper will attempt to present a case study example where it is felt that the eventual airmass modification was primarily in response to organized, large-scale vertical motion associated with PVA. While it would be very difficult to analytically prove that the quantitative effects of factors other than PVA influences were isignificant, these factors will be mentioned and briefly evaluated subjectively in the synoptic review.

2. UPWARD MOTION AND ATMOSPHERIC DESTABILIZATION

During this segment of the year, the convective condensation level (CCL) in Arizona normally ranges around 12 or 13 thousand feet mean sea level (MSL). Generally located within a few thousand feet above this level is a slightly stable layer presumably caused by mechanical mixing. This layer typically serves as a damper on potential desert thunderstorm development. Over higher terrain, orographic influences frequently act to overcome the 'capping' effect of this stable layer and allow the release of potential instability.

It is generally recognized that as a result of PVA, an increase in upward motion (with the normal maximum near the level of this stable layer) may occur. At times, only slight PVA associated with vorticity values as low as $6x10^{-5}$ or $8x10^{-5}$ s^{-1} can rapidly and quite effectively unbalance the overall state of atmospheric equilibrium characteristic of the monsoon regime. The associated middle and upper tropospheric cooling and destabilization, though slight by middle latitude standards, can frequently be quite instrumental in the explosive release of instability nearly anywhere in the state.

3. UPWARD VERTICAL MOTION AND MOISTURE

Even slight upward motion can alter moisture distributions substantially, particularly in the middle troposphere, during a relatively short period of time. MacDonald (1975) illustrated this by assuming a large, horizontally homogeneous airmass in which the mixing ratio decreases with height. An initial relative humidity value at 50 kPa of 30% undergoing weak upward motion ($w=1$ ms^{-1}) was found to increase to 100% in a little over 24 h.

Upward motion, with a maximum at middle levels, generally has three primary effects on the existing moisture field. The first two are that mixing ratio and relative humidity of the air at any given pressure level above the surface will increase. Figure 2 is an illustration of the equation of conservation of water mass, which states:

Change of mixing ratio at a point = horizontal advection + vertical advection.

The horizontal advection does not alter the mixing ratio since the airmass was originally assumed to be horizontally uniform. However, since the mixing ratio was assumed to be highest at lower levels and generally decreases with height, the mixing ratio at all levels (except the surface) will increase as a result of vertical advection.

Relative humidity is defined as:

Relative Humidity = Observed Mixing Ratio/ Saturation Mixing Ratio.

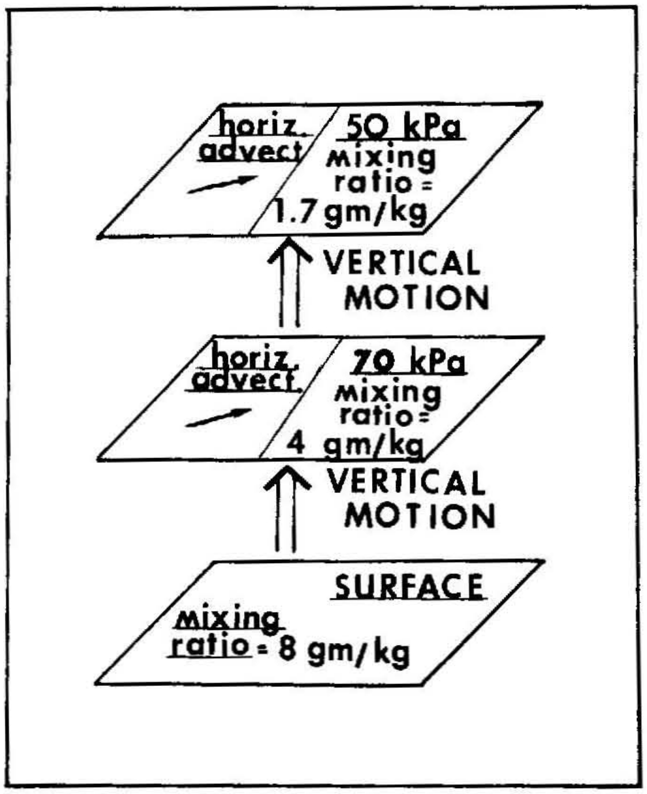


Figure 2. Increasing mixing ratio at all levels above the surface due to upward motion assuming a horizontally uniform airmass and decreasing mixing ratio with height

The saturation mixing ratio, being a function of temperature, decreases for a stable lapse rate because temperature would be decreasing. As discussed above, during periods of upward motion, observed mixing ratio increases at a given level above the surface. As a result, the relative humidity increases much more rapidly than other moisture parameters.

Figure 3 displays a third effect, which is how the precipitable water may increase during upward motion. The continuity of mass equation implies upward motion is associated with low level convergence and upper level divergence. Due to values of mixing ratio being much higher in the lower levels of the atmosphere, the water vapor that is converged inward at lower levels is not fully compensated by that which is diverged outward at higher altitudes. This results in a net increase in precipitable water. However, it should be noted that Figure 3 also suggests that consequent deep convection is even more effective in raising the moisture content of the middle levels. This process is actively engaged during Gulf Surges.

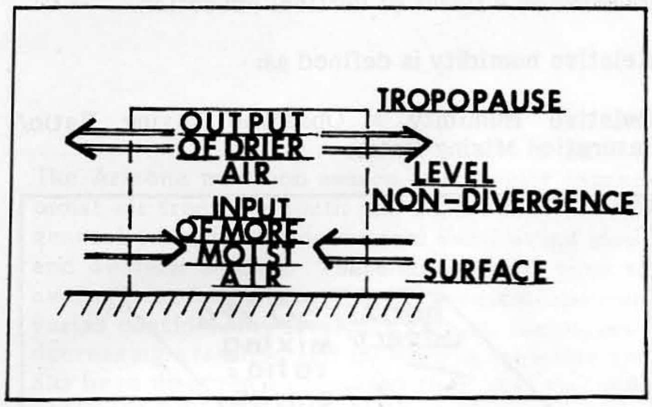


Figure 3. Increasing precipitable water during upward motion. Moisture increase at low levels due to convergence is not compensated fully by upper moisture divergence

4. SYNOPTIC REVIEW

A fine example of rapid airmass modification believed to have resulted primarily from vertical motion effects occurred during the 24 h period ending 0000 GMT 2 September 1976.

On 31 August (Figure 4), the surface situation was such that a thermal low was located near Thermal (TRM), California. A dissipating cold front extended southwestward from northeast South Dakota into northeast New Mexico. On 1 September (Figure 5), a relatively strong surface high was centered over south central Wyoming. The thermal low deepened nearly 4 mb during the last 24 h and was situated along the Colorado River near Blythe (BLH), California. This surface high-low combination created an unusually strong surface gradient for this time of year. Moderate to occasionally strong southeasterly winds dominated at Yuma (YUM) and Tucson (TUS) until midmorning when the gradient relaxed enough to weaken the winds. Over higher terrain, light to moderate northeast winds prevailed.

Although several of the prime ingredients for a true Gulf of California moisture surge were indeed present, it does not appear that this mechanism was involved during the period of this study. As observed in Figure 6; surface dewpoints did increase at YUM between 1700 LST 31 August and 0500 LST 1 September. This was in response to the strong low level wind flow crossing the north portion of the Gulf of California on its way

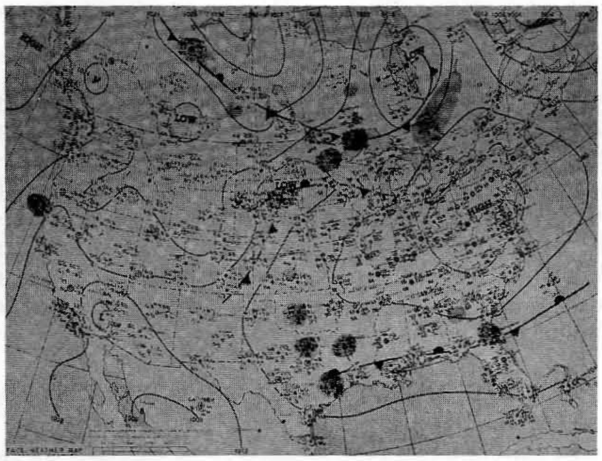


Figure 4. Surface analysis for 1200 GMT 31 August 1976

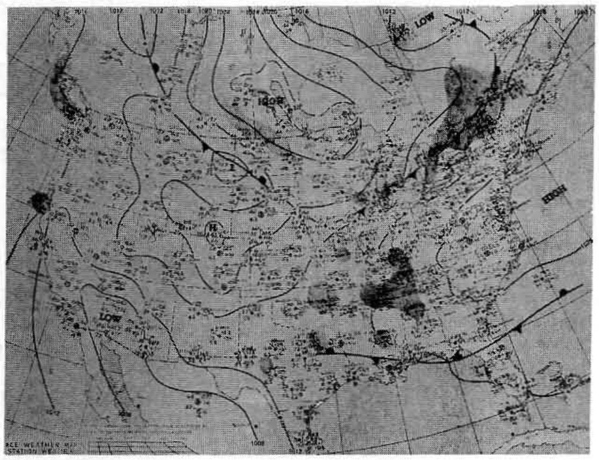


Figure 5. Surface analysis for 1200 GMT 1 September 1976

toward YUM. The primary difference between this situation and a Gulf Surge was that the low level high pressure cell was located over south central Wyoming rather than the central or southern portion of the Gulf of California. Therefore, being more of a sea-breeze than a Gulf Surge, the dewpoints began to lower at YUM as soon as the winds began to subside. In addition, the changes in the 85 kPa temperatures (not shown) at TUS, Empalme (EPM), and Mazatlan (MZT) did not follow the trend characteristic of a Gulf Surge (Brenner 1974). Further argument against the existence of a Gulf Surge from Figure 6 was the lack of any significant dewpoint increases at TUS or PHX.

Thunderstorm activity in Arizona for the 12 h period ending at 0000 GMT 1 September 1976, was somewhat less than characteristic of a normal monsoon day. A few to widely scattered thunderstorms were confined along and just below the east central mountains and over the higher terrain of southeastern Arizona. The 50 kPa analysis for

0000 GMT 1 September 1976 (Figure 7), indicated a ridge over the western states with general 'dry' northerly flow through Utah into northern Arizona. A short-wave trough moving southward into central Utah and northern Colorado was indicated by this more detailed analysis of the flow. By 1200 GMT 1 September 1976 (Figure 8), this short-wave trough continued southward and sharpened while phasing with a trough over Oklahoma and Kansas. This caused a slight retrogression of the western U.S. Ridge aloft. Ahead of this shortwave feature, in Arizona, considerable cooling and height falls began to affect the area. Winslow (INW) had cooled in 12 h 5°C concurrent with a height fall of 50 m at the 50 kPa level. TUS cooled 2°C and also realized a 50 m height fall. In addition, large temperature/dewpoint spreads at both stations at 0000 GMT 1 September 1976, had now modified to become quite small - in only 12 h. The refined 50 kPa analysis at 0000 GMT 2 September (Figure 9), showed a very sharp trough now situated across northern Arizona. The air at this level was saturated at both INW and TUS.

Figure 10 shows the initial vorticity analysis for 1200 GMT 1 September 1976 from the Primitive Equation (PE) model as well as the respective 12 h prognoses. Figure 11 displays the same for the Limited Fine Mesh (LFM) model. The Barotropic was not used in the analysis since the southward moving trough was considered to be baroclinic in nature. When compared with Figure 8, it can be seen that neither model initialized the contour pattern associated with the trough sharp enough. However, in view of the events observed on the available satellite pictures, it was concluded that the location of the vorticity maximum, the configuration of the vorticity trough, and the PVA pattern of the LFM analysis was superior to that of the PE. A further comparison with Figure 9 also indicated that both 12 h progs did a poor job in forecasting the configuration of the 588 contour in the region of the trough through northern Arizona and southern Nevada. Despite this, each model did appear to forecast the location and orientation of the associated vorticity trough with relative accuracy. The forecast vorticity pattern of the LFM, however, was considered the better product at the time, since the initial analysis was the best.

The LFM initial analysis for 0000 GMT 2 September, was in fact not too unlike the corresponding 12 h prognosis from Figure 11. In an attempt to obtain a reasonably accurate representation of the observed vorticity advection pattern at 0000 GMT 2 September, this initial vorticity analysis was superimposed upon the refined 50 kPa analysis of Figure 9. The result, shown in Figure 12, clearly indicates an area of weak PVA across northern Arizona.

An examination of the vertical wind profiles (not shown) at both INW and TUS revealed a general increase in wind speeds with height at both stations to be an altitude of nearly 12,000 m. From the Omega equation, PVA at 50 kPA concurrent with increasing wind speeds with height yields upward motion.

Effects of the increase in upward motion can be seen graphically in Figure 13. Shown is a plot at 12 h intervals of the increasing observed mixing ratio (gm/kg) at both INW and TUS at three standard levels from 0000 GMT 1 September

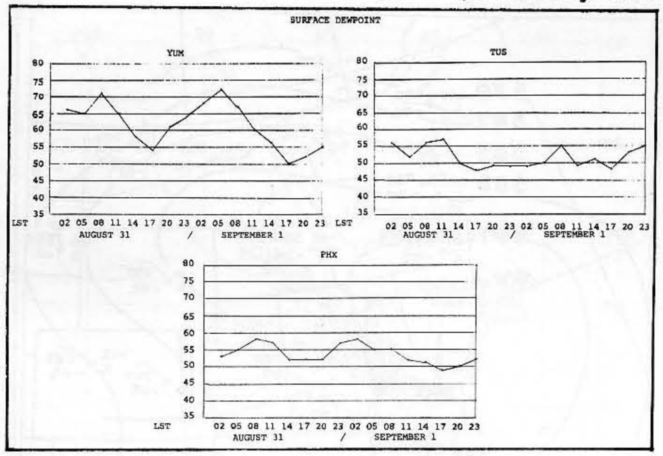


Figure 6. Dewpoint values at 3 h intervals at YUMA, TUCSON and PHOENIX

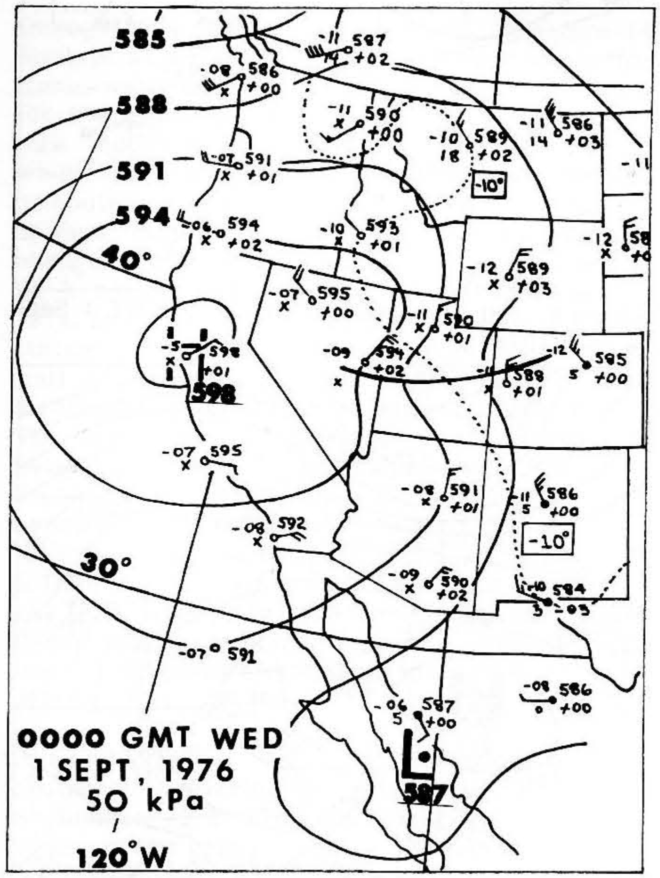


Figure 7. 50 kPa analysis for 0000 GMT 1 September 1976

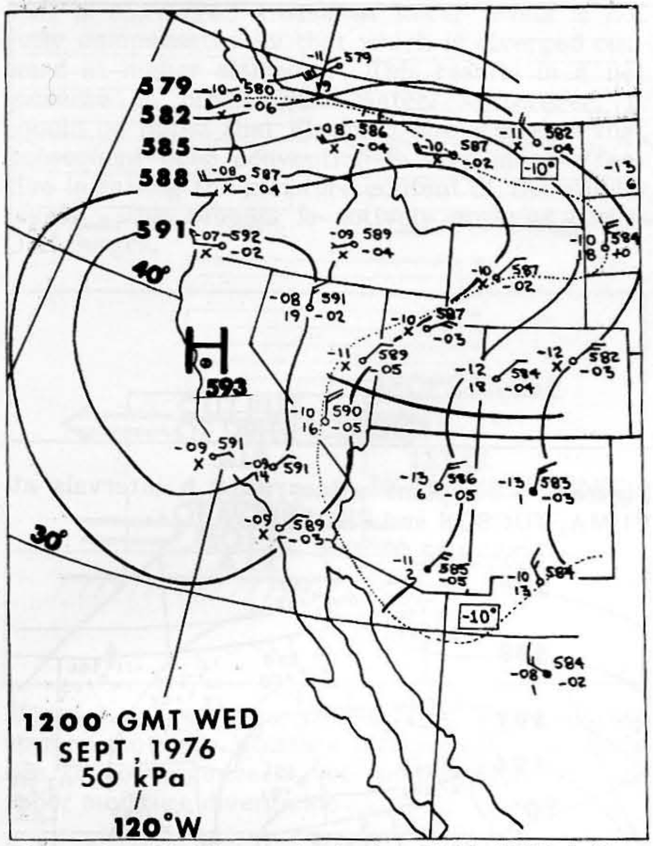


Figure 8. 50 kPa analysis for 1200 GMT 1 September 1976

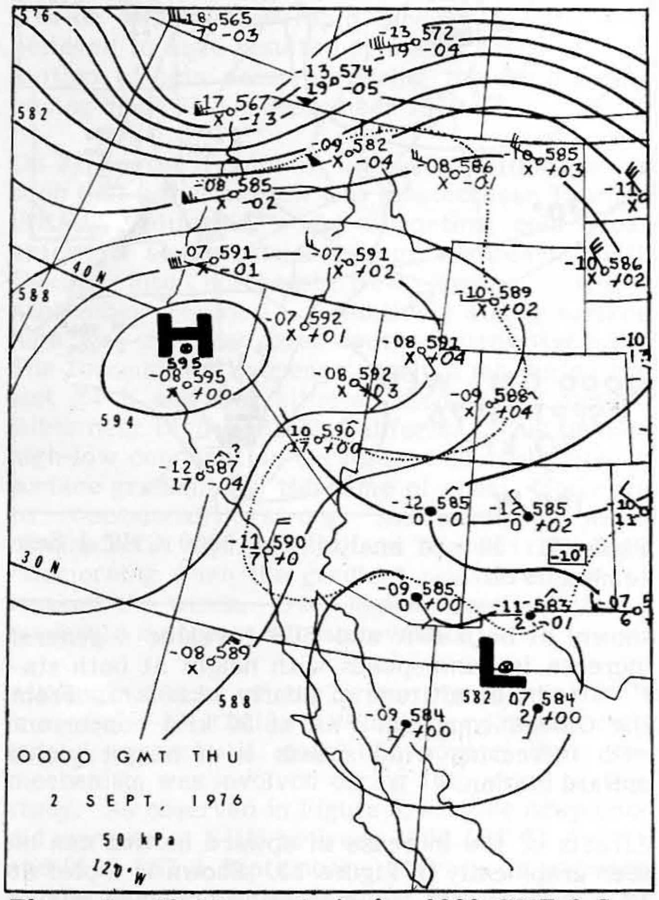


Figure 9. 50 kPa analysis for 0000 GMT 2 September 1976

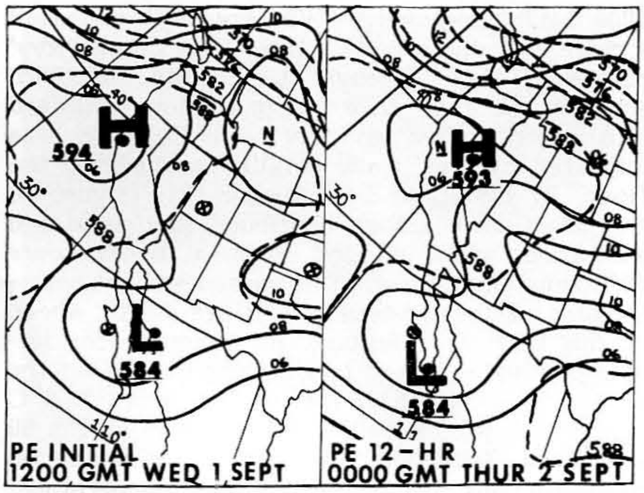


Figure 10. Initial vorticity analysis for 1200 GMT 1 September 1976 from the Primitive Equation (PE) model and 12 hr prognosis

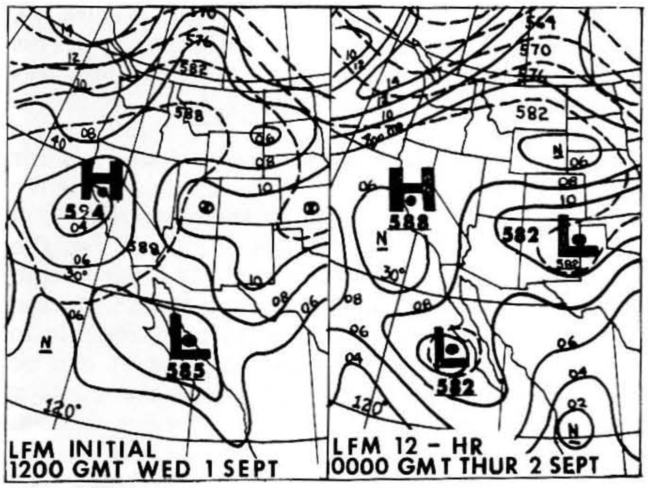


Figure 11. Initial vorticity analysis for 1200 GMT 1 Septembe 1976 from the Limited Fine Mesh (LFM) model and 12 hr prognosis

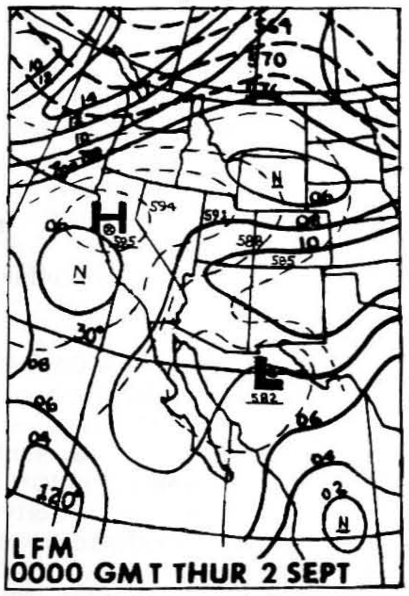


Figure 12. LFM initial vorticity analysis for 0000 GMT 2 September 1976 with refined 50 kPa analysis for same time superimposed

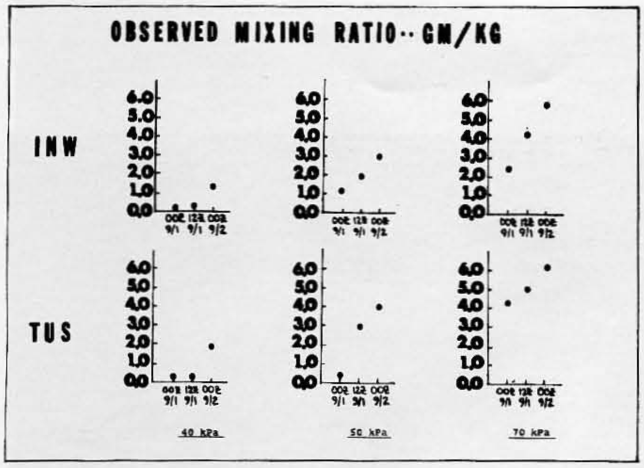


Figure 13. Observed mixing ratio at INW and TUS at 12 hr intervals from 0000 GMT 1 September 1976 at 40 kPa, 50 kPa, and 70 kPa

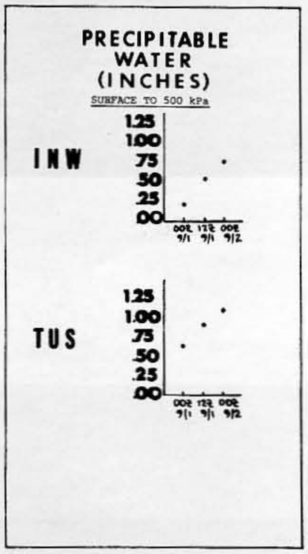


Figure 14. Precipitable water values (surface to 50 kPa) at INW and TUS at 12 hr intervals from 0000 GMT 1 September 1976

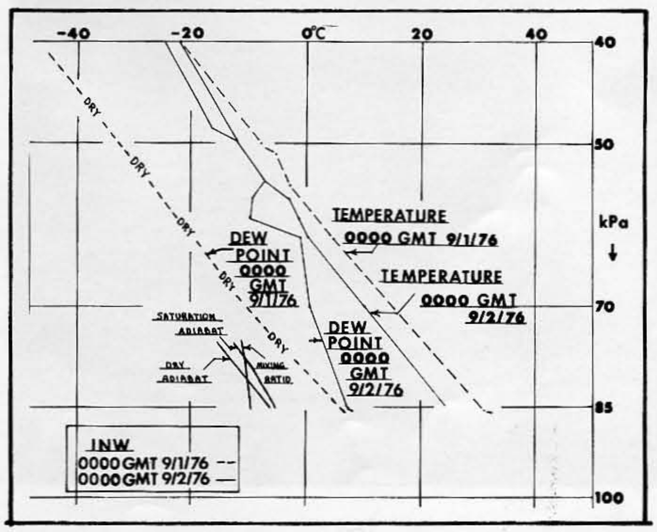
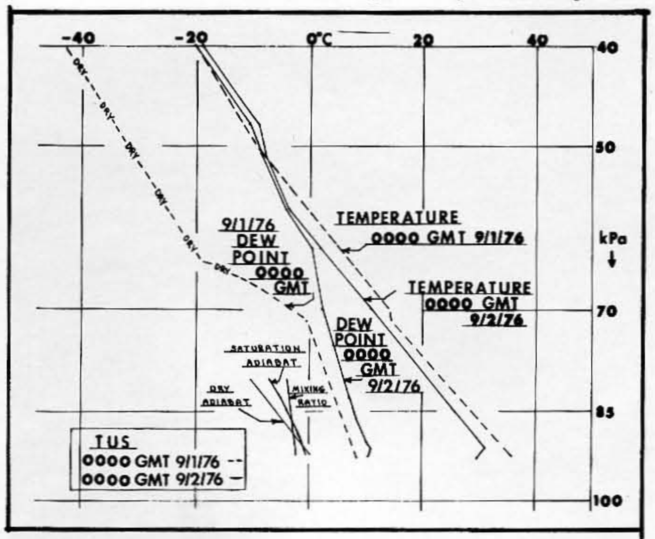


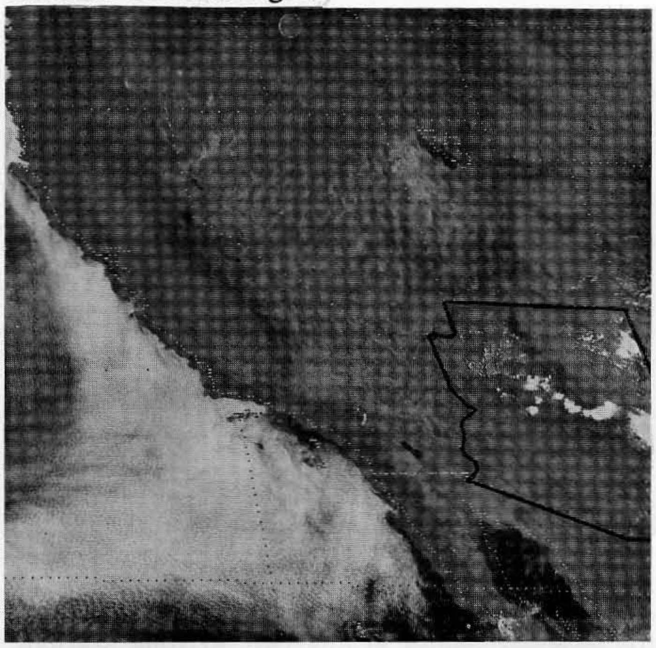
Figure 15. Vertical temperature and moisture profiles at a) INW and b) TUS for the 24 hr period ending at 0000 GMT 2 September 1976



through 0000 GMT 2 September 1976. Figure 14 displays at 12 h intervals the increase in precipitable water values at the two Arizona stations for the same period. Both figures exhibit moisture modification remarkable similar to that which MacDonald and Bullock (1978) obtained in a computer simulation of the idealized effects of upward motion. Temperature and moisture changes in the vertical at INW and TUS during the 24 h period ending at 0000 GMT 2 September 1976, are shown in Figures 15a and 15b. At each station the striking modification of moisture, as well as temperature fields, is nearly identical to MacDonald and Bullock's computer simulation. The small-scale retrogression of the ridge aloft between 0000 GMT 1 September and 1200 GMT 1 September, undoubtedly allowed some of the moist air over New Mexico to shift into Arizona. However, this was believed to be a small contribution, as the main trajectory of the flow at 50 kPa into Arizona by 1200 GMT 1 September, was from Utah and western Colorado - a region where large temperature/dewpoint spreads were indicated just 12 h previous.

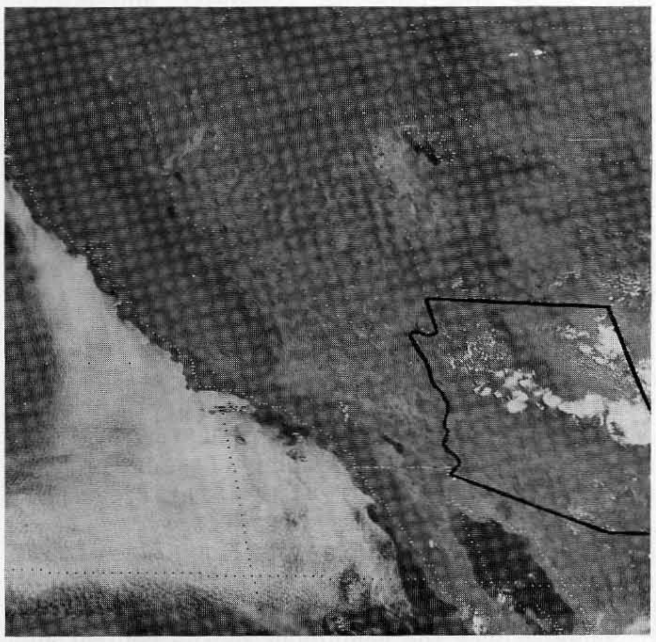
Available SMS-2 half-mile resolution satellite photographs covering the period 1915-2315 GMT 1 September 1976, are shown in Figures 16a-16h. Although the grid is slightly off center, initially, it can be seen that cumulonimbus development appeared to be favoring the usual orographic areas of Arizona. Wide-spread activity had already developed over the White Mountains of east central Arizona. However, by 2045 GMT, it became apparent that thunderstorms were not developing over the remainder of the central and northern mountains, as was normally the case, but rather from the White Mountains westward toward the lower terrain and deserts of western Arizona.

Thunderstorm development so early in the day over western Arizona was a clue to the existence of a dynamic mechanism. By 2145 GMT, a well

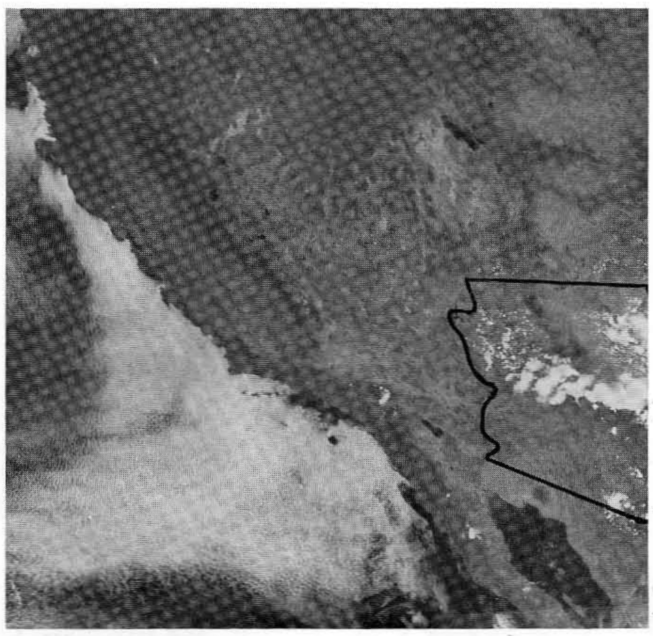


16a

16c

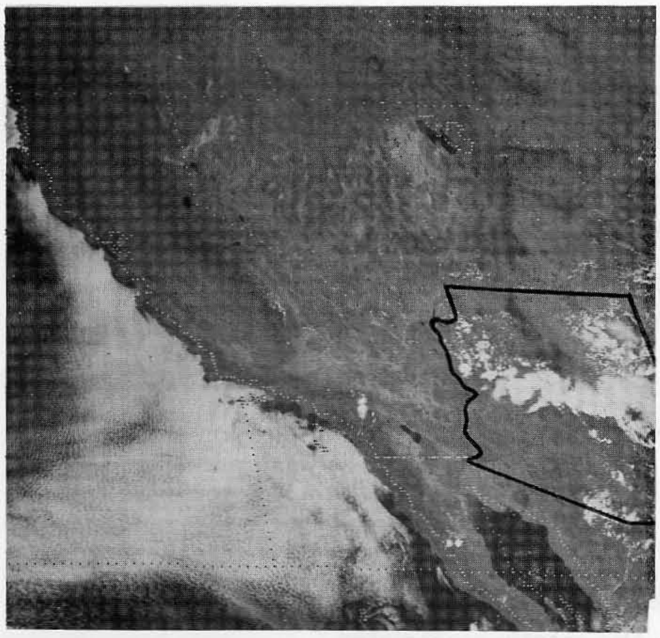


16b

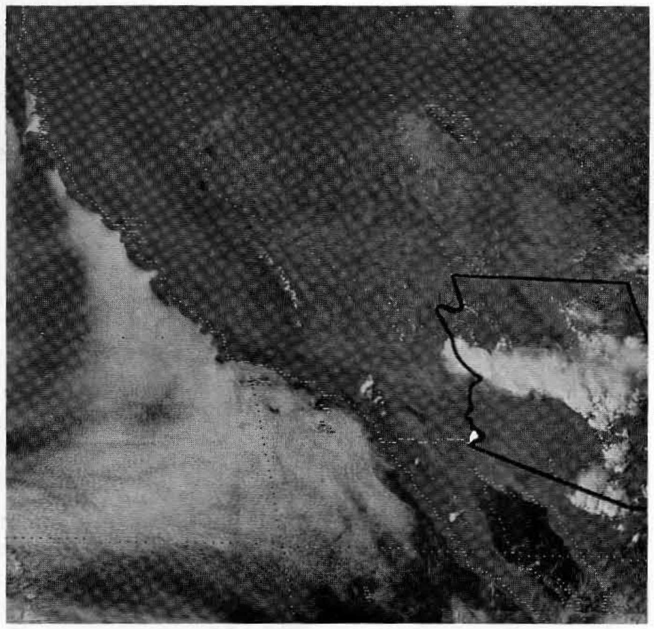


16d

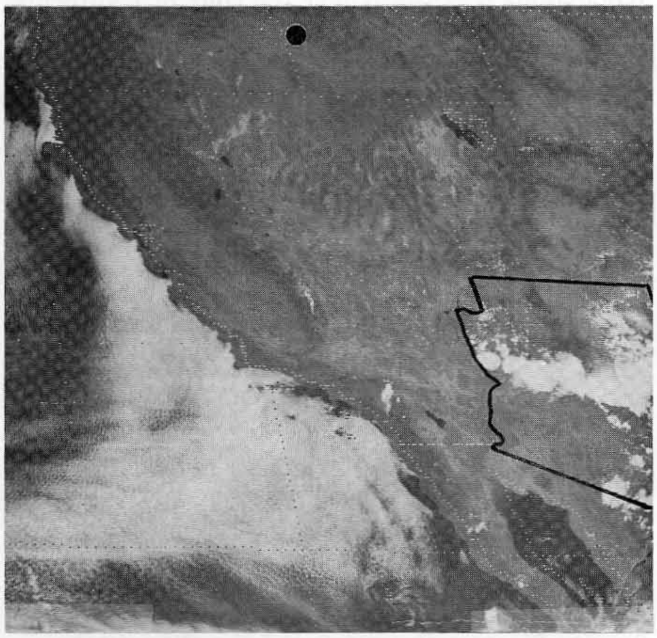
Figure 16. a) – h) Available SMS-2 half-mile resolution satellite photographs for the period 1915 GMT through 2315 GMT 1 September 1976



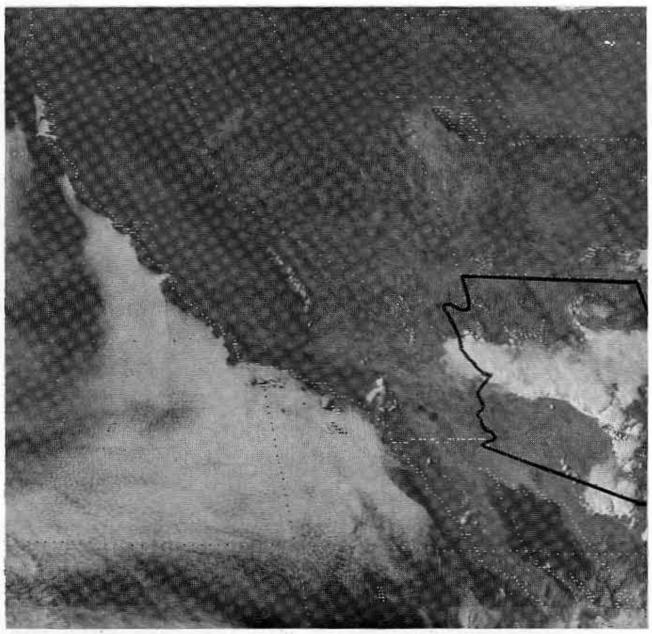
16e



16g



16f



16h

developed east-west line of vigorous thunderstorms stretched across central Arizona. The lack of any significant thunderstorms on either side of this line illustrated the existence of a very concentrated region of upward motion. With the aid of the low sun angle, the 2315 GMT picture clearly shows newly developing thunderstorms along the southern edge of the line.

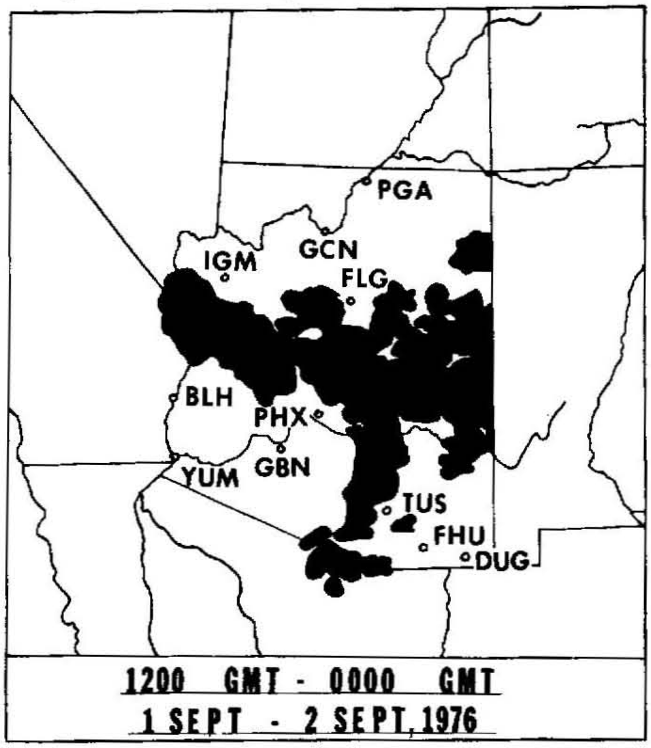


Figure 17. Composite radar chart west of the Arizona-New Mexico border for the 12 hr period ending 0000 GMT 2 September 1976

The Western Region composite radar chart for the area west of the Arizona-New Mexico border covering the 12 h period from 1200 GMT 1 September 1976, to 0000 GMT 2 September (Figure 17), delineates the thunderstorm areas quite well.

5. CONCLUSIONS

Upward motion can rapidly modify existing stability and moisture fields. The associated middle and upper level cooling and destabilization can allow an explosive release of potential instability. The effects on moisture distribution in the vertical are primarily threefold in nature:

1. Mixing ratio will increase, with the most rapid rate of increase in the middle troposphere.
2. Relative humidities will increase with the maximum rate of increase in the middle troposphere.
3. Precipitable Water will increase.

It is, therefore, quite important to realize that even when the atmosphere appears "dry", sufficient moisture does exist to allow rapid modification when an upward motion field is superimposed on the area. Advection of moisture or cloud fields should certainly be a main consideration of forecasters contemplating a possible precipitation regime. However, consideration must also be given to how a given moisture or cloud field is expected to be modified by the vertical motion field.

ACKNOWLEDGMENTS

Special thanks for both inspiration and evaluation are in order for Len Snellman and Dr. Alexander E. MacDonald, Chief and Meteorologist, respectively, of Scientific Services Division of the National Weather Service Western Region Headquarters. The conscientious typing effort of Mrs. Tommie McCabe, secretary of Phoenix WSFO, is also greatly appreciated.

REFERENCES

Brenner, I. S., 1974: A surge of maritime tropical air - Gulf of California to the southwestern United States. *Mon. Wea. Rev.*, V. 102, pp. 375-389.

Hales, J. E., Jr., 1972a: Surges of maritime tropical air northward over the Gulf of California. *Mon. Wea. Rev.*, V. 100, pp. 298-306.

Hales, J. E., Jr., 1972b: A study of radar echo distribution in Arizona during July and August. *NOAA Tech. Memo, NWS WR-77*, 21 pp.

Hales, J. E., Jr., 1973: Southwestern United States summer source - Gulf of Mexico or Pacific Ocean? *NOAA TEch. Memo, NWS WR-84*, 26 pp.

Ingram, R. S., 1972: Arizona summer monsoon: true or false? NWS Manuscript, on file National Weather Service Forecast Office, Phoenix, Arizona, 17 pp.

Jurwitz, L. R., 1953: Arizona's two-season rainfall pattern. *Weatherwise*, V. 6, pp. 96-99.

MacDonald, A. E., 1975: Modification of moisture fields by vertical motion. *Western Region NWS Tech. Attachment No. 75-24*, National Weather Service Western Region, Salt Lake City, Utah.

MacDonald, A. E., and C. S. Bullock, 1978: Effects of vertical motion. Western Region NWS instructional video tape, Salt Lake City, Utah.

Sellers, W. D., and R. H. Hill (Eds.), 1974: *Arizona climate.* Tucson University of Arizona Press, 616 pp. (see pp. 6-19).