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MOISTURE DISTRIBUTION MODIFICATION BY UPWARD VERTICAL MOTION

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ABSTRACT. During the Arizona summer monsoon season, large-scale air-mass changes within the state are generally quite minimal. Nevertheless, the coverage and intensity of Arizona's daily thunderstorm activity does vary considerably. Increases in thunderstorm activity can frequently be attributed to decreasing stability, as well as increasing precipitable water, mixing ratio, and relative humidity due to upward vertical motion commonly associated with positive vorticity advection. It has been found that "dry" air, undergoing weak upward vertical motion, can easily become saturated at middle and upper levels in slightly over 24 hours. A case study during which these processes were actively engaged is presented.

I. INTRODUCTION

Arizona thunderstorms are almost a daily occurrence during the summer monsoon season (Sellers 1974). These thunderstorms 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 1972).

During the period of the Arizona monsoon, large-scale moisture-laden easterly flow prevails over the state (Jurwitz 1953, Ingram 1972). Complementing this generally light flow aloft are surges of very moist tropical maritime air at low levels which move into Arizona from the west coast of Mexico and the Gulf of California regions (Hales 1972, 1973; Brenner 1974).

Intense solar insolation prevails during the monsoon months and results in very unstable lapse rates over the state daily (Hales 1972). However, counterbalancing this otherwise explosive condition is the fact that, in general, air-mass changes over the state are quite subtle (Brenner 1974), since the main belt of the westerlies are so far removed to the north. Thermal advective patterns through the troposphere are very weak or nearly nonexistent. Day to day precipitable water values vary little during typical monsoon conditions (Reitan 1957).

Therefore, meteorological factors that can significantly alter the magnitude and intensity of Arizona's daily thunderstorm activity are primarily restricted to atmospheric destabilization and enhancement of upward vertical motion due largely to positive vorticity advection (PVA). At times, slight PVA associated with vorticity values as low as 6×10^{-5} or 8×10^{-5} sec^{-1} can rapidly and quite effectively unbalance the overall state of atmospheric equilibrium characteristic of the monsoon regime. A situation that is perhaps unique to Arizona during this segment of the year is that the convective condensation level normally ranges around 12 or 13 thousand feet MSL. Generally located within a few thousand feet above this level is a slightly stable layer due to mechnical mixing that typically serves as a damper on potential desert thunderstorm development. Over higher terrain, orographic influences act to overcome the "capping" effect of the stable layer and allow the release of potential instability.

However, as a result of PVA, an increase in upward vertical motion (UVV), with the normal maximum near the level of this stable layer, may result. 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 potential instability nearly anywhere in the state.

The effects of upward vertical motion on stability conditions should not be underemphasized. However, this paper will primarily concentrate on the modifying influence UVV exerts on moisture distribution.

II. UPWARD VERTICAL MOTION

Even slight upward vertical motion can significantly alter moisture distributions, particularly in the middle troposphere, during a relatively short period of time. MacDonald (1975) illustrated this by assuming a large, horizontally homogenous air mass in which the mixing ratio decreases with height. An initial relative humidity value at 50 kPa of 30% undergoing weak UVV ($\omega = -1$ microbar per sec) was found to increase to 100% in a little over 24 hours.

Upward vertical motion, with a maximum at middle levels, generally has three primary effects on the existing moisture field. The first two are that mixing ratio of the air at any given pressure level above the surface will increase as will the relative humidity. Figure 2 is an illustration of the equation of conservation of water mass, which states (assuming no precipitation):

CHANGE OF MIXING RATIO AT A POINT = HORIZONTAL ADVECTION + VERTICAL ADVECTION.

The horizontal advection does not alter the mixing ratio since the air mass 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 during upward vertical motion.

Relative humidity is defined as:

RELATIVE HUMIDITY = OBSERVED MIXING RATIO/SATURATION MIXING RATIO.

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 vertical 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 the third effect, which is how the precipitable water also increases during UVV. Due to values of mixing ratio being much higher in the lower levels of the atmosphere, the water vapor that is converged inward is not compensated by that which is diverged outward at higher altitudes. This results in a net increase in precipitable water.

III. SYNOPTIC REVIEW

A fine example of modification of moisture and stability fields due to upward vertical motion occurred during the 24-hour period ending 0000 GMT 2 September 1976. Thunderstorm activity in Arizona for the 12-hour period ending 0000 GMT 1 Septmeber 1976, was somewhat less than characteristic of a normal monsoon day. A few to widely scattered thunderstorms were confined along and just downstream of the east-central mountains and over the higher terrain of southeastern Arizona.

The 50-kPa analysis for 0000 GMT 1 September 1976 (Figure 4), indicated a ridge over the western states with general "dry" northerly flow through Utah into northern Arizona. A suggestion of a short-wave trough moving southward into central Utah and northern Colorado was indicated by the height changes and more detailed analysis of the flow. By 1200 GMT 1 September 1976 (Figure 5), this short-wave trough continued southward and sharpened while phasing with a trough over Oklahoma and Kansas. Ahead of this short-wave feature, in Arizona, considerable cooling and height falls began to affect the area. By 1200 GMT 1 September 1976, Winslow (INW) had cooled in 12 hours 5 degrees C concurrent with a height fall of 50 meters at the 50-kPa level. Tucson (TUS) cooled 2 degrees C and also realized a 50 meter height fall. In addition, large temperature/dew-point spreads at both stations at 0000 GMT 1 September 1976, had now modified to become quite small--in only 12 hours. Horizontal advection of moist air at middle and high levels as the primary cause of this change appeared unlikely. The trajectory of the flow at 50 kPa, for instance, into Arizona was now from Utah and western Colorado--where large temperature/dew-point spreads were indicated 12 hours previous. All factors strongly suggest that an increase in upward vertical motion over the state, ahead of the short-wave trough, contributed significantly to the changes that were occurring.

Figures 6 and 7 show the initial vorticity analyses for 1200 GMT 1 September 1976, from both the Primitive Euqation (PE) and Limited Fine Mesh (LFM) models as well as the respective 12-hour prognoses. The locations of the vorticity trough over Utah on both initial analyses were adequate. The LFM indicated considerable PVA into Arizona during the day (Figure 7a). The PE also showed PVA, although not with the vigor of the LFM (Figure 6a). Both models indicated that a well-defined trough would be aligned east-west across northern Arizona by 0000 GMT 2 September 1976, with PVA over central Arizona (Figures 6b and 7b).

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 an altitude of nearly 12,000 meters. From the Omega equation, PVA at 50 kPa concurrent with increasing wind with height yields upward vertical motion.

Effects of the increase in upward vertical motion can be seen graphically in Figure 8. Shown is a plot at 12-hour intervals of the increasing observed mixing ratio (gm/kg) at both INW and TUS at three standard levels from 0000 GMT 1 September through 0000 GMT 2 September 1976. Figure 9 displays at 12-hour intervals the increase in precipitable water values at the two Arizona stations for the same period. Temperature and moisture changes in the vertical at INW and TUS during the 24-hour period ending at 0000 GMT 2 September 1976, are displayed in Figures 10a and 10b. In both cases, the striking increase in moisture that is clearly indicated, particularly at middle and higher levels, cannot be satisfactorily explained by advection.

Available SMS-2 half-mile resolution satellite photographs covering the period 1915-2315 GMT 1 September 1976, are shown in Figures 11a-11h. Initially, cumulonimbus development appeared to be favoring the usual orographic areas of Arizona with widespread activity already over the White Mountains. However, by 2045 GMT, it became apparent that thunderstorms were <u>not</u> 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 had the signature of dynamic lifting. By 2145 GMT, a well-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 strong subsidence regime bracketing the area. With the aid of the low sun angle, the 2315 GMT picture clearly shows the newly developing thunderstorms along the southern edge of the line.

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

IV. CONCLUSIONS

Upward vertical motion can rapidly modify existing moisture and stability fields. 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 earth's atmosphere is "dry", sufficient moisture exists to result in rapid modification as a function of the vertical motion field superimposed on the area. It follows that advection of moisture or cloud fields should not necessarily be the primary concern of forecasters contemplating a possible precipitation regime. Consideration must be given to how a given moisture or cloud field is expected to be modified by the vertical motion field.

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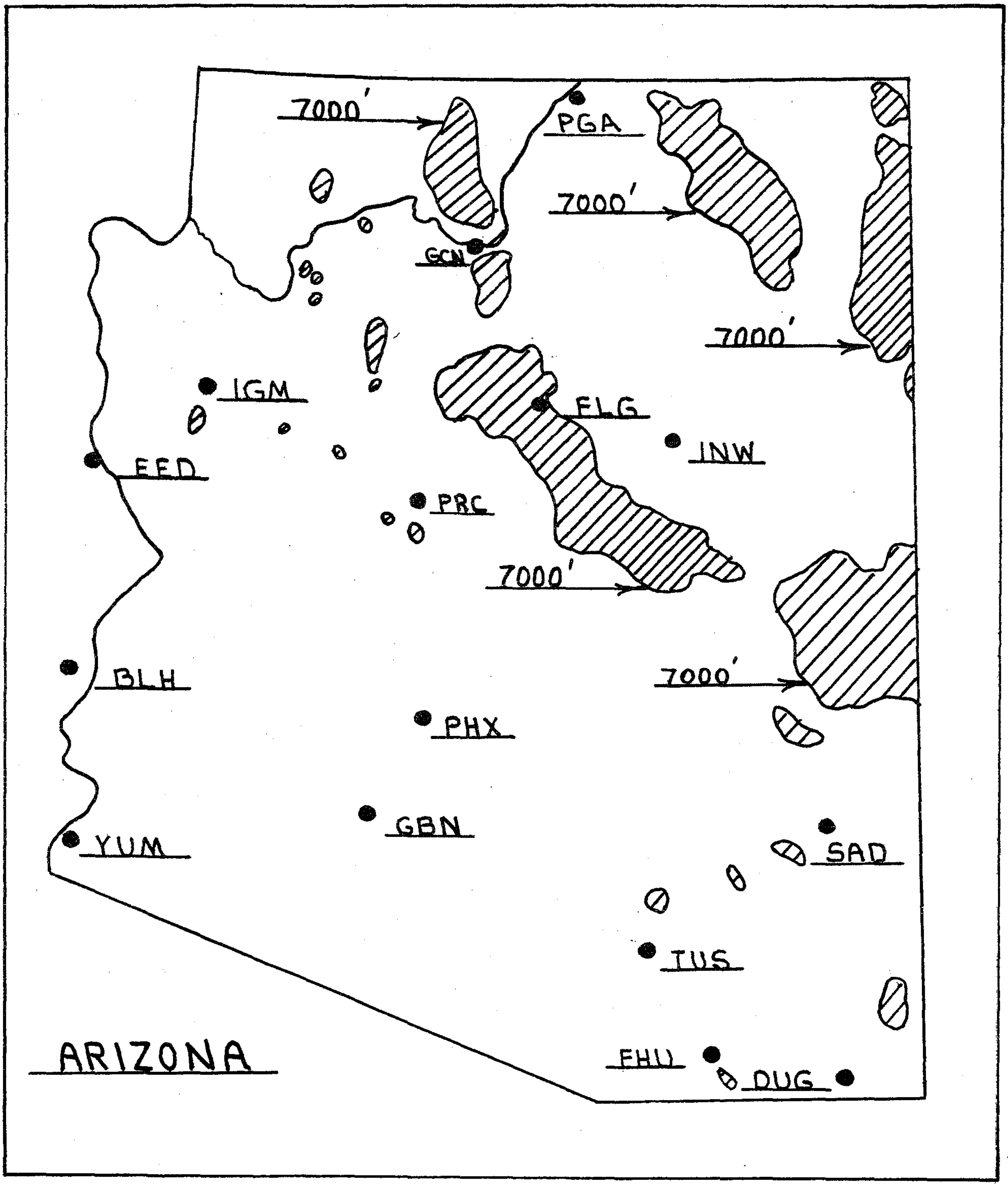


Figure I. Schematic showing 7000-ft. elevation contour in Arizona.

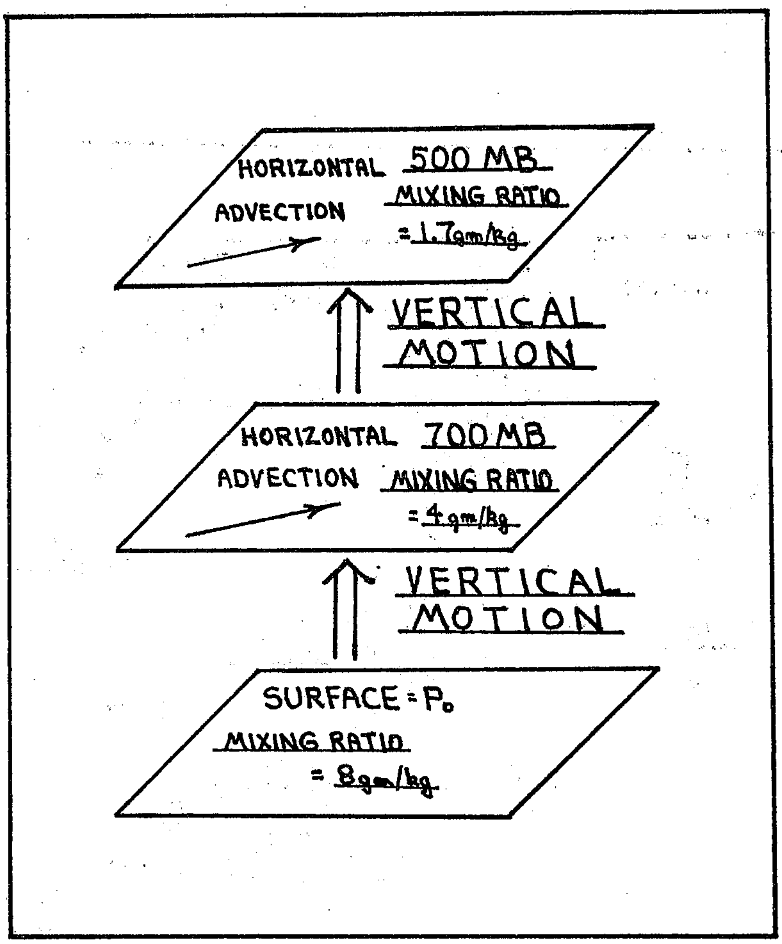


Figure 2. Increasing mixing ratio at all levels above the surface due to upward vertical motion assuming a horizontally uniform air mass and decreasing mixing ratio with height.

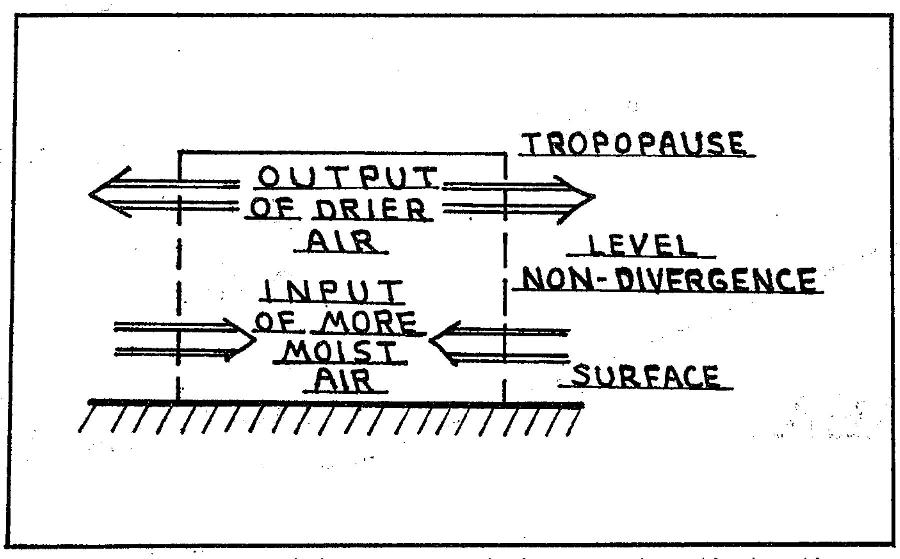


Figure 3. Increasing precipitable water during upward vertical motion. Moisture increase at low levels due to convergence is not compensated fully by upper level moisture divergence.

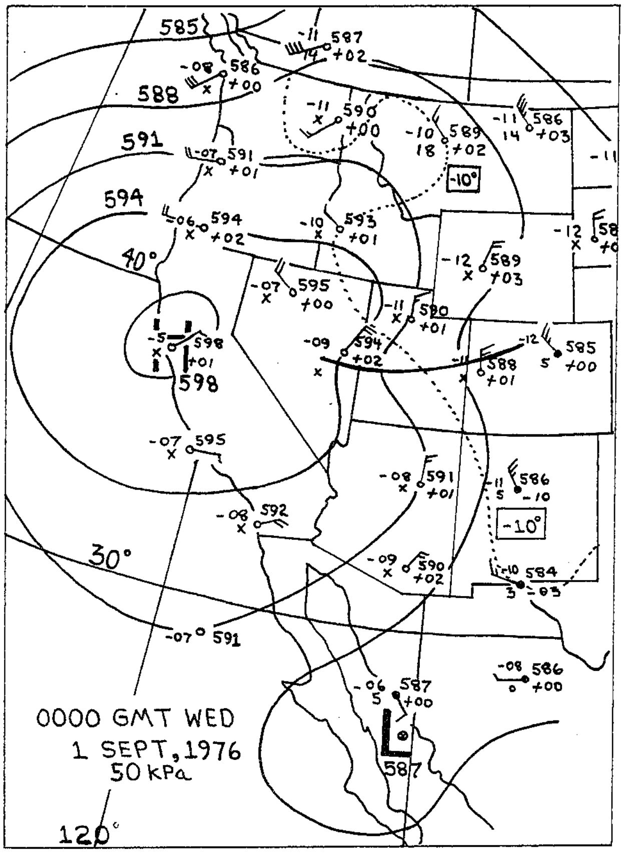


Figure 4. 50-kPa analysis for 0000 GMT 1 September 1976.

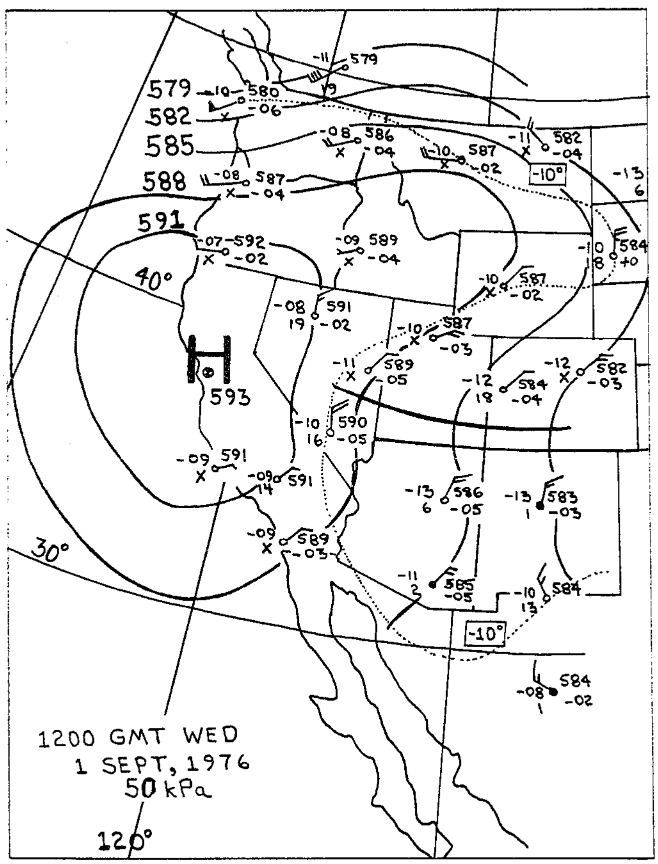


Figure 5. 50-kPa analysis for 1200 GMT 1 September 1976.

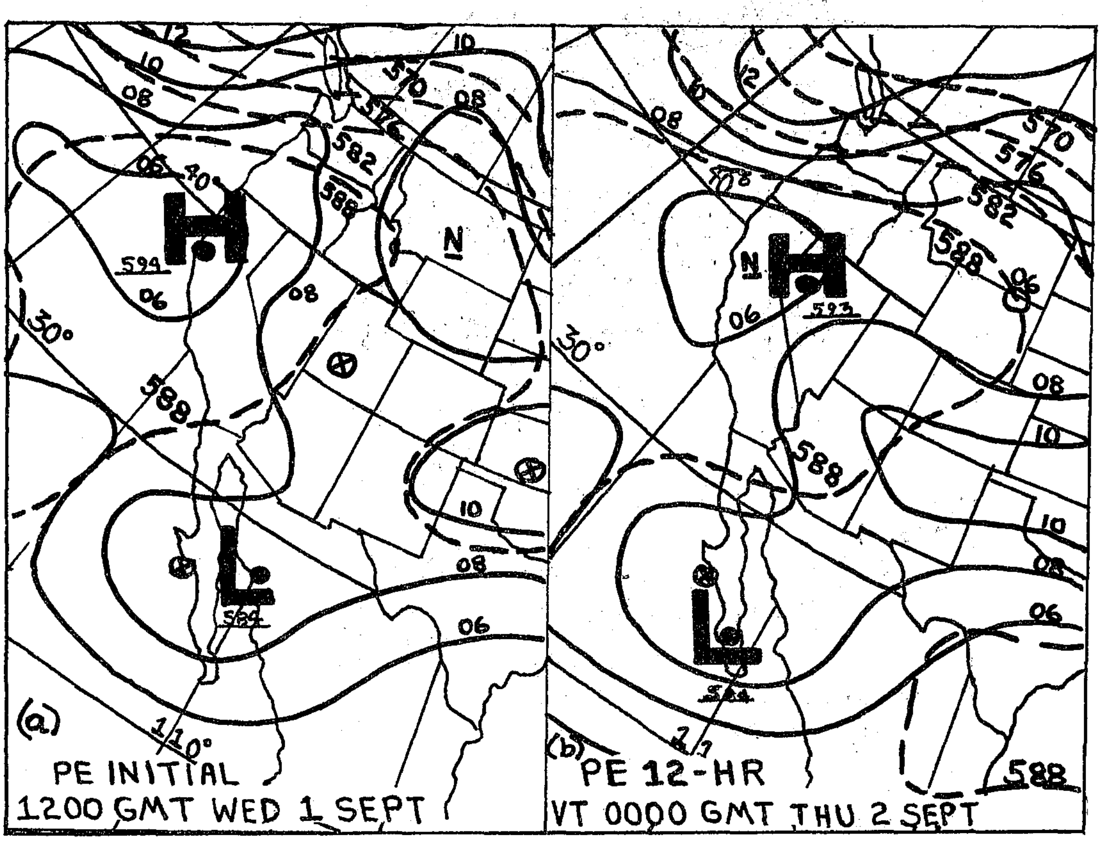


Figure 6. a) Initial vorticity analysis for 1200 GMT 1 September 1976 from the Primitive Equation (PE) model and b) 12-hour prognosis.

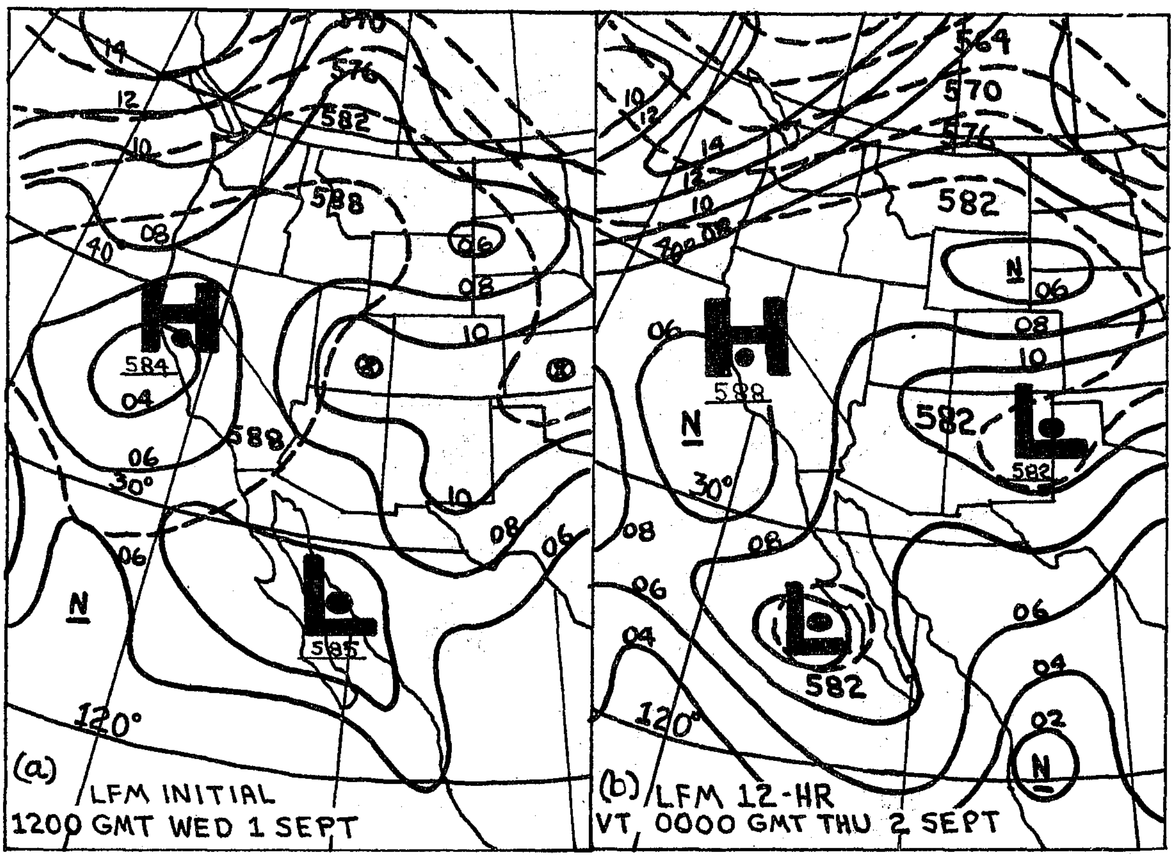


Figure 7. a) Initial vorticity analysis for 1200 GMT 1 September 1976 from the Limited Fine Mesh (LFM) model and b) 12-hour prognosis.

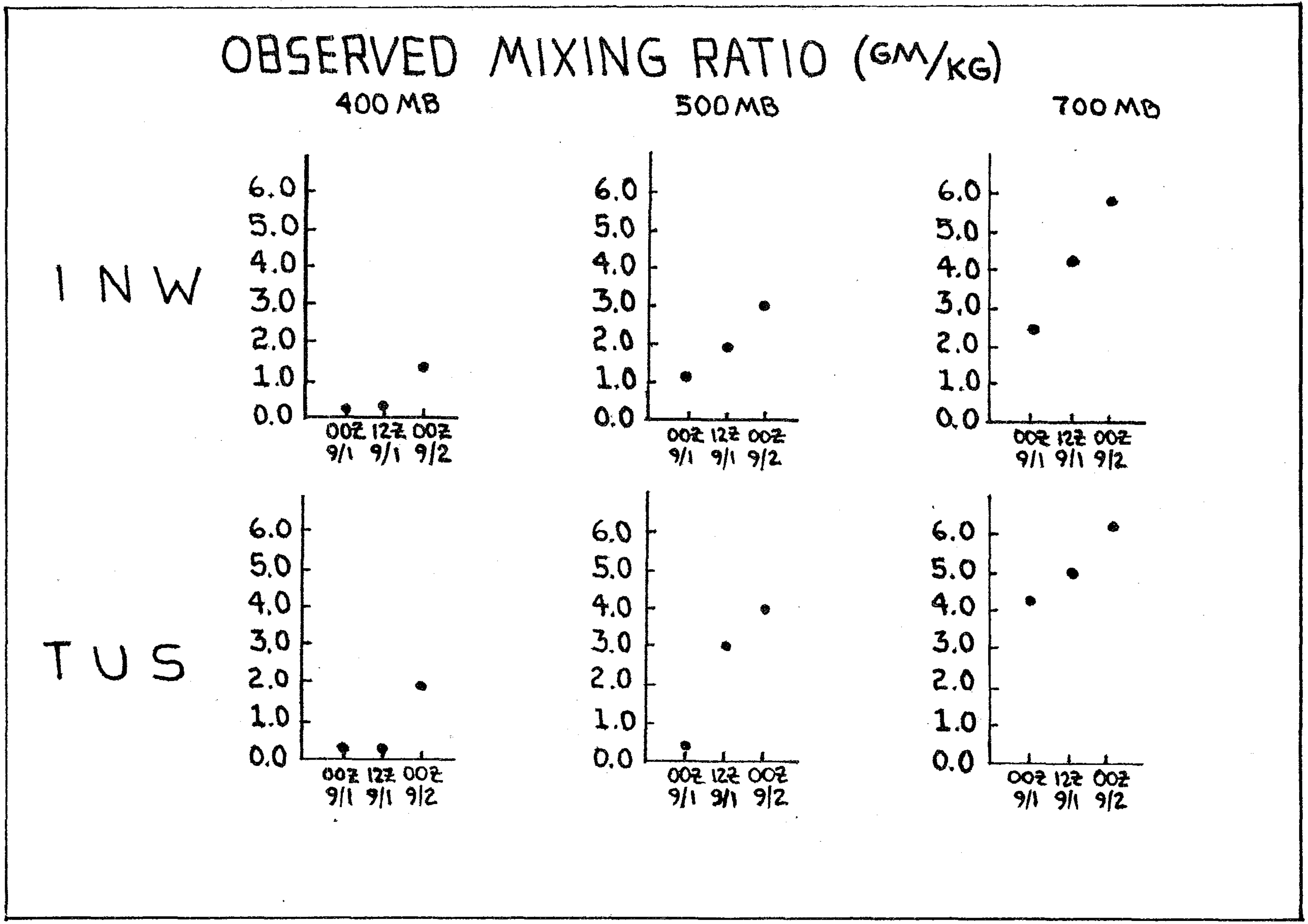


Figure 8. Observed mixing ratio at INW and TUS at 12-hour intervals from 0000 GMT 1 September 1976 at 400 kPa, 500 kPa, and 700 kPa.

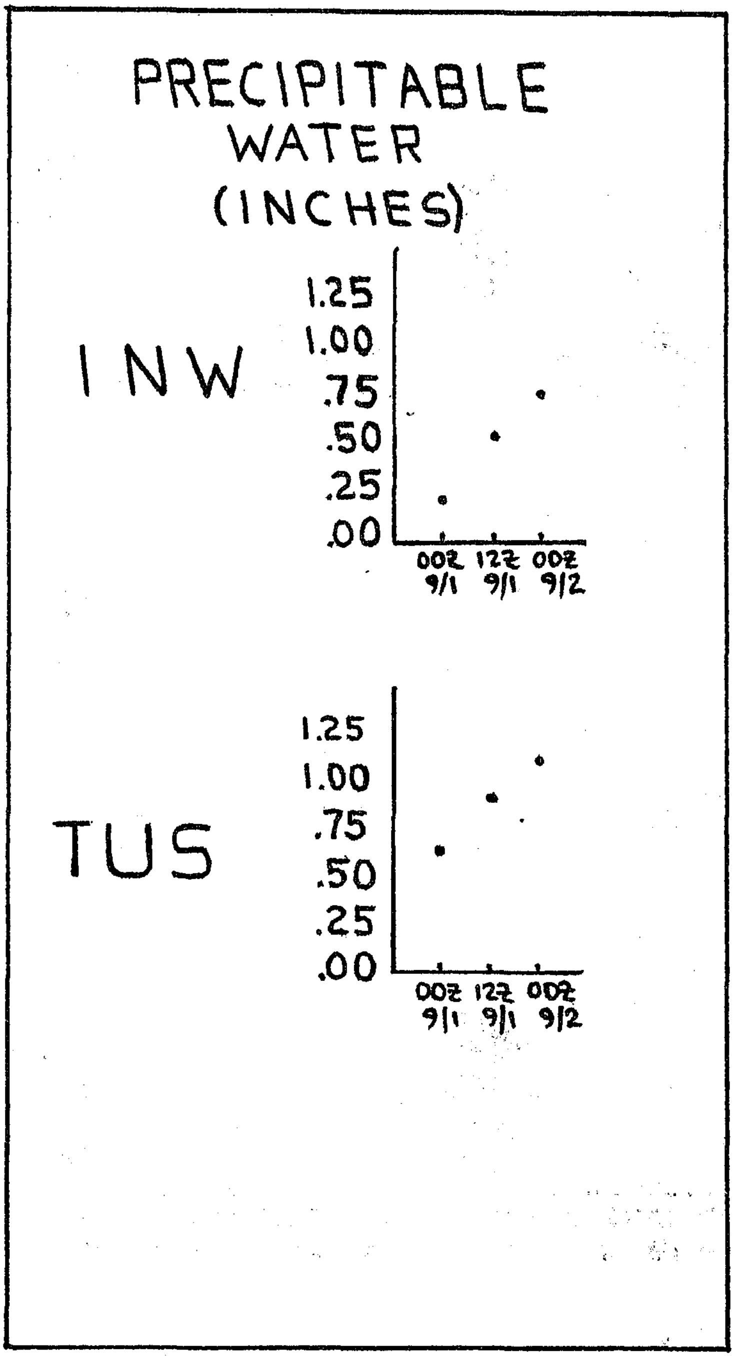
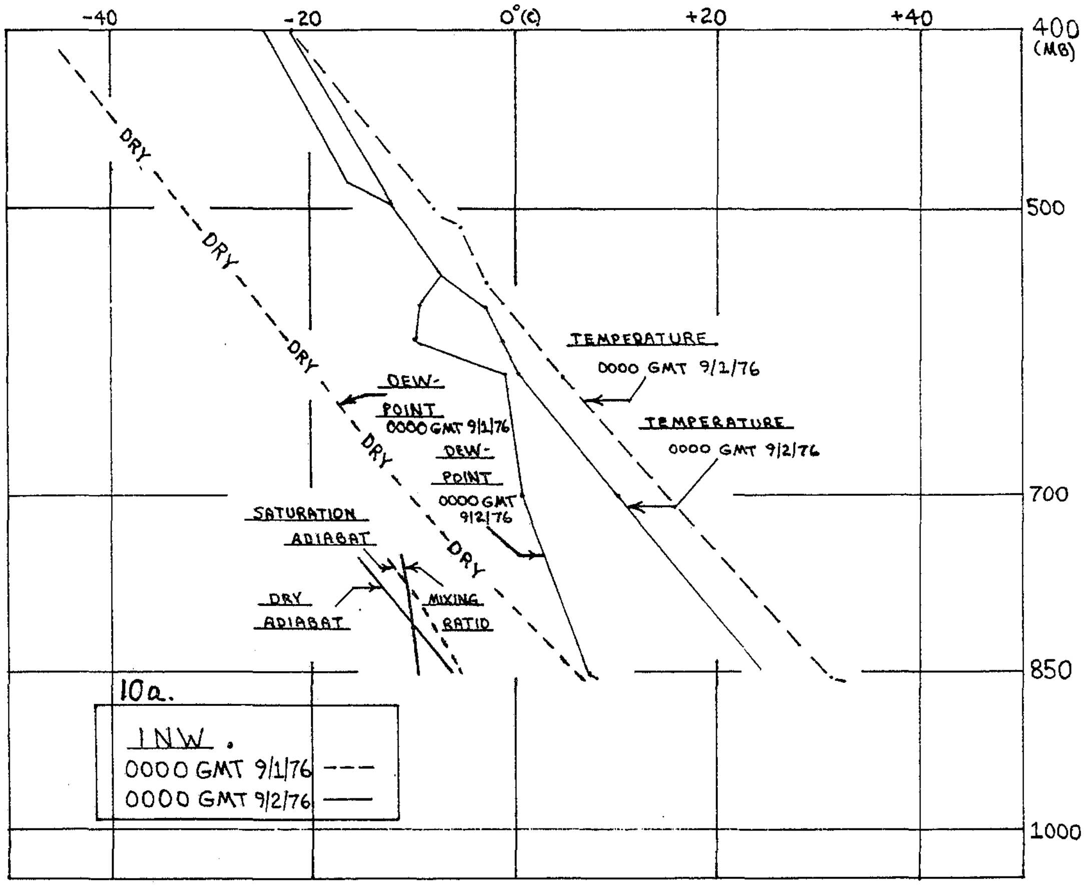


Figure 9. Precipitable water values at INW and TUS at 12-hour intervals from 0000 GMT 1 September 1976.



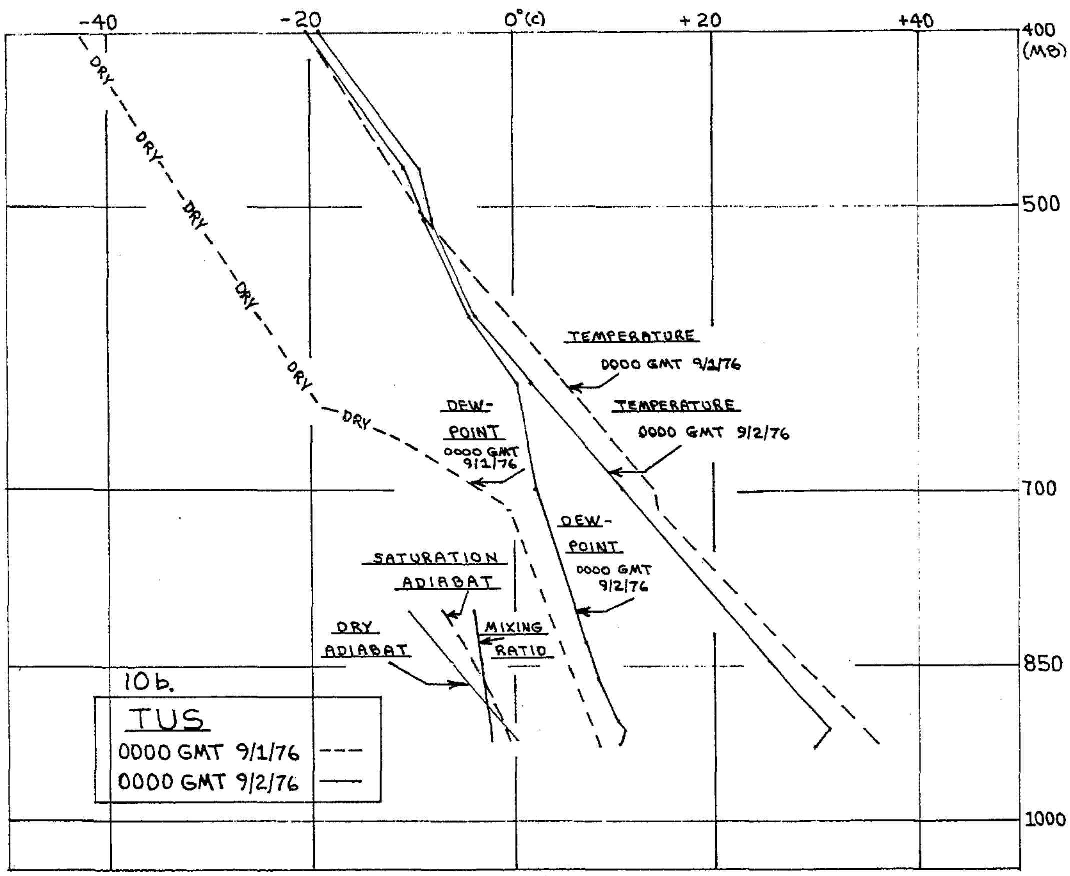


Figure 10. Vertical temperature and moisture profiles at a) INW and b) TUS for the 24-hour period ending at 0000 GMT 2 September 1976.

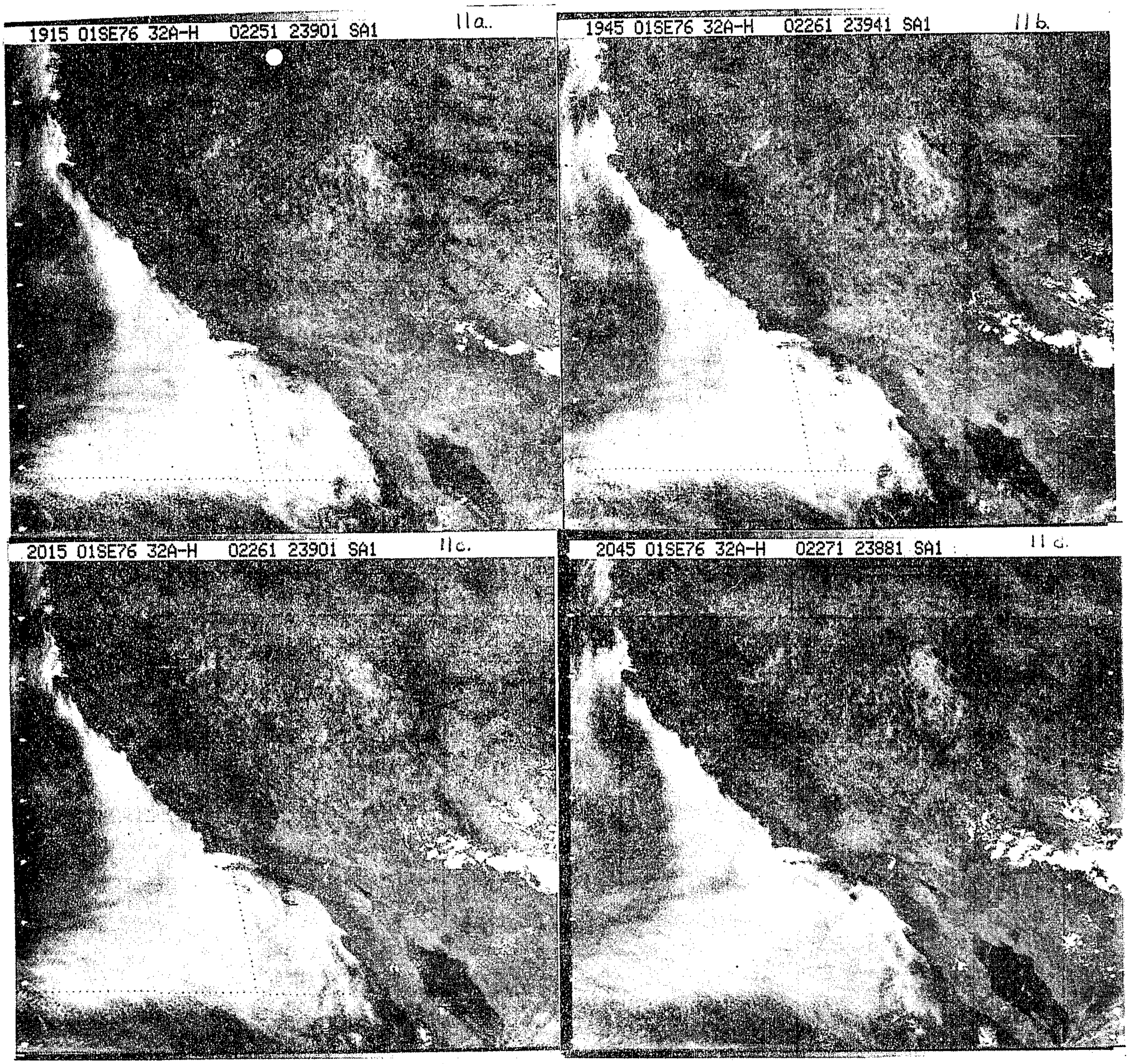
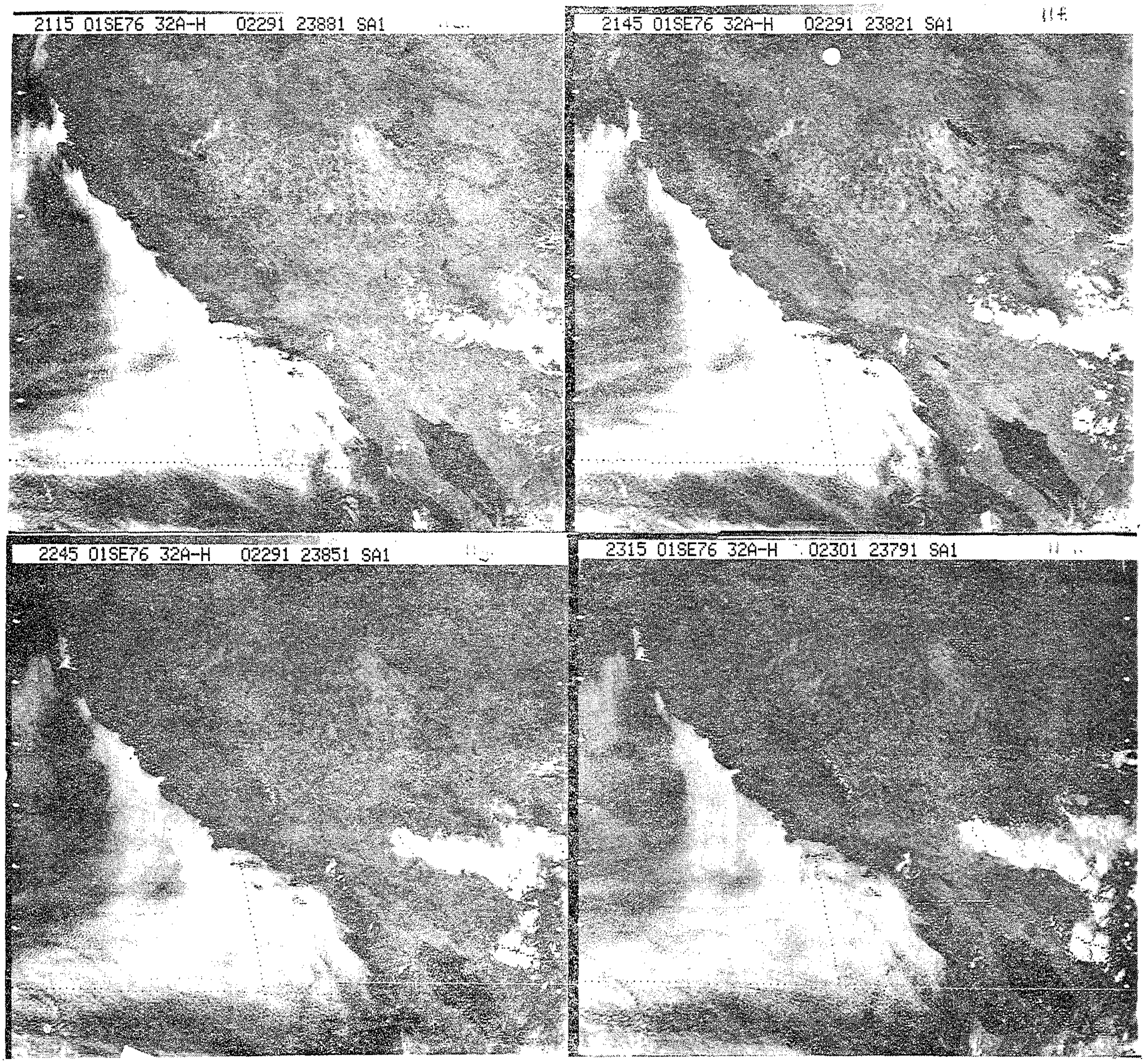


Figure 11. (a - h) Available SMS-2 half-mile resolution satellite photographs for the period 1915 GMT through 2315 GMT 1 September 1976.


2115 01SE76 32A-H 02291 23881 SA1
2145 01SE76 32A-H 02291 23821 SA1
2245 01SE76 32A-H 02291 23851 SA1
2315 01SE76 32A-H 02301 23791 SA1

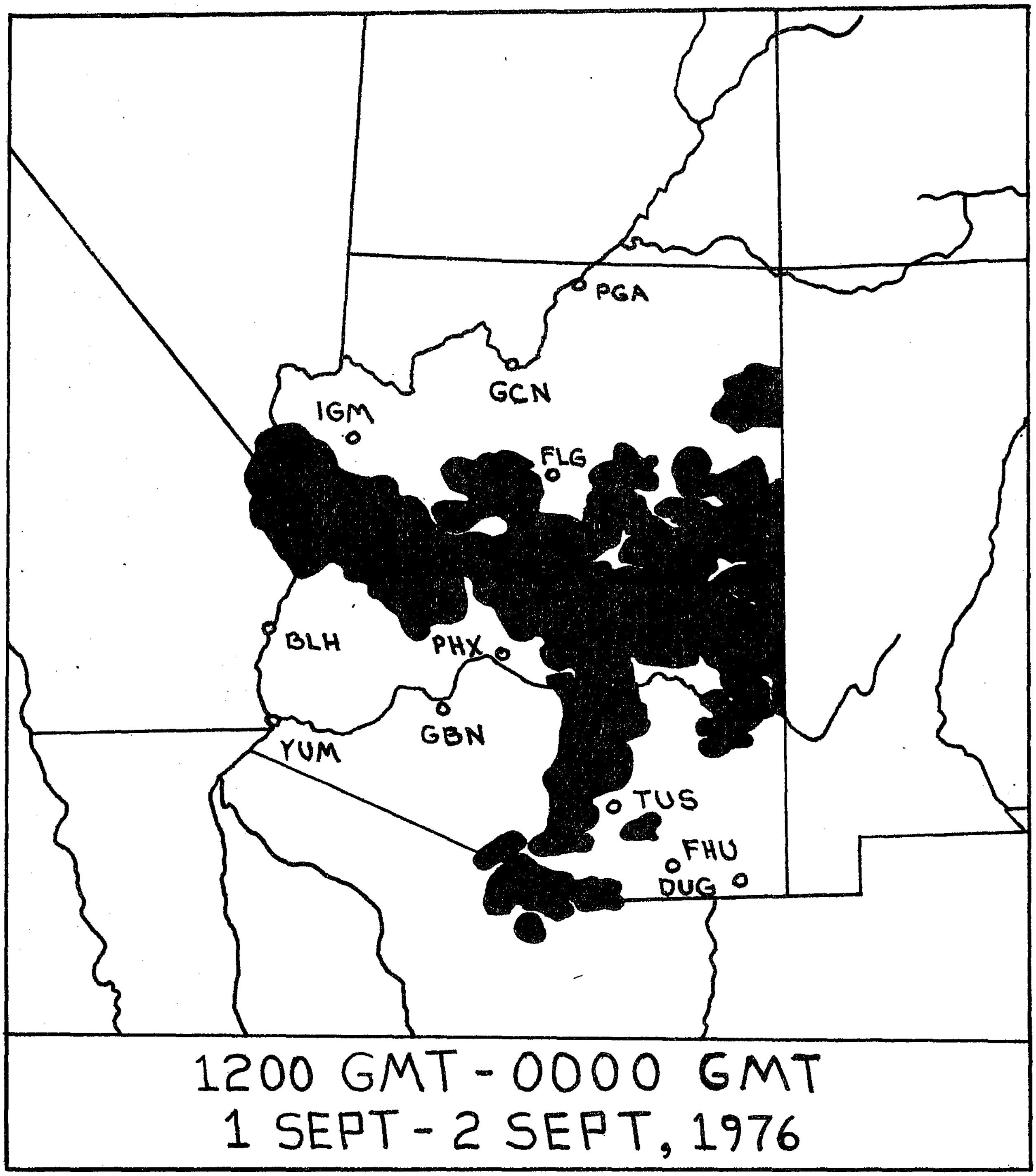


Figure 12. Composite radar chart west of the Arizona-New Mexico border for the 12-hour period ending 0000 GMT 2 September 1976.

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