# EFFECTS OF PRECIPITABLE WATER AND CAPE ON PRECIPITATION IN SOUTHERN ARIZONA

P. GRADY DIXON, Department of Geosciences, Mississippi State University, PO Box 5448, Mississippi State, MS 39762

## ABSTRACT

This study analyzes integrated precipitable water (IPW) over Arizona southern during the months of July and August. The results show total column (up to 300 hPa) atmospheric moisture, despite illustrating success in predicting precipitation occurrence and spatial extent, does not predict precipitation occurrence, spatial extent, or amount significantly better than do simple low-level dewpoints. Yuma appears to be the exception, as IPW is much more successful in forecasting nearby precipitation occurrence and spatial extent than is low-level dewpoints.

CAPE (convective available potential energy) values are also calculated and compared to precipitation across the region. The results show that CAPE, much like IPW, shows some success predicting precipitation occurrence during the monsoon in Arizona, although it is still less than IPW. Similar to IPW, CAPE is a poor predictor of precipitation totals.

## INTRODUCTION

During the annual North American monsoon, weather across the desert Southwest is significantly altered by increased moisture. Initially, the Gulf of Mexico was thought to be the primary source of monsoon moisture (Jurwitz 1953, Bryson and Lowry 1955, Reitan 1957, Green and Sellers 1964, Hastings and Turner 1965). Hales (1972) and Brenner (1974) both expressed doubts that moisture from the Gulf of Mexico could cross two mountain ranges in Mexico, which rise 1,800 m and 3,600 m above sea level as well as the Continental Divide in the United States, and still contribute significant amounts of moisture to the lower elevations of the Sonoran Desert. This argument is supported by Reitan (1957), who found the greatest amount of moisture in Phoenix to be at low levels (50% below 800 hPa; 86% below 600 hPa). Consequently, Hales (1972) argued that monsoon moisture originated over the tropical eastern Pacific Ocean and was channeled up the Gulf of California in the form of surges induced by a pressure gradient up the Gulf of California. Likewise, Schmitz and Mullen (1996), using European Center for Medium Range Forecasting reanalysis data, determined that most water vapor enters the Sonoran Desert region at low levels (below 700 hPa) from the northern Gulf of California, and that most of the upper-level moisture (above 700 hPa) comes from the Gulf of Mexico. Nevertheless, Schmitz and Mullen (1996) argue that limited amounts of moisture from the Gulf of Mexico do reach the low levels of Arizona, and the relative importance of each moisture source remains uncertain.

Wallace et al. (1999) show that local surface observations across central Arizona provide little help in forecasting monsoon thunderstorms. Further, it has been shown that increased low-level moisture across the study area (lower elevations of Arizona and southern Nevada) is significantly related to the amount and spatial extent of precipitation (Dixon 2006). There are certainly other factors contributing to the initiation and enhancement of monsoon rainfall (including elevation), but it is clear that low-level moisture (~1,000 m above the surface) is one, and perhaps the most important, controlling variable. This finding supports Hales' (1972) theory that the Gulf of California is a more crucial source of moisture than is the Gulf of Mexico. However, the impact of total-column moisture and instability measures on precipitation across this area have not been formally studied. According to previous studies (Hales 1977, Maddox et al. 1995, McCollum et al. 1995), thunderstorm formation over the Arizona desert is dependent upon numerous variables, but instability (due to moisture and heating) appears to be a common atmospheric attribute. Therefore, this paper addresses the effects of integrated precipitable water (IPW) and convective available potential energy (CAPE) on precipitation across the low-lying desert of Arizona during the monsoon season.

## DATA AND METHODS

Upper-air sounding data from Phoenix, AZ (PHX), Tucson, AZ (TUS), and Yuma, AZ (YUM) are used to calculate IPW and CAPE (Fig. 1). IPW is calculated using all available sounding times, but CAPE is calculated using only 0000 UTC soundings in order to capture the most unstable time of day. Some soundings are likely influenced by nearby convection, especially in Tucson, but most significant thunderstorms and precipitation do not reach the lower elevations until after 0000 UTC (1700 Mountain Standard Time), reaching a maximum near 0700 UTC (Balling and Brazel 1987).

DIXON, P. G. 2008. EFFECTS OF PRECIPITABLE WATER AND CAPE ON PRECIPITATION IN SOUTHERN ARIZONA. *JOURNAL OF THE ARIZONA-NEVADA ACADEMY OF SCIENCES* 40(1):66-73.

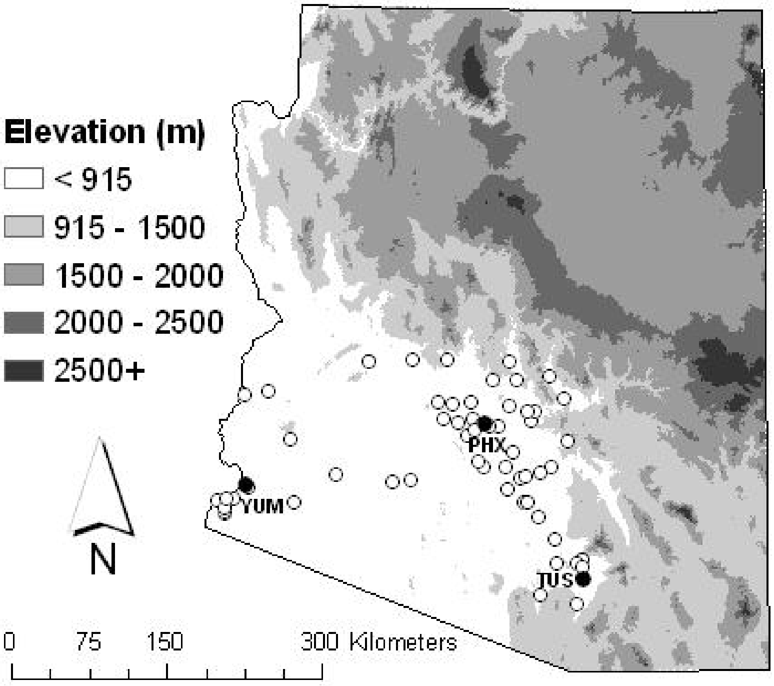

***Figure 1.*** *Elevation map of the study region. Areas of concern are those at or below 915 m, including the cities of Yuma (YUM), Tucson (TUS), and Phoenix (PHX), with the respective sounding locations indicated by black dots. White dots identify surface weather stations used in this study.*

Only 1200 UTC sounding data are available from Yuma. Therefore, Yuma is not included in the comparisons of CAPE values. Sounding data for the years 1993-2004 were obtained from the National Climatic Data Center (NCDC) in Asheville, NC, and from Salt River Project (SRP) in Phoenix, AZ. Precipitation data are based on observations from 40 stations within 100 km of Phoenix, 10 stations within 100 km of Tucson, and 12 stations within 100 km of Yuma (Fig. 1). These data were obtained from NCDC and the Arizona Meteorological Network (AZMET). All of the stations record precipitation totals at least once per day.

IPW is calculated using sounding observation variables of pressure, temperature, and dewpoint for consecutive layers. Mean-layer precipitable water ( $\overline{w}$ ) is defined by:

$$\overline{w} = \frac{(p_1 - p_2)}{g}\,\overline{r} \tag{1}$$

where $g$ is the acceleration due to gravity (9.8 m s$^{-2}$), $p$ is air pressure (hPa), and $\overline{r}$ is mixing ratio (g kg$^{-1}$). Equation 1 is the algebraic version of the precipitable water equation given in the American Meteorological Society's *Glossary of Meteorology* (Glickman 2000):

$$w = \frac{1}{g}\int_{p1}^{p2} x\,dp \tag{2}$$

where $g$ is the acceleration due to gravity (9.8 m s$^{-2}$) and $x(dp)$ is the mixing ratio at the pressure level, $dp$. The $d$ represents the total derivative of pressure (i.e., change in pressure with height). IPW is calculated for the layer stretching from the surface up to 300 hPa using 0000 UTC soundings.

CAPE is calculated using sounding observation variables of pressure, height, temperature, and dewpoint for consecutive layers. Mean layer CAPE is defined by:

$$CAPE = g\left[\frac{\overline{\theta}_p - \overline{\theta}_s}{\overline{\theta}_s}\right](z_2 - z_1) \tag{3}$$

where:
$g$ is the acceleration due to gravity (9.8 m $s^{-2}$),
$\overline{\theta}_p$ is the mean parcel potential temperature (K),
$\overline{\theta}_s$ is the mean environmental sounding potential temperature (K), and z is the geopotential height (m).

Equation 3 is the algebraic form of the equation given by Weisman and Klemp (1982):

$$CAPE = g\int_{LFC}^{EL} \frac{\theta'(z)}{\theta(z)}\,dz \tag{4}$$

where: $g$ is the acceleration due to gravity (9.8 m $s^{-2}$), $\theta'$ is the parcel potential temperature minus the environmental potential temperature (K), $\theta$ is the environmental potential temperature (K), and $z$ is geopotential height (m) all calculated throughout the layer between the Level of Free Convection (LFC) and the Equilibrium Level (EL) up to a pressure level of 300 hPa. Variables were interpolated between data points at every 1 hPa in order to create a smoother, more realistic parcel lapse rate. The virtual temperature correction detailed by Doswell and Rasmussen (1994) is not employed here since most operational forecasting computer software does not use that method. Therefore, the values shown here should be relatively consistent with those encountered by forecasters, but it is understood that CAPE values can vary greatly depending on the calculation method.

This study employs linear regression and discriminant analyses (Glahn 1968) to test the relationships, and their degree of statistical significance, that IPW and CAPE share with occurrence, accumulated totals, and spatial extent of precipitation. Linear regression ($r^2$) simply shows the percentage of variance shared between IPW or CAPE and precipitation. However, due to many days with no rainfall, precipitation data are not normally distributed. Therefore, to ensure normality, linear regression is performed only on days that experienced precipitation. Discriminant analyses are also applied to determine whether the variance in IPW or CAPE can accurately diagnose the occurrence of precipitation across the study area.

# RESULTS

## Integrated Precipitable Water

The average integrated precipitable water (IPW) values during the months of July and August for Phoenix, Tucson, and Yuma are 3.28 cm, 3.17 cm, and 3.02 cm, respectively, and most of the moisture is in the lower levels of the atmosphere (Table 1). While all three sites show the majority of the local moisture to be below 600 hPa, a relatively small percentage of the moisture at Tucson is below 850 hPa. This is likely attributable to the fact that the elevation at Tucson is approximately 450 m higher than Phoenix (i.e., less space between the surface and 850 hPa). Unfortunately, very few Phoenix soundings are available for other times of the year, so a comparison between Phoenix and Tucson cannot be made for each month in order to see how the percentage of moisture at low-levels changes throughout the year.

Nevertheless, it is seen that both Tucson and Yuma experience dramatic increases in IPW (for all three layers) during the summer months (Figs. 2 and 3). However, it also appears that a smaller percentage of the total moisture is present in the lower levels during the summer than any other time of year. This can be attributed to increased advection of moisture in the mid-levels during the summer, but it is more likely due to the dramatic increase in boundary layer thickness during the hot summer months.

Dixon (2006) shows that low-level moisture (below 850 hPa at Tucson and Phoenix; below 925 hPa at Yuma), as measured by dewpoint values and gulf surge events, has significant and notable effects on the occurrence, distribution, and amount of precipitation during the months of July and August.

***Table 1**. Mean IPW (cm) values for Phoenix, Tucson, and Yuma (1993-2004).*

| Station | IPW (cm) | IPW Below 850 hPa (cm) | % Below 850 hPa | IPW Below 600 hPa (cm) | % Below 600 hPa |
|---|---|---|---|---|---|
| PHX | 3.28 | 1.11 | 33.8 | 2.79 | 85.1 |
| TUS | 3.17 | 0.74 | 23.2 | 2.58 | 81.3 |
| YUM | 3.02 | 1.21 | 40.1 | 2.61 | 86.4 |

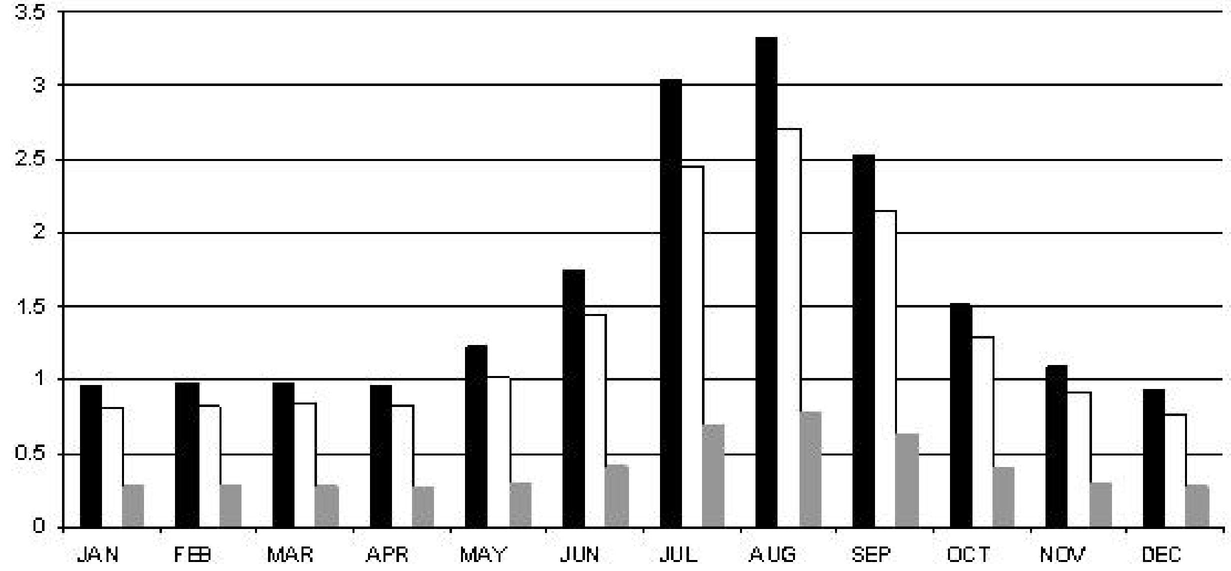

***Figure 2.*** *Monthly Integrated Precipitable Water (IPW) values (cm) for Tucson. Black bars represent IPW below 300 hPa, white bars represent IPW below 600 hPa, and gray bars represent IPW below 850 hPa.*

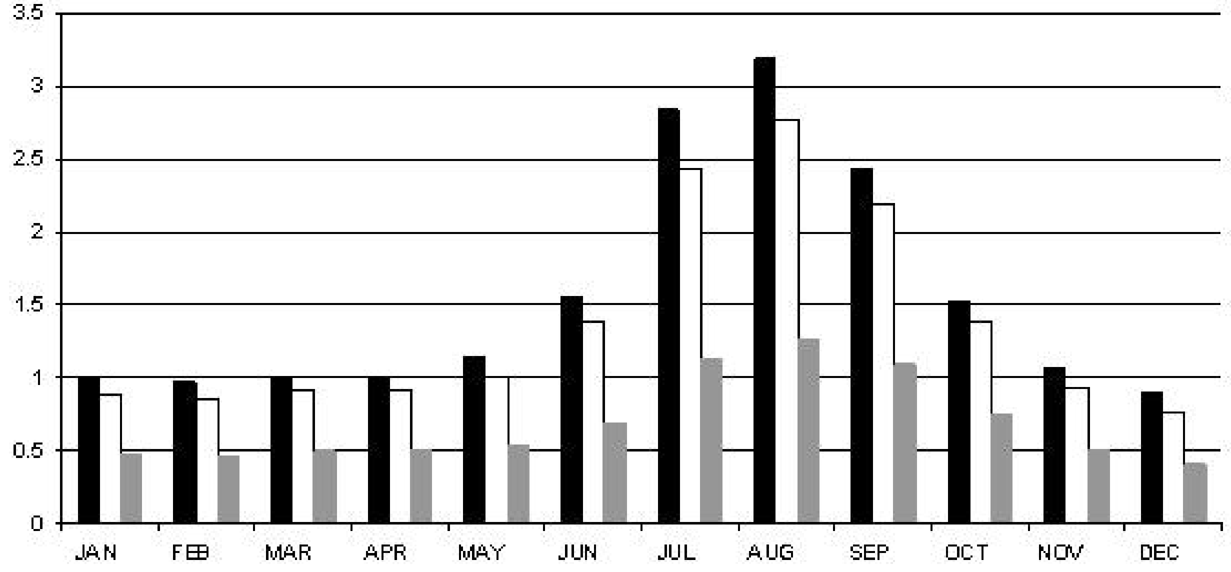

***Figure 3****. Same as Figure 2, but for Yuma.*

Although statistically significant (α=0.05), the relationships between IPW and precipitation (occurrence and amount) are not any stronger than those between low-level dewpoints and precipitation (Table 2). According to Dixon (2006), as much as 98.2% of the variance between wet and dry days can be explained by low-level dewpoints, but results from this study show no more than 35.3% (Wilks' λ=0.647) is due to the variance in IPW (Table 2). For further explanation of discriminant analysis, see Wilks (2006). Nevertheless, the mean IPW for wet days (those receiving any precipitation) is notably higher than on dry days. Further, based on the variance of IPW, precipitation events can be accurately predicted as much as 87.0% of the time and dry days can be predicted as often as 76.0% of the time (Table 2). This provides a valuable operational tool for forecasters across the study area.

Similarly, variation in IPW appears to have a comparable effect on the spatial extent of precipitation as do low-level dewpoints. Dixon (2006) shows that low-level dewpoints at Phoenix, Tucson, and

***Table 2.** Results of discriminant analyses between IPW and local (within 100 km) precipitation occurrence.*

| | | | Wet Days | | Dry Days | |
|---|---|---|---|---|---|---|
| Location | Wilks' λ | ρ | Mean IPW | Predicted | Mean IPW | Predicted |
| PHX | 0.779 | <0.001 | 3.47 | 78.7% | 2.58 | 65.1% |
| TUS | 0.817 | <0.001 | 3.43 | 74.1% | 2.70 | 66.4% |
| YUM | 0.647 | <0.001 | 4.12 | 87.0% | 2.61 | 76.0% |

***Table 3.** Linear regression ($r^2$) of IPW and CAPE, as observed at each sounding site, versus the spatial extent of precipitation within 100 km of each sounding site.*

| | PHX | | | TUS | | | YUM | | |
|---|---|---|---|---|---|---|---|---|---|
| | $r^2$ | n | ρ | $r^2$ | n | ρ | $r^2$ | n | ρ |
| IPW | 0.190 | 412 | <0.001 | 0.144 | 588 | <0.001 | 0.274 | 340 | <0.001 |
| IPW below 850 | 0.151 | 412 | <0.001 | 0.110 | 588 | <0.001 | 0.173 | 340 | <0.001 |
| CAPE | 0.083 | 412 | <0.001 | 0.103 | 588 | <0.001 | n/a | n/a | n/a |

Yuma account for 17.2%, 14.2%, and 11.9% of the variance in spatial extent of local precipitation, respectively. Likewise, linear regression results show that 19.0%, 14.4%, and 27.4% of the variance in spatial extent of local precipitation is explained by variance in IPW at Phoenix, Tucson, and Yuma, respectively (Table 3). This is important because it shows that low-level dewpoints and IPW yield similar predictive results at Phoenix and Tucson while IPW is superior at Yuma.

With respect to only those days that experience precipitation, it appears that IPW is not strongly correlated with the amount of rainfall (Table 4). Only as much as 11.0% of the variance in precipitation amounts (among only days receiving measurable precipitation) can be explained by the variance in IPW. This is rather surprising since IPW is often used as a measure of potential precipitation totals (Reitan 1960, Market et al. 2003). However, it has been noted by McCollum et al. (1995) that rapid moisture advection (e.g., gulf surges) can be a very important factor when forecasting rainfall over central Arizona during the monsoon season.

## Convective Available Potential Energy

During the study period, the mean CAPE based on 0000 UTC soundings at Phoenix is 466.2 J kg$^{-1}$ during July, and 652.6 J kg$^{-1}$ during August. The mean values at Tucson are 608.5 J kg$^{-1}$ during July, and 757.6 J kg$^{-1}$ during August. However, these averages are significantly affected by a relative few days with CAPE values greater than 2000 J kg$^{-1}$. CAPE values exceeded 600 J kg$^{-1}$ less than half of the time during the study period at both locations. Nevertheless, it is the days experiencing CAPE values in excess of 600 J kg$^{-1}$ that are most likely to experience precipitation (Table 5).

***Table 4.** Linear regression ($r^2$) of IPW and precipitation amount (for only days experiencing these events) in Phoenix, Tucson, and Yuma.*

| Location | $r^2$ | n | ρ |
|---|---|---|---|
| PHX | 0.110 | 262 | <0.001 |
| TUS | 0.028 | 359 | 0.002 |
| YUM | 0.086 | 78 | 0.009 |

Despite the apparent precipitation threshold around 600 J kg$^{-1}$, the relationship between CAPE and precipitation occurrence is much weaker than that between IPW or low-level dewpoints and precipitation (Table 6). Wet days do tend to experience higher CAPE values than dry days, but the accuracy of wet days based on the variance in CAPE is relatively low. This is likely due to the fact that

***Table 5.*** *Percentage of days experiencing precipitation for various levels of CAPE.*

| CAPE (J kg$^{-1}$) Categories | PHX | | TUS | |
|---|---|---|---|---|
| | % | n | % | n |
| < 600 | 52.2 | 186 | 46.7 | 409 |
| 600-1000 | 80.0 | 50 | 74.8 | 115 |
| 1000-2000 | 84.9 | 53 | 81.5 | 168 |
| 2000+ | 81.8 | 11 | 85.6 | 42 |

***Table 6.*** *Results of discriminant analyses between CAPE and local (within 100 km) precipitation (days with any precipitation versus days with none).*

| | | | Wet Days | | Dry Days | |
|---|---|---|---|---|---|---|
| Location | Wilks' $\lambda$ | $\rho$ | Mean CAPE | Predicted | Mean CAPE | Predicted |
| PHX | 0.914 | <0.001 | 712.7 | 52.4% | 318.1 | 75.2% |
| TUS | 0.879 | <0.001 | 882.1 | 55.8% | 369.7 | 78.2% |

***Table 7.*** *Linear regression ($r^2$) of CAPE and precipitation amount (for only days experiencing precipitation) in Phoenix and Tucson.*

| Location | $r^2$ | n | $\rho$ |
|---|---|---|---|
| PHX | 0.041 | 191 | 0.005 |
| TUS | 0.019 | 457 | 0.003 |

precipitation occurs often with relatively low CAPE values (<600 J kg$^{-1}$) just because most days do not experience high CAPE. However, some of the highest predictive percentages (based on discriminant analyses) in this study are displayed by the predictions of dry days (no measurable precipitation) based on the variance in CAPE (Table 6). Therefore, despite the occurrence of wet days during low CAPE and dry days during high CAPE, it is apparent that precipitation is increasingly likely with increasing CAPE.

Much like IPW, CAPE is less reliable for diagnosing the potential amount of rainfall than it is for diagnosing the simple occurrence of rainfall (Table 7). Despite statistically significant ($\rho$=0.05) relationships (likely due to a large number of observations), less than 5% of the variance in precipitation amount on days with measurable rainfall can be explained by the variance in CAPE.

## CONCLUSIONS

The results of this study show that integrated layer measures of atmospheric moisture and instability do not necessarily provide increased utility over low-level dewpoints with respect to predicting precipitation across the lower elevations of Arizona during the monsoon season. This is especially true for Phoenix and Tucson, but Yuma appears to be different. IPW values at Yuma are clearly more useful for predicting precipitation occurrence and spatial extent than is low-level dewpoints. The reason for this difference is unclear at this time, but it does not appear to be due to a lack of data at Yuma as the only category (precipitation amount) that shows a weak IPW correlation at Yuma is the only variable with significantly fewer observations than Phoenix and Tucson. Furthermore, with the exception of IPW values below 850 hPa, elevation should not play a role as the total IPW values include data from the surface through 300 hPa. Likewise, low-level dewpoint values used by Dixon (2006) were measured at ~1000 m above the surface (925 hPa for Yuma; 850 hPa for Phoenix and Tucson). Therefore, more research in this area is certainly warranted. In the meantime, while low-level dewpoints can be used in place of IPW values for predicting precipitation at Phoenix and Tucson, IPW appears to be the better option for Yuma.

IPW does illustrate success in diagnosing the spatial extent of precipitation; however, low-level dewpoint values provide nearly the same success in this area (Dixon 2006). In addition, IPW is no more accurate than low-level dewpoints for predicting precipitation amount and distinguishing between "wet" and "dry" days across the study area. The use of IPW below 850 hPa appears to be the least effective method of the three.

These findings are significant because they illustrate the relative usefulness of simple low-level dewpoint values. Dixon (2006) shows that low-level dewpoints provide better representations of gulf surge moisture than do surface dewpoints. Likewise, the results of this study show the low-level dewpoints are as, if not more, useful as integrated layer measures of moisture.

Much like IPW, CAPE appears to be a better predictor of precipitation occurrence rather than precipitation amount. Furthermore, it is evident that, while useful, CAPE is less successful in predicting precipitation occurrence and amount than is IPW. Nevertheless, it is shown that precipitation likelihood increases with CAPE, and that precipitation is far more likely to occur when CAPE values are >600 J kg$^{-1}$. Therefore, CAPE appears to be a useful tool for forecasting precipitation across the study region, especially when used in conjunction with IPW and/or low-level dewpoints. Specifically, this study suggests that summer precipitation is most likely to occur in southern Arizona when IPW values are >3 cm and CAPE values are >600 J kg$^{-1}$.

The importance of moisture at the various levels during the North American monsoon has been a source of debate for many years (Bryson and Lowry 1955, Reitan 1957, Hales 1972, Brenner 1974, Carleton 1985, Schmitz and Mullen 1996). Part of the reason for this debate is to better understand the role of various moisture sources (Gulf of California, Gulf of Mexico, Pacific Ocean) on the climate of the desert regions of the southwest United States. While there is still uncertainty about how much of the moisture in Arizona originates from each source and whether Gulf of Mexico moisture is able to reach the lower levels of the atmosphere after crossing multiple mountain ranges, this study has reinforced the fact that integrated total column measures of moisture are not any more important than low-level measures of moisture with respect to precipitation prediction. In addition, almost all of the atmospheric moisture above Phoenix, Tucson, and Yuma is located below 600 hPa, and about half of the moisture is below 850 hPa. Therefore, regardless of the source, moisture in the lower atmosphere is much more abundant and important than upper-level moisture.

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