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THE INFLUENCE OF TROPICAL STORMS ON RUNOFF-PRODUCING RAINFALL IN THE SOUTHWESTERN UNITED STATES

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INTRODUCTION

Moist tropical air can flow into southern Arizona at any time during the year, but is concentrated in the summer "monsoon" season, from July through early September. The summer rainy season is characterized by widely-spaced late afternoon and early evening thunderstorm rains of high intensity, short duration, and limited areal extent. The thunderstorms may develop and dissipate individually, or propagate along lines over a period of several hours. The flow of moist air may be interrupted at any time during the rainy season by a drying period, which introduces an added uncertainty into predicting summer thunderstorm rains. The magnitude, density, areal extent and duration of thunderstorm rainfall are determined by available moisture, orographic and convective lifting, and atmospheric conditions. The available moisture depends upon the strength and duration of the flow of moist tropical air into the region. Normally, thunderstorms are too widely spaced to cause flooding on other than very small watersheds (200 mi^2 and less). However, on occasion, a tropical storm (or hurricane) will push massive amounts of moist tropical air into the southwest, causing major regional and statewide flooding.

MOISTURE SOURCES

For many years, the predominant theory was that the major source of tropical moisture for the southwestern United States was the Gulf of Mexico (Jurwitz, 1953; Sellers, 1960; Osborn and Reynolds, 1963). The theory was that clockwise circulation around the Bermuda High drew moist air into the Southwest from the Gulf of Mexico, and that shifts in the High, and related lows to the West, determined where this moisture would push into the Southwest. The fact that thunderstorm rains began earlier in the year in New Mexico than in Arizona seemed to reinforce this theory. It was recognized that tropical storms originating in the Pacific Ocean, off Baja California, could push moisture into southern Arizona, but it was believed that such occurrences were the exception rather than the rule (Sellers, 1960).

With the advent of weather satellites in the 1960's, questions were soon raised about the sources and paths of moisture into the Southwest, and particularly into southern Arizona. Hales (1973) and Brenner (1973) were instrumental in recognizing and identifying the sources and mechanisms now most accepted for the flow of moist tropical air into southern Arizona. Hales pointed out that the Gulf of California could serve as an excellent path along which "surges" of low level moisture could move rapidly into southern Arizona (Figure 1). Brenner (1973) made a more detailed synoptic study of a specific "surge" of moisture into southern Arizona. Brenner also pointed out that such low level surges of moisture could mix with upper level moisture from the Gulf of Mexico, improving the

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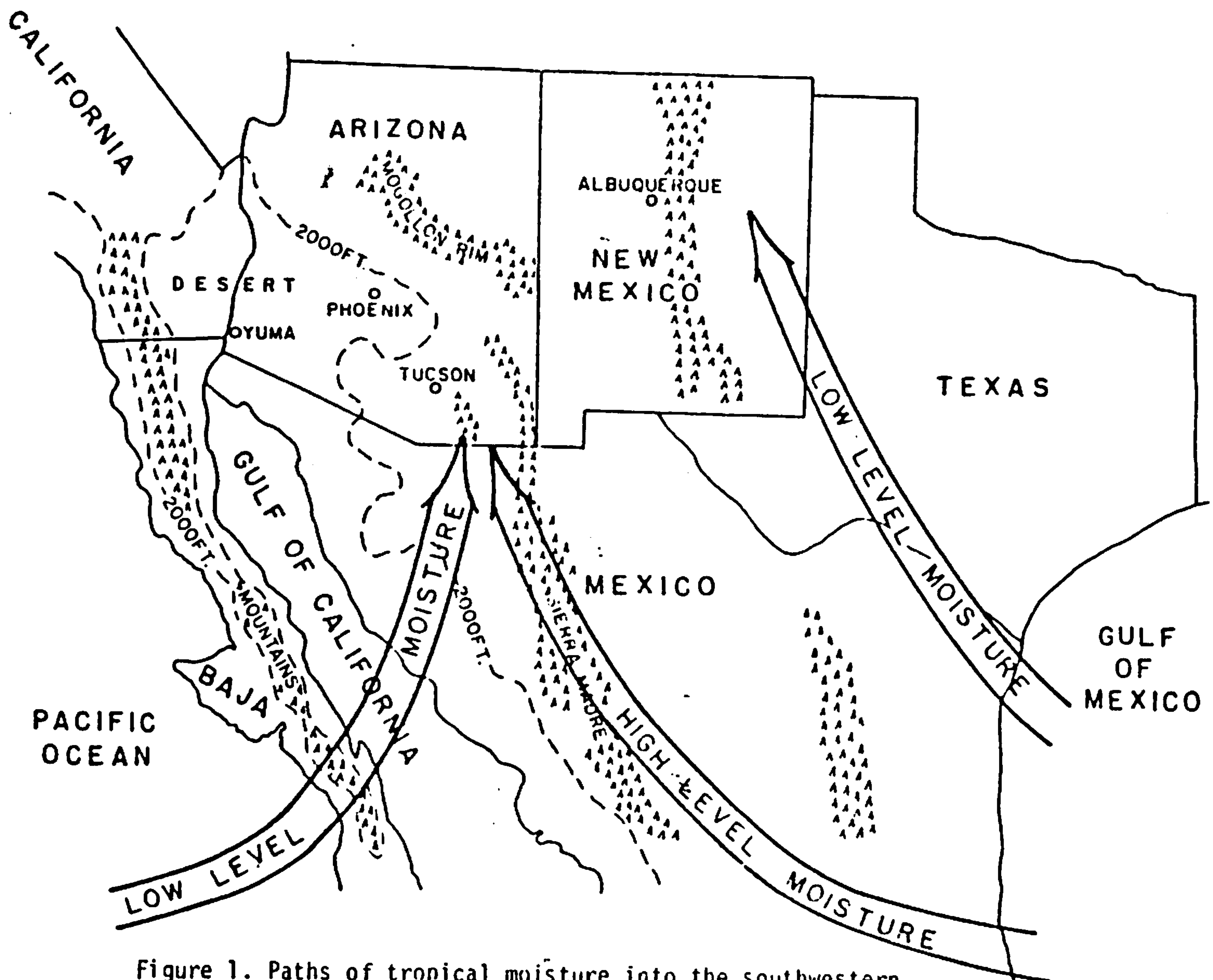

Figure 1. Paths of tropical moisture into the southwestern United States and northern Mexico.

the chances for significant thunderstorm rainfall in southern Arizona. Osborn and Davis (1977) and Osborn et al. (1980) suggested that both the Pacific Ocean and the Gulf of Mexico could be moisture sources for rainfall in the Southwest. The Pacific is the primary source for central and western Arizona, and the Gulf of Mexico the primary source for eastern New Mexico. Both, or either, are the sources of moisture for southwestern New Mexico and southeastern Arizona.

TROPICAL STORMS

The eastern tropical North Pacific Ocean is an extremely prolific region for tropical storm activity (Renard and Bowman, 1976). For example, for the period 1965-1974, tropical storm activity peaked in the last 2 weeks in July, and hurricane frequency in the first 2 weeks in August, with an average of 16 tropical storms and hurricanes per year. Most events move "out to sea," but occasionally, a tropical storm or hurricane moves inland. Even the events that move out to sea, however, can have an influence on rainfall in the Southwest.

TROPICAL STORM NORMA

Sellers (1960) reported that, ". . . every four or five summers, when conditions are right, a tropical storm may come rampaging through Arizona." Such storms occurred in 1970, 1977, 1978, and 1983. Tropical storm Norma led to the Labor Day Floods of 1970 in Arizona (NWS, 1971; Thorud and Ffolliot, 1971). Thorud and Ffolliot reported:

> "The 1970 Labor Day Storm caused more loss of human life than any other storm in Arizona's recent history. In addition, many dwellings, roads, bridges, and other structures were damaged by record flooding. Consequently, the meteorological and hydrological features of this event, and the resulting damage to human, cultural, and natural resources should be documented and analyzed. Such analyses may contribute to improved estimates of the magnitude and frequency of future storm and flood events, and could assist engineers and planners in the design and location of new communities, drainage systems, bridges, dams, and other cultural features."

The National Weather Service published a detailed report on the tropical storm, including a meteorological analysis (NWS, 1971).

Late on the afternoon of Thursday, 3 September, 1970, tropical storm Norma was centered near latitude 23°N and longitude 115°W, approximately 5 degrees longitude west of the southern tip of Baja, California (Figure 1). Moist tropical air from this storm was already flowing into southern Arizona. At the same time, a cold front was located across the Pacific Northwest, and a minor trough was located over the southern California Coast. On Friday, as Norma continued to push moist air northward, the trough moved eastward, triggering thunderstorms across southern Arizona. The minor trough had passed over Arizona by Friday afternoon. By Saturday morning, the cold front had pushed southward into Arizona. The NWS reported that "The general upward flow of moist air over Arizona and southern Utah, ahead of the cold trough and cold front, combined with strong orographic uplifts of moisture-laden, unstable, tropical air along the south side of mountains and the Mogollon Rim escarpment, caused extremely heavy rains throughout central Arizona and southern Utah." The runoff-producing rainfall peaked during Saturday, the 5th of September. The storms of 1977, 1978, and 1983 were similar to the 1970 storm, although each storm had its own identity.

DISCUSSION

Tropical storms play an important role in the occurrence and amount of thunderstorm rainfall in southern Arizona. Usually, the role of tropical storms is to provide a trigger, or mechanism, for pushing or initiating surges of moisture into southern Arizona. These storms are clearly identified as the principal source of moisture (for example, the 1970 Labor Day Floods). Other factors, however, must be present to ensure enough instability for significant thunderstorm rainfall. In at least one case (the 1970 Labor Day Floods), the push of moist tropical air into Arizona, coincided with an unusually strong early season cold front which pushed into Arizona from the North. The advent of weather satellites, and the work of Hales, Brenner and others, has certainly improved our knowledge of the casual mechanisms of thunderstorm rainfall in southern Arizona. It seems that such events could be modeled stochastically, but it also appears that such models may be far more complex than originally believed. However, such models are needed to estimate probabilities of such events, and to specify space-time distribution of rainfall as input to rainfall-runoff models used to compute flood peaks and water yields.

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