On the Relationship of Convective Cooling to Nocturnal Thunderstorms at Phoenix

JOHN E. HALES, JR.

National Severe Storms Forecast Center, Kansas City, Mo. 64106

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ABSTRACT

The diurnal variability of thunderstorm occurrence in Arizona is complex and related to terrain elevations. Generally, thunderstorms occur in the higher mountains during the afternoon with activity primarily of the nocturnal nature in the adjacent desert valleys, most noticeably the Phoenix area.

Aircraft temperature probes have found cooling in cumulus areas. This cooling can frequently advect with the steering wind to destabilize the desert air mass and increase nighttime thunderstorms. The same destabilization process could contribute to nocturnal thunderstorms in the High Plains.

1. Diurnal characteristics of Arizona thunderstorms

The proximity of a large mountain complex to a low-elevation desert area in Arizona provides the opportunity to study the relationship between two topographically different but adjacent regions. The spatial and diurnal distribution of thunderstorms in Arizona during summer is highly dependent on terrain. Of particular interest is the temporal relationship between the occurrence of thunderstorms over the central mountain complex of Arizona and the adjacent desert valleys (Fig. 1).

In a study of hourly distribution of radar echoes over Arizona, Hales (1972) showed the strong influence of elevation. Over the central mountains there is a pronounced mid-afternoon maximum of thunderstorm activity directly attributable to diurnal heating (Orville, 1965). However, while afternoon convection is prevalent over the south central desert valleys, thunderstorm activity is at a minimum in mid-afternoon (the hottest time of day), and increases rapidly during the evening to a peak just before midnight. This nocturnal maximum is clearly shown in the rainfall distribution at Phoenix (Fig. 2).

The cause of the midnight maximum at Phoenix has been elusive. Nocturnal thunderstorms occur in other areas, most notably the Great Plains of the United States and over oceans adjacent to land masses in

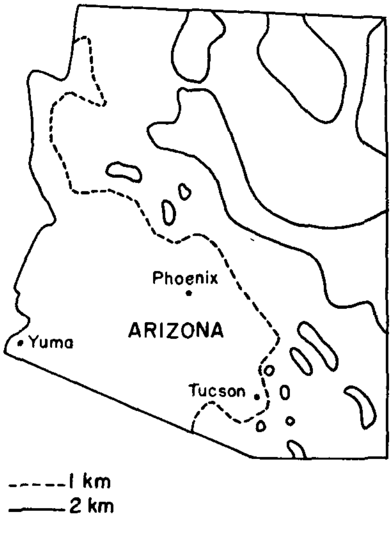

FIG. 1. Topography of Arizona.

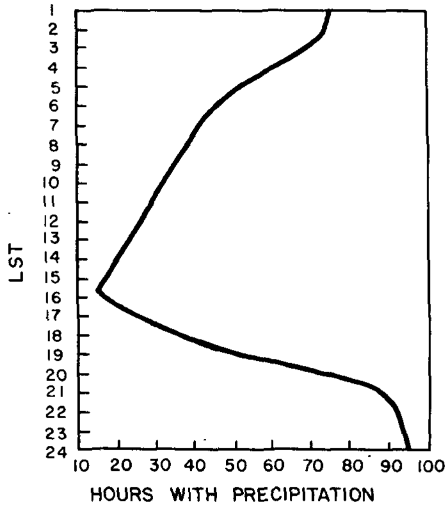

FIG. 2. Total number of hours with a trace or more of precipitation at Phoenix during July and August, 1951–70.

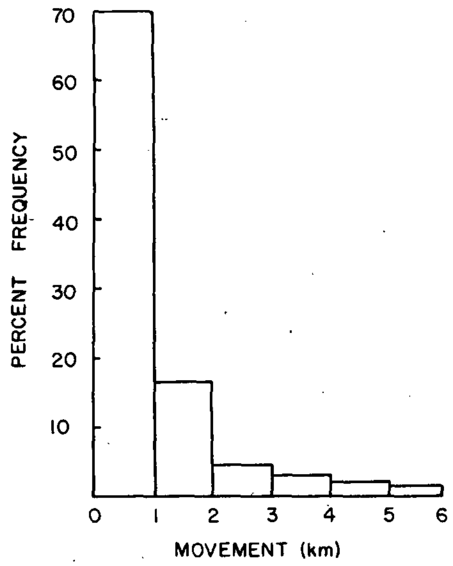

FIG. 3. Frequency distribution of total echo movement over Arizona during 1955.

tropical regions. These storms have been related to low-level jets and land breezes, respectively. Neither of these mechanisms seems to apply in Arizona.

Also, the nocturnal maximum cannot be attributed to the movement of storms off the mountains. In a study of radar echoes around Tucson, Braham (1958) found that "the rain showers (echoes) which occur over the lowlands near the mountains did not form and drift off the mountains." In support of this, a frequency distribution of echo motion over Arizona for the year 1955 (Fig. 3) shows that only about 10% of the cells move more than 3 km. Braham further states that "those storms which appear to have drifted from off the mountains actually result from progressive development of new cells at successively greater distances from the mountains."

2. Case studies

During the 1950's, Phoenix released rawinsondes at 0800 and 2000 LST. The change in the temperature profile between these two soundings was computed for five days when evening thunderstorms were observed at Phoenix prior to 2000 LST. The mean change was compared to one computed from five days when thunderstorms either did not occur, or occurred after 2000 LST (Fig. 4). The non-thunderstorm soundings exhibit warming to above 500 mb. However, the soundings that were modified by thunderstorms show cooling from 700 mb to above 600 mb, with the 2000 LST temperature averaging about 1°C cooler at about 630 mb than the 0800 LST soundings. Above about 500 mb the profiles reversed with the modified soundings showing warming to 400 mb while the non-thunderstorm soundings exhibit slight cooling above 450 mb.

To examine this thunderstorm-related mid-level cooling, a project was undertaken to sample the temperature characteristics in the vicinity of convective clouds over the desert. Over a period of two summers, several vertical and horizontal temperature profiles were taken from a single engine Cessna 172 aircraft with a thermocouple probe attached to a wing strut. Care was taken to avoid exposure of the probe to direct sun and engine heat.

a. Case I

On 13 August 1970, two vertical soundings were taken over the Phoenix area (Fig. 5). At 1600 LST, the sky was clear over the desert valley with the closest cumulus being some 30 km to the north. A nearly dry adiabatic lapse rate was measured to about 830 mb. From there to 750 mb, a more stable region with a lapse rate of less than 7°C km^{-1} existed. Above this, the lapse rate again was nearly dry adiabatic. While noticeable turbulence was observed in the dry adiabatic layer, the air was smooth above it. Two hours later, at 1800, convective cloudiness had developed near Phoenix. A second aircraft sounding was taken with the aircraft near, but out of the clouds at all times, and under visual flight regulations (VFR). Warming had occurred from near the surface to about 800 mb. However, from 750 mb to the termination of the sounding at 600 mb, cooling of 1.5–2.0°C had occurred. The slight stable layer was gone and the lapse rate was dry adiabatic to about 680 mb. The bases of the cumulus clouds were just below the top of the deep dry adiabatic layer, at about 700 mb.

Thus, while the lower levels warmed, mid-level cooling had occurred with the development of cumulus clouds. While it might be argued that upward vertical velocity and adiabatic cooling account for the observed temperature decrease, velocities of ~30 cm s^{-1} would be necessary to lift a parcel from the top of the initial

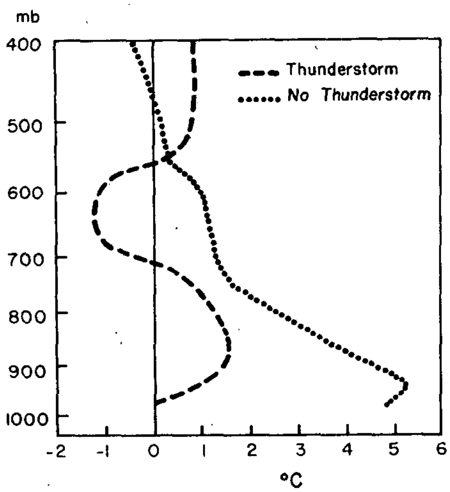

FIG. 4. Average temperature change between 0800 and 2000 LST at Phoenix on five thunderstorm and five non-thunderstorm days.

low-level inversion to the 600 mb level where data collection was terminated. Further, in the air adjacent to clouds, subsidence rather than rising motions would be expected.

b. Case II

On 3 September 1970, an unusually intense Haboob (mesothunderstorm system) was moving toward the Phoenix area from Tucson. A vertical aircraft sounding was started over Phoenix at 1540 LST. It had characteristics similar to those of the early sounding in the previous case. The dry adiabatic boundary layer was capped by a slightly stable layer around 850 mb with another dry adiabatic region starting at about 650 mb. There were some small cumulus clouds over the nearby mountains, but no convective clouds were near Phoenix.

The aircraft then flew to the thunderstorm area about 70 km south of Phoenix. A vertical wall of clouds with blowing dust below arced from horizon to horizon, east to southwest, as the aircraft approached. Detailed temperatures were taken near the cloud cluster. About 6 km north of the cloudy area the temperature at an altitude of 3 km ranged from 13.7 to 15.4°C. Upon entering the clear air between the clouds, the temperature dropped immediately to 10.9°C.

c. Case III

On 29 July 1971, the horizontal temperature distribution in the vicinity of a developing convective cloud region was measured. The extent of cumulus development into the desert valley, along with the location of two thunderstorm cells, are shown in Fig. 6. Outside of this area, which had at least 50% cloud coverage, the sky was clear. The horizontal temperature profile was made at 3.5 km (cloud base). The initial temperature reading was made between clouds, 25 km behind the leading edge of the cloud cluster. From this point to about 5 km behind the edge of cloud development, the temperature ranged from 8.5 to 9.5°C. (It should be reiterated that the flight and temperature measurements were all in the clear air.) At the edge of the cloud zone, the temperature rose to 10.4°C and jumped to 11.1°C immediately outside of it. From this point back to Phoenix, the temperature remained between 10.6 and 11.1°C. There was a mean difference between the temperature inside the cloud development zone and that within the cloud-free area of 1.6°C. Since measurements in both zones were taken in clear air, the change reflected a change in the air mass structure.

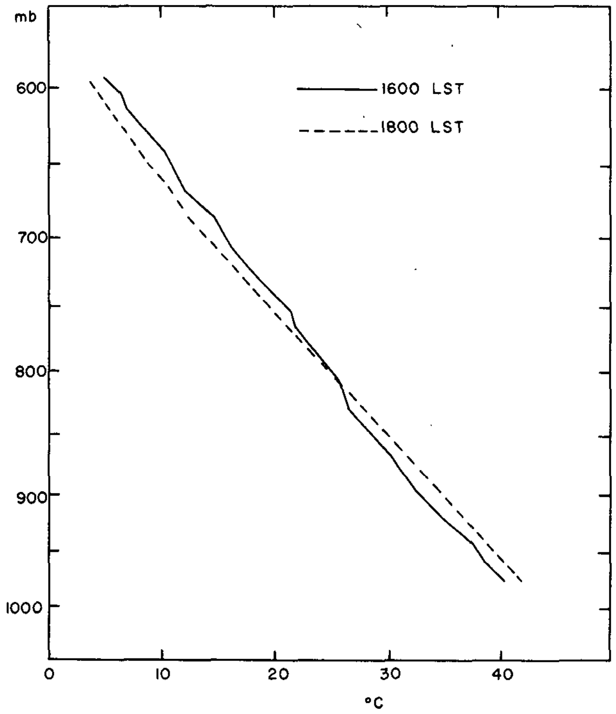

FIG. 5. Temperature profiles derived from aircraft data taken at 1600 and 1800 LST 13 August 1970 over Phoenix, Ariz.

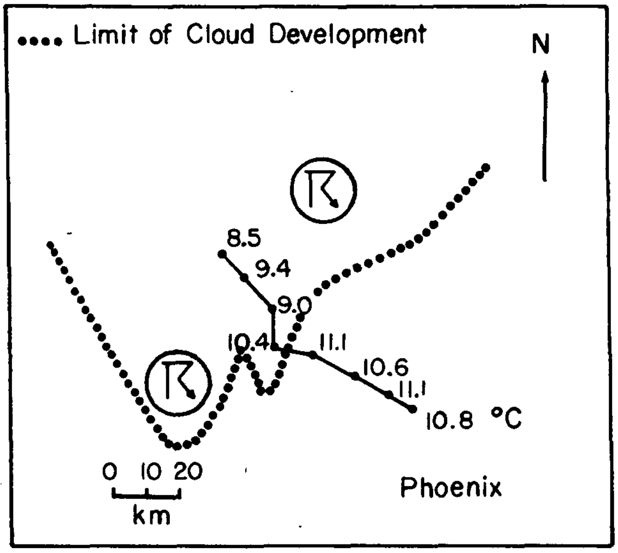

FIG. 6. Horizontal temperatures measured by aircraft at 3.5 km with respect to significant cloud features at 2000 LST 30 July 1971.

Many other flights were made in and out of cumulus development regions over the two-year period, and similar observations of cooler temperatures in the cloud-free air were made.

3. Possible cooling mechanism

The cooling associated with cumulus clouds in Arizona can be explained by a mid-latitude extension of the work in the tropics done by Gray (1973), Lopez (1973) and Kininmonth (1970). It was found that tropical cumuli and cumulus cloud systems act as cooling towers instead of performing the often hypothesized warming role. This cooling arises from evaporation. The latent heat released from cumulus clouds (both precipitating

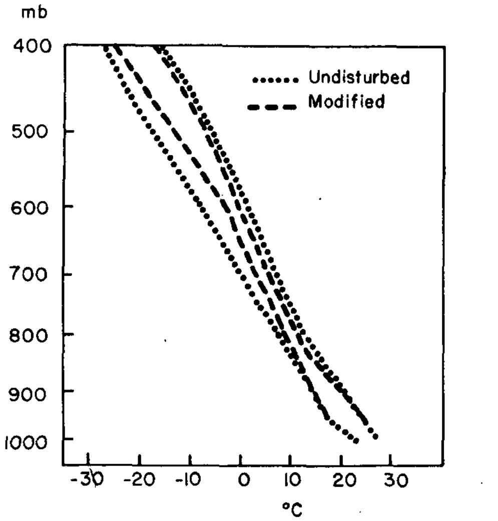

FIG. 7. A comparison of the average of five soundings undisturbed by convection to that of five modified by close mesoscale cloud systems near Anaco, Venezuela (after Kininmonth, 1971).

and non-precipitating) goes primarily into a potential energy gain. The small temperature excess (1–2°C) of the rising parcel required for buoyancy does not warm the environment unless it directly mixes out from the cloud at a higher temperature. More typically, a parcel continues rising until it loses its buoyancy. It then mixes with the environment at a temperature little different (or even lower) than that of the environment. The cloud droplets, which remain after the vertical motion in the cumulus has stopped, cool the air in and around the clouds.

While this evaporation-cooled air sinks, due to its negative buoyancy, the amount of subsidence is determined by both the environmental stratification and the actual magnitude of the cooling. Air which is cooled in an active precipitation region is often dense enough to reach the ground and forms the thunderstorm outflow. However, the air which originates on the cloud periphery is only slightly cooler than the environment. It oscillates around its thermal equilibrium point which is in the region of the low-level inversion. Mixing occurs during this oscillation and results in a net cooling of the environment near the clouds.

This is not implying that the total effect of the convection on a synoptic scale is not one of warming. As Fritsch (1975) showed, dry adiabatic sinking at some other location (to satisfy mass balance) can more than compensate for the local cooling if there has been rainfall. In this way, the cumuli act to produce a *local* cooling, but a *global average* warming.

A phenomenon similar to that found in Arizona has been observed in Venezuela (Kininmonth, 1970). He gives a comparison of the mean of five soundings following the onset of convection made near the cloud edge of mesoscale cloud systems near Anaco, Venezuela (Fig. 7). Note that the modified air is cooler from 900 to 400 mb than the undisturbed air.

Modahl (1974) observed direct modification by cumulus clouds in a continental, mid-latitude mesoscale environment during the 1972 National Hail Research Experiment in northeast Colorado. Fig. 8 from Modahl shows the mean departure of temperature from 15-day running averages for clear days and hail days at 1700 LST over Sterling, Colo. These data show that on clear days the temperature in the layer between 700 and 400 mb is warmer than would be normally expected. However, on hail days this layer is markedly cooler. This suggests that even in mid-latitudes, the local effect of cumulus activity is to produce local net cooling of the middle troposphere through evaporation of spent cloud debris.

4. Implications

It is proposed that this mid-level evaporational cooling is in part responsible for the nocturnal thunderstorm maxima over the Arizona desert. While convec-

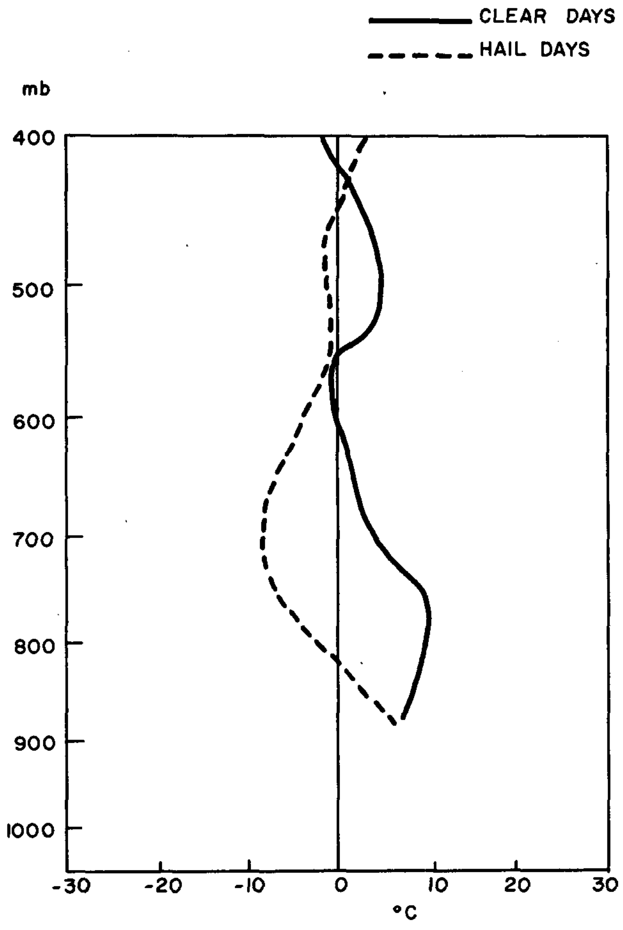

FIG. 8. Profile of average temperature departure from mean conditions for five clear and five hail days at Sterling, Colo. (after Modahl, 1974).

TABLE 1. Diurnal distribution (percent) of summer thunderstorms at Phoenix and Yuma (data from Hydrometeorological Rep. No. 5, 1947).

	Time LST			
	0000–0600	0600–1200	1200–1800	1800–2400
Phoenix	15.4	10.2	26.5	47.8
Yuma	23.5	14.3	32.8	29.4

tion is prevalent there during the mid-afternoon, the extremely high levels of free convection (LFC) limit thunderstorm development. However, blowoff from the orographically induced thunderstorms, some 120 km upwind, advects westward, thereby reducing mid-level stability and allowing storms to develop.

During Arizona's summer thunderstorm season, mid-level winds are generally from the east through the south at speeds of less than 10 m s^{-1}. During the 30 min of an individual storm's lifetime, very little movement is observed. However, the westward advection of relatively cool mid-level air allows for redevelopment of thunderstorms downstream. This cool air, which originates over the mountains in mid-afternoon reaches the Phoenix area by mid-evening. Even though the boundary layer is being stabilized by radiational cooling at this time, the lowering of the LFC increases the thunderstorm potential of the environment. The actual triggering mechanism is unknown, but given the extreme roughness of the terrain and the presence of thunderstorms upstream, there is no dearth of potential candidates.

The importance of this convective cooling for downstream storm development can be seen by comparing the diurnal distribution of thunderstorms at Phoenix to that at Yuma (Table 1). This city in the southwest corner of Arizona is also in the desert, but the mountain complex is about 300 km upstream. In contrast to the nocturnal maxima at Phoenix, the thunderstorm activity at Yuma is almost uniformly spread throughout the day, with a slight maximum occurring in the afternoon. Further, there are almost four times as many thunderstorms at Phoenix than at Yuma.

The same pattern of thunderstorm development toward lower elevations during the night has been found to occur on the east side of the Rocky Mountains from Montana to New Mexico. Karr and Wooten (1976) found that thunderstorm activity progresses eastward from the eastern slopes of the Colorado Rockies during the afternoon to well into Kansas at night.

The primary effort of this study has been to present ideas and some case studies on the concept of evaporative cooling due to dissipation of convective cloud debris. This mechanism helps to answer some of the questions relating to the development and distribution of nocturnal thunderstorms.

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