UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

The Microclimate in Carlsbad Caverns, New Mexico

By J. S. McLean

Open-file report

Prepared by the U.S. Geological Survey
for the National Park Service under
NPS Research Project CACA-N-1a

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Abstract

The U.S. Geological Survey in 1968 began a study of Carlsbad Caverns in cooperation with the National Park Service to determine the cause of drying of cave pools. Data on airflow, water levels, evaporation, temperature, carbon dioxide, and relative humidity were collected. Rainfall data indicate the cave may be undergoing a slight dry spell, but that the number of storms with rainfall exceeding computed evapotranspiration is about average. The cool temperature (57°F) throughout the visited parts of the cave is lower than the mean annual temperature at the surface. This cooling is caused by the circulation of cold air, part of which moves up and out the elevator shaft. The primary cause of drying is excessive airflow up the elevator shaft during winter months. The airflow results in a net loss of about 83,000 liters (22,000 gallons) of water per year from the cave. A secondary cause of drying is the increased evaporation due to heat added to the cave by the lighting system, which is six times the natural heatflow. In contrast, paving the surface over the cave, the presence of visitors in the cave, air conditioning the visitor center with air from the cave and the below-average precipitation in recent years have caused very little drying.

Recommendations include: sealing the elevator shaft against airflow, using more efficient bulbs to reduce heating by the lighting system and refilling scenic pools.

Introduction

The scenic beauty of Carlsbad Caverns is enhanced by the clear, green pools scattered throughout the cave. Since about 1940, however, guides and visitors have noticed that the water level in some pools has declined. Photographs taken in 1950 show some pool levels more than 0.3 meter (1 foot) above present (1970) levels. To determine the cause of the drying of the pools and discover possible remedies, the U.S. Geological Survey in 1968 began a study of Carlsbad Caverns in cooperation with the National Park Service. This report contains a basic description of the cave microclimate, a discussion of man-caused changes in the cave microclimate that have affected the cave pools, and suggested methods of restoring the microclimate and pools to more nearly natural conditions.

Location and extent

Carlsbad Caverns are in the eastern Guadalupe Mountains of south-central New Mexico about 43 kilometers (27 miles) southwest of Carlsbad, Eddy County (fig. 1). The cave entrance (fig. 2) is at an altitude of 1,325 meters (4,348 feet). Much of the cave is at an altitude of 1,082 to 1,143 meters (3,550 to 3,750 feet); the lowest area is Lake of the Clouds (fig. 3) at an altitude of 1,009 meters (3,311 feet); the elevator shaft (fig. 3) extends from the Visitor Center on the surface at an altitude of 1,343 meters (4,406 feet) to the Underground Lunch Room at an altitude of 1,113 meters (3,652 feet). Over 24 kilometers (15 miles) of passage have been mapped in Carlsbad Caverns. The only known entrances to the cave are the large Natural Entrance and two smaller openings in the Bat Cave section, one of which is artificial. Unknown passages for airflow to the surface or to unknown parts of the cave may exist.

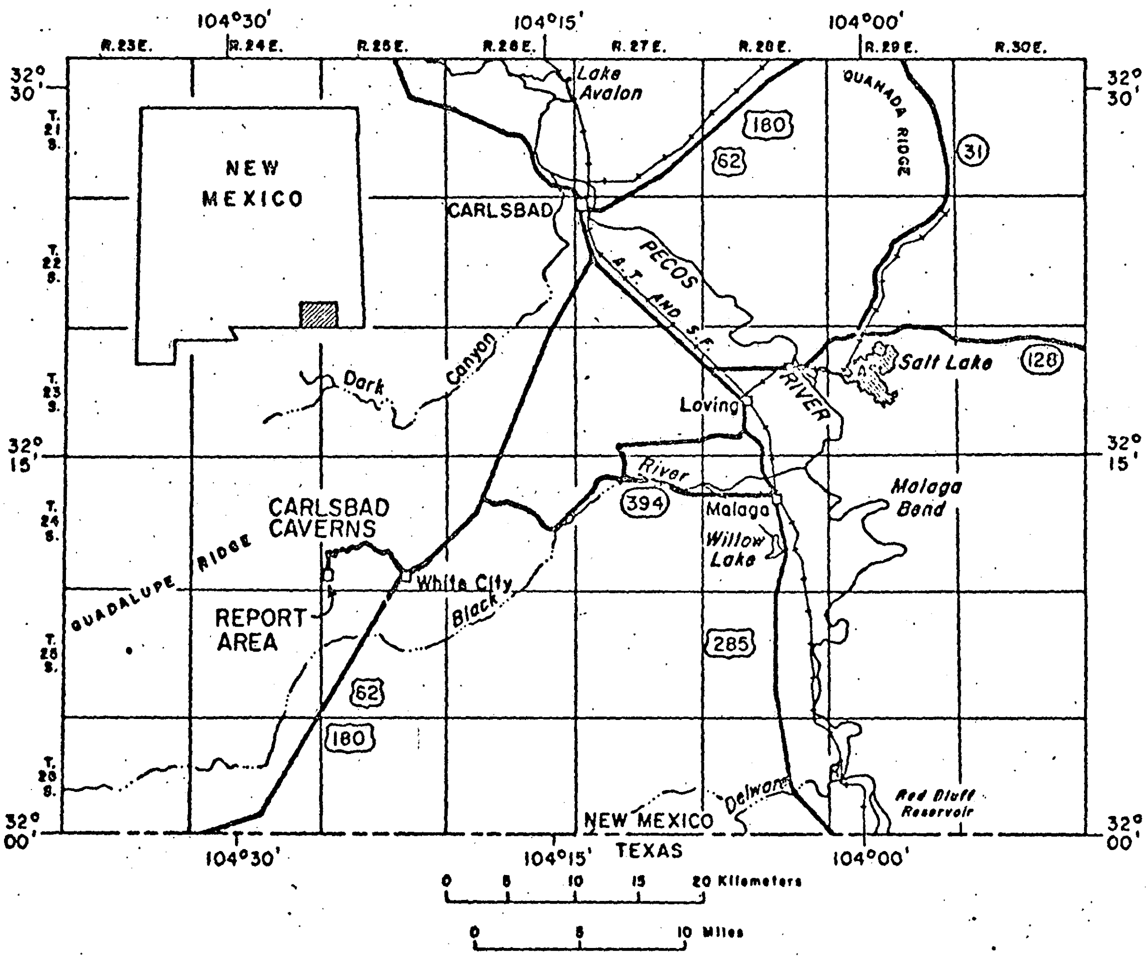


Figure 1.--Index map.

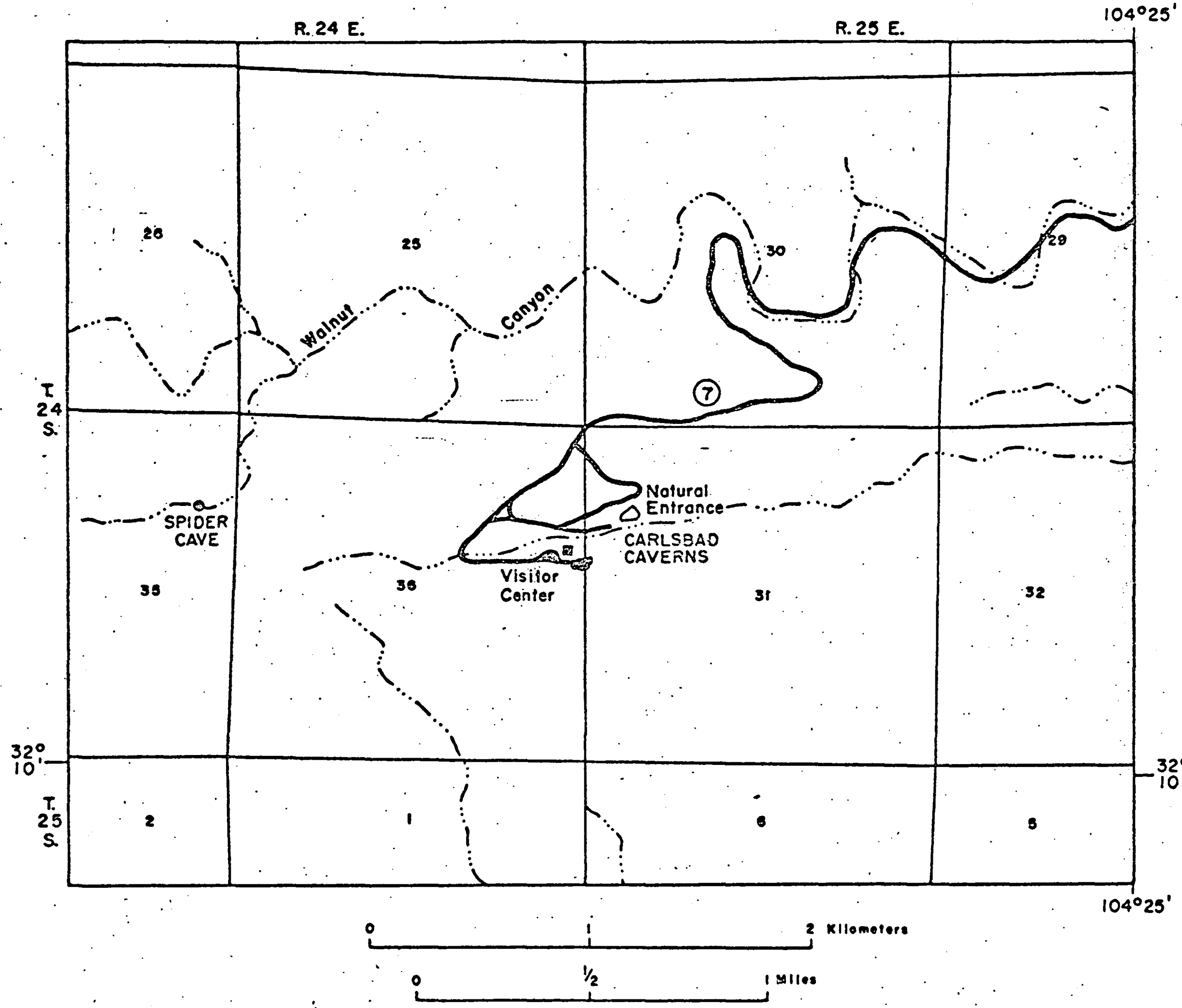
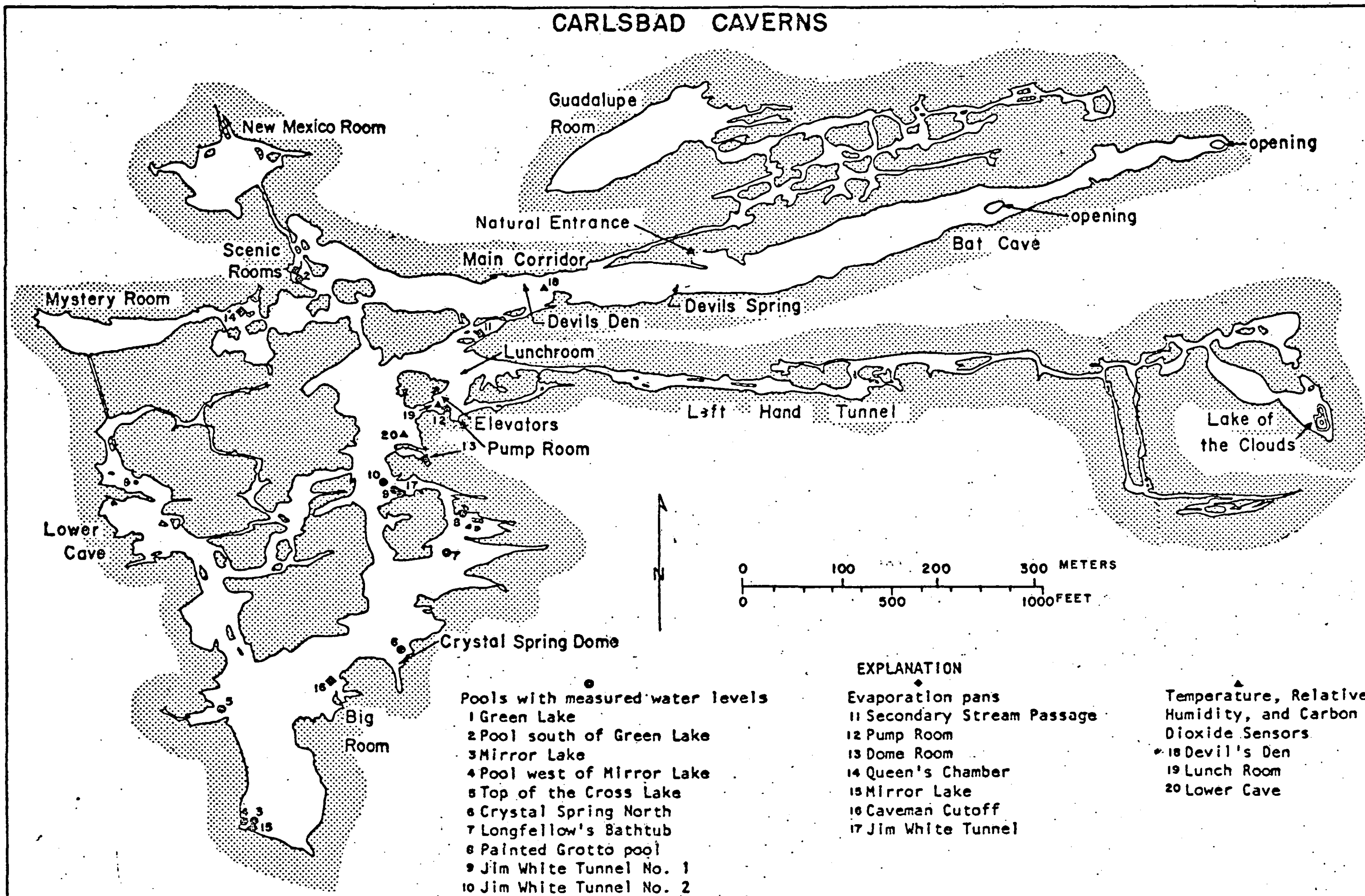


Figure 2.--Sketch map of the Carlsbad Caverns area.



Base modified from Moore, 1960

Compiled by J.S. McLean, 1970

Figure 3.--Location of measuring points.

Method of study

A 24-channel recorder was connected to units capable of measuring temperature, relative humidity, and carbon dioxide. Temperature was measured by thermistor probes accurate to ±0.1°C. Relative humidity was measured by gold-electrode units accurate to about ±2 percent relative humidity. Carbon dioxide was sampled at three locations in the cave with an air pump and measured with an infrared analyzer, accurate to about 5 ppm (parts per million). Each channel records five times per hour--a total of more than a million points for all channels in 1 year. Selected weekly temperature, humidity, and carbon dioxide at three locations in the cave (fig. 3) was reduced by hand. Variations in evaporation were obtained from eight nonstandard plastic evaporation pans, each with an area of 794 square centimeters (123 square inches). The locations of these pans are shown in figure 3. Rulers with millimeter scales were placed in pools in the cave, and water-level changes were recorded. A portable thermistor probe, accurate to 0.1°C, was constructed and used to measure soil temperatures throughout the cave. Data on visitor use and power consumption were supplied by the National Park Service.

Acknowledgments

Neal G. Guse and Philip Van Cleave of the National Park Service supplied data on visitor use and power consumption in the cave. Neal Bullington of the National Park Service collected data on pool levels and evaporation from remote cave locations. Numerous other individuals supplied survey data for the cave. F. C. Koopman and Steve Uurtamo installed, modified, and calibrated many of the sensors. The study was conducted under the direct supervision of F. C. Koopman, Supervising Hydrologist, and W. E. Hale, District Chief, Water Resources Division, U.S. Geological Survey, Albuquerque, N. Mex.

Surface climate

The climate at the land surface over Carlsbad Caverns is semi-arid; the mean annual rainfall is 37 centimeters (14.4 inches). Seventy-eight percent of the mean annual rainfall occurs in May through October and 22 percent in November through April. Historically, Carlsbad Caverns appears to be undergoing a slight "dry spell" as shown in figure 4. This figure shows the cumulative departure of the annual rainfall from the long-term average. Rising and falling parts of the curve indicate wet and dry periods, respectively. The steepness of the falling curve indicates the severity of the drying. Rainfall since 1958, though irregular, has been slightly below average, although not as low as the extreme drying in the period 1946-57, which followed the wet years of the early 40's.

Mean monthly temperatures range from 7.5°C (degrees Celsius) or 45.6°F (degrees Fahrenheit) in January to 26.1°C (78.9°F) in July. The mean annual temperature is 17°C (63°F). Monthly rainfall and mean monthly temperatures at Carlsbad Caverns from January 1969 to June 1970 are shown in figure 5.

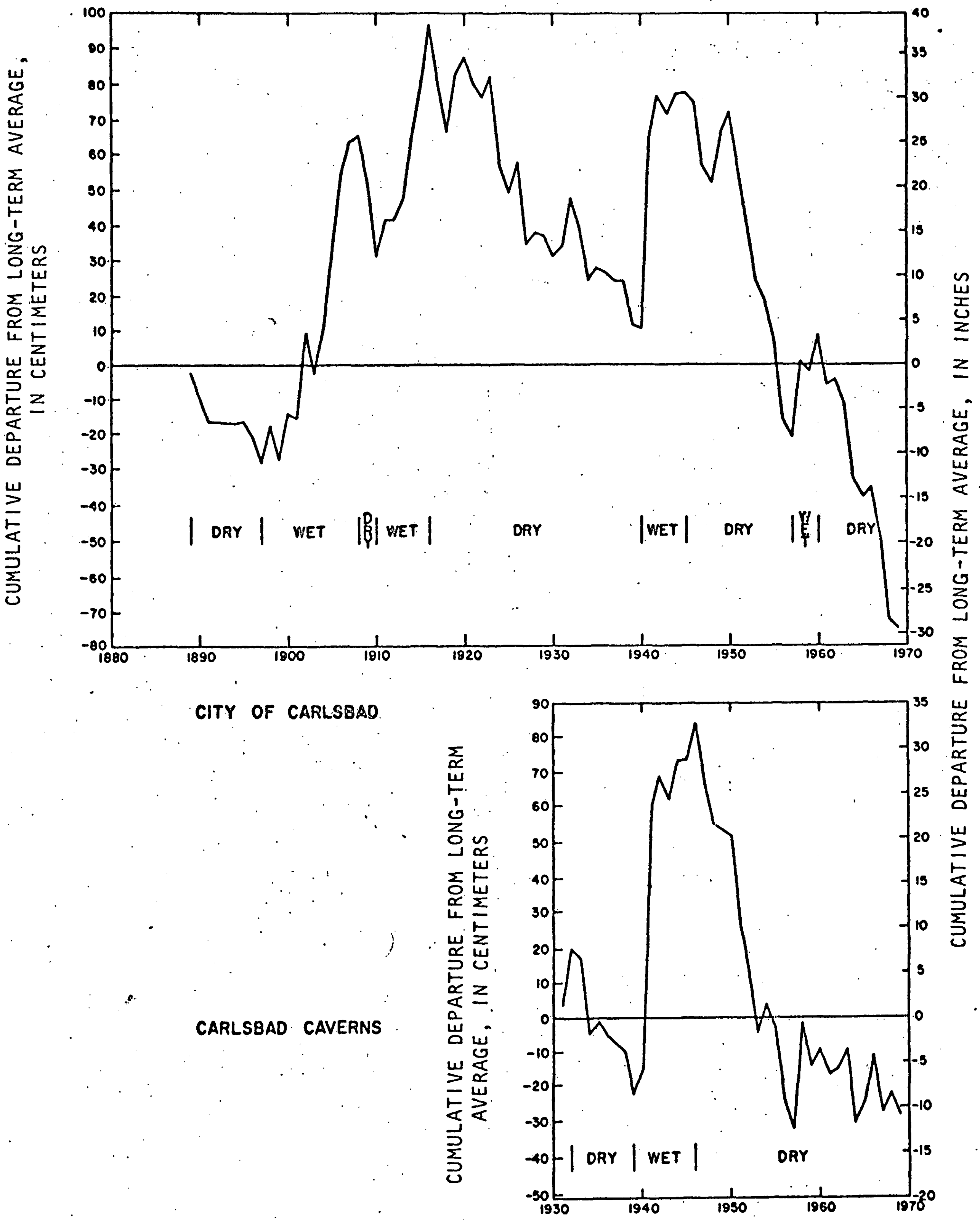
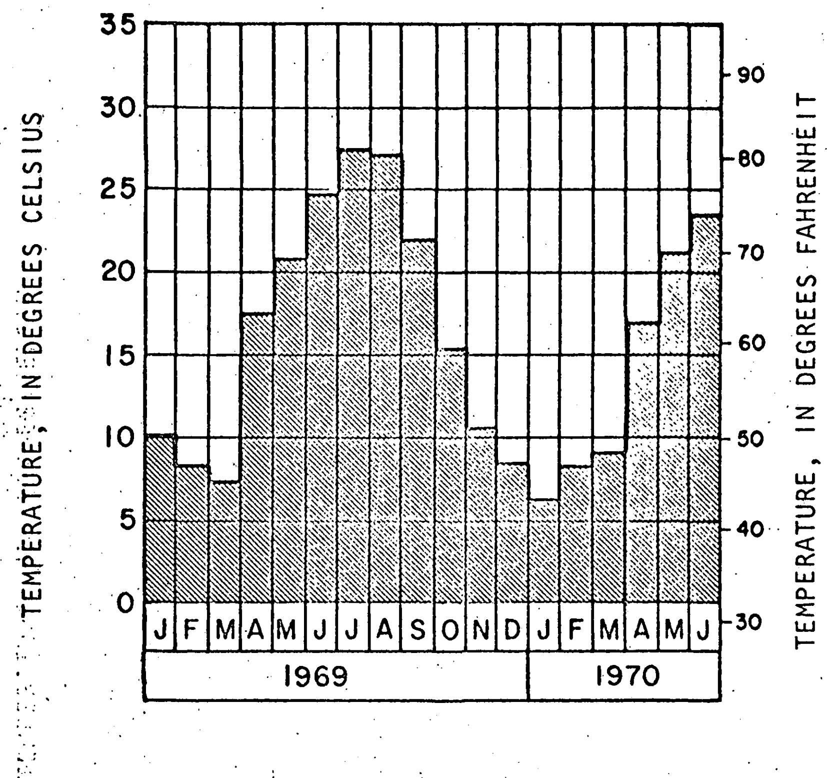


Figure 4.--Cumulative departure of rainfall from long-term average.



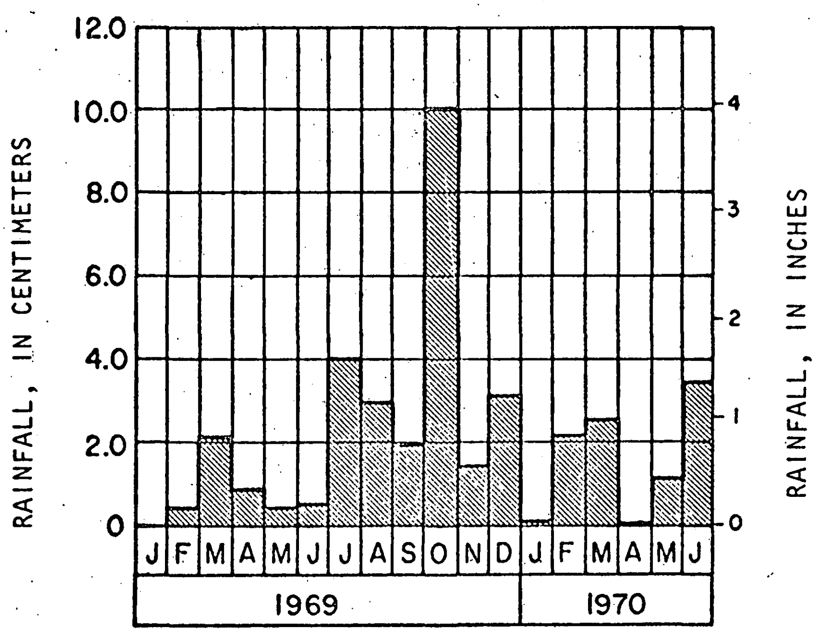


Figure 5.--Monthly rainfall and mean monthly temperature at Carlsbad Caverns.

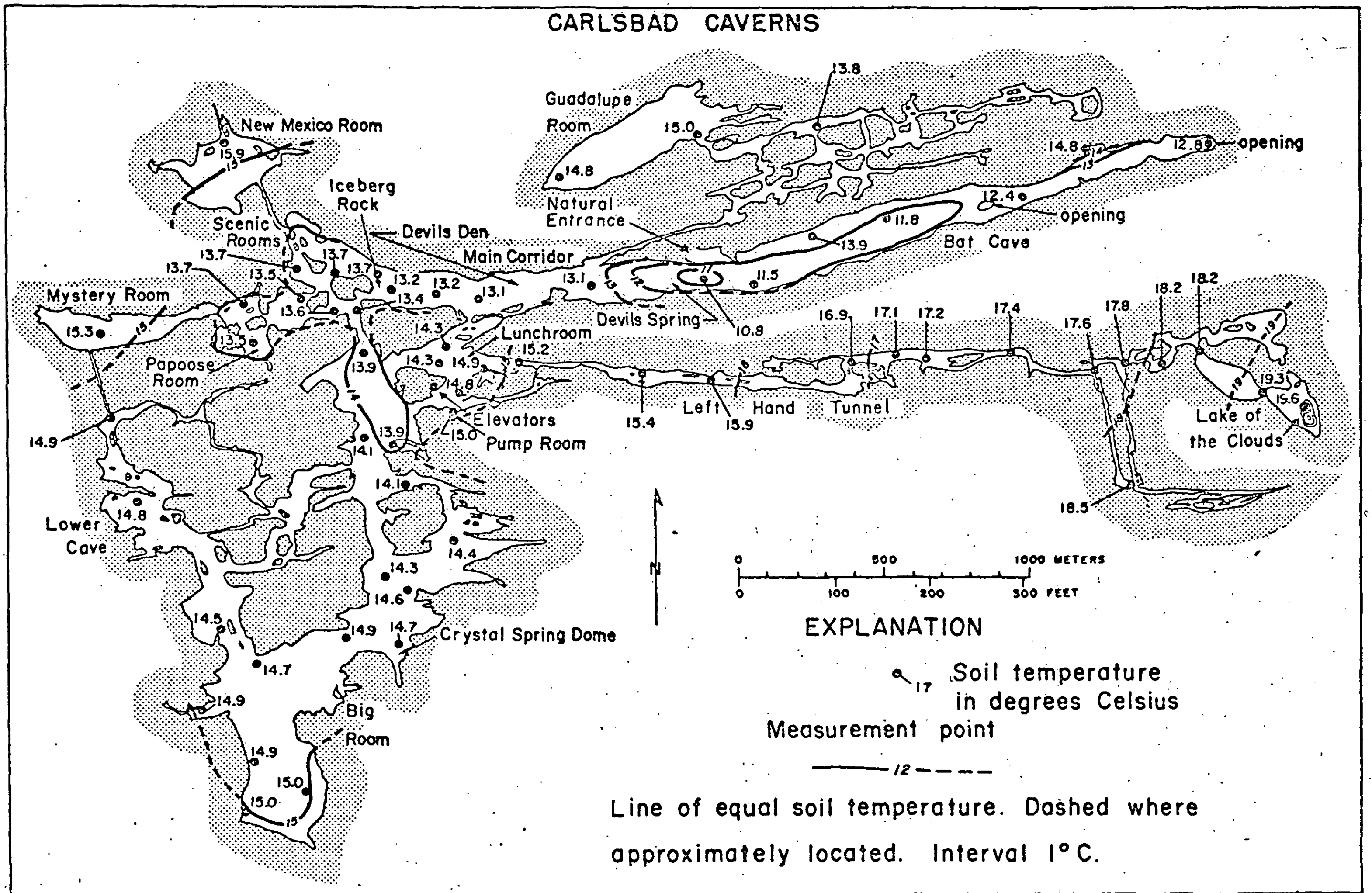
Cave microclimate

In the geologic past Carlsbad Caverns contained much more water than at present. This is evidenced by the massive gypsum beds deposited in the cave and by the many dry rimstone pools. As erosion destroys the ridge containing the cave, air circulation and evaporation in the cave increases. Superimposed on this long-term drying trend are two short-term effects: First, rare wet events (periods of very high rainfall lasting several days or more) may recharge some cave pools more than the average seasonal precipitation. Thus, some pools may show rapid increases in water level followed by a slow, irregular decline. Second, cave visitors, elevator shafts, lighting, and sewage removal have altered the microclimate.

Temperature and heat exchange

The temperature in the commonly visited parts of Carlsbad Caverns, a relatively constant 14°C (57°F), is lower than the mean annual temperature at the surface: 17°C (63°F) (Houghton, 1967). This cooling of the cave is believed to be due to cold air circulation from the surface through the Natural Entrance and through the shafts in Bat Cave (fig. 3).

The temperature distribution in the cave soil in September 1969 is shown in figure 6. These measurements were made with a thermistor which was buried 3 centimeters deep in the cave soil to reduce the effect of short-term variations on the measured temperature. Minimum temperatures in September occur beneath the Natural Entrance and in Bat Cave. Maximum temperatures occur in the Lake of the Clouds area, the lowest and most isolated part of the cave presently accessible.



Base modified from Moore, 1960

Compiled by J.S. McLean, 1970

Figure 6.--Cave soil temperatures, September 1969.

The cave soil temperature distribution with altitude in Carlsbad Caverns is shown in figure 7. The temperature at a point 600 feet inside nearby Spider Cave, a maze-type cave with a small entrance and restricted airflow, is shown for comparison. The air temperature at three locations within Carlsbad Caverns is shown in figure 8. During the summer air conditions are stable; that is, the overlying air is less dense than the air in the cave. (The density of air is a function of its pressure, temperature, and moisture content. At a constant pressure warm air is less dense than cold air and moist air is very slightly less dense than dry air.) During the winter air conditions are unstable as cold, dense air flows into the cave and displaces the warm, moist (less dense) air in the cave.

The winter cooling of the cave by cold air circulation takes place through the direct cooling of the cave walls by the inflowing air and by evaporation of water from pools and damp areas in the cave.

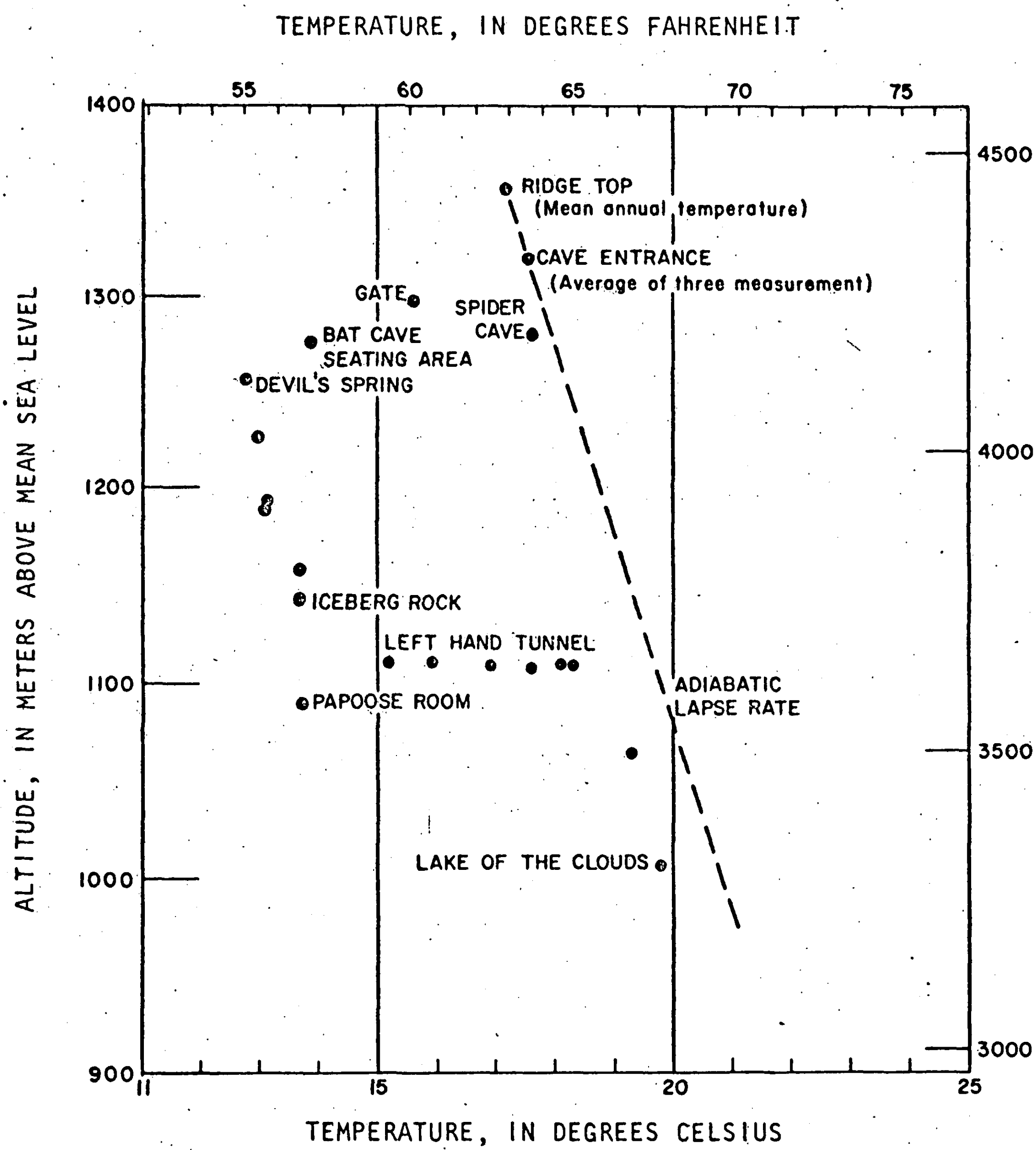


Figure 7.--Cave soil temperature distribution with altitude, September 1969.

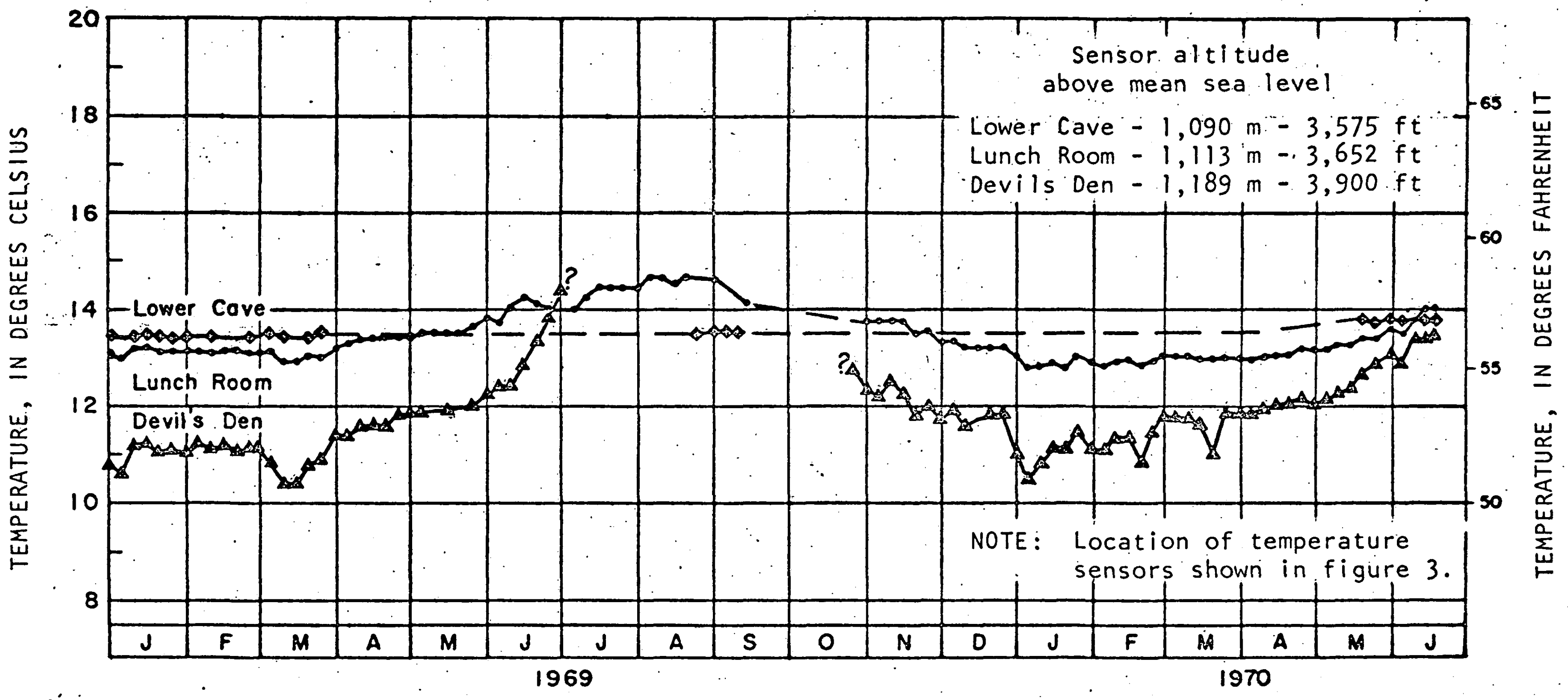


Figure 8.--Temperature at three locations in Carlsbad Caverns.

Heat is added to the cave primarily by geothermal heatflow, by heatflow from the surface, and by the addition of heat through the lighting system. The magnitude of the heatflow that balances the heat lost through evaporation and cold air circulation (cold trap effect) can be calculated roughly using the heatflow equation (Carslaw and Jaeger, 1959, p. 2).

$$Q = \frac{K\ (T_0 - T_1)\ S}{d}$$

where Q = heatflow, in cal/sec (calories per second)

K = thermal conductivity, in cal/sec/cm/°C (calories per second per centimeter per degree Celsius)

T = temperature, in °C (Celsius)

S = surface area, in cm^2 (square centimeters)

d = thickness, in cm (centimeters)

The area of Carlsbad Caverns at the 230-meter (750-foot) level is about 1.65×10^9 cm^2 (1.78×10^6 ft^2). The geothermal gradient, as measured in a well in sec. 23, T. 22 S., R. 24 E., about 24 kilometers (15 Miles) north of the Caverns is 18°C per 1,000 m or 10°F per 1,000 feet. K for limestone is 0.004 cal/sec/cm/°C (Carslaw and Jaeger, 1959, p. 497). The geothermal heatflow from below into Carlsbad Caverns, neglecting side effects, is about

$$\frac{(0.004 \text{ cal/sec/cm/°C})\ (18°\text{C})\ (1.65 \times 10^9 \text{cm}^2)}{10^5 \text{ cm}}$$

$$= 1{,}200 \text{ cal/sec.}$$

Likewise, the heatflow through the limestone from the surface which has a mean-annual temperature of 17.2°C (63.0°F) to the 230-meter level in the cave with a temperature of 15.0°C (59.0°F) is:

$$\frac{(0.004 \text{ cal/sec/cm/°C})\ (17.2°\text{C}-15.0°\text{C})\ (1.65 \times 10^9 \text{cm}^2)}{2.3 \times 10^4 \text{ cm}}$$

$$= 630 \text{ cal/sec.}$$

The total natural heat flowing into the cave through the surrounding limestone is about 1,800 cal/sec. This figure is probably somewhat low because much of the cave is colder than 15°C (59°F) and because side effects are neglected.

Heat in excess of the natural flow is added to the cave by lighting, pumping, food-preparation, water for sewage, and the body heat of cave visitors. About 385,000 kilowatt hours per year are used for lighting and other electrical needs in the cave (Philip Van Cleave, oral commun., 1969). Thus, about 10,500 cal/sec, or about six times the natural heatflow, are introduced into the cave through the electrical system. The cave visitors give off an estimated average of only 6 cal/sec[1/].

1/ The average adult metabolizes about 2,500 calories per day, most of which is converted into heat. Assuming 2,000 calories of this is used during an active 12-hour period, the average cave visitor gives off about 330 calories during the 2 hours he is in the cave. Because about 600,000 persons visited Carlsbad Caverns during 1969, a total of 2×10^8 calories were released into the cave,--about 6 calories per second.

The addition of water to the Pump Room area and the removal of sewage also affects the heat balance in that area. The temperature of the inflowing water was 12.5°C (54.5°F) in January and 23.0°C (73.4°F) in May 1970. If this water has a mean annual temperature of 18°C (64.4°F) and is allowed to reach the temperature of the Pump Room 15°C (59°F) the addition of 6 million liters (1.6 million gallons) of water per year at 18°C and its removal as sewage at 15°C produces a net addition of heat to the cave of 60 cal/sec. Thus, the heating effect of the waterflow, while more than the heat added by cave visitors, is much less than the heat added by the lighting system. As this effect is confined to the Pump Room area, rather than being distributed throughout the cave, it is probably partly responsible for the higher temperature in the Pump Room (fig. 6).

The above presentation is not intended as a heat balance, but simply to indicate the relative importance of sources of heat in the cave. The heat introduced through the lighting system is an important disturbance of the natural environment in the cave. Since the cave has not warmed measurably over the short period of study, it is assumed that the heating effect of the lighting system is largely balanced by increased airflow and evaporation.

The heat lost from the cave in the air leaving the cave through the elevator shaft can be calculated roughly by measuring the difference in temperature between the air entering and leaving the cave, and correcting this difference for the adiabatic lapse rate so that

$$Q = CaV\rho\ (\Delta T - Ta)$$

where Ca = specific heat of air

V = volume of airflow in m^3/sec (cubic meters per second)

ρ = density of air in gm/m^3 (grams per cubic meter)

ΔT = temperature difference between inflowing and outflowing air

Ta = adiabatic temperature change

Ca and ρ are variable, but an estimate of the heatflow up the elevator shaft can be made using average values for Ca of 0.239 cal/gm/°C and for ρ of 1,056 gm/m^3 2/. Ta is the temperature change due to the movement of air from the surface or Devil's Den to the Lunch Room: the adiabatic lapse rate times the altitude difference (10°C/1,000 m x 212 = 2.1°C). The results are summarized in table 1. The mean annual heatflow out the elevator shaft is about 570 cal/sec, most of which is derived from above Devil's Den. Heat added during the summer is neglected, since airflow into the cave occurs primarily during the cool nights. The heatflow induced by the elevator shaft is, therefore, much less than the heat added to the cave by the lighting system. The rest of the heat is dissipated by the circulation of air out the Natural Entrance.

2/ Ca is the specific heat of air at constant pressure and ρ is computed from an average pressure at Carlsbad Caverns of 660 millimeters (26 inches) of mercury, an average relative humidity in the Lunch Room of 68 percent, and a temperature of 15°C (59.0°F). A vapor pressure of 11.74 millimeters and a density of 1,056 gm/m^3 is computed from tables (Handbook of Chemistry and Physics, 47th ed., p. F-7).

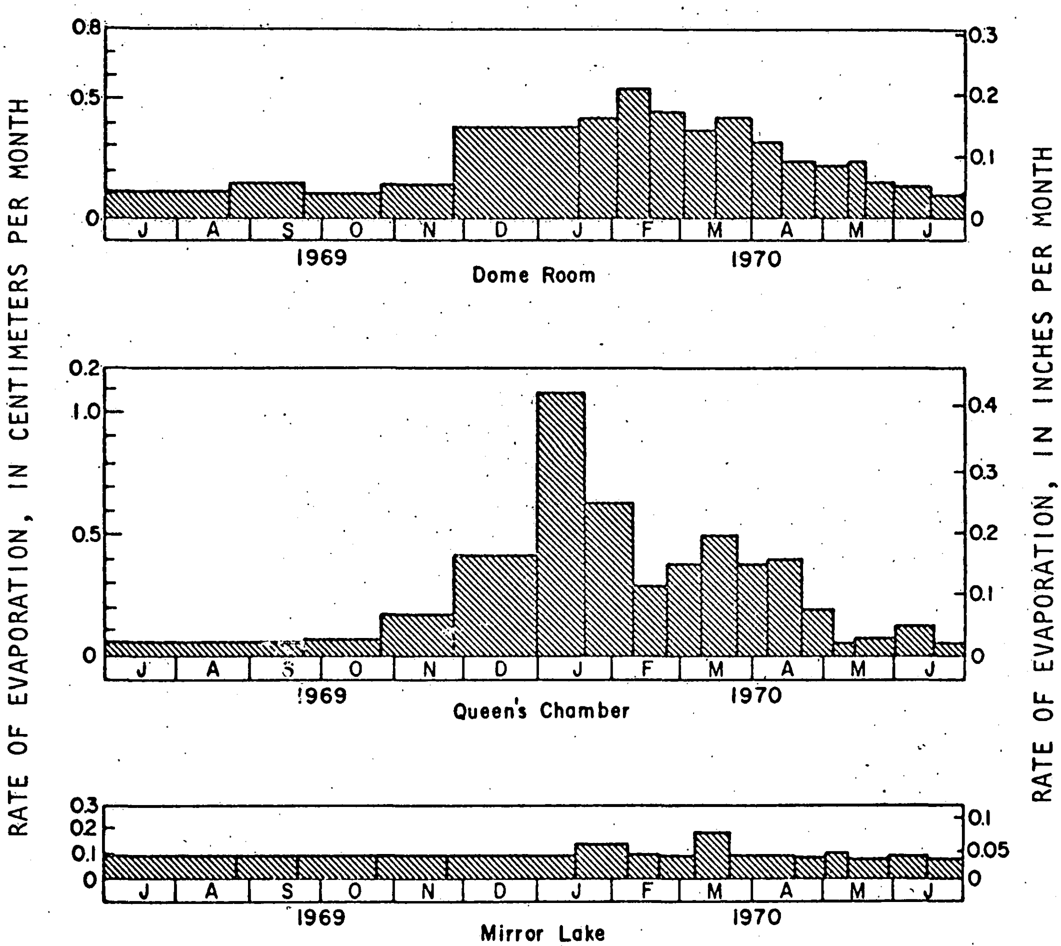
Table 1.--Monthly heat transfer by air out of the Carlsbad Caverns elevator shaft

Month and Year	Ca	V	ρ	Heat transfer below Devil's Den			Heat transfer from Caverns		
				ΔT	ΔT-Ta	Q	ΔT	ΔT-Ta	Q
	cal/gm/1°C	m^3/sec	gm/m^3	°C	°C	cal/sec	°C	°C	cal/sec
1969									
July	0.239	0.57(?)	1,056	-2.2	-3.3	---	-13.1	-15.2	---
August	.239	.57	do.	-3.4	-4.5	---	-12.4	-14.5	---
September	.239	.60	do.	-1.3	-2.4	---	-7.8	-9.9	---
October	.239	1.20	do.	.4	-.7	---	-1.5	-3.6	---
November	.239	1.28	do.	1.4	.3	97	2.9	.8	260
December	.239	1.62	do.	1.5	.4	164	4.7	2.6	1,060
1970									
January	.239	2.32	do.	1.9	.8	468	8.3	6.2	3,630
February	.239	1.71	do	1.7	.6	259	4.5	2.4	1,040
March	.239	1.76	do	1.4	.3	178	3.9	1.8	800
April	.239	1.65	do.	1.1	0	0	-3.7	-5.8	---
May	.239	.85	do.	.9	-.2	---	-7.6	-9.7	---
June	.239	.68	do.	.4	-.7	---	-10.1	-12.2	---

Evaporation and relative humidity

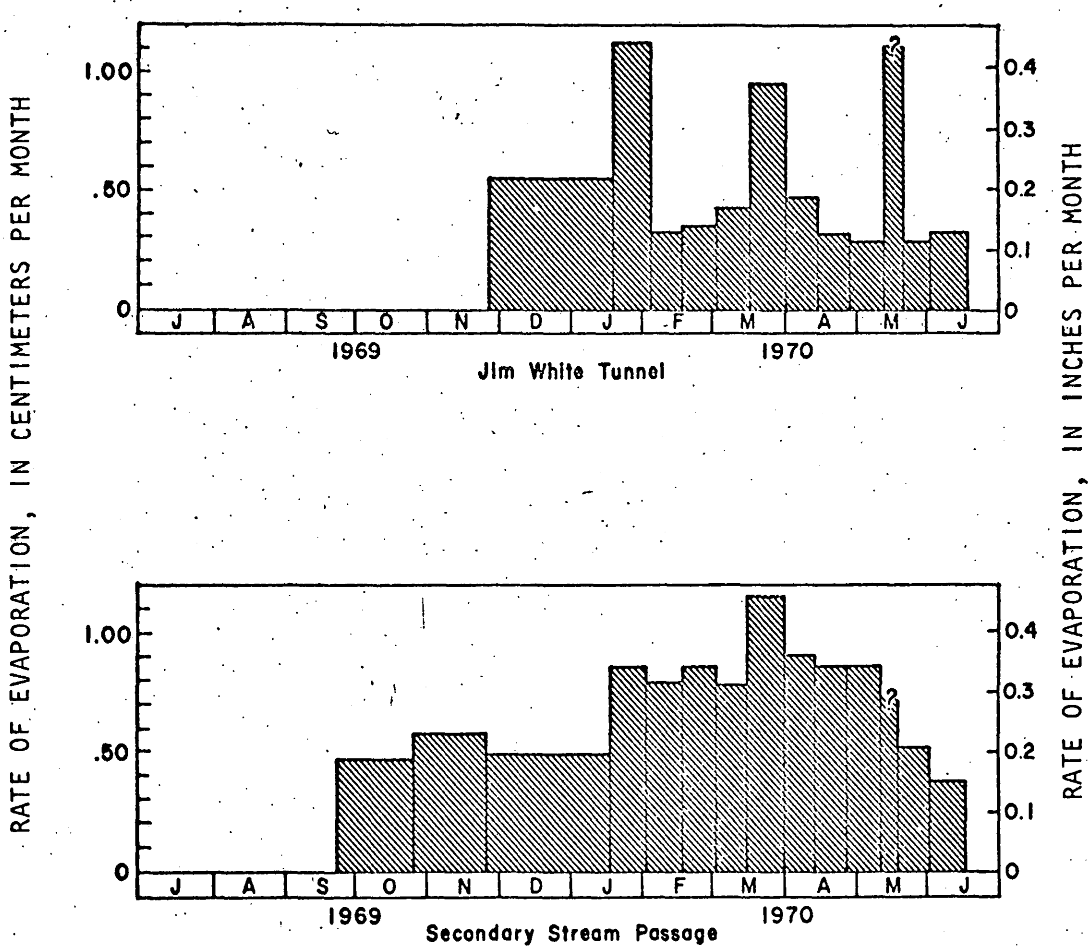
Cold air moving into the cave during the winter evaporates water very efficiently. The cold air passing over a cave pool is warmed by water in the pool, decreases in relative humidity, takes up moisture from the water surface of the pool and rises to be replaced with more cold air. For example: a cubic foot of air at 10°C (50°F) can contain 0.266 grams of water vapor at saturation. If warmed to 13°C (55.4°F) while taking up moisture it can contain an additional 0.052 grams of water vapor at saturation; thus evaporation can occur even though the humidity remains high. Figures 9 to 11 show the evaporation, in centimeters per month, at seven locations within the cave. These measurements show a general increase in evaporation from summer to winter, as would be expected if entrance and warming of cold winter air were the chief mechanism by which evaporation occurs. This is, of course, the opposite of what occurs on the surface, where annual evaporation is about 50 times as great as annual evaporation in the cave. The evaporation rates vary greatly throughout the cave (figs. 9-11).

The relative humidity in the cave averages about 69 percent in Devil's Den, 86 percent in the Lunch Room, and more than 95 percent in isolated parts of Lower Cave. Variation of relative humidity is shown in figure 12. Humidity is high during the summer months, lower and variable during the winter.



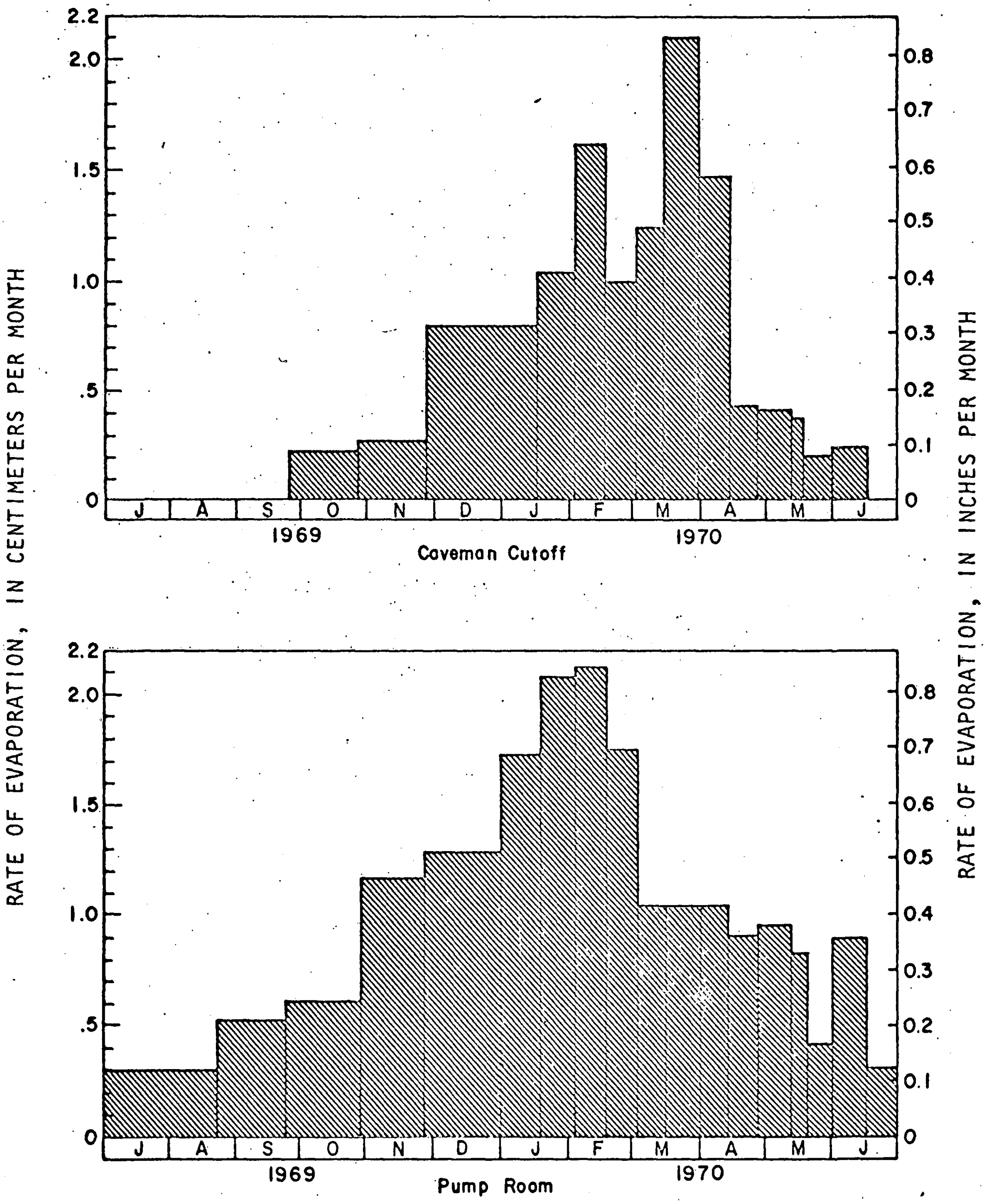
NOTE: Width of bar indicates duration of measurement.
Locations of evaporation stations are shown in figure 3.

Figure 9.--Evaporation at the Dome Room, Queen's Chamber, and Mirror Lake.



NOTE: Width of bar indicates duration of measurement. Locations of evaporation stations are shown in figure 3.

Figure 10.--Evaporation at Jim White Tunnel and the Secondary Stream Passage.



NOTE: Width of bar indicates duration of measurement.
Locations of evaporation stations are shown in figure 3.

Figure 11.--Evaporation at the Caveman Cutoff and Pump Room.

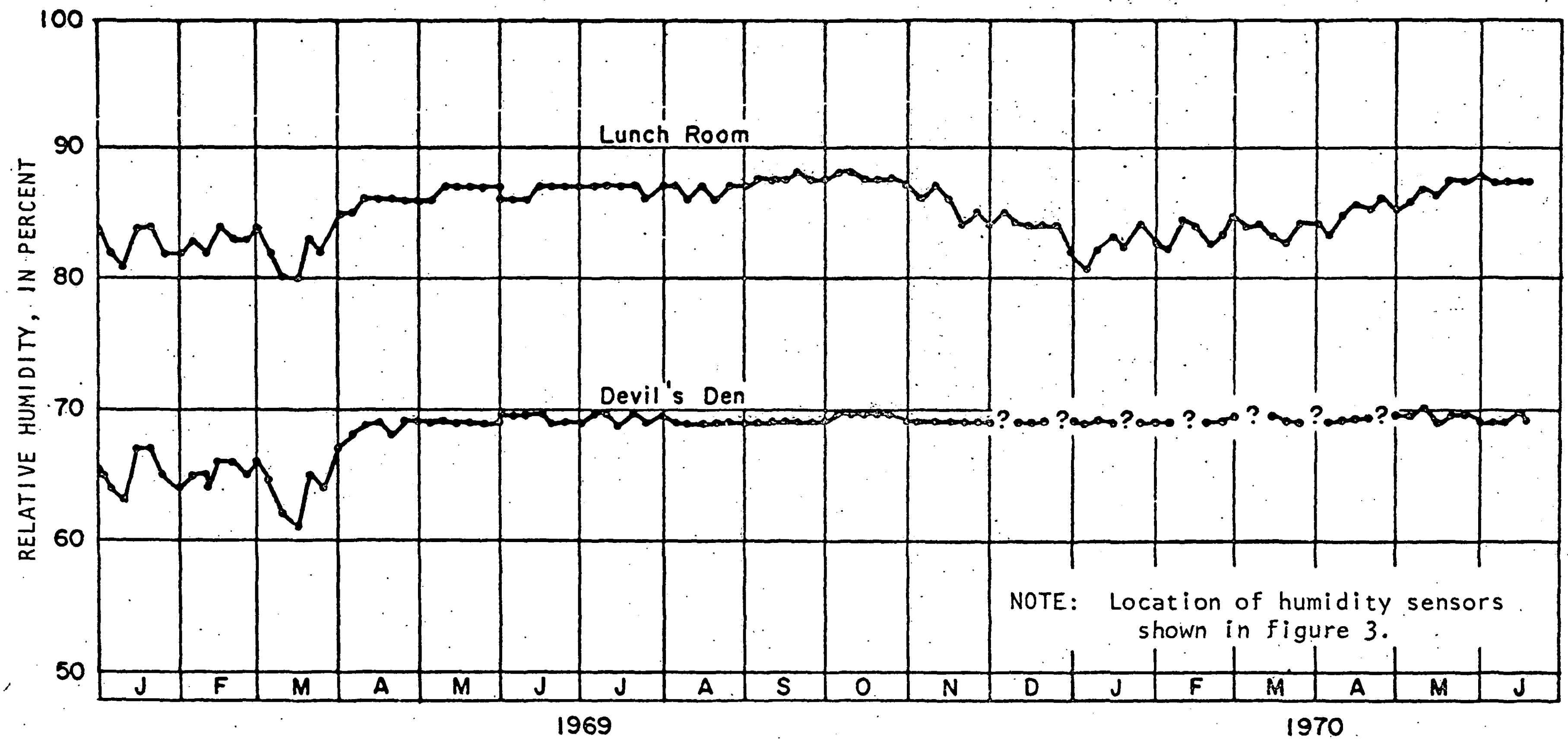


Figure 12.--Relative humidity at two locations in Carlsbad Caverns.

Carbon dioxide

The carbon dioxide (CO_2) content of the atmosphere outside the cave is commonly about 330 ppm. In caves the carbon dioxide content is generally higher due to the loss of carbon dioxide from cave waters depositing calcite.

Figure 13 shows the variation in carbon dioxide content of the cave atmosphere in the Lunch Room. The CO_2 content of the cave atmosphere varied from 345 ppm in March 1969 to 490 ppm in August 1969. The CO_2 at the other sensor locations rarely varied measurably from the Lunch Room values. The maximum separation observed was 10 ppm between the Lunch Room and Devil's Den sensors. The maximum CO_2 concentration is lower than that recorded in other caves: 1,040 ppm in Lehman Caves, Nevada (Samuel Bamberg, written commun. 1969), 3,000 ppm in Black Chasm Cave, California (Moore and Nicholas, 1964, p. 15). The low concentration of atmospheric CO_2 in Carlsbad Caverns is due to the high rate of air circulation. The graph of CO_2 (fig. 13) reflects the higher winter airflow rates.

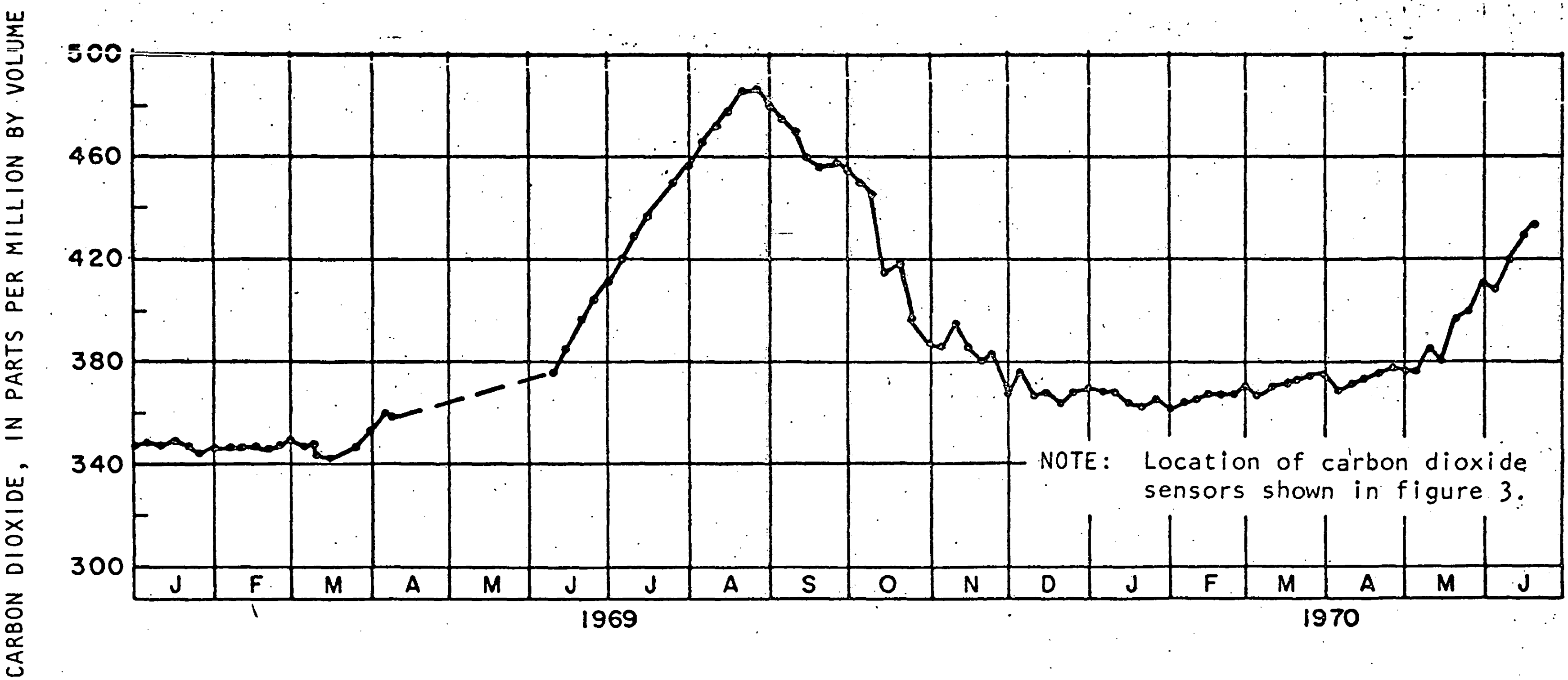


Figure 13.--Carbon dioxide content of the air in the Lunch Room.

It was suggested that loss of water from pools might be caused by respiration of CO_2 by cave visitors. This excess CO_2, it was theorized, would cause the pool water to become undersaturated with respect to calcite and dissolve the seal of the bottom of the pools. This is untrue for two reasons: First, the "cave coral" on the pool will be dissolved in preference to the cracks in the bottom of the pool (Lange, 1968). Second, data from Thrailkill (1965, p. 115-116) indicate that, in all field measurements of pools, the minimum partial pressure of carbon dioxide (PCO_2) of 2,050 ppm was 42 times as great as the maximum (490 ppm) in the cave atmosphere. The movement of CO_2 is always from the cave pools to the atmosphere. It would require a concentration of CO_2 in the atmosphere many times that observed to reverse this movement and produce an increased concentration of CO_2 in the cave pool water.

Airflow

The natural airflow which is responsible for the "cold trap" condition in the cave enters through the Natural Entrance and the Bat Cave openings. These entrances are well situated to receive cold air drainage because they occur low in the hillside near a wash. The air entering the cave flows down the Main Corridor, dividing at Devil's Den pits to the secondary stream passage to the Lunch Room and down through the scenic rooms. Cold air entering the Big Room from the Lunch Room and Main Corridor flows downward through pits causing a soil temperature differential of 0.5°C (1.0°F) between parts of the Big Room and Lower Cave. The air which is warmed by contact with the cave walls or pools circulates out along the roof and out the Natural Entrance (and possibly out presently unknown blowholes on the ridge top). The airflow distribution in the Natural Entrance in January 1970 is shown in figure 14.

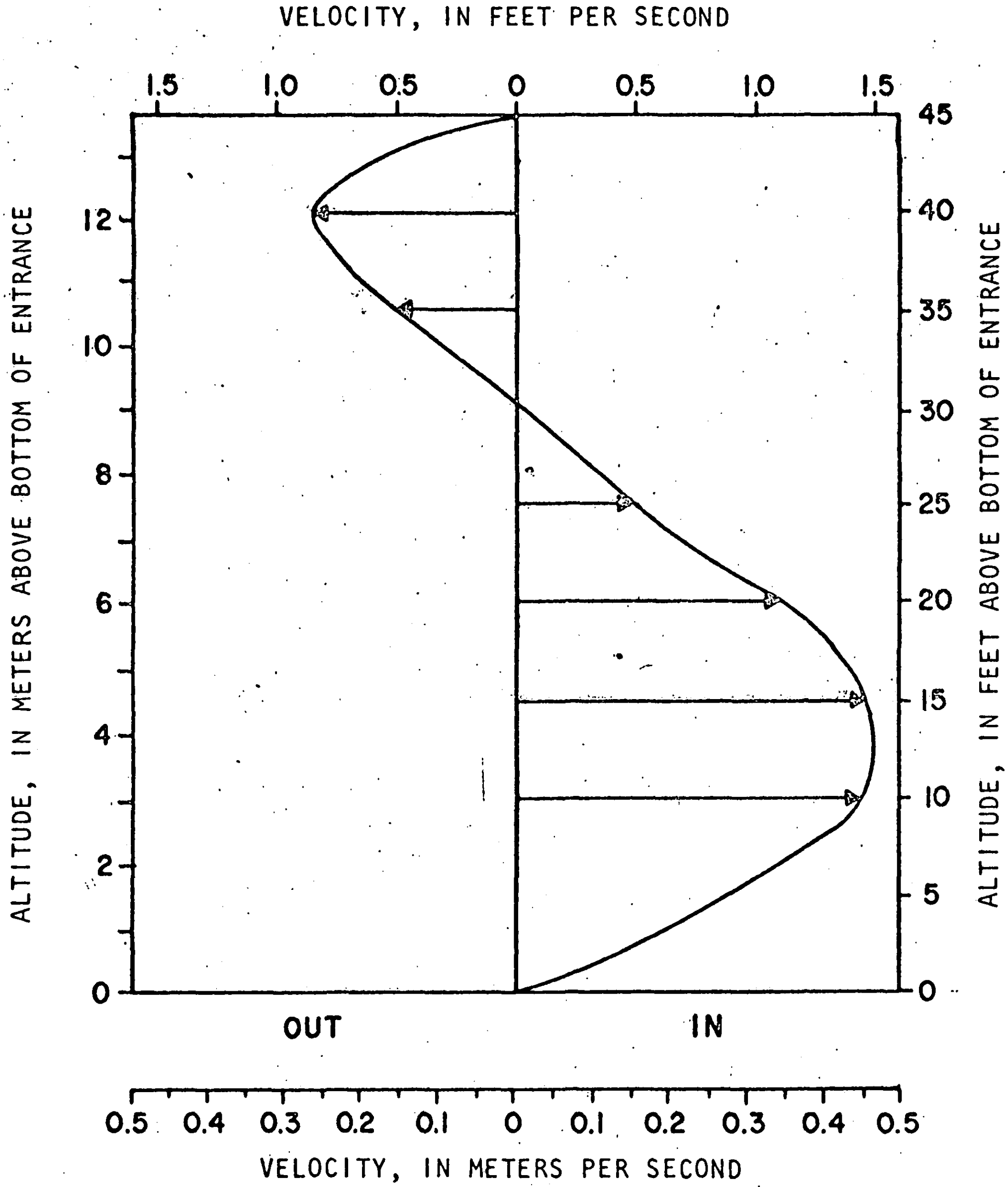


Figure 14.--Airflow velocity distribution in the Natural Entrance, 8:00 p.m., January 11, 1970.

The introduction of the elevator shaft into this system redirects certain air currents. In addition, the elevator shaft provides another point of discharge for the lighter air in the cave, avoiding the circuitous route along the Main Corridor and mixing of air masses in the Natural Entrance. The rock walls of the elevator shaft continually warm the air in the elevator shaft, causing a chimney effect which induces a continuous flow out the elevator shaft. The quantity of water lost through the elevator shaft may be computed from the measured airflow (fig. 15), the relative humidity (fig. 12), and temperature (fig. 8) of the air masses entering and leaving. The airflow up the elevator shaft was measured three times a week with hand-held anemometer in the doorway of the lower elevator lobby. The quantity of water lost through the elevator shaft is shown in table 2. This is equivalent to about 83,000 liters (22,000 gallons) per year.[1/] The exact effect of the elevator shaft cannot be computed without knowing the exchange of air in the main corridor; however, it is probable that if the elevator shaft were sealed, friction and mixing of air along the longer route up the main corridor would significantly reduce the rate of air exchange and moisture loss, as well as eliminating the moisture lost due to the chimney effect.

[1/] The water loss is measured between the surface and Devil's Den and the Lunch Room. Air moving up the elevator shaft is assumed to have the temperature and relative humidity of the air in the Lunch

Room. Air entering the cave is represented by data from the weather station on the ridge above the cave. Air moving down the Main Corridor to replace air removed by the elevator shaft is assumed to have the same relative humidity and temperature as Devil's Den. The water lost is the difference in moisture content of the air at the two locations times the rate of airflow.

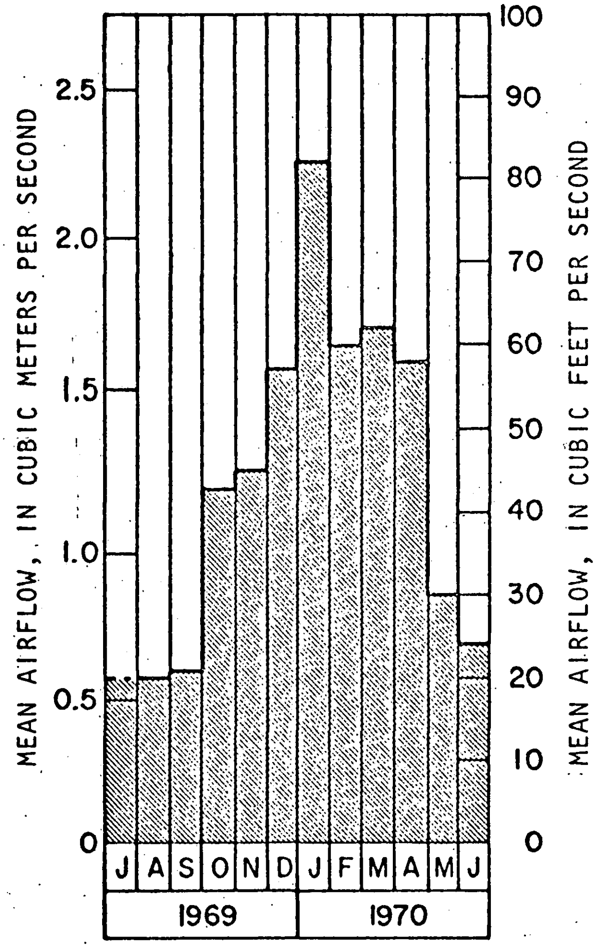


Figure 15.--Mean monthly airflow up the elevator shaft.

Table 2.--Water lost due to airflow through the elevator shaft

Month and year	Air outside the Caverns: Temperature °C	Air outside the Caverns: Relative humidity (percent)[1/]	Air outside the Caverns: Moisture content (gm/m^3)	Air at Devil's Den: Temperature °C	Air at Devil's Den: Relative humidity (percent)	Air at Devil's Den: Moisture content (gm/m^3)	Air in Lunch Room: Temperature °C	Air in Lunch Room: Relative humidity (percent)	Air in Lunch Room: Moisture content (gm/m^3)	Airflow (m^3/sec)	Caverns below Devil's Den Water lost (gm/sec)	Caverns below Devil's Den Water lost (liters/mo)	Caverns below Devil's Den Water lost (gal/mo)	Caverns Water lost (gm/sec)	Caverns Water lost (liters/mo)	Caverns Water lost (gal/mo)
1969																
July	27.4	63	16.6	16.5	69	9.8	14.3	87	10.7	0.57	0.5	$1.3x10^3$	300	-3.4[2/]	$8.8x10^3$	-2,400
August	27.0	58	15.0	18.0	69	10.6	14.6	88	11.0	.57	0.2	$.52x10^3$	100	-2.3	$6.0x10^3$	-1,600
September	22.0	50	9.7	15.5	69	9.2	14.2	88	10.6	.60	0.8	$2.1x10^3$	600	.5	$1.3x10^3$	300
October	15.3	44	5.7	13.4	70	8.1	13.8	89	10.6	1.20	3.0	$7.8x10^3$	2,100	5.9	$15.3x10^3$	4,000
November	10.7	58	5.8	12.2	69	7.5	13.6	86	10.2	1.28	3.5	$9.1x10^3$	2,400	5.6	$14.6x10^3$	3,800
December	8.5	44	3.8	11.7	69	7.2	13.2	84	9.7	1.62	4.0	$10.4x10^3$	2,700	9.6	$25.0x10^3$	6,600
1970																
January	4.6	70	4.6	11.0	69	6.9	12.9	82	9.3	2.32	5.6	$14.6x10^3$	3,800	10.9	$28.3x10^3$	7,500
February	8.4	65	5.5	11.2	69	7.0	12.9	83	9.4	1.71	4.1	$10.7x10^3$	2,800	6.7	$17.4x10^3$	4,600
March	9.1	62	5.5	11.6	69	7.2	13.0	84	9.5	1.76	4.0	$10.4x10^3$	2,700	7.0	$18.2x10^3$	4,800
April	16.7	43	6.2	11.9	69	7.3	13.0	85	9.6	1.65	3.8	$9.9x10^3$	2,600	5.6	$14.6x10^3$	3,800
May	20.9	44	8.0	12.4	69	7.6	13.3	86	9.9	.85	2.0	$5.2x10^3$	1,400	1.6	$4.2x10^3$	1,100
June	23.8	36	7.8	13.3	69	8.0	13.7	87	10.3	.68	1.6	$4.2x10^3$	1,100	1.7	$4.4x10^3$	1,200

[1/] Values of relative humidity are not available for outside the Caverns for this period. Relative humidities are averages for Roswell Airport Weather Station.

[2/] (-) indicates water added to cave through condensation on cave walls.

The heat required to evaporate the water lost through the elevator shaft is an average of 4.12 gm/sec x 607 cal/gm or 2,500 cal/sec. This is much more than the 570 cal/sec lost from the cave in the air moving out the elevator shaft (page 29), indicating that evaporation is important in cooling the cave.

Pool levels and infiltration

Records of historic water levels in the pools are unavailable. The estimates of water-level decline shown below have been obtained by comparing water levels recorded in photographs with present (1970) water levels.

Pool	Date of photograph	Water level (in centimeters above present level)
Mirror Lake	1950	34 (1.1 feet)
Do.	1950	37 (1.2 feet)
Do.	March 1953	30 (1.0 foot)
Do.	August 4, 1959	30 (1.0 foot)
Green Lake	1924	3 (0.1 foot)(?)

The decline of water level in Mirror Lake since 1959 agrees well with the 1969-70 decline of 3 centimeters (1.3 inches). While the water level in Green Lake fluctuates slightly, it appears to have remained relatively stable throughout recent historic time. Inflow to the pool appears to have been sufficient to maintain the pool at the present outlet.

Pool levels measured from June 1969 to June 1970 are shown in figure 16. The datum is arbitrary. Locations of the measured pools are shown in figure 3. Three pools (Jim White Tunnel No. 2, Crystal Spring North, and Painted Grotto) had large yearly declines; one pool (Mirror Lake) had a moderate decline; and four pools (Jim White Tunnel No. 1, Top of the Cross, Green Lake, and Green Lake No. 2) remained stable or rose slightly. Three of the four pools which lost water are broad, shallow pools with irregular bottoms and with water levels far below the levels at which the pools would overflow. The high rate of water loss from these pools is probably due in part to the large capillary fringe present on the irregular, sloping sides of the pool.

Some infiltration occurs seasonally, as indicated by the hydrograph of Mirror Lake (fig. 16). In some areas infiltration is regular, and fluctuations in pool levels are caused primarily by evaporation, such as the variation at the pool south of Green Lake (fig. 16).

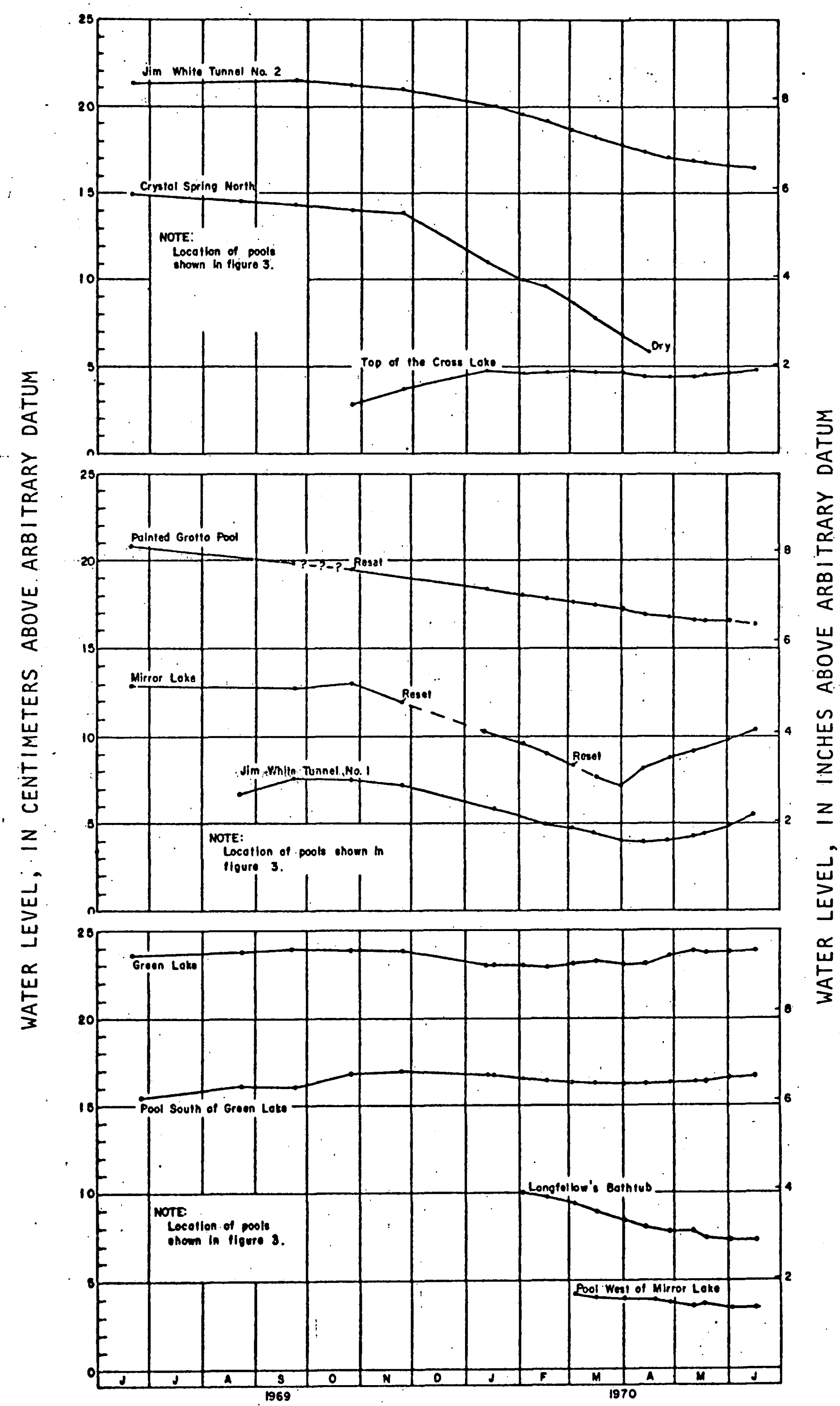


Figure 16.--Hydrographs of selected pools.

A comparison of the mean annual rainfall with the potential evapotranspiration at Carlsbad Caverns (fig. 17) indicates that recharge occurs primarily through irregular events, rather than seasonally on a regular basis.[1/] Normally, monthly potential evapotranspiration is higher than precipitation for all months of the year; however, due to the thin soil cover and sparse vegetation, storms may cause infiltration for a short period of time. Additional infiltration occurs irregularly during periods of unusually high rainfall. Such an event probably occurred in October 1969 (fig. 17).

Rainfall records for Carlsbad Caverns were analyzed for periods of high rainfall in the following manner: records of monthly rainfall were compared with the mean monthly potential evapotranspiration for the period of record and cumulative departure curves of both the number of months each year in which rainfall exceeded computed evapotranspiration and the amount of rainfall in excess of computed evapotranspiration. While this method is not exact, it does weigh the curve in favor of the winter storms and against the intense summer thunderstorms which produce much runoff and less infiltration. The cumulative departure curves (fig. 18) show that rainfall in excess of potential evapotranspiration decreased from 1941 to 1957, but since 1957 the rainfall potentially available for infiltration has increased slightly.

1/ Potential evapotranspiration was computed using the method of Thornthwaite (1948).

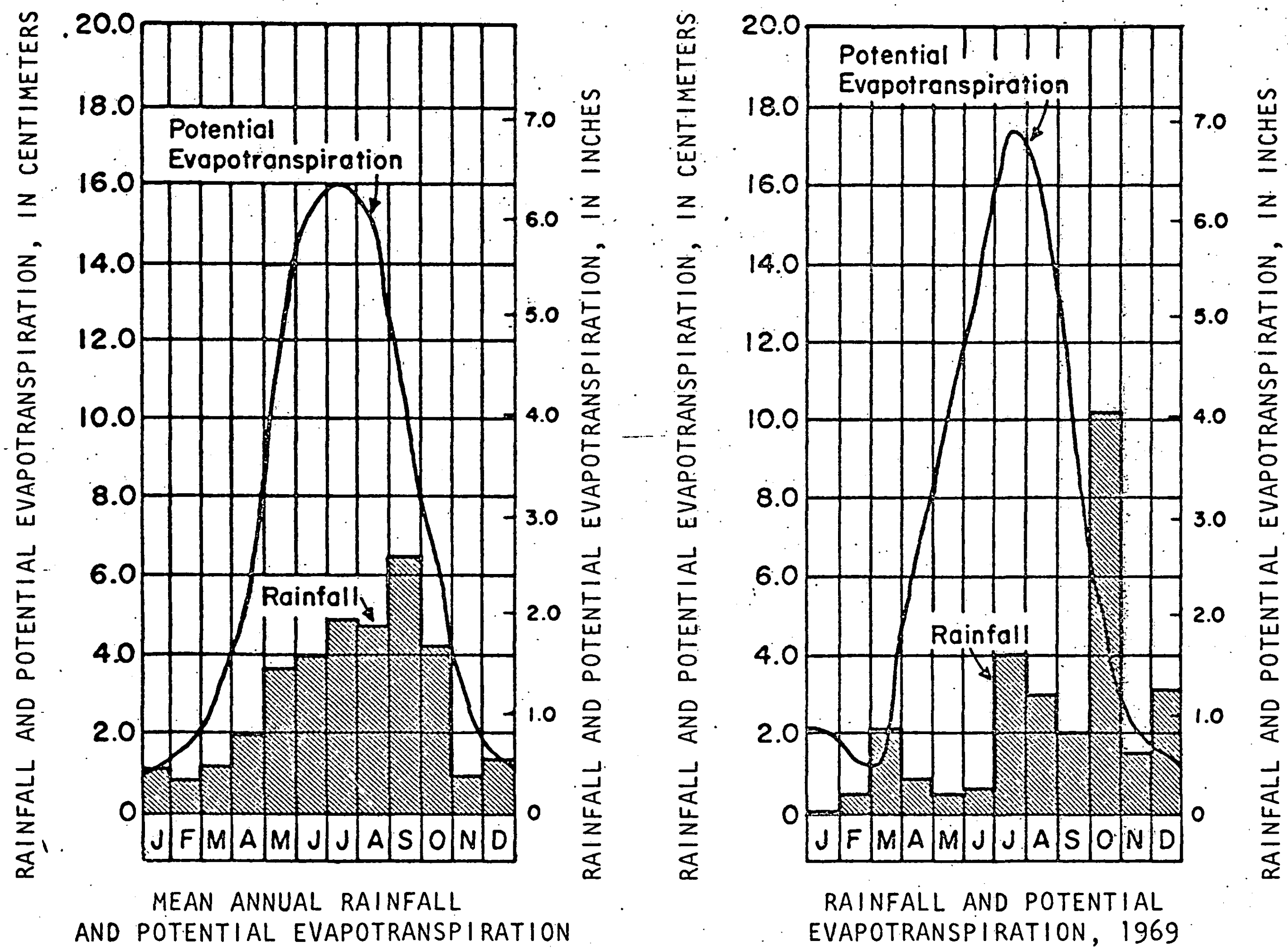


Figure 17.--Rainfall and potential evapotranspiration at Carlsbad Caverns.

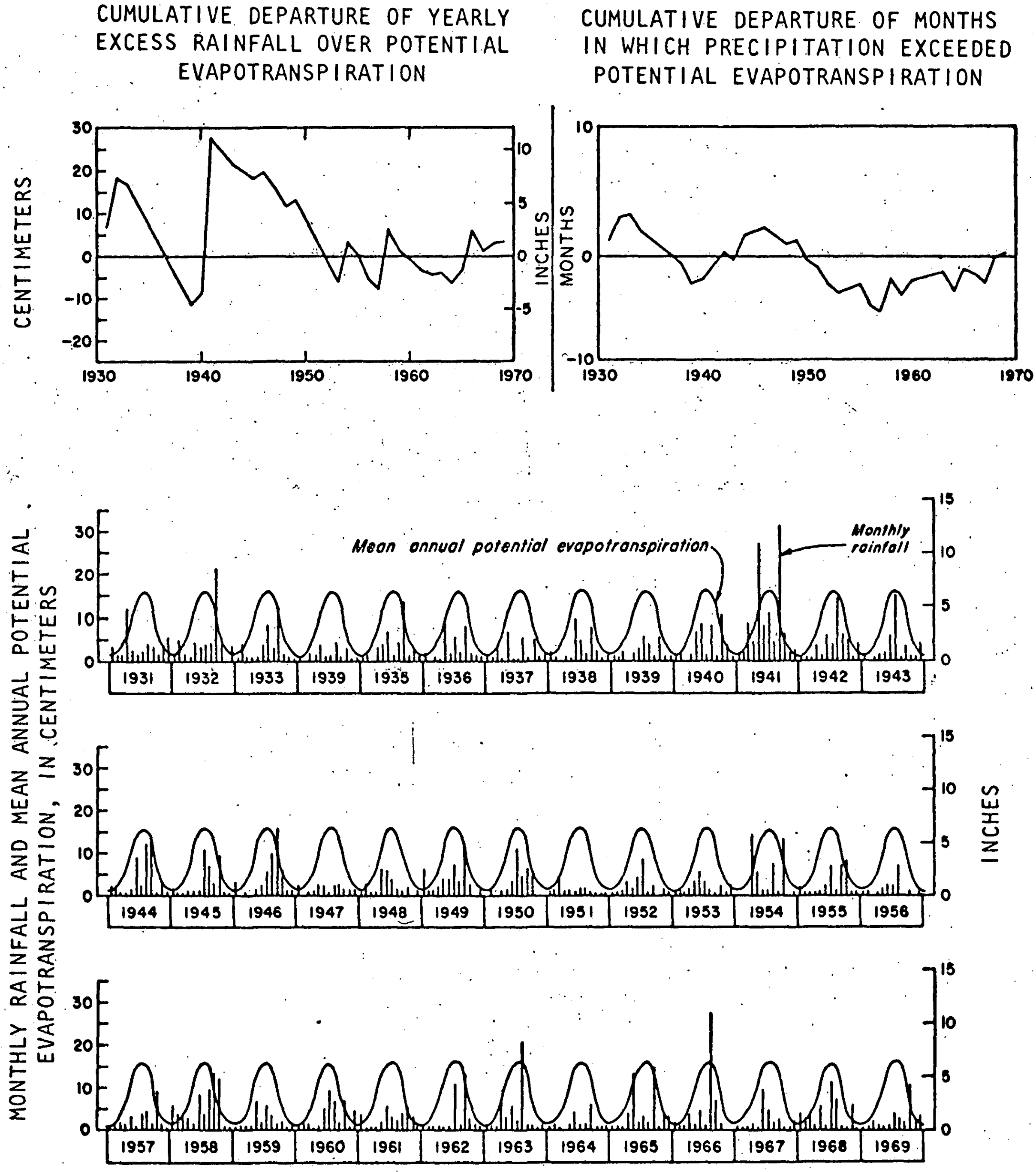


Figure 18.--Monthly rainfall, mean annual potential evapotranspiration and cumulative departures for Carlsbad Caverns, 1931-69.

Lag times between rainfall events and their effect on pool levels are difficult to determine from the short period of record, but may be 10 days at Devil's Spring (Jon Hamman, unpublished data, 1964-66) and about 1 month at Crystal Spring Dome (unpublished data in National Park files, 1941).

Summary of cave microclimate

Most infiltration to the cave occurs during infrequent, irregular periods of high rainfall. Some water infiltrates seasonally during winter storms. Water loss from the cave is maximum during the winter when the cave microclimate is characterized by low humidity, high evaporation rates, a high rate of airflow, unstable air conditions, low air temperature, and falling water levels in many pools. During the summer, temperatures are higher, relative humidity is high and stable, evaporation is low, airflow is slower, carbon dioxide content of the air increases, and water levels in most pools stabilize or rise.

Much of the cave is cooler than the mean annual surface temperatures, due to cold-air inflow and evaporation. The cave is probably cooled more by evaporation than by heat radiated or advected into the cold air.

Causes of drying

Many explanations for the drying in Carlsbad Caverns have been suggested by personnel of the National Park Service and others; all have been considered in this investigation.

Conditions suggested as causing or contributing to the drying are as follows:

a) The drying is not man induced, but is either the natural drying common to all caves which exchange air with the surface, or the result of a long-term drying trend in the climate.

b) The paved parking lot is diverting water away from the cave and reducing infiltration of water in certain areas of the cave.

c) Trail-construction crews have in the past removed water from the pools thus lowering them below a critical level.

d) Cave visitors adversely affect the moisture balance through respiration of CO_2 or heat generation.

e) The elevator shaft changes airflow patterns in the cave, and increases the total airflow through the cave, causing increased evaporation.

f) The lighting system is causing the cave to heat and evaporate more water.

g) Air pulled up the elevator shaft during the summer for air-conditioning the Visitor Center reduces the relative humidity in the cave.

The relative effects of each of these suggested conditions are discussed below:

a) Data on historic pool levels are sparse, with only a few photographs (p. 42) and reports from guides and visitors to indicate that pool levels have fallen rapidly in recent years. The present rate of drying of some pools could not have persisted for many years, however, or they would now be dry. Rainfall in the period 1946-57 was greatly below average, and rainfall since 1958 has been irregular and slightly below average. The amount of rainfall potentially available for infiltration has increased since 1957 (p. 42), due to an increase in late fall and winter storms. Since water levels have continued to decline during the period of study, however, it is concluded that much of the drying is recent, and related to the commercialization of the cave.

b) The total area of the paved parking lots is about 48,000 m^2 (518,000 ft^2), only 340 m^2 (3,700 ft^2) of which is directly over visited parts of the cave. Rainfall in the area is 37 centimeters (14.4 inches) per year, or about 18,000 m^3 (623,000 ft^3) over the area of the parking lot, 126 m^3 (4,400 ft^3) of which is over the visited cave. Studies in other areas in southern New Mexico (Theis, 1969) indicate that in unpaved areas less than 1 percent of the rainfall infiltrates, the remainder being evaporated or transpired. Thus, even if the pavement were not present, less than 1,300 liters (350 gallons) would infiltrate to the cave from the overlying (paved) area in 1 year. In addition, the area in which the drying is most readily noticed (Mirror Lake) is more than 240 meters (800 feet) away from the parking lot. Crystal Springs Dome is about 780 meters (600 feet) from the parking lot. It is unlikely that the parking lot would significantly affect pools at that distance.

c) The water level of pools, in the absence of man-induced changes, represents a balance between inflow and evaporation. When the pool level is lowered, assuming a constant inflow, the pool should gradually recover until its surface area is large enough to evaporate the water entering. In the case of shallow pools with irregular bottoms, however, lowering the water level may expose a capillary fringe larger in area than the pre-existing pool surface (fig. 19). In such a case water evaporates from the pool at a faster rate. This effect will be accelerated if the evaporation is increased by man-induced changes in the same environment. This effect can be seen in the rapid lowering of Crystal Spring North and Jim White Tunnel No. 2 (fig. 16), the first of which is now dry, the second nearly dry. Thus, if removing water from the pools for trail construction lowers the water level enough to expose a larger capillary fringe, the pools will decline more rapidly.

d) Carbon dioxide respired by visitors has no effect on the cave pools, since the pools have a CO_2 partial pressure greater than that of the cave atmosphere (page 38). The heat given off by each visitor is equivalent to a 100-watt light bulb, but even though over 600,000 visitors entered Carlsbad Caverns in 1969, the yearly average heat added is only 6 cal/sec, compared to over 10,000 cal/sec added by the lighting system.

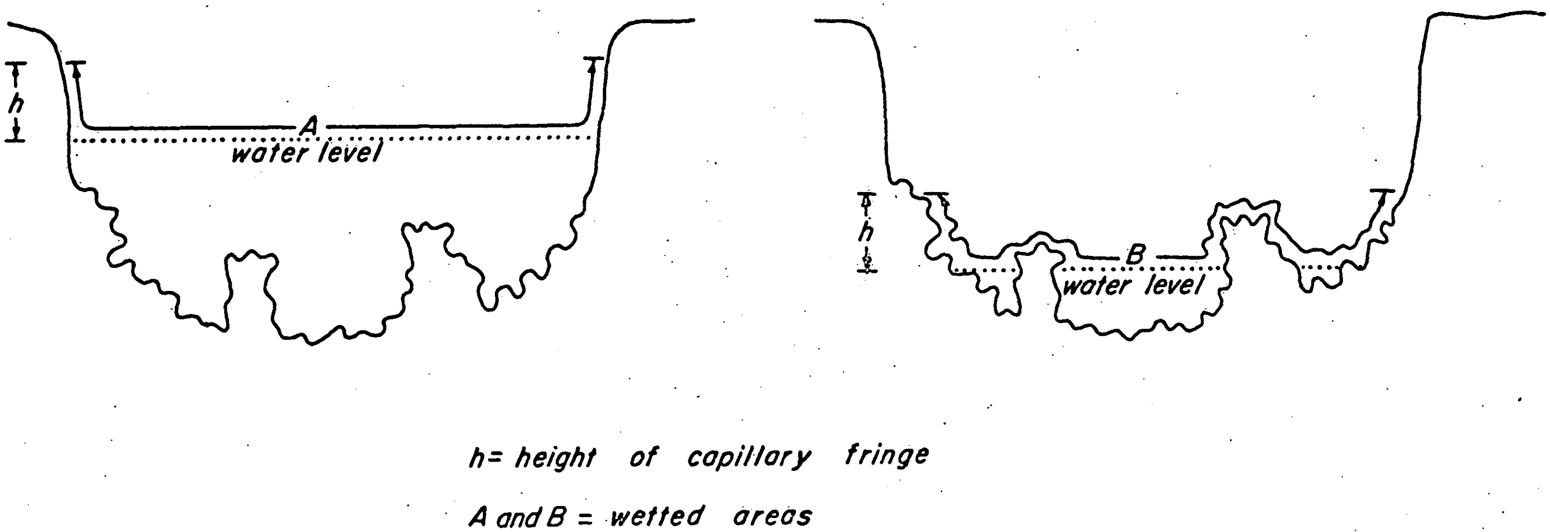


Figure 19.--Idealized sections of a cave pool showing increased wetted area due to lowering of the water level.

e) There is a measurable airflow up the elevator shaft which reaches a maximum in mid-winter. This airflow results in a a net loss of about 83,000 liters (22,000 gallons) of water per year from the cave below Devil's Den. If the elavator shaft were sealed, the longer path up the Main Corridor would allow more mixing and increase friction, decreasing the moisture loss, and would eliminate the moisture loss due to the chimney effect in the elevator shafts.

f) The effect of the lighting system is the most difficult to evaluate. If the 385,000 kilowatt hours introduced to the cave were used only in evaporating water, 17.3 grams of water per second, or 545,000 liters per year (144,000 gallons per year) would be evaporated. In fact, the lighting system heats the cave air and the cave walls as well as the cave pools. The heated cave air is decreased in relative humidity and rises, and is thus capable of evaporating water dropping from the roof of the cave (although many of the rapidly drying pools are in alcoves with low ceilings and are affected less by the heated air rising in the Big Room). If the air in the Big Room is at 85 percent relative humidity at 15°C (59°F) it contains 0.0102 grams of water per cubic meter. If the temperature is raised 1°C (1.8°F) by the lighting system the air must evaporate an additional 0.0006 grams of water per cubic meter to remain at 85 percent relative humidity. Raising the temperature of a cubic meter of air 1°C (1.8°F) requires 0.239 cal/gm/°C x 1056 gm/m^3 x 1 m^3 x 1°C = 252 calories. Since the heat added to the cave is 10,500 cal/sec this represents the capacity to evaporate 0.0236 gm/sec or 744 liters (197 gallons) per year.

Although much of the heated air flows out of the cave without affecting the evaporation, the true effect is probably between the above mentioned extremes. The relative effect of the airflow and heating is difficult to calculate, but is indicated by the difference in evaporation in the Dome Room (fig. 9) which is well-lighted, but has little air circulation and the secondary stream passage (fig. 10) which is unlighted and has high airflow. It thus appears that changes in airflow rates will have more effect on evaporation than changes in heat added through lighting. Maximum evaporation occurs in the Pump Room (fig. 11) where use of electricity is highest and airflow (through the elevator shaft) is also high.

g) Air conditioning the Visitor Center with cave air is less important to the moisture balance in the cave than is the winter airflow up the elevator shaft. During the summer, the warm air moving down the main corridor to replace that being drawn up the elevator shaft is cooled by the cave walls with a consequent increase in relative humidity. Where the air is in contact with cold rock it is sometimes cooled below the dew point, and condensation forms on rocks and trails. The release of the latent heat of condensation warms the rock, and this reduces the condensation later in the summer and increases the evaporation early in the winter. The exact effect on the moisture balance in the cave of operating the air conditioning in the Visitor Center cannot be computed without relative humidity data from the surface. The effect on relative humidity (fig. 12) and evaporation (figs. 9 to 11), however, appears to be small (air conditioning was turned on July 1 and off September 15, 1969).

Conclusions

The moisture present in Carlsbad Caverns has been decreased by excessive airflow up the elevator shaft during the winter, and by heating of the cave by the electrical system. The increased evaporation is most pronounced in pools where the water level is already very low (p. 49). Cavern visitors, the paved parking lots, air conditioning the Visitor Center, and long-term changes in precipitation have had less effect on cave moisture.

Recommendations

The scenic beauty of Carlsbad Caverns is partly dependent on the cave pools. To retain this beauty, the effects of past and present disturbances could be reduced by the following actions:

1) Stop winter airflow up the elevator shaft by carefully grouting the bottom of the shaft and installing airtight doors, revolving doors, or an airlock.
2) Reduce the heat added to the cave through the electrical system by replacing incandescent bulbs, where possible, with bulbs giving more visible light (and less infrared) with less power consumption, such as fluorescent light.
3) Refill the scenic pools to their optimum levels so as to reduce excessive evaporation from the capillary fringe.

Selected analyses of water from cave pools and from Rattlesnake Springs are shown in table 3. Water from Rattlesnake Springs, which supplies the domestic water for Carlsbad Caverns, is compatible with water in the cave pools.

The recommendations listed should decrease evaporation in the cave. It is recommended, however, that the present monitoring of cave microclimate parameters by National Park Service personnel be continued to evaluate the relative effectivness of attempts to reduce evaporation.

Table 3.--Selected chemical analyses

(Analyses by U.S. Geological Survey)

9-268 q (Constituents in milligrams per liter except specific conductance, pH, and color)

Sample	1/	B-186 2/	3/			
Date of collection		7/5/63				
Silica (SiO_2)	20		18			
Iron (Fe)						
Manganese (Mn)						
Calcium (Ca)	22	18	121			
Magnesium (Mg)	41	12	27			
Sodium (Na)	18	9.0	9.6			
Potassium (K)		2.3				
Bicarbonate (HCO_3)	237	191	274			
Carbonate (CO_3)	0	0	0			
Sulfate (SO_4)	38	12	187			
Chloride (Cl)	11	9.9	5.6			
Fluoride (F)						
Nitrate (NO_3)	14		3.3			
Dissolved solids						
Calculated	281	157	504			
Residue on evaporation at 180°C						
Hardness as $CaCO_3$	222		415			
Noncarbonate hardness as $CaCO_3$	28		190			
Alkalinity as $CaCO_3$						
Specific conductance (micromhos at 25°C)	473		750			
pH	8.0	7.8	7.4			
Color						

GPO 830-857

1/ Pool in lower cave, near location 20, figure 3.
2/ Mirror Lake (after Thrailkill, 1965, p. 93).
3/ Rattlesnake Springs (domestic supply for Carlsbad Caverns).

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