THE CLIMATE OF DEATH VALLEY, CALIFORNIA

BY STEVEN ROOF AND CHARLIE CALLAGAN

The notoriously extreme climate of Death Valley records shows significant variability in the long-term, including a 35% increase in precipitation in the last 40 years.

Death Valley National Park, California, is widely known for its extreme hot and dry climate. High summer temperatures, low humidity, high evaporation, and low precipitation characterize the valley, of which over 1300 km^2 (500 mi^2) are below sea level (Fig. 1). The extreme summer climate attracts great interest: July and August visitation in Death Valley National Park has doubled in the last 10 years. From June through August, the average temperature at Furnace Creek, Death Valley [54 m (177 ft) below sea level] is 98°F (37°C).[1] Daytime high temperatures typically exceed 90°F (32°C) more than half of the year, and temperatures above 120°F (49°C) occur

[1] Weather data are reported here in their original units in to order retain the original level of precision recorded by the observers.

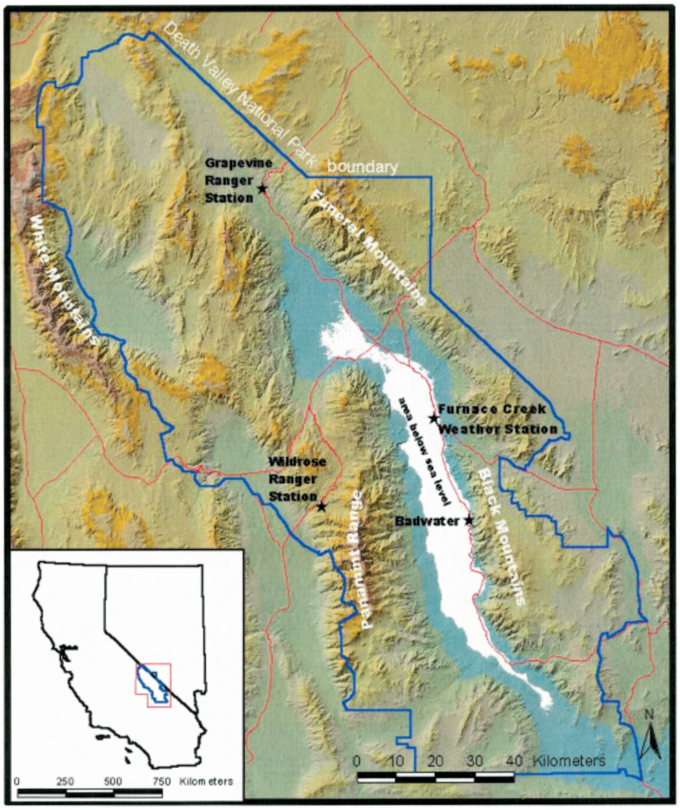

FIG. 1. Location map of the Death Valley region. Death Valley National Park is outlined in blue, main roads shown in red, and the portion of the park below sea level is highlighted in white.

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DOI: 10.1175/BAMS-84-12-1725
In final form 17 January 2003

5–20 times each year. Even the minimum temperature of summer nights can remain above 100°F (38°C), which occurs nowhere else in the United States.

Death Valley's extreme climate is of great interest to researchers and the general public from all over the world, even if they are not planning to visit the region. Although several older reports and analyses of Death Valley's climate exist, none has compiled the complete weather records available for Furnace Creek from 1911 onward. This report presents the complete daily weather observations for the Furnace Creek (formerly Greenland Ranch) weather station through 2002. Daily maximum and minimum temperatures, and daily precipitation amounts, were gathered from several sources and compiled into a single database. In this paper, we describe the data sources and briefly summarize the climate of Death Valley. We explain why Death Valley is so hot and dry, and compare the climate of Death Valley with other regions in the world. The complete dataset is available (from the authors) to enable researchers of all ages to explore and analyze the climate of Death Valley and to compare their local climate to that of Death Valley. While exploring these data from Death Valley, please recognize that climate observations from a single location do not provide a solid basis for reconstructing regional patterns and trends.

DEATH VALLEY PHYSICAL GEOGRAPHY AND EARLY HISTORY. Death Valley is in the Mojave Desert in the westernmost basin and range province about 320 km (200 mi) northeast of Los Angeles, California (Fig. 1). The Mojave Desert is characterized by short, mild winters and long, hot summers. Death Valley is an elongated fault-bounded basin formed as the valley floor drops relative to the surrounding mountains. The part of the valley below sea level is approximately 120 km (75 mi) long and between 8 and 18 km wide (5 and 11 mi). More than 1300 km^2 (500 mi^2) are below sea level, and about 520 km^2 (200 mi^2) are salt flats more than 60 m (200 ft) below sea level (Hunt et al. 1966). The lowest point in the eastern floor of the valley is 86 m (282 ft) below sea level while only 24 km (15 miles) to the west, the Panamint Range towers over 3350 m (11 000 ft) elevation. On the east, the Grapevine, Black, and Funeral Mountains reach to 2440 m (8000 ft) over the valley floor. Badwater, the lowest point in the Western Hemisphere [86 m (282 ft) below sea level lies in the southern part of the basin and consists of salt deposits, mud, and shallow saline water from the terminus of the Amargosa River (Hunt 1975). Note that Death Valley National Park encompasses over 13 700 km^2 (5300 mi^2) of terrain, including the surrounding mountain ranges and adjacent valleys. In this report, "Death Valley" refers to the valley area below sea level, unless otherwise specified.

Death Valley has been a seasonal home for Paiute and Shoshone Indians for more than 10 000 Years (Hunt 1975). Euro-American settlers entered the region regularly after lost gold-seeking emigrants accidentally passed through the valley in 1849–50, attempting to shortcut the Spanish Trail (Hunt 1975; Lingenfelter 1986). Prospectors combed the region throughout the latter half of the nineteenth century for gold and silver, but due to lack of water and wood, few hard-rock mines were truly profitable until railroads penetrated the region in the early 1900s. However, borax was successfully mined and profitably shipped out of the valley beginning in 1880. Greenland Ranch, later named Furnace Creek Ranch, was established at 54 m (177 ft) below sea level in 1883 to take advantage of voluminous freshwater springs emanating from the Funeral Mountains to grow crops and raise cattle to supply nearby mining communities (Lingenfelter 1986). Furnace Creek Ranch was the headquarters for the Pacific Coast Borax Company, which operated the famous 20-mule-team wagons to transport valuable borax minerals to the railroad depot at Mojave. The borax extraction process could not operate during summer months, as the water-filled tanks that were used to crystallize the purified borax could not cool enough in the summer heat (Lingenfelter 1986). It was at the Pacific Coast Borax Company headquarters that the U.S. Weather Bureau set up a permanent standard weather observation station in July 1911, with the superintendent of the company in charge of taking readings (Eklund 1933).

A miner passing through Greenland Ranch in October 1919, Frank Crampton, commented on how a visitor to Death Valley coped with the heat: "The Ranch already had a visitor. He was camped in a tent with a canvas fly over it, and water was fed from a pipeline that had been hooked onto the windmill pump especially for the purpose of dripping water on the tent quarters . . . . Inside the tent, established as comfortably as if in a swank hotel, was Zane Grey" (Crampton 1956).

WHY IS DEATH VALLEY SO HOT AND DRY? Death Valley is dry because it sits in the rainshadow of four major mountain ranges to the west (Sierra Nevada, White/Inyo Mountains, the Argus Range, and the Panamint Range). Moisture from winter storms moving inland from the Pacific Ocean must pass eastward over four mountain ranges to reach Death Valley. As air masses are forced over each range, they cool and moisture condenses to fall as rain or snow on the western slopes. By the time these air masses reach Death Valley, most of the moisture has been "squeezed out" leaving very little to fall as rain in the valley.

Answering the question "why is Death Valley so hot?" is more difficult. There are several plausible reasons, but little research has been undertaken to determine the exact causes of extremely high temperatures in Death Valley. One important consideration is that temperature records are only available from inhabited places with weather stations. Furnace Creek in Death Valley is one of the few inhabited places in the world below sea level that maintains an official weather station (and unlike other places below sea level such as the Imperial Valley in California or the Dead Sea, Death Valley is far removed from large bodies of water that moderate extreme temperatures). There are likely places in the world with more extreme temperatures than Furnace Creek, but they are undocumented.

Several factors most likely lead to the occurrence of very high air temperatures in Death Valley (e.g., Lamb 1958):

i) Clear, dry air, and dark, sparsely vegetated land surfaces enhance the absorption of the sun's heat, which in turn heats the near-surface air. This is especially strong in the summer when the sun is nearly directly overhead.
ii) Air masses subsiding into the below sea level valley are warmed adiabatically.
iii) Subsiding air masses also inhibit vertical convection, keeping heated air trapped near ground level.
iv) The deep trench-like nature of Death Valley and its north–south orientation in an area where winds often blow west to east also acts to keep warm air trapped in the valley.
v) Warm desert regions surrounding Death Valley, especially to the south and east, often heat the air before it arrives in Death Valley (warm-air advection).
vi) Air masses forced over mountain ranges are progressively warmed (the foehn effect). As air masses rise over mountains, adiabatic cooling and condensation releases latent heat that directly warms the air; during subsequent descent, the air is warmed further by adiabatic compression. Death Valley is surrounded by mountain ranges; each time air is forced over mountains, it becomes warmer on the downwind side for a given elevation due to the foehn effect.

The hottest days in Death Valley typically occur when a ridge of high pressure is centered over western Nevada. This high pressure ridge blocks the flow of cooler coastal air from the west and, along with a commonly occurring thermal low centered in southernmost California, directs very warm air from southern Arizona and Mexico toward Death Valley. Lamb (1958) notes that based on analyses of surface weather maps from the southwestern United States and northern Africa, the hottest surface temperatures are recorded in front of advancing cold fronts, where clear air and a long fetch over warm land surfaces allow the air to reach unusually high temperatures. Furthermore, Lamb (1958) suggests that the actual peak temperatures may be very localized, associated with locally forced turbulence and adiabatic compression.

Death Valley's extreme dryness also contributes to high temperatures by limiting vegetation cover. Vegetation helps cool near-surface air by reducing the amount of heat absorbed by the ground and also by the cooling effect of evapotranspiration. Many other desert areas are somewhat cooler because they receive more rainfall, which leads not only to more vegetation, but to increased cloudiness, which reduces direct solar heating. This is especially true of the desert areas south and east of Death Valley, which experience the late summer monsoons.

EARLIEST WEATHER OBSERVATIONS. The author of the first U.S. mineral resources report, in 1868, J. Ross Brown, commented on Death Valley's climate:

> "The climate in winter is finer than that of Italy . . . [though] . . . perhaps fastidious people might object to the temperature in summer . . . . I have even heard complaints that the thermometer failed to show the true heat because the mercury dried up. Everything dries; wagons dry, men dry, chickens dry; there is no juice left in anything living or dead, by the close of summer" (cited in Hunt, 1975, p. 8).

Government survey teams beginning in the 1860s recorded the earliest weather observations in Death Valley. Surveyors at the time relied on barometers to determine elevation, and temperature readings were required to calibrate the barometers. Among the earliest recorded temperatures are those from the United States and California Boundary Survey, recorded by James McLeod in March 1861, who confirmed for the first time that the floor of Death Valley was below sea level. This survey team used camels as pack animals, which were thought to be better suited to the temperature extremes and dryness of the Mojave Desert (they were not better than mules, however, because they refused to carry loads up steep hills). McLeod recorded relatively comfortable temperatures between 70° and 80°F (21°–27°C) during the daytime and 40°–50°F (4°–10°C) during the night as they passed south to north through Death Valley. Summer temperatures measured by the Wheeler survey in 1875 recorded a high temperature of 121°F (49.4°C) in Death Valley, which was thought to be the highest temperature recorded in the United States (Harrington 1892; Lingenfelter 1986). Subsequently, however, 130°F (54.4°C) was reported at Mammoth Tank (a railroad depot in the Salton Sink) in July 1885, and 129°F (53.9°C) (23 June 1902) and 128°F (53.3°C) (5 July 1905) temperatures were recorded at Volcano Springs (also a railroad depot in the Salton Sink, now under the Salton Sea) using a Weather Bureau standard maximum thermometer in a standard shelter (Willson 1915; Lott and Ross 2002).

The first consistent weather observations were taken near Furnace Creek Ranch in 1891 between May and September, and the results were discussed in the very first U.S. Department of Agriculture Weather Bureau Bulletin, published in 1892 (Harrington 1892). As part of a survey by the U.S. Geological Survey and the U.S. Signal Service, the Weather Bureau established a standard weather station "using standard equipment supplied to the regular second-order stations of the Bureau, with the addition of a barograph and thermograph" (Harrington 1892). Instruments used in this study were carefully calibrated before and after the 5-month study, and detailed observations were made many times each day. Conditions were difficult; Harrington (1892) reported that the observer in charge fared well, but his assistant succumbed to the heat soon after arrival and had to leave Death Valley for treatment. Nonetheless, these measurements remain the most detailed weather observations in Death Valley to the present day. Temperatures recorded in 1891 were not extreme compared to the 1911–2002 record, although the high temperature on 26 August 1891 tied the all-time high (through 2002) recorded for this day [121°F (49.4°C) recorded in 1913] and the low temperatures recorded on 13 July and 7 August 1891 tied the record low temperatures for those days (through 2002). Precipitation measured from May through September 1891, however, was unusually high, totaling 1.4 in. (3.6 cm). Over one-third of this amount fell within a single half-hour time span during a severe August thunderstorm. Precipitation greater than 1.4 in. (3.6 cm) during May–September has occurred only five times between 1911 and 2002, and in 17 of these years, no precipitation greater than a trace was recorded during these months. Thus Harrington's extrapolated estimate of Death Valley's annual precipitation of 4–5 in. (10–13 cm) was biased by the unusual conditions in 1891; the annual average precipitation recorded 1911–2002 is 1.9 in. (4.8 cm).

DATA COMPILED FOR THIS ARTICLE.

Data sources. Since 1911, daily maximum (TMAX), daily minimum (TMIN), and precipitation (PRECIP) were recorded by trained observers in Death Valley at the Greenland Ranch or Furnace Creek weather station (Fig. 2; Tables 1 and 2). Each of these values represents the highest or lowest temperature, or precipitation accumulation, in the 24 h preceding the daily station observation. Daily observations are generally complete (only 10 yr are missing more than 32 daily observations per year, except for missing data from September 1957 through February 1958). From 1911 through 1981 (except for a few months in 1956 and 1957), daily observations always took place at 1600 or 1700 LST, which is generally after the high temperature of the day, but it is possible that the maximum temperature recorded for a day actually occurred on the previous day. Likewise, precipitation that occurred after the time of observation would be attributed to the next day. However, for a few scattered months in 1956 and 1957, and continuously from 1982 to the present, daily observations have been

Fig. 2. The weather station at Greenland Ranch in 1926. The floor of the enclosure was reported to be 3.5 ft (1.1 m) above the ground in 1924. Courtesy of the Bancroft Library, University of California (BANC PIC 1978.027—ALB).

made at 0800 LST. Thus the TMAX temperature recorded in the morning most likely occurred during the afternoon of the previous calendar day. The TMAX data in this compilation have been "adjusted" for these changes in observation time; for days when the observation time was in the morning, TMAX has been reassigned to the previous day. No adjustments were attempted for TMIN or PRECIP readings.

Table 1. Sources of data for this report.

Time span	Station location	Source of data
1 Jul 1911–31 Dec 1933	Greenland Ranch	Daily records archived in Death Valley NPS library (data keyed in by S. Roof) and Guttman (2002) when necessary
1 Jan 1934–31 Oct 1937	Greenland Ranch	National Climatic Data Center (Guttman 2002)
1 Nov 1937–31 Dec 1948	Greenland Ranch	Western Region Climate Center at the Desert Research Institute (DRI) with missing data filled in from Guttman (2002).
Jan 1949–present	1949–61, Greenland Ranch; 1961–present, Furnace Creek	National Climatic Data Center

Errors and problems with the data. Potential errors may have crept into the data files from a variety of sources: instruments may have malfunctioned or were misread (missing data are generally due to recognized instrument malfunction), data were recorded incorrectly or were transcribed incorrectly, data were entered incorrectly, and unexplained errors.

Daily data from 1911 to 1933 were not publicly available at the time this report was being prepared. These data were manually typed from paper records archived in the Death Valley National Park Service (NPS) library. During final stages of completion, the National Climate Data Center (NCDC) released pre-1948 daily data for many stations (Guttman 2002), including Furnace Creek. The pre-1948 data were preliminary, and comparisons with our hand-entered data revealed many discrepancies. Discrepant values were double-checked against the original paper records in the Death Valley National Park library. Often the hand-printed numbers on the original sheets were hard to read (e.g., difficult to tell if 104 or 109 was originally written). We used our best interpretation of the numbers from the original sheets in the Death Valley library to resolve discrepancies with the Guttman (2002) data. From January 1934 through October 1937, the Guttman dataset was used with no corrections. From November 1937 through December 1948, the more complete dataset obtained from Western Region Climate Center (WRCC) was used, with occasional missing data filled in from the Guttman dataset. From 1934 onward, data obtained from the NCDC or the WRCC were not double-checked against paper records. NCDC subjects data submitted by cooperative (COOP) observers to various quality control checks, sometimes rejecting anomalous values. The data for 1911–33 were not subjected to this quality control.

Table 2. Meteorological stations in Death Valley National Park.

COOP station ID no.	Station name	Lat	Long	Elevation	Dates of operation
042319	Death Valley (Furnace Creek)	36°28′N	116°52′W	–57 m (–188 ft)	26 Apr 1961–present
043603	Greenland Ranch	36°27′N	116°52′W	–55 m (–179 ft)	8 Jun 1911–26 Apr 1961
049671	Wildrose Ranger Station	36°16′N	117°11′W	1280 m (4200 ft)	1 Dec 1966–1 May 2000
042092	Cow Creek	36°30′N	116°52′W	–34 m (–113 ft)	1 Jul 1934–31 Dec 1961

Note that the "official" weather station of the National Park Service was located at the Cow Creek Park Service Headquarters between 1933 and 1961, not at Furnace Creek. However, the Greenland Ranch observation station remained active through this interval, and all of the data accompanying this report are from either Greenland Ranch or Furnace Creek.

Data archive. The complete dataset [daily temperature, precipitation, evaporation, and wind movement data from Greenland Ranch and Furnace Creek (Death Valley), California] can be obtained from the authors by request.

DEATH VALLEY CLIMATOLOGY. *Temperature extremes.* Furnace Creek, Death Valley, is the hottest and driest place in the United States. Furnace Creek held the world record for highest reliable air temperature ever measured for nearly 10 years for the 134°F (56.7°C) reading made 10 July 1913, until a reading of 136.4°F (58.0°C) was recorded in El Azizia, Libya. Questions have been raised about the accuracy of these extreme temperature measurements (e.g., Court 1949, 1953), but both remain officially recognized (Willson 1915; Gentilli 1955; Lamb 1958; McKittrick et al. 1991; Krause and Flood 1997). Even though El Azizia experienced a higher absolute maximum temperature, the average temperatures in Death Valley are consistently greater than El Azizia (Table 3).

TABLE 3. Average daily maximum and minimum temperatures (°F) for Furnace Creek, CA and El Azizia, Libya.

Month	Furnace Creek average daily max temp (°F), 1913–51	El Azizia average daily temp (°F), 1913–51	Furnace Creek average daily min temp (°F), 1955–66	El Azizia average daily min temp (°F), 1955–66
Jan	65	63	39	43
Feb	72	68	45	43
Mar	81	73	54	46
Apr	90	82	63	52
May	99	88	72	58
Jun	109	96	82	65
Jul	116	100	88	67
Aug	113	99	87	68
Sep	106	96	76	65
Oct	91	88	64	59
Nov	76	76	48	52
Dec	66	66	39	45

The mill superintendent of the Pacific Borax Company, F. W. Corkhill, describes the conditions in Death Valley on 10 July 1913 when the temperature reached 134°F (56.7°C): "I remember the day very distinctly, as a man by the name of Busch perished in the valley north of the ranch that day on account of the heat. The chauffeur who was with Mr. Busch at the time he perished also very nearly lost his life. I saw him a few days later and he said that a terrific wind prevailed in the valley on that day" (Willson 1915).

Death Valley is hot and dry, and indeed experiences more heat in a year than any U.S. city (as measured by cooling degree days). But Death Valley is not the hottest and driest place in the United States every month of the year. Death Valley holds

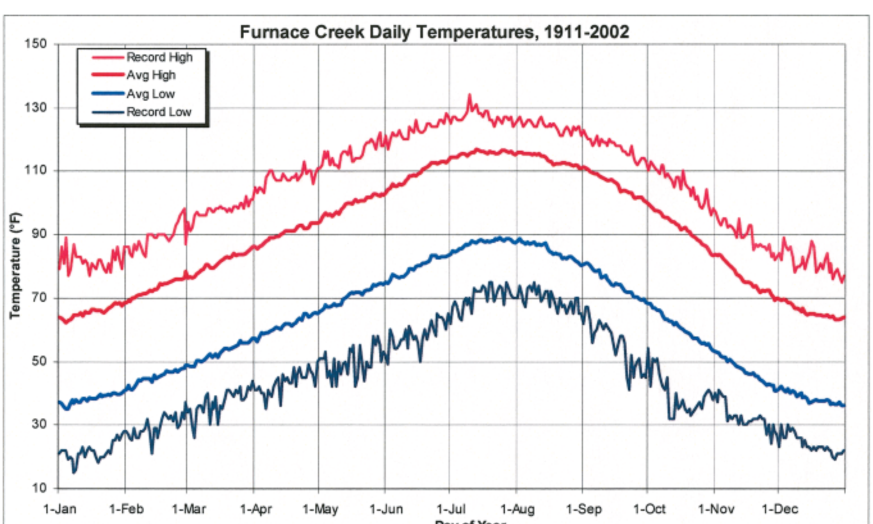

FIG. 3. Daily average and record temperatures. Furnace Creek, 1911–2002.

the record for highest temperature in the United States only for the months of May, July, and August (Death Valley and Lake Havasu City, Arizona, tie for second place in June at 128°F (53.3°C), but Volcano in Amador County, California, reached 129°F (53.9°C) in June 1902 (Lott and Ross 2002). Nine other U.S. states have experienced high temperatures greater than 120°F, including not only the southwestern states but also Great Plains states as far north as North Dakota (Lott and Ross 2002).

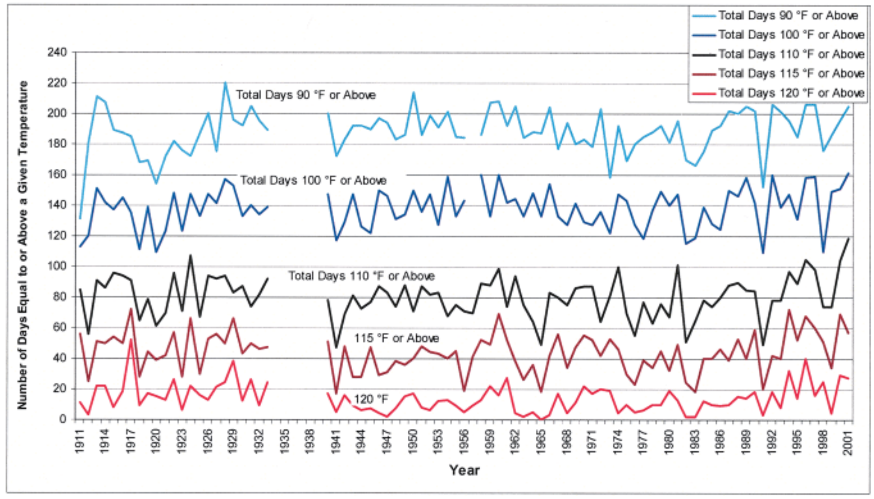

Fig. 4. Number of days with TMAX above a given temperature. Years with more than 20 days of missing data are excluded.

Precipitation extremes. Death Valley receives the least precipitation of any National Weather Service (NWS) station in the United States (Robinson and Hunt 1961; McKittrick et al. 1991; Krause and Flood 1997) with a 1911–2002 average of 1.9 in. yr^{-1} (4.8 cm yr^{-1}), but it is certainly not among the driest places in the world or even North America. Bataques, Mexico, receives 1.2 in. yr^{-1} (3.0 cm yr^{-1}), and Death Valley's annual average of 1.9 in. (4.8 cm) is like a rain forest compared to Arica, Chile, where the annual average precipitation is only 0.03 in. (0.08 cm) (Krause and Flood 1997; Lott and Ross 2002). And while Death Valley went 393 days without any measurable precipitation in 1928–30, Iquique, Chile, went for 14 consecutive years with no rain. Interestingly, in southernmost Chile there is a town that gets rain an average of 325 days yr^{-1}! (Krause and Flood 1997).

Annual temperature extremes at Furnace Creek. Ninety years of continuous daily records now provide a clear indication of the climate of Furnace Creek, Death Valley. Figure 3 shows average TMAX and TMIN as well as record TMAX and TMIN for each day of the year. Figure 3 allows one to check the "usual" (i.e., average of TMAX and TMIN) temperatures for any day of the year, and also check the highest and lowest temperatures ever recorded for that day. At Furnace Creek, all but 8 yr experienced more than 120 days above 100°F (37.8°C) and typically 13–14 days per year reach above 120°F (48.9°C); however, 1917 experienced 52 days of 120°F (48.9°C) and above and 1996 saw 40 (Fig. 4). Daily TMAX exceeds 90°F (32.2°C) for more

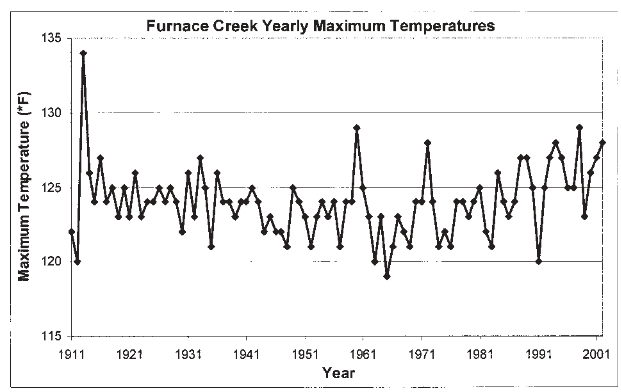

Fig. 5. Maximum temperature experience each year at Furnace Creek, 1991–2002.

than half of the year (Fig. 4). Furnace Creek baked at 100°F (37.8°C) for more than 134 consecutive days in the summer of 1974, and for 154 consecutive days in 2001. Death Valley's hottest temperature of the year has occurred from late May through the end of August (Table 4). From 1911 through 2002, the hottest temperature of the year ranged from 134°F (56.7°C) in 1913 to 119°F (48.3°C) in 1965 (Fig. 5 and Table 4). The year 1965 was the only year that did not experience a maximum temperature above 119°F (48.3°C).

Many people hold the misconception that the desert always cools down quickly at night. During summer months, even the coolest temperature (TMIN) of the day may not drop below 100°F (37.8°C) and for all but 2 yr (1911, 1912) the maximum TMIN has been 93°F (33.9°C) or above. The highest TMIN is 110°F (43.3°C), recorded in 1918, 1922, 1923, and 1924. Since 1937, the maximum TMIN

Table 4. Maximum temperature experience each year at Furnace Creek, 1911–2002.

Year	Max temp of year (°F)	Date(s) of max temp	Year	Max temp of year (°F)	Date(s) of max temp
1911	122	14 Jul, 20 Aug	1957	121	25, 27 Jul; 17 Aug
1912	120	29 May, 5 Jun, 8 Aug	1958	124	11 Jul
1913	134	10 Jul	1959	124	16 Jul
1914	126	6, 7 Aug	1960	129	18 Jul
1915	124	11 Aug	1961	125	20, 21 Jun; 10, 11 Jul
1916	127	23 Jul	1962	123	15 Aug
1917	124	21–25 Jul	1963	120	15, 16 Jul
1918	125	3 Aug	1964	123	24 Jul
1919	123	20 Aug	1965	119	7, 9, 10 Aug
1920	125	31 Jul	1966	121	5–7 Aug
1921	123	1, 8 Jul	1967	123	1–4 Jul
1922	126	15 Jul	1968	122	22 Jun
1923	123	29 Jul	1969	121	31 Jul; 1–4, 15 Aug
1924	124	1 Jul, 27 Aug	1970	124	18, 19 Jul
1925	124	13, 14, 17 Jul	1971	124	29 Jul, 10 Aug
1926	125	16 Jul	1972	128	14, 15 Jul
1927	124	14 Jul	1973	124	6 Jul
1928	125	27 Jul	1974	121	28, 29 Jul
1929	124	23 Jun	1975	122	25–27 Jul; 5, 6 Aug
1930	122	14 Jul	1976	121	8–10 Jul
1931	126	19, 20, 26 Jul	1977	124	2 Aug
1932	123	5 Aug	1978	124	8, 9 Aug
1933	127	26 and 27 Jul, 12 Aug	1979	123	17–19 Jul
1934	125	12, 27 Jul	1980	124	26 Jul
1935	121	13 Jul	1981	125	8 Aug
1936	126	6 Aug	1982	122	30, 31 Jul
1937	124	11–13 Aug	1983	121	13 Jul
1938	124	1, 2 Aug	1984	126	4 Jul
1939	123	13, 14, 22, 23 Jul	1985	124	4, 5 Jul
1940	124	11 Aug	1986	123	5 Aug
1941	124	22 Jul	1987	124	14 Jul, 3 Aug
1942	125	24 Jul	1988	127	18 Jul
1943	124	26, 27 Jul	1989	127	7 Jul
1944	122	12, 13 Aug	1990	125	1, 12 Jul
1945	123	26 Jul, 24 Aug	1991	120	9, 24, 25 Aug
1946	122	3 Aug	1992	125	3 Aug
1947	122	19 Jul	1993	127	2 Aug
1948	121	30 Aug, 1 Sep	1994	128	29 Jun
1949	125	16 Jul	1995	127	29 Jul
1950	124	1 Jul	1996	125	2, 25 Jul; 1, 13 Aug
1951	123	18 Jul	1997	125	6, 7 Aug
1952	121	4 Aug	1998	129	17 Jul
1953	123	22, 24 Jul	1999	123	1 Jul
1954	124	22 Jun	2000	126	15 Jun
1955	123	7 Jun	2001	127	2, 3 Jul
1956	124	28 Jun	2002	128	9 Jul

has not exceeded 101°F (38.3°C), although the TMIN was 100°F (37.8°C) or 101°F (38.3°C) in 10 yr since 1937. No other place in the United States experiences minimum temperatures 100°F (37.8°C) or above. Nighttime temperatures remain warm in Death Valley because of the immense heat stored in the ground and rocks.

In surprising contrast to summertime, Death Valley can be cold during the winter (Eklund 1933). During December and January, average daily temperatures in Furnace Creek are warmer than San Francisco, but slightly cooler than Los Angeles. Daily TMIN drops below 60°F (15.6°C) for about half the year (Fig. 3) and freezing temperatures have been recorded from October through April. The lowest temperatures occur in late December and early January, with average TMIN dropping to 32°F (0°C), but temperatures below (20°F (−6.7°C) are not uncommon (Fig. 3). During the winter of 1928/29, there were 72 consecutive days at or below the freezing mark. The coldest temperature recorded in Death Valley, 15°F (−9.4°C), occurred on 18 January 1913, which was the same year as the record high.

Temperatures elsewhere in Death Valley National Park. A visitor to Death Valley National Park can easily find refuge from the extreme heat on the valley floor. Death Valley National Park is a very large geographic region, and temperatures measured on the floor of the valley at Furnace Creek, 57 m (187 ft) below sea level, are naturally not representative of the entire park. Weather observations kept at National Park Service ranger stations show that at the Wildrose Ranger Station [elevation 1280 m (4200 ft); Fig. 1] summertime temperatures are typically 20°F (11°C) cooler than at Furnace Creek (the difference in winter temperatures is slightly less). At Grapevine Ranger Station [elevation 680 m (2230 ft), a non-NWS weather station; Fig. 1] July temperatures are typically 8°–15°F (4°–8°C) cooler than at Furnace Creek. Hunt (1975) notes that during still nights, the valley floor may be cooler than surrounding alluvial fans by 10°F (6°C) due to cooling by evaporation and plant transpiration around the edges of the salt pan [while this sort of pattern can be caused by cool air draining into the topographic low of the valley, Hunt (1975) found no indication of cooler air flowing down the canyons].

For visitors seeking the hottest temperatures, Badwater, the lowest point on the salt flat in Death Valley, is likely hotter than Furnace Creek. However, official temperature records are not measured at Badwater. Robinson and Hunt (1961) report that Badwater temperature maximums were often 3°F (≈2°C) warmer than those at Furnace Creek. This conclusion was probably based on an unpublished study by a Park Service ranger (Wauer 1959) that reports temperatures at Badwater were 3°–5°F (2°–3°C) higher than at Furnace Creek during July and August 1959 (Wauer used NWS quality recording thermographs in a standard shelter, but he emphasizes the thermographs were not calibrated daily and thus are not recognized as official readings).

Air versus ground temperature. Official NWS air temperatures are measured in standardized, ventilated shelters 5 ft (1.5 m) above the ground surface. During the daytime, temperatures closer to the ground can be much hotter than the measured air temperature. A U.S. Army Yuma Proving Grounds study measured air temperature from the ground surface up to 8 ft (2.4 m) above, using high quality U.S. Army Meteorological thermocouples in solar radiation shields that were calibrated daily (Roberts 1969, personal communication). The study found that during a 120°F (48.9°C) day at the Furnace Creek station, the temperature of the uppermost soil of the natural desert surface exceeded 150°F (65.6°C) and air temperatures 1 ft (0.3 m) above the ground exceeded the air temperature at 8 ft (2.4 m) by 10°F (5.6°C). Hunt et al. (1966) report a maximum ground surface temperature of 190°F (87.8°C) recorded in August 1958 on the surface of the massive gypsum at Tule Spring.

Daily conditions. Of great importance to visitors in Death Valley is how the temperature changes throughout the day. Current official observations do not include hourly temperature readings, but Harrington (1892) reports hourly temperature measurements made during the summer of 1891, and additional thermograph records have been made at

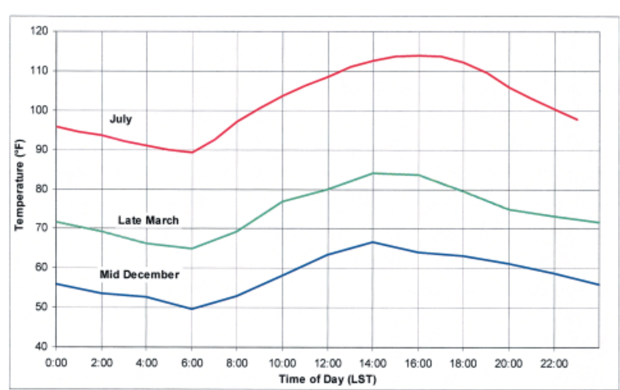

Fig. 6. Daily temperature ranges at Furnace Creek. Jul profile is from Harrington (1892); Mar and Dec profiles are from 1977 Furnace Creek Visitors Center circular charts.

the National Park Visitors Center, although the accuracy of the recording thermometers is not known. Together, these data show daily temperatures increasing from the coolest time of the day around 0600 LST throughout the year, but the hottest time of the day shifts from about 1400 LST in winter to 1600 LST in summer (Fig. 6). These records are for the Furnace Creek area, 57 m (187 ft) below sea level in the geographic Death Valley, and Court (1952) reached similar conclusions from observations made at the Cow Creek weather station in 1949. However, Death Valley National Park encompasses mountain ranges to 3350-m (11 000 ft) elevation, where temperature profiles will obviously be much different; but unfortunately, no detailed records are available for higher elevations.

The average daily temperature range (i.e., difference between TMAX and TMIN) in the summer (30°–32°F) (17°–18°C) is not much greater than in the winter (26°–29°F) (14°–16°C). Maximum daily temperature ranges experienced (not averages) vary from 45° to 50°F (25° to 28°C), with differences greater than 55°F (31°C) more frequent during the fall. The largest temperature ranges occur in fall as the nights cool off quickly during that time of year.

During late summer months, rapid temperature changes often accompany thunderstorms. Harrington (1892) reports temperature drops of 20°F (11°C) in less than 30 min associated with the first violent winds of summer thunderstorms. Relief from sweltering temperatures is usually temporary; often after a thunderstorm passes, temperatures will climb 10°F (6°C) or more (and higher humidity increases the effective temperature).

Precipitation patterns. Precipitation is infrequent and slight in Death Valley. Annual precipitation (by calendar year) ranges from 0 to a maximum of 4.63 in. (11.8 cm), recorded in 1941 (Fig. 7). When precipitation is measured by water year, from October through September, the highest recorded was 6.40 in. (16.2 cm) recorded 1987–88. Extremely wet years in Death Valley are listed in Table 5, along with wettest winter seasons (October–June) and summers (July–September). The wettest water years and winter seasons are frequently associated with El Niño events, although some El Niño years were drier than average [i.e., winter 1993/94 received only 0.50 in. (1.3 cm) of precipitation]. The wettest single month was recorded in January 1995 with 2.59 in. (6.6 cm).

Annual precipitation measured at Furnace Creek has increased in the last 40 years, but since 1980, year-to-year precipitation amounts have become more variable (Fig. 6). Based on the data compiled in this project, annual average rainfall for the entire period 1911–2002 is 1.9 in. (4.8 cm), for the interval 1911–60 annual rainfall averaged 1.6 in. (4.1 cm), and for 1961–2002 annual rainfall has been 2.2 in. (5.6 cm)

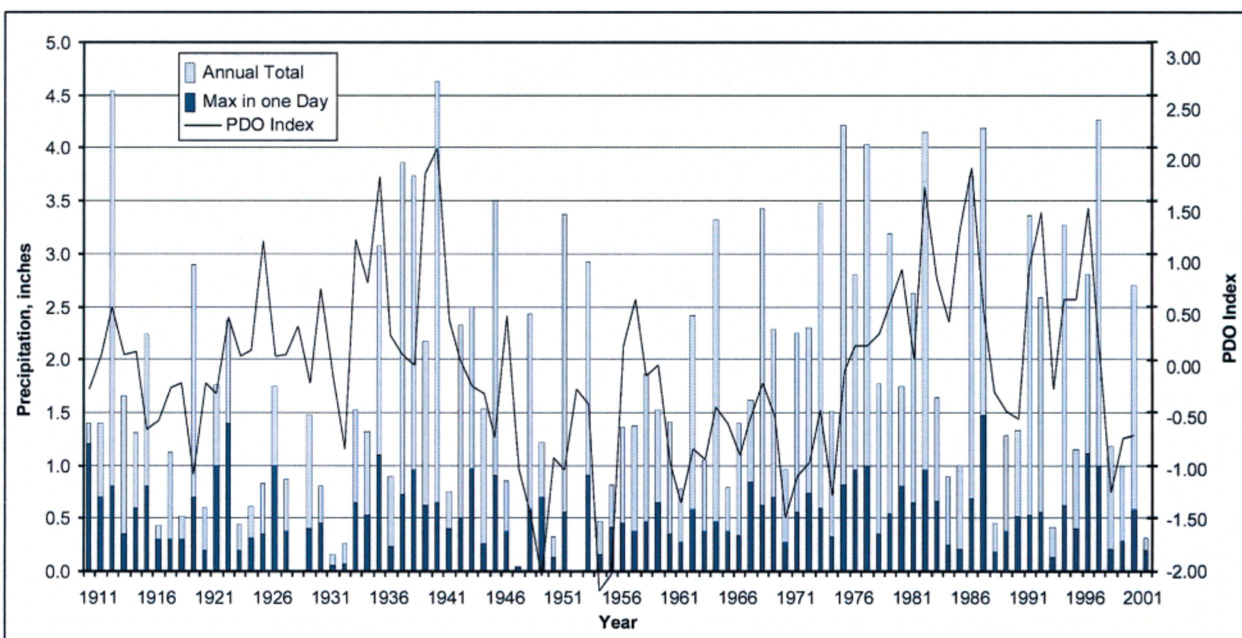

FIG. 7. Annual and maximum daily precipitation recorded at Furnace Creek, 1911–2002. Annual precipitation correlates to the PDO. [The PDO index courtesy of N. Mantura (information available online at ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest).]

Table 5. Top-ten wettest years (calendar and water years) and winter/summer seasons recorded at Furnace Creek. Water years and winter rains are designated by the year of the month ending the interval. Boldface years indicate strong El Niño intervals.

Annual total (in., calendar year)		Water year total (in., 1 Oct–30 Sep)		Winter season (in., 1 Oct–30 Jun		Monsoon season (in. 1 Jul–30 Sep)	
1941	4.63	**1988**	6.40	**1988**	5.77	1936	1.91
1913	4.54	1939	5.25	**1998**	4.32	1939	1.79
1998	4.26	**1998**	4.83	1978	3.95	**1997**	1.77
1976	4.21	1978	4.37	**1973**	3.58	1984	1.62
1988	4.19	**1983**	4.18	**1993**	3.51	1983	1.32
1983	4.15	**1941**	3.91	1939	3.46	1950	1.22
1978	4.03	1976	3.83	**1941**	3.38	1977	1.14
1938	3.89	**1973**	3.58	**1995**	3.16	**1963**	1.12
1939	3.76	**1993**	3.51	1980	2.93	1938	1.08
1987	3.74	1920	3.20	**1983**	2.86	1976	1.07

(numbers are the same for calendar and water years). Ten-to-twenty-year intervals of relative dryness or wetness at Furnace Creek generally follow the Pacific decadal oscillation (PDO), a recently recognized 10–20-yr oscillation of sea surface temperature in the Pacific Ocean (Mantura et al. 1997; Biondi et al. 2001) (Fig. 6).

Intense winter storms may dump several inches of rain over a few days. Such conditions lead to flash floods, which are the main processes that deepen canyons and enlarge alluvial fans. In February 1976, a 5-day storm dumped 2.37 in. (6.0 cm) of rain, causing flash floods through Golden Canyon that permanently washed out a paved road in the canyon that had been built in the 1930s.

Strangely enough, 0.5 in. (1.3 cm) of snow was reported on the ground by the COOP observer at Furnace Creek on 10 January 1922 (rain was also reported for the day, so it is not a case of the observer writing the precipitation value in the wrong column of the record sheet). Low temperatures for 29–30 January 1922 were 36° and 34°F (2.2° and 1.1°C) in Death Valley. Both the *Inyo Independent* and the *Goldfield Daily Tribune* newspapers reported heavy snowfall in the region for 29–30 January and temperatures were well below normal. Four inches (10.2 cm) of snow fell in Goldfield, Nevada. Twelve inches (30.5 cm) were reported in Los Vegas, and snow fell on Mount Lowe near Pasadena and Mount Talampias near San Francisco. Both newspapers reported problems with vehicles getting stuck in the snow in Goldfield and Tonopah, and two travelers were stuck in 14 in. (35.6 cm) of snow on Emigrant Pass on the western margin of Death Valley. These reports confirm unusual conditions throughout the West, but independent verification of snow in Death Valley has not been found (so far). Snow has fallen in Stovepipe Wells, 25 km (16 mi.) northwest of Furnace Creek at an elevation of sea level.

The Furnace Creek weather station receives most (64%) of its precipitation during the winter months (November–March) (Fig. 8), from storms originating in the eastern Pacific and Gulf of Alaska low pressure systems. During the summer, the eastern Pacific high generally blocks airflow from the west and the region is affected by air masses from the south and southeast, bringing generally drier conditions but occasional summer thunderstorms. Summer rains in July and

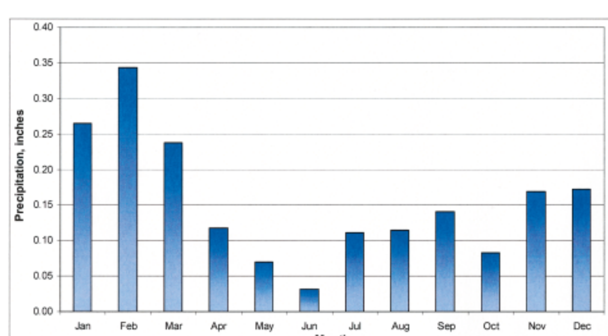

Fig. 8. Average monthly precipitation recorded at Furnace Creek.

August are fed by the "Arizona monsoon," which is derived from southern and southeastern moisture sources. Death Valley is near the northern limit of the Arizona monsoon so the summer rain contribution is not as great here as it is farther south and east.

A significant fraction of Death Valley's annual rainfall comes during intense 1-day storms. On average, the wettest day of the year contributes 35% of the annual total precipitation (Fig. 7). Summer thunderstorms, in contrast to winter storms, may drop up to an inch (2.54 cm) of rain in a matter of an hour or less, but few records are kept of individual storms. Summer thunderstorms are very localized and the rain buckets at a few stations widely scattered across the vast valley floor cannot accurately record the frequency or intensity of such events. For example, during a September 2000 thunderstorm, National Park Service rangers recorded 1.5 in. (3.8 cm) of rain in 20 min at the Cow Creek Administrative Offices, but no rain was recorded at the Furnace Creek weather station 5 km (3 mi) to the south. Therefore it is difficult and risky to reconstruct rainfall patterns from a single weather station. Nonetheless, it appears that there has been a long-term trend toward less summer rain (1984 being a notable exception, Fig. 9) and an increase in the number of days with measurable rain (Fig. 10). Similar patterns for the entire Mojave Desert region have also been documented (Hereford 2000; Schmidt and Webb 2001).

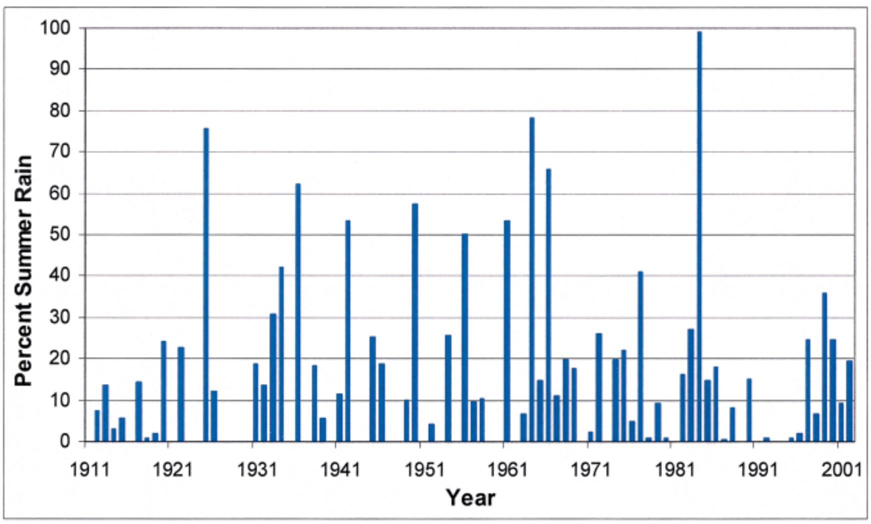

FIG. 9. Summer rain (Jun–Aug) as a percentage of annual total. Except for 1984, the fraction of summer rain received at Furnace Creek has decreased from the norm established between 1935 and 1964.

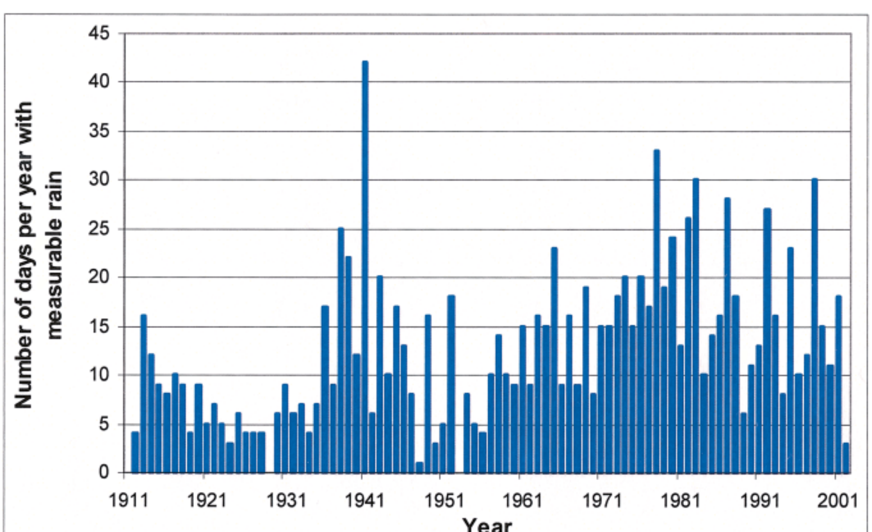

FIG. 10. Days per years with measurable rain at Furnace Creek. The average number of days with measurable rain recorded at Furnace Creek has increased since 1950, although year-to-year variability has also increased.

Wind. Wind may be the most underappreciated element of Death Valley's weather, at least until a visitor experiences a windstorm first hand. Detailed wind speed measurements are not archived at Furnace Creek, but daily wind movement, which measures the total distance the wind moves each day, are recorded each day. Average daily wind movement measured at Furnace Creek has decreased by more than 50% over the last 25 yr, most likely not due to changes in weather patterns, but due at least in part to growth of trees near the weather station. Average daily wind movement is lowest during the winter and peaks during the early spring (Fig. 11). During March–May, daily wind movement commonly exceeded 250–300 mi day^{-1} (400–480 km day^{-1}). Harrington's (1892) reports of gales during the summer months of 1891 are typical of those that plague the tents, awnings, and eyes of campers today: "They generally blew from the south every three or four days, rarely lasting more than seven hours, usually only two or three, and dying out toward midnight. The velocity was usually above 30 mph (48 km h^{-1}), some reaching 45 mph (72 m h^{-1}) or more, and one 51 mph (82 m h^{-1}). They usually began suddenly and died out gradually. More than half were from the south, and four-fifths were from southern points of the compass" (Harrington 1892, p. 33). Violent winds may also accompany thunderstorms; a strong gust on 25 July 1891 blew the wooden roof off an adobe building and "scattered it 15 yards westward" (Harrington 1892, p. 32). Wind gusts of 60 mph (96 km h^{-1}) have been recorded during thunderstorms (Harrington 1892, p. 35).

Humidity and evaporation. The effects of extreme temperatures experienced by visitors in Death Valley during the summer are moderated somewhat by the very dry air (as long as visitors drink enough water to offset perspiration, which can easily be several liters per day). Humidity is not measured regularly, but hand measurements indicate relative humidity (RH) typically ranges from 5% to 60% at Furnace Creek, with only occasional storm events raising the RH above 80% (McAdie 1913). During the summer, RH may remain below 30% for weeks at a time, and Hunt et al. (1966) report minimum RH measurements of 3%–4% made between 1958 and 1960. Longtime residents in Death Valley say that the most uncomfortable conditions are not the hottest days, but the times when temperature is above 110°F (43.3°C) and the RH is more than 30%. Death Valley's air remains unsaturated most of the time, and dew is a rare phenomenon. Even during rainstorms, air near the ground remains unsaturated (Harrington 1892). During warm months, precipitation often evaporates before it reaches the ground (the phenomenon is termed virga).

The low humidity leads to high rates of potential evaporation. Daily evaporation records are available for Furnace Creek from 1961 through 2002. Evaporation is measured as the daily drop in water level in a standard evaporation pan about 1.5 m (3 ft) in diameter. Typical winter daily evaporation is 0.15 in. day^{-1} (0.38 cm day^{-1}) (January–February) increasing to 0.75 in. day^{-1} (1.9 cm day^{-1}) (May–August) (Fig. 12). Maximum evaporation may reach 0.60 in. day^{-1} (1.5 cm day^{-1}) in the winter, and 1.50 in. day^{-1} (3.8 cm day^{-1}) during the summer (some spikes in maximum daily values seen in Fig. 12 may be due to readings accumulated over several days).

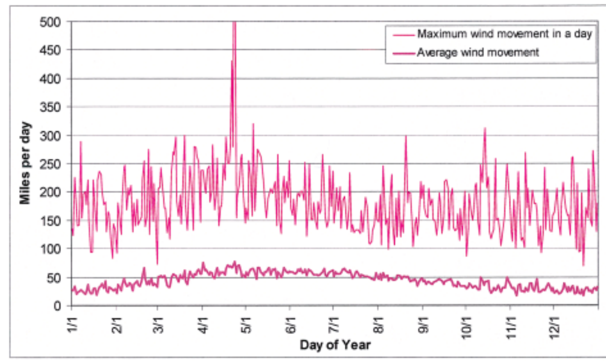

Fig. 11. Average daily wind movement recorded at Furnace Creek, 1961–2002. Maximum daily wind movement exceeded 350 mi day^{-1} (560 km day^{-1}) twice in late April 1965.

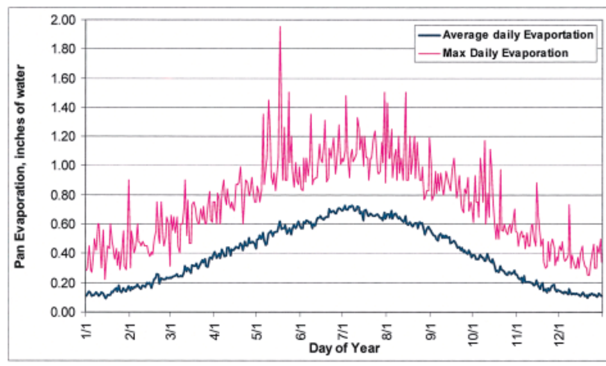

Fig. 12. Daily pan evaporation recorded at Furnace Creek, 1961–2002.

The long-term (1961–2002) annual total potential evaporation is 143 in. yr^{-1} (363 cm yr^{-1}), greatly exceeding the average annual precipitation of 1.9–2.2 in. (4.8–5.6 cm) yr^{-1}. Even with such great potential evaporation, standing water and damp mud persist on the salt flats in Death Valley because evaporation is hindered by high salt content (Hunt et al. 1966). As with wind movement, measured evaporation has decreased in recent decades due to growth of trees around Furnace Creek. From 1961 to 1972, measured average annual evaporation was 162 in. (411 cm). From 1991 to 2002, measured average annual precipitation was only 125 in. (318 cm).

CONCLUSIONS. The daily weather records from Death Valley reveal fascinating details of the most extreme climate in the United States and perhaps the world. Visitors to Death Valley will likely experience hot and dry conditions, but they may also experience very strong winds, intense thunderstorms, and freezing cold weather during the winter (Table 6). While conditions recorded at a single station do not allow us to reconstruct past regional patterns or future trends, Death Valley has seen significant changes in the total amount and nature of its precipitation in the last 90 years. In the near future the National Oceanic and Atmospheric Administration (NOAA) will install a pair of Climate Reference Network (CRN) stations in Death Valley (Furnace Creek and Stovepipe Wells), with electronic sensors that will have their accuracy traced to laboratory standards. These stations will be part of a network of several hundred climate-monitoring stations designed to detect climate change over the next 50–100 years (NCDC 2002). Data from the past 90 years will remain an invaluable archive against which future climate can be compared.

ACKNOWLEDGMENTS. Much of this work was completed while the first author was hosted by Death Valley National Park as a "geologist in the park." Blair Davenport, curator of the Death Valley National Park museum, helped find weather records and historical reports central to this project. The authors wish to thank several friends and anonymous reviewers whose comments greatly improved this manuscript.

Table 6. Death Valley weather landmarks.

1911	Permanent weather station established at Greenland Ranch, now known as Furnace Creek Ranch
1913	Coldest temperature, 15°F (–9.4°C) recorded on 8 Jan; hottest temperature, 134°F (56.7°C) recorded on 10 Jul; five consecutive days reach 129°F (53.9°C) or above; For 10 yr, Death Valley retains title of hottest place on Earth
1922	136.4°F (58°C) recorded at El Azizia, Libya, in the Sahara Desert; which remains the current world record high temperature through 2002
1929	No rain recorded
1931–34	Driest period on record—only 0.68 in. (1.7 cm) of rain from 1 Mar 1931 to 30 Jun 1934 (40 months)
1933	Death Valley becomes a national monument; official weather station moves to Cow Creek, 3 mi (4.8 km) north of Furnace Creek (measurements continue at Greenland Ranch, however)
1941	4.63 in. (11.8 cm) of rain—most rainfall recorded in a calendar year
1953	No rain recorded at Greenland Ranch
1960	129°F (53.9°C) recorded 18 Jul at Greenland Ranch
1961	Official Death Valley National Monument weather station moves to new visitors center at Furnace Creek
1976	Flash floods wash out Golden Canyon Rd; 5-day Feb storm brings record 2.37 in. (6.0 cm) of rain
1977–78	5.09 in. (12.9 cm) of rain from Jul to Jun—highest water year precipitation for 10 yr
1987–88	6.40 in. (16.2 cm) of rain from 1 Oct 1987 to 30 Sep 1988—wettest water year on record
1995	Wettest month ever,— 2.59 in. (6.6 cm) of rain in Jan
1997–98	Above average precipitation through the winter leads to most spectacular spring wildflower season in decades
1998	129°F (53.9°C) recorded on 17 Jul
2001	Hottest summer—a record 154 consecutive days of 100°F (37.8°C) or higher, a total of 161 days 100°F (37.8°C) or higher, and a record 119 days 110°F (43.3°C) or above

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