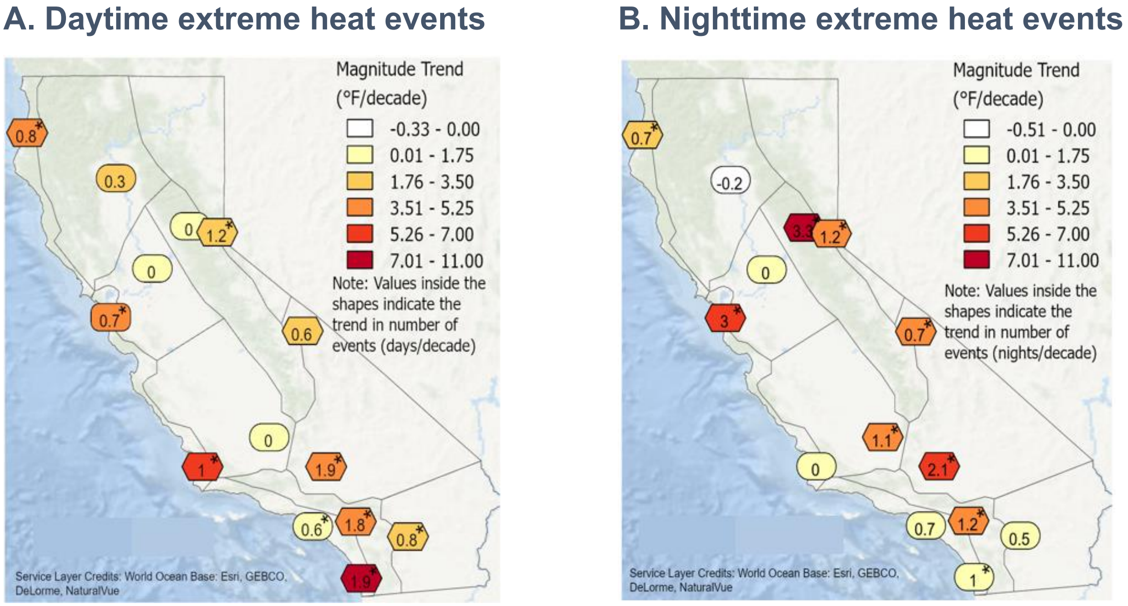
EXTREME HEAT EVENTS

Extreme heat has become more frequent in California since 1950, especially at night. Across most locations studied here, the number and magnitude of extreme heat events have significantly increased. Heat waves – two or more consecutive heat events – vary from year to year, but have become more frequent in the past decade.

Figure 1. Magnitude and frequency of extreme heat events (trend per decade, 1950-2021)



A. Daytime extreme heat events

B. Nighttime extreme heat events

Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

An extreme heat event occurs between April and October when the temperature is at or above a location-specific historical temperature threshold, set at the 95th percentile of daily maximum for daytime extreme events (Figure 1A), or of daily minimum temperatures for nighttime events (Figure 1B), during the 1960-1990 reference period.

*The rate of change (per decade) in **frequency,** the total number of extreme heat events each year, is the value in each shape (hexagon or oval); an asterisk indicates a statistically significant trend ($p \le 0.05$). The rate of change (per decade) in **magnitude**, the annual sum of daily exceedances above the historical temperature threshold, in degrees Fahrenheit (°F), is presented using the fill colors (see legend); a hexagon denotes a trend that is statistically significant ($p \le 0.05$), while an oval is not significant. The outlines on the map show the boundaries of the eleven climate regions, as defined by the Western Regional Climate Center.*

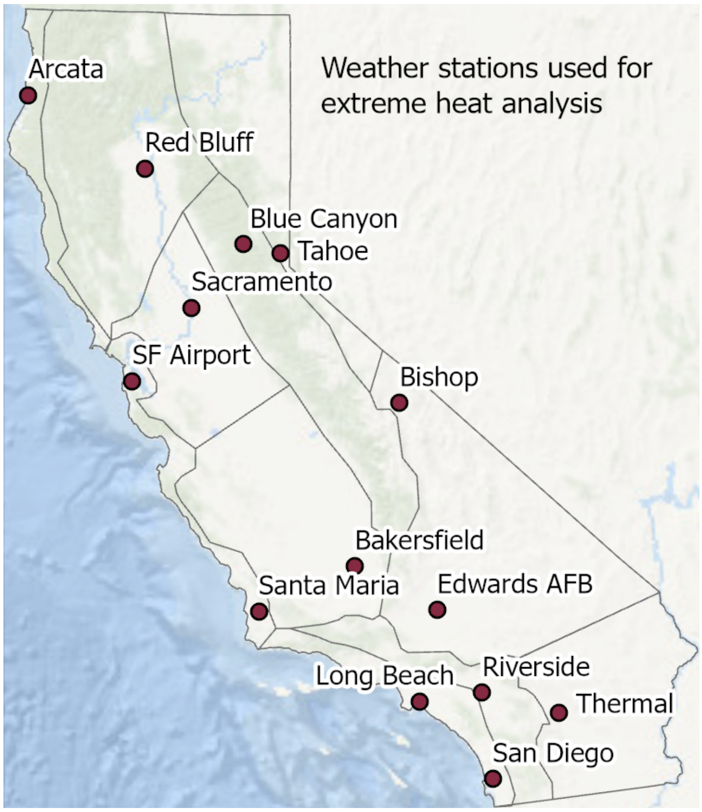
What does the indicator show?

Since 1950, nighttime extreme heat events have increased in magnitude and frequency more than daytime heat events, as shown in Figure 1. The maps show decadal trends in the magnitude and frequency of daytime and nighttime extreme heat events during the warm months between April and October at selected locations (see Figure 2 map of weather stations).

For a given location, a daytime extreme heat event occurs when the historical threshold for daily maximum temperature is exceeded, and a nighttime extreme heat event, when the historical threshold for daily minimum temperature is exceeded. There is no standard temperature for defining an extreme heat event. Researchers often apply a threshold between the 85th and 98th percentile of historical values. Here, the threshold is set at the location-specific 95th percentile of either the daily maximum temperatures (for daytime events) or the daily minimum temperatures (for nighttime events) from April to October during the 1960-1990 reference period.

From 1950 to 2021, the magnitude of extreme heat events increased by at least 1.76 degrees Fahrenheit (°F) per decade during the day at 10 of the 14 stations and at night at 8 stations (stations with orange to dark red fill in Figure 1A and B, respectively). During the same period, the frequency of heat events increased by at least 1 event per decade at 5 stations for daytime events, and at 7 stations for nighttime events (values inside shapes in Figure 1A and 1B, respectively). Out of the stations analyzed, the number of daytime heat events increased the fastest in Edwards AFB and San Diego, with the latter also showing the fastest increase in magnitude (Figure 1A). Blue Canyon experienced the greatest increase in the number of nighttime heat events (with San Francisco Airport a close second) and magnitude (Figure 1B).

Figure 2. Selected weather stations*

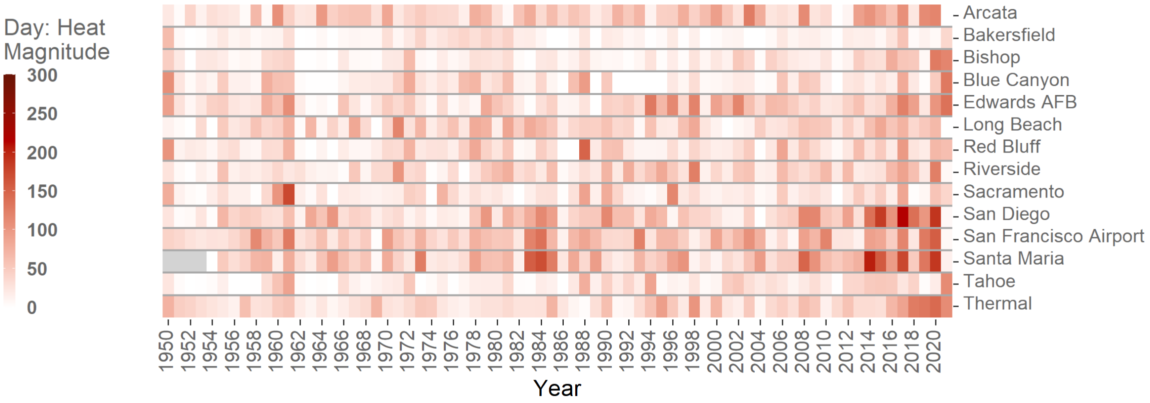


**At least one weather station is from each of California's eleven climate regions (outlined in gray; refer to map, Figure 8). Data sources are discussed in "Technical considerations."*

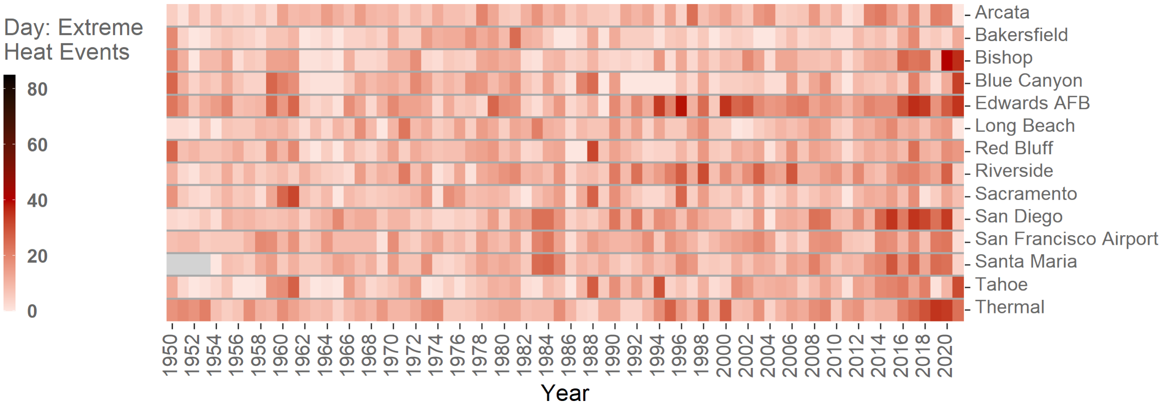
The magnitude and frequency of daytime and nighttime extreme heat events each year at the selection locations are presented in Figures 3 and 4, respectively. The magnitude shown is the sum of daily or nightly exceedances above the historic threshold in a given year at that location.

Figure 3. Annual daytime extreme heat events at the selected locations (1950-2021)

A. Daytime Extreme Heat Events: Magnitude (°F)



B. Daytime Heat Events: Frequency (days)



Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

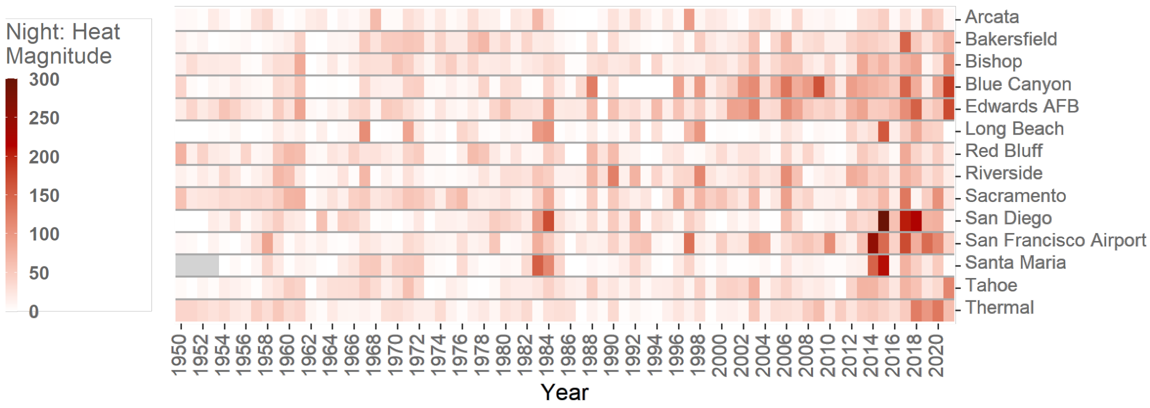
Annual values for magnitude and frequency are presented for each location. Greyed out areas mean no data are available for that timeframe. A location-specific threshold of the 95th percentile was used to determine extreme heat events.

At Edwards AFB, San Diego, San Francisco Airport, and Santa Maria, the magnitude of daytime extreme heat in the last decade is especially notable with at least one year having reached at least 150°F (Figure 3A); note that this is the annual sum of the daily exceedance above the 95th percentile. Similarly, daytime heat events have become more frequent in the last decade, notably at Bishop, Edwards AFB, San Diego, and Thermal, where at least one year having reached 35 or more events (Figure 3B).

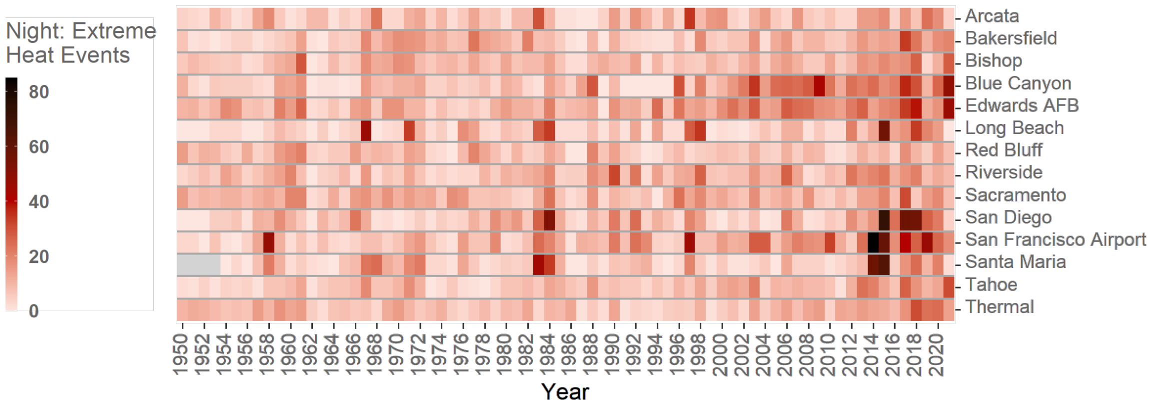
Compared to daytime heat events, nighttime events have seen greater increases in magnitude and frequency (Figure 4). Blue Canyon, Edwards AFB, Long Beach,

Figure 4. Annual nighttime extreme heat events at the selected locations (1950-2021)

A. Nighttime Heat Events: Magnitude (°F)



B. Nighttime Heat Events: Frequency (days)



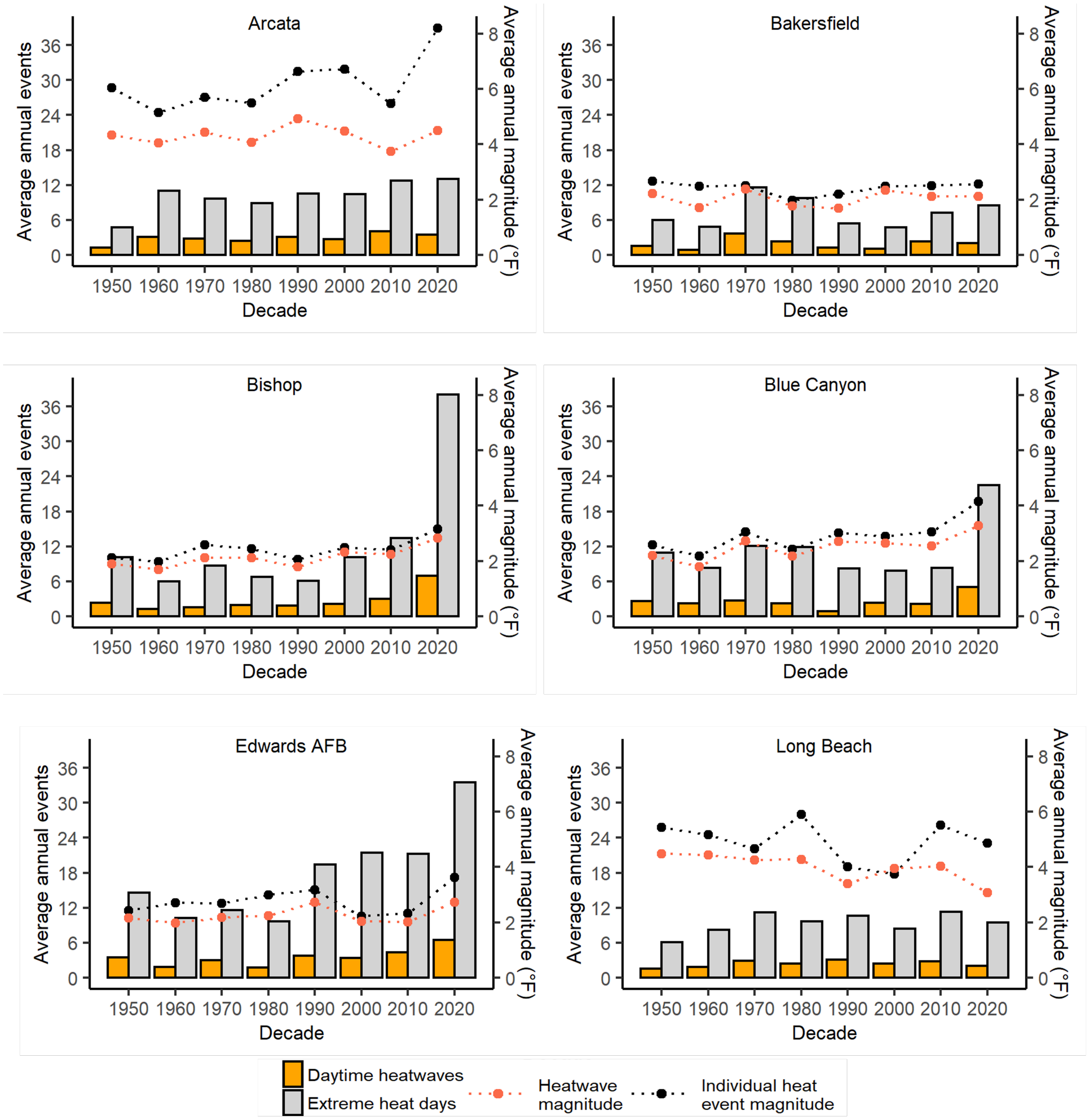
Source: Cal-Adapt, 2018, Dunn 2019, and RCC-ACIS, 2021

Annual values for magnitude and frequency are presented for each location. Greyed out areas mean no data are available for that timeframe. A location-specific threshold of the 95th percentile was used to determine extreme heat events.

San Diego, San Francisco Airport and Santa Maria had at least one year when the magnitude of nighttime heat events reached at least above150°F; San Diego and San Francisco Airport experienced one and three year(s) above 200°F, respectively, during this period (Figure 4A). The last decade also saw the same locations reaching over 35 nighttime heat events on at least one year, with San Diego, San Francisco Airport and Santa Maria recording over 50 nighttime heat events (Figure 4B).

There is no set definition for how many consecutive events make up a heatwave. For purposes of this indicator, a heat wave consists of two or more consecutive daytime or nighttime heat events. Figures 5 and 6 present location-specific averages by decade for daytime and nighttime heatwaves, respectively; values presented for the last decade ("2020") are for 2020 and 2021 only. For comparison, the frequency and magnitude of extreme heat events are also presented.

Figure 5. Daytime heat wave and extreme heat by decade at the selected locations



The average annual values by decade for the number of daytime heatwaves and extreme heat events (bars) and their magnitude (the sum of daily exceedances above the historical threshold, in degrees Fahrenheit (°F)) (dots and lines) are presented for each station. A daytime heatwave is defined as two or more consecutive extreme heat days at a given location. Note: Values for the "2020 decade" include data from 2020 and 2021.

Figure 5, continued

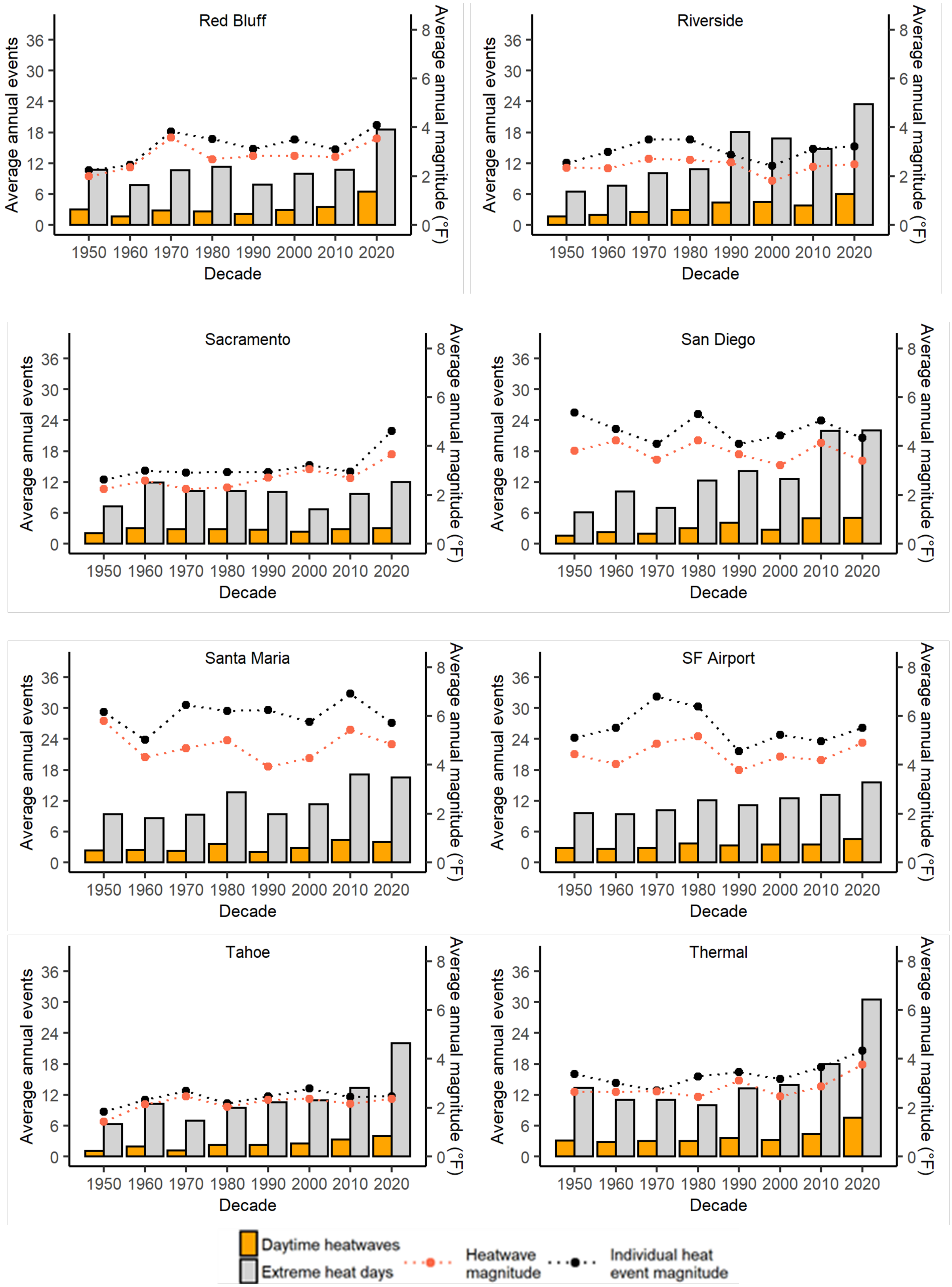
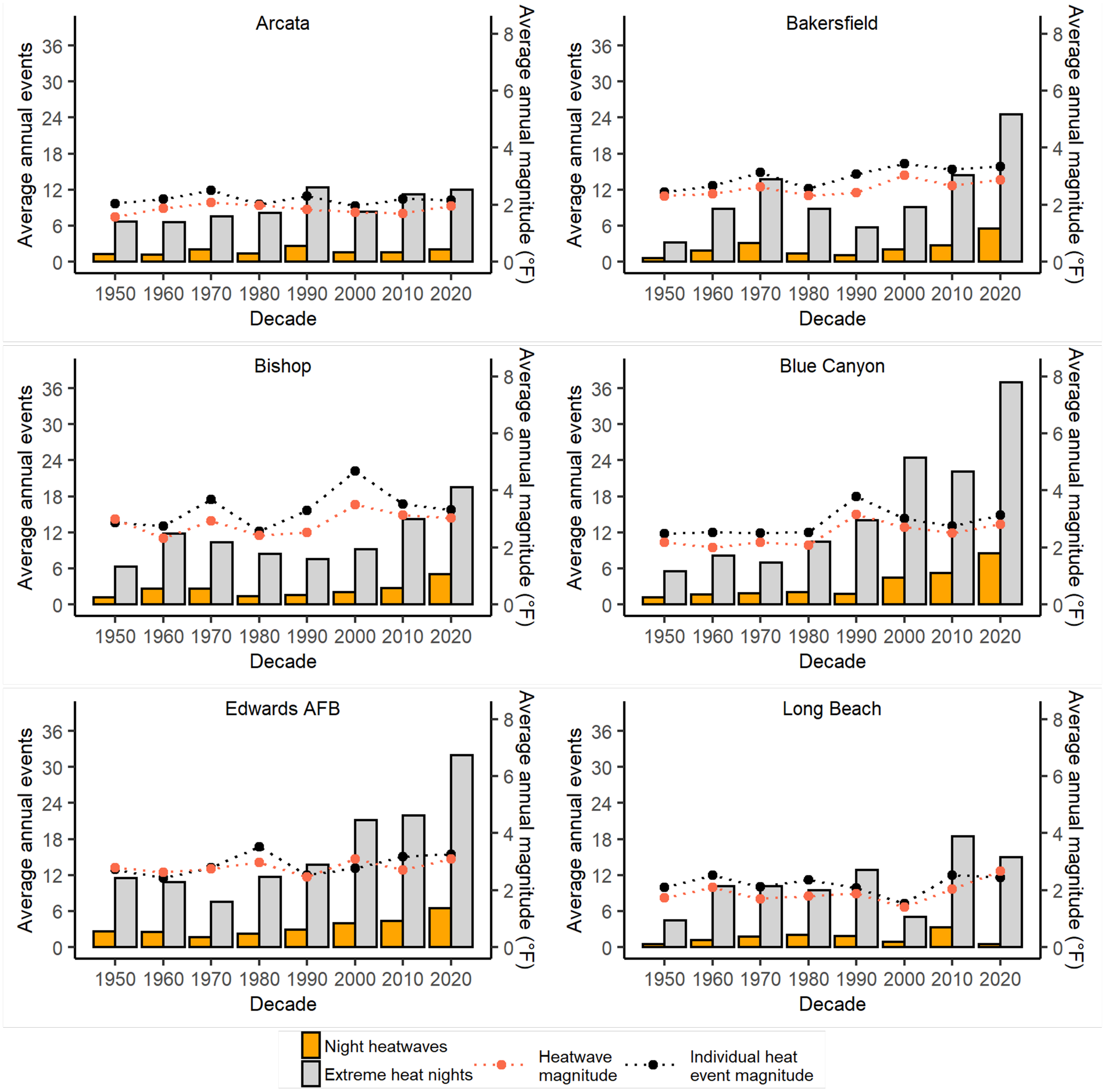
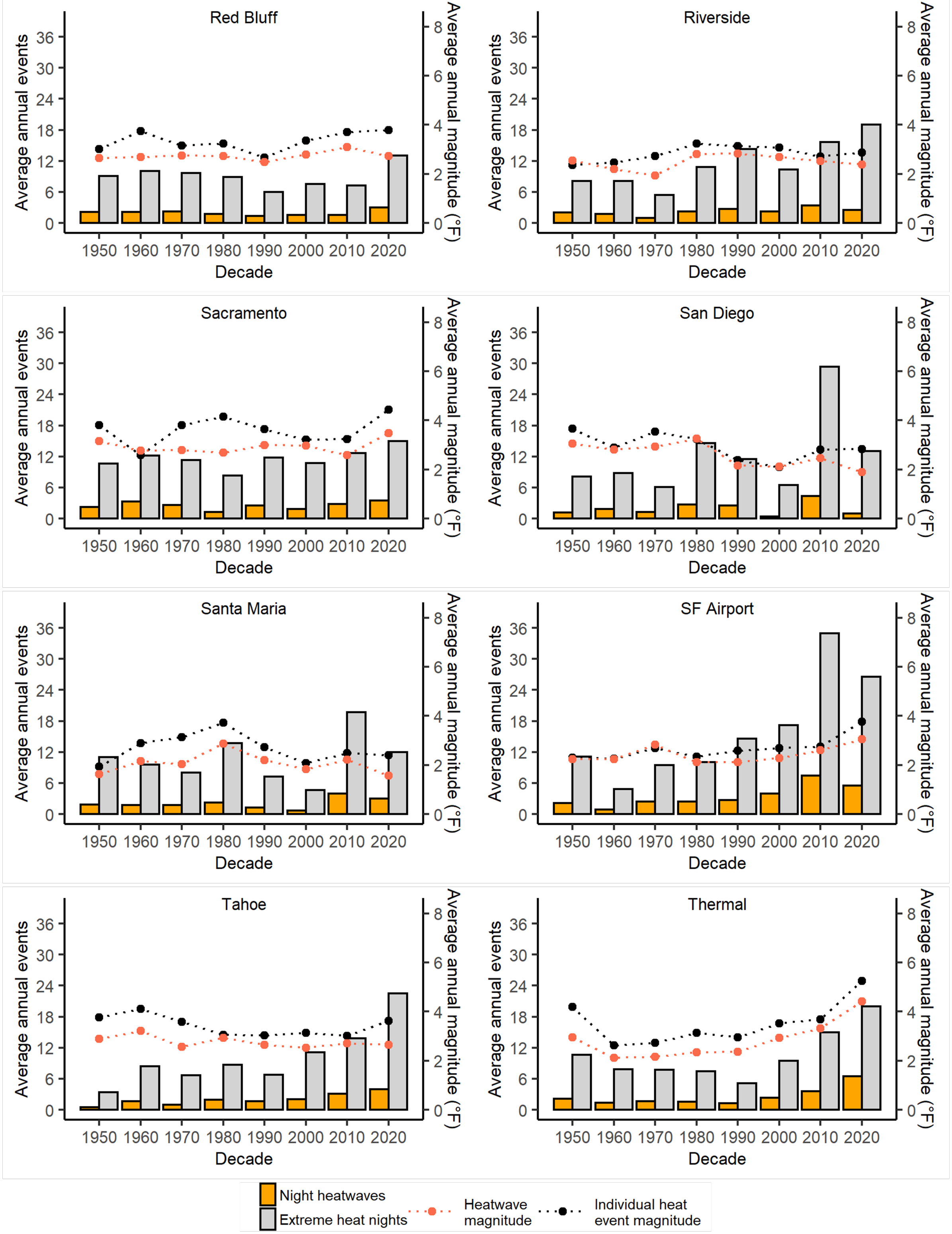


Figure 6. Nighttime extreme heat wave and extreme heat by decade at the selected locations



The average annual values for the number of nighttime heatwaves and extreme heat events (bars) and their magnitude (the sum of nightly exceedances above the historical threshold, in degrees Fahrenheit (°F)) (dots and lines) are presented for each station by decade. A nighttime heatwave is defined as two or more consecutive extreme heat nights at a given location. Note: Values for the "2020 decade" include data from 2020 and 2021.

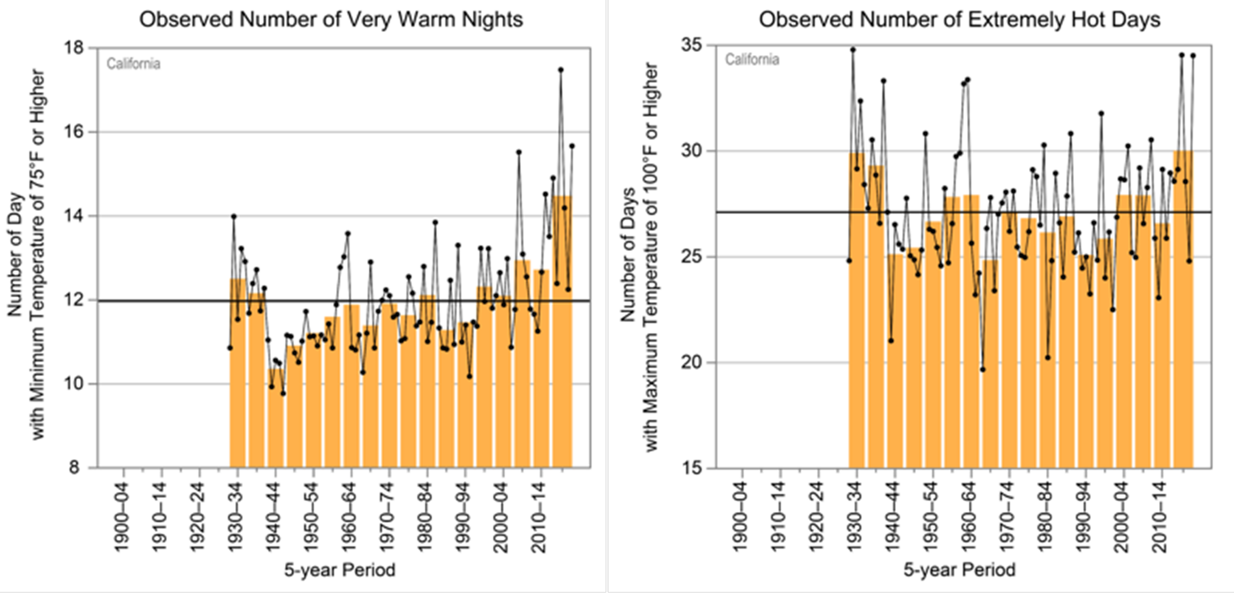
Figure 6, continued



Since 1950, the average number of daytime heatwaves per decade at each station has been relatively constant, ranging between 1 and 3 at most stations, however certain stations have experienced more frequent daytime heatwaves in the 2010s and in 2020/2021: Bishop, Blue Canyon, Edwards AFB, Red Bluff, and Thermal (Figure 5).

The magnitude of daytime heat waves shows no clear trends, although several stations experienced more intense heatwaves in 2020/2021 (Arcata, Bishop, Blue Canyon, Edwards Air Force Base, Red Bluff, Sacramento, San Francisco Airport, and Thermal). Several stations have recorded more frequent nighttime heat waves in the 2010s and in 2020/2021, including Bakersfield, Bishop, Blue Canyon, Edwards AFB, San Francisco Airport, Thermal, and Tahoe (Figure 6). Nighttime heatwave and extreme heat event magnitude are variable but appear to be increasing at San Francisco Airport and Thermal. In general, the magnitude of heat events and heatwaves are higher during the day than at night, but there are more nighttime extreme heat events and heat waves. For most of the stations, the magnitude and frequency of extreme heat events and of heatwaves are higher in the second half of the time series for both nighttime and daytime events.

Figure 7. Statewide number of extremely hot days and very warm nights


Observed Number of Very Warm Nights

Observed Number of Extremely Hot Days

Source: Figures 2a and 3 from Frankson et al., 2022

Left: Observed annual number of extremely hot days (maximum temperature of 100°F or higher) 1930 to 2020. Right: Observed annual number of very warm nights (minimum temperature of 75°F or higher). Dots show annual values. Bars show averages over 5-year periods (last bar is a 6-year average). The horizontal black lines show the long-term (entire period) averages: 27 days and 12 nights, respectively.

Statewide, the number of extremely hot days (Figure 7, right) – defined as days on which the maximum temperature was at or above 100°F – has been variable since

1930, both in terms of annual and five-year averages; the greatest number of hot days were observed during the 2015-2020 period, followed by 1930-1934. A more pronounced increase is evident in the number of very warm nights (Figure 7, left), when minimum temperatures were at or above 75°F. As with extremely hot days, the 2015-2020 period had the greatest number of very warm nights; numbers have exceeded the long-term average on all five-year periods since 1995-1999. Figure 7 is based on statewide analyses conducted by the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (Frankson et al., 2022).

Why is this indicator important?

Periods of extremely high temperatures have significant public health, ecological and economic impacts. Heat causes the most weather-related deaths in the United States (NOAA, 2021). Heat waves accompanied by high humidity are especially dangerous to human health. Humidity prevents surfaces from cooling down at night, leading to higher nighttime temperatures (Gershunov et al., 2009). People, animals (including household pets) and plants adapted to California's traditionally dry daytime heat and nighttime cooling are unable to recover from extreme heat, especially when humidity is high at night. Heat can accelerate the formation of ground-level ozone, and trap ozone, particulate matter and other harmful air pollutants (Peel et al., 2013). Temperature specifically is frequently the leading metrological driver to ozone formation (Nolte et al., 2018). Air pollution may also work in synergy with extremely high temperatures to increase adverse cardiovascular, respiratory and other health effects (Anenberg et al., 2020; see *Heat related mortality and morbidity* indicator).

Although warmer temperatures are likely to impact a range of individuals and populations, certain subgroups are at greatest risk of health impacts from extreme heat due to intrinsic factors (such as age and health status), greater likelihood of exposures, or less capacity for adaptive measures (such as access to air conditioning). These include the elderly, children, those with lower socioeconomic status, those who are socially, linguistically, or geographically isolated, or those who work in agriculture, construction, landscaping or other outdoor occupations (see *Heat related mortality and morbidity* and *Occupational heat-related illness* indicators).

Extreme heat impacts infrastructure and economies (LCI, 2021). Urban infrastructure is especially threatened by cascading effects of extreme heat stress on interdependent water, power, and transportation systems. High heat can deteriorate pavement, buckle railway tracks, and restrict aircraft operations. During hot weather, increased use of air conditioning and refrigeration increases electricity usage, thus straining the electrical grid (see *Cooling and heating degree days* indicator). Further, the increase in electricity generation to meet the demand for air conditioning during extreme heat events leads to increased emissions of nitrogen oxides (NO_x) (Abel et al., 2017; Peel et al., 2013). NO_x has been associated with decreased lung function, lung inflammation, asthma symptoms, and decreased immune response. It is also a precursor for ozone formation.

Water resources are strained during heat events due to increased domestic, industrial and agricultural demand. Extreme heat conditions can also influence tourism, such as in California's Coachella Valley, where it is projected that hotter temperatures will deter visitors and pose a major financial impact to the local economy (Yanez et al., 2020).

Agricultural systems across California and globally are experiencing the impacts of heat stress and decreased water supplies (Parker et al., 2020). Extreme heat exposure stresses plants and stunts development of agricultural crops, resulting in reduced quality and lower yields. Scientists fear that current heat adaptation practices such as enhanced irrigation and crop breeding may not be sustainable under future climate conditions. Heat stress also affects livestock by reducing weight gain or milk and egg production; in extreme cases, heat stress can lead to animal mortality (Walsh et al., 2020).

Climate scientists report that the Western United States has experienced a larger frequency of simultaneously occurring dry and hot years in recent decades (see *Drought* indicator). Multiple extreme events can amplify ecological and societal damages, as shown by the exceptionally dangerous wildfire seasons in recent years. For example, the Thomas fire in December 2017 and the Woolsey fire in November 2018, which caused tremendous devastation in four southern California counties, were both preceded by record-breaking heatwaves and extraordinarily dry autumn conditions (Hulley et al., 2020). A warming climate promotes concurrence of weather extremes, a higher risk of environmental disasters and greater reliance on emergency management and relief resources.

Heat events are projected to become more intense, more frequent, and longer lasting (IPCC, 2021). Taking action to mitigate and adapt to the impacts of extreme heat in California is critical, particularly given the largely preventable adverse effects on public health (LCI, 2021). Recognizing the need for a comprehensive, statewide approach to extreme heat, California is developing a strategic framework of state actions to adapt and build resilience to extreme heat (CNRA, 2021).

What factors influence the indicator?

The increased frequency and intensity of temperature extremes since pre-Industrial times is attributable to human-induced greenhouse gas emissions (IPCC, 2021). Some recent hot extreme events would have been extremely unlikely without human influence on the climate system. Regional patterns are influenced by feedback processes involving land-atmosphere interactions (for example, between soil moisture and evapotranspiration), local land use and land cover changes, aerosol concentrations, and El Niño-Southern Oscillation events and other large-scale modes of climate variability.

Air temperature varies according to the time of day, the season of the year, and geographic location. Urbanization can amplify the effects of global warming in cities, especially at night (the urban heat island effect). However, rural locations see comparable increases in extreme heat days and nights and all regions of California are affected by regional climate change (see *Annual Air Temperature* indicator). The asymmetric increase in nighttime California heat wave activity and extreme heat nights compared to daytime heat extremes is consistent with impacts expected under global climate change.

As air temperatures rise due to anthropogenic emissions of other greenhouse gases, the water vapor content of the atmosphere increases. Water vapor absorbs outgoing longwave terrestrial radiation and re-radiates energy back to the surface, thus impeding radiative cooling. Therefore, there is less nighttime respite from heat when specific humidity is high. Moreover, humid heat waves tend to last longer due to the stronger coupling of maximum and minimum temperatures during humid heat waves (Gershunov et al., 2009).

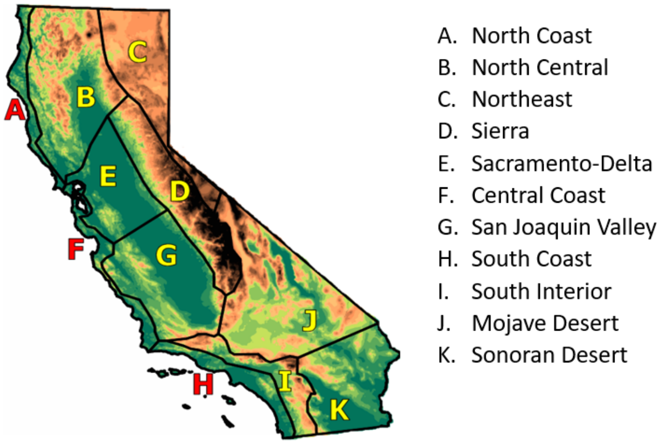
Technical considerations

Data characteristics

This indicator uses station data from Hadley Integrated Surface Dataset (HadISD) global record, hosted by CalAdapt, and station data from the National Oceanic and Atmospheric Administration's (NOAA) Regional Climate Centers (RCCs) cooperative observation network acquired from the Applied Climate Information System (ACIS). The stations using the RCC-ACIS data include: Blue Canyon, Bishop, Tahoe, and Thermal, all the other data used here are from the CalAdapt dataset. Both the RCC-ACIS and HadISD datasets have gone through quality control checks.

At least one station from each of California's climate regions, preferably those located in large urban centers, was selected for the analysis. The climate regions are shown in Figure 8. Only stations with NOAA complete records were used in the analysis. All stations have data starting from at least 1950, except for Santa Maria where data are available starting in 1954. Trends were calculated using the Mann-Kendall analysis.

Figure 8. California's Climate Regions



Source: WRCC, 2017

Strengths and limitations of the data

The datasets hosted on CalAdapt consist of hourly observed historical station datasets with at least 30 years of observations from the HadISD global record. The HadISD dataset is compiled from NOAA's Integrated Surface Database, which is a collection of highly quality-controlled weather data from various data sources. The RCC-ACIS (or SCENIC) dataset is comprised of station data containing minimum and maximum daily temperature. RCC-ACIS station data pulls weather information from various networks such as the Cooperative Observer Program (COOP) and the Weather-Bureau-Army-Navy (WBAN). The vast majority of the COOP observers are trained volunteers, and the network also includes the National Weather Service (NWS) principal climatological stations. The observing equipment used at all the stations, whether at volunteer sites or federal installations, are calibrated and maintained by NWS field representatives, Cooperative Program Managers, and Hydro-Meteorological Technicians.

The station data have received a high measure of quality control through computer and manual edits, and are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations. Station coverage is not uniformly distributed geographically, and a limited number of stations were analyzed. Recorded temperatures in urban areas can also be affected by the urban heat island effect due to land surface modification and other human activities. Since most of California's population resides in urban areas, heat impacts from urban-induced warming on health are significant. Quantification of the specific magnitudes of station-based urban heat contributions are beyond the scope of the present study but are the subject of ongoing research.

OEHHA acknowledges the expert contribution of the following to this report:

Western Regional Climate Center

Benjamin Hatchett, Ph.D.
Desert Research Institute
Western Regional Climate Center
Benjamin.Hatchett@dri.edu
(775) 674-7111

Michael L Anderson, Ph.D., P.E.
State Climatologist
California Department of Water Resources
michael.l.anderson@water.ca.gov
(916) 574-2830

References:

Abel D, Holloway T, Kladar RM, Meier P, Ahl D, et al. (2017). Response of Power Plant Emissions to Ambient Temperature in the Eastern United States. *Environmental Science & Technology* **51**(10): 5838-5846.

Alizadeh MR, Adamowski J, Nikoo MR, AghaKouchak A, Dennison P, et al. (2020). A century of observations reveals increasing likelihood of continental-scale compound dry-hot extremes. *Science Advances* **6**: eaaz4571.

Cal-Adapt (2018). Cal-Adapt website developed by University of California at Berkeley's Geospatial Innovation Facility under contract with the California Energy Commission. Data derived from the HadISD global record. Retrieved December 16, 2021.

CCSP (2008). *Analyses of the Effects of Global Change on Human Health and Welfare and Human Systems. Final Report, Synthesis and Assessment Product 4.6. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research.* U.S. Climate Change Science Program.

CEDA (2020). Met Office Hadley Centre; National Centers for Environmental Information - NOAA (2020): HadISD: Global sub-daily, surface meteorological station data, 1931-2019, v3.1.0.2019f. Centre for Environmental Data Analysis. Retrieved August 31, 2021.

CNRA (2021). *2021 California Climate Adaptation Strategy, Extreme Heat Framework*. California Natural Resources Agency and the Governor's Office of Planning and Research.

Dunn RJH (2019). *HadISD version 3: monthly updates, Hadley Centre Technical Note.*

Forster P, Ramaswamy V, Artaxo P, Bernsten T, Betts R, et al. (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon S, Qin D, Manning M, Chen Z, Marquis M, et al. (Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Frankson R, Stevens LE, Kunkel KE, Champion SM, Easterling DR, et al. (2022): *California State Climate Summary 2022. NOAA Technical Report NESDIS 150-CA.*

Gershunov A, Cayan DR and Iacobellis SF (2009). The Great 2006 Heat Wave over California and Nevada: Signal of an Increasing Trend. *Journal of Climate* **22**(23): 6181–6203.

Guirguis KJ and Avissar R (2008). A precipitation climatology and dataset intercomparison for the western United States. *Journal of Hydrometeorology* **9**(5): 825-841.

Hausfather, Z, Menne MJ, Williams CN, Masters T, Broberg R and Jones D (2013). Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records. *Journal of Geophysical Research: Atmospheres* **118**: 481-494.

Heinzerling A, Laws RL, Frederick M, Jackson R, Windham G, et al. (2021) Risk factors for occupational heat-related illness among California workers, 2000–2017. *American Journal of Industrial Medicine* **63**(12): 1145-1154.

Hulley GC, Dousset B, and Kahn BH (2020). Rising trends in heatwave metrics across Southern California. *Earth's Future.* **8**: e202 0EF001480.

IPCC (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Masson-Delmotte VP, Zhai A, Pirani SL, Connors C, Péan S, et al. (Eds.). Cambridge University Press. In Press.

LCI (2021). *Adapting to Extreme Heat in California: Assessing Gaps in State-Level Policies and Funding Opportunities.* UCLA Luskin Center for Innovation.

Maurer EP, Wood AW, Adam JC, Lettenmaier DP and Nijssen B (2002). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. *Journal of Climate* **15**(22): 3237-3251.data updated to 2010

NOAA (2021). National Oceanic and Atmospheric Administration, National Weather Service: Weather Related Fatality and Injury Statistics. Retrieved December 31, 2021.

Nolte CG, Dolwick PD, Fann N, Horowitz LW, Naik V, et al. (2018). Air Quality. *In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, et al. (Eds.). U.S. Global Change Research Program, Washington, DC, USA, pp. 512–538.

Parker LE, McElronec AJ, Ostojaa SM and Forresteld EJ (2020). Extreme heat effects on perennial crops and strategies for sustaining future production. *Plant Science* **295:** 110397.

Peel JL, Haeuber R., Garcia V, Russell AG and Neas L (2013). Impact of nitrogen and climate change interactions on ambient air pollution and human health. *Biogeochemistry* **114**(1–3): 121–134.

RCC-ACIS (2021). Regional Climate Centers - Applied Climate Information System. "Applied Climate Information System." NOAA Regional Climate Centers, Retrieved December 16, 2021.

Richman MB and Lamb PJ (1985). Climatic Pattern Analysis of Three- and Seven-Day Summer Rainfall in the Central United States: Some Methodological Considerations and a Regionalization. *Journal of Climate and Applied Meteorology* **24**(12): 1325-1343.

USGCRP (2016). *Chapter 2: Temperature-Related Death and Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. US Global Change Research Program.

Walsh MK, Backlund P, Buja L, DeGaetano A, and Melnick R (2020). *Climate Indicators for Agriculture.* USDA Technical Bulletin 1953. Washington, DC.

Yañez CC, Hopkins FM and Porter WC (2020). Projected impacts of climate change on tourism in the Coachella Valley, California. *Climatic Change* **162:** 707–721.