**Title and Subtitle:**
Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions - Hawaii Region

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**Abstract:**
To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Hawaii Region, is part of a series of twenty-one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

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**Water Resources Region 20: Hawaii Region**

1. **Introduction**

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities and making decisions that affect resources, programs, policies and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty-one regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of the 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii and Puerto Rico. The twenty-one Water Resources Regions included in this series of reports is shown in Figure 1.1 along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions and regional vulnerability assessment tools.

This report focuses on Water Resources Region 20, the Hawaii Region, the boundaries for which are shown in Figure 1.2. The Honolulu District covers Water Resources Region 20.
Figure 1.1. 2-digit Water Resources Regional Boundaries for the Continental United States, Alaska, Hawaii and Puerto Rico.
Figure 1.2. Water Resources Region 20: Hawaii Region Boundary.
1.1 A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUC (Water Resources Region) and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Regional scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 20, both the 2-digit and 4-digit HUC boundaries are shown in Figure 1.2.
2. **Observed Climate Trends**

Observed climate trends within Water Resources Region 20 are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014) this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth’s climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed the reader is referred to the specific references cited, including the third National Climate Assessment (NCA), which includes not only regional assessments, but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the Hawaii Region or to individual islands were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic region revealed additional, secondary, climatic variables that have been studied such as drought indices and soil moisture.

The results presented below indicate an upward trend in temperature in the Hawaii Region, in urbanized areas or areas at high elevation, but the degree of warming is uncertain based on existing literature. Studies on precipitation and streamflow for the study area show a general decrease, but do exhibit spatial and temporal climate variability across the Hawaii Region. The effects of the El Niño Southern Oscillation (ENSO) and other patterns of oceanic and atmospheric variability are significant. They include large variations in sea surface temperatures (SST), the strength and persistence of the trade winds, the position of jet streams and storm tracks and the intensity of rainfall (Leong, 2014). ENSO is a multi-year climatological phenomenon that affects temperature and precipitation, among other variables, in the Pacific Ocean and has consequences for climate patterns around the world. The Pacific Decadal Oscillation (PDO) is a long-lived El Niño-like pattern of Pacific climate variability that shifts phases on a multi-decadal scale, usually 20 to 30 years (Eversole et al., 2014).

**2.1. Temperature**

A limited number of studies focusing on observed trends in historical temperatures were reviewed for this report. Many national studies were performed for the contiguous U.S. and therefore, were not relevant to Water Resources Region 20. Regional or local studies were
focused more specifically and exclusively on the region. Results from the studies are discussed below.

The study by Kunkel et al. (2008) in support of the U.S. Climate Change Science Program evaluated weather and climate extremes, specifically for Hawaii, in a synthesis and assessment study. The study concluded that the number of very warm nights has increased by 10 or more per year for Hawaii from 1950 to 2004. The study is not statistically significant at the $p = 0.05$ level.

Different islands in the Pacific Ocean will be affected by different factors, including natural variability patterns that affect storms and precipitation, as well as climate trends that are strongly influenced by specific geographic locations. The third National Climate Assessment (NCA) report chapter specific to Hawaii (Leong et al., 2014) states that surface air temperature in Hawaii has increased and at a greater rate at high elevations. The author found that both air and sea surface temperatures have risen. The section of the NCA that discusses U.S. temperature trends (Walsh et al., 2014) also concludes that temperature changes over the past 22 years (1991-2012), compared to the 1951-1980 average for Hawaii, indicate an increasing trend since the 1960s (Figure 2.1).

![Figure 2.1.](image)

**Figure 2.1.** Average temperature changes by decade for 1901-2012 (relative to 1951-1980) for Hawaii. The far right bar (2000s decade) includes 2011 and 2012. The period from 2001 to 2012 is warmer than any previous decade (Walsh et al., 2014).

The foundation of the temperature findings is based on a study performed by Giambelluca et al. (2008). The author evaluated temperature changes in the Hawaiian Islands for approximately the past 85 years based on an index of 21 temperature stations, a comprehensive analysis deriving a Hawaii Temperature Index (HTI). Results show a relatively rapid rise in surface temperature in approximately the past 30 years, with stronger warming at higher elevations. For each station, annual anomalies were calculated as departures from the respective 1944-1980 mean. Average surface temperature anomalies were calculated using time series from monthly state data after removing the calendar month means and averaging it into calendar years (Figure 2.2). The smoothed curve is the annual data filtered with the seven year running mean. Linear trends were computed for two periods: 1919-2006 and 1975-2006. The latter period emphasizes the enhanced level of global warming documented by the Intergovernmental Panel on Climate Change (IPCC).
Figure 2.2. Average surface temperature anomalies in Hawaii (top) all stations, (middle) at lower elevation stations located at <800 meters and (bottom) at higher elevation stations located at >800 meters. Error bars show +0.5 standard deviations, thick lines show a seven-year running mean and asterisk indicate slopes significant at \( p = 0.05 \) (Giambelluca et al., 2008).

Giambelluca et al. (2008) also examined trends in mean daily maximum temperature (\( T_{\text{max}} \)) and minimum (\( T_{\text{min}} \)) temperatures and the associated changes in the diurnal range. \( T_{\text{max}} \) is found to have no significant long-term (1919-2006) warming or cooling trends for annual, summer, or winter periods, except for high-elevation and non-urban stations during winter, which has moderate warming trends. Data analysis for \( T_{\text{min}} \), however, has indicated significant long-term and recent increases for both elevation ranges and both seasons with the exception of low-elevation stations during the summer. Remarkably steep increases in \( T_{\text{min}} \), approaching 0.5°C/decade (0.9 °F/decade) are evident since 1975 at higher elevations. These changes imply a decrease in the daily temperature range. For annual mean temperature, there is an increase in 0.27 °C/decade (0.49 °F/decade) at higher elevations compared to 0.09 °C/decade (0.16°F/decade) at lower elevation sites. Temperature variation appears to be tightly coupled to the PDO, perhaps through regional SST variation.

Diaz et al. (2011) found consistency with previous studies showing warming trends, especially evident at high elevations. The authors illustrated changes in the vertical profiles of annual mean temperature and specific and relative humidity for the period 1958 through 2009 and spatially averaged. Linear trends were fitted to the annual values from twice-daily averages. The authors document a decrease in the frequency of occurrence of freezing temperatures in the upper slopes of the higher terrain in Maui and the Island of Hawaii and a concomitant rise in freezing level surface in the region, which suggest a warming throughout the lower troposphere in the region of
the Hawaiian Islands. An approximately 50-year record of nearshore SST exhibits a strong warming trend that exceeds the value recorded over open ocean areas away from the islands.

Since 1958, observations at the Mauna Loa Observatory establish a systematic increase of anthropogenic CO$_2$ in the atmosphere. Hourly temperature records were examined to determine linear trends as a function of the time of day (Malamud et al., 2011). The temperature records were averaged annually for 1977-2006. The authors concluded that there is a near-uniform warming of 0.04 °C/year (0.07 °F/year) at night and a slight cooling of -0.014 °C/year (-0.0252 °F/year) at 12:00 noon local time. Systematic temperature change depends on the time of day. Overall, at the Mauna Loa Observatory, there is a mean warming trend of 0.021 °C/year (0.04 °F/year). The dominance of nighttime warming results in a relatively large annual decrease in the diurnal temperature range.

On Oahu, island-wide minimum temperature has increased by 0.17 °C/decade (0.31 °F/decade) (Safeeq et al., 2013). Trends in minimum and maximum temperatures were evaluated for two time periods: the past 39 years (1969-2007) and the past 25 years (1983-2007). The year 1983 is identified as the change point in the island-wide minimum temperature. There is no detectable trend found in maximum temperature over the same time period. At two of the evaluated stations, long-term trends from the past 39 years indicated a highly significant annual and seasonal warming ($p \leq 0.05$) in $T_{\text{min}}$. Both of these locations are located in highly urbanized leeward areas of Honolulu. The warming rates across all stations varied substantially and spatially (Figure 2.3). For $T_{\text{max}}$, long-term trends showed non-significant warming and cooling in the five long-term stations on Oahu.

![Figure 2.3](image)

**Figure 2.3.** Spatial variability of the magnitude of annual minimum temperature trends and their levels of significant during 1983-2007. Upward (downward) hollow triangles indicate positive (negative) direction of trends and their size corresponds to the magnitude of trends. Black triangles indicate trends significant at $p \leq 0.05$ (Safeeq et al., 2013).
Key point: A general consensus amongst peer-reviewed literature indicates an apparent warming in the region. Minimum temperatures are increasing, especially in urban areas. Changes in maximum temperatures are not well studied.

2.2. Precipitation

For extreme precipitation trends, the third NCA report also discusses potential changes in the U.S. climate (Walsh et al., 2014; adapted from Karl, 2009). The study concludes an observed change in very heavy precipitation (defined as the heaviest 1% of all daily events) from 1958 to 2012 decreased by 12% (Figure 2.4). However, the trends are not larger than the natural variations in climate in Hawaii. The NCA report also details changes across the U.S. of average annual precipitation. Unlike other parts of the U.S., precipitation since the 1970s has decreased in Hawaii by over 15% in the last decade (Figure 2.5).

![Observed Change in Very Heavy Precipitation](image)

**Figure 2.4.** Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1% of all daily events) from 1958 to 2012 for each region of the continental United States (Walsh et. al, 2014; updated from Karl et al., 2009).
The U.S. Geological Survey performed an extensive analysis on long-term trends and variations in streamflow on the islands of Hawaii, Maui, Molokai, Oahu and Kauai, where long-term stream gaging stations exist (Oki, 2004). For the study, information related to streamflow, rainfall and regional climate indices were used to evaluate trends and variations. To determine whether the downward trends in rainfall extend to the period before 1913, annual rainfall data for the period 1893 to 2001 were analyzed (Figure 2.6). Annual rainfall is detected at 23 of the stations evaluated. Statistically significant downward trends in annual rainfall were detected at two sites in northeastern Maui; a statistically significant upward trend is detected at one site near the northern part of the island of Hawaii. Although rainfall trends commonly were downward during the 89-year period from 1913 to 2001, over the 109-year period 1893 to 2001, significant trends were much less common. The authors performed a series of similar analyses for shorter periods from 1933 to 2001 (70 years), 1953 to 2001 (50 years), and 1973 to 2001 (30 years). The percentage of statistically significant trends in rainfall for the period 1973 to 2001 is much lower than for the period 1913 to 2001. However, trends in rainfall based on a few decades of data may not be representative of long-term conditions for a given location. Furthermore, detection of patterns in trends over time scales of a few decades may be confounded by high spatial and temporal variability. Interpretation of trend patterns from short-term rainfall may be uncertain. Patterns in long-term trends in rainfall may be highly dependent on the time period selected for analysis.

The author concludes that short-term variability in streamflow is related to ENSO and this relation may be partly modulated by PDO. The ENSO phenomenon occurs at a relatively short time scale (years, not decades), and more closely corresponds with variations in direct runoff than variations in baseflow. The authors also found a nearly statewide positive correlation during periods of positive PDO phase of winter (January to March) streamflow and Southern Oscillation Index (SOI) during the previous 0 to 9 months. The positive correlation indicate that streamflow during the winter months tends to be low following El Niño periods and high during La Niña periods, particularly during the positive PDO phases. Similar relationships were observed during the spring (April to June), but during summer (July to September) and fall (October to December) the relationships were negatively correlated or less defined. The correspondence of ENSO and PDO with flow characteristics is also not always spatially consistent.
Figure 2.6. Trends in annual rainfall during 1893-2001. Indicated slopes are normalized by dividing the mean annual rainfall during the specified period. Stations shown have annual-rainfall values (calendar year) for at least 90 percent of the years over the indicated period (Oki, 2004).

Chen and Chu (2014) studied trends of annual maximum 1-day precipitation at 24 stations on Oahu, Maui and Hawaii for the period 1960 to 2009. The purpose of the study is to investigate whether precipitation extremes in Hawaii have changed with time. The study evaluates the trends based on a nonparametric Mann-Kendall method and Sen’s test in addition to a non-stationary, three-parameter generalized extreme value (GEV) distribution to detect trends in precipitation extremes. Both methods indicate that there are negative precipitation trends for Oahu and Maui, but positive trends that dominate the Island of Hawaii (Figure 2.7). Downward trends are displayed at all of the eight stations on Oahu and all of the eight stations on Maui. Consistent downward trends from the precipitation stations on both islands indicate that urbanization is not likely a cause of a change in precipitation extremes. A positive relationship is found between the precipitation extremes and SOI, implying greater extreme events during La Niña years and the opposite for El Niño years.
Figure 2.7. Spatial pattern of trends for (a) location parameter $\mu_1$ and $\sigma_1$ for 1-day maximum precipitation according to non-stationary GEV distribution. Triangles denote the locations of the individual stations. Upward (downward) triangles indicate positive (negative) direction of change and their size corresponds to the magnitude of trends. Black triangles indicate trends significant at the 5% level. Field significance is reached for Oahu in both (a) and (b) (Chen and Chu, 2014).

The return-level threshold values are found to considerably change with time. The study evaluates the trends associated with the 2-, 20-, and 100-year return levels. Negative trends dominate on Oahu and Maui, while positive trends prevail on the Island of Hawaii. As a result, a rare storm with daily precipitation of 300 mm (20-year return period) in 1960 has become a rather common storm event (3- to 5-year return period) in 2009 on the Island of Hawaii. The opposite trend behavior in extreme events is observed on Oahu and Maui, where rainfall extremes have become less frequent in the last five decades (Chen and Chu, 2014).

In a similar study evaluating changes in precipitation extremes, Chu et al. (2010) evaluated four different climate indices: simple daily intensity index (SDII), total number of days with precipitation $\geq$25.4 mm (R25), annual maximum consecutive 5-day precipitation amount (R5d) and the fraction of annual total precipitation from events exceeding the 1961-1990 95th percentile (R95p) and consecutive dry days (CDD). Two different epochs were analyzed (1959-1979 and 1980-2007). The authors conclude that after the 1980s, there has been a change in the types of precipitation intensity, resulting in more frequent light precipitation and less frequent moderate and heavy precipitation intensity. Both Kauai and Oahu are dominated by long-term decreasing trends of the four precipitation-related indices, while increasing trends are evident on the Island of Hawaii.
Mair and Fares (2010) investigated the spatio-temporal relationship between groundwater, streamflow and rainfall for a small Hawaiian watershed: the Makaha Valley on the leeward coast of Oahu. They evaluated daily rainfall data from three long-term rain gages of varying elevations and distances from a mountain ridgeline were used in the analysis. Length of record varied from 21 to 49 years. None of the rainfall time series showed statistically significant trends over the entire record; however, significant decline since 1979 is indicated. Although the shorter evaluation periods have reduced statistical significance, they do indicate that rainfall has declined in the upper valley and headwaters over the past 30 years. Results from the study imply that recent rainfall decline has occurred more rapidly at higher elevations. Trends in rainfall frequency and rainfall intensity were examined in the study. Among the three stations, both upward and downward trends in rainfall frequency and intensity were seen. Variations in seasonal rainfall and rainfall intensity were examined, but no consistent, statistically significant trends were found.

In a study evaluating rainfall changes in Hawaii over the last century, Diaz et al. (2005) concluded that there has been a strong decline, which approximately coincides with the mid-1970s climate change in the Pacific Ocean, as depicted by tropical SST. Serially complete monthly rainfall totals for the 50-year period 1951 to 2000 were obtained, principally from the National Climatic Data Center, for 132 stations across the majority of the Hawaiian Islands (Hawaii, Maui, Oahu, and Kauai). The authors used cluster analysis to identify seasonal rainfall regimes of each island as well as important features of the interannual variability. Seasonal variation in precipitation were divided into cool (November to April) and warm (May to October) months (Figure 2.8). A decline in precipitation is evident in the last 15 years or so, amounting to about a 15% decline from the long-term mean.

Figure 2.8. Precipitation time series (1920-2003) averaged over the Hawaiian Islands (in inches). Values are in percent departures from a 1951-2000 mean (Diaz et al., 2005).
A study by Timm et al. (2011) investigates how the frequency of heavy rainfall events (95% quantile in the rainfall distribution) has varied in the last 50 years in Hawaii during the wet season (October-April). The time period between 1958 and 2005 is found to be most suitable because of data availability and homogeneity. Twelve stations with daily reports of rainfall amounts were used to count the number of heavy rain days during wet seasons. A multiple linear regression (MLR) model indicated that the Pacific/North American pattern and the Southern Oscillation indices can explain the significant interannual to interdecadal variability and trends for 9 out of the 12 stations, five of which were statistically significant, in addition to the variability associated with the number of heavy rain events. The MLR model demonstrates a trend toward fewer heavy rain events in the years after the Pacific climate shift in the mid-1970s. The negative trend is widespread across the islands (Figure 2.9).

![Figure 2.9](image)

**Figure 2.9.** (Top) average number of heavy rainfall events in the observations (corrected for missing data). The mean of the number of events during 1958-1976 (left color) vs. the mean of the number of events during 1977-2005 (right color). (Bottom) Same as the top panel, but displays the MLR model estimates of the mean number of heavy rainfall events (Timm, 2011).

*Key point: A general consensus amongst recent peer-reviewed literature indicates an overall decrease in annual rainfall and fewer heavy rain events since the 1970s. Spatial and temporal anomalies have been studied and have indicated a decrease in precipitation intensity on Oahu and Maui, but an increase on the Island of Hawaii.*
2.3. Hydrology

Many of the existing streamflow or hydrologic studies related to climate change have focused on the continental U.S. and did not include the Hawaii Region. However, the U.S. Geological Survey performed a comprehensive analysis on long-term trends and variations in streamflow on the islands of Hawaii, Maui, Molokai, Oahu and Kauai, where long-term stream gaging stations exist (Oki, 2004). For the study, information related to streamflow, rainfall and regional climate indices were used to evaluate trends and variations for 16 stream gage stations on the islands of Hawaii, Maui, Molokai, Oahu, and Kauai. Oki (2004) discuss the causation of changes in streamflow related to global climate variables. In general across the Hawaii Region, a decrease in overall streamflow trends is observed.

- From 1913 to 2002 baseflows generally decreased in streams for which data are available, and this trend is consistent with the long-term downward trend in annual rainfall during that period. Trends in the median and lower flows were statistically significant at the 5% level of significance.
- Trends in the higher flows, as indicated by the annual Q10 (streamflow is as high as this only 10% of the time), Q25 (streamflow is as high as this value only 25% of the time), and mean total flows, also generally were downward, although the trends were statistically significant (5% level of significance) at only one of the seven stations. Trends in the median and lower total flows are consistent with the statistically significant downward trends in annual baseflow percentiles at all seven stations, as well as the statistically significant downward trends in minimum 1-, 7-, and 30-day mean flows at five of the seven stations.
- Monthly mean baseflows generally were above the long-term average from 1913 to the early 1940s and below average after the early 1940s to 2002, and this pattern is consistent with the detected downward trends in baseflows from 1913 to 2002.
- From 1973 to 2002, trends in streamflow were spatially variable (up in some streams and down in others) and, with a few exceptions, generally were not statistically significant.

Mair and Fares (2010) investigated the spatio-temporal relationship between groundwater, streamflow and rainfall for a small Hawaiian watershed: the Makaha Valley on the leeward coast of Oahu. Results of this study confirm that trends in total flow (-5.4 mm/year) and base flow (-1.7 mm/year) were significantly downward from 1960 to 2008. The downward trend in streamflow began occurring as early as 1991 and is largely evident throughout much of the year by 1995. The greatest declines in total flow and base flow occurred from June to October. Near perennial streamflow conditions were recorded before 1994 with a mean of nine days/year of zero-flow, which then increased to a mean of 157 days/year from 1994 to 2008.

More recently, Bassiouni and Oki (2013) conducted a study evaluating changes in streamflow and baseflow (groundwater discharge to streams) in Hawaii during the past century. Statistically significant long-term (1913-2008) downward trends were detected (using the nonparametric Mann-Kendall test) in low streamflow and baseflow records. The downward shift corresponds to a decrease of 22% in median streamflow and a decrease of 23% in median baseflow between the periods 1913-1943 and 1943-2008. The shift coincides with other local and regional factors, including a change from a positive to a negative phase in the PDO, shifts in the direction of the trade winds over Hawaii, and a reforestation program.
Key point: There are limited studies for observed hydrologic trends. The studies that do exist are in general consensus that there is a long-term, downward trend in baseflows and total flows in streams. The detected shift and long-term trends reflect region-wide changes in climatic and land-cover factors.

2.4. Summary of Observed Climate Findings

The general consensus in the recent literature points toward an increase in annual and monthly average temperatures in the Hawaii Region over the past century. Most of the studies indicated an increase in average temperatures at night and a slight increase in temperatures during the day. An overall warming trend is detected across all studies. Areas of higher elevation and potentially those in urban areas experienced a greater rate of increasing temperatures. Temperature variations appears to be tightly coupled to the PDO and changes in SST.

There are spatial and temporal variations in precipitation trends within the Hawaii Region. Across the entire region, average precipitation and precipitation falling heavy events has decreased since the 1970s. The findings of these studies were not always statistically significant. Regarding precipitation extremes, more spatial variability is encountered. Decreases in precipitation trends exist on Oahu and Maui, but positive trends are found on the Island of Hawaii. Multiple studies found that Oahu and Maui exhibit one trend, which is the opposite of the trend found on the Island of Hawaii. Changes to precipitation, similar to variations in temperature, appear to be coincident with changes to the PDO and global climate patterns.

Long-term hydrologic responses to climate change have not been extensively studied for the region. A limited number of studies were evaluated; however, those that were evaluated indicate that there is a long-term decreasing trend in baseflow of streams. Trends in both median and lower flows were decreasing. Since the 1970s, trends in streamflows are spatially variable across the region. High variability is due to cyclical climate patterns such as ENSO and the PDO (Leong et al., 2014).

3. Projected Climate Trends

While historical data is essential to understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2005). Consequently, the scientific and engineering communities have begun using computer models of the Earth’s atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed global climate models (GCMs), are widely accepted as representing the best available science on the subject and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Hawaii Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships.
between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth’s climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of “climate futures” so each study’s assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA, which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin-scale water resources management decisions. These data and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate a strong consensus in the scientific literature that air temperatures will trend upward over the next century in the Hawaii Region. There is less consensus on the future trending, or lack thereof, in precipitation and streamflow in the region. The studies that include both climate variables suggest that temperature changes will outweigh other factors such as changes in precipitation.

3.1. Temperature

GCMs have been used extensively to project future climate conditions across the country. At a national scale, model projections generally show a significant warming trend throughout the 21st century, with a high level of consensus across models and modeling assumptions. Results of studies inclusive of the Hawaii Region typically fall in line with this generalization.

The physical climate framework for the 2013 NCA report is based on climate model simulations of the future using the high (A2) and low (B1) emissions scenarios. The future regional climate scenarios are based on the global climate model from Phase 3 of the Coupled Model Intercomparison Project (CMIP3). CMIP3 multi-model mean analyses are provided for the periods of 2021-2050, 2041-2070, and 2070-2099. Each model’s data is first regredded to a common grid of approximately 2.8 degrees latitude (~190 miles) by 2.8 degrees longitude (~130-170 miles) (NOAA/NESDIS, 2013). Air temperature has increased and is expected to rise over the entire region, especially in areas at high elevations. In the third NCA report’s chapter specific to Hawaii and the U.S. affiliated Pacific Islands, Leong et al. (2014) describes that the projected increases in regional average temperature ranges from 1.5 °F (0.83 °C) by 2055 (relative to 1971-2000) under a scenario of substantial emissions reduction (B1) to 3.5 °F (1.9 °C) assuming continued increases in emissions (A2). Walsh et al. (2014) using similar models projected an increase in temperatures ranging from 3 °F to 5 °F (1.7 °C to 2.8 °C) for the two scenarios as shown in Figure 3.1.
The NCA report also discusses U.S. temperature trends (Walsh et al., 2014) associated with more recent model projections due to climate change. The results expand on the range of future scenarios and are consistent with older model results presented above. The most recent model projections (from Phase 5 of the Coupled Model Intercomparison Project, [CMIP5]) take into account a wider range of options with regard to human behavior, including a lower greenhouse gas emissions scenario than has been considered before (RCP 2.6). Depending on the scenario, the projected change in average temperature in the later part of the 21st century (2071-2099) relative to the last part of the last century (1970-1999) indicate an increase in temperatures between 3 °F (1.7 °C) for the RCP 2.6 scenario to 6 °F (3.3 °C) for the RCP 8.5 scenario, which represents emissions continuing to rise throughout the 21st century.

Regionally, the Weather Research and Forecasting (WRF) model is configured for the Hawaii Region to assess the usage of different warming increments from CMIP5. The simulations show that, despite large inter-experiment spread, a single downscaling experiment using multimodal mean warming increments give similar results to the ensemble mean from ten individual CMIP5 models. These methods were compared and tested for uncertainties. The simulations also show that changes of the projected climate by the end of the 21st century (2090-2099) in the Hawaii Region include an increase in 2-meter temperatures with stronger warming at higher elevations, a large increase in precipitable water, and an increase in the number of days with a trade wind inversion (Lauer et al., 2013). Statistical significance related to these climate projections were not discussed in the study.

As part of efforts through the U.S. Global Change Research Program in support of the National Climate Assessment, possible future climate scenarios were evaluated and summarized for the Hawaii Region. The CMIP3 simulations indicate a statistically significant increase in annual...
mean temperature for three time periods through the end of the 21st century. Spatial variations across the region are relatively small (Keener et al., 2013). Under the B1 (low) scenario, by the end of the 21st century, annual mean temperatures are projected to increase by 2 °F (1.1 °C). Under the A2 (high) scenario, annual mean temperatures are projected to increase by 5 °F (2.8°C) as shown in Figure 3.2.

![Simulated Change in Annual Mean Temperature](image)

**Figure 3.2.** Projected changes in annual mean temperature (°F) between 2021-2099 for the A2 (high emissions) scenario (left) and B1 (low emissions) scenario (right) (Keener et al., 2013).

*Key point: Strong consensus exists in the literature that projected temperature will increase in the study area, but to varying degrees of warming over the next century dependent upon the climate scenario. Surface air temperatures are highly dependent on changes to sea surface temperatures and trade wind inversions.*

### 3.2. Precipitation

In order to simulate future climate change, global climate models need to accurately represent observed climate. The third NCA report chapter on Hawaii (Leong et al., 2014) concludes that precipitation trends are variable in the Hawaii Region and that it is equally difficult to project the magnitude of precipitation changes. For later this century, projections from global models for the region give a range of results. Generally, they predict annual rainfall to either change little or to increase by up to 5% for the main Hawaiian Islands and to change little or decrease up to 10% in the northwestern Hawaiian Islands, although there is low confidence in these projections. Different islands will be affected by different factors, including natural variability patterns that affect storms and precipitation (like El Niño and La Niña events), as well as climate trends that are strongly influenced by specific geographic locations.
The NCA report (Walsh et al., 2014) further distills projections using the A2 (higher) emissions scenario to evaluate potential changes by season. For the Hawaii Region, the winter and spring seasons are projected to have little to no change. However, the summer and fall seasons are projected to increase between 10 and 30%. The projected changes were not statistically significant for the region.

For the IPCC 4th Assessment Report, the middle-of-the-road (A1B) emissions scenario, Timm and Diaz (2009) analyzed six models to investigate changes in wind fields around Hawaii in the late 21st century and the effects on mean seasonal rainfall. Two models clearly indicate opposite findings in the anomalies. One model projects an increase of 20-30% in rainfall over the islands. Another model suggests a rainfall decrease of about 10-20% during the wet season. Moderate rainfall changes may occur by the end of the century. Using the ensemble suite of models, the most likely projection is a 5-10% decrease during the wet winter season. The dry season has a broader distribution of likelihood, but a modest (5%) shift of an increase in rainfall is indicated (Figure 3.3).

![Projected rainfall changes (anomalies with respect to the 1970-1999 climatological mean in %) during the (a)-(c) dry and (d)-(f) wet season using the six model ensemble mean. The top row is the maximum likelihood of occurrence. The middle row is the estimated lower margin of the 95% statistical confidence interval. The bottom row is the upper margin of the 95% statistical confidence interval (Timm and Diaz, 2009).](image)

Figure 3.3.

Timm et al. (2011) studied the frequency of heavy rainfall events during the wet season and their correlation to large-scale climate modes of the Pacific, namely the Pacific/North American (PNA) pattern and the SOI. The authors used MLR to derive the linear relationships between the frequency of heavy rain days and the state of ENSO and PNA. The MLR model is applied to
projected PNAI and SOI indices obtained from six IPCC AR4 climate models based on the A1B and A2 emissions scenarios for the mid and late 21st century. The simulations project relatively small and equivocal changes during the 21st century. To the extent that variations in the frequency and magnitude of ENSO and PNA are responsible for extreme rainfall occurrences in Hawaii, the results indicate only small changes in the projected number of heavy rainfall days with large uncertainties resulting from disparities among the climate models.

The same authors performed a similar study using National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) reanalysis data from wet season months (November to April) between 1958-2010 for twelve rainfall stations in the Hawaiian Islands (Timm et al., 2013). The statistical downscaling model developed in this study is able to reproduce the observed interannual variations in the number of heavy rain events during the more recent interval of 1978-2010. Application of the model to two scenarios from the CMIP3 database indicates a reduction of heavy rain events in the mid- to late 21st century. Based on these models, a reduced number of heavy-rain weather patterns in the emission scenarios A1B for the mid- and late 21st century. The study is consistent with the identified trend toward drier wet-season conditions and a likely reduction in heavy rain days that the Timm et al. evaluated in previous studies, but does differ from conclusions of other authors (Norton et al., 2011).

A study by Murakami et al. (2013) evaluated potential impacts of global warming on regional tropical cyclone activity for the Hawaii Region. A suite of future warming experiments (2075-2099), using the Meteorological Research Institute Atmospheric GCM, predicts an increase in tropical cyclone frequency of occurrence around the Hawaiian Islands with the A1B climate scenario.

For Oahu, Norton et al. (2011) used a statistical model to downscale daily extreme precipitation events from general GCM outputs. The authors used the 5th generation European Centre Hamburg Model (ECHAM) GCM and the A2 scenario for their prediction. Results suggest a tendency for increased frequency of heavy rainfall events, but a decrease in rainfall intensity during the next 30 years (2011-2040) for the southern shoreline of Oahu.

*Key point: Consensus exists that variable precipitation trends are expected in the Hawaii Region in the future. The degree to which annual average precipitation trends change compared to seasonal changes is unclear.*

### 3.3. Hydrology

A number of global and national scale studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro-scale hydrologic models. These studies include projections of potential hydrologic changes in the Hawaii Region.

There are significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of study by Hagemann et al. (2013). In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic
models for projecting precipitation, evapotranspiration and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro-scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections from Hagemann et al. (2013) for the general Hawaii Region show an overall increase in runoff by approximately 160-200 mm per year for their future planning horizon (2071-2100) compared to the recent historical baseline (1971-2000) (Figure 3.4), assuming an A2 emissions scenario.

**Figure 3.4.** Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2071 vs. 1971. The Hawaii Region is within the red oval (Hagemann et al., 2013).

Döll and Zhang (2010) present similar results in their global modeling study focused on climate change impacts on ecologically relevant flow indices. As above, these authors used a combination of GCMs and a macro-scale hydrologic model (WaterGap) to project hydrology across a coarse spatial resolution (0.5 degree x 0.5 degree grid). They used two different GCMs simulating two bracketing emission scenarios (A2 and B2). Globally, they quantified a shift of peak flow by at least one month (earlier) for one third of the global land area, a significant increase in mean annual flow for approximately half of the land area and a significant decrease in mean annual flow for approximately one quarter of the land area. Only small differences between the two emissions scenarios were noted. They demonstrate that climate change is expected to have as much, or more, of an impact to ecologically relevant flow characteristics as dams and withdrawals over the next century. For the Hawaii Region, projections show mild (relative to global results) impacts to both low and average annual flows (Figure 3.5). Projected regional impacts include small (c. 10 to 20%) decreases in both metrics for their 2055 planning horizon, compared to historical baseline.
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a) Percent changes in river low flows ($Q_{90}$), A2 and B2 emissions scenarios

![Maps showing percent changes in river low flows for different emissions scenarios.]

b) Percent changes in average annual runoff, B2 emissions scenario

![Maps showing percent changes in average annual runoff for different emissions scenarios.]

Figure 3.5. Projected changes in global hydrology, 2041-2070 vs. 1961-1990. Water Resources Region 20 is within the black oval (Döll and Zhang, 2010).

In the Hawaii Region, average precipitation, average stream discharge, and stream baseflow have been trending downward for nearly a century (Leong, et al., 2014). These trends have occurred in recent decades, but with high variability due to cyclic climate patterns such as ENSO and PDO.
In a study focused on the mountainous Hawaii watershed, Safeeq and Fares (2012) studied the impact of potential future climate change scenarios on streamflow and evapotranspiration using the distributed hydrology soil vegetation model (DHSVM). The hydrologic response of the watershed is simulated for 43 years for different levels of CO$_2$, temperature, and precipitation. The results of the study indicated that evapotranspiration is less sensitive than streamflow for a similar level of change in precipitation. On the basis of a range of climate scenarios, DVHSM predicated a change of evapotranspiration by +/- 10% and streamflow between -51% and 90%. From the six ensemble mean scenarios, simulations suggest a reduction in streamflow of 6.7% to 17.2%.

*Key point: There are limited references in regards to studies related to projected changes in hydrologic responses. Global models indicate a potential increase in runoff and streamflow, while regional or local models indicate a decrease in streamflow.*

### 3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study area and throughout the country, over the next century. The studies reviewed here generally agree on an increase in mean annual air temperature of approximately 0.8 °C to 2.8 °C (1.5 °F to 5 °F) by the latter half of the 21st century for the Hawaii Region. Spatial variations among the Hawaiian Islands for projected temperature changes are minor.

Projections of precipitation in the study area are mixed and less certain than those associated with air temperature. Spatial variability across the main Hawaiian Islands indicate that Oahu and Maui have decreasing precipitation trends, while the Island of Hawaii has potentially increasing trends. Rainfall trends are also projected to be both increasing and decreasing depending on the wet or dry seasons. Other studies concluded that the region should expect more frequent tropical cyclones, an increase in the frequency of heavy rainfall events, while others project a decrease in heavy rain events.

Similarly, clear consensus is lacking in the hydrologic projection literature for the study region. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate an increase in future streamflows, but in regional applications, indicate a potential decrease in streamflows. Of the limited number of studies available, results are approximately split.

A number of studies reviewed here employed probabilistic modeling methods to capture and quantify some of this projection uncertainty, resulting from both climate and runoff modeling steps. These methods frame output in the form of probability distributions that can be viewed as characterizations of likelihood of occurrence (risk) or levels of consensus among modeling scenarios.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.6**.
Figure 3.6. Summary matrix of observed and projected climate trends and literary consensus.
4. **Business Line Vulnerabilities**

The Hawaii Region is made up of the State of Hawaii. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE’s missions, a set of primary USACE business lines were identified. They include:

- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Emergency Management
- Regulatory
- Military Programs

USACE implements flood risk management projects in the region, which include structural projects such as storm and hurricane barriers. The increased frequency of storm events and a possible increase in runoff may make flood risk management projects important for reducing the residual flooding impacts.

USACE assists with fresh water supply projects in Hawaii. Managing competing water needs can be a challenge, especially when water demand is high and water supply is low. While this report does not highlight the impacts of sea level change, changes in coastal conditions can have impacts which penetrate to inland water bodies. Sea levels along the Hawaiian coastline of the United States are projected to increase and may exacerbate salt water intrusion into freshwater water supply. Tools and information related to sea level change can be found on the USACE Responses to Climate Change website (USACE, 2014). Water supplies may also be strained due to increased temperatures and a possible change in flows. Maintaining necessary flows for competing sources such as ecosystem management, may present some significant, additional challenges to an already complex water resource system.

The ecosystem restoration mission is an important one in the Hawaii Region, given the unique habitats and species found on the islands. Increased air temperatures will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies. Possible streamflow and runoff changes raise ecological concerns and may threaten ecosystems.

USACE is actively investigating the potential for hydropower in the Hawaii Region. The frequency of large storm events are expected to increase in the region, which may be beneficial for hydropower plants in the region, as flooding may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these project sites.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency
managers and assigned staff in each region and subregion that are able to quickly mobilize. Large precipitation events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Hawaii Region. Since precipitation is expected to fall in larger events, these disaster situations may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE’s regulatory mission has a serious commitment to protecting aquatic resources while allowing for reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulations or an increase in the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. Such interrelationships must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt.
<table>
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<tr>
<th>CLIMATE VARIABLE</th>
<th>VULNERABILITY</th>
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| Increased Ambient Temperatures | Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region:  
- Loss of vegetation due to a change in ecosystem, may have impacts within the region. It may impact sediment stabilization in the watershed. Loss of vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.  
- Increased temperatures may have negative consequences for all infrastructure, habitats, and people in the area.|
| Increased Storm Intensity and Frequency | Extreme storm events may become more frequent which is expected to influence the following vulnerabilities on business lines in the region:  
- Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.  
- Possible increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality.  
- Increased groundwater recharge rates, as residence times are shortened within areas where evapotranspiration takes place during high intensity events.  
- Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.|
| Streamflow Variability | There is low consensus on the impacts of climate change on streamflows. The variability of streamflows may result in:  
- Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality.  
- Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns.  
- Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area.  
- Loss of vegetation from reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system.  
- Decrease in flow has implications for maintaining water levels in the rivers.|
| Sea Level Rise | Sea level rise may exacerbate saltwater intrusion into fresh water supplies. |

**NOTE:** The Regulatory and Military Program business lines may be impacted by all climate variables

- = Navigation  
- = Flood Risk Management  
= Ecosystem Restoration  
= Hydropower  
= Recreation  
= Water Supply  
- = Emergency Management

**Figure 4.1.** Summary of projected climate trends and impacts on USACE business lines
## Appendix A: References Climate/Hydrology Summary Table

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<tr>
<th>References</th>
<th>Observed</th>
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<td>Norton, S.W., Chu, P., T., S. (2011)</td>
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<td>Saleeq, M., Mair, A., Fares, A. (2013)</td>
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Appendix B: Reference List


CDM Smith (2012) Incorporating Climate Change into Water Supply Planning and Yield Studies: A Demonstration and Comparison of Practical Methods


