A century of spatial and temporal patterns of drought in Hawai'i across hydrological, ecological, and socioeconomic scales

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Abstract

Drought is a prominent feature of Hawaii's climate, however, the biological, ecological, cultural, and socioeconomic impacts of drought in Hawaii are not well understood. This paper provides a comprehensive synthesis of impacts of past droughts in Hawaii that we integrate with a geospatial analysis of drought characteristics (duration, frequency, severity, and geographic extent) using a newly developed 93-year (1920-2012) gridded Standardized Precipitation Index (SPI) dataset. The synthesis examines past droughts classified into five categories: meteorological, agricultural, hydrological, ecological, and socioeconomic drought. Results show that drought duration, magnitude, and frequency have all increased significantly, consistent with trends found in other Pacific Islands. Most droughts, though not all, were associated with El Nino events, and the two worst droughts in the past century were 1998-2002 and 2007-2012. The most severe drought in the record (2007-2012) had the greatest impacts on Hawaii Island, whereas the islands of Oahu and Kauai experienced more severe drought conditions during the 1998-2002 event. Both droughts exerted a large and quantifiable impact on the agricultural sector, and although anecdotal evidence points to strong impacts on ecological and socioeconomic sectors, more research is needed to understand drought impacts to these sectors. This synthesis is an example of how coupling quantitative SPI analysis with economic and ecological impacts can provide the historical context needed to better understand future drought projections, and will contribute to more effective policy and management of natural, cultural, hydrological, and agricultural resources.

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Key Points:

- Droughts in Hawai‘i have increased in frequency, duration, and magnitude; the two worst droughts in the past century were 2007-2012 and 1998-2002
- Socioeconomic impacts have been substantial, with droughts costing over $80 million since 1996 in the agricultural sector alone
- Many droughts (though not all) were associated with El Niño events

Abstract

Drought is a prominent feature of Hawai‘i’s climate, however, the biological, ecological, cultural, and socioeconomic impacts of drought in Hawai‘i are not well understood. This paper provides a comprehensive synthesis of impacts of past droughts in Hawai‘i that we integrate with a geospatial analysis of drought characteristics (duration, frequency, severity, and geographic extent) using a newly developed 93-year (1920-2012) gridded Standardized Precipitation Index (SPI) dataset. The synthesis examines past droughts classified into five categories: meteorological, agricultural, hydrological, ecological, and socioeconomic drought. Results show that drought duration, magnitude, and frequency have all increased significantly, consistent with trends found in other Pacific Islands. Most droughts, though not all, were associated with El Niño events, and the two worst droughts in the past century were 1998-2002 and 2007-2012. The most severe drought in the record (2007-2012) had the greatest impacts on Hawai‘i Island, whereas the islands of O‘ahu and Kaua‘i experienced more severe drought conditions during the 1998-2002 event. Both droughts exerted a large and quantifiable impact on the agricultural sector, and although anecdotal evidence points to strong impacts on ecological and socioeconomic sectors, more research is needed to understand drought impacts to these sectors. This synthesis is an example of how coupling quantitative SPI analysis with economic and ecological impacts can provide the historical context needed to better understand future drought projections, and will contribute to more effective policy and management of natural, cultural, hydrological, and agricultural resources.

1. Introduction

Drought is a costly natural hazard that affects human populations worldwide (Wilhite, 2000). Droughts impact nearly all ecosystem types, from lowland deserts to wet tropical forests (McDowell et al., 2018), and the impacts of drought can range from biomass loss and tree mortality in forests (Breshears et al., 2005) to drinking water shortages and economic losses from a variety of sectors including tourism and agriculture (Wilhite, 2000). In the tropical Pacific, droughts are often synchronous across vast areas, driven by large-scale modes of climate variability such as the El Niño-Southern Oscillation (ENSO; Lyon, 2004; Polhemus, 2017). In the U.S. State of Hawai‘i, most El Niño events, the warm phase of ENSO, produce atmospheric conditions that are unfavorable for rainfall (Chu, 1995) which results in dry boreal winter conditions (Chu & Chen, 2005; Frazier et al., 2018; Lyons, 1982).

Drought is a prominent feature of the climate of Hawai‘i and can cause severe impacts across multiple sectors. According to Hawaiian oral traditions, dryland agricultural systems were particularly vulnerable to droughts, with some political upheavals linked directly to devastating droughts (Kirch, 2010). Today, droughts in Hawai‘i often result in reduced crop yields, loss of livestock, drying of streams and reservoirs, depletion of groundwater, increased wildland fire activity, and damage to terrestrial and aquatic habitats – all of which can contribute to substantial economic losses (CWRM, 2017). Drought can give rise to water use restrictions and emergency declarations, and dry spells have contributed to conflicts between agricultural and other instream water users (CWRM, 2017). Total demand for freshwater is projected to increase 5% to 15% by 2040 due in part to population growth (Keener et al., 2018), and this combined with increased temperatures (McKenzie et al. 2019) and declining precipitation (Elison Timm et al., 2015; Frazier & Giambelluca, 2017), will further stress water supplies and intensify the impacts of future droughts in Hawai‘i.

Assessments of historical droughts are fundamental for natural resource planning and management (Mishra & Singh, 2010). Due to the multi-sector nature of drought impacts, it is not only freshwater resource managers who are concerned with planning for drought, but also many land management sectors (e.g., forestry and fire protection, wildlife, and ecosystem restoration). Efforts to mitigate drought impacts require knowledge of historical drought characteristics. However, defining drought is a complex task, as the definition varies among different disciplines. In general, drought can be defined as "the extreme persistence of precipitation deficit over a specific region for a specific period of time" (Zargar et al., 2011), though definitions can also include the impacts of the drought and other indicator variables such as evapotranspiration, soil moisture, near-surface-air temperature, streamflow, groundwater level, and vegetation cover (Mishra & Singh, 2010). Drought is typically classified as one of five types depending on the impacts and duration: meteorological, agricultural, hydrological, socioeconomic, and ecological (Crausbay et al., 2017; Wilhite & Glantz, 1985; Figure 1). The three types of physical drought typically occur in order, while socioeconomic and ecological drought can occur at any drought duration (Figure 1). Meteorological drought is defined by the degree of dryness and by the duration of the dry period. This deficiency of precipitation typically depletes soil moisture, and if a subsequent crop failure results from a lack of precipitation, this is then known as agricultural drought. When dry conditions continue to persist and eventually impact surface water and groundwater supply, this is called hydrological drought. Socioeconomic drought considers the human demand for economic goods and is defined as when societal demand for goods exceeds supply as a result of a weather-related deficit in water supply. This can also encompass the differential impacts of drought on different groups of people based on their access to resources and other political factors, and conflicts that may arise over limited resources (Wilhite & Buchanan-Smith, 2005). A new drought type, "ecological drought," has recently been defined by Crausbay et al. (2017) to characterize the direct and indirect impacts of drought on ecosystems, such as drought-induced tree mortality (Allen & Breshears, 1998; McDowell et al., 2008) or increased extent of fire disturbance (Chu et al., 2002).

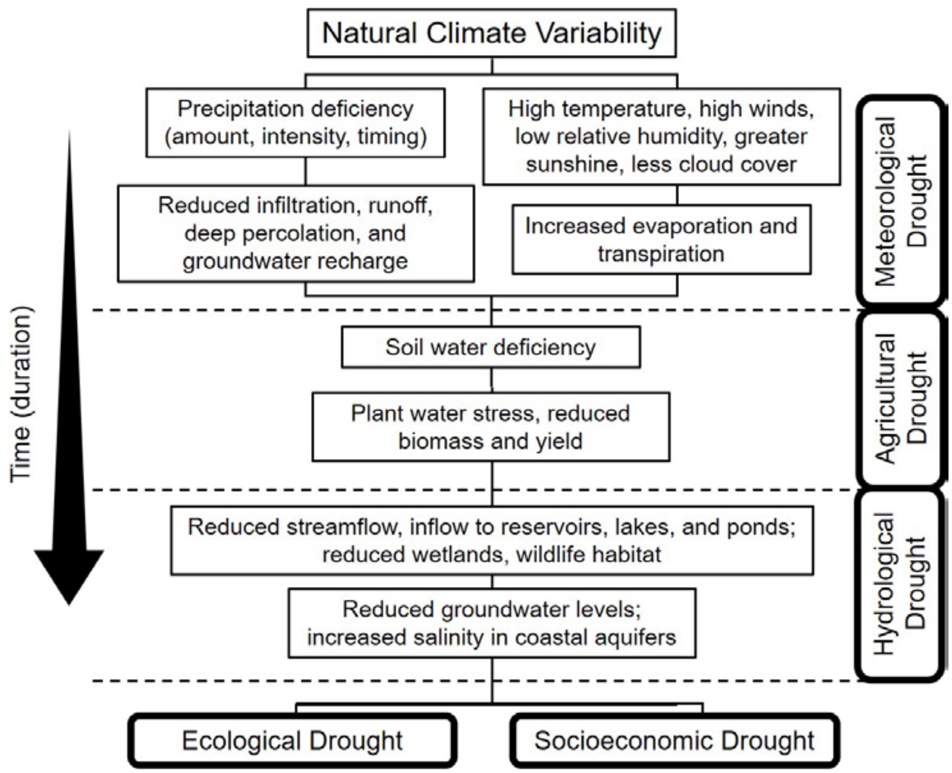


Figure 1. The general sequence for the occurrence and impacts of different drought types (adapted from the National Drought Mitigation Center; https://drought.unl.edu/).

Droughts are typically characterized by an index that combines indicator variables into a single numerical value. However, since no single accepted definition of drought exists, no drought index is universally accepted and more than 100 have been developed (Zargar et al., 2011). Some of the most common indices include the Standardized Precipitation Index (SPI; McKee et al., 1993); Palmer Drought Severity Index (PDSI; Palmer, 1965); Standardized Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010); Keetch-Byram Drought Index (KBDI; Keetch and Byram, 1968); Crop Moisture Index (CMI; Palmer, 1968); and the U.S. Drought Monitor (USDM; Svoboda et al., 2002). The primary source for monitoring drought in Hawaiʻi since 2000 is the USDM (https://droughtmonitor.unl.edu/; Figure 2), a hybrid index that is highly useful for communicating drought conditions and impacts to the public. However, the relatively arbitrary spatial delineations and categorical drought values, lack of spatial detail, and short record history (only since the year 2000) limit the utility of the product for more sophisticated numerical analyses and applications.

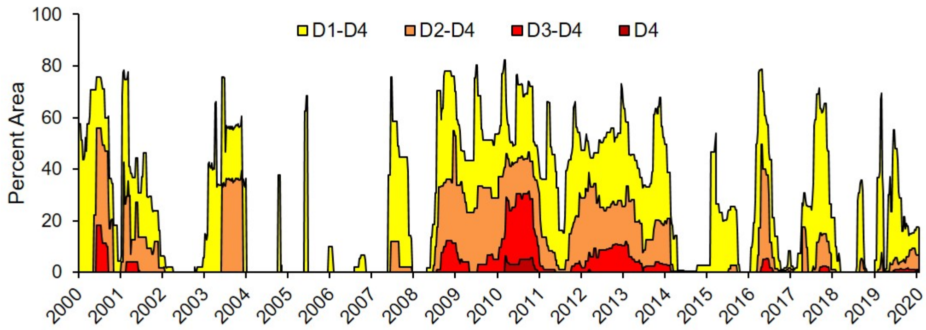


Figure 2. Hawai‘i State Drought Monitor percent area time series, moderate drought (D1 category) or worse, from January 2000 through December 2019. D2 corresponds to severe drought; D3 to extreme drought; and D4 to exceptional drought. Data source: https://droughtmonitor.unl.edu/.

In the last comprehensive drought report for Hawai‘i, Giambelluca et al. (1991) analyzed three meteorological drought indices for the period 1885-1986. The results showed that the most severe drought statewide started in September 1977 and lasted for six months, and many droughts (though not all) were associated with El Niño events and higher-than-normal temperatures. This report has been critical to understanding drought and its impacts in Hawai‘i, but it does not include information from the most recent three decades. Given the observed changes in the climate (e.g., Frazier & Giambelluca, 2017; McKenzie et al., 2019), and the availability of new high-resolution gridded climate datasets (e.g., Frazier et al. 2016; Longman et al., 2019), an updated analysis of historical drought conditions and impacts across the state is needed. Having a comprehensive understanding of drought in Hawai‘i will provide information for resource managers to institutionalize awareness of drought effects and responses to ensure that short- and long-term planning and management will be effective (Vose et al., 2019).

The objectives of this study are twofold: First, to conduct a comprehensive geospatial analysis of a new 93-year (1920-2012) gridded SPI dataset (Lucas et al., *In Review*) to characterize historical drought in Hawai‘i; Second, to review and synthesize the recent literature documenting droughts and their impacts in Hawai‘i. The study area is described in Section 2. Methods are presented in Section 3 and results are given in Section 4 for the spatiotemporal drought analysis. Section 5 contains a synthesis of the recent drought literature and a discussion of the relevance of the SPI results for different sectors, and concluding thoughts are presented in Section 6.

2. Study Area

The main Hawaiian Islands are located in the Pacific Ocean between 18.90°N and 22.24°N latitude, and 160.25°W and 154.80°W longitude. This study considered seven of the eight major islands where climate data are available: Kaua‘i, O‘ahu, Moloka‘i, Lāna‘i, Maui, Kaho‘olawe, and Hawai‘i. These islands were grouped into the following four regions for analysis and discussion: Kaua‘i, O‘ahu, Maui Nui, and Hawai‘i Island; “Maui Nui” herein refers to all islands in Maui County (Maui, Kaho‘olawe, Moloka‘i, and Lāna‘i). The climate of Hawai‘i is extremely diverse due in part to the large elevation range (from 0 to 4,205 m) and complex topography. Mean annual rainfall ranges from 204 to 10,271 mm (Giambelluca et al., 2013), with some of the steepest rainfall gradients in the world, particularly on leeward slopes (Figure 3). Prevailing surface winds are east-northeast (trade winds), and much of the rainfall is produced through orographic lifting, resulting in wet windward (east-facing) slopes and dry leeward lowlands. Annual rainfall in most areas is characterized by two distinct seasons: a wet season (November to April) and a dry season (May to October). Climate in Hawai‘i is also strongly influenced by large-scale modes of natural climate variability, in particular, ENSO, the Pacific Decadal Oscillation (PDO), and the Pacific North American (PNA) pattern (Chu & Chen, 2005; Frazier et al., 2018).

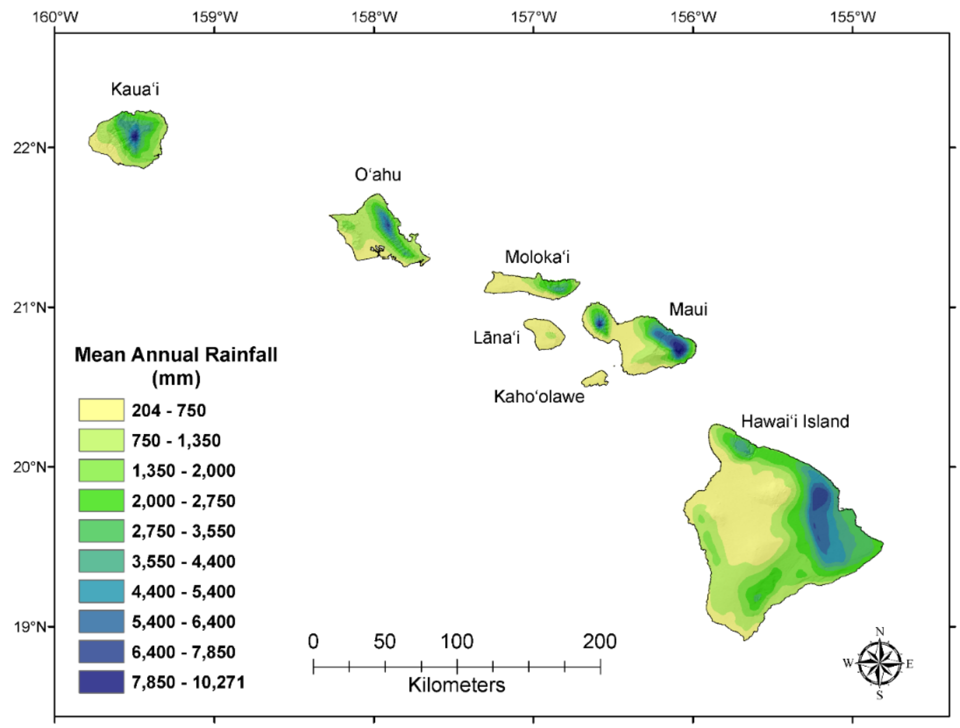


Figure 3. State of Hawaiʻi mean annual rainfall (1978-2007) in millimeters (Giambelluca et al. 2013). "Maui Nui" refers to all islands in Maui County (Maui, Kahoʻolawe, Molokaʻi, and Lānaʻi).

Agricultural plantations were responsible for establishing many of the early climate monitoring stations in Hawaiʻi, as growers required detailed water availability data to develop methods to maximize crop yields (Giambelluca et al., 1986). In 1980, agricultural and pasture lands made up 35% of the total state land area. Over the past 50 years, however, agriculture in Hawaiʻi has undergone substantial changes, including the closure of these large-scale monocrop plantations, a decline in the amount of pasture land (31% decline between 1980 and 2015), a rise in diversified agriculture, and an increase in commercial forestry and biotechnology (Perroy et al., 2016). With statewide initiatives to increase local food production, Hawaiʻi's agricultural sector will continue to play an important economic role in the coming decades.

Terrestrial ecosystems in Hawaiʻi are known for their remarkably high levels of endemism. Given the well-recognized extreme climatic and edaphic gradients, Hawaiʻi's natural areas contain the majority of Holdridge life zones (bioclimatic zones), spanning across tropical rain forests, arid grasslands, and alpine tundra (Asner et al., 2005). Since European contact in Hawai‘i, the rate of species introductions has been one million times the estimated natural rate, resulting in the widespread displacement of native species (Juvik & Juvik, 1998). The combined effects of invasive species, disease, and land cover change have severely impacted native plant and animal communities in many areas of the state, resulting in a "biodiversity crisis," with native ecosystems giving way to alien-dominated ecosystems and species endangerment or extinction (Sakai et al., 2002). These diverse co-occurring threats are now being exacerbated by climate change, and any changes to drought frequency, severity, or duration will likely further impact native species and their competitive interactions with non-native invasive species (e.g., Camp et al., 2018; Fortini et al., 2013; Vorsino et al., 2014).

3. Methods

In 2011, the SPI was recommended by the World Meteorological Organization as the internationally preferred index for meteorological droughts (Hayes et al., 2011). The SPI is based solely on precipitation and compares precipitation with its local multi-year average, allowing wet and dry climates to be represented on a common scale to enable comparisons. It allows characterization of dryness (and wetness) across different timescales, which can reflect meteorological, agricultural, and hydrological drought impacts (McKee et al., 1993). A disadvantage of the SPI is that it does not consider other important variables relating to drought, such as soil moisture or potential evapotranspiration (PET; Vicente-Serrano et al., 2010). In Hawai‘i, however, neither monthly nor daily gridded data exist for soil moisture and PET, and few stations measure the necessary variables (e.g., calculating PET requires radiation, humidity, and wind speed), therefore indices such as the PDSI or the SPEI cannot yet be calculated. The KBDI, used to monitor fire risk, is currently only calculated operationally at one location, the Honolulu Airport (CWRM, 2017), and the State of Hawaiʻi is not included in many of the products available for the contiguous U.S. (e.g., CMI).

The input dataset used for the retrospective drought analysis is a new gridded monthly SPI product created for the Hawaiian Islands from 1920 to 2012 (Lucas et al., *In Review*). Using a gridded monthly rainfall time series (Frazier et al. 2016), Lucas et al. (*in Review*) calculated the SPI at each 250 m pixel by fitting a Gamma distribution to the original rainfall data (Beguería and Vicente-Serrano 2017; R Core Team 2017). Gridded results were validated using independent station-based SPI supplied by the National Weather Service and compared with the USDM; full quality control methods and results are described in Lucas et al. (*In Review*). The gridded SPI was calculated for 10 different timescales (from one month up to 60 months), where each new value is determined from the previous months. A 3-month SPI in August 1990, for example, compares the June-July-August (JJA) precipitation in 1990 to the JJA totals of all 93 years in the record. For this study, the following six SPI timescales were analyzed: SPI-1, SPI-3, SPI-6, SPI-9, SPI-12, and SPI-24 corresponding to the 1-, 3-, 6-, 9-, 12-, and 24- month SPI timescales, respectively. Most results shown here use the SPI-6 and SPI-12, as these span the timescales needed to reflect short-term to long-term precipitation patterns (World Meteorological Organization, 2012).

To examine the spatiotemporal characteristics of the SPI dataset at selected timescales, maps of mean SPI by decade were calculated based on the average SPI at each 250 m pixel. Due to the odd number of years in the time series, the last "decade" contains three extra years (2000-2012). To represent drought frequency, the proportion of months in drought were calculated (from 0 months in drought up to all months in drought, converted to a proportion: 0 to 1). This was calculated by decade for four different drought category thresholds: SPI < 0 (mild drought), SPI < -1.0 (moderate drought), SPI < -1.5 (severe drought), and SPI < -2.0 (extreme drought).

Drought events were defined as periods during which the SPI values were continuously negative and reached a value of -1.0 or less (McKee et al., 1993). The start date of each drought was determined as the date when the SPI values first fell below zero, and the end of the drought occurred when the values changed from negative to positive (after reaching a value of -1.0 or less). Drought events were calculated based on the average statewide and island time series. For each event, the start and end dates were determined, and five metrics were calculated to characterize each event: duration (the number of months in drought), magnitude (the sum of SPI values during drought), intensity (the magnitude divided by the duration), peak intensity (the minimum SPI value during drought), and average spatial extent (average of the percent of land area with SPI < -1 during event). Droughts were ranked based on each of these five metrics, and the average of these five ranks was calculated to provide an overall ranking of droughts.

To map each drought, bi-variate maps of drought intensity and percent time in drought were produced. To display the maps, the SPI pixels were aggregated to a coarser resolution by averaging 250 m pixel values within 5 km grid cells, and these coarse-resolution raster grid cells were then converted to points. Total percent time in drought at each point location was calculated as the percent of months in any drought category during the event years. To calculate intensity, first the number of months in each of the four drought categories (mild, moderate, severe, and extreme) was divided by the total number of months in any drought category. A weighted sum of these proportional intensities was calculated to determine the overall drought intensity at each point, with weights assigned as: 0.05, 0.15, 0.30, and 0.50 from mild drought to extreme drought, respectively. The total percent time in any drought category during the years identified for each event was used to scale the size of the points, while the weighted proportional drought intensity was used to scale the color of the points.

Drought trends were analyzed by decade from 1921 to 2010 focusing on drought frequency (DF; number of events per decade), total drought duration (TDD) and total drought magnitude (TDM). TDD and TDM are the sums of the durations and magnitudes of drought events that occurred in the considered period, expressed as number of months for duration, and a dimensionless severity score for magnitude (McGree et al., 2016). These metrics were calculated based on the statewide and island-wide average time series in 10-year intervals. Linear trends were calculated for each metric over the nine decades using a Student's *t* test at the 95% confidence level. Analysis of DF, TDD, and TDM is preferred to calculating trends on the actual SPI values (e.g., using the December SPI-12 values to represent annual trends), which would provide trends in standardized precipitation rather than drought (McGree et al., 2016).

To represent the strength and phase of ENSO, the Multivariate ENSO Index (MEI) was used (Wolter & Timlin, 2011). The MEI is derived from six variables over the tropical Pacific: sea-level pressure, meridional surface wind, zonal surface wind, surface air temperature, sea surface temperature, and total cloudiness fraction. The MEI was chosen because it incorporates more information into a single variable than indices that focus only on sea surface temperatures or atmospheric pressure fields. Scatterplots between MEI and SPI were plotted for the wet and dry season to determine the relationship between ENSO and historical droughts. Seasonal SPI was calculated as the mean of the SPI values during wet and dry season months for each year.

4. SPI Analysis Results

The mean SPI maps for each decade between 1920 and 2012 indicate strong decadal variability, with wet and dry decades apparent (1930s were generally wetter, while 1970s and 2000s were dry) and greater variations in the western leeward sides of the islands (Figure 4). Although the mean calculated over the entire period would show zero values everywhere, as this is how the SPI is defined, considering individual decades shows general wetter and drier periods over the time series. These temporal patterns are also seen in the statewide average time series (Figure S1), in which the period 2000-2012 stands out as having the driest conditions, followed by the 1970-1979 period, in both the short- and long-term drought metrics (all six SPI timescales). For drought frequency, Figure 5 shows maps of the proportion of months in each decade where locations experienced mild drought or worse (SPI < 0), moderate drought or worse (SPI < -1), severe drought or worse (SPI < -1.5), or extreme drought (SPI < -2.0), based on SPI-12. In general, all decades experienced some proportion of mild drought months but the last three decades showed a high proportion of both moderate and extreme drought months.

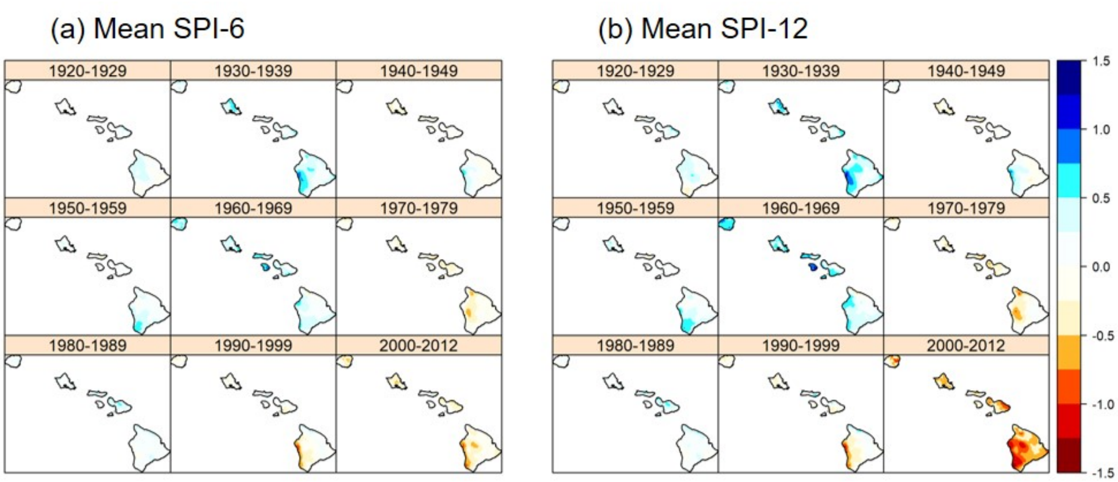


Figure 4. Mean 6-month (a) and 12-month (b) SPI by decade for the State of Hawai‘i. Note: last decade includes 2000-2012.

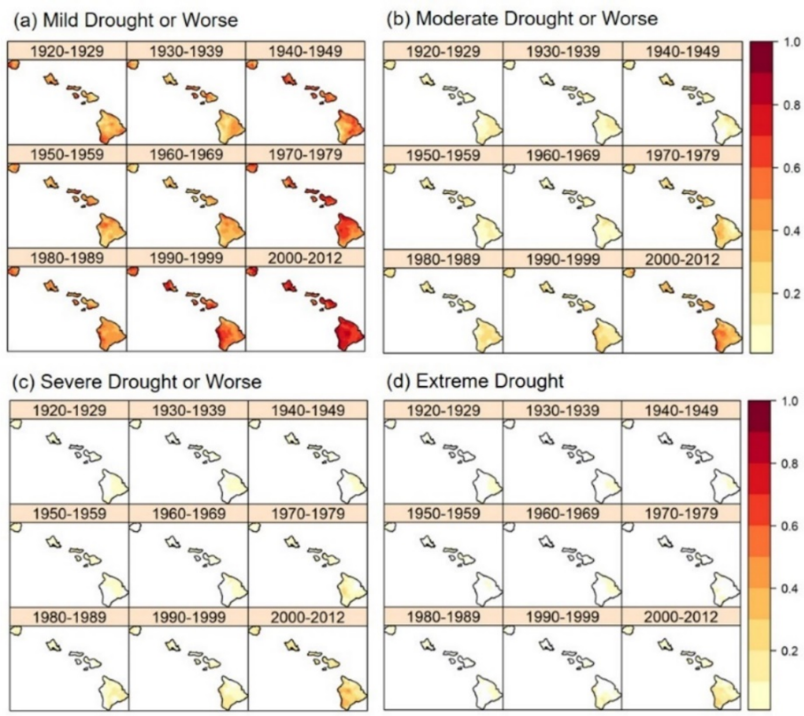


Figure 5. Proportion of months (from 0 to 1) in each decade where locations experienced (a) mild drought or worse (SPI-12 less than 0); (b) moderate drought or worse (SPI-12 less than -1); (c) severe drought or worse (SPI-12 less than -1.5); and (d) extreme drought (SPI-12 less than -2.0). Note: last decade includes 2000-2012. Zero values shown in white.

A total of 28 statewide droughts were found for SPI-6 (Table S1, Figure 6), and 15 droughts were identified for SPI-12 (Table 1, Figure 6). The two highest magnitude and longest duration droughts for both SPI-6 and SPI-12 were the 2007-2012 drought followed by the 1998-2002 drought (years based on SPI-12, Table 1). The 2007-2012 drought also had the highest peak intensity. Based on SPI-6, July and November were the most common months when droughts began, and August, November, and February were the most common months of drought termination (Table S1). For the SPI-12 series, January and February were the most common starting months and December was the most common end month; no droughts in SPI-12 began or ended in the dry season months (May-August) (Table 1). These droughts are in agreement with the droughts identified by Giambelluca et al. (1991); the 1952-54, 1983-85, and 1975-78 droughts (ranked 3rd , 4th, and 5th, respectively, in Table 1) were all identified as some of the most intense and longest island droughts (Giambelluca et al., 1991), though the exact months and ranks differ due to the difference in methods. According to the U.S. Drought Monitor, the 2007-2012 drought persisted beyond the end date of the SPI dataset used here (2012), and rainfall did not return to normal conditions until early 2014 (Figure 2).

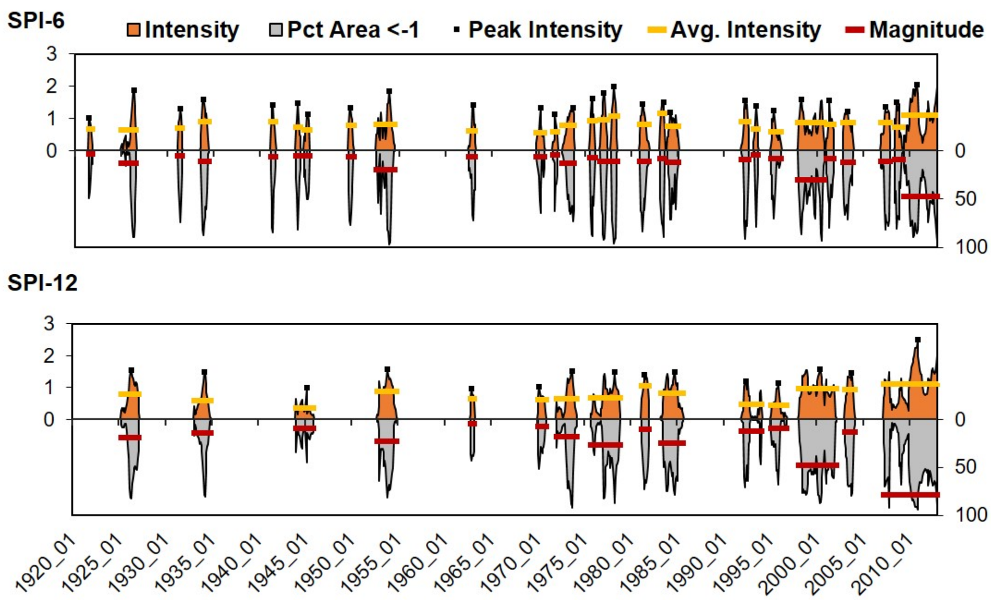
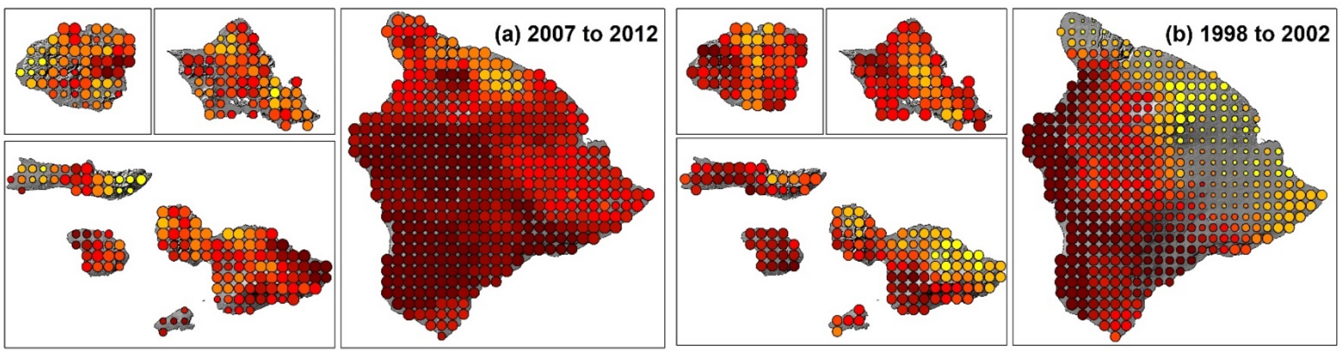


Figure 6. Droughts identified from the statewide average SPI time series (SPI-6, top panel; SPI-12, bottom panel). Intensity (absolute value of SPI values), Peak Intensity, Average Intensity, Magnitude, and Percent Area in moderate drought or worse (SPI < -1) shown for each drought; Magnitude and Percent Area shown on reverse axis.

Table 1. Statewide droughts identified by average SPI-12, sorted by overall rank. Overall rank is the average of the ranks of the five metrics shown here: average intensity (absolute value of SPI values), peak intensity, duration, magnitude, and average percent area. Average percent area is the average of the percent of state land area with SPI-12 < -1 during event (moderate drought or worse).

Overall Rank	Start	End	Avg. Intensity	Peak Intensity	Duration	Magnitude	Avg. Percent Area
1	Mar. 2007	Dec. 2012	1.12	2.49	70	78.7	52.23
2	Feb. 1998	Feb. 2002	0.98	1.57	49	48.0	54.21
3	Oct. 1952	Nov. 1954	0.88	1.57	26	22.8	40.18
4	Apr. 1983	Sep. 1985	0.81	1.48	30	24.4	40.02
5	Sep. 1975	Dec. 1978	0.67	1.49	40	26.9	32.90
6	Apr. 1925	Mar. 1927	0.80	1.54	24	19.2	35.84
7	Jan. 1972	Mar. 1974	0.66	1.53	27	17.9	34.82
8	Jan. 2003	Feb. 2004	0.95	1.45	14	13.3	49.64
9	Mar. 1981	Dec. 1981	1.06	1.41	10	10.6	51.53
10	Feb. 1933	Dec. 1934	0.60	1.48	23	13.8	27.79
11	Dec. 1991	Feb. 1994	0.46	1.20	27	12.5	19.91
12	Jan. 1970	Dec. 1970	0.61	1.02	12	7.3	28.56
12	Feb. 1995	Oct. 1996	0.46	1.14	21	9.7	23.19
14	Oct. 1962	Mar. 1963	0.65	0.98	6	3.9	34.74
15	Jan. 1944	Dec. 1945	0.36	0.99	24	8.8	18.72

To examine the spatial characteristics of these droughts, maps of the two worst (highest ranking) droughts on record (2007-2012 and 1998-2002, identified based on the overall rank in Table 1) were plotted based on SPI-12 (Figure 7). Both droughts were severe and persistent in the leeward areas of the islands. The largest spatial differences between these two droughts were seen in the windward areas of Hawai‘i Island and Maui, which experienced less time in drought and lower drought severity during the 1998-2002 drought compared to the 2007-2012 drought. For the islands of Kaua‘i and O‘ahu, the 1998-2002 drought was more severe than the 2007-2012 drought (Figure 7).



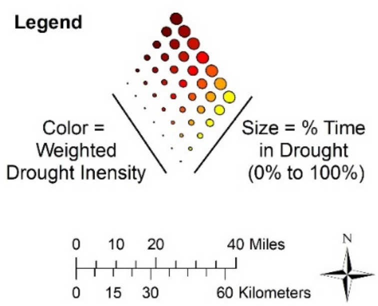


Figure 7. Drought maps based on SPI-12 for the two worst droughts (based on ranks in Table 1): (a) 2007-2012; (b) 1998-2002. Color indicates weighted proportion of drought intensity (mild drought in yellow to extreme drought in dark red). Size of points indicates proportion of time spent in drought (smallest points: 0-25% time in drought, largest points: 85-100% time in drought during drought years).

Decadal DF, TDD, and TDM all showed increasing trends statewide for both SPI-6 and SPI-12 from 1921-2010 (Figure 8). A considerable increase in drought duration and magnitude occurred in the 1970s, and TDD and TDM continued to increase through the 1990s and 2000s. All statewide trends were significant at the 95% level except for DF in SPI-6 (p-value = 0.07). Island-wide decadal DF, TDD, and TDM also increased, but these trends were only significant (95%) for Maui Nui and Hawai‘i Island

(Figure 8). These results indicate that droughts in Hawai‘i have become more frequent, longer, and more severe, particularly on Maui Nui and Hawai‘i Island.

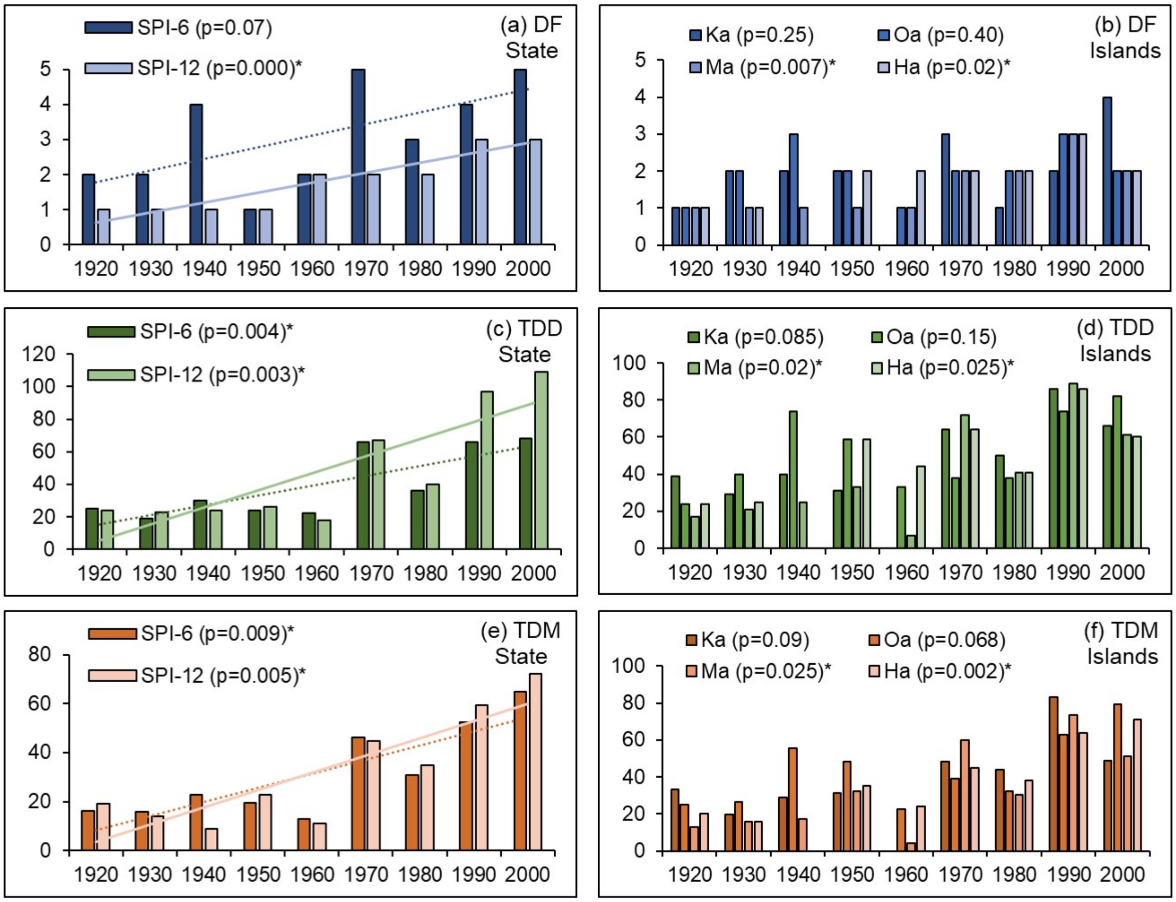


Figure 8. State and island drought frequency (DF; number of events) (a, b), total drought duration (TDD; number of months) (c, d), and total drought magnitude (TDM; unitless) (e, f) by decade from 1921-2010. Statewide trends (a, c, e) shown for SPI-6 (darker colors, dashed trend line) and SPI-12 (lighter colors, solid trend line). Island trends (b, d, f) shown for SPI-12; Ka = Kaua‘i, Oa = O‘ahu, Ma = Maui Nui, and Ha = Hawai‘i Island. P < 0.05 indicated with asterisk*.

To examine the relationship between ENSO and drought, plotting the smoothed MEI time series with the SPI-12 time series showed that many dry periods (negative SPI) were preceded by the onset of El Niño conditions (e.g., the 1997/98 El Niño event preceded the 1998-2002 drought) (Figure 9). However, not all droughts were associated with El Niño events, and not all El Niño events led to droughts (e.g., 1987/88 El Niño). The 2007-2012 drought was associated with a moderate El Niño event in 2009/10, however, the dry conditions began prior to this event, and persisted through two La Niña events from 2010-2012. The relationships between seasonal SPI and the MEI show that wet season (November to April) correlations were negative, indicating that El Niño events were associated with drier-than-average wet season conditions, and La Niña events with wetter-than-average wet seasons (Figure 10). In the dry season months (May to October), the correlations were positive, indicating that ENSO events had the opposite effect on rainfall (El Niño events associated with wetter dry seasons, La Niña events associated with drier dry seasons).

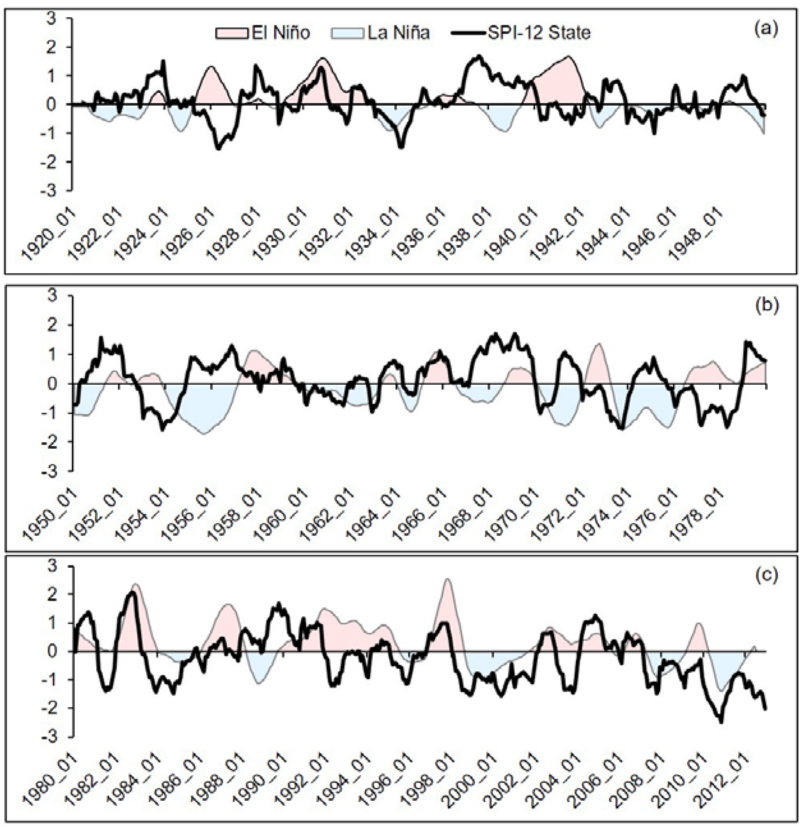


Figure 9. Time series of average monthly statewide SPI-12 plotted with the decadally smoothed MEI time series. (a) 1920-1949; (b) 1950-1979; (c) 1980-2012. Positive MEI (El Niño conditions) shown in pink, negative MEI (La Niña conditions) shown in blue.

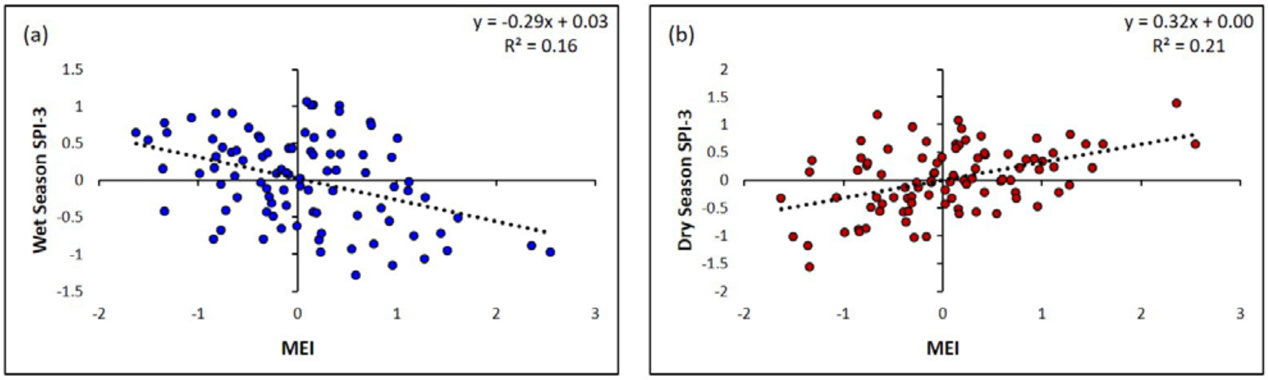


Figure 10. Scatterplots of (a) wet season (November-April) and (b) dry season (May-October) SPI-3 plotted with annual MEI (based on the year from July to June of the following year). Positive values of MEI correspond to El Niño conditions, whereas negative values indicate La Niña conditions.

5. Synthesis and Discussion

5.1 Meteorological Drought

Since the previous drought synthesis report by Giambelluca et al. (1991), many studies have documented long-term drying trends for Hawai‘i in both annual and seasonal rainfall (Chu & Chen, 2005; Diaz & Giambelluca, 2012; Diaz et al., 2016; Frazier & Giambelluca, 2017; Kruk & Levinson, 2008; Longman et al., 2015; O’Connor et al. 2015). The years 2010 and 2012 were the driest statewide since the record began in 1920 (Frazier et al., 2016), and based on a 500-year reconstruction of winter rainfall, a drying trend has been evident over the past 160 years (Diaz et al., 2016). A significant upward trend in consecutive dry days, particularly in already dry leeward areas, and rainless days per year in high elevation areas have also been reported (Chu et al., 2010; Kruk et al., 2015; Krushelnycky et al., 2013). Only two studies directly analyzed drought metrics for Hawai‘i. Koch et al. (2014) spatially interpolated rainfall and temperature maps for the period 1920 to 2007, which were then used to develop different drought products, including annual drought frequency grids for different drought intensity levels (mild, moderate, severe, and extreme). The range of variability in drought frequency was small within each intensity class, although results showed a slightly higher frequency of mild and moderate drought on the leeward sides of most islands. McGree et al. (2016) calculated SPI-12 using data from 24 stations in Hawai‘i to examine decadal trends DF, TDD, and TDM for the period 1951-2010. Overall, results showed positive trends in these drought metrics on both the leeward and windward sides of the islands, though many of these trends were not statistically significant at the 95% level. Similar trends were found across the Pacific Islands region. In Figure 8, these same metrics calculated from the gridded SPI dataset from 1921 to 2010 show significant increases at the 95% level, indicating that over this longer period droughts have become significantly more frequent, severe, and longer lasting.

It has long been recognized that a strong relationship exists between ENSO and wet season rainfall in Hawai‘i (Chu, 1989; Chu & Chen, 2005; Frazier et al., 2018; Lyons, 1982). Most El Niño events correspond with above average dry season rainfall in Hawai‘i (Figure 10), due in part to increased tropical cyclone activity (Chu & Wang, 1997), followed by below average wet season rainfall, though not all droughts have been associated with an El Niño event (Chu et al., 1993), and not all El Niño events have led to drought (Figure 9). Conversely, La Niña events typically lead to below average dry season rainfall and above average wet season rainfall (Figure 10), although a drying trend in La Niña wet season rainfall in Hawai‘i is evident since 1983 (O'Connor et al., 2015). The effects of El Niño on seasonal rainfall vary depending on whether the El Niño event is classified as a warm pool Central Pacific (CP) type or a cold tongue Eastern Pacific (EP) type, with EP events leading to drier conditions in the wet season, and CP events resulting in near-normal wet season conditions in Hawai‘i (Bai, 2017; Hsiao, 2020). Sequential El Niño and La Niña events also appear to be a dominant factor for long-duration droughts in Hawai‘i (e.g., drier wet season from El Niño followed by drier dry season with La Niña) (Frazier, 2016). Recent evidence has called into question the stability of teleconnection patterns in the Pacific (Coats et al., 2013; McAfee, 2014; Wang et al., 2020; Yeh et al., 2018) which has important implications for predicting drought. How these relationships between ENSO and Hawaiian rainfall will change with future warming is still unknown. However, some research indicates that the frequency and intensity of El Niño events will increase significantly (Wang et al., 2019; Wang et al., 2017), which could lead to increased frequency of extreme drought in Hawaiʻi.

5.2 Agricultural Drought

Rain-fed fields and pasture lands are the most vulnerable to drought impacts in Hawaiʻi, although if drought persists, irrigated areas also can become vulnerable. State agencies can implement mandatory water conservation measures at county and local levels to reduce the amount of water used for irrigation (CWRM, 2017; KHNL, 2012). During drought, ranchers lose pasture and forage resources, which can force them to purchase expensive supplemental feed and possibly reduce herd sizes. This, along with increased cattle mortality and reduced calving rates leads to large decreases in revenue. The 1980-1981 drought resulted in $1.4 million in losses for both farmers and ranchers. During the 2000-2002 drought, all counties were designated as primary disaster areas by the U.S. Secretary of Agriculture (at least eight consecutive weeks of Severe Drought (D2) level on the USDM, Figure 2), and statewide cattle losses alone were estimated at $9 million (CWRM, 2017). Between 2008 and 2016, the state lost approximately $44.5 million in cattle production and more than 20,000 head of cattle due to drought. Recovery to 2008 levels is estimated to take an additional 10-14 years and will cost the state $4-6 million dollars in production each year.

Many farmers and ranchers are able to capitalize on federal insurance programs, such as the USDA Risk Management Agency (RMA), and disaster relief programs, such as the Farm Service Agency (FSA) Disaster Assistance Program, which includes a Noninsured Crop Disaster Assistance Program

(NAP), the Livestock Forage Disaster Program (LFP), and the Livestock Indemnity Program (LIP) (Reyes & Elias, 2019; USDA, 2019). In the RMA program, drought has been the number one cause of crop loss for Hawai‘i, resulting in over $9.7 million in payouts since 1996, with excessive rain as a distant second cause of crop loss resulting in $2.1 million in payouts (Figure 11a). The insured crops that have experienced the largest payouts due to drought in the past 10 years have been macadamia nuts ($8 million) and coffee ($1 million) (Reyes & Elias, 2019). For uninsured crops, the NAP has paid out over $23.8 million between 2010 and 2018 (Figure 11b; USDA, 2019). The two livestock disaster programs have paid out even more in recent years. Between 2008 and 2018 the LFP paid out over $50 million to ranchers in the state who suffered grazing losses due to drought, and over the same period the LIP paid out almost $800,000 for ranchers who lost livestock (either livestock sold at a lower price or livestock deaths) (Figure 11b; USDA, 2019). Between 1996 and 2018, these programs have paid out a total of over $84.5 million in the state of Hawai‘i due to drought.

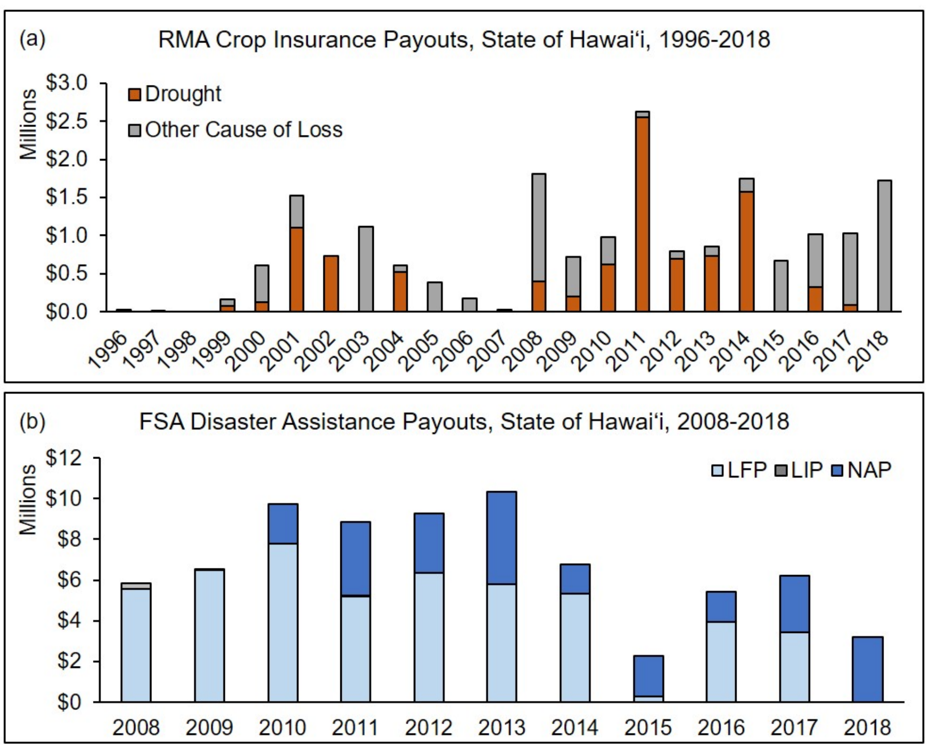


Figure 11. (a) Crop insurance indemnities (payouts) by year for the State of Hawai‘i from 1996 to 2018 from the USDA Risk Management Agency (RMA), separated by cause of loss: drought versus all other causes of loss. (b) Farm Service Agency (FSA) Disaster assistance payouts by year for the State of Hawai‘i from 2008 to 2018 shown for three programs: Livestock Forage Disaster Program (LFP), Livestock Indemnity Program (LIP), and the Noninsured Crop Disaster Assistance Program (NAP).

5.3 Hydrological Drought

In Hawai‘i, the first indication of hydrological drought is reduced streamflow (Wilhite & Glantz, 1985), which decreases the water available to support stream and wetland habitats, meet irrigation needs, sustain cultural practices, maintain watershed processes, and replenish reservoirs. Groundwater discharge and surface water runoff into streams are also reduced during drought (Strauch et al., 2017a; Strauch et al., 2015), which can result in higher concentrations of fecal bacteria in streams immediately following rain events (Strauch et al., 2014). As hydrological drought progresses, groundwater levels are eventually reduced. Groundwater in Hawai‘i is mainly found as a convex-shaped layer, or basal lens, floating on and displacing denser saltwater, and at higher elevations in inland dike-impounded systems. Thicker freshwater lenses like in the Pearl Harbor aquifer on O‘ahu are generally less sensitive to substantive salinity changes caused by periods of low rainfall compared to thinner lenses. However, higher pumping rates due to increased demand can cause the basal water table to decline (Izuka, 2006), and this can lead to saltwater intrusion. Thinner aquifers like those in coastal areas of the western part of Hawai‘i Island are more vulnerable to increased salinity during droughts. For these thin lenses, the transition zone between freshwater and saltwater is closer to the pump intakes, and thinning of the freshwater lens due to reduced recharge possibly coupled with increased pumpage during droughts may lead to increased salinity in the pumped water (Giambelluca et al., 1991). Lower groundwater levels exacerbate the potential for saltwater intrusion, which negatively impacts drinking and agricultural water supply. Over the past century, stream base flows have declined statewide (Bassiouni & Oki, 2013), likely as a result of decreases in groundwater recharge and storage, making Hawai‘i’s aquifers more vulnerable to saltwater contamination during droughts.

5.4 Ecological Drought

Ecological drought in Hawai‘i is commonly manifested today as an increase in wildfire occurrence (Dolling et al., 2005; Dolling et al., 2009; Trauernicht et al., 2015). Wildfires in Hawai‘i are most extensive in dry and mesic non-native grasslands and shrublands, which cover 24% of total land area in the state and account for about 80% of annual area burned (Hawbaker et al., 2017), although wildfire can occur outside of normally dry habitats, even in native wet forests during more severe droughts (Frazier et al., 2019; Tunison et al. 2001). During drought, wildfire risk in grasslands increases rapidly, making drought an important contributor to the invasive grass-wildfire cycle (Nugent et al., 2020; Trauernicht et al., 2015). The observed changes in land use from agricultural lands to non-native fire-prone grasses and shrubs (Perroy et al., 2016) combined with recurring incidences of drought are expected to increase the risk of future wildfire in Hawai‘i (Trauernicht, 2019). The relationship between wildfire and El Niño occurrence in Hawai‘i is particularly apparent (Chu et al., 2002). The relatively wet summer months preceding the El Niño event increase biomass accumulation (Trauernicht, 2019), and as an El Niño event progresses and wet season drought conditions occur, the resulting widespread senescence, curing of vegetation, and reduced moisture all drive an increase in wildfire danger. During the 1997-98 El Niño event, for example, over 37,000 acres burned across the state, including several large fires in the usually wet Puna district of eastern Hawai‘i Island (Trauernicht, 2015). Heavy rainfall on recently burned areas can cause higher rates of erosion and increased sediment delivery to streams and nearshore areas (Trauernicht et al., 2015), which negatively impacts stream fauna and coral reef communities (Brasher et al., 2004; Stender et al., 2014). Freshwater ecosystems are particularly vulnerable to drought, and stream fauna are negatively impacted by reductions in streamflow through the limited availability of freshwater habitat, loss of hydrological connectivity, and reduced water quality (Clilverd et al., 2019; Hau, 2007; McIntosh et al., 2002; Strauch et al., 2017b; Tsang et al. 2019).

Reduced surface water and groundwater inputs into nearshore environments may also have negative effects on organisms in brackish and marine environments (Hau, 2007), however, more research is needed to evaluate the impacts of reduced groundwater discharge on nearshore ecosystems, including threatened anchialine ponds (Tribble, 2008).

Forest responses to drought have been characterized from remote sensing analyses, which have shown that dry forest areas in the state “brown down” during droughts (Pau et al., 2010), and strong reductions in canopy greenness and volume have been observed on Hawai‘i Island as a result of long-term precipitation declines (Barbosa & Asner, 2017). Field-based evidence suggests that El Niño-induced droughts determine the upper elevation of the forest line (Crausbay et al. 2014; Leuschner & Shulte, 1991). Drier conditions have been linked to mortality of the Haleakalā silversword (*Argyroxiphium sandwicense* subsp. *macrocephalum*), an iconic and endangered high elevation endemic plant (Krushelnycky et al., 2013; Krushelnycky et al., 2016). Extreme drought can also cause mortality among some of the dominant native woody species (Lohse et al., 1995; Weller et al., 2011), and insect infestations during drought can lead to native tree mortality in dry forest areas (Frazier et al., 2019). Drought tolerance of native species has been documented, with some native grass species having greater drought tolerance than invasive species (e.g., Goergen & Daehler, 2002), and other tolerance variations found across different elevation, moisture, and light conditions (Barton et al., 2020; Craven et al., 2010; Krushelnycky et al., 2020; Michaud et al., 2015; Westerband et al., 2020). Drought causes invasive ungulates (e.g., feral pigs, goats, deer, and sheep) to change their foraging patterns in search of food and encroach into residential and agricultural areas, causing erosion and damage to infrastructure and crops (CWRM, 2017; Frazier et al., 2019; KHNL, 2012), and the simultaneous threats of drought, wildfire, and browsing pressure from ungulates have resulted in drastic range reductions for endangered Hawaiian bird species such as the palila (*Loxioides bailleui*) (Banko et al., 2013; 2014).

5.5 Socioeconomic Drought

The full extent to which drought impacts social and economic systems depends not only on the physical characteristics of the drought, but also the characteristics of the resources and systems exposed to the drought. Water shortages can occur, prompting state and county agencies to make declarations to implement voluntary or mandatory water conservation measures. On O‘ahu, both voluntary conservation measures and city policies such as the low flow toilet ordinance (1993) helped to mitigate drought impacts in the 1998-2002 drought (CDM Smith, 2016). Cost of water transport and any crop or livestock production losses can result in significant income losses for farmers and ranchers, higher food prices for consumers, unemployment, decreased land prices, population migration, and mental and physical stress (CWRM, 2017; Anderson et al. 2012). In some cases, federal insurance programs could mask or buffer the true financial impacts of crop losses, moreover, increased hedging by farmers on crop insurance may inadvertently reduce their cash flow and ability to respond to other disasters (Reyes et al., 2020).

Drought can increase threats to public health and safety from water shortages, wildfires, and even mosquito-borne diseases. An estimated 30,000 to 60,000 residents in Hawai‘i use rainwater catchment systems for drinking water (Macomber, 2010), and are the most directly impacted by drought and water shortages. Approximately 99% of domestic water used in Hawai‘i comes from groundwater (Gingerich & Oki, 2000). Future freshwater stress is expected to be particularly acute for island populations as evaporative demand increases and recharge rates are reduced (Holding et al., 2016; Karnauskas et al., 2016; Mair et al., 2019), which in combination with increased sea levels will likely enhance saltwater intrusion into groundwater (Gingerich & Oki, 2000; Polhemus, 2017). Wildfires have direct effects on human communities as they can damage infrastructure and other valued resources, and in some cases can result in road closures, power outages, and evacuations. Additionally for public health, droughts can result in more localized breeding sites for mosquitoes as streams dry and leave behind pockets of standing water, contributing to increased risk of mosquito-borne diseases such as the 2001-2002 dengue outbreak in Hawaiʻi (Kolivras, 2010). All of these may have negative effects on tourism, although the direct and indirect effects of drought on tourism have not been explicitly studied for Hawaiʻi.

Other human dimensions of drought, such as loss of educational opportunities, physical and mental health problems, interpersonal conflict, and loss of cultural traditions are not easy to quantify (Finucane & Peterson, 2010). Drought directly affects traditional and customary practices of native Hawaiian communities that rely on freshwater resources. These practices can include wetland cultivation of taro (*Colocasia esculenta*), gathering of aquatic and riparian species, traditional fishpond aquaculture, changes in nearshore fisheries, and change in accessibility of important freshwater heritage sites (springs and seeps) (CWRM, 2017; Frazier et al., 2019; Sproat, 2016). The socioeconomic impacts of drought in Hawaiʻi are severely understudied to date; more research is needed to identify the full range of direct and indirect socioeconomic effects of drought, and how these effects vary across communities.

5.6 Looking Ahead

Novel categories of drought are emerging due to anthropogenic climate change, expanding human water use, and land use change (e.g., "Hotter Drought" (Allen et al., 2015); "Flash Drought" (Otkin, 2018); "Human Induced" or "Human Modified Drought" (Van Loon et al., 2016); "Transformational Ecological Drought" (Crausbay et al., 2017)). These new forms of drought are increasingly difficult to anticipate and manage (Crausbay et al., 2020). Whether droughts in Hawaiʻi are beginning to show characteristics reflective of anthropogenic influence is unclear. However, the frequency, intensity, and duration of droughts were all higher in the second half of the study period (Figures 7, 9), with the two longest duration and most severe droughts in Hawaiʻi occurring since 1998. While the 2007-2012 drought was unprecedented over the past century (Figures 2, 7), detecting an anthropogenic signal at small spatial scales like that of the Hawaiian Islands is difficult, and at this time evidence suggests that rainfall changes in Hawaiʻi are still predominantly driven by large-scale modes of natural variability (Frazier et al., 2018). Regardless, these multi-year, severe droughts have serious biophysical and socioeconomic impacts on a diversity of sectors across the state. Work is ongoing to create an updated gridded SPI dataset for Hawaiʻi to allow for real-time monitoring and continue these analyses beyond 2012 (Lucas et al., *in Review*). From the USDM (Figure 2), additional drought periods in 2016, 2017, and 2019 are evident, highlighting the need for an SPI dataset that is updated near-real time.

If these regional trends of increasing frequency, intensity, and duration continue in Pacific Islands (Figure 8; McGree et al., 2016; 2019), it will become increasingly important for resource managers to proactively and comprehensively plan and design drought resilient management systems. Modeling studies of future conditions have shown that drier future climate conditions (Elison Timm et al., 2015) will result in lower groundwater recharge in already water-stressed leeward areas (Mair et al., 2019), and appropriate land management strategies can help mitigate the impacts (Brewington et al., 2019). A retrospective, lessons-learned approach to engaging drought planning can also lead to powerful insights about preparing for future drought (Frazier et al. 2019). Indigenous peoples living in drought prone areas have accumulated knowledge over many generations about how to persist and even thrive during droughts. Where possible, engaging traditional knowledge to inform actions will represent an important strategy for future drought mitigation and resilience efforts (Kagawa & Vitousek, 2012; Lincoln & Ladefoged, 2014). Researchers and resource managers need to collaborate closely to coproduce usable and actionable drought science to better navigate future novel drought conditions (Meadow et al., 2015).

6. Conclusions

Drought is a regular and natural component of the climate in Hawaiʻi with severe impacts across many sectors statewide. By coupling a quantitative SPI analysis with a review of the economic and ecological impacts of drought across different sectors, a more thorough understanding of historical drought trends can be used to better understand future projections in a given region. Although drought is experienced differently across landscapes, this combined analysis provides a framework that enables a holistic yet spatio-temporally relevant view that can contribute to more effective management. Recent droughts in Hawaiʻi have been the worst in the past 100 years, echoing increasing drought trends across the Pacific Islands. Longer duration and higher intensity droughts have brought attention to drought in a way that now points to the importance of higher-level responses that address policy and large-scale resource management practices. While residents are aware that Hawaiʻi is home to areas that are among the wettest on Earth, many areas of the state are highly vulnerable to drought, in particular, the dry, leeward parts of all islands, and the frequency, duration, and severity of droughts have all increased over the past century. This has critically important implications for: (*i*) sustaining the agricultural sector, especially rain-fed or surface water reliant farming and ranching; (*ii*) meeting the hydrological needs of municipalities and ecosystems that depend critically on groundwater; (*iii*) reducing the growing health and human safety impacts of wildland fire, which are increasing due to an expanding cover of non-native fire prone plants, a warming climate, and a worsening drought regime; and (*iv*) designing socio-ecologically based approaches to engaging a future world that will be warmer and, for large areas of Hawaiʻi, likely drier. Further drought research needs include real-time SPI updates, as well as additional research on ecological and socioeconomic drought impacts and the opportunities for policy and management to mitigate some of these impacts. To support resource management under a warmer and potentially drier future, and to understand how droughts and their impacts may change in the future as global temperatures continue to rise and the climate system becomes more variable, additional investments in understanding drought and protecting water resources are needed in Hawai‘i.

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