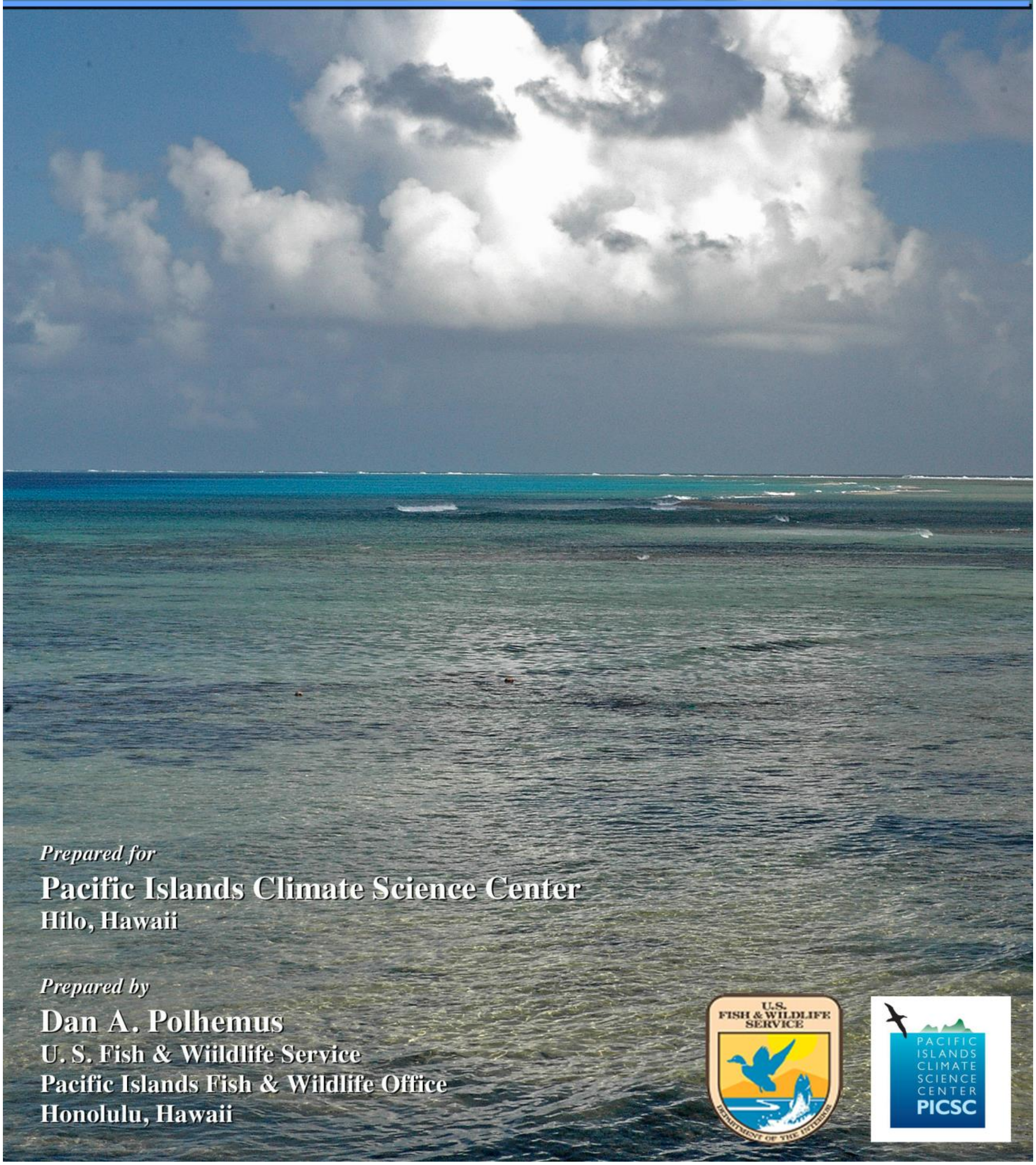
Drought in the U. S. - Affiliated Pacific Islands
A Multi-level Assessment

FINAL REPORT **July 2017**



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Cover photo: Convection over Kwajalein Atoll, Republic of the Marshall Islands

DROUGHT

IN THE U. S.-AFFILIATED PACIFIC ISLANDS:

A MULTI-LEVEL ASSESSMENT

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Abbreviations

ACI	Aridity Change Index
CNMI	Commonwealth of the Northern Mariana Islands
CTE	Cold Tongue El Niño Event
EEZ	Exclusive Economic Zone
FAO	Food and Agriculture Organization, United Nations
FAS	Freely Associated States
FSM	Federated States of Micronesia
ME	“Mixed” El Niño Event
NWS	NOAA National Weather Service, U. S. Dept. of Commerce
PDO	Pacific Decadal Oscillation
ENSO	El Niño /Southern Oscillation
IPCC	Intergovernmental Panel on Climate Change
PDSI	Palmer Drought Severity Index
RCP	Representative Concentration Pathways
RMI	Republic of the Marshall Islands
SPCZ	South Pacific Convergence Zone
SST	Sea Surface Temperature
USAPI	United States-Affiliated Pacific Islands
WNPM	Western North Pacific Monsoon
WPE	Warm Pool El Niño Event

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SCOPE AND CONTEXT OF CURRENT ASSESSMENT

Geographic Scope

Although the tropical Pacific islands are generally perceived as having wet climates, they are vulnerable to periodic episodes of drought. The current study undertakes a literature review to determine the current base of information relating to such drought events in the U. S.-affiliated Pacific Islands (USAPI), examining the phenomena at several different levels of cause and effect, including meteorological, hydrological, ecological, agricultural, and socioeconomic drought. As noted by Kruk et al. 2015, the Pacific islands have been largely overlooked in previous global or national-level studies of weather and climate (CCSP 2008; IPCC 2012), which have tended to disproportionately focus on continental areas.

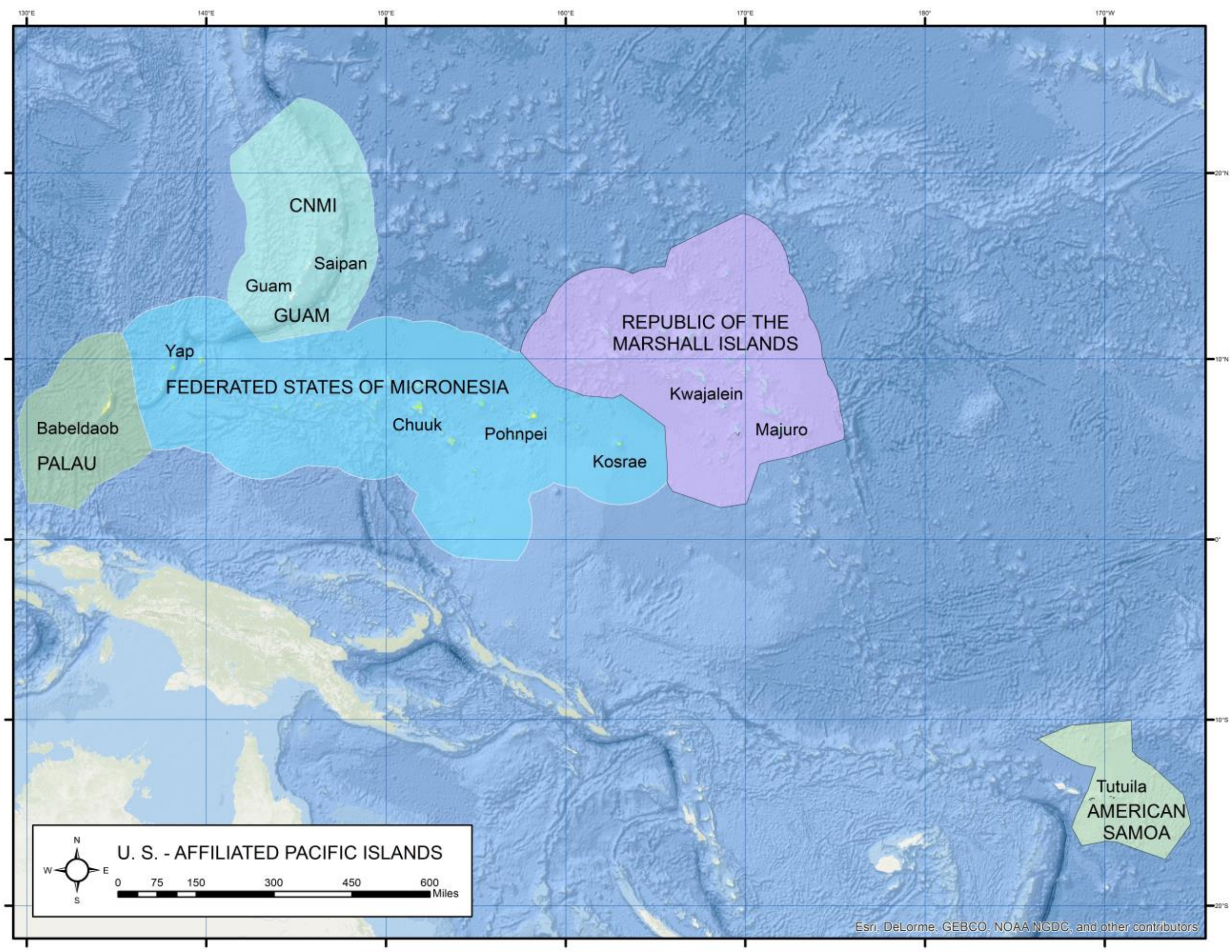

Figure 1. Map of the U. S-Affiliated Pacific Islands, showing EEZ boundaries and locations of major islands or atolls discussed in the text.

The USAPI as defined herein include approximately 2000 islands of varying sizes and elevations, lying in the Western Pacific in tropical latitudes within 20 degrees to the north or south of the equator, and including the U. S. jurisdictions of Guam, the Commonwealth of the Northern Mariana Islands (CNMI), and American Samoa, as well as the independent nations of the Republic of the Marshall Islands (RMI), the Federated States of Micronesia (FSM), and the Republic of Palau (Fig. 1). In combination, they occupy a wide range of latitude and longitude, from 20°30’N to 14°30’S, and from 171°56’E to 131°07’E, an aggregate east-west distance of over 2700 miles, which exceeds the width of the continental United States. All of these islands, except those of American Samoa, lie north of the equator in the broad region of Oceania known as Micronesia. As a result, these Micronesian islands possess some general similarities in regard to their overall climate regimes and meteorological forcing mechanisms. The Samoan Islands, by contrast, lie south of the equator, and as a result are subject to a somewhat different meteorological regime. Given this, the current study provides successive treatments of the Micronesian jurisdictions first, followed by a consideration of American Samoa. The State of Hawaii, which has been subject to significantly more previous analysis in regard to past and future patterns of temperature and precipitation (Kruk and Levinson, 2008; Chu et al., 2009, 2010; Diaz et al., 2005; Timm et al., 2011), is not included in the current study, which is restricted to the USAPI.

Overview of Climate Change Drivers and Impacts in the Insular Pacific

For the region under study, Kruk et al. (2015) drew a meteorological distinction between a Western North Pacific subregion, which they defined as extending from the coast of east Asia southward to the Equator and eastward to the International Date Line, and a South Pacific subregion, lying south of the Equator and extending from eastern Australia eastward to 135 degrees west longitude. In the Western North Pacific, weather and climate are strongly influenced by the trade winds, the North Pacific High, and the proximal East Asian Monsoon and local Western North Pacific Monsoon (WNPM) systems. In the South Pacific, by contrast, climate and weather are predominantly driven by the position of the South Pacific Convergence Zone (SPCZ), a branch of the larger Intertropical Convergence Zone (ITCZ), with some summer influence from eastern extension of the Australian Northwest Monsoon. Precipitation in both regions is also strongly influenced in any given year by El Niño—Southern Oscillation (ENSO) cycles, and by the number, severity and tracks of tropical cyclones. The latter appear to have decreased since 1990, both in the southwest Pacific (Diamond et al.2013) and globally (Webster et al. 2005; Maue 2011).

The USAPI jurisdictions are generally subject to similar climate variables driven by the larger Pacific Ocean as a whole. Meteorologically, all six areas lie within tropical latitudes, with consistently warm temperatures, high humidity, very high dewpoint temperatures of 75-80° F., high levels of precipitable water in the atmosphere in the range of 2-3 inches (51-76 mm), and average annual rainfall exceeding 70 inches (1778 mm) per year at all sites. Specifically, average daily air temperature is near 82° F. in the Marianas (Johnson 2012), 81° F. at Moen airport in Chuuk, in the Federated States of Micronesia (Takasaki 1989), and 81° F. at the airport on Tutuila in American Samoa (Izuka et al. 2005). Humidity on Guam ranges from 60-85% during the day, and 85-100% at night (Johnson 2012), and from 55-100% at Moen in Chuuk, generally exceeding 75 percent (Takasaki 1989). Similar patterns also prevail across the remainder of Micronesia and in American Samoa. Prevailing winds are northeasterly in the CNMI and on Guam, becoming lighter, more southeasterly and variable, with occasional periods of strong southwest wind, during the wet season from July to December (Johnson 2012); are predominantly from the east in the FSM and RMI, with occasional swings to the west and southwest in the summer months (Lander & Khosrowpanah 2004); and are predominantly southeasterly in American Samoa, becoming weaker and more variable from December to early April, with occasional gusts of northwest monsoonal winds (Izuka et al. 2005). All of the USAPI are vulnerable to strong tropical cyclones, which are often associated with extreme rainfall events (Lander & Guard 2003; Lander & Khosrowpanah 2004; Lander 2004; Kruk et al. 2015).

The impacts of modern industrial society are now being translated to these remote islands via climate change effects, in the form of rising and warming seas, increasing air temperatures, and potential changes in wave regimes and precipitation. Many of these threats are well delineated on a broad Pacific scale, but determining how they will manifest themselves locally within any given archipelagic or ocean sector is still difficult based on current climate models, and validation is hindered by inadequate local instrumentation networks. Despite these constraints, the overall scientific consensus is that the atmosphere and the ocean will continue to warm over at least the next 50–100 years, sea level will rise indefinitely due to thermal expansion of water and melting of land-based ice sheets, and circulation patterns in both the oceans and atmosphere are likely to change at local, regional and global scales (Bindoff et al. 2007; Gattuso et al. 2015). Storm intensity may also increase, and extreme flood and drought events may become more frequent (IPCC 2014). All of these aspects of climate change will impact the ecological and social systems of the tropical Pacific Islands, including the USAPI jurisdictions considered here.

In support of the larger National Climate Assessment effort, a Pacific Islands Regional Climate Assessment (PIRCA) was produced in 2012 (Keener et al. 2012). This document incorporated the contributions of nearly 100 independent experts, and evaluated the state of knowledge related to climate drivers, impacts, and adaptive capacity within three sub-regions of the Pacific: (1) the Western North Pacific (which includes the CNMI, Guam, Palau, the FSM, and the RMI); (2) the Central North Pacific (containing Hawaii, which is not treated further in this document); and (3) the Central South Pacific (which includes American Samoa). Within each of these sub-regions, three main focal areas were evaluated: (1) fresh water and drought; (2) sea-level rise and coastal inundation; and (3) aquatic and terrestrial ecosystems. The paragraphs below summarize the findings bearing on freshwater and drought; readers wishing greater detail should consult the PIRCA, which treats these subjects in far greater depth.

Depending on representative concentration pathway (RCP) model employed, CO_2 concentrations are projected to reach levels between 420– 935 parts per million (ppm) by the end of the century (IPCC 2014). As of May 2017 atmospheric CO_2 stood at 409 ppm, an increase of over 89 ppm from when standardized readings first began to be collected in the late 1950s at the Mauna Loa Observatory in Hawaii. The accumulation of carbon dioxide and other greenhouse gases in the atmosphere has led to warming of both the atmosphere and the oceans due to the enhanced greenhouse effect. Temperature projections from both the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (Parry et al. 2007) and the second national assessment (U.S. Global Change Research Program, 2014) indicate continued warming into the foreseeable future, with global average surface temperature projected to increase 1.2–6.4 C by 2100, with best recent estimates placing the range between 1.2 and 3.2 °C (IPCC 2104; Gattuso et al. 2015). Average tropical sea surface temperature (SST) is expected to increase by 50–80% of the average rate of atmospheric change (Guinotte et al. 2003; Lough 2007). Therefore, average sea temperatures in the USAPI will probably increase by 1-2 degrees Celsius over the course of this century. Such increases in ocean and air temperature are related to changes in atmospheric circulation patterns that may result in more severe periods of drought and more acutely episodic precipitation events, a trend already observed in Hawaii (Chu et al. 2010) where long-term stream and precipitation gauging records depict clear declines in precipitation and stream base flow over the past century, but high variations in stream total flow (Oki, 2004; Bassiouni & Oki 2013; Frazier & Giambelluca 2017).

Global circulation models project that under a global warming regime fewer tropical storms will form, due to increased propensity for wind shear in high SST environments (Nolan & Rappin 2008), but that those storms which do form will be more intense (Bengtsson et al. 2007). Modeling of the hydrological cycle under a regime of warming climate results in a projection of a 27% increase in atmospheric water vapor in the tropics over the next 100 years. Perhaps counter-intuitively, because this is also coupled with a longer residence time of water in the atmosphere, this increase in atmospheric water vapor does not necessarily result a marked increase in precipitation; instead, the moister atmosphere simply becomes capable of retaining greater heat content, thereby spawning stronger storms (Bengtsson et al. 2007). Global circulation models therefore project an increase in the proportion of extreme weather events in the most severe categories (Webster et al. 2005; IPCC 2104), with the associated potential for extreme precipitation events.

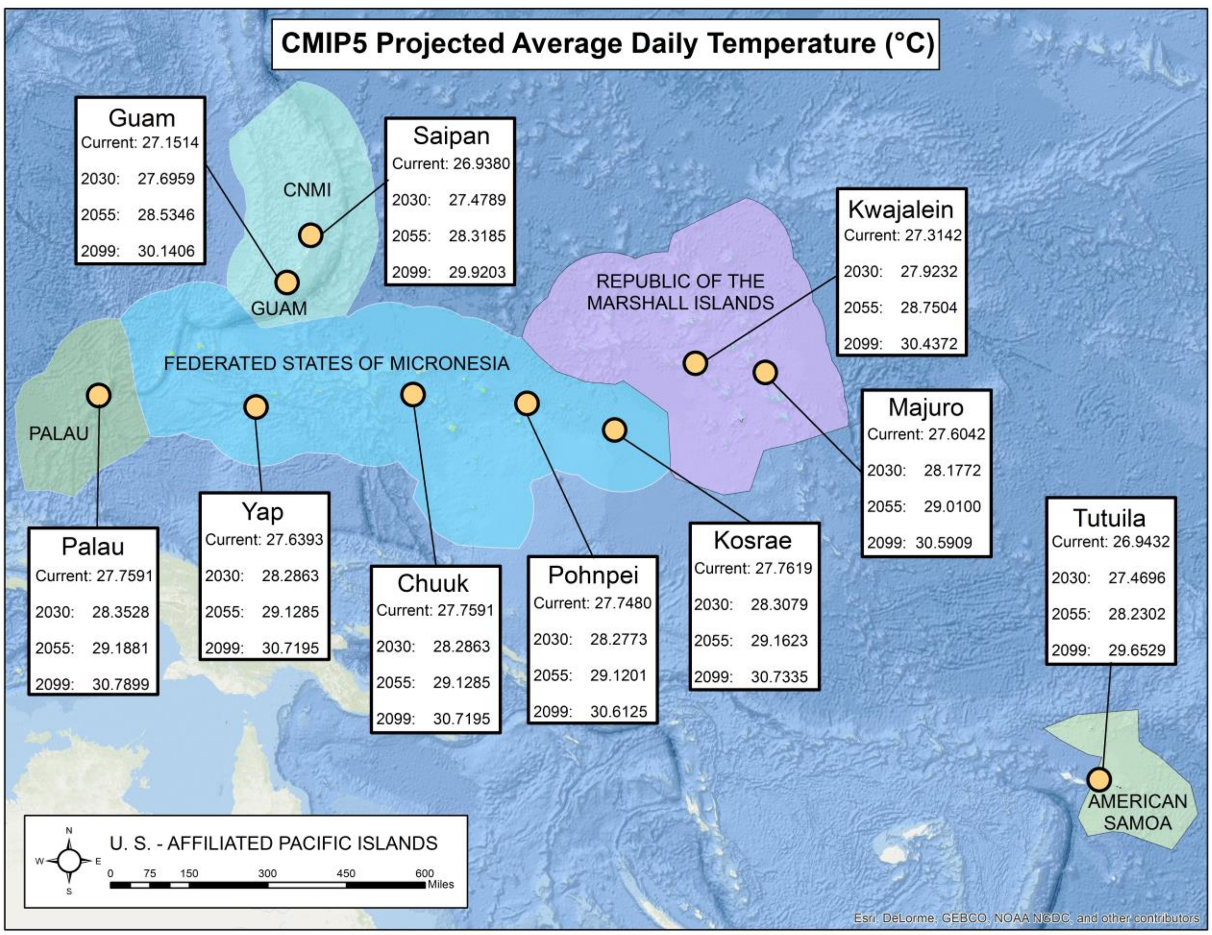

Figure 2. Projected increases in average daily temperature based on the CMIP5 model ensemble. Current baseline values represent 1995-2004 averages for each location. For supporting data see Appendix 1.

The intensity and frequency of days of extreme heat are also projected with high confidence to increase over the course of the 21st century for the regions encompassing the USAPI. The CMIP3 model ensemble under several emissions scenarios produced projections that annual surface air temperatures (SATs) for the Central South Pacific sub-region would range from 1.1° to 1.3°F higher than 1971–2000 averaged baseline values by 2030, 1.9° to 2.5°F higher by 2055, and 2.5° to 4.8°F higher by 2090 (Australian Bureau of Meteorology & CSIRO, 2011). Warming trends were similarly projected for the Western North Pacific, with annual SATs for all scenarios ranging from 1.1° to 1.3°F higher by 2030, 1.9° to 2.6°F higher by 2055, and 2.7° to 5.1°F higher by 2090 (Australian Bureau of Meteorology & CSIRO, 2011). A subsequent analysis using the CMIP4 model ensemble further supported these projections (Parry et al. 2007). Model runs from the current CMIP5 ensemble under RCP 8.5 generate somewhat revised projections, with SATs in the Central South Pacific sub-region ranging from 0.2° to 1.8°F higher than 1995-2004 averaged baseline values by 2030, 1.8° to 3.2°F higher by 2055, and 4.4° to 5.7°F higher by 2090, and similar values for the Western North Pacific ranging from 0.4° to 2.0°F higher by 2030, 2.0° to 3.5°F higher by 2055, and 4.8° to 6.4°F higher by 2090 (Fig. 2 and Appendix 1, Table 3).

For precipitation, projections of future trends across the USAPI are less well constrained than those for mean annual temperature. Whereas initial approaches to climate model downscaling are being undertaken

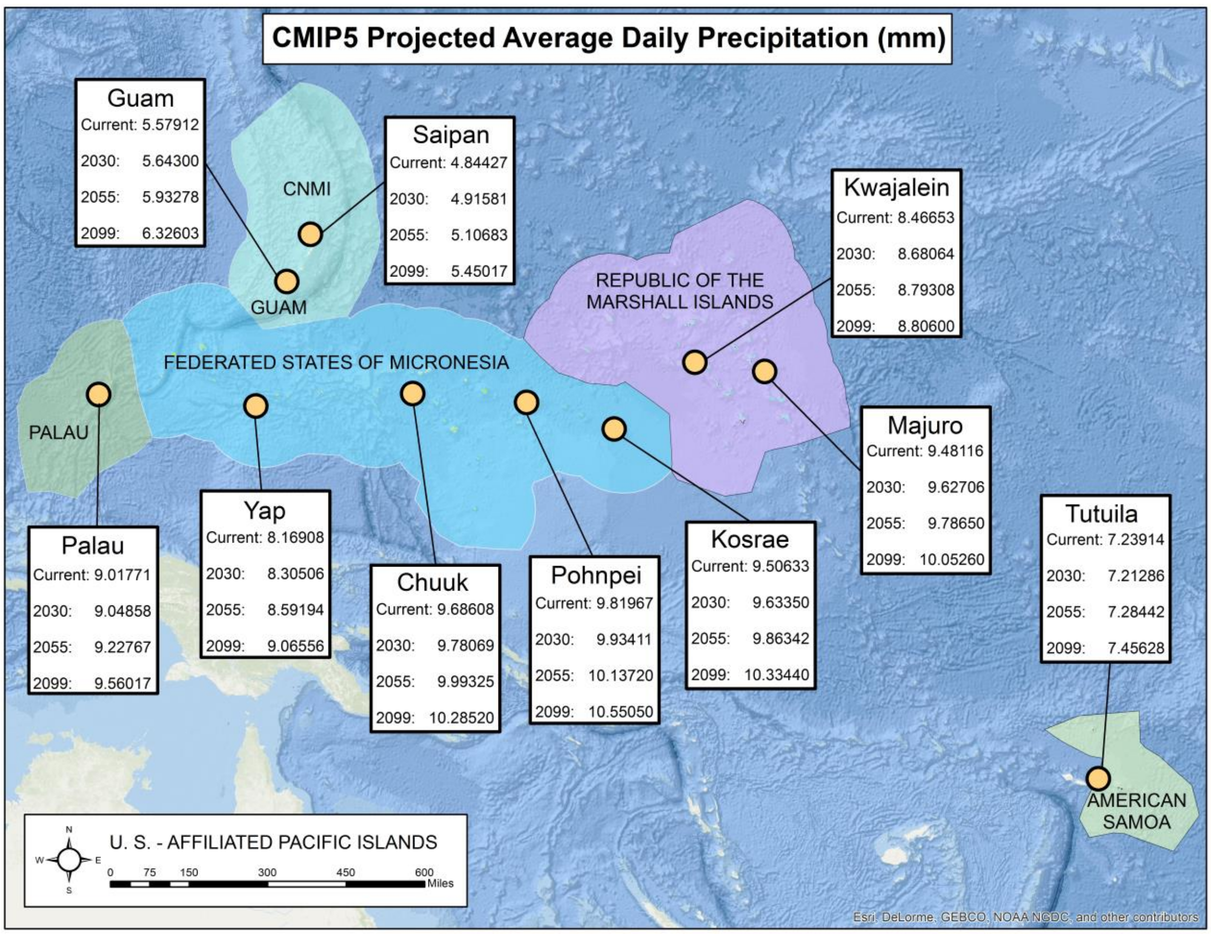

Figure 3. Projected increases in average daily precipitation based on the CMIP5 model ensemble. Current baseline values represent 1995-2004 averages for each location. For supporting data see Appendix 1.

for the Marianas and American Samoa, such efforts are incipient at best, and results of recently funded modelling are not yet in hand. Any projections therefore have considerable uncertainty, which can only be reduced by future improvements in regional model downscaling. An initial run with the current CMIP5 ensemble under RCP 8.5 produces projections that average daily precipitation will show a slight increases across all the USAPI between now and 2100, ranging from a 12-13 percent increase in the Marianas to a 3 percent increase in American Samoa (Fig. 3 and Appendix 1, Table 4). These projections do not, however, provide any information as to potential changes in the temporal distribution of rainfall within any given year.

The projected changes in ocean and atmospheric temperature, precipitation patterns, tropical storm intensity and sea-level rise over the coming decades all have serious implications for human communities and natural resources in the USAPI jurisdictions. The warming projected during the next 50 to 100 years will create heat-related stress for human communities, agricultural and water supply systems, transportation and other infrastructure, and increased extinction risk for native plant and animal species (Urban, 2015). Seasonal changes in precipitation patterns, coupled with increased temperature and evapotranspiration, have the potential for widespread and significant effects on water resources and agriculture, which will create both societal and ecological problems. Based on historical and projected patterns of land-cover change in this region, often associated with fire during drier periods, impacts from invasive species and human development are likely to amplify the adverse effects of climate change on habitats and species. The current study evaluates such impacts in the context of drought, with the understanding that drought stresses represent a synergy involving both precipitation and air temperature, and the temporal variations in each.

JURISDICTIONAL DROUGHT ASSESSMENTS

Although there is no single definition of drought, in simplest meteorological terms drought can be defined as a “prolonged and abnormal moisture deficiency” (Palmer 1965). This meteorological anomaly can in turn produce translated effects to hydrological, ecological, agricultural and socioeconomic systems. In order to describe and quantify these various manifestations of drought, over 100 different drought indices have been proposed (Zargar et al. 2011). It is not the purpose of the present review to strictly quantify drought in the USAPI, or to apply a wide range of indices to its description. Such an endeavor is beyond the scope of the present review, and would inevitably be constrained by the limited amount of information available regarding past droughts in the region. Instead, the current work provides an overview of the information available by which to evaluate past droughts in the USAPI, and seeks to synthesize this into a basis for more refined future study.

In each of the sections below, the individual USAPI jurisdictions are reviewed in regard to five separate types of drought, which are functionally linked. The precipitation deficit over a given period of time which characterizes meteorological drought eventually influences soil moisture content, which then leads to hydrological, ecological, and agricultural drought. The aggregate effects of these perturbations in turn create societal disruptions, or socioeconomic drought. The five types of drought considered in this review are as follows:

1) *Meteorological drought* – Meteorological drought is defined as a deficiency in precipitation caused by a change in its amount, intensity, or timing. Such diminished precipitation my often be accompanied by low relative humidity, reduced cloud cover, and consequently higher than average air temperatures, insolation, and wind.

2) *Hydrological drought* – Meteorological drought may lead to reduced runoff, soil infiltration, deep percolation and ground water recharge. This results in reduced streamflow, contraction of wetlands, and reduction of inflow into lakes, ponds and reservoirs.

3) *Ecological drought* – At the level of naturally occurring plant communities, meteorological drought may lead to increased evapotranspiration, soil water deficiency, and increased plant water stress. This in turn leads to drying and increased flammability of both living and dead fuels, promoting the spread of wildland fire. In extreme cases drought can lead to dieback of mature trees or forest stands even in the absence of fire, particularly on atolls. It is important to note that with increasing temperatures, ecological drought can occur even with slightly increased levels of precipitation, given the associated increase in evapotranspiration. Therefore, ecological drought must be viewed as an interaction of both precipitation and temperature acting in combination.

4) *Agricultural drought* – The ecological drought stresses noted above are also translated into agricultural systems, where they can lead to crop losses, stunted growth or mortality of cultivars, and consequent reduced yield.

5) *Socioeconomic drought* – The aggregate effects of the hydrological, ecological, and agricultural outcomes noted above may have profound impacts on local communities, ranging from lack of drinking water and shortages of food to spread of disease. Increased incidence of fire may also threaten lives and property.

For each of the six jurisdictions involved, a review of the literature has been undertaken to glean information relating to each drought category. In some cases this information is extremely limited, and clearly highlights areas in need for future research.

Commonwealth of the Northern Mariana Islands

The CNMI is the most northerly of the USAPI jurisdictions, extending from the island of Rota at 14°10’N, 145°13’E northward along an arc of progressively smaller islands to Farallon de Pajaros (also known as Uracas) at 20°32’N, 144°53’E. The population of approximately 54,000 is concentrated on the more southerly islands of Rota, Tinian and the administrative center at Saipan (Fig. 4), with most of the smaller islands in the northern section of the chain being lightly inhabited, if at all. The islands of the CNMI are derived from a volcanic island arc, having formed along a subduction zone at the Pacific Plate margin, and are generally steep sided, although Saipan does have an extensive reef-bounded lagoon and adjacent coastal plain on its western side. The highest point is Mt. Manira, on Rota, which rises to 1624 ft. (495 m.). The inhabited high islands in the southern end of the CNMI have thick limestone caps overlying volcanic basement rocks. As such, there are few perennial streams, except on the island of Rota, and even these latter emerge from caves not far above sea level at the bases of limestone escarpments.

Figure 4. Map of Saipan showing the location of the NWS rain gauge and other localities discussed in the text. The inset map at the upper left shows the relation of Saipan to other islands in the southern CNMI also discussed in the text.

Native forest cover has been extensively disturbed on Rota, Tinian and Saipan, but remains relatively intact on some of the northern islands, particularly Pagan, which is still volcanically active. The total land area of all islands in the CNMI combined is 183 miles^2 (475 kilometers^2), with Rota (33 miles^2), Tinian (39 miles^2) and Saipan (44 miles^2) accounting for the substantial majority.

Meteorological Drought

Long-term rainfall records in the CNMI are available only for the island of Saipan, and even these are badly fragmented. The period of record on Saipan extends from 1901 to the present, with significant gaps, based on German records from 1900-1912, Japanese records from 1924-1937, and American records from 1954 to present. There is some ambiguity as to the locations of the gauges involved, although all were located on the west side of the island, therefore their data are not precisely representative of any single location, and no single location has a 30-year record generally deemed necessary to establish an accurate rainfall climatology, although a 46-year record has been approximated by combining various data sets (Lander 2004). Based on these aggregate records, Saipan receives approximately 80 inches (2032 mm) of rainfall per year, with 67 percent of this arriving during the wet season which extends from July to November (Carruth 2003; Lander 2004). Intra-island variation in rainfall appears to span a relatively narrow range, from 75 inches (1905 mm) annually at the airport to 90 inches (2286 mm) annually at Capitol Hill (Lander 2004), with no pronounced leeward versus windward dichotomy. Air temperature data are also available from Saipan from at least 1954 to present, which could potentially be coupled with the rainfall data to generate a hindcast monthly Palmer drought index for this island spanning at least the past 46 years, or perhaps longer if older records were also incorporated.

Droughts linked to El Niño events can be severe in the CNMI, particularly in the typically drier months of December through June. During the 1982-1983 drought, Saipan received only 27 percent of its long-term average rainfall in the period from January to June 1983 (van der Brug 1986). During the 1998 drought, Saipan received only 34 inches (864 mm) of rainfall for the entire year, or 42.5 percent of normal, this being the lowest annual total recorded to that date; in particular, rainfall for the month of January 1998 was only 0.1 inch (2.5 mm) (Carruth 2003). On Tinian, the annual rainfall in the 1998 drought year was 43 inches (1092 mm), 53 percent of the normal 81 inches (2057 mm) (Gingerich 2002). Similarly, on Rota, rainfall for the entirety of 1998 was only 58 inches (1473), representing 60 percent of the island's long-term annual average of 95 inches (Carruth 2005). Based on data presented in van der Brug (1986), very low dry season monthly rainfall totals for certain individual months were also recorded on Saipan in 1912, 1936, 1967, and 1978, which may provide some additional indication of drought periodicity.

At the opposite end of the spectrum, tropical cyclones can bring heavy rains to Saipan and the other islands of the CNMI. This was well illustrated in 1978, when tropical systems Carmen, Winnie and Tess passed over the island, creating an annual rainfall total of slightly over 145 inches (3683 mm). Even so, there appear to have been a decreasing number of such extreme rainfall events in the CNMI since 1950 (Lander & Guard 2003; Lander & Khosowpanah 2004).

Hydrological Drought

Almost no perennial streams exist in the CNMI. The few that are present occur on Rota, where they emerge from caves near sea level, and as such represent basal leaks from the overlying aquifer. None appear to be actively gauged.

On Saipan, there are numerous small springs originating from elevated limestone aquifers in the central uplands of the island, but few are monitored. Discharge was measured at Donni Spring from 1952-1954, and again from 1969-1983 using a continuous-recording gauge, and streamflow was measured on the South Fork of Talufofo Stream from 1968-1983. During the drought of 1982-1983, flow at Donni Spring registered only 69 percent of normal, and stream flow in Talufofo Stream only 13 percent of normal, dropping to less than one-tenth of a cubic foot per second (van der Brug 1986). Gauging efforts were discontinued in 1983, so no further data for surface water flows are available subsequent to that year. As such, it is not possible to quantitatively evaluate the effect of the 1998 or 2016 El Niño droughts on surface hydrology.

Because Saipan relies on a network of 140 shallow ground water wells for 90 percent of its municipal water supply, there are 6 monitor wells present in the various major lowland aquifers on the island. Records from these wells allow an assessment of hydrological drought in the context of subsurface waters, and indicate that during the 1998 drought the thickness of these freshwater lenses decreased by 25 percent. Recovery from such depletion required several years following the return of normal rainfall regimes (Carruth 2003). By contrast, these well heads were not appreciably affected by the 2016 drought (Lander, pers. comm.).

On Rota, the major town of Songsong was supplied in the 1980s by the high-level, high-volume Lupig Spring, which rendered that island’s water source less susceptible to drought-induced depletion or salinity intrusion. By the time of the 1998 drought, water was being supplied by the Matan Hanom and As Onan springs, both of which exhibited reduced flow volume from April through June of that year (Carruth 2005). Following the 1998 drought several new upland wells were drilled on the plateau near Sinapalo, and water supply disruptions were recorded on Rota during the 2016 drought, although its small population of 3000 people exerts far lesser demand than is present on more heavily inhabited Saipan.

Ecological Drought

Overall, there appear to have been few studies directly assessing the ecological impact of drought in the CNMI. The Commonwealth’s forest resource and assessment strategy (CNMI SWARS 2010) does not identify drought as a major threat to forests in the jurisdiction, although it is noted that wildfires are more common during the dry months of March through July. Because nearly all wildland fires in the CNMI are anthropogenic in origin, set by arson, carelessly discarded cigarettes, or hunters seeking to provide new grass shoots for introduced deer, the number of ignitions seems to hold relatively constant from year-to-year, irrespective of drought.

Agricultural Drought

The agricultural impacts of the 1983 drought on the CNMI were relatively minor, in large part because the jurisdiction does not have a well-developed commercial agriculture sector, with most farming being done for subsistence purposes. There was some impact to livestock, with cattle production on Tinian declining by 11 percent during the 1983 drought period (van der Brug 1986), with additional losses in 1998, due to lack of forage (Guard, pers. comm.).

Socioeconomic Drought

Ninety percent of the municipal water supply on Saipan is obtained from a system of 140 shallow wells (Carruth 2003). During periods of drought, increased pumping rates and the thinning of the freshwater lens can cause a rise in chloride concentrations in these wells, rendering the water brackish. On Saipan during the 1983 drought, excessive pumping from low-lying wells caused their chloride concentrations to rise to over 1000 mg/L. This led to increased pumping of perched water wells at Akgak and from the infiltration tunnel at Maui I, near Saipan airport, leading to alarming drops in the water level of the former, and temporary drying and loss of production at the latter (van der Brug 1986). The result was a minor reduction in the periods of water service, with increasingly brackish water being supplied.

Tinian has a surface geology that is over 95 percent limestone and possesses no surface streams, so all municipal water is supplied by wells, which have potential vulnerabilities during drought periods similar to those seen on Saipan. The majority of municipal water supply was obtained from the Municipal Well from 1945 to 1999. Although several minor irrigation wells on Tinian went dry during early 1983 (van der Brug 1986), there were no municipal water service disruptions at that time.

During the 1998 drought, wells on Saipan were again pumped to their limits, and the average chloride concentrations in certain production wells again increased to 1150 mg/L, which is far above WHO standards for drinking water (Carruth 2003). This reduction in water quality and quantity again led to temporary shortages and water restrictions on Saipan. On Tinian, two additional wells had been added to the municipal system in 1997 to provide additional capacity during peak demand hours, and as a result the island did not suffer any reductions in water service or quality (Gingerich 2002). On Rota, two major perched springs supply the central water system; discharge from both also declined during the drought of 1998, leading the Commonwealth Utility Service to restrict water deliveries and usage for the period from April through June of that year (Carruth 2005). In all these cases, the reduction in water supply created minor social inconvenience, but did not rise to the level of an emergency.

More recently, in 2000 a new infiltration gallery was built on Tinian to supersede the Municipal Well, which is now held as a reserve facility. Recent groundwater modeling indicates that this island now has sufficient infrastructure and water supply to cope with another drought of 1998 magnitude (Gingerich 2002). By contrast, the more populous island of Saipan is rapidly approaching the limits of its sustainably exploitable ground water supply (Carruth 2005). During the 2016 drought chloride concentrations again begin to rise in the island’s shallow wells (PEAC 2016b), but supplies from these were not curtailed or interrupted. By contrast, the Donni Spring pumping station did lose the ability to draw water, resulting in a loss of 24-hour municipal service in the tourist hub of Garapan, although water was flowing downstream from the pump (Lander, pers. comm.). In response to these looming supply limitations, some of the larger resort hotels have now begun to purify their own water (Guard, pers. comm.).

Territory of Guam

Guam is the largest and southernmost island in the Mariana Archipelago, lying immediately south of the CNMI at 13°27'N, 144°47'E. It is also the most populous of the Mariana Islands, with 162,000 residents, and as such the most populous USAPI jurisdiction. Guam is of hybrid geological origin, consisting of volcanic uplands on the southern half and an elevated, cliff-bound limestone plateau in the north (Fig. 5). The highest point on the island is Mt. Lamlam, in the southern highlands, which reaches 1334 ft. (407 m.). The coastlines of Guam are for the most part steeply dropping, although there are extensive beach areas on the western side at Tumon and Agana bays, and a reef-fringed lagoon in the south at Merizo. In contrast to the CNMI, Guam has a large number of perennial streams, although all of these occur in the volcanic southern portion of the island. Native forest cover on Guam was extensively damaged during World War II, but has regenerated in many areas of the north, which are under military control, while continuing to suffer regular damage from poorly controlled wildland fires in the south. Despite consisting of only a single island, the Territory of Guam has a total land area of 212 miles^2 (549 kilometers^2), which is larger than the combined land area of all the islands within the CNMI.

Meteorological Drought

Guam exhibits a pattern of alternating annual wet and dry seasons similar to that of the CNMI, with a wet season from July to December, during which two-thirds of the annual rainfall occurs in a typical year (Lander 1994), and a drier season from January to June, during which mean monthly rainfall is less than 8 inches (203 mm) (Johnson 2012). It is estimated that somewhere between 12 and 30 percent of Guam's wet season rainfall is produced by the passage of tropical cyclones within 180 nm, with the remainder arising through convection (Lander 1994; Johnson 2012). Although rainfall data has been collected from over 60 sites on the island since 1906, most of these gauges have short periods of record (excepting the military measurements taken at Sumay from 1906-1941), so that our understanding of long-term rainfall climatology from 1950 to the present is largely based on records from a limited number of gauges at Umatec, Ylig River, the former NWS meteorological observatory at Taguac, Andersen Air Force Base, and Naval Air Station Tiyan (Fig. 5), the latter two stations having the longest periods of record (Lander & Guard 2003). Mean annual rainfall at the various locations gauged on Guam ranges from 84-116 inches per year (2134-2946 mm) (Johnson 2012), with the wettest areas in the southern mountains, and the driest areas at scattered points along the west coast (Lander & Guard 2003). Average over-water rainfall away from land is 100 inches (2540 mm) per year, about two-thirds as much as occurs in the Caroline Islands to the south. Rainfall data from 1950-1979 were compiled by Beck (1980), and a 50-year rainfall climatology from 1950-1999 was generated by Lander & Guard (2003).

Inter-annual rainfall on Guam is strongly influenced by ENSO cycles, with droughts tending to occur in the winter and spring seasons following an El Niño event (Lander 1994). For example, droughts which occurred on Guam in 1965, 1973, 1977, 1983, 1987, 1998 and 2016 were all correlated with El Niño events, with the 1973, 1983, 1998 events being particularly severe. The period from 1969-1973 still stands as having the lowest total rainfall of any 5-year period recorded at the NWS observatory at Taguac (Gingerich 2013). During the 1983 drought, the Taguac station received only 29 percent of its long-term average rainfall in the period from January-June 1983, this being the least rain recorded to date in any dry season on Guam (van der Brug 1986). The Taguac station was regrettably deactivated in 1995, just prior

Figure 5. Map of Guam, showing locations of rainfall gauging stations discussed in the text.

to the particularly severe drought of 1998, so did not record comparative data for this latter event. At other longer-term recording stations on Guam, 1998 had the lowest full-year rainfall total in a century (Lander & Guard (2003), with the island recording only 65.6 percent of average precipitation.

In addition to ENSO, other longer-period cyclic phenomena may also influence rainfall on Guam. A hindcast analysis of cave dripwater and stalactite formation on Guam as a proxy for surface rainfall indicates that the island experienced periods of reduced groundwater recharge from 1875-1925, 1955-1975, and 1995-2005 (Partin et al. 2012). It should be noted that these periods of drought inferred from stalactite formation span multiple ENSO cycles, but roughly correspond to negative phases of the Pacific Decadal Oscillation (Fig. 6).

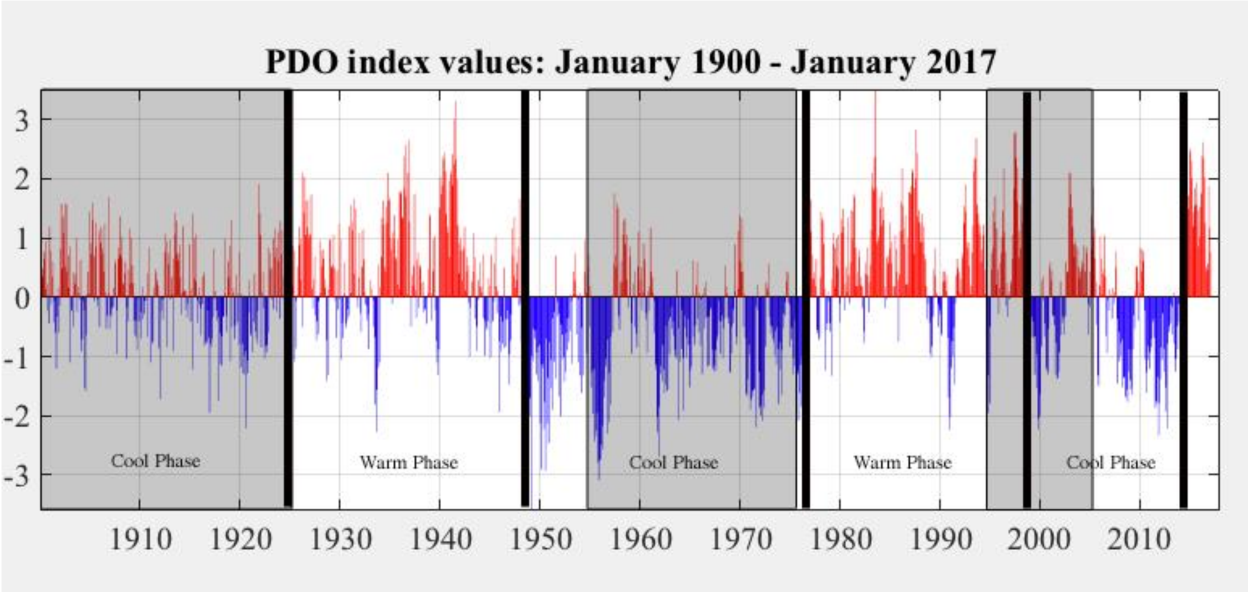

Figure 6. Periods of reduced water recharge on Guam (grey bands) as indicated by cave dripwater isotope ratios and stalagmite formation (Partin et al. 2012) superimposed on a plot of the Pacfic Decadal Oscillation. The transitions between warm and cool phases of the PDO are indicated by thick vertical bars. The cave dripwater data were collected only through 2010 so no inferences can be made subsequent to that year.'

Hydrological Drought

Assessing hydrological responses to drought on Guam is complex, in that the island is divided into two discrete geomorphological units: southern Guam, which has low permeability volcanic terrain drained by numerous perennial streams, and northern Guam, which is an elevated limestone plateau of high permeability that lacks flowing surface watercourses but contains large subsurface aquifers (Johnson 2012). In this regard, the island functions as two disparate units in regard to its hydrological response to precipitation inputs, with volcanic southern Guam being a surface water sector, and limestone northern Guam being a groundwater sector. In southern Guam, data are available from 19 USGS stream gauging stations with periods of record extending from 1951 to the present, although none of these gauges have continuous records for this entire period, 10 of these gauges do not have records extending beyond 2003, and only two of the gauges having more than 35 years of record are not affected by upstream diversions (Keener et al. 2012; Heitz & Khosrowpanah 2015). Critically, 14 of these 19 gauges were either out of service or temporarily inoperative during the severe El Niño drought of 1998, significantly reducing the surface flow hydrological record for that event.

The Guam stream gauging network does, however, provide useful data on drought events preceding 1998. In particular, the period from 1965-1966 was marked by very low rainfall on Guam, which led to record low stream flows at all operating gauging stations for the months of November through May. These low records from mid-1960s were not broken during the 1982-1983 drought, even though rainfall was less during this later period than in the mid-1960s. Readings from gauging stations with shorter periods of record, established subsequent to the 1960s, also indicate other periods of low discharge in 1973, 1975 and particularly 1979, when 3 of 7 gauges recorded all-time low discharges that were not equaled in 1983 (van der Brug 1986). Overall there is a strong correlation and in-phase tracking between annual rainfall and stream discharge in southern Guam, although the relationship is not strictly linear. As noted by Lander (1994), maximum streamflow peaks in an average year strongly match maximum medial rainfall, which occurs in September, whereas minimum stream flows have a lag, occurring in April, about one month after the normal annual rainfall minimum. The above data, fragmentary as it is, clearly demonstrates a relationship between meteorological and hydrological drought on Guam, and also suggests that the average return interval for severe droughts may be close to 10 years.

Recharge rates for Guam's aquifers were investigated by Johnson (2012), who estimated that under drought conditions the recharge rate was 32 percent lower than mean baseline recharge. Increased reliance on pumping from the island's freshwater aquifers during periods of drought caused decreases of 10-50 ft in the thickness of the lens in the Yugo-Tumon basin (Gingerich 2013), with recovery to pre-drought conditions requiring 5 years, and occurring primarily during the wet seasons (Partin et al. 2012). Based on readings from Well A-20 in northern Guam, which is not heavily influenced by tidal cycles, Lander (1994) concluded that the water levels in the aquifer during a typical year ran essentially 180 degrees out of phase with annual precipitation cycle, with the water level in the well peaking in February, 6 months after the maximum rainfall was received in September. This represents a significant lag between the time rainfall reaches the ground and when it actually enters the water table, indicating that it may take up to half a year to initiate aquifer recovery following a period of drought.

Ecological Drought

The most obvious ecological effect of drought on Guam is increased incidence of wildland fire. The frequency of such fires on Guam was analyzed by Minton (2006) for the period from 1979-2000. He noted that although the island averaged 730 fires per year over this period, burning an annual average of 4800 acres (1942 hectares), the incidence of fire was highly variable from year-to-year, with a low of 152 ignitions in 1994, and a high of 1944 ignitions in the severe drought year of 1998. As in the CNMI, fires were concentrated in the dry season months, with over 95 percent of ignitions occurring between January and June. Overall, Minton (2006) concluded that annual fire variability was strongly correlated with rainfall, in regard to both the number of fires (Pearson correlation; ρ = -0.82; p = <0.001) and fire size (Pearson correlation; ρ = -0.69; p = <0.001). Years immediately following ENSO events also displayed a significantly higher incidence of fire with the number of fires more than doubling and the number of acres burned more than tripling in comparison to non-ENSO years, implying a link between El Niño-mediated droughts and subsequent fire frequency and size. In recent decades, particularly severe fire seasons occurred on Guam in 1983, 1987, 1988, 1992, and 1998 (YSDPS 2009).

The proliferation of wildland fire on Guam during drought years was also noted by Lander & Guard (1994), who also commented in passing on other ecological effects of drought, including shedding of leaves by certain species of trees and drying of grasslands. Mortality in ironwood trees (*Casuarina* sp.) as a result of drought was also alluded to by Mafnas (2010). Other documented manifestations of ecological drought on Guam include yellowing vegetation and cracks in areas of clay soil (PEAC 2016c). Initial points of ignition are often concentrated along roadways, where discarded cigarettes can easily ignite fuels in these areas where ground surface temperatures are much higher than ambient air temperatures, and relative humidity is very low (Guard, pers. comm.).

The translated ecological effects of increased wildland fire on Guam include spread of invasive, non-native grasses which promote additional fire and loss of remaining forests, as well as higher rates of erosion from the burned areas resulting in increased sedimentation deposition on adjacent coral reefs. In particular, Minton (2006) found a six-fold increase in erosion rates from recently burned savannahs in the Piti-Asan watershed, and a two-fold increase in such sedimentation even after some degree of recovery two years later, in comparison to unburned areas. As such, ecological drought in Guam can include impacts to both terrestrial and nearshore marine systems.

Agricultural Drought

Agriculture on Guam consists of both commercial agriculture, mostly for local sales in the Guam and Saipan market areas, and subsistence agriculture for home or family consumption. Agricultural production statistics compiled by Khamoui (1984) for the period from 1970-1983 reflect significant losses of production for many crops on Guam during the drought of 1983. During this dry period, production of taro fell by over 90 percent; breadfruit, bananas and avocadoes by over 60 percent; and coconuts by over 50 percent. By contrast, production of sweet potatoes and yams was not strongly affected.

This pattern of lost agricultural production does not appear to have been repeated during the 1997-1998 drought. Agricultural statistics for the period 1998-2007 (BSP 2013) show no obvious loss of yield in 1998 as compared to subsequent years for the crops noted above, and in fact production for many crops declined by 2007 compared to 1998 levels, possibly due to economic factors unrelated to drought, or changing land use practices.

Socioeconomic Drought

Guam has a central water system that taps a network of about 75 wells in the elevated aquifer on the northern part of the island. This water system was basically unaffected by the 1982-1983 drought, although a few local communities utilizing spring and stream water sources on the south end of the island, notably Umatac and Merizo, did experience water shortages during this period (van der Brug 1986). Between 1970 and 2010, however, the population of Guam increased from 86,000 to 181,000 residents, and consequent withdrawals from the freshwater lens of northern Guam increased threefold, from 15 to 45 million gallons per day (Johnson 2012). As a result, the aquifers of Guam are now more potentially vulnerable to drought-linked depletion than in the past.

Republic of Palau

The Republic of Palau lies in the western North Pacific to the southwest of Yap, being roughly equidistant from both the Philippines to the west and Indonesian New Guinea to the south (Fig. 1). The country contains a diverse mixture of island types, including the high island of Babeldaob in the north (Fig. 7) which contains both volcanic and metamorphic rocks; numerous smaller but steeply elevated limestone islands with some intermixed volcanic rocks, including Koror, Peleliu, Angaur, Ngeruktabel and Mecherchar, as well as many dozens of uninhabited karst pinnacles in the Rock Islands area; the low-lying Kayangel Atoll in the far north; and a set of very isolated islands far to the southwest including Hatohobei Atoll and Tobi, which lie closer to Indonesia than to Babeldaob. These 250 islands are distributed in a roughly northeast to southwest alignment along the western margin of the Caroline tectonic plate, from the small islet on Velasco Reef in the north at 8°10’N, 134°28’E to Tobi in the south at 3°00’N, 131°07’E. The relatively modest population of approximately 21,000 is largely concentrated on the island of Koror, although the administrative center is at Melekeok on Babeldaob. The population is relatively aggregated, with only 9 of the approximately 200 islands in Palau being permanently inhabited. The highest elevation in the Palau is Mt. Ngerchelchauus on Babeldaob, at 794 ft. (242 m.). There are also numerous perennial streams on Babeldaob, many of which form attractive waterfalls, while the remaining islands, being porous limestone or sand, have few permanent watercourses, although flowing springs may be present. Native forests are dense and species-rich, due to the close proximity to Asian and Melanesian source areas, and although forest cover is now heavily disturbed in many parts of Babeldaob, it remains by contrast relatively intact on the steep, rugged limestone islands. There are also extensive mangrove stands along the western coast of Babeldaob. Palau contains 179 miles^2 (465 km^2) of land, giving it the largest land area of the three FAS nations, with 75 percent of this total represented by the large island of Babeldaob. Palau’s maritime boundaries are still the subject of a dispute with Indonesia in the Tobi sector.

Meteorological Drought

Rainfall records for Palau consist primarily of data from a gauging station on Koror (Fig. 6), which has a long period of record, although with some gaps, for the years 1905 to present. This includes German records from 1905-1912, Japanese records from 1924-1941, and American records from 1947 to present. These data were summarized as monthly mean values and extremes through 1982 by van der Brug (1984c), and potentially allow the generation of a hindcast monthly rainfall climatology for Koror spanning the past 110 years. Scattered shorter term rainfall records are also available from 9 rain gauges that were operated at various times between 1924 and 1983 on the large island of Babeldaob, and 4 other gauges that were present on the smaller islands of Koror, Malakal and Ngerekebesang; the locations of these gauges are shown in Figs. 7 and 8 of van der Brug (1984c). Most of this rainfall data was provided as monthly records for the various gauging stations involved by van der Brug (1984c); air temperature records are also available from Koror from 1945 to present, and were summarized as monthly and annual means for each consecutive year from 1948-1981 by van der Brug (1984c). If integrated with NWS air temperature data recorded subsequent to 1981 and the historic base of rainfall data noted above, a hindcast monthly Palmer drought index at Koror could thus potentially be generated for the past 60 years. Air temperatures at sea level in Palau are remarkably stable, with the mean annual temperature during the 1945-1981 period varying by only 1° C, and the difference between the long term mean of the warmest

Figure 7. Map of northern Palau, showing locations of major islands and rainfall gauging stations discussed in the text.

versus coldest month in any given year varying by only 0.8° C van der Brug (1984c). Therefore, any calculation of drought stress in Palau is likely to be predicated largely on variations in rainfall.

During the 1982-1983 drought, rainfall for the January to May 1983 period was 29 percent of the long-term average, and was the lowest on record to that time during the period from February to March inclusive. Calculations by van der Brug (1986) led him to conclude that the probable recurrence interval of such a drought in Palau was 125 years. However the drought of 1997-1998, a mere 14 years later, was even more severe, with the meteorological station at Koror recording only 86.09 inches (2187 mm) for the period from August 1997 to July 1998 , making this the driest 12-month period in the 80-year precipitation record at that site, which includes data from the period of Japanese administration. This record precipitation deficit was nearly reached again 17 years later during the 2015-2016 drought, when rainfall in the 12-month period from April 2015 to March 2016 was 86.25 inches (2191 mm) (PEAC 2016c). All of these droughts were correlated with strong El Niño events, and at least based on the record of the past eight decades, it appears that the recurrence interval for severe meteorological drought in Palau may be on the order of 10-15 years. Concurrently, precipitation may have become more episodic, since Kruk et al. (2015) concluded that there had been an increasing number of 1-day (24-hour) extreme rainfall events in Palau over the past century.

Hydrological Drought

Palau has numerous freshwater streams, predominantly on Babeldaob and some of the other northern islands. The limestone islands of the country lack watercourses. Stream flow data was recorded during the Trust Territory period from 1969 onward at six continuous record gauging stations on Babeldaob, although not all these gauges have congruent periods of record. An additional 4 partial record gauges were also operated for various periods of time on Malakal and Ngerekebesang (for locations of all the above gauges see Figs. 9 and 10 in van der Brug (1984c).

Of the Babeldaob gauges, 5 were operational during the 1982-1983 drought. Based on these records, stream flow on Babeldaob declined to 16-20 percent of long-term averages during the period from January to May 1983, with the Diongradid River in northern Babeldaob exhibiting its all-time record low discharge up to that date (van der Brug 1986). This demonstrates a clear relationship between meteorological and hydrological drought for flowing surface waters in Palau. Based on data from the Babeldaob gauges for the period from 1972-1981, a runoff-to-rainfall ratio was calculated, indicating that approximately 70 percent of the rain falling on the island runs off into the sea (van der Brug 1984c), once again emphasizing the strong and relatively linear relationship between rainfall and stream discharge on this island, where base flows are low but total flows are high. As a surface water sector with limited infiltration, Babeldaob is thus remarkably vulnerable to hydrological drought during periods of depressed rainfall, such as those of 1982-1983, 1997-1998, and 2015-2016, even when annual calendar year rainfall totals exceed 100 inches (2540 mm). As noted by PEAC (2016c): “It is hard to imagine that an annual sum rainfall of approximately 100 inches could set an all-time record low. That is, however, the case for Koror, Palau, where the 2015 annual total rainfall of 97.06 inches (66%) recorded at the Koror Weather Service Office was the driest calendar year in the stations 63-year post WWII climate record.” Dry periods such as this rapidly reduce water production from the Babeldaob catchments, leading to acute water shortages in storage reservoirs.

Ground water lenses are poorly developed on Babeldaob, due to its laterite clay soil overlying impermeable volcanic bedrock. Only 30 percent of the annual rainfall infiltrates, so only small springs are present, and dug wells are of necessity shallow and monitoring wells are absent. Therefore, assessing the effect of drought on the ground water resources of Babeldaob is difficult. The limestone islands of Pelieliu and Angaur, by contrast, are more porous have well developed aquifers that allow practical development of groundwater wells, but because most wells are located at low elevations, their water tends to be somewhat brackish, so the inhabitants of these islands largely rely on rainfall catchments for drinking water. There do not appear to be any monitoring well records for these islands that could be used to evaluate hydrological drought.

One available example of the linkage between meteorological and hydrological drought in Palau involves the population center of Koror, which has typically obtained its municipal water via pipeline from reservoirs constructed on rivers in southern Babeldaob. During World War II these supply systems were destroyed, so immediately following the war the town switched to using flow from the Elodesachel Spring on Koror Island for its municipal needs. This spring, originating from limestone, discharges 5000-50,000 gallons per day, depending on the season of the year. A drought year in 1948 nearly eliminated the flow from this spring, however, necessitating construction of a new reservoir and pipeline system on the Ngerimel River (van der Brug 1984c). Both the seasonal fluctuations in the discharge of this spring, and its near disappearance during a drought year, thus serve demonstrate the close linkage between ground water discharge and precipitation on the limestone islands of Palau during periods of drought.

Ecological Drought

As with most USAPI jurisdictions, studies of the ecological effects of drought on Palau's ecosystems are very limited. Wildland fire is again the most obvious ecological manifestation of drought, with the incidence increasing during ENSO-related drought years (Kitalong 2010), including large, uncontrollable fires that burn across the remote savannah areas of Babeldaob and into the riparian gallery forests along the major rivers. As in the other USAPI jurisdictions, fire frequency is highest during the months of lower rainfall, these in the case of Palau being February-April. Even so, the frequency and extent of wildland fire is much lower in Palau than in the Marianas, with Babeldaob reporting 68 fires burning 17 acres (7 hectares) in the period from 2007-2009 (Kitalong 2010), compared to an average of 730 fires burning 4800 acres (1942 hectares) on the island of Guam, which is only 1.6 times larger (Minton 2006). Overall, it appears that Palau's wetter climate, higher degree of forest cover, and numerous uninhabited limestone islands serve to reduce the impact of drought-related fire in comparison to other areas in the USAPI.

During the 2015-2016 drought, which included the second-driest 12-month period on record for the weather station at Koror, several additional ecological manifestations of drought were observed. These included the yellowing of vegetation on the limestone pinnacle islands in the central part of the archipelago, and a major die-off of jellyfish in the popular Jellyfish Lake, apparently due to reduced freshwater inflows (PEAC 2016b). It is not clear if the latter phenomenon was strictly linked to drought, or was the result of other ecological drivers triggered by the 2015-2016 El Niño.

Agricultural Drought

Agriculture in Palau consists primarily of subsistence agriculture involving traditional crops such as bananas, breadfruit, taro, yams, sweet potatoes and coconuts for home or family consumption. The 1982-1983 drought had significant impacts to such traditional agriculture in Palau, although the effects were disparate in relation to the cultivars involved. Losses to taro (which requires irrigation) and cassava crops on Babeldaob ranged from 80-95 percent, while by contrast banana and coconut trees were little affected on this high island (van der Brug 1986).

Socioeconomic Drought

The central municipal water system for the major population center of Koror and adjacent Malakal and Ngerekebesang islands is supplied via pipeline from the Gihmel Reservoir on the Ngerimel River on Babeldaob. During the 1983 drought, this reservoir ran dry for the first time since its construction in 1969. Additional water sources were subsequently integrated into this system from the Edeng River, but use of these required residents of Koror to travel to a communal showering and laundry station on Babeldaob, causing significant social inconvenience. Water was also distributed to Koror by trucks and in 55-gallon drums. This period of emergency measures lasted during all of March and April 1983, and even when the central water system was partially restored in May, regular water service was limited to 2 hours each day in the evening until the latter half of 1983 (van der Brug 1986). In the drought of 2016 this system was once again drawn down to critical levels, with a state of drought emergency declared and tap water rationed to three hours per day on Koror (PEAC 2016c). Due to an obligatory reliance on riverine reservoirs due to the near-absence of aquifers on Babeldaob, such periodic episodes of socioeconomic drought will likely be a continuing vulnerability for Palau into the foreseeable future.

Federated States Micronesia

The Federated States of Micronesia lie immediately to the west of the RMI and occupy a vast expanse of ocean extending across the central and western Pacific north of the equator, from Kosrae in the east at 5°19'N, 162°58'E to Ngulu Atoll in the west at 8°18'N, 137°39'E (Fig. 1), a distance of over 1600 miles (2700 km.). The 607 islands of the FSM are distributed in an east-west band, partially along the northern margin of the Caroline tectonic plate, and include the high islands of Kosrae, Pohnpei, the four main islands of Yap (which contain metamorphic rocks older than any others in the FAS), and 16 rocky islands rising from the Chuuk lagoon. In addition, there are over 500 low islets on the outlying atolls of the country. The population of approximately 106,000 is concentrated on the high islands, particularly at Chuuk, with nearly 55,000 inhabitants, and at the administrative center of Pohnpei, with 35,000 persons, although most other islands in the FSM are populated to some degree. The highest elevation in the FSM is Mt. Totolom on Pohnpei, which reaches 2595 ft. (791 m.), with other notable summits being Mt. Fenkol on Kosrae at 2080 ft. (634 m.), Mt. Winipat on Tol Island in the Chuuk lagoon, which reaches 1440 ft. (440 m.), and Mt. Tabiwol on Yap which rises to 584 ft. (178 m.). There are numerous perennial streams on Pohnpei and Kosrae, as well as on certain high islands in the Yap and Chuuk groups. Native forest cover is botanically diverse, and still relatively intact at the highest elevations on the more mountainous islands, including upland cloud forests on Pohnpei and Kosrae, but has by contrast been significantly degraded in all lowland areas, as well as at intermediate elevations on Pohnpei. Similar to the RMI, the coral reef systems in the FSM are extensively developed and species-rich. Overall, the FSM contains

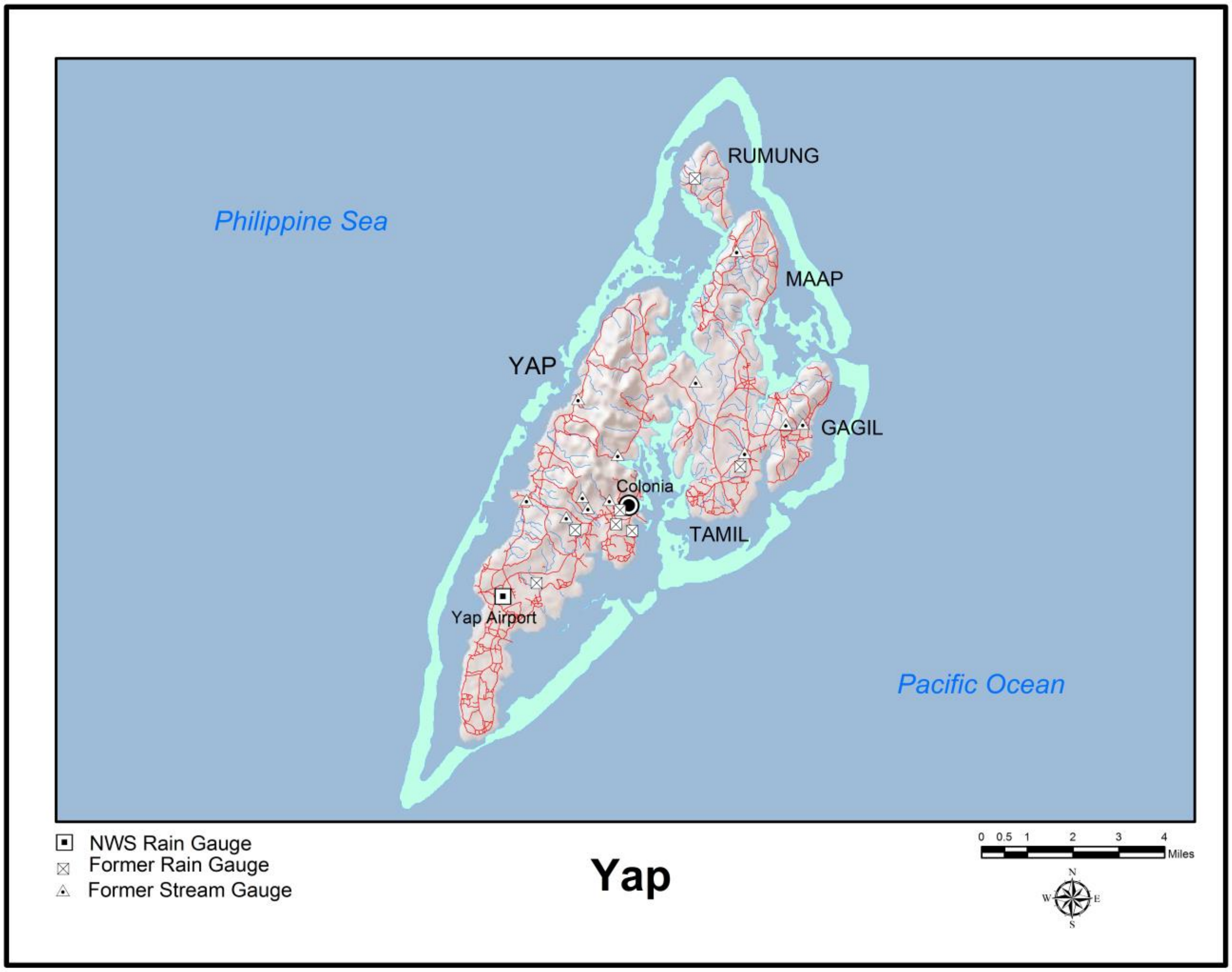

Figure 8. Map of the Yap high islands, showing locations of major islands and rainfall gauging stations discussed in the text.

750,000 miles^2 (1.9 million kilometers^2) of ocean within its boundaries, but only 271 miles^2 (702 km^2) of land, the largest island being Pohnpei at 133 miles^2 (345 km^2).

Meteorological Drought

For Yap, trustworthy rainfall records, including German and Japanese observations, are available spanning the period from 1901 to present, with missing data for the years 1909, 1910, and 1944-1948. This data was summarized as monthly averages through 1982 by van der Brug (1983b). Not all of these readings were taken at the same sites, with the German observations being recorded near the location of the present Yap airport from 1901-1914 (Fig. 8); the Japanese observations coming from Meeth, near the current administrative center at Colonia, from 1914 to 1942; and the post-World War II American records coming initially from Colonia from 1948-1968, then from the NWS station at the airport from 1968 to present (for locations of these recording stations see Fig. 2 in van der Brug 1983b). However, given the small size and relatively gentle topography of Yap Island, where all the above stations lie, these siting differences are unlikely to adversely affect data comparability. Therefore, it is possible on Yap to potentially reconstruct a 117-year hindcast rainfall record on at least a monthly basis. Air temperature records are also available for Yap from 1921 to present, and were summarized on a monthly basis from

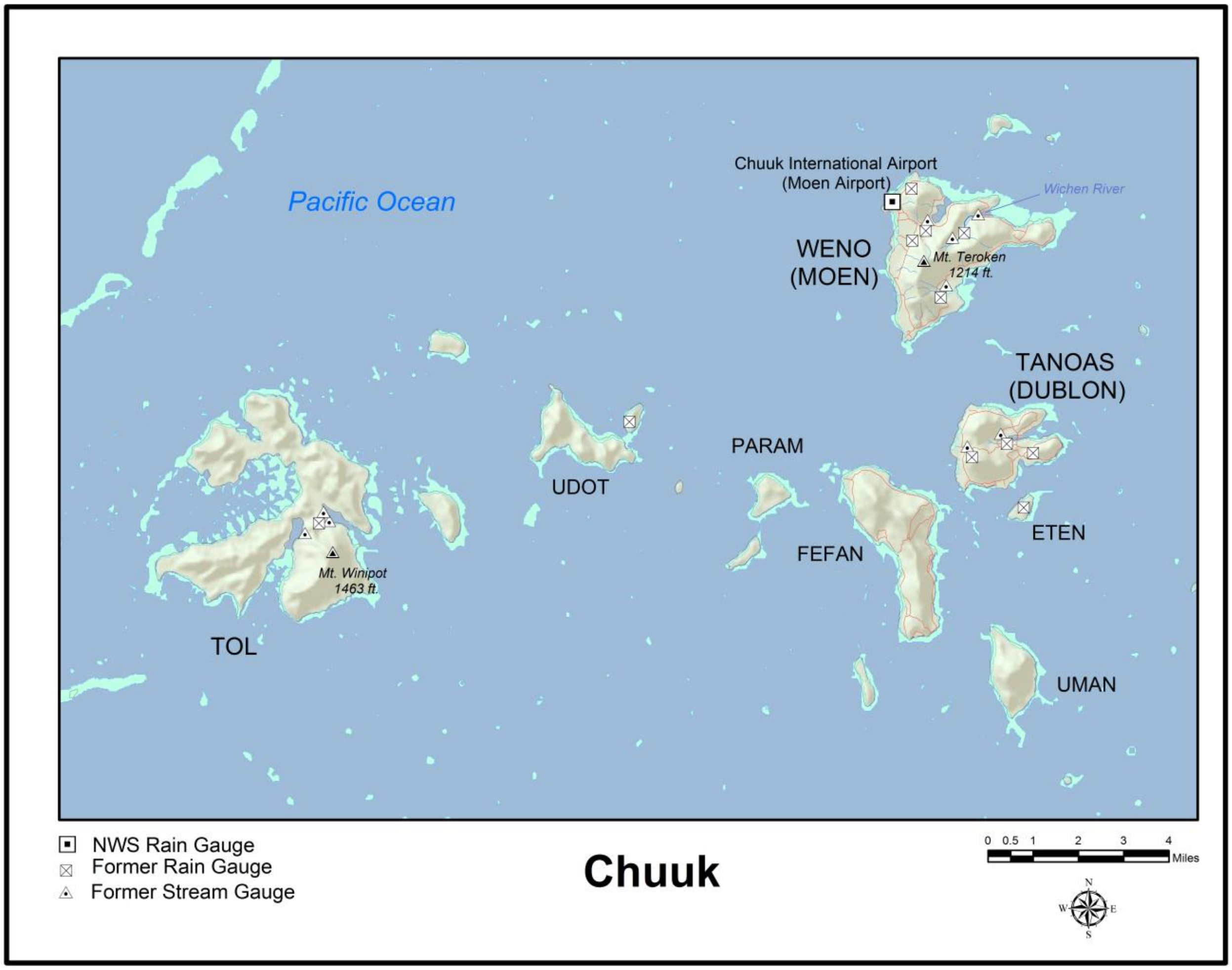

Figure 9. Map of the Chuuk high islands, showing locations of major high islands and rainfall gauging statiosn discussed in the text.

1921-1981 by van der Brug (1983b), which if coupled with NWS data subsequent to 1981 and the rainfall data could potentially allow hindcast calculation of a monthly Palmer drought index at Yap for the past 90 years. More recently, Kruk et al. (2015) concluded that there have been an increasing number of 1-day (24-hour) extreme rainfall events on Yap over the past century.

Due to its excellent harbor, Chuuk was the administrative center for the Caroline Islands during periods of German and Japanese administration prior to World War II. Rainfall records were collected by the Germans on Eten Island from 1903-1913, and by the Japanese on Dublon Island (now Tanoas Island) from 1927-1940; these data were compiled and converted from millimeters to inches in an unpublished USGS climatological study of Chuuk in 1956, and presented as monthly averages for the respective periods of record by van der Brug (1983a). Following World War II, temperature and rainfall records were collected from 1945 to present at the site of the current NWS station at Moen (now Weno) airport (van der Brug 1983; Hamilton & Takasaki 1996). An additional 13 rain gauges with much shorter periods of record were also operated at various times between 1933 and 1977 at scattered locations on Udot, Tol,

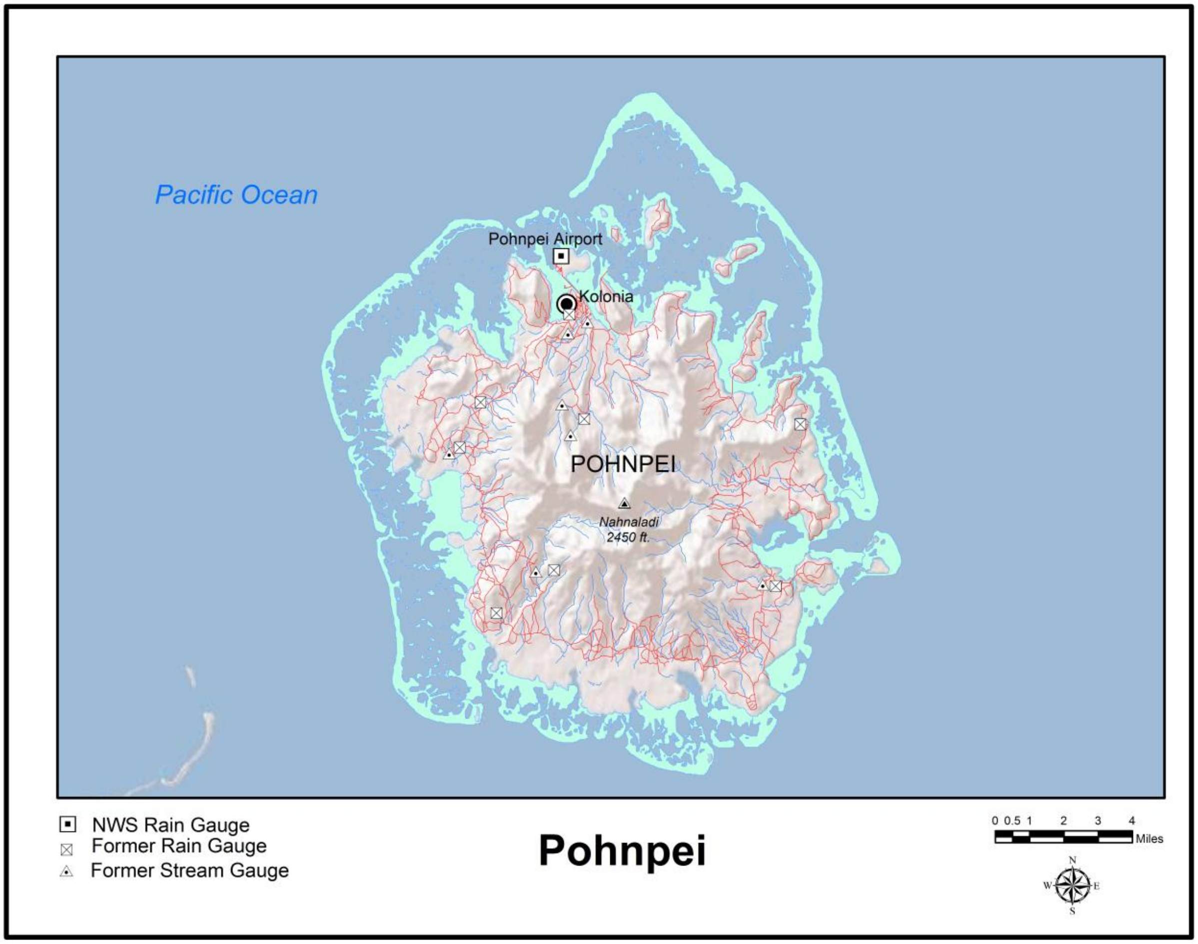

Figure 10. Map of Pohnpei, showing locations of rainfall gauging stations discussed in the text.

Uman and Eot islands, with readings taken at intervals ranging from hourly to monthly (for the relative locations of these islands see Fig. 9). This base of data would potentially allow for the reconstruction of a reasonably accurate hindcast rainfall record at Chuuk over a 115-year time span. Air temperature data are also available from 1935-1940 at Dublon (Tanoas) Island, based on Japanese records, and from 1949 onward at the NWS station on Moen (Weno) Island, which when combined with the rainfall data would allow potential calculation of a hindcast monthly Palmer drought index at Chuuk over an 80 year period.

On Pohnpei, rainfall records are available from gauges maintained the administrative center at Kolonia (Fig. 10) for the period from 1900 to present, although with some gaps, consisting of German records from 1900-1911, Japanese records from 1928-1943, and American records from 1949 to present. The above data were summarized as monthly averages by van der Brug (1984a). In addition, 8 other rainfall gauges with various periods of record, none exceeding 16 years, were operated from 1910-1983 at other sites scattered around the island; the locations of some of these gauges are shown in Figure 2 of van der Brug (1984a). More recently, a rainfall climatology study of Pohnpei was undertaken by Lander & Khosrowpanah (2004), who emplaced 9 new, electronically recording rain gauges at various elevations on the island. Using these combined data, it may be possible to produce a provisional monthly rainfall record

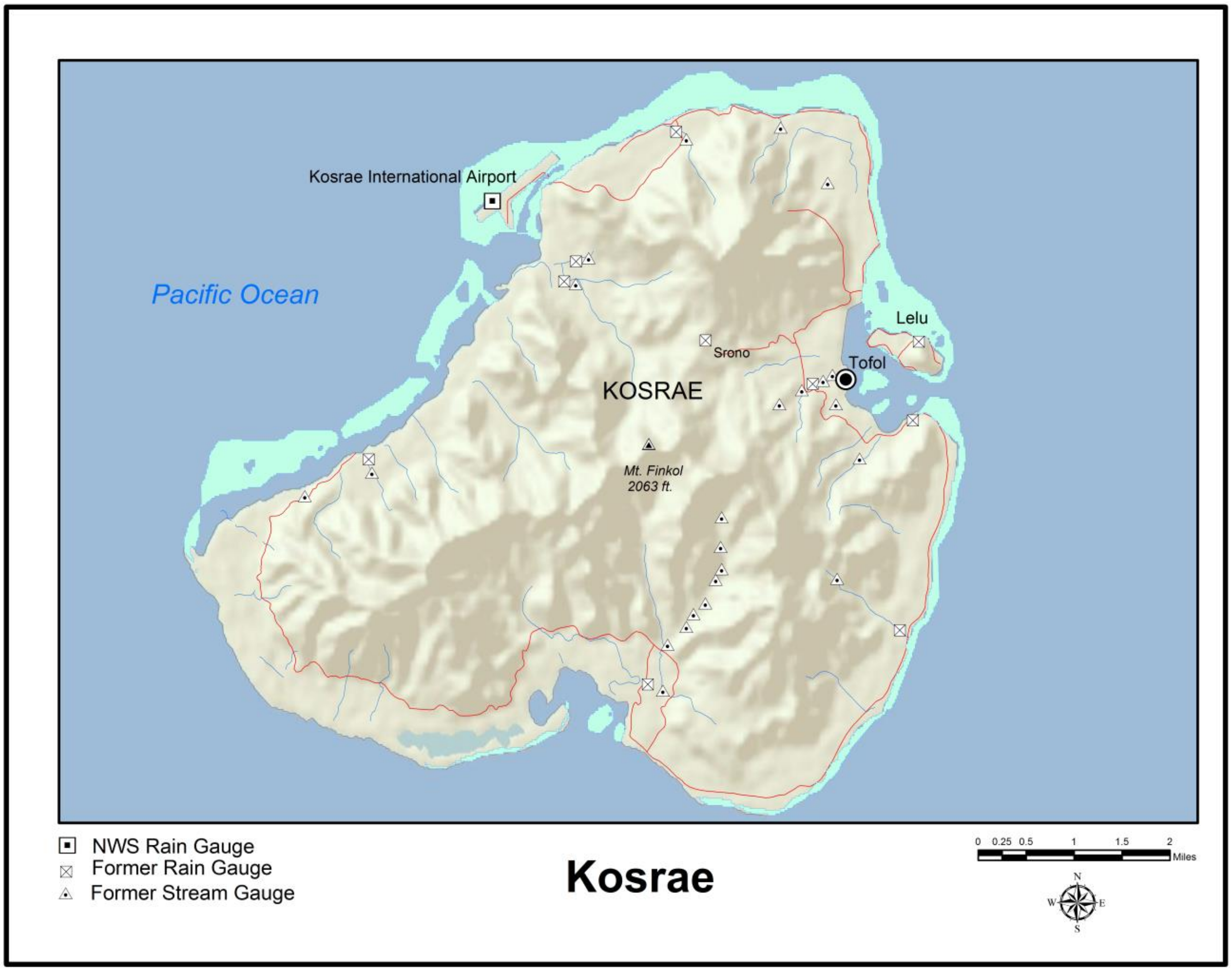

Figure 11. Map of Kosrae, showing location rainfall gauging station discussed in the text.

for Pohnpei over the past 115 years. Monthly mean air temperatures at Kolonia for the period from 1949-1981 were summarized by van der Brug (1984a), and if integrated with subsequent NWS records and combined with the rainfall data could allow potential calculation of a hindcast monthly Palmer drought index over the past 65 years at this location.

Unlike the three areas discussed immediately above, rainfall records for Kosrae during the periods of German and Japanese administration are intermittent, scattered, and incomplete. As such, our knowledge of rainfall climatology on the island consists primarily of the American records taken at Lelu Island (Fig. 11) from 1954 to 1987, then at the site of the current international airport from 1987 to present (van der Brug 1984b; NOAA-NCEI Climate Data Online). In addition, 8 other gauges scattered across the island were operated for varying periods of time by the USGS from 1971-1983, with the locations of these gauges being shown in Fig. 3 of van der Brug (1984b). Based on these data, it may be possible to generate a monthly rainfall record for the island spanning at least the past 63 years. Air temperature readings are also available from the two stations mentioned above from 1956 to present, which when combined with the rainfall data could allow potential calculation of a hindcast monthly Palmer drought index at Kosrae over this same time span. Monthly rainfall averages for Lelu, based on German data from 1903-1912, and American data from 1954-1978, as well as air temperature data from this same location for the years 1956-1978, were summarized by van der Brug (1984b), and a full summary of data for this station from 1954 to present is available from the NOAA National Centers for Environmental Information - Climate Data Online website.

In comparison to the Mariana and Marshall island groups lying slightly further to the north, the high islands of the FSM do not in general experience a strong alternation of wet and dry seasons (Lander & Khosrowpanah 2004), although both Chuuk and Yap have annual periods of lesser rainfall, running from roughly January to March on Chuuk and February to April on Yap, during which monthly totals are only about half as great as those recorded during the other months of the year (van der Brug 1983b; Hamilton & Takasaki 1996). These same drier months also exhibit slightly higher air temperatures. On Pohnpei and Kosrae, by contrast, rainfall is evenly distributed throughout the year (van der Brug 1984a, 1984b). There is also a trend of steadily decreasing rainfall as one progresses from east to west through the FSM, with mean over-water annual rainfall being 180 inches (4572 mm) at Kosrae, 160 inches (4064 mm) at Pohnpei, 140 inches (3556 mm) at Chuuk, and 120 inches (3048 mm) on Yap (Lander & Khosrowpanah 2004).

The atolls of the FSM, being too low to create any significant topographic forcing, have annual rainfall totals reflective of these mean annual over-water precipitation totals for the sectors in which they lie, this being in excess of 120 inches (3048 mm). By contrast, the high islands of the FSM, which have formed along the margin of the Caroline tectonic plate and now lie in the Intertropical Convergence Zone within the northern flank of the West Pacific Warm Pool, have mountains that are capable of creating local convective forcing that can greatly amplify their annual rainfall totals. This latter phenomenon is exemplified within the high islands of the FSM by Pohnpei, which stands out as an extremely wet locality. Gauges placed by the University of Guam’s Water and Environmental Research Institute (WERI) repeatedly recorded annual rainfall totals in excess of 300 inches (7600 mm) in the island’s central mountains (Kruk et al. 2003). Even the “drier” sites on the island, such as the international airport, typically receive in excess of 140 inches (3500 mm) per annum (Heitz & Khosrowpanah 2010). The geographically smaller but topographically similar island of Kosrae has a similar distribution of rainfall, ranging from 260 inches (6604 mm) per year in the interior to 185 inches (4699 mm) on the coast (Heitz & Khosrowpanah 2012).

Although there is no striking leeward versus windward precipitation dichotomy as seen in the Hawaiian Islands, on Pohnpei there is evidence that daily convection tends to set up slightly downwind, on the western side of the island during the prevailing easterly flow regime, such that the “dry” lowlands on the eastern side of the island receive only 160 inches (4000 mm) of annual rainfall (Heitz & Khosrowpanah 2012). Limited rain gauge data also suggest that a similar pattern may prevail on Kosrae (van der Brug 1984b). Such local variations, however, are of little functional significance given the overall high annual rainfall totals involved, especially when compared to the extreme windward to leeward order-of-magnitude dichotomies seen in the Hawaiian Islands, where wet upland or windward locations can receive 236 inches (6000 mm) of rainfall per year, while nearby dry leeward zones on the same island receive only 22 inches (550 mm) (Giambelluca et al. 2013).

All of the islands in the FSM can be thus considered to have meteorologically wet climates, and as such, periods of meteorological drought lasting weeks, or in some cases months, are unusual occurrences that often produce significant ecological, agricultural and social impacts, particularly for the atoll communities. In certain cases, these droughts can be prolonged and severe. During the drought of 1982-1983, Yap Island received only 27 percent of its normal rainfall from January-May 1983. The recording station at Moen, in Chuuk State, was anomalous in recording a record low annual rainfall total for all of 1982, prior to the drought in other parts of the FSM, and then received only 31 percent of its normal rainfall for the period from October 1982 through May 1983. The precipitation deficit on Pohnpei was even more dramatic, with the weather station at Kolonia receiving only 12 percent of its normal mean precipitation in the period from January-June 1983, thus leaving it 65 inches (1651 mm) below normal by mid-year. On Kosrae, only a single rain gauge, in the interior of the island at Srono, was in operation in 1982-1983. Readings from gauge, lying at 330 feet elevation in an area wetter than the coast, were of necessity compared to the longer term gauging record at Lelu, which lies on the coast, and indicated a pattern similar to Pohnpei, with only 12 percent of mean rainfall recorded from January-April 1983, equating to a water deficit of at least 62 inches (1575 mm). Although no rain gauging data was available from the atolls, the same pattern of severe drought pattern affected those low islands as well.

The drought of 2015-2016 was in some parts of the FSM even more severe than in 1983. Yap recorded only 39 percent of average precipitation, slightly less than 22 inches (559 mm), for the period from October 2015 through March 2016 inclusive, making this the driest such period in the post-World War II climate record. This same period was also extremely dry at Chuuk, although it did not set records. Neither Pohnpei nor Kosrae saw drought conditions as severe as Yap and Chuuk during 2015-2016, and it was generally agreed that at all levels the events of 1982-1983 and 1997-1998 had been more severe. The most recent drought was thus focused more to the west in the FSM, extending into adjacent Palau.

Fletcher & Richmond (2010) noted that such drought episodes in the FSM are strongly influenced by ENSO cycles, being more common and severe under El Niño conditions, a conclusion echoed by McGhee et al. (2016). In addition, because the high islands involved do not exhibit strongly defined windward to leeward segregation of wet and dry zones, meteorological drought when it does occur tends to affect all lowland localities with equal severity.

Hydrological Drought

Stream gauge data from the FSM, and Micronesia in general, is basically absent prior to the end of World War II, except for limited Japanese records from Chuuk. The islands involved were German colonies from the late 1800s until World War I, then Japanese colonies through World War II, and although some stream flow observations were likely collected during these periods (particularly during the period of Japanese oversight from 1926-1937), there seems to have been no attempt as of yet to integrate these readings, to the extent they exist, into the available time series of observations. As such, the hindcast hydrological records for the FSM can be considered to roughly span the period of the past 65 years, and even then are highly incomplete.

Assessing the hydrological effects of drought in the FSM is further complicated by the fact that the stream flow gauging network in the country that was set up prior to independence has been essentially abandoned for nearly 25 years, due to lack of funding. On the island of Pohnpei, 7 USGS streamflow gauges provide records spanning the period from 1970 to 1994, but all have data gaps of varying durations throughout this period, with the data being most complete in the period from 1982-1992 (Heitz & Khosrowpanah 2010).

On the island of Kosrae, 6 USGS streamflow gauges provide records spanning the period from 1971 to 1992. As on Pohnpei, all have data gaps of varying durations throughout this period, although overall the data are more complete, with 5 of these gauges being almost continuously operational in the period from 1974-1990 (Heitz & Khosrowpanah 2012). As a result, there is no stream flow data that can be correlated with the severe El Niño drought of 1997-1998, or the more recent El Niño drought event of 2016.

On the high islands of the Chuuk Lagoon, data is available from 11 USGS streamflow gauges distributed across the islands of Moen, Dublon and Tol, with highly disparate periods of record spanning the years 1955-1981 (van der Brug 1983a). All of these gauges appear to have gone out of service prior to the El Niño droughts of 1997-1998 and 2015-2016.

On Yap, data is available from 9 USGS continuous record stations with varying periods of record spanning the years 1968-1982, with most of these gauges operational throughout much of this entire period. In addition, low-flow data from a further 14 partial-record gauges are also present from this same time period (van der Brug 1983b). Once again, none of these gauges were operational during the El Niño droughts of 1997-1998 or 2015-2016.

Previous published observations indicate that streams on all the high islands of the FSM tend to have low volume aquifer-fed base flows in comparison to high volume rain-fed total flows, rendering them susceptible to prolonged drought conditions, as previously discussed in relation to the island of Babeldaob in Palau. On Pohnpei, a strong correlation between stream discharge and rainfall was illustrated by van der Brug (1984a, Fig. 3) for the Nanpil River. Both here and on Kosrae it has been estimated that approximately 65 percent of all rainfall enters the ocean as runoff (van der Brug 1984a, b). On Yap Island, the underlying green schist petrology has very poor water retention characteristics, producing low base flows that recede to the hyporheic zone and leave dry beds devoid of surface flow for an average of 10 weeks each year, or 26 percent of the time, even under normal rainfall regimes. The role of geology in structuring stream discharge, and thus susceptibility to hydrological drought, is illustrated by the fact that on adjacent Gagil-Tamil island, also in the main Yap group (Fig. 8), the stream catchments have formed in weathered volcanic formations that release some level of continuous base flow throughout the year (van der Brug 1983b), so that all streams on that island are perennial.

During the drought of 1982-1983 the stream gauge network was still largely functional across the islands of the FSM, and provided a clear quantification of the hydrologic impacts to surface waters. On Yap Island in the first half of 1983, stream flow was only 5-6 percent of the January-June long-term average. In Chuuk State, the mean discharge in the Wichen River on Moen from January-May 1983 was only 8.4 percent of normal, and half the monthly mean flows recorded from October 1982 to May 1983 were the lowest on record up to that time. On Pohnpei, stream discharges at 3 continuous-recording gauging stations with at least 10 years of record each were 5 percent of normal, with the mean discharges at these sites from January to May 1983 being the lowest on record for each of those months. A similar situation prevailed on Kosrae, where streamflow in east coast catchments was 4 percent of normal, and that in west coast catchments 7 percent of normal (all figures above from van der Brug 1986). All of these observations serve to emphasize the degree to which the high islands of the FSM are surface water sectors with low base flows and highly variable, precipitation-driven total flows.

Qualitative observations also provide a stark illustration of the effects of drought on stream flow in the FSM in early 1983. Takasaki (1989) notes that on Chuuk "The flow of perennial and near-perennial streams in the high islands visited were the lowest recorded or remembered by the villagers. All small streams were dry. Most small springs were dry, and the flow of larger springs was down to a trickle...The decline in ground-water levels caused many dug wells, especially at high altitudes away from coastal areas, to go dry, and they were abandoned…The decline in water levels in the dug wells in coastal areas was less severe and most did not go dry." These observations clearly indicate that on the relatively small-sized high islands in Chuuk Lagoon, a nine-month drought was sufficient to produce significant hydrological impacts to both flowing surface waters and to the underlying aquifers.

Lack of quantitative data from monitoring wells has also hampered proper hydrologic assessment of drought effects to aquifers, particularly on atoll islands. As noted by Fletcher & Richmond (2010): "Atoll aquifer systems are poorly understood and there is little knowledge of what sustainable groundwater withdrawal rates are appropriate from one island to the next, as well as among the main islands." Studies have been undertaken for a limited number of individual atoll islands, including Pingelap Island on Pingelap Atoll (Anthony 1996a), Kahlap Island on Mwoakilloa Atoll (Anthony 1996b), Ngatik Island on Sapwuahfik Atoll (Anthony 1996c), Lenger Island (Anthony & Spengler 1996), and the outer islands of Chuuk State in the Western, Namonuito, Hall and Mortlock groups (Hamilton & Takasaki 1996). In total, this represents data for just 28 of the over 500 atoll islands present in the FSM.

Ecological Drought

As with other USAPI jurisdictions, studies directly assessing the effects of drought to ecosystem processes in the FSM are few. Reduced freshwater flows during the 1998 drought led to increased salinity levels in mangrove estuaries on Kosrae, although it is not clear if there was any functional impact to these ecosystems (Drexler & Ewel 2001).

As alluded to previously, there is a noticeable declining precipitation gradient running from east to west across the FSM, so that more western jurisdictions such as Yap and Chuuk are more prone to wildland fire in response to drought than are the very wet islands of Pohnpei and Kosrae. Yap in particular is vulnerable to increased incidence of wildland fires during ENSO-linked droughts, with 22 percent of the Yap high islands being burned during the 1983 and 1998 events (YSDPS 2009). Even in years of normal rainfall, the incidence of fire in Yap is higher during the dry months from December through June. Such fires generally start in savannah areas, but may burn into the margins of adjacent intact forest tracts, a concern given that Yap now has less than 20 percent of its land area remaining in forest (YSDPS 2009; FSM 2010). A map of Yap showing areas of wildfire vulnerability under drought conditions was presented in the FSM's Statewide Assessment and Resource Strategy 2010-2015+ (FSM 2010), and the state remains the only one in the FSM with a comprehensive fire reduction and control strategy. This improvement in institutional capacity may account for the lesser incidence of fire during the 2015-2016 drought, when only 4.5% of the Yap high island area burned (PEAC 2016c).

Forest damage due to wildfires sparked during the drought year of 1983 has also been observed in Chuuk (FSM 2010), with such fires promoting the spread of invasive pennesetum grass that makes the landscape more prone to subsequent burning. In contrast to Yap, there is no local fire suppression plan, nor has there to date been any mapping or quantification of the areas burned annually by wildfire. As such, our understanding of the interaction between fire and drought in Chuuk State is largely circumstantial.

Wildfires are uncommon on Pohnpei, due to its wet climate, but can occur during particularly severe droughts. This was the case during the drought of 1982-1983, when an estimated 50 percent of Pohnpei's upland forest burned to some degree (FSM 2010), in some cases for weeks. The exceptional nature of the 1983 fire event can be judged by the fact that it was not repeated on the same scale during the 1998 drought, which was considered nearly as severe, although 20 percent of the forest was also estimated to have burned during this latter event (Guard, pers. comm.). Wildfires also occurred more recently during the drought of 2015-2016, including one at the prominent local landmark of Sokehs Rock in January 2016 (PEAC 2016A).

Kosrae is similar to Pohnpei in that it has a wet climate that makes wildfires uncommon. During extreme drought periods, however, the island can experience up to 3 fires per year that can burn an aggregate area of 3 acres (1.2 hectares), generally in areas that have been previously cleared and now support savannah rather than closed canopy forest (FSM 2010). Although such fires are unusual and attract notice when they occur, the total area involved in very small when compared to the area burned annually on islands such as Guam or Saipan in the Marianas.

In summary, wildland fire appears to be the major ecological manifestation of drought in the FSM, and is strongly correlated with the annual drier months from December to June, and with periodic strong droughts associated with El Niño events. The ecological effects of drought are more strongly expressed in the western states of Yap and Chuuk, and far less so in the eastern states of Pohnpei and Kosrae. On the low-lying atolls of the FSM, where most native forests have been converted to agro-forests by many centuries of habitation, the effects of drought largely play out in the hydrological and agricultural sectors, though thinning of freshwater lenses and reduction in food crop harvests, while other ecological effects are not well studied.

Agricultural Drought

As in neighboring Palau, agricultural production in the FSM consists primarily of subsistence agriculture involving traditional crops such as bananas, breadfruit, taro, yams, sweet potatoes and coconuts grown for home or family consumption. The 1997-1998 El Niño drought significantly reduced harvests of many staple crops, including coconut, taro, breadfruit, banana, yam, sweet potato, sugar cane and citrus fruits (Fletcher & Richmond 2010), leading to food shortages, particularly on the atolls. FAO crop production data for the FSM, accessed via the Knoema search engine, reflect a drop in coconut production from 49,300 tons in 1998 to 40,000 tons in 1999, an approximately 20 percent decline. This depressed production continued for the next four years, before rebounding steadily back to 50,000 tons by 2006. Based on these data, it appears that recovery from the 1998 drought took 5 years, as new trees matured and came into production. Other food crops were, by contrast, little affected, with production of bananas rising by over 165 percent from 1997-2001, and sweet potato production also increasing slightly during this period.

Current policies regarding climate effects to future food security in the FSM have focused on the challenges posed by higher annual and seasonal mean rainfall, under the assumption that extreme precipitation events will become more frequent and intense. Drought, by contrast, is not considered a significant future problem, given that in the view of the government it is likely to become less frequent.

Socioeconomic Drought

With its combination of both low and high islands, the FSM has a spectrum of socioeconomic vulnerabilities to drought. Pohnpei has a moderately well-developed, pressurized municipal water system that water serves over half its population, with expansion underway (DTCI 2004). The Yap high islands are in a similar situation, with a central water supply system in Colonia and vicinity, and improvements underway in outlying communities (DTCI 2004). Kosrae has a generally abundant streamflow due to its wet climate, although its water delivery systems are poorly developed and in need of structural improvement (GlobalWorks 2004). All three of these states therefore have some capacity to withstand periods of drought, at least on their high islands, with supply disruptions occurring only during the most extreme events. The improvement in institutional capacity is illustrated by the fact that although Yap's main reservoir became nearly depleted during the 2016 drought, use of alternative wells and water storage avoided any service interruptions (PEAC 2016b). Chuuk, with its scattered high islands in a single lagoon presents a more complex set of vulnerabilities, with pressurized central water supply systems only on Weno and Tonoas (DTCI 2004). Water supply on all the other Chuuk high islands relies primarily on catchment systems kept filled by the generally regular rainfall that normally prevails, as well as shallow hand-dug wells, springs, and seeps fed by shallow groundwater. Such sources, however, are susceptible to rapid depletion during drought, as happened in both 1982-1983 (van der Brug 1986; Takasaki 1989), and again in 1997-1998, and may also be left dry by transient drops in sea level during El Niño events (Guard, pers. comm.). These latter vulnerabilities are also applicable to atoll communities in all of the FSM states. During the 1997-1998 El Niño drought, many remote atoll communities across the entire FSM required emergency deliveries of food, bottled water, and reverse osmosis pumps (Fletcher & Richmond 2010). Periodic drought impacts have continued into the current century; in July 2008, the FSM requested a major disaster declaration and direct Federal assistance due to the effects of unusual high tides and drought, a request that was denied in early October 2008. As more severe drought developed in 2015-2016 emergency supplies of water were supplied by ship or reverse osmosis units to remote atolls, including Ulithi in Yap State; potable water supplies became limited in Chuuk State, with the northern atolls of Onoun and Fananu particularly dry; and water restrictions were implemented on Pohnpei during February and March 2016. Overall, however, the 2015-2016 drought had lesser socioeconomic impacts in the FSM than did the previous droughts of 1982-1983 or 1997-1998 (PEAC 2016c).

Republic of the Marshall Islands

The Republic of the Marshall Islands lies north of the equator in the western North Pacific Ocean (Fig. 1). The country consists of 29 atolls containing over 1100 individual islands and islets, extending from Mili Atoll in the east at 6°08'N, 171°56'E to Ujelang Atoll in the west at 9°49'N, 160°54'E, and from Ebon Atoll in the south at 4°37'N, 168°43'E to uninhabited Taongi Atoll in the north at 14°40'N, 168°57'E. The atolls form two groups, the Ralik Chain in the west and the Ratak Chain in the east. Some of these atolls enclose extensive lagoons, including Kwajalein in the Ralik Chain, the largest atoll on the planet, which has a lagoon 70 miles long. The population of approximately 75,000 is concentrated at the administrative center of Majuro on Majuro Atoll, which holds 31,000 persons, and on island of Ebeye at Kwajalein Atoll, although all but 5 of the other atolls in the country have some degree of habitation. The islands of the RMI are entirely low-lying, with the highest natural elevation being a 33 foot (10 m.) rise on Likiep Atoll, and the average elevation across all islands being 7 feet (2.1 m.). The coastlines are mostly sandy beaches or low limestone platforms topped by alluvium. There are no perennial streams or freshwater lakes in the RMI, although the interiors of some islands do support brackish ponds, some of which are used for taro cultivation. Native forest cover consists of closed-canopy stands in the island interiors, often dominated by *Pisonia* and *Pandanus*, although this has been extensively disturbed in many areas. Due to the isolated position of the islands, overall species richness in terrestrial systems is relatively low, while by contrast the marine systems surrounding the atolls support coral reefs with high species diversity. Despite the large expanse of ocean within its national boundaries, which totals 750,000 miles^2 (1.9 million km^2), the total land area of all islands in the RMI combined is only 70 miles^2 (181 km^2), which is roughly equivalent to the area of Washington, DC. Most of the emergent islands in the country are quite small, being at most one or two miles long and perhaps one-quarter mile in width.

Meteorological Drought

Only two long-term NWS rainfall recording stations are present in the RMI: Kwajalein, with a period of record from 1945 to present, and Majuro, with a period of record from 1955 to present (Fig. 12). The average long-term annual rainfall at these two stations through 1986 was 103 and 136 inches (2616 and 3454 mm) respectively (van der Brug 1986), and 133 inches (3378 mm) on Majuro in the period from 1954-2000 (Presley 2005). The averages at Majuro from these two disparate periods of record indicate that average rainfall at this location has slowly but steadily declined over the 45-year interval from 1955 to 2000, and a longer term analysis including data from the period of Japanese administration reinforces the validity of this pattern over the 100-year interval from 1915-2015 (Lander, pers, comm.). Other stations with shorter periods of record include Ujelang Atoll in the west of the country, with an annual average rainfall of 77 inches (1956 mm) based on a period of record from 1894-1913; Jaluit Atoll in the south, with an annual average rainfall of 159 inches (4039) based on a period of record from 1935-1972 (van der Brug 1986), and a more recent average of 126.46 inches (3212 mm) from 1986-2007 (Guard, pers. comm.); and other readings from Eniwetak and Ailinglapalap. These records demonstrate that rainfall decreases across the RMI as one moves from south to north, and from east to west, with the northwestern atolls being the driest (Donnegan et al. 2011, Fig. 3). The RMI also experiences a drier season each year from January through March, with monthly rainfall totals for these months being only about half as much as monthly totals for each of the other nine months in the year (Presley 2005).

The rainfall data for Majuro from 1965-2000 was plotted on a monthly basis by Presley (2005), and reveals periods of very low rainfall and drought in 1965, 1970, 1977, 1983, 1992 and 1998. These dry periods on Majuro for the most part reflect broad drought events that encompassed the entire USAPI and surrounding insular Pacific, and also correlate with the El Niño events of 1965-1966, 1969-1970, 1976-1977, 1982-1983, 1991-1992 and 1997-1998. This indicates that the variations in the ENSO cycle are a strong and predictive driver of meteorological drought in the RMI, but it should be noted that based on

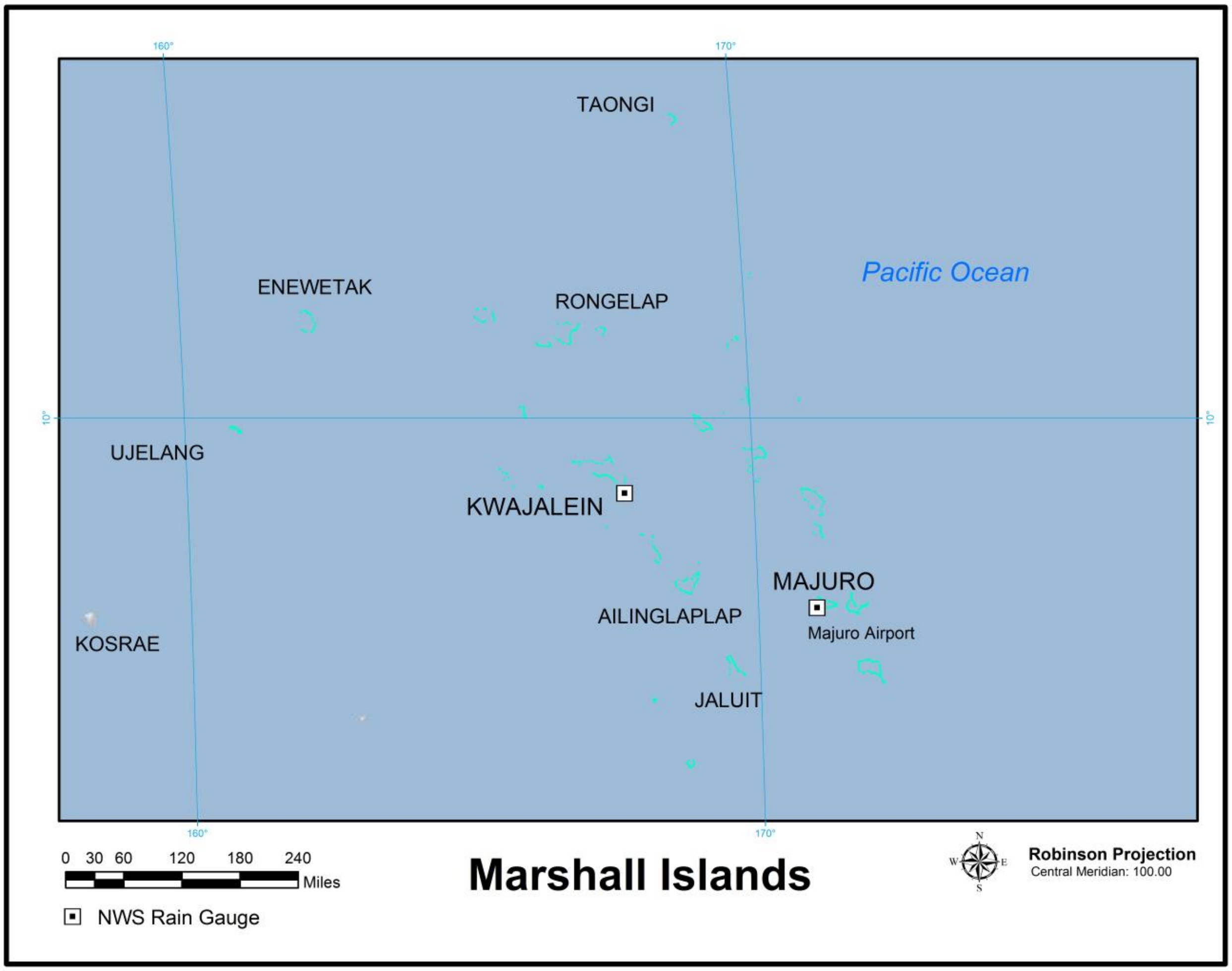

Figure 12. Map of the RMI, showing locations of major atolls and rainfall gauging stations discussed in the text.

data from Majuro, not all El Niño events that have occurred since 1950 have led to corresponding episodes of drought in the RMI (Fig. 13), and there seems to be a tenuous connection between the strength of any given El Niño and the severity of drought affecting the country Presley (2005).

During the drought of 1982-1983, rainfall at both Kwajalein and Majuro for the period from January through May was only 13 percent of the long-term averages for each location. Based on calculations by van der Brug (1986) the predicted recurrence interval of a 6-month drought of this severity was 125 years. However, the data for Majuro presented by Presley (2005) indicate that the meteorological drought events of 1992 and 1995 were equally severe on that atoll. In addition, during the 2015-2016 total rainfall at Majuro from October 2015 to July 2016 was the driest 10-month period in the 62-year historical record at that station (PEAC 2016c). Therefore, the recurrence interval of severe meteorological drought at Majuro seems to be closer to 10-15 years, in close track with ENSO cycles.

Kruk et al. (2015) concluded that there had been a decreasing number of 1-day (24-hour) extreme rainfall events in the RMI over the past century, a pattern opposite to that seen in Palau and the FSM. A statistically significant drying trend for the RMI from 1954-2011 was reported by Keener et al. (2012), with a 15 percent decline in rainfall over the past 60 years, and this seems to have been a particularly chronic problem for the northern atolls of the country, which have suffered repeated recent droughts in 2001, 2007, 2013 and 2016. Most recently, the period from December 2016 through May 2017 has been very dry at Wotje, Utirik, Enewetak, Ailuk, Likiep, and other atolls north of Kwajalein, as well as at Mejit Island (Guard, pers. comm.).

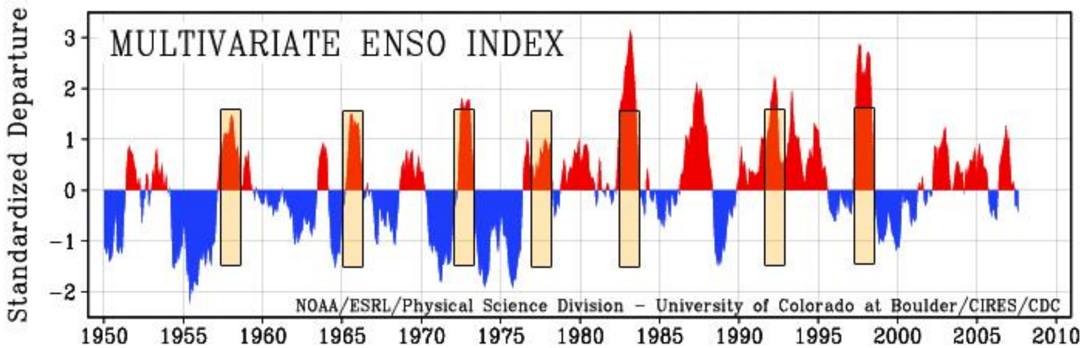

Figure 13. Periods of drought in one or more of the USAPI jurisdictions (pale orange bars) superimposed on a time series of ENSO cycles from 1950-2007. The correlation between periods of drought and El Niño events (red peaks extending vertically above the zero axis) is evident, although not all El Niño events are linked to a corresponding period of drought. The drought period marker bars are all of equivalent size and for illustrative purposes only, with their widths and heights not indicative of drought duration or severity.

Hydrological Drought

Surface watercourses are completely absent on the sandy atolls of the RMI, so assessment of hydrological drought in the context of stream flow is moot. Instead, hydrological impacts of drought are assessed through monitoring of the freshwater lenses that underlie the atoll islands. The best studied of these is the Laura Lens on Majuro. Hamlin & Anthony (1987) estimated that due to evapotranspiration, only 50 percent of the rain falling on Majuro actually contributed to the recharge of this lens, thereby illustrating its vulnerability to over-use, particularly during periods of drought. These authors further noted that the freshwater component of the lens responded “quickly and dramatically to variation in natural recharge”, and suggested that a sustainable rate of withdrawal should be no greater than 20 percent of the annual recharge rate, a general rule that would presumably apply to lenses on other atoll islands as well. During periods of drought, dual pressures are brought to bear on such freshwater lenses, with usage increasing at rainfall catchment is exhausted, while recharge also decreases due to lack of precipitation, leading to seawater intrusion.

The Laura lens was studied using monitoring wells between 1984 and 1985, immediately following the severe 1983 drought, and again during the drought years of 1998-1999, following the 1998 drought, after the lens had been developed as a partial water supply for Majuro (Hamlin & Anthony 1987; Presley 2005). It was expected that these studies would provide insights in regard to the depletion and recovery of the aquifer during drought. Counter to expectations, the lens was actually thicker following the 1998 drought than after the 1983 drought, despite having been subjected to new development and municipal withdrawals of up to 334,000 gallons per day in the interim. This indicates that the dynamics of rainfall and lens recharge may be more complex than previously understood, and that accurate monitoring and prediction of sustainable yield must take into account inter- and intra-annual rainfall patterns, ENSO-linked sea level fluctuations, the locations of the monitoring wells in relation to the shape of the underlying lens, and standardization or cross-calibration of the monitoring instruments used.

Ecological Drought

The Marshall Islands, due to their small overall land area and low-lying islands, do not support extensive areas of completely native forest, although some stands of closed canopy *Pisonia* and *Neisosperma* forest do remain, such as on the protected islet of Eniwetak (Barney Islet) at Kwajalein Atoll. Instead, most original forests in the RMI have been replaced by agroforests that are to some degree structured by human intervention to support a variety of trees which provide food sources or construction materials, such as coconut and breadfruit (Donnegan et al. 2011). Consequently, wildfires correlated with droughts are not common in the RMI, are a minimal source of forest disturbance (Donnegan et al. 2011), and do not factor heavily into the country's forest management strategy (MRD 2010). There is passing reference in this strategy document to the role of drought in placing stress on forests, but given that these systems are predominantly agroforests this stress is better understood in the context of agricultural drought.

Agricultural Drought

Agricultural production in the RMI is concentrated on the atolls away from Majuro and Kwajalein, with coconuts and breadfruit representing the major crops. The former is grown for commercial export as copra, while the latter is used for subsistence at the family level. Both of these cultivars are susceptible to drought, particularly older coconut trees. During the 1982-1983 drought, approximately half of all food crops were lost across most of the central, southern and western atolls, while losses ranged from 10 to 90 percent in the eastern atolls, and 10 to 20 percent in the northern atolls, except for Mejit where losses approached 60 percent for coconut and 80 percent for breadfruit. The overall loss of copra production across the RMI, an economic mainstay for the more remote atolls, was estimated at 20-30 percent, and the loss of breadfruit trees necessitated an increase in food imports to these communities (van der Brug 1986). FAO crop production data for the RMI, accessed via the Knoema search engine, indicates that coconut production fell from 23,500 tons in 1998 to 4080 tons by 2001, reflecting the loss of mature trees to the 1998 drought (FAO 2008). However, production had rebounded to 33,000 tons by 2003, apparently reflecting production from younger trees that had survived the drought and subsequently matured. As with coconut production in the FSM already mentioned, these data would indicate that the recovery period for agriculture in the RMI following the 1998 event was on the order of 4-5 years. Pit taro was also formerly common on the atolls of the RMI, but its production has declined steadily over the past 50 years (FAO 2008), due both to periodic droughts, and progressive saline intrusion into former taro ponds due to steadily rising sea levels.

Socioeconomic Drought

The major RMI population centers on Majuro and Kwajalein atolls are both served by international airports whose runways also serve as rainfall catchments that feed centralized water delivery systems.

Such catchment-fed systems are vulnerable to prolonged periods of below-normal rainfall, and during such times must be supplemented by water from reverse osmosis units and wells, the latter often becoming rapidly brackish due to overuse. During the 1982-1983 drought, these sources became so depleted on Majuro that water service from the central delivery system was restricted to two hours each morning and evening, then cut back even further to one hour every third day in February 1983. By May 1983, this system was so depleted that water deliveries were primarily reserved for use at the hospital, with the populace relying largely on shallow wells hastily developed by the government. These wells retained fresh water throughout the drought at Rita and Laura, near the east and west ends of Majuro respectively, but became brackish throughout most of the intervening sector. At Kwajalein, the extensive and well-maintained infrastructure at the U. S. military base provided water throughout the drought, and also allowed supplemental deliveries to town of Ebeye and other small islets on the same atoll. On the other more remote atolls beyond Majuro and Kwajalein, which rely on small catchments and shallow wells, the water supply situation became acute, with daily rations reduced to one gallon per day per person (van der Brug 1986).

During the drought of 1997-1998, when a national state of emergency was declared, water sources on Ebeye Island, at Kwajalein Atoll, became depleted and compromised, leading to unsanitary conditions (Ahlgrenet al. 2014). Acute socioeconomic drought effects were again seen in 2015-2016, when a state of drought disaster was declared for the northern atolls of the RMI (USAID 2016). Overall, the RMI continues to be poorly equipped to deal with drought outside of the major population centers at Majuro and Ebeye, and periodic social disruptions from drought can be expected to continue into the foreseeable future.

American Samoa

American Samoa lies south of the equator, consisting of the eastern portion of the Samoan Archipelago, a hotspot chain that forms a series of progressively younger islands from west to east, although this age pattern has been to some degree confounded by late stage volcanism on the most western islands lying with independent Samoa. American Samoa extends from the high island of Tutuila at 14°16'S, 168°09'W (Fig. 14) eastward to Rose Atoll, at 14°32'S, 168°09'W, the latter being the most southerly point in the United States. The territory has approximately 56,000 residents, most of them on Tutuila, which is also the administrative center. American Samoa's highest point is reached on the small but high eastern island of Tau, where Mt. Lata rises to 3159 ft. (963 m.), the highest point in any of the USAPI jurisdictions considered by this study. The coastlines of the high islands in American Samoa, consisting of Tutuila, Ofu, Olosega and Tau, are very steep, with few beaches, whereas Swains and Rose atolls, which are jurisdictionally part of the territory but geologically of separate origin, are low-lying, with extensive beaches and reef flats. The island of Tutuila has many perennial streams, whereas the remaining high islands have few, and the atolls none. Native forest cover is still extensive on all of the high islands in American Samoa, while the atolls by contrast have a much less diversified vegetative assemblage consisting of widespread Pacific species. The total land area of the all islands in American Samoa is only 76 square miles (197 km^2), the least of any of the USAPI.

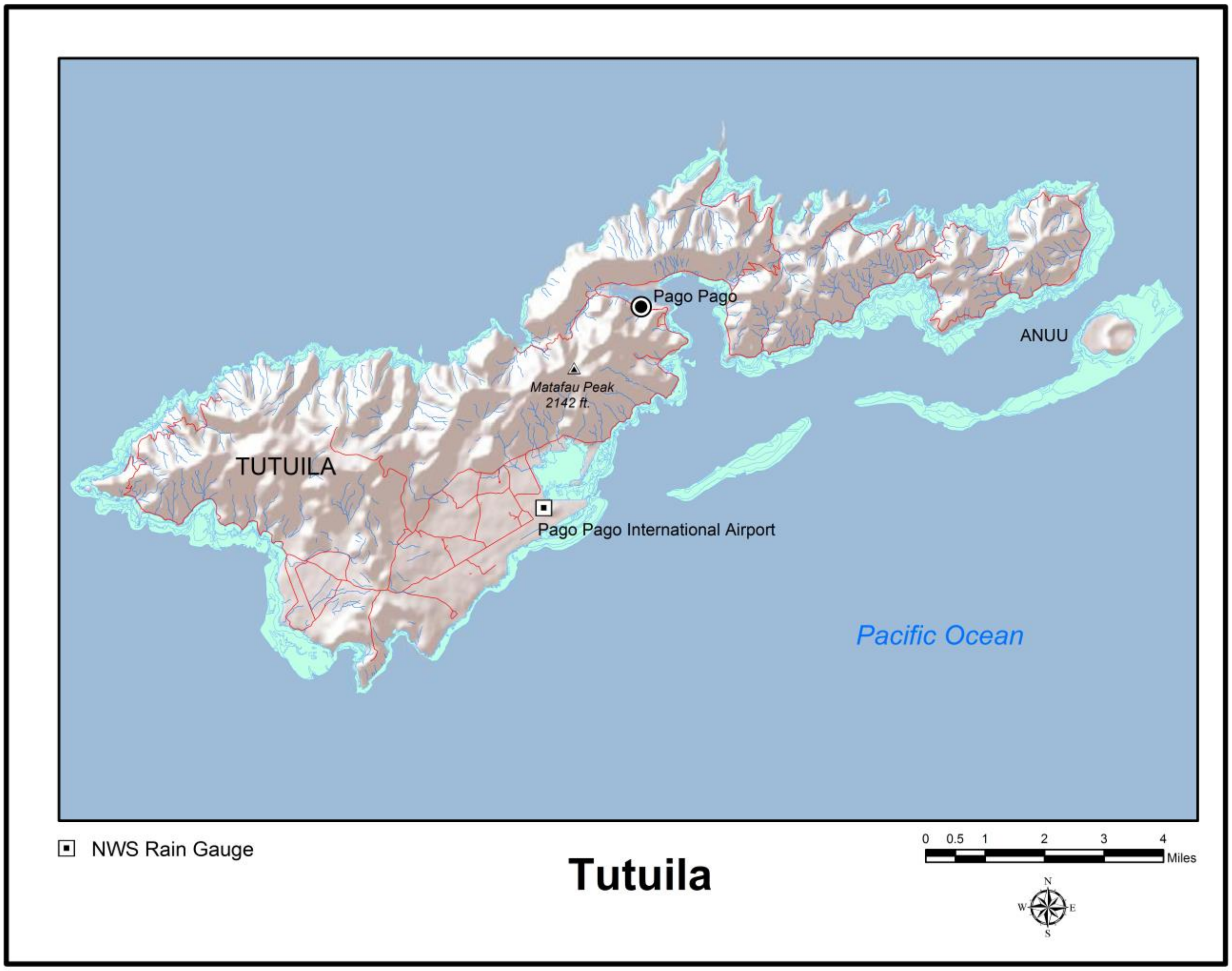

Figure 14. Map of Tutuila, showing location of rainfall gauging station discussed in the text.

Meteorological Drought

American Samoa lies in the South Pacific, and as a result its precipitation dynamics are affected by the SPCZ, rather than the WNPM trough that influences rainfall in the Micronesian islands to the north. As such, one of the primary determinants of precipitation in the southwestern Pacific, including American Samoa, is the position of the SPCZ. Based on a 60-year time series incorporating data from numerous recording stations spanning the area from New Caledonia to French Polynesia, Griffiths et al. (2003, 2010) concluded that annual rainfall totals had decreased since the 1940s within and south of the mean location of the SPCZ, but had increased to the north. This same general conclusion was reached by Greene et al. (2007), who determined that there were fewer extreme rainfall days and an overall decrease in annual rainfall at stations south and east of the SPCZ. During this same period, however, there is also evidence to indicate that extreme precipitation events increased in number at all recording stations east of the International Date Line, irrespective of their location relative to the SPCZ (Kruk et al. 2015). A more recent study by Murphy (2014) examined the relationship of ENSO cycles to such patterns, concluding that during El Niño events the SPCZ moves northward toward the equator and merges with the broader

ITCZ, shifting rainfall to the eastward, with the high rainfall zone that normally occurs over the West Pacific Warm Pool moving closer to the equator, and subject to enhancement by locally positive SST anomalies.

American Samoa has a limited time series in regard to meteorological data, with the weather recording station at Pago Pago International Airport, at Tafuna on Tutuila (Fig. 14), having only been in operation since 1965, and all other rain gauges in the territory now discontinued (Keener et al. 2012). By contrast, both rainfall and temperature data from Apia, on the island of Upolu in the adjacent independent nation of Samoa (visible from Tutuila on a clear day), have been continuously recorded on a daily basis since 1890, and at the same exact location since 1902 (Solofa & Aung 2004). Therefore, many of the longer term hindcast trends for the Samoan Archipelago as a whole are based on the Apia data, which given its relative proximity to Tutuila is likely to provide a reasonable proxy. As noted by Keener et al. (2013) in regard to precipitation patterns in American Samoa: "Little detailed work has been undertaken examining trends in extreme events in his sub-region." The analysis of Kruk et al. (2015) found no statistically significant trend in consecutive dry days in American Samoa, although it did exhibit a statistically significant increase in the number of consecutive wet days. Data presented by the Australian Bureau of Meteorology & CSIRO (2011) indicate a gradual increase in annual and dry season rainfall at Apia since 1890. Based on the analysis of Buxton (1930), the months of May to August inclusive at Apia are notably drier than the remainder of the year, with only 16 percent of annual rainfall occurring during this period, and these same months also appear to be drier on Tutuila.

Significant drought episodes from the recent past in American Samoa occurred in 1974, 1983, and 1998, the latter two correlated with strong El Niño years. The 1998 drought was the most meteorologically severe, with the NWS office at Tafuna Airport recording only 59.76 inches (1518 mm) of precipitation for the entire year, a mere 49% of the mean annual rainfall of 120.80 inches (3068 mm) at that location based on a 32-year period of record from 1966-1998. At this same recording station, the previous droughts of 1974 and 1983 resulted in 77.89 and 87.36 inches (1978 and 2219 mm) of rainfall respectively (Dworksy & Crawley 1999). The 1998 drought was also accompanied by very high air temperatures, being the warmest year on record to that date, with the station at Tafuna Airport recording an apparent all-time high record of 96° F. on 27 February 1998, a reading not approached again until February 2016 during the warmest year ever recorded globally. The combination of record low rainfall coupled with record high air temperatures thus combined to increase the overall severity of the 1998 drought episode. During the 2015-2016 El Niño event, Pago Pago was again very dry initially, receiving only 60 percent of average rainfall for the period from January-March 2016, but this was followed by the wettest April rainfall total in the historical record, at 30.43 inches (773 mm). This anomalous month brought 2016 up to 101 percent of average rainfall overall, and obscured what was otherwise a moderately strong drought signal for the El Niño period, with all other months in calendar years 2015 and 2016 having rainfall below average (PEAC 2016). However, this example also serves to illustrate that American Samoa does not have a strong and unambiguous correlation between ENSO cycles and drought.

Hydrological Drought

Overall, the base of studies upon which to assess patterns of hydrological drought in American Samoa is limited. The USGS has conducted stream gauging on the island of Tutuila since 1957, in cooperation with the Government of American Samoa, and a summary of analytical methods for calculating streamflow characteristics was provided by Wong (1996), based on records from 11 continuous-record stations, 75 low-flow partial record stations, and 49 miscellaneous sites. Since 1996, however, the number of maintained stream gauges on Tutuila has declined substantially, and little additional analysis of flow characteristics appears to have been undertaken. At present, only a single stream gauge on the island of Tutuila has more than 35 years of record which is unaffected by upstream diversions (Keener et al. 2012).

Stream base flows on Tutuila are generally perennial, but in many cases low and highly variable on an intra- and inter-annual basis (Matsuoka 1978; Wong 1996). Total flows are also highly variable, with peak discharges concentrated in the wetter season from October through April. These are often in response to episodic high rainfall events generated by passing cyclones, although Diamond et al. (2013) have documented a decline in such tropical cyclone activity over the southwest Pacific since the early 1990s. Conversely, the majority of low flows occur during the drier May through September season.

Ecological Drought

In contrast to other USAPI jurisdictions, there seems to be little correlation between drought and wildland fire in American Samoa, with wildfires themselves being very uncommon due to the absence of a strong annual dry season, with fuels tending to remain moist throughout the year. As noted in the *American Samoa Forest Assessment and Resource Strategy*, "Fire is not a part of the natural disturbance and succession processes of American Samoa's forests." As such, nearly all fires other than structural fires occur in areas of human habitation (ASCC 2010) and have little impact on the surrounding forest.

In lotic systems, Mirinov et al. (2015) noted that dragonflies were less abundant during the months of the year from May-September when stream flows are lower, but did not provide any comparative data spanning multiple years.

Agricultural Drought

FAO crop production data for American Samoa, accessed via the Knoema search engine, indicate that in a pattern similar to that seen in the FSM and RMI, coconut production fell sharply from 1998 to 2001, declining from 8166 tons to 3835 tons, a reduction of 53 percent. This data is partly skewed by a sharp increase in harvests during 1997 and 1998, so the true decline from average long-term production was actually less, and production had recovered to previous average levels by 2004. As in FSM and RMI, however, the 1998 drought event was clearly correlated with reduced harvests in the years following, and it required about 5 years to regain previous levels of yield.

Other food crops in American Samoa did not fare as poorly during the 1998 drought. Taro production increased in 1998, with a small decline in 1999, and yam production increased substantially from 1997-2000, rising six-fold over this period. Similarly, banana production nearly doubled between 1997 and 2001. These statistics serve to illustrate that as in the FSM, not all food crops are equally affected by drought conditions.

Socioeconomic Drought

The droughts of 1974 and 1983 resulted in the need to impose water rationing, with supplementary water being brought to American Samoa by ships for drinking water supplies and use in the tuna canneries, the latter a mainstay of the local economy (Dworksy & Crawley 1999). Although the 1998 drought was even more severe than the previous two, it did not result in the same degree of social impact, due to both better advance forecasting of impending drought conditions by the Pacific El Niño -Southern Oscillation Center and the National Climate Prediction Center, based on improved understanding of ENSO cycles, as well as more robust water supply infrastructure and institutional response capacity by the American Samoa Power Authority (which also oversees water supply) that had been developed in the intervening years also reduced impacts. The 2016 drought was not as severe as 1998, and did not result in any water supply disruptions (PEAC 2016c).

SYNTHESIS

Meteorological Drought

The available time series of meteorological data for the Micronesian islands in the USAPI is variable prior to World War II, but in some cases provides temperature and rainfall records spanning over 100 years. The more comprehensive modern time series of meteorological data largely begins following World War II, and provides a moderately reasonable profile of temperature and precipitation over the past 65 years, including 5 major drought episodes which occurred in 1970, 1983, 1992, 1998 and 2016, as well as other more minor events. In the Samoan Archipelago the time series for meteorological data is even longer and more complete, due to the previous British recording station at Apia, which continued to operate under the government of the independent nation of Samoa, and provides a 127-year period of record. Because a 30-year average is generally considered sufficient for computation of baseline monthly and annual averages, and recurrence intervals of extreme events, the overall base of meteorological data for the USAPI has been sufficient for regional analyses (Kruk et al. 2015) as well as some more locally focused studies (Lander & Khosrowpanah 2004). Even so, these recent studies have tended to concentrate on the predicted periodicity of extreme rainfall events (Kruk et al. 2015), rather than drought (Spinoni et al. 2014; McGree et al. 2016).

Inter-annual variations in precipitation in the USAPI very clearly correlate with ENSO cycles, in particular El Niño events, but as investigated by Murphy et al. (2013), not all El Niño events are equivalent. This study, which included Palau, the FSM and the RMI, but not Guam, the CNMI or American Samoa, subdivided El Niño events from 1979-2010 into three classes: "cold tongue" El Niños (CTE) whose strongest manifestations were in the Eastern Pacific (zone Niño 3); "mixed" El Niños (ME) that had their anomalous ocean surface heat concentrated in the Central Pacific (zone Niño 3.4); and "warm pool" El Niños (WPE) whose heat anomalies lay in the western Pacific (zone Niño 4). These authors concluded that the CTE events, which occurred in 1982-1983, 1997-1998 (and more recently in 2015-2016 subsequent to their period of study) are uncommon, but have the largest overall impact on Pacific Basin climate and rainfall deficiency. ME events produced lesser but still statistically significant reductions in rainfall in Palau, Yap and Chuuk, while WPE events correlated with dry years only in Palau

(Murphy et al. (2013). La Niña events produced the opposite effect, correlating with increased precipitation in Palau, Pohnpei and Kosrae, but exhibiting minimal effects in Yap, Chuuk or the RMI, although near-equatorial western Pacific islands such as Kapingamawrangi in Pohnpei State of the FSM usually have a severe drought during La Niña conditions, and such dry weather can even spread northward to Nukuoro and Kosrae (Guard, pers. comm.). The Murphy et al. (2013) study did not break out effects to the far northern atolls of the RMI, but it appears that these islands are also subject to drought conditions during ME events. In Guam, the CNMI and American Samoa, which were not specifically analyzed, the three most recent CTE events all correlated with severe drought, and in addition there was a marked increase in the number of acres burned by wildfire on Guam during the ME events of 1987, 1988, and 1992 (YSDPS 2009).

During a CTE event, the temporal initiation and progression of drought is not congruent across the USAPI. In all of the jurisdictions north of the equator the initial onset of CTE is marked by the eastward extension of the WNPM trough, a higher incidence of tropical cyclones, and above-normal precipitation, which then transitions rapidly into a period of below-normal precipitation, with extreme drought occurring in the normal dry season following the El Niño year. In Palau, Yap, Chuuk, Pohnpei, Kosrae and the RMI, the drying trend begins in the second half of the year in which El Niño peaks, sometime between June and December. By contrast, in Guam and the CNMI the onset of drying is somewhat later, generally beginning around January of the year following El Niño, whereas in American Samoa it is later still, occurring in February or March of that year. All the above areas then experience a severe dry season with much lower than average rainfall lasting through June of the post- El Niño year, with recovery to normal rates of rainfall in the latter half of that year, although this recovery is often slower in Guam and CNMI (PEAC 2016a, 2016b). Overall, CTE-linked droughts appear to be more prolonged in Palau, the FSM and the RMI, and shorter but still severe in Guam and the CNMI. The weakest relationship between this ENSO pattern and drought occurs in American Samoa, which is the only jurisdiction south of the equator, being predominantly influenced by the SPCZ rather than the WNPM.

Within this framework of El Niño classification, it may be informative to compare standardized indices of drought within the USAPI over the past 65 years to the progression of ENSO events. Based on the current assessment, sufficient rainfall and temperature records are at hand to attempt calculation of a hindcast rainfall climatology and Palmer drought severity index (PDSI) for each of the following islands in the USAPI for periods of record spanning the past 65-105 years, depending on the location: Saipan in the CNMI; Guam; Koror in Palau; Yap Island; the Chuuk Lagoon high islands, Pohnpei and Kosrae in the FSM; Majuro and Kwajalein in the RMI; and Tutuila in American Samoa (see Table 1). The PDSI appears relatively well suited to the USAPI in that it relies on monthly averages of temperature and precipitation, rather than daily values, and assumes all precipitation falls in the form of rain (Palmer 1965), an assumption that is not always met in temperate continental settings, or on taller Pacific island groups such as Hawaii, where a certain amount of annual precipitation falls as snow. As potentially superior alternative to the PDSI, individual drought events, particularly subsequent to 1950, can also be analyzed using the Standardized Precipitation Index (SPI), which examines the difference from the mean for rainfall over a specific time period divided by the standard deviation (McKee et al. 1993). Due to their small sizes and general lack of rain gauging except at key sites (generally airports), the islands involved would need to be treated as points rather than gridded areas for the purposes of such analyses, but this would still provide initial insights into the temporal dynamics of drought in each of the jurisdictions. In standardized drought category scores used by the U. S. National Drought Monitor program (ie., D0, D1, D2, etc.) can now be assigned to current and future drought events in the USAPI (PEAC 2016c), so as to provide an objective basis for comparison moving forward.

Post World War II rainfall data from all the above stations have already been utilized in a previous regional analysis using the Consecutive Dry Days (CDD) index, which found trends from 1951-2011 to be largely non-significant (McGree et al. 2014). The CDD index is based on the maximum number of days with precipitation below 1 mm, as such tends to be poor at detecting sub-average precipitation during the wet season, when some rain might fall, but less than average. Subsequently, McGree et al. (2016) again incorporated data from all the above stations into a drought analysis spanning the Southwest Pacific, calculating SPI values at 10-year intervals for the period from 1951-2010. This study focused on 11 broad zones, and did not present conclusions regarding specific localities or jurisdictions. The overall conclusion was there was some evidence to indicate that droughts had become more frequent, longer and more intense since 1981.

Even discounting pre-World War II data sets, daily readings for temperature and precipitation from 1951 onward at NWS recording stations in the USAPI are available through the NOAA Global Historical Climatology Network site (*https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn*). Pre-1951 data from the USAPI is partially available online through the PACRAIN online database system (*http://pacrain.ou.edu/*) (Greene et al. 2008). Summary data for locations and periods of record for meteorological recording stations in the USAPI is available through the Western Regional Climate Center (*http://www.wrcc.dri.edu/*). All of the above data sets have gaps, but in aggregate they form a starting point for hindcast drought analyses. In addition, maps of average monthly precipitation, minimum and maximum temperature, relative humidity, and mean dew point temperature for the period 1971-2000 are available through the PRISM Climate Group at Oregon State University (*http://www.prism.oregonstate.edu/projects/pacific_islands.php*).

Despite the fact that the interior uplands of the high islands in the USAPI are clearly wetter than their coastal zones, the current base of rainfall data for the USAPI is for the most part sufficient only to treat the islands in question as single coastal points in the context of local drought analyses, with little insight as to intra-island distribution of precipitation. As noted by Lander & Khosrowpanah (2004), “Existing annual rainfall maps for most of the islands of Micronesia are incomplete, inaccurate and/or non-existent for many areas.” These same authors also note the potential for a bias in existing analyses toward ascribing a “trade-wind-type precipitation distribution” of the type prevailing in Hawaii and to some degree the Marianas to the high islands of the FSM which lie in closer proximity to the Equator, and are therefore largely outside both the trade wind and cyclone belts. Rainfall dynamics in this latter area, particularly on Pohnpei and Kosrae, are instead more directly related to the interaction of deep convection, which prevails year-round, with local elevation and topography. A more extensive deployment of rain gauges and other instrumentation across the region, particularly within individual high islands as was done for a limited period on Pohnpei (Lander & Khosrowpanah 2004), will be necessary before such patterns can be properly understood, and a more realistic understanding of high island rainfall in the USAPI can be achieved.

Hydrological Drought

Assessing the hydrological effects of drought in the USAPI is challenging due to a lack of data, and by the physical characteristics of certain islands. Streams are absent in the RMI and on the atolls of the FSM, and nearly so on the volcanic and limestone islands of the CNMI. By contrast, numerous perennial streams are present on Guam, Palau, the high islands of the FSM, and the island of Tutuila in American Samoa. As a result, assessment of streamflow responses to drought is possible only for the latter areas. Information on water-resources in the Micronesian islands is largely absent for the periods of German and Japanese administration, so available records for this area, for all practical purposes, commence in with American studies begun in 1946 (van der Brug 1983a).

Evaluating stream functional responses to drought on those islands where streams are present is further hindered by the current absence of gauging stations, with those previously present having been largely abandoned (Keener et al 2012). Although the USGS and the Trust Territory of the Pacific entered into a joint funding agreement in 1968 to collect streamflow data across the high islands of Micronesia, the responsibility for matching funds and services was transferred to the FSM and Palau following their emergence as independent nations in the 1970s, following which the previously existing stream gauge networks were steadily reduced and eventually became defunct. Fortunately, the stream gauging network was still in good working order during the drought of 1982-1983 (van der Brug 1986), and the readings obtained during those years still stand as the most comprehensive quantification within the region of hydrological drought in the context of surface waters. Reactivating a proper network of stream gauges is therefore important pre-requisite to accurate future assessment of stream flow responses to variations in precipitation across the region.

The gauging data from the 1950-1985 period has allowed for calculation of rainfall-to-runoff ratios for a number of the high islands in the USAPI (van der Brug 1983a, 1983b, 1984a, 1984b; Heitz & Khosrowpanah 2015), which is summarized in Table 2. The numbers reveal that most of the high islands in the USAPI are surprisingly impermeable, due to their surfaces of weathered clays derived through chemical weathering of underlying dense basalts, such that in most catchments well over 50 percent of the annual rainfall moves to the sea as runoff, rather than recharging any underlying aquifers. This trend is particularly pronounced on the large island of Babeldaob in Palau, where 77-91 percent of rainfall ends up as surface runoff. This has of necessity led Palau to rely almost entirely on stream-fed reservoirs to supply water to the capitol of Koror, leaving it vulnerable to states of water emergency during periods of severe drought when such runoff is greatly diminished, as occurred in 1983 and 2016. Geologically, the high islands in Palau and the FSM are thus vulnerable to hydrological drought, and it is only their very wet average rainfall regimes in excess of 160+ inches (4064+ mm) per annum that buffer them from such episodes on an even more regular basis than presently occurs.

All of the islands in the USAPI also contain freshwater lenses and aquifers to greater or lesser extents, these being the only non-rainfall water sources on the atolls, but few of these are monitored in any systematic fashion. Therefore, interpretations of groundwater responses to periodic drought episodes in the region are based on studies of a few key features, such as the Laura Lens on Majuro (Hamlin & Anthony 1987; Presley 2005), or the aquifers on Guam (Wuerch et al. 2007; Johnson 2012; Gingerich

2013), Saipan (Carruth 2003) and Tinian (Gingerich 2002). Such studies indicate that depletion of such aquifers is common during periods of severe drought, and that recovery may take up to 5 years.

Ecological Drought

Ecological responses to drought events have been very poorly investigated or monitored throughout the USAPI. The most obvious manifestation of such ecological effects is wildland fire, which represents a particularly acute problem on Guam. Fire does not play a natural role in structuring most Pacific island ecosystems, due to their closed canopy forest structures, moist tropical climates and near-absence of natural ignition sources (Minton 2006). Most USAPI ecosystems that are vulnerable to fire therefore consist of anthropogenic savannahs which might be considered "fuel limited" in the sense of Littell et al. (2016), in that their grass cover must grow back following burning. As such, their flammability, fuel loads, and fire response to drought may to some degree be conditioned by the level of antecedent moisture and fuel re-accumulation over previous years. In this regard, the fact that El Niño droughts are often preceded by periods of above average precipitation which rapidly transition to drought (Lander 1994; Lander & Guard 2003; PEAC 2016a) is reminiscent of the fire regime in the deserts of southwestern North America, where wet summer monsoon years allow accumulation of a dry grass fuel load that sets the stage for extensive fire during subsequent dry years (McKenzie & Littell 2017). In the well-studied forest systems of North America, the area burned on an annual basis generally increases with increasing temperature, decreasing precipitation, and lower PDSI values (Littell et al. 2016), whereas the correlation between drought and fire severity is less direct, and such relationships also seem to hold for the USAPI based on the limited data available (Minton 2006). It must be noted that while drought sets the stage for fire by reducing fuel moisture, the vast majority of ignition sources in the USAPI are anthropogenic (e.g., hunters and arson) rather than meteorological (e.g., lightning), therefore there is a social component to fire ignition that operates independent of drought cycles. Overall, however, the relationship between drought and wildland fire in the USAPI is strongly correlated and demonstrably coupled to ENSO cycles, and as such represents the most obvious manifestation of ecological drought in the region.

The slow but steady retreat of native forest areas in the face of repeated wildland fires also constitutes a gradually increasing threat to the native biota of all the USAPI high islands, which contain a significant number of endemic species (NEMSDC 2002; Hinchley et al. 2007). Even on wet islands such as Pohnpei and Kosrae, upland forests suffered severe impacts in the droughts of 1982-1983 and 1997-1998 (FSM 2010), particularly from fires, which are otherwise rare in such ecosystems. In addition, areas scarred by fire are often recolonized by invasive non-native grass species that constitute ready fuel sources during drier months or years and thus promote additional fire-mediated landscape transformation (Minton 2006). Therefore, drought-mediated mortality and loss of habitat for the native biota, accompanied by expansion of invasive-dominated landscapes - as has been well characterized in Hawaii (Trauernicht et al. 2015 and references therein) - represents another aspect of ecological drought in the USAPI, but one that has been inadequately studied or documented across these islands as a whole. Fire-scarred areas are also prone to increased erosion once rains do return, leading to increased sediment delivery onto nearshore reefs, a phenomenon particularly evident on Guam (Minton 2006). It should be emphasized that the above dynamics play out almost entirely on high islands, with such fire-mediated landscape conversion representing a minor component of forest disturbance on the atolls of the USAPI (Donnegan et al. 2011).

Agricultural Drought

The agricultural impacts of drought in the USAPI are clearly variable depending on island characteristics and the individual crops involved. Coconut production on atolls seems to be particularly vulnerable to drought, with losses following the 1998 event ranging from nearly 80 percent in the RMI, where all islands are atolls, to 20 percent in the FSM, with its mix of both low and high islands. The loss of mature coconut and breadfruit trees also means that the agricultural effects of severe drought are persistent, with coconut production in both the RMI, FSM and American Samoa taking approximately 5 years to recover from the 1998 losses as new trees slowly matured. Corn also shows losses in yield during periods of drought, but also demonstrates highly variable yields during non-drought periods as well, and as such does not provide a strong an illustration of agricultural drought. Still other food crops, such as bananas and sweet potatoes, show no strong correlative patterns between drought and yield across the USAPI.

Drought measurement tools typically used in the continental United States, such as soil moisture percentiles, crop moisture indices, and integrated drought indices are not currently generated for the USAPI. Although data exist to calculate PDSI values for at some of the high islands in the USAPI, this index does not appear to have enjoyed wide use to date in the region.

Socioeconomic Drought

Of the jurisdictions in the USAPI, none has suffered greater socioeconomic impacts from drought over the past 50 years than the RMI. Partially this is reflective of the fact that the country is composed entirely of atolls, which exhibit rather rapid responses to drought conditions lasting more than several months. In addition, the northern atolls of the RMI lie in a sector that has exhibited an anomalously drying climate regime in comparison to surrounding areas. Whereas drought is an episodic phenomenon in the Marianas, Carolines, and Samoa, it has by contrast become a nearly chronic condition in the northern RMI. This emphasizes the fact that while the pattern and periodicity of drought are aspects of climate, drought in and of itself is an aspect of weather in any given year, the effects of which are intensely local and play out with many individual variations across the widely scattered islands of the USAPI.

In all cases of severe drought in the USAPI the social effects are similar, being manifested in form of water rationing, brackish wells, and loss of food crops, with consequent expenses to pay for imported food products. Such social disruptions, however, are usually transient, lasting 3-6 months until the onset of the next wet season. In the northern RMI, by contrast, the loss of mature breadfruit and coconut trees during a succession of droughts has led to a longer-term switch from locally grown and harvested staples to more expensive and often less nutritious imported foods such as white flour, rice, canned tuna and SPAM (Ahlgren et al. 2014). As with the climatological trends, the social impacts of drought in this sector also seem to be making a transition from episodic to chronic, which will necessitate cultural and institutional adaptations.

The recognition following the Vietnam War of ENSO cycles and their important linkage to periodic episodes of drought in the USAPI also has allowed better advance prediction of such events. For example, during the 1997-1998 El Niño drought there were no deaths, and suffering was minimized due to timely predictions from the Pacific El Niño -Southern Oscillation Applications Climate Center (PEAC) and the Climate Prediction Center, based on improved understanding of ENSO cycles and their impacts

(Schroeder et al. 2012). The Water and Environmental Research Institute of the University of Guam, as part of the PEAC, also visited each of the main islands in Micronesia (Palau, Yap, Chuuk, Pohnpei, Kosrae, and Majuro) in late 1997 and assisted island decision makers with setting up Drought Response Committees, providing essential drought and drought response education (Hamnett et al. 1999). The PEAC also worked with FEMA on a Presidential Disaster Declaration for the FSM and the RMI based on PEAC predictions of an extended severe drought, with President Clinton signing the Declaration based on these predictions. As a result, FEMA has developed a new paradigm for the USAPI, seeking to avert drought disasters instead of waiting for them to occur.

In certain jurisdictions, this has also led to institutional responses in advance of drought that reduced the social impacts of water shortages, a good example being American Samoa during the drought of 1998. Similarly, the average recurrence interval of drought is now being factored into infrastructure planning, such as in Kosrae State in the FSM, where plans for water supply improvements evaluate whether proposed infrastructure upgrades are sufficient to meet projected 2020 water use demands under average 1-in-10 year drought conditions (GlobalWorks 2004). Both of the above cases involve high islands which can tap elevated aquifers free from the threat of saline contamination or reservoir storage fed by generally abundant stream flow. For atoll communities, even with better advance prediction of drought, adaptation options will be more limited and challenging, consisting largely of reverse osmosis systems coupled with the associated renewable energy infrastructure to power them. Although this may ensure sufficient drinking water supplies during dry periods, transitions in the agricultural sector will also be necessary, given that the current suite of atoll tree crops, particularly coconuts, have proven consistently vulnerable to drought, requiring multi-year cycles for recovery.

At the federal government level, the efforts of the NWS over the past 20 years, especially the Weather Forecast Office on Guam and the PEAC, have greatly enhanced the adaptation capabilities of the USAPI in regard to drought by conducting monthly teleconferences and annual training workshops, and by providing quarterly predictions of rainfall, tropical cyclone activity and sea level changes tailored to each of the island jurisdictions. The NWS offices on Palau, Yap, Chuuk, Pohnpei, and Majuro also play critical roles in working with the local government officials to prepare to for anticipated drought events. The steadily quality of such guidance, predictions, special products and outreach has clearly lessened the impacts of socioeconomic drought across the region.

DISCUSSION

Based on an analysis of 1931 precipitation recording stations from across the tropical Pacific, with an average period of record of 61.2 years per station, Kruk et al. (2015) concluded that for the period from 1940 to 2010, both consecutive dry days and consecutive wet days had increased on an annual basis, indicating that precipitation was becoming more episodic. Such trends were not uniform across the region spanned by the islands of the USAPI, however, with 1-day extreme precipitation events increasing both annually and in the winter season (October through April) in the Western Pacific, but decreasing in the South Pacific. Although the above study focused on extreme rainfall events, not drought, the conclusion that consecutive dry days had increased on both an annual basis, and in the winter and summer (May through September) seasons, might suggest that extreme dry episodes are now alternating with extreme wet periods on a more regular basis. However, much of the statistical trend in regard to this metric for the

South Pacific was driven by results for stations in northern coastal Australia, with the smaller South Pacific Islands, including American Samoa, showing no statistically significant trend in consecutive dry days, although some did exhibit a statistically significant increase in the number of consecutive wet days. The conclusions of Kruk et al. (2015), however, mesh well with forecast studies based on the CMIP5 ensemble, which have projected a 73% increase in extreme La Niña events in the period from 2000-2099 (Cai et al. 2015), with 75% of these La Niña events being coupled with a corresponding extreme El Niño event. Under this scenario, the insular Pacific over the next eighty years would continue to oscillate between extremes of heavy precipitation and severe drought, both of which will bring challenges to island communities and ecosystems.

In recent years, several key thresholds of drought have been advanced for the USAPI, consisting of levels of monthly rainfall below which various social and ecological effects are triggered (PEAC 2016a). At less than 8 inches (203 mm) per month, precipitation is generally inadequate to replenish home rain catchments and municipal water supplies, or provide for adequate streamflow to refill reservoir catchment systems. This is therefore a key threshold for hydrological and socioeconomic drought. Below 4 inches (102 mm) per month, threats to agriculture rapidly escalate, and the extent and severity of wildfire increases significantly. This is thus a key threshold for agricultural and ecological drought. These thresholds are typically breached during droughts linked to CTE events, of which three have occurred in the past 67 years, in 1982-1983, 1997-1998, and 2015-2016.

An extremely detailed report on effects of the drought of 1982-1983 across all the USAPI, with the exception of American Samoa, was prepared by van der Brug (1986). This analysis benefitted from the continued presence at that time of rain and stream gauges installed during the Trust Territory period, many of which were subsequently deactivated or abandoned. As such, the 1983 event stands as the best quantified drought in the USAPI to date. At the time, it was the most severe drought to be recorded in the colonial and post-colonial history of the USAPI, and it was optimistically calculated at that time that the probable recurrence interval of such a drought was 125 years.

Only 15 years later, however, the drought linked to the very strong El Niño event of 1998 was in certain locations even more severe than that of 1983. By this time, Palau, the FSM and RMI were fully independent, and there were far fewer rainfall or stream gauging stations still in place to quantify the meteorological and hydrological effects. The social impacts of the 1998 drought were severe, however, and can be evaluated from reports issued by USAID and other aid organizations (Hamnett et al. 1999; Schroeder et al. 2012).

Following the 1997-1998 drought, the USAPI enjoyed a nearly 20-year hiatus in which no strong El Niño events or droughts occurred. Instead, the period was marked by 3 strong La Niña events, and prolonged periods of ENSO-neutral conditions, with the 3 El Niño events that did occur being very weak. Climate guidance provided by international aid organizations to Palau, the FSM, and the RMI during this period predicted that droughts would become less frequent throughout the current century, while the number of extreme rainfall events was projected to increase (Australian Bureau of Meteorology 2011a, b, c; GCCA 2013). As a result, local planners shifted their focus to coping with extreme rainfall and flooding events rather than drought, on the assumption that the Western Pacific had moved into a permanently wetter phase (Greene & Skeele 2014). This was exemplified by a statement in the FSM Statewide Assessment and Resource Strategy that “The recent trend toward greater rainfall and shorter and less severe droughts will also make it more difficult to burn forests” (FSM 2010). Such predictions, however, considered future incidence of drought only in the context of precipitation, while overlooking the associated increasing temperature component of changing climate. As noted by Littell et al. (2016) “As temperatures continue to warm, all else being equal, droughts of a given magnitude and low fuel moistures may become more likely in summer-dry climates even if precipitation increases, because potential evapotranspiration will also increase.”

The optimistic assumptions regarding future drought in the USAPI were to some extent tempered by the strong El Niño event of 2015-2016 and events preceding it, which led to another severe drought in the region. As early as the fall of 2012, the northern atolls of the RMI were suffering from steadily worsening drought, which led the RMI to declare a State of Emergency for the area on April 19, 2013, followed by a State of Disaster on May 7, 2013, the latter based on imminent threats to life (USAID 2013). A NOAA (2016) analysis of precipitation data spanning 1951 to 2016 indicated that September 2015-June 2016 was the driest ten-month period on record for Yap and Majuro, and apparently also for the atolls of Woleai in Yap State, Pingelap in the FSM and Jaluit in the RMI, although the latter islands have shorter periods of record by which to judge the data. Koror in Palau saw its driest October-March period on record, and Nukuoro atoll in Pohnpei State had its driest 12-month April-March period on record (PEAC 2016b). A Standardized Precipitation Index (SPI) summary prepared by the National Weather Service rated the 6-month period from January-June 2016 as moderately dry at Koror and Kwajalein, very dry at Yap and Korsae, and extremely dry at Majuro (NOAA 2016). As a result, a drought disaster was declared, including a United States presidential disaster declaration by U. S. President Barack H. Obama on April 27, 2016 for the RMI that eventually provided over $2.5 million for supplemental food assistance and other relief (USAID 2016). Palau also suffered from severe drought at this same time, with President Tommy Remengesau declaring a State of Emergency Due to Extreme Drought on March 22, 2016, noting that cumulative rainfall for December-March was the lowest recorded since 1951, and that the remaining water reservoir serving the capitol was down to 19 percent of capacity (Republic of Palau 2016). In the FSM, reverse osmosis units were necessary to provide supplementary drinking water on Ulithi atoll (PEAC 2016c). By contrast, the 2016 early year dry seasons in Guam, the CNMI, Pohnpei and at Chuuk, although more pronounced than normal, were not as severe in 2016 as during the drought of 1998 (PEAC 2016b), thus the manifestations of the 2015-2016 ENSO event, at least in terms of precipitation, seem to have played out closer to the equator than occurred in 1982-1983 and 1997-1998.

Drought effects have continued to linger locally in the RMI even following the cessation 2016 El Niño event. As late as May 2017, NOAA reported that many atolls in the northern RMI, including Ailuk, Mejit, Likiep, Wotje-Wodmej and Wotho, continued to experience drought conditions, with the atolls north 8° N considered to be in severe drought, and those north of 10° N latitude experiencing extreme drought (NOAA 2017). This led to a declaration of a State of Emergency by RMI President Hilda C. Heine on April 24, 2017. Although global climate models may still be correct in projecting that the USAPI are moving into a wetter climate regime overall, it appears that this new regime may indeed be one marked by alternating extremes of both rainfall and drought (Kruk et al. 2015), which will necessitate adaptations for the USAPI jurisdictions going forward.

One clear conclusion that emerges from the present study, and the three CTE-linked drought case histories summarized above, is the dichotomy in the dynamics of drought as it plays out on high islands versus atolls. High islands, with their potential to create orographically-forced local precipitation due to convection over mountainous terrain, more extensive perched aquifers with lesser vulnerability to salt water intrusion, and opportunities for reservoir storage along their numerous perennial streams, are better equipped to endure episodes of severe drought than are low-lying atolls, which lack topographic complexity or perennial stream networks. On these latter islands, water supplies are basically limited to rainwater catchment, sometimes supplemented by reverse osmosis units, plus a generally shallow freshwater lens underlying each island on the atoll rim. Therefore, dropping below the 8-inch monthly precipitation threshold has more immediate and severe consequences on atolls in comparison to high islands, and dropping below the 4-inch threshold for any period of time can be catastrophic.

On atoll islands, drought rapidly increases demands on these freshwater lenses, which are heavily tapped as rainfall catchment storage proves insufficient to sustain local populations (Wallace & Bailey 2014). Islands on the windward sides of atolls contain thinner lenses, and as such are more vulnerable to drought effects linked to diminished precipitation (Bailey et al. 2012). Such freshwater lenses are also vulnerable to saline contamination due to marine overwash events generated by transient phenomena such as extreme local high tides or tsunamis, further exacerbated by steadily rising global sea levels. Numerical modeling of such events indicates that following such saline intrusion, it may take 6-12 months for a freshwater lens to recover 60% of its former capacity, depending on an island's windward or leeward position and associated lens thickness and rainfall regime (Bailey 2015). Therefore, drought on atolls cannot be viewed merely through the prism of meteorology and correlated ecological and socioeconomic effects, but must also be considered in the context of rising sea level as well.

In regard to drought resilience on atolls looking forward, potential changes in future rainfall have been modelled on a worldwide basis for islands too small to be resolved within current GCM grid cells (Karnauskas et al. 2016). These authors calculated an aridity change index (ACI) for each island or island group based on a ratio of the fractional change in potential evaporation to the fractional change in precipitation over two time periods, running from the present to 2050 and 2090 respectively. Their model results indicate that increasingly wet conditions will prevail across both time intervals for all of the USAPI jurisdictions north of the equator, while slightly drier conditions will develop over time south of the equator, including in American Samoa. Their results also indicate, however, a high degree of internal variability over these same time spans, particularly for the atolls of the FSM and the RMI. This produces the interesting prediction that although rainfall may increase over time, strong inter-annual variations in precipitation will still occur due to ENSO cycles, such that drought events are still likely to occur even in a wetter climate.

On the basis of a similar ACI calculation, predicted aquifer recharge rates for 40 exemplar small island groups, including those covered by this study, were calculated by Holding et al. (2016). Their results indicate that future recharge volume will increase for the islands of the CNMI, FSM, and RMI, remain relatively steady for Palau, and decrease for Guam and American Samoa. These projected future recharge rates do not take into account any measure of temporal variability, but do provide some confidence that going forward to 2100, atoll freshwater lenses and other aquifers across most of the USAPI should be able to recover from any temporary depletion that may occur during periodic episodes of drought.

The area covered by the USAPI and its associated maritime Exclusive Economic Zones is larger than that of the continental United States. In North America, however, drought in any given year tends to be highly sectoral, occurring in California, or the Great Plains, but not across the continent as a whole. In the USAPI, by contrast, there is frequently a synchronicity of drought that spans the entire vast geography of the central and western Pacific. This is likely due to the very large-scale forcing mechanisms, such as PDO and ENSO, that operate within the region, coupled with the fact that weather in this oceanic sector is largely a product of the atmosphere's interaction with the ocean rather than land. Increasingly, ENSO predictions are being factored into advanced forecasts of drought in the USAPI (Annamalai et al. 2014, 2015; Luchetti et al. 2016), allowing for better planning in regard to adaptation strategies. Such inter-annual ENSO variations, however, play out on top of the broader underlying oscillations of the PDO, which can create multi-decadal episodes of increased or decreased precipitation affecting both the WNPM and the SPCZ to either side of the equator (Partin et al. 2013; Maupin et al. 2014). As such, efforts should also be made to integrate these longer-periodicity cycles into guidance to local governments and communities in order to promote the most effective and comprehensive drought adaptation strategies in the USAPI going forward.

Although the underlying forcing mechanisms of drought in the USAPI are now comprehended (Annamalai et al. 2014), the proximal manifestations of drought at the level of individual jurisdictions or islands are less well understood. There is a clear dichotomy of functional responses between high islands, with their perched aquifers and local convective forcing, and low-lying atolls with their shallow freshwater lenses and minimal topography. The working assumption is that the latter islands have a discountable meteorological signature (Morrissey & Greene 1993), and although this has been debated in the context of calibrating satellite proxy measurements for open-ocean rainfall (Reed 1980; Dorman 1982), it is possible that even such small and low-lying features can influence local precipitation. The author has observed a very high resolution missile tracking radar at Kwajalein Atoll detecting a narrow but persistent band of local condensation on a clear day as moist air crossed a narrow islet on the atoll rim, which was warmer than the surrounding waters of the ocean or lagoon lying to either side. The extent to which such phenomena bear on local ecology and hydrology is unknown, and given the scales involved are clearly not captured by current meteorological observations or climate models.

The assessment of drought at all levels across the USAPI also continues to be challenging simply due to the great distances and numerous individual islands involved. Going forward, remote sensing data clearly holds promise in addressing data gaps, given that it will not be feasible to emplace a sufficient number of recording stations across this vast seascape. For the moment, however, acquisition of such comprehensive data similar to that routinely acquired for oceanography still presents certain technical challenges. In particular, there are significant uncertainties associated with satellite precipitation estimates, due to the unknown variation in statistical relationships between precipitation and satellite- sensed radiance in space and time (Huffman et al. 1997). As a result, satellite-based sensors, although able to discriminate dry versus wet zones over open ocean where other instruments are absent, often overestimate low values of precipitation as well as underestimating high values (Greene and Morrissey 2000), thereby to some extent dampening out the signal of both drought and extreme rainfall events. Precipitation-estimating radars such as NEXRAD can also be useful for providing representations of spatial patterns and relative gradients across individual islands such as Guam, but can yield underestimates of rainfall magnitude on the order of

15 to 20 percent (Lander & Guard 2003), thereby creating potential illusions of drought. Although advances to addressing these lingering technical problems are steadily being made, our present quantitative assessment of drought in the USAPI will of necessity continue to be based on a few widely scattered rainfall and hydrological gauging stations with reliable long-term records, against which current and future remotely sensed observations can be calibrated, and with which climate model projections can validated. The retention or expansion of this basic data network, which is already at a minimum functional level across the region, is a critical need if accurate detection, modeling and prediction of drought in the USAPI is to be undertaken in the future.

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Table 1 – Data sets available for calculation of site-specific monthly Palmer Drought Stress Indices for islands in the USAPI. Other drought indices may also be potentially calculated from these data.

Jurisdiction	Location	Temperature[1] Record	Rainfall[1] Record	Potential PDSI Period .
CNMI	Saipan	1954-present	1901-present	63 years
Guam	Guam	1950-present	1905-present	67 years
Palau	Koror	1945-present	1905-present	72 years
FSM	Yap (Colonia)	1921-present	1901-present	96 years
FSM	Chuuk (Lagoon)	1935-present	1903-present	82 years
FSM	Pohnpei (Kolonia)	1949-present	1900-present	68 years
FSM	Kosrae (Lelu/Airport)	1954-present	1954-present	63 years[2]
RMI	Majuro	1955-present	1955-present	62 years
RMI	Kwajalein	1945-present	1945-present	72 years
American Samoa	Pago Pago	1965-present	1965-present	52 years
Samoa	Apia[3]	1890-present	1890-present	127 years

[1]Short gaps are present in some of these data sets.

[3]Kosrae is a relatively small island, and the linear distance between the two coastal weather stations with 30+ year periods of record is only 5 miles, therefore these two periods of record can be reasonably combined to obtain a 63-year aggregate period of record for this island. The station at Lelu Island was active from 1954 to 1987, while the station at the International Airport has been active from 1987 to present.

[3]Although not technically part of the USAPI, the station at Apia is included due to its relative proximity to western Tutuila (69 miles) and very long period of record.

Table 2 – Rainfall runoff rates for sites in the USAPI, indicating percentage of rainfall that runs off into the ocean rather than percolating to local aquifers. Based on data from van der Brug (1983a, 1983b, 1984a, 1984b; Heitz & Khosrowpanah 2015). Percentages for Yap are based on wet season flows only (June-December) because most streams lack surface flow in the dry season (November-May). Gauging records are insufficient to calculate a rainfall-runoff ratio for Kosrae.

Jurisdiction	Location	Runoff Rate	Period of Record
Guam	Umatac	52%	1953-1977
Guam	Imong	62%	1960-1984
Guam	Pago	65%	1953-1983
Guam	Ylig	61%	1953-1984
Guam	Finile	68%	1960-1983
Guam	Inarajan	52%	1953-1983
Guam	Tinaga	39%	1953-1983
Guam	Geus	43%	1953-1976
Palau	Babeldaob, Diongradid River	77%	1970-1981
Palau	Babeldaob, Tabecheding River	85%	1971-1981
Palau	Babeldaob, Edeng River	77%	1970-1981
Palau	Babeldaob, Ngerdorch River (S.)	91%	1972-1981
FSM	Yap, Qaringeel Stream	59%	1969-1981
FSM	Yap, Daloelaeb Stream	68%	1969-1981
FSM	Yap, Peemgoy Stream	55%	1969-1981
FSM	Yap, Taalgum Stream	56%	1969-1978
FSM	Yap, Burong Stream	53%	1969-1981
FSM	Chuuk, Wichen River	48%	1969-1977
FSM	Chuuk, Nachipong Stream	44%	1969-1976
FSM	Pohnpei, Lewi River	66%	1971-1982

Appendix 1: Supporting climate model data for Figure 1 and Figure 2

The data in Tables 3 and 4 represents preliminary outputs from the CMIP5 ensemble of 36 dynamical climate models. Each CMIP5 model was interpolated horizontally to 1 degree by 1 degree grids, over a time series beginning in 2010 and ending at 2099. Those regridded data were then interpolated to each island point using the bilinear interpolation method. Ten years are chosen as the time slice to represent the specific year, e.g., the mean value from 2025-2034 to represent the value of 2030, the mean value form 2050-2059 to represent the value of 2055, and the mean value from 2090-2099 to represent the value of 2100.

Minimum and maximum projected air temperature envelope bounds of each of the above time steps were calculated from data representing a subset of the CMIP5 ensemble, using only those models that project t-min and t-max over the three time windows indicated above. These data represent the average value of t-min and t-max taken over the sampling windows, and thus are not strictly the t-min and t-max of the daily average temperature, and will have a slightly broader variance from central tendency, but are sufficient to indicate approximate envelopes of uncertainty.

The present-day reference values were calculated as averages for period 1995-2004, using the full CMIP5 model ensemble.

It should be further noted that the CMIP5 outputs are based on 1 arc-second (100 km x 100 km) GMC pixels. As such, the average temperature and precipitation values are most likely to be representative of low islands and atolls in the USAPI, but may under-represent the effects of topographic forcing on precipitation by high islands.

Table 3

CMIP5 Air Temperature °C

36 model ensemble	Guam	Saipan	Rota	Tinian	Tutuila	Majuro	Ebeye	Kosrae	Pohnpei	Yap	Chuuk	Palau
Average												
Daily Temp Average Current	27.1514	26.9380	27.0635	26.9602	26.9432	27.6042	27.3142	27.7619	27.7480	27.6393	27.7591	27.7591
Daily Temp Average 2030	27.6959	27.4789	27.6060	27.5011	27.4696	28.1772	27.9232	28.3079	28.2773	28.1749	28.2863	28.3528
Daily Temp Average 2055	28.5346	28.3185	28.4444	28.3404	28.2302	29.0100	28.7504	29.1623	29.1201	29.0094	29.1285	29.1881
Daily Temp Average 2099	30.1406	29.9203	30.0498	29.9430	29.6529	30.5909	30.3472	30.7335	30.7019	30.6125	30.7195	30.7899
Mininum Range												
Daily Temp Min Current Av.	26.7807	26.5623	26.6923	26.5850	26.5341	27.2083	26.9410	27.3530	27.3399	27.2347	27.3531	27.4219
Daily Temp Min 2030	27.4638	27.2553	27.3763	27.2769	27.1423	27.8812	27.6548	28.0030	27.9828	27.9016	27.9961	28.0691
Daily Temp Min 2055	28.3640	28.1559	28.2762	28.1775	27.9604	28.7701	28.5299	28.8972	28.8727	28.7850	28.8911	28.9438
Daily Temp Min 2099	29.9273	29.7067	29.8348	29.7299	29.3945	30.3489	30.1413	30.4599	30.4420	30.3655	30.4783	30.5287
Maximum Range												
Daily Temp Max Current Av.	27.4726	27.2652	27.3860	27.2864	27.3360	27.9764	27.6733	28.1458	28.1184	27.9795	28.1226	28.2022
Daily Temp Max 2030	28.1615	27.9792	28.0841	27.9981	27.9311	28.6444	28.4020	28.7721	28.7302	28.6075	28.7300	28.7977
Daily Temp Max 2055	29.0484	28.8559	28.9669	28.8759	28.7257	29.5200	29.2671	29.6573	29.6189	29.4862	29.6198	29.6678
Daily Temp Max 2099	30.6311	30.4235	30.5439	30.4455	30.1509	31.1178	30.8840	31.2443	31.2188	31.0878	31.2264	31.2789

Table 4

CMIP5 Precipitation mm

36 model ensemble	Guam	Saipan	Rota	Tinian	Tutuila	Majuro	Kwajalein	Kosrae	Pohnpei	Yap	Chuuk	Palau
Average												
Daily Precip Average Current	5.5791	4.8443	5.2325	4.9000	7.2391	9.4812	8.4665	9.5063	9.8197	8.1691	9.6861	9.0177
Daily Precip Average 2030	5.6430	4.9158	5.3049	4.9765	7.2129	9.6271	8.6806	9.6335	9.9341	8.3051	9.7807	9.0486
Daily Precip Average 2055	5.9328	5.1068	5.5665	5.1781	7.2844	9.7865	8.7931	9.8634	10.1372	8.5919	9.9933	9.2277
Daily Precip Average 2099	6.3260	5.4502	5.9364	5.5235	7.4563	10.0526	8.8060	10.3344	10.5505	9.0656	10.2852	9.5602
Mininum Range												
Daily Precip Min Current	2.5840	1.9550	2.3180	2.0020	2.3790	6.8630	4.7850	5.9900	7.5980	4.5250	6.7040	6.2900
Daily Precip Min 2030	2.7180	2.0240	2.4600	2.0870	2.0610	7.3430	4.2640	5.9100	7.7880	4.7250	6.9660	6.5460
Daily Precip Min 2055	2.9870	2.1490	2.6370	2.2150	1.4190	7.2730	5.6990	6.0040	7.7630	5.8010	6.7880	6.3260
Daily Precip Min 2099	2.9780	2.1350	2.6180	2.1970	1.1960	7.2530	5.5700	5.5040	8.2270	6.2770	7.3210	6.5120
Maximum Range												
Daily Precip Max Current	9.8770	8.0190	8.7060	8.1160	11.4570	12.6970	16.1810	12.6190	13.3420	13.8680	15.6420	11.8190
Daily Precip Max 2030	9.2680	7.6350	8.3740	7.7500	10.6130	13.7070	16.0590	12.1580	14.5700	15.0150	16.9200	13.3220
Daily Precip Max 2055	9.2580	7.3810	8.4870	7.5650	11.0340	12.2130	15.4080	12.4140	13.3250	12.8130	15.2110	11.8610
Daily Precip Max 2099	10.0540	8.3730	9.3320	8.5300	13.1090	13.4160	14.5130	13.9770	13.9720	12.5320	13.9200	13.0690