



Historical and future drought impacts in the Pacific islands and atolls

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Abstract

Drought is known as a “creeping disaster” because drought impacts are usually noticed months or years after a drought begins. In the Pacific Island Countries and Territories (PICTs), there is almost no ability to tell when a drought will begin or end, especially for droughts other than meteorological droughts. Monitoring, forecasting and managing drought in the PICTs is complex due to the variety of different ways droughts occur, and the diverse direct and indirect causes and consequences of drought, across the PICT region. For example, the impacts of drought across the PICTs vary significantly depending on (i) the type of drought (e.g. meteorological drought or agricultural drought); (ii) the location (e.g. high islands versus atolls); (iii) socioeconomic conditions in the location affected by drought; and (iv) cultural attitudes towards the causes of drought (e.g. a punishment from God versus a natural process that is potentially predictable and something that can be managed). This paper summarises what is known and unknown about drought impacts in the PICTs and provides recommendations to guide future research and investment towards minimising the negative impacts of droughts when they inevitably occur in the PICTs.

Keywords Water security · Adaptation · Climate variability · Climate change · Agriculture

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1 Introduction

Water, water, everywhere, And all the boards did shrink; Water, water, everywhere, Nor any drop to drink. (The rhyme of the ancient mariner)

It is a cruel irony that, though surrounded by the vast expanse of the largest ocean on the planet, the islands and atolls of Micronesia can run out of drinkable water. (Thompson 2016)

The World Economic Forum estimates that drought costs \$US6–8 billion a year globally due to losses in agriculture and related businesses alone—this does not include non-agricultural economic costs or non-economic costs (e.g. impacts on mental health and well-being, changes to community/culture, environmental damage) (Below et al. 2007; Botterill and Cockfield 2013). Multidecadal climate variability (e.g. Kiem and Franks 2004; Vance et al. 2015; McGree et al. 2016), as well as projected impacts of anthropogenic climate change (e.g. IPCC 2013; Van Loon et al. 2016a, 2016b), also means that drought will remain a key concern into the future.

Despite their significance, and existing literature on drought, droughts are still poorly understood (e.g. van Dijk et al. 2013; Blauhut et al. 2015; Kiem et al. 2016). This is because the cause-effect relationships between drought and the variety of factors that contribute to drought are complicated and not satisfactorily monitored, modelled or predicted. Also lacking, especially for Pacific islands and atolls (Fig. 1), is information on the direct and indirect impacts of the different types of drought and how these vary across locations, communities and industries. These two knowledge gaps make it challenging to develop robust drought mitigation and management strategies.

Pacific Island Countries and Territories (PICTs) are heterogeneous. The Pacific region comprises 28 countries, which are divided into the sub-regions of Micronesia, Melanesia and Polynesia (Fig. 1), and these countries contain ~20,000 islands and atolls that are scattered across the Pacific Ocean. The PICTs cover 46% of Earth's water surface (Goldberg 2018) and are home to ~10 million people (Sisifa et al. 2016). The larger Melanesian countries of Papua New Guinea (PNG), Fiji, New Caledonia, Solomon Islands and Vanuatu represent 90% of the total Pacific Island population and 85% of the total land area. The Pacific region also includes some of the smallest, remote, scattered and lowest elevation countries in the world (e.g. the land area of Tuvalu is only 26 km² with the highest point only 5 m above sea level (Sisifa et al. 2016; Wairiu et al. 2012)). Heterogeneity exists both between and within PICTs. The higher islands have rivers, streams and groundwater. In contrast, the smallest islands and atolls rely exclusively on rainwater and shallow groundwater in lenses sometimes sitting above saline water (UNESCAP 2007) for drinking, cooking, washing and other socioeconomic functions (Sisifa et al. 2016). The vulnerability of PICTs to drought therefore depends on geographic location and the type of island. This paper includes case studies of impacts representing high islands (PNG, Fiji, Vanuatu, Samoa, Tonga) and atolls (Tuvalu and Republic of the Marshall Islands (RMI)) across the three Pacific sub-regions (i.e. Micronesia, Melanesia and Polynesia).

This paper (i) summarises the causes of meteorological and agricultural droughts in the PICTs, (ii) identifies how drought impacts Pacific people, with particular focus on better understanding drought impacts in high islands versus atolls, and (iii) quantifies how drought is projected to change in the future for Pacific islands and atolls. The paper concludes by highlighting the major uncertainties and challenges relating to drought management in the Pacific along with some recommendations for how to address these challenges.

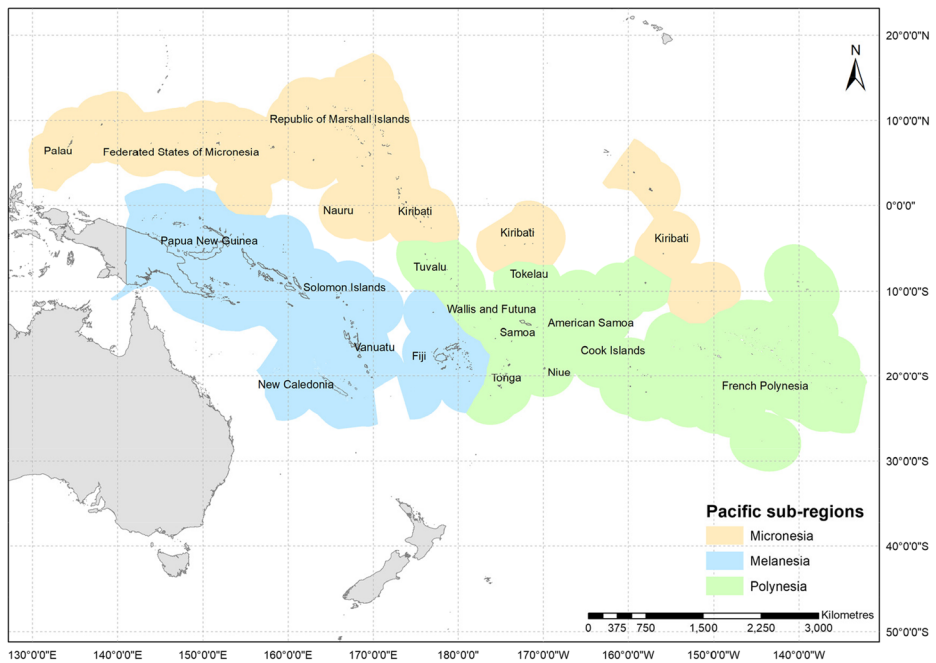


Fig. 1 Pacific islands and atolls (Source: Peter McDonald (SPREP))

2 Defining drought

Unlike other natural hazards which have more graphic, immediate and measurable impacts (e.g. floods, tropical cyclones, coastal inundation events), droughts are considered to be slow-onset hazards, are spatially extensive, can persist for more than a year and often go unnoticed until wide-spread water, food, energy, economic, health or environmental impacts are triggered (e.g. Wilhite et al. 2007; Van Loon 2015; Kiem et al. 2016). By the time a drought is identified, it is usually already well underway, remediation costs are mounting and the opportunity for proactive mitigation or adaptation is gone. Complicating this are uncertainties or knowledge gaps around defining, monitoring and forecasting drought (including the termination of drought) (e.g. Parry et al. 2016) and for deriving accurate and practically useful quantification of drought likelihoods and consequences.

Droughts have a wide range of cascading impacts that may be exacerbated by different drought aspects or other external factors like land use change, increase in water demand and change in policies to name a few (e.g. van Dijk et al. 2013). Previous research (e.g. Peterson et al. 2013; Lloyd-Hughes 2014; Masih et al. 2014; Garner et al. 2015; Van Loon 2015; Kiem et al. 2016) has increased understanding into drought and—based on the acknowledgement that drought is more than a rainfall deficiency—led to various drought definitions and categories. This paper focuses only on meteorological drought and agricultural drought. This is because (i) the Pacific atolls have a fragile freshwater resource base that can be quickly depleted when there is a lack of rainfall (i.e. meteorological drought) (Barnett and Campbell 2010) and (ii) the larger/higher Pacific islands have a heavy reliance on agricultural productivity (Barnett 2011; Iese et al. 2018). While the focus here is on meteorological and agricultural drought, it is important to recognise that other types of drought are also important

in the PICTs (e.g. hydrological droughts are important in Fiji, and socioeconomic droughts are important everywhere).

3 Historical drought in Pacific Island Countries and Territories

3.1 What does the literature say about historical droughts in the PICTs?

Drought is a recurrent climate feature in the Australia-Pacific region (Nunn 2007; Vance et al. 2015). Kiem et al. (2016) document the factors that cause (or contribute to) drought in Australia and most of the influential factors for eastern Australia (e.g. El Niño/Southern Oscillation (ENSO) and the location/phase of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ)) and also apply to the wider Pacific region (e.g. McGree et al. 2016).

There are anecdotal accounts of pre-colonial droughts that caused famines in the PICTs (Roberts 1958; Allen 2015; Iese et al. 2018). Early European settlers also documented the occurrence of droughts in the PICTs (McGree et al. 2016). However, despite the long history of drought in the PICTs, long-term, objective documentation of droughts in PICTs is limited due to the lack of long-term (i.e. 100 years or more) hydroclimatic records coupled with limited understanding into the causes and impacts of drought at the PICT scale (McGree et al. 2016). This is also evident in the limited information on historical droughts included in the Pacific Climate Change Science Programme climate assessment of PICTs in 2011 and 2013—there is information on dry and wet seasonal variations of rainfall but minimal details on droughts (Australian Bureau of Meteorology and CSIRO 2014; CSIRO et al. 2015).

McGree et al. (2016) attempted to address these knowledge gaps when they analysed meteorological drought frequency, duration and magnitude using precipitation records from 21 PICTs for the period 1951 to 2010. McGree et al. (2016) found that the frequency, duration and magnitude of meteorological droughts for PICTs was greater during the 1981–2010 period than the 1951–1980 period. This finding confirmed the perception of Pacific Islanders that they are experiencing more frequent and intense droughts. However, McGree et al. (2016) explain that this is mostly due to interannual to decadal climate variability given the lack of statistically significant trends in drought frequency, duration and magnitude over the 1951–2010 period. Deo (2011) also reported that drought duration and severity was non-uniform in Fiji between 1949 and 2008, especially for western and northern Fiji where rainfall deficiencies for the period 1969–1988 led to a dramatic increase in moderate and severe droughts and a “net shift towards drier conditions since the 1950s”. This reinforces recommendations made in drought studies from other parts of the world (e.g. Van Loon 2015; Kiem et al. 2016) for the development of an agreed set of drought definitions/categories that clearly differentiates drought from long-term changes in aridity and water scarcity and that captures attributes of drought such as start, duration, magnitude and spatial extent.

Despite limited studies looking at trends in the occurrence and intensity of droughts in PICTs, the drivers of meteorological droughts in the Pacific are well researched. ENSO is the primary driver of interannual variability and Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO) the primary driver of multidecadal hydroclimatic variability in the Pacific Islands region (e.g. Tigona and de Freitas 2012; Australian Bureau of Meteorology and CSIRO 2014; Murphy et al. 2014; Salinger et al. 2014). Previous studies have also summarised the influence of ENSO and IPO/PDO, and their interactions with other climate

drivers (e.g. the location/phase of the ITCZ, SPCZ, West Pacific Warm Pool (WPWP)), on meteorological drought in the PICTs (e.g. Cai et al. 2012; Liberto 2016; McGree et al. 2016; Howes et al. 2018; Paeniu 2018; Keremama et al. 2019; Chand 2020).

While insights exist into the relationship between Pacific climate drivers and historical droughts in PICTs, it is unclear how climate change is influencing, and will potentially continue to influence, Pacific climate drivers and rainfall in PICTs. Time spent in drought is projected to decrease slightly or remain the same for most PICTs. However, there are regional nuances and also low confidence in projections of how climate change may affect spatial and temporal rainfall variability (e.g. IPCC 2013), and therefore, drought frequency, duration and spatial extent across the PICTs (Lefale et al. 2018).

3.2 What do the people say about historical droughts in the PICTs?

National meteorological services were consulted to (1) select drought events where the impacts were severe and affected local communities; (2) describe the characteristics of selected droughts (e.g. drought duration, rainfall conditions); and (3) provide documentation on drought impacts (e.g. duration, rainfall totals, and loss/damage assessments). Drought events identified were further profiled using the rainfall deficiency monitoring function of the Seasonal Climate Outlook for Pacific Island Countries (SCOPIC, <https://www.pacificmet.net/products-and-services/seasonal-climate-outlooks-pacific-island-countries-scopic>), which provides information on drought duration at selected stations, total rainfall during the drought and the ENSO phase the drought occurred in. The drought events associated with El Niño in 1982–1983, 1997–1998 and 2015–2016 for Fiji, Samoa, Vanuatu, PNG, Tonga and Federated States of Micronesia (FSM) and La Niña in 2010–2012 were selected. A narrative analysis (i.e. a synthesis of anecdotal and qualitative information provided by officers from the national meteorological services) was conducted to illustrate the exposure of PICTs to droughts as well as the adverse effects on vulnerable communities.

ENSO, and associated drought conditions, affect many PICTs simultaneously. Table 1 shows that droughts associated with El Niño events that occurred in 1982–1983, 1997–1998 and 2015–2016 affected PICTs scattered in central-western regions and in both north and south Pacific sub-regions. Although they had different intensities, the duration of meteorological droughts ranged from 5 to 27 months in 1982–1983; 5 to 13 months in 1997–1998 and 2 to 23 months in 2015–2016.

Individual PICTs cover large ocean areas, often comprising multiple islands that are spatially scattered. Therefore, the occurrence and intensity of droughts differ within countries relative to the spatial impact regions of the rainfall drivers mentioned above—ENSO, SPCZ, ITCZ, IPO/PDO and the Walker Circulation. For example, as shown in Table 1, the drought of 1982 in Vanuatu started in Peko (North Vanuatu) a year earlier than Port Vila (Central Vanuatu) and 16 months before Southern Vanuatu. Overall, Vanuatu government had to respond to 27 months of drought conditions. Another example was in Tuvalu during the La Niña of 2011–2012 where Funafuti (Central Tuvalu) experienced the drought for 1 year (December 2010–December 2011) while Niulakita (Southern Tuvalu) experienced three droughts between February 2010 and June 2013. Tuvalu communities and government suffered the impacts of drought for almost 3 years.

Table 1 shows information on meteorological droughts for the PICTs, with detailed information on drought duration, magnitude and timing. In the PICTs, and elsewhere in the world, it is difficult to know when agricultural droughts start and end (e.g. Kiem et al. 2016;

Table 1 Summary of selected meteorological droughts in some PICTs (drought and rainfall information shown is sourced from SCOPIC, <https://www.pacificmet.net/products-and-services/seasonal-climate-outlooks-pacific-island-countries-scopic>)

Location	Start	End	Duration (months)	Total rainfall received during the drought (mm)	Long-term average rainfall (mm) between start and end months	% decrease from average rainfall during the drought	Notes
1982–1983 El Niño Nadi, Fiji Apia, Samoa	Jun 1983	Oct 1983	5	260.1	344.6	25%	Occurred in second year of El Niño Total rainfall received during this drought was dominated by two tropical cyclone events, resulting in two short-lived extreme rainfall events punctuating an otherwise very dry 13-month period This drought is related to the influence of the SPCZ which shifts during El Niño
	Nov 1982	Dec 1983	14	2136.6	3499.7	39%	
Ha'apai, Tonga	Dec 1982	Oct 1983	11	749.0	1618.0	54%	No tropical cyclone occurred near Nukualofa during the 1982–1983 season resulting in no drought relieving rainfall This long drought for the north was unusual. TC Joti passed close to Peko on the 4th Nov 1982 and brought some relieving rain El Niño ended in April 1983, but the normal dry season started in May continued to Oct 1983
Nuku'alofa, Tonga	Nov 1982	Jan 1984	15	1136.0	2239.9	49%	Drought ended around the same time TC Atu was close to Port Vila.
Pekoa, North Vanuatu	Mar 1982	May 1984	27	3030.0	5517.9	45%	Drought ended by rainfall associated with TC Atu.
Port Vila, Central Vanuatu	Mar 1983	Dec 1983	10	920.0	1567.9	41%	
Whitegrass, Southern Vanuatu	Jun 1983	Dec 1983	7	229.9	460.9	50%	
Kwajalein, RMI	Feb 1983	Jul 1983	6	519.1	1085.9	52%	

Table 1 (continued)

Location	Start	End	Duration (months)	Total rainfall received during the drought (mm)	Long-term average rainfall (mm) between start and end months	% decrease from average rainfall during the drought	Notes
Majuro, RMI	Feb 1983	Jul 1983	6	816.5	1551.1	47%	
1997–1998 El Niño							
Nadi	Nov 1997	Nov 1998	13	883.5	2049.4	57%	Drought included the normally rainy months—TC Susan (Jan 1998) and TC Lusi (Oct 1997) did not disrupt the drought
Apia	Apr 1998	Jan 1999	10	1859.5	2200.5	15%	Started after TC Ron (3rd–4th Jan 1998) and TC Tui (26th Jan 1998)
Ha'apai, Tonga	Feb 1998	Dec 1998	11	1051.0	1523.1	31%	Drought started after TC Ron passed Central Tonga on 8th Jan 1998
Nuku'alofa, Tonga	Jul 1997	Mar 1998	9	1044.0	1388.2	25%	Drought started earlier here than for Ha'apai because Nuku'alofa did not receive significant rainfall from TC Ron
Nuku'alofa, Tonga	Jun 1998	Nov 1998	6	512.0	662.2	23%	Some wetter than average conditions in April and May 1998 but then drought continued at Nuku'alofa
Pekoa, North Vanuatu	Oct 1997	Mar 1998	5	719.8	1422.7	49%	Drought started here 6 months after the drought started in Southern Vanuatu. Drought in North Vanuatu broken by rainfall associated with TC Zuman in March 1998
Port Vila, Central Vanuatu	Sep 1997	Mar 1998	7	1096.6	1386.9	21%	Drought started here 5 months after the drought started in Southern Vanuatu. Drought in Central broken by rainfall associated with TC Yali in March 1998
Whitegrass, Southern Vanuatu	Mar 1997	Mar 1998	13	1186.4	1414.3	16%	

Table 1 (continued)

Location	Start	End	Duration (months)	Total rainfall received during the drought (mm)	Long-term average rainfall (mm) between start and end months	% decrease from average rainfall during the drought	Notes
Kwajalein, RMI	Jan 1998	Jul 1998	7	519.1	1196	57%	The 1997/98 drought in Vanuatu started in Southern Vanuatu. Drought in Southern Vanuatu broken by rainfall associated with TC Yali in March 1998
	Dec 1997	Jun 1998	7	700.8	1737.8	60%	
2015–2016 El Niño Nadi, Fiji	Apr 2014	Feb 2016	23	2379.2	3458.3	31%	Drought started during neutral state and continued when 2015–2016 El Niño started. Drought ended Feb 2016 with rainfall from TC Winston
	Sep 2015	Nov 2015	3	604.0	876.1	31%	
Apia, Samoa	Mar 2016	Apr 2016	2	582.1	922.6	37%	Drought ended when TC Amos hit Samoa on 23 April 2016
Ha'apai, Tonga	Aug 2014	Feb 2015	7	717.7	1005.5	29%	Drought ended when TC Rueben hit Tonga (Ha'apai group) on 21 Mar 2015
Ha'apai, Tonga	May 2015	Aug 2015	4	359.7	384.4	6%	Drought ended by rainfall associated with TC Zena, 7 Apr 2016
Ha'apai, Tonga	Dec 2015	Mar 2016	4	655.5	831.2	21%	
Nuku'alofa, Tonga	Oct 2015	Apr 2016	11	1098.9	1645.9	33%	
Pekoa, North Vanuatu	Oct 2015	Apr 2016	7	1052.8	1705.6	38%	Drought ended by rainfall associated with TC Zena, 5 Apr 2016
Pekoa, North Vanuatu	Jul 2016	Nov 2016	5	495.7	675.3	27%	
Port Vila, Central Vanuatu	Aug 2015	Nov 2016	16	1134.0	2540.2	55%	
Whitegrass, Southern Vanuatu	Apr 2015	May 2015	1	209.9	339.9	38%	Worst drought in Luganville according to SCOPIC

Table 1 (continued)

Location	Start	End	Duration (months)	Total rainfall received during the drought (mm)	Long-term average rainfall (mm) between start and end months	% decrease from average rainfall during the drought	Notes
Whitegrass, Southern Vanuatu	Nov 2015	Mar 2016	5	648.3	706.5	8%	Drought started 1 month after TC Pam (March 2015) TC Ula moved close to Southern Vanuatu in Jan 2016 but not break the drought
Port Moresby, Central PNG	Jun 2015	Sep 2015	4	60.3	126.3	52%	
Port Moresby, Central PNG	Oct 2015	Aug 2016	11	694.4	1077.4	36%	
Highlands, Goroka	Aug 2015	Mar 2016	8	1154.0	1428.3	19%	
Kavieng	Oct 2015	Jan 2016	4	885.4	1107.7	20%	
Nadzab-Lae	Sep 2015	Dec 2015	4	460.7	482.2	4%	
Kwajalein, RMI	Jan 2015	Feb 2015	2	159.3	194.3	18%	
Majuro, RMI	Nov 2015	Sep 2016	11	1798.6	3001.8	40%	Impacts on agriculture and water were very severe (considered to be the worst drought by the local islanders)
2010–2012 La Niña							
Funafuti, Central Tuvalu	Dec 2010	Dec 2011	13	2168.1	3909.2	45%	
Niulakita, Southern Tuvalu)	Feb 2010	Apr 2010	3	920.0	924.6	1%	
Niulakita, Southern Tuvalu)	Oct 2010	Jan 2011	4	1206.6	1258.0	4%	

Start and end refer to the first and last month of a drought, where drought is declared if the rainfall total in the previous 3- or 6-month period is in the bottom 25% of historical rainfall totals for that corresponding 3- or 6-month period

Gibson et al. 2020; Askarimamani et al. 2021). This makes it difficult to plan drought emergency relief interventions as evident in 2015–2016 in Fiji—without data the Food Security and Agriculture Cluster found it hard to know where intense agricultural drought was occurring and how many farmers were affected. This has often led to delays in drought response planning and implementation in the agriculture sector.

3.3 Observed impacts of droughts in the PICTs

3.3.1 Vanuatu

The impacts of droughts in PICTs are severe and diverse. As Table 1 shows, the El Niño induced 2015–2016 drought that affected many PICTs. In Vanuatu the people rely on rainwater harvesting systems and wells for consumption, as there are no rivers. During the drought, most water tanks in Vanuatu were empty or had only small amounts of heavily contaminated water at the bottom of the tank. Villagers from ~20% of households walked for long distances (more than 30 min) for washing and showering and to collect water for cooking and drinking (OCHA 2015). Households with money paid about \$US12/trip to hire a truck to fetch water for drinking and cooking. Primary schools were operational for half-day classes only because students walked in the afternoon to bath in the sea due to water shortages (Marango 2015; Roberts 2015). The 2015–2016 drought which followed Category 5 TC Pam destroyed vegetation across Vanuatu, and lack of foliage worsened the impacts of the drought on soils and crops, reducing food security. Savage et al. (2021) reported that all yams and taro died forcing 90,000 people (about 30% of the total population) to rely on food aid which was often spent on expensive food that had low nutritional value. Food shortages were particularly severe in the southern part of Vanuatu, especially Tanna Island, where lack of food contributed to the death of a child who consumed only nipatem (a root plant which is usually considered a weed but is consumed during periods where there is a shortage of food) for 4 days because root crops and vegetables did not grow (Willie 2015).

3.3.2 PNG

The 2015–16 drought also reduced food security in PNG. For areas with very high elevation (2200 to 2800 m), the effects of the drought were compounded by the effects of frost on crops. The drought and frost affected ~700,000 people and ~450,000 people faced critical food shortages. Food shortages were concentrated in four ecological zones: (i) very high altitude areas (2200 to 2800 m); (ii) the central highlands, inland and lowland areas in the Western Province; (iii) locations in South Fly and Middle Fly districts; and (iv) small and remote islands in the Milne Bay Province. Food shortages affected peoples' health and increased the death rate in some locations. People were relegated to eating unusual foods or famine foods in abnormally large quantities. The drought caused water shortages and forced many women and girls to walk long distances to obtain drinking water, often from sources that they would not normally use. Women reported experiencing increased harassment on the journey and at water collection points. The drought increased the workload of women as they were involved in collection of water from distant sources and reestablishment of gardens. Other social and health impacts were also reported (e.g. as stealing, high consumption of alcohol, increased incidences of gut and skin diseases) (Bourke et al. 2016; PNG National Disaster Centre 2016).

3.3.3 RMI

The 2015–2016 El Niño triggered a severe drought that impacted the entire RMI chain, leading to a declaration of a state of emergency on 3rd February 2016. About 81% of the population of RMI experienced severely reduced access to water and extensive damages and losses of food crops. People conserved what little water they had for drinking and cooking at the expense of hygiene causing an increase in the spread of diseases like conjunctivitis. The following quote highlights the severity of the drought impacts on RMI and northern Pacific Islands:

Wells have become brackish or run dry; the rain barrels that perch on the corners of houses have little or no rainwater left in them. Water rationing is limited to a couple hours a day in some of the worst-hit communities, while expensive reverse-osmosis machines have been shipped out to the most far-flung atolls to make the seawater drinkable. Staple foods like breadfruit and bananas have shrivelled on the trees, inedible. (Thompson 2016)

3.3.4 Tuvalu

The Central Pacific has also experienced severe drought impacts (e.g. Paeniu 2018). For example, the prolonged drought that affected Tuvalu during the 2011–2012 La Niña (Table 1) led to severe water shortages and loss of crops critical for food security. The Government of Tuvalu declared a state of emergency on 28th September 2011 as the drought directly or indirectly affected the entire population of Tuvalu. Communal water supplies were rationed to as little as 2.1 L/person/day. In some islands, 61% of households relied solely on brackish well water for bathing, washing clothes and flushing toilets. Well water was tested and found not fit for human consumption. Four children and three adults were hospitalised for diarrhoea and vomiting in Nukulaelae during the drought (Sinclair et al. 2012). The limited crops that can grow in a hostile atoll environment—such as coconut, breadfruit, bananas and giant swamp taro (pulaka)—wilted and died or became inedible (Tekinene 2014). Giant swamp taro, which is a core crop for socio-cultural and food security in atoll islands and is planted in excavated pits reaching the water table, showed a high degree of stress caused by exposure to prolonged water stress and salt-coated soil left by high evaporation of water in the pulaka pits. Prolonged impacts on pulaka yield worsen traditional staple diets and leads to abandonment of pulaka cultivation and associated loss of traditional knowledge (Tekinene 2014; Paeniu 2018).

Prolonged lack of rainfall (related to La Niña conditions) contributed to the growth of invasive seaweed (*Sargassum polycystum*) species in Funafuti, Tuvalu in 2011 (N'Yeurt and Iese 2015). Tuvaluans also consider droughts as a punishment from God for sin or bad traditional leadership. Some islands replaced their chiefs because of the negative impacts of droughts:

People normally associate drought with bad omen. When drought struck, people tend to blame those in leadership for bringing bad omen. This traditional belief demands that leaders do step down and give way for new leaders with the hope of prosperity. (Paeniu 2018)

3.3.5 Variability in the timing, intensity and type of drought impacts across the PICTs

The location of countries is an important influence on the timing and intensity of droughts (Kuleshov et al. 2014). For example, Samoa being in the south central Pacific experienced the impacts of El Niño and La Niña differently to, for example, Tuvalu which is further to the northwest. As shown in Table 1, drought conditions in Samoa associated with the 1997–1998 El Niño event were delayed due to excess rainfall from TC Ron and TC Tui earlier in 1998. In addition, although Tuvalu experienced drought during the weak 2011–2012 La Niña event, Samoa experienced a drought in 2010–2011 when ENSO was in its neutral phase. The impacts of droughts are severe in Samoa. For example, droughts in 1972, 1983, 1987 and 1997 triggered forest fires and destroyed 80% of food crops (Adriaens and Deelen 2012). The 2010–2011 drought event (a) reduced the Samoa Electrical Power Corporation generation from 35.9 to 10.8% (Adriaens and Deelen 2012); (b) resulted in Samoa Fire Services reporting 800 ha of forest destroyed by bushfires at Asau and Aopo (Kuleshov et al. 2014), the main habitat for the critically endangered tooth-pilled pigeon (*Manumea*) (Shuster n.d.); and (c) saw the Samoan government charter boats to supply about 97,000 L of water to the three main atoll islands of Tokelau which reported 10–20% less water in their household tanks (OCHA 2011).

Other recorded impacts of droughts in PICTs include an increase in the incidence of pests and diseases such as parasitoids of *Cyrtorhinus* egg predator on aroids and increase of weevil (*Cylas formicarius*) that can cause losses of 60–100% on sweet potato (Taylor et al. 2016). Droughts also affect the nutrient and chemical composition of some crops. For example, there is a significant increase of cyanogen in cassava during droughts (McGregor et al. 2016).

Droughts also affect the livelihood of people by destroying economic crops. The 1997–1998 El Niño event is a case in point where losses in the sugar cane industry were around \$US53 million, while other agriculture losses including livestock death amounted to \$US8 million. In the 1998 drought, Fiji lost approximately \$US63 million in the agriculture sector, and in an effort to combat this issue, the Fiji Government introduced the Crop Rehabilitation Programme (CPR) at a cost of \$US22 million (McKenzie et al. 2005; Iese et al. 2016).

There are also recorded larger scale impacts of historical droughts such as ecosystem changes in Rapa Nui (Wallin et al. 2005; Tromp and Dudgeon 2012), inter-island relocation in Tuvalu in 1600–1800 (Roberts 1958), tribal wars that led to internal displacements in Samoa “309 years ago” (Fepuleai et al. 2017) and British colonial resettlement of Gilbertese from Kiribati to Solomon Islands in the 1960s (Tabe 2019).

3.4 Interactions between droughts and tropical cyclones in the PICTs—communities in a cycle of recovery mode

ENSO events are associated with droughts in the PICTs, but ENSO events also shift the position of the ITCZ/SPCZ and, hence, increase the probability of tropical cyclones occurring within 6 to 10° south of the SPCZ (Vincent et al. 2011; Howes et al. 2018; Magee et al. 2020). For this reason, the tropical cyclone tracks during the years corresponding to the case study drought events mentioned above were extracted from the Australia Bureau of Meteorology’s (BOM’s) Objective Tropical Cyclone Reanalysis database in order to analyse the interaction of droughts and tropical cyclones in selected countries (<http://www.bom.gov.au/cyclone/history/tracks/beta/?region=sh>).

There is a relationship between the occurrence and breaking of droughts and the close proximity of tropical cyclones to some south central-western Pacific Islands (Kuleshov et al.

2014). Either delay in drought onset or ending of droughts were associated with the presence of tropical cyclones in the South Central-Western area. Tropical cyclones bring rainfall. For example, the droughts in 1982–1983 in Central and Southern Vanuatu ended at the same time TC Atu was close by. The 1998 drought in Northern Vanuatu and Central Vanuatu ended in March 1998 around the same time TC Zuman landed in the Northern Islands of Vanuatu and TC Yali was close to Central and Southern Vanuatu. The most severe meteorological drought according to SCOPIC for Fiji started during the neutral ENSO phase and later continued when 2015–2016 El Niño started. This drought ended in February 2016 at the same time TC Winston landed in Fiji with the impacts of TC Winston making recovery from drought conditions very difficult. The same drought behaviour was observed in Vanuatu during the El Niño of 2015–2016. Drought conditions started 5 months before TC Pam and continued about a month after TC Pam, coupling the impacts and delaying the effectiveness of recovery responses. Droughts followed tropical cyclones in Samoa in February 1998 after two tropical cyclones landed in January. Tonga also experienced a drought in February 1998 after TC Ron. This highlights one of the limitations of using meteorological drought indices as a proxy for agricultural drought, since rainfall associated with tropical cyclones can cause the meteorological drought index to suggest the drought is terminated when, from an agricultural perspective, it has not.

From a PICTs community and vulnerability perspective, understanding the succession between droughts-cyclones-droughts is important in terms of exposure and impacts. Sequential hazards may take place over 2–3 years, making it difficult for PICT communities to recover completely and causing communities to be “always in a recovery mode” (Iese et al. 2020). The drought-cyclone-drought succession contributes to severe impacts because of incomplete recovery from the previous disaster, compounding the vulnerability of communities (e.g. communities in Vanuatu were planting drought tolerant crops that were destroyed by TC Pam). When communities planted early maturing vegetable crops to help household recovery of food security and livelihoods after TC Pam, the following drought killed crops and further delayed the recovery of communities. This was also observed in Fiji after TC Winston. It is important to note that some El Niño events have ended but dry conditions continue because of entry into the normal dry season. This was observed in Northern Vanuatu in 1982–1983 and 2015–2016. Understanding the high exposure and vulnerability of communities to multiple and compound hazards (e.g. tropical cyclones bringing strong winds, high rainfall, floods, storm surges, salt water inundation (e.g. Chand et al. 2020) and droughts (lack of water, continuous high temperatures) coupled with slow-onset impacts of climate change such as sea level rise is crucial for risk reduction planning. This is the most important for coastal communities and low-lying islands (including atolls). The availability of other livelihood assets for drought resilience such as limited land for agriculture, reliance on wells (often brackish during droughts) for cooking and washing are severely reduced by rising sea level due to salt-water intrusion into wells and coastal erosion reducing arable lands (Thompson 2016).

4 Future drought in the PICTs

4.1 What does the literature say about future droughts in the PICTs?

The propagation of drought from meteorological to socioeconomic droughts (e.g. van Dijk et al. 2013) is influenced by many factors, including water infrastructure, farming practice,

socio-cultural contexts and relevant supportive policy. The interactions between these factors are complex, and current understanding on how these interactions could change in the future is limited. For the PICTs, there is limited research into the impacts of future droughts and climate change on water quantity, water quality or agriculture productivity. This is mostly due to lack of observed data (Section 3.1) and limited modelling capacity which could mean such issues are currently too wicked a problem to resolve.

Existing literature generally estimates future drought impacts in the PICTs by extrapolating historical impacts in light of projected climate change (e.g. Lal 2011) or through social-learning processes (e.g. Butler et al. 2014; Butler et al. 2020). Notwithstanding significant uncertainties associated with the climate model projections, national meteorological service across the PICTs is concerned that potential changes in drought will reduce local ability to alleviate water shortages and associated sanitation issues, reduce crop (e.g. cocoa) production and value and reduce copra export volume, and these impacts will be magnified if followed/preceded by heavy rains, floods or tropical cyclones.

Future drought impacts in the PICTs have also been assessed using conceptual models (e.g. Mukheibir et al. 2017) or empirical models (e.g. White 2010; Loco et al. 2015). Loco et al. (2015) estimated the impact of projected climate change on the sustainable yield of fresh groundwater lenses in Kiribati and found that when droughts occur, the fresh groundwater lenses can contract considerably. For example, White et al. (2007) documented a reduction in thickness of 50% of the Bonriki lens in Kiribati. In addition, low-lying atoll islands are also vulnerable to inundation by seawater, which in turn can make groundwater saline and unfit for human consumption. Potential drought impacts in atoll nations such as Tuvalu, therefore, can be catastrophic. The combination of rising sea level risks, shrinking water table and deterioration of water quality has the potential to lead to relocation of communities (as has happened before in the 1960s (Tabe 2019)).

4.2 Projections for future drought in the PICTs based on the Standardised Precipitation Index

In this study, projections for future drought are defined based on the Standardised Precipitation Index (SPI) of McKee et al. (1993), a widely used index for determining meteorological drought, including in the Pacific (e.g. McGree et al. (2016), McGree et al. (2019) and SCOPIC). As per Kirono et al. (2020), the analyses used data from 34 climate model simulations of rainfall under historical (1900–2005) and future (Representative Concentration Pathway RCP8.5, 2006–2100) scenarios, which are available at the Coupled Model Intercomparison Project Phase 5 (CMIP5) and used in the IPCC Fifth Assessment Report (IPCC 2013) and the Australian Bureau of Meteorology and CSIRO (2014) study for the western tropical Pacific. Under RCP8.5 the projected range in mean temperature increase for 2081–2100 relative to 1986–2005 is 2.6–4.8 °C globally (IPCC 2013) and 2.0–4.0 °C for the western Pacific (Australian Bureau of Meteorology and CSIRO 2014).

Three drought metrics (i.e. duration, frequency and intensity) for a 20-year baseline (reference) period and four future time periods are presented to characterise change in future drought relative to current (baseline) conditions. The baseline period is 20 years centred on 1995 (1986–2005, as used in IPCC (2013)), while the four future periods are centred on 2030 (2020–2039), 2050 (2040–2059), 2070 (2060–2079), and 2090 (2080–2099).

As per Kirono et al. (2020), a 12-month SPI time series is used to represent time required for water deficit conditions to affect various agricultural and hydrological systems (e.g. Szalai

and Szinell 2000; Zargar et al. 2011). The SPI time series was calculated for both the modelled historical (1900–2005) and future (2006–2100) period, resulting in negative (positive) values for dry (wet) conditions. A drought event is defined when SPI is continuously negative for 3 months or more and reaches an SPI value of -1.0 or less at some time during the event. The event starts when the SPI first falls below zero and ends with the first positive value of SPI following a value of -1.0 or less. The associated maximum negative value reached in a given event can then be used to define three drought categories: moderate drought, severe drought and extreme drought. The thresholds for categorisation are moderate drought ($-1.5 < \text{SPI} \leq -1.0$), severe drought ($-2.0 < \text{SPI} \leq -1.5$) and extreme drought ($\text{SPI} \leq -2.0$) (McKee et al. 1993).

The drought metrics within a period of interest (e.g. 1986–2005) were then calculated as:

- Drought frequency (DF): the number of droughts in a given period of interest.
- Drought duration (DD): the average length (in months) of drought events for the selected period.
- Drought intensity (DI): the average of cumulative SPI from all events for the selected period. The more negative the value the more intense the event.

As shown in Fig. 2, drought projections for the PICTs vary by country and by the drought category and metrics. However, these variations are smaller than the range of projections coming from the use of a multi-model ensemble. This is consistent with findings from global studies (e.g. Touma et al. 2015; Cook et al. 2018), regional studies elsewhere (e.g. Kirono et al. 2011; Tan et al. 2019; Kirono et al. 2020) and previous studies in the Pacific (Australian Bureau of Meteorology and CSIRO 2014).

Overall, droughts are projected to occur less often, become less intense and become shorter, except for in Samoa, Vanuatu and Tuvalu (Fig. 2). For Fiji, PNG and Tonga, the multi-model median shows significant decrease in the duration, frequency and intensity for most drought categories by the second half of the century. The range of projections are large (i.e. from increase to decrease), particularly for extreme droughts, but tend towards a decrease.

On the contrary, for Samoa, Tuvalu and Vanuatu, the decrease is apparent only for moderate and severe drought. For extreme drought, the multi-model median indicates little change, while the range of uncertainty, albeit large, is skewed towards an increase for most metrics. This implies that future drought events, when they occur, will tend to more often fall under what is currently classified as the extreme drought category rather than the moderate or severe drought category.

In general, the projected long-term changes to drought are consistent with the historical trends in droughts reported by McGree et al. (2016, 2019) (see also Section 3.1). McGree et al. (2016) used observed station data in the PICTs and found that historical trends were spatially heterogeneous and largely non-significant. More recently, McGree et al. (2019) reported non-significant sub-regional trends in the 12-month SPI over New Guinea Islands, North Papua New Guinea, Central Pacific, Southwest Pacific and Southeast SPCZ locations.

The projected trends for most of the drought metrics over most countries are also in accordance with the overall projected increase of the equatorial Pacific rainfall in a warmed climate (e.g. Australian Bureau of Meteorology and CSIRO 2014; Watanabe et al. 2014). The expected wetter conditions relate to the intensification of the South Pacific Convergence Zone (SPCZ) and the West Pacific monsoon due to increased atmospheric moisture content in a warming world. The tendency towards a future with drought events that are more extreme is also consistent with studies finding that rainfall variability over the equatorial Pacific is

projected to increase under warmer climate conditions (e.g. Watanabe et al. 2014; Cai et al. 2014; Power et al. 2017).

When interpreting these results, it is important to note the weaknesses associated with climate model projections for the Pacific (Grose et al. 2014). In particular, as discussed in Section 3, natural climate variability (e.g. ENSO, IPO) plays an important in influencing the interannual to multidecadal variability of drought risk in the PICTs (e.g. McGree et al. 2016), but this relationship is not yet realistically simulated by climate models (see Section 5 for further discussion on this). One way to, at least partially, deal with this issue is to use multi-model ensemble (as we have done in this study) with the assumption being that the spread across the different climate models captures ENSO variability. The validity of this assumption is the topic of ongoing research (see Section 5 for further details).

5 Knowledge gaps and recommendations for future work

The main knowledge gaps associated with understanding and managing drought in the PICTs, along with recommendations for future work needed to address them, are the following:

- Lack of understanding into agricultural and hydrological droughts. Some data and research exists on meteorological droughts but there is no detailed information on the duration, frequency and intensity of agricultural or hydrological droughts in the Pacific Islands. To properly characterise drought and to successfully quantify and manage the environmental and socioeconomic impacts of drought, drought indicators should be developed that realistically capture how all the different types of drought evolve. This is challenging for many parts of the PICTs due to limited (or non-existent) ground-based hydrometeorological observations of important drought-related variables (e.g. precipitation, near-surface air temperature, wind speed, atmospheric water vapour, relative humidity, and atmospheric evaporative demand). Furthermore, the available observations are usually not sufficient to capture the true spatiotemporal variability of drought (e.g. Easterling 2013; Gibson et al. 2020; Askarimarnani et al. 2021) or the lag of months to years between rainfall deficits (i.e. meteorological drought) and the progressive depletion of surface, soil and groundwater stores (i.e. agricultural, ecological and hydrological drought) (e.g. van Dijk et al. 2013; Kiem et al. 2016). These realities require a paradigm shift that supplements ground-based point observations or interpolated grids with satellite remote sensing information about relevant hydrological and ecological processes (or other sector based indicators) that are linked to drought (e.g. AghaKouchak et al. 2015). First, however, research is required to assess the strengths and weaknesses of satellite remote sensing information in detecting and monitoring the different types of drought in the PICTs.
- Lack of quantification and attribution of historical drought trends and variability. Analysis is required to determine if and how droughts have changed in the past across the different PICTs (including better understanding into the role of SPCZ and its association with ENSO, IPO and droughts across the PICTs). This is important given the warming already experienced over the last few decades and the need to establish what, if any, impact that warming has had on drought behaviour (i.e. frequency, duration, magnitude) in the PICTs. Also required is a critical examination of model simulations of historical climate conditions to determine which climate models are likely to give the most credible information

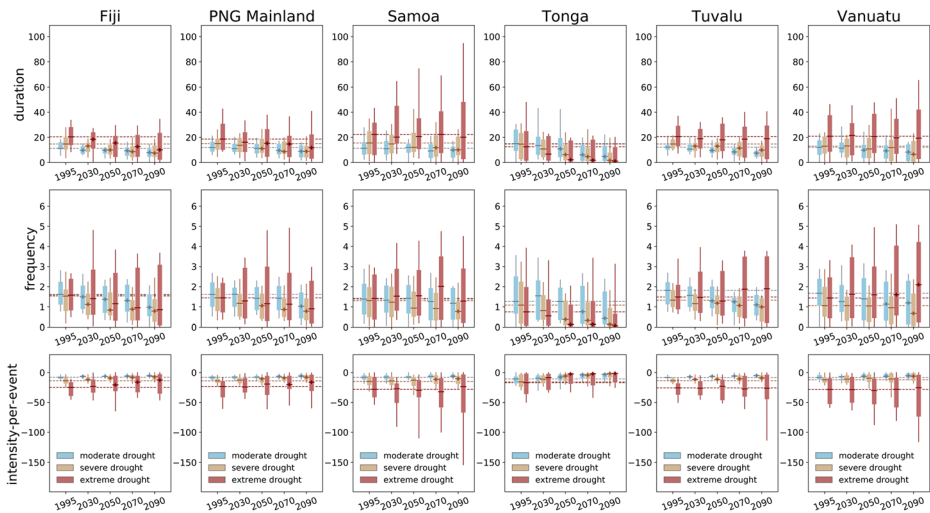


Figure 2 Regional (country) average of drought metrics for each drought category in the reference (20 years centred on 1995) and future (20-year periods centred on 2030, 2050, 2070, 2090) periods (drought duration is in months, frequency is in “number of events per period”, while intensity is unitless). The multi-model ensemble is shown as median, 10th and 90th percentile (bars) and minimum and maximum values (whiskers). The dashed-lines show the multi-model median for the baseline period for each category drought. The diamond symbols denote that the median metric at a given period in the future statistically differs (with $p < 0.05$) to the mean metrics in the reference period (1995). For drought intensity, the more negative the value, the more intense the event

about the future (e.g. climate models that can realistically simulate historical changes to drought are more likely to realistically simulate future drought behaviour).

- Inadequate predictions/projections of drought start, duration, magnitude and spatial extent (as opposed to the current focus on just rainfall) with seasonal lead times. Predictions/projections require understanding into, and realistically modelling of, the influence of multiple large-scale climate drivers on rainfall in the PICTs (e.g. To what extent do cold front systems bring drought breaking rainfall to southern Vanuatu, southern Fiji and Tonga?). Predictions/projections also require a better understanding of soil properties at small and large-scales to capture the soil moisture dynamics (agricultural drought) and the hydrologic connectivity within the system (hydrological drought). The drought predictions (and longer-term projections) also need to meet stakeholder requirements in terms of lead-time, skill/reliability and seasonality/timing (e.g. physical parameters that have longer lead-time need to be identified and imported into SCOPIC). For the longer-term drought projections in particular, it is especially important that the climate models producing those projections more realistically simulate the processes and impacts of natural climate variability (e.g. ENSO, IPO), especially at the local/regional scale, and how anthropogenic climate change will contribute to or alter that.
- Lack of understanding into the drought-cyclone-drought succession which has been identified as a critical component of the vulnerability of communities in the PICTs to drought. Drought recovery programs or adaptation options aimed at increasing drought resilience are often interrupted or destroyed by tropical cyclones. This is especially the case for coastal communities and low-lying islands (including atolls). Further research is needed to (i) better understand and quantify the drought-cyclone-drought succession, if/how it has varied in the past, and if/how it is projected to change in the future and (ii)

ensure that drought recovery programs and adaptation options aimed at increasing drought resilience consider and allow for the fact that in the PICTs these activities are likely to coincide with the impacts from one or more tropical cyclones.

- Lack of drought management strategies that recognise different parts of the PICTs are affected differently by the different types of droughts. Heterogeneity exists both between and within the different PICTs (e.g. the high islands have rivers, streams and groundwater so are affected by meteorological, agricultural and hydrological drought whereas the smaller islands and atolls rely exclusively on rainwater and therefore are only influenced by meteorological drought). Such location-specific impacts require location-specific drought management and adaptation strategies that are informed by both traditional and non-traditional knowledge. Research is required to identify and implement location-specific and fit-for-purposes drought management and adaptation strategies across the parts of the PICTs that are most vulnerable to drought. This includes:
 - Reviewing and updating existing “standard operating procedures (SOPs)” used by National Meteorological Services to forecast, monitor and deal with drought (or establishing drought SOPs for the PICTs where none exist) to ensure the drought SOPs are consistent with international best practice.
 - Developing decision support tools such as crop models that can simulate the impacts of drought on specific crops and agriculture systems in different agro-ecological zones. This information can then be used to identify and evaluate investments to improve agriculture adaptation so as to maximise resilience, productivity and sustainability.
 - Developing/implementing early warning systems that improve the capacity of communities to forecast, prepare for and respond to drought events and thereby minimise social and economic impacts. This is a challenge in PICTs, and elsewhere, because the majority of early warning systems are established to predict and reduce the impacts of rapid-onset, short-lived climate-related disasters such as floods and cyclones.
 - Development and validation of impact models that realistically simulate the location- and sector-specific impacts of drought in the PICTs. The impact models should be holistic such that environmental, economic, social and community impacts are considered in an integrated way.
- Lack of documentation and data on the impacts of drought in the PICTs in some of the sectors that are most vulnerable (e.g. water supply, health, tourism and agriculture). Therefore, it is important for future research, capacity building activities and other funding incentives to consider behavioural change such that drought impact reporting and awareness of drought is enhanced.

6 Conclusion

Successfully managing the impact of drought on society and the environment depends on the ability to successfully identify and characterise drought, in particular how the impacts of drought vary in different locations and different socioeconomic contexts. This is particularly important in the PICTs because the impacts of drought vary significantly depending on (i) the type of drought (e.g. meteorological drought compared with agricultural drought); (ii) the

location (e.g. high islands versus atolls); (iii) socioeconomic conditions in the location affected by drought; and (iv) cultural attitudes towards the causes of drought (e.g. a punishment from God versus a natural process that is potentially predictable and something which can be managed).

For many locations within the PICTs, there is currently almost no ability to tell when a drought will begin or end, especially for droughts other than meteorological droughts. This is because monitoring, forecasting and managing drought in the PICTs is complex due to the variety of different ways droughts occur, and the diverse direct and indirect causes and consequences of drought, across the PICT region.

This paper uses a narrative analysis (i.e. a synthesis of anecdotal and qualitative information provided by officers from the national meteorological services) to demonstrate the diversity and spatial variability of drought impacts across the PICTs. The paper also quantifies, as best we can with existing climate model information, how drought is projected to change in the future for Pacific islands and atolls. Based on these two pieces of analysis, the major uncertainties and challenges relating to drought management in the Pacific are summarised along with some recommendations for how to address these challenges. It is hoped that recommendations identified are useful in guiding future research and investment towards minimising the negative impacts of droughts when they inevitably occur in the PICTs.

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