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RESEARCH ARTICLE

A study of the changing climate in the US-Affiliated Pacific Islands using observations and CMIP5 model output

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This exploratory research examines the impacts of changing climate on the vulnerable US-Affiliated Pacific Islands (USAPI) from the perspective of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) coupled with General Circulation Models (GCMs). Island-wide projections of future climate change (e.g. temperature, rainfall, and net water flux) were made using the latest IPCC AR5 GCMs protocol (Coupled Model Intercomparison Project Phase—CMIP5) with 38 GCMs with up to 105 model runs. A review was also made of studies on model-based future projections of the El Niño–Southern Oscillation (ENSO). The CMIP5 model's results clearly illustrate that the past trend in temperature (1950–2017) is rising while the rainfall trend remains more or less static. It is also clear from the projections that the long-term trend for temperature rise is fast and significant, while the trend for rainfall and net water flux (P-E) rise appears to be slow and marginal. On the perspective of CMIP5 model's evaluation for the USAPI region, the temperature projections are found to be promising, while the rainfall projection potentials, despite some limitations, are also encouraging. The prime concerns for future disruptions in the USAPI region are the consequences of increasing frequency of the ENSO and related rainfall activities. The long-term warming signal may further complicate the problem. Therefore, the currently water-stressed islands and low-lying atolls in the Federated States of Micronesia (FSM) and Republic of Marshalls Islands (RMI) are particularly vulnerable to El Niño-related heat stress or drought and La Niña-related inundations or flooding. In both cases, the future demand-oriented climate-sensitive water resources sector will be severely affected. A climate-information-based comprehensive water resources management plan (for the 2030s) is therefore essential with more detailed ENSO-related climate information and impacts in terms people can understand and respond to.

KEYWORDS
climate, CMIP5, ENSO, KNMI climate explorer, USAPI

1 | INTRODUCTION

The general consensus of the scientific community, and an important conclusion of the 2007 report issued by the Intergovernmental Panel on Climate Change (IPCC) (2007), is that global temperatures are increasing. In general, if the higher temperature is coupled with drier conditions, it means that freshwater supplies will decrease on some Pacific Islands. The temperature rise affects agriculture, fisheries, infrastructure, biodiversity, health, human settlement, energy and water resources across the US-Affiliated Pacific Islands (USAPI) region, which is composed of the Territory of Guam (Guam), Commonwealth of the Northern Mariana Islands (CNMI; Saipan), Republic of Palau (Malakal

Harbor), Republic of the Marshall Islands (RMI; Majuro, Kwajalein), Federated States of Micronesia (FSM; the States of Chuuk, Kosrae, Kapingamarangi, Pohnpei (including Kapingamarangi) and Yap), and American Samoa (Pago Pago) (Figure 1). Except for American Samoa, which is located in the South Pacific (SP), all are located in the North Pacific (NP).

In 1990, the governments in the USAPI region expressed their need for customized climate services with understandable technical information and products for climate-sensitive sectors. This was partly because the spatial resolution of general circulation models (GCMs) is too coarse to render them directly applicable to local island environments. The large-scale models used do not provide island-specific information and therefore do not meet the critical need of the people. For example, during the weak La Niña in 2017–2018, the GCM forecasts were aggressively indicating above-average rainfall throughout the year across Guam, the CNMI, and, indeed, across most of the rest of Micronesia. However, such aggressive forecasts for wetter-than-average rainfall for Guam and the CNMI were incorrect. What occurred instead was a localized or "personal" drought, which is a drought that occurs only in a very limited area, while everywhere else is wet (Mark Lander, personal communication, 12 June 2018); also see Brinkley and Chowdhury (2018)). A good example of a personal drought is Guam and Saipan in 2017–2018 when they were both very dry with almost everywhere else wet. The Pacific ENSO Applications Climate (PEAC) Center (PEAC Center and PEAC are used synonymously) manually tempered the model aggressiveness for above-average rainfall for Guam and the CNMI, resulting in a gradual movement out of dry conditions to near-average rainfall by the spring of 2018. Therefore, in order to overcome these limitations, the PEAC Center has provided El Niño-Southern Oscillation (ENSO)-based seasonal climate information products (i.e. sea level, rainfall, tropical cyclone and ENSO diagnostic discussion) for the USAPI region (Chowdhury *et al.*, 2007, 2014; Chowdhury and Chu, 2015; Yu *et al.*, 1997; see also Widlansky *et al.*, 2018). These island-specific forecasts allow the USAPI governments to respond better to seasonal climate variability and avoid or minimize potentially disastrous impacts.

In addition to seasonal-to-interannual time-scale products, there has been an overwhelming demand for information on longer time-scale climate change projections—particularly the island-specific physical interpretation of the latest IPCC Fifth Assessment Report (AR5)-Coupled Model Intercomparison Project Phase (CMIP5) model-based projections. The need for island-specific projections has significantly increased to support their long-term planning and management scheme in climate-sensitive sectors. This study is, therefore, primarily intended to provide island-specific future climate change projections by using the IPCC's AR5 CMIP5 GCMs multi-model ensembles under different representative concentration pathway (RCPs) scenarios, which, as part of PEAC's education and outreach programme, is important.

2 | METHODOLOGY AND DATA

The CMIP5 provides a state-of-the-art multi-model data set. It includes "long-term" simulations of 20th-Century climate and projections for the 21st Century and beyond. This is the first time that conventional atmosphere–ocean GCMs and Earth system models (ESMs) are being combined so that both types of models can be compared with observations on an equal footing (Taylor *et al.*, 2012). The "near-term" decadal prediction experiments are an entirely new addition to CMIP.

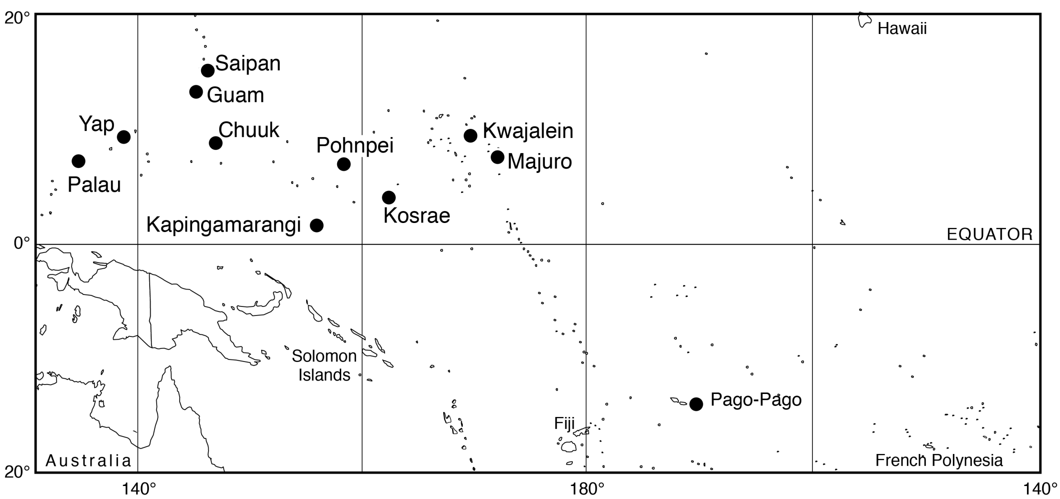

FIGURE 1 Locations of US-Affiliated Pacific Islands; those discussed herein are labelled with black dots. The Republic of Marshalls Islands (RMI) is composed of Majuro and Kwajalein; the Federated States of Micronesia (FSM) is composed of the states of Chuuk, Kosrae, Pohnpei (which includes the island of Kapingamarangi), and Yap

Irving *et al*. (2011) found that when evaluating CMIP3 model results in the Pacific, it was difficult to identify a superior subset of models, although poorly performing models could be identified, and omitting these from Pacific climate studies may improve the robustness of results. Ruane and McDermid (2017) found it was possible to find a small subset of models that captures much important information from the full model. However, using all available models (e.g. 38 GCMs with a total of 105 runs for RCP4.5 and 78 runs for RCP8.5) provides a more robust and comprehensive estimation of past and future climate. Hence, that is what is done in the present paper.

Data sources and tools used for analyses are described below. Note that the future projection of the ENSO has been synthesized from an extensive literature review.

2.1 | Data source

The gridded temperature and rainfall data are taken from the National Climate Data Center (NCDC) (now National Center for Environmental Information—NCEI; NCDC and NCEI are used synonymously). The station-based observed rainfall data (1950–2004) are from the NCEI data portal and most recent rainfall data (2005–2017) are from the PEAC monthly conference call summary (https://www.weather.gov/peac/PEAC_Monthly_Call). (Note that the National Weather Service (NWS) field offices are the primary source for these rainfall data and the PEAC Center is continuously monitoring the station-based monthly rainfall information for each island.) The potential future changes in temperature and precipitation extremes are evaluated using data generated during AR5 based on the protocol CMIP5 multi-model ensembles using 38 GCMs and ESMs (for simplicity, they are referred to as GCMs) (https://verc.enes.org/data/enes-model-data/cmip5/resolution; accessed February 2017) and up to 105 model runs (Rupp *et al*., 2013) (see Appendix S1[1]) (this is more robust and comprehensive estimation as mentioned above). Using the CMIP5 global climate modelling system (Taylor *et al*., 2012), the distribution of change in temperature and precipitation over the region and on each USAPI island in the past century (1900–2015) was calculated. While the past temperature and precipitation change for all islands were evaluated from gridded data at 5° resolution, the station-based rainfall data were also used as complementary information to verify the past rainfall trend from the observed and gridded data. Results from the NCDC (NCEI) gridded data are reported in Figures 2 and 4. (These results were compared with high-resolution temperature (e.g. Climatic Research Unit, CRU TS 3.10) and precipitation (e.g. Global Precipitation Climatology Project, GPCP V6) data and found to be comparable.)

2.2 | The KNMI tool and climate scenario

The Koninklijk Nederlands Meterologisch Instituut (KNMI) Climate Explorer (http://climexp.knmi.nl/start.cgi?id=someone@somewhere, accessed February 2017), a research tool used to investigate climate, was used to generate future temperature and rainfall projections (note that Chowdhury and Ndiaye, 2017, adopted a similar methodological approach to study the CMIP5 GCMs-based climate change and variability impacts on the forests of Bangladesh.) The data set used in the KNMI Climate Explorer was the same as used in the IPCC Working Group I (WG I) AR5 Annex I "Atlas". The KNMI Climate Change Atlas supports using three methods to select an area for the map or time-series plots. For the purpose of this study, IPCC WG1 predefined areas and countries were used.

By using this KNMI research tool, the past trend and future projections (i.e. 2030s, 2050s, 2080s or 2100s) were analysed at various representative concentrations pathways (RCP) scenarios (note that the four RCPs, 2.6, 4.5, 6 and 8.5 are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values 2.6, 4.5, 6.0 and 8.5 W/m^2, respectively). While initial analyses were made based on different RCPs (2.6–8.5), the final results were mainly focused on high emissions (RCP8.5), as recent global emissions are already slightly above RCP8.5 (Peters *et al*., 2013; Zou and Zhou, 2013).

The projections of future climate change are conditional on assumptions of climate forcing, affected by shortcomings of climate models, and inevitably also subject to internal variability when considering specific periods. Note too that the information presented here is only intended to be a starting point for anyone interested in more detailed information on projections of future climate change and it complements the assessment in near- and long-term climate change.

3 | RESULTS

Climatology of climate change including past trend and future projections of temperature, rainfall and surface pressure is provided below.

3.1 | Temperature variability and change

3.1.1 | Past trend

Both observation and model-based annual mean relative temperature change (1950–2017) in the northern (0°–20° N) and southern (0°–20° S) tropical Pacific Ocean is shown in Figure 2. The observed temperature records are a combination of the temperature of the air above the surface, over land and the temperature of the surface waters of the ocean. Therefore, comparing global air temperatures from the models with a combination of air temperatures and sea surface temperatures in the observations is problematic. To overcome this problem, a "blended field" is created from the

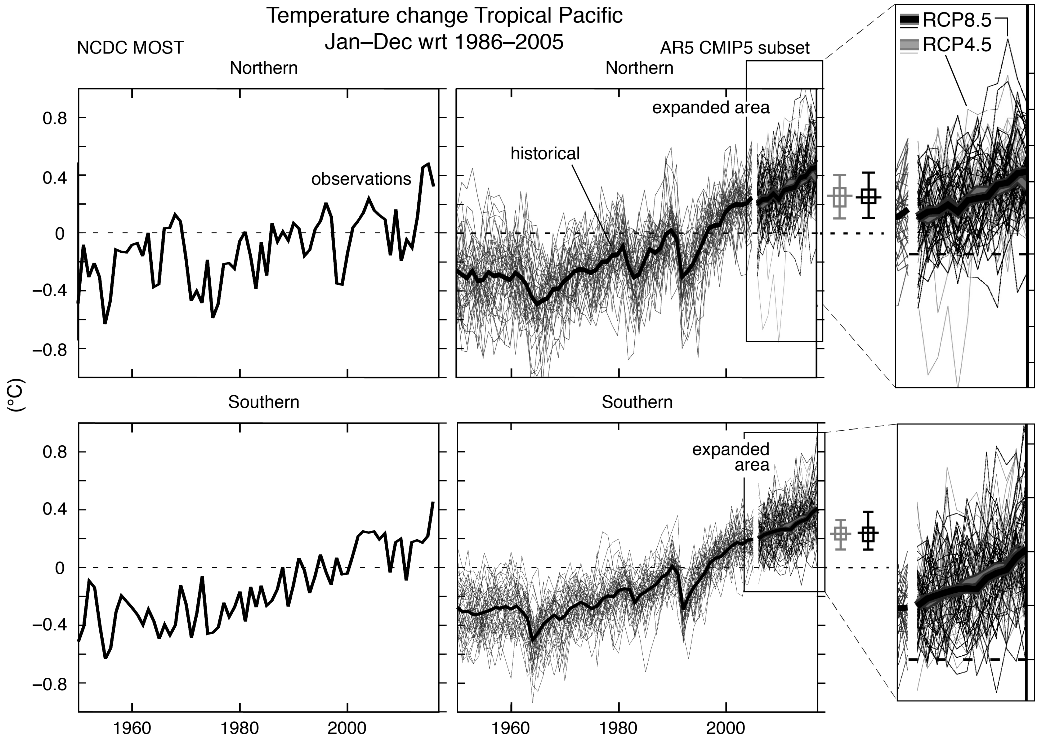

FIGURE 2 Time-series plots of annual relative mean temperature change (5° resolution gridded data; anomalies with respect to the baseline period, 1986–2005) for the North Pacific (NP) (top) and South Pacific (SP) (bottom). The left panel shows observation-based time-series plots from 1950 to 2017. Source: National Climate Data Center (NCDC) (now National Center for Environmental Information—NCEI). The right panel shows corresponding multi-model ensemble spread and means (thick line) (*y*-axis is 0°C). A box plot for representative concentration pathways (RCPs) 4.5 (grey) and 8.5 (black) is also shown. MOST (now changed to MLOST, Merges Land Ocean Surface Temperature)

climate model, which includes ocean surface temperatures and surface air temperatures over land. This blended field matched what is actually measured in the observations.

The left panel of Figure 2 shows the observation-based time series (NCDC MOST: a less interpolated data set with other homogeneities, 5° resolution gridded data set; http://climexp.knmi.nl/help/atlas_dataset.shtml) and the right panel shows the multi-model ensemble mean from 38 models. On average, the observed mean temperature increased at a rate of 0.2°C/decade since 1950 (left), relative to the mean of the 1986–2005 baseline periods (henceforth, 1986–2005 is referred to as "present-day climate"). Increasing temperature in the NP (1.2°C) (left top) were slightly higher than in the SP (1.0°C) (left bottom). The rise is quite pronounced. The equatorial Pacific (not shown in Figure 2) registered an even higher temperature increase during the same time period (1.4°C during 1950–2015). The observed data set (left) is compared with the AR5 CMIP5 model output data (right). The observed anomalies ranging from –0.2°C in 1950 to 0.4 or 0.5°C in 2017 are consistent with the model results. Thus, a good correspondence is seen between the observed historical data (1950–2017) and the corresponding data derived from the CMIP5 models. The variability of temperature projections is also slightly larger for the RCP8.5 scenario. The island-specific observation and model-based temperature change for the same time period was also compared (not shown in Figure 2). The observed changes for all stations appeared to be much larger than those from the models. Only at Guam, where the observed temperature changes are comparable with those from the models. is shown in Figure 3.

3.1.2 | Future projection

Figure 4 shows temperature variation in the past and future as simulated by GCMs for the NP (top) and SP (bottom) for the period 1900–2100. By the 2050s, average temperature increases by approximately 1–1.5°C (for RCPs 2.6–8.5) relative to the present-day climate. The rise in the NP is slightly higher (about 0.3°C) than the SP (Figure 4, bottom). By the 2100s, the NP will experience about a 3.5°C rise under the RCP8.5. The SP is slightly lower than this value but is still projected to be warmer than the present temperature (3.0°C). Temperature will also rise for all other RCPs 2.6, 4.6 and 6.0 scenarios. The largest temperature increase and greatest uncertainly are found in RCP8.5 (Figure 4). Table 1 summarizes island-specific temperature change projections (anomalies with respect to 1986–2005) at RCP8.5. Note that the recent global emission is already slightly above RCP8.5 (Peters *et al.*, 2013; Zou and Zhou, 2013); therefore, the high emission (RCP8.5) scenario was chosen for the following island-wide temperature analyses.

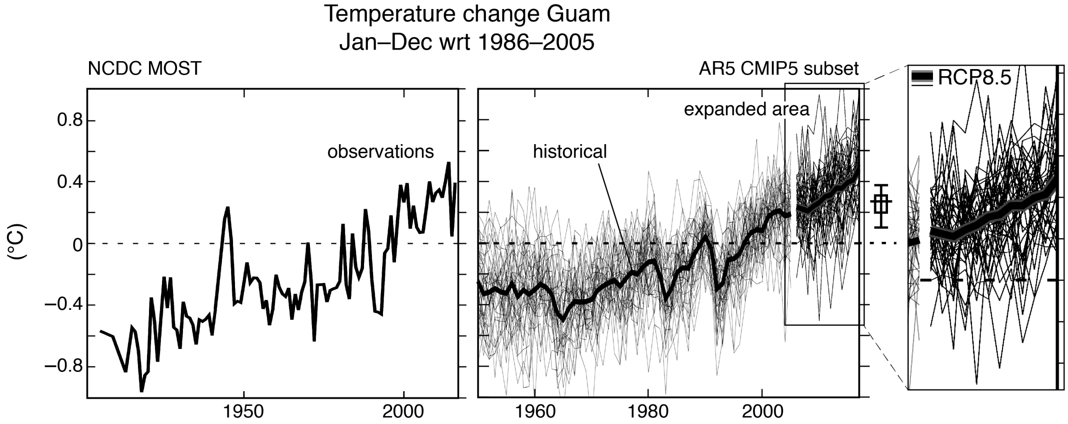

FIGURE 3 Same as for Figure 2, except for Guam. Same as for Figure 2, except for Guam at RCP8.5

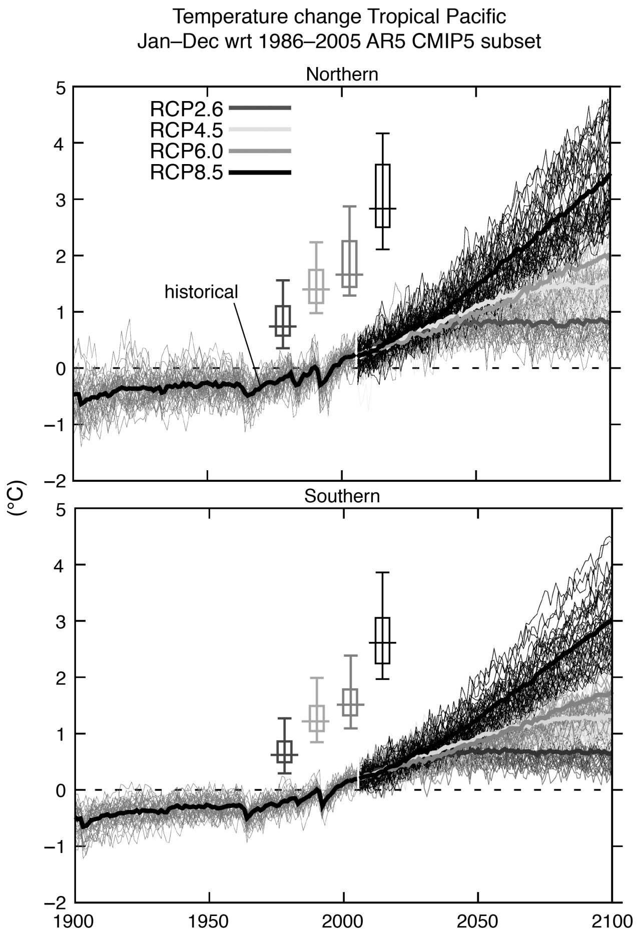

FIGURE 4 Mean annual (January–December) relative temperature change projections (multi-model ensemble spread and mean) (anomalies with respect to the period 1986–2005) over the North Pacific (NP) (top) and South Pacific (SP) (bottom) for representative concentration pathways (RCPs) 2.6 (dim grey), 4.5 (light grey), 6.0 (grey) and 8.5 (black) (*y*-axis is 0°C). The heavy black line denotes model-based historical changes from 1900 to 2014. Box plots for RCPs 2.6, 4.5, 6.0 and 8.5 are also shown

The mean rise of temperature across the entire USAPI region/countries shows a similar pattern. By the 2080s, all islands are expected to experience at least 3°C warming relative to the present-day climate. For most of the islands the temperature increase is slightly higher in summer than in winter.

3.2 | Rainfall variability and change

3.2.1 | Past trend

The annual relative precipitation trend is plotted in Figure 5 (note that the ordinate of the left panel should be multiplied by 0.1 to match the right panel), where the left and right panels are observation (NCDC anomalies: low-resolution (5°) analysis with missing data) and multi-model-based time-series plots, respectively. An increasing trend in the observation is noted over the tropical NP (left-top). In contrast, there is a period of dry conditions observed in the SP (left-bottom) during 2010s, but this does not necessarily represent a long-term rainfall decline. The multi-model ensemble mean (1950–2017) does not correspond well with the observed historical rainfall trend (1950–2017). While the observed rainfall indicated an increasing trend, the CMIP5 values remained very flat without showing any variability (Figure 5, right). This limitation of the GCMs is noticeable here (this is discussed further below) as they sometimes fail to capture many local small-scale features, even though they may represent regional or even global climate reasonably well. The island-specific gridded data and the coarse resolution global model-based rainfall change was also compared (not shown in Figure 5), and all islands showed similar inconsistencies.

To verify the relationship further, a station-based observed time series of rainfall data was used (Figure 6). It is evident that Guam and Koror stay flat (e.g. very similar to Figure 5, right) without showing any noticeable trend during 1966–2017. In the FSM, Chuuk stays flat (not shown in Figure 6), Yap shows a sign of marginal rise and Pohnpei shows a marginal fall (Figure 6c, d). Both Majuro (Figure 6e) and Kwajalein (not shown) in the RMI displayed a marginal fall. Pago Pago in American Samoa shows some sign of increase (Figure 6f). On the contrary, these data provide an encouraging correlation with the CMIP5 model output for rainfall and justifies arguing that there is a quantitative correspondence between the station-based observed

TABLE 1 Island-specific mean temperature change projections (°C) at representative concentration pathway (RCP) 8.5 (anomalies with respect to 1986–2005) for May–August (MJJA) and November–February (NDJF) during the 2030s, 2050s and 2080s

	Temperature (°C) change projections at RCP8.5					
	2030s		2050s		2080s	
	MJJA	NDJF	MJJA	NDJF	MJJA	NDJF
Guam	1.1	0.8	1.8	1.4	3.6	3.4
Palau (Malakal)	1.0	0.9	1.8	1.6	3.4	3.3
FSM	1.0	0.9	1.8	1.5	3.4	3.2
RMI	0.9	0.8	1.6	1.4	3.3	3.3
American Samoa	0.9	0.8	1.3	1.4	3.0	3.0

Note: MJJA and NDJF are summer and winter in the North Pacific and opposite in the South Pacific (i.e. American Samoa). FSM: Federated States of Micronesia; RMI: Republic of Marshall Islands.
Source: Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Coupled Model Intercomparison Project Phase (CMIP5) subset.

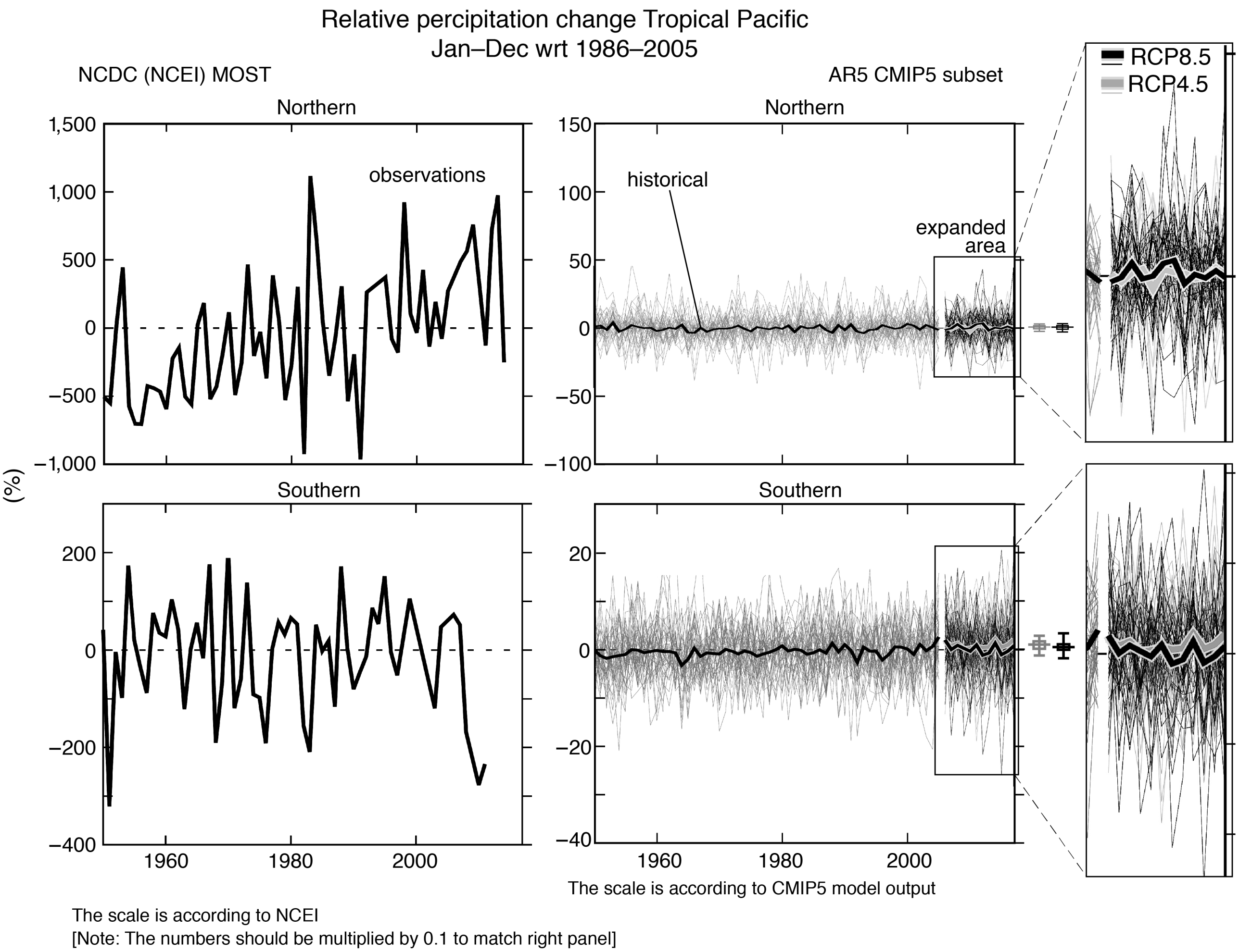

FIGURE 5 Same as for Figure 2, except for time-series plots of annual relative mean precipitation (5 ° resolution gridded data) change (anomalies with respect to the period 1986–2005) from 1950 to 2017 for North Pacific (NP) (top) and South Pacific (SP) (bottom). The left panel shows observation-based time-series plots (source: National Climate Data Center (NCDC); now National Center for Environmental Information—NCEI); the right panel shows multi-model ensemble spread and mean (*y*-axis is percentage change). The ordinate of the left panel should be multiplied by 0.1 to match the right panel. A box plot for representative concentration pathways (RCPs) 4.5 (grey) and 8.5 (black) is also shown

rainfall variations and CMIP5 model output in the USAPI region. Rainfall projections, therefore, were encouraging when the real-time station-based observed data were compared.

This is an interesting finding for which the authors currently do not have any scientifically proven explanation. However, the best possible explanation can be stated as that the gridded observation data (NCDC or NCEI MOST) used in this study are of coarse resolution (5°). While the gridded data represented an average value of a large area, the station data represented the real-time observed local rain gauge that covered a particular station and a particular climate zone of

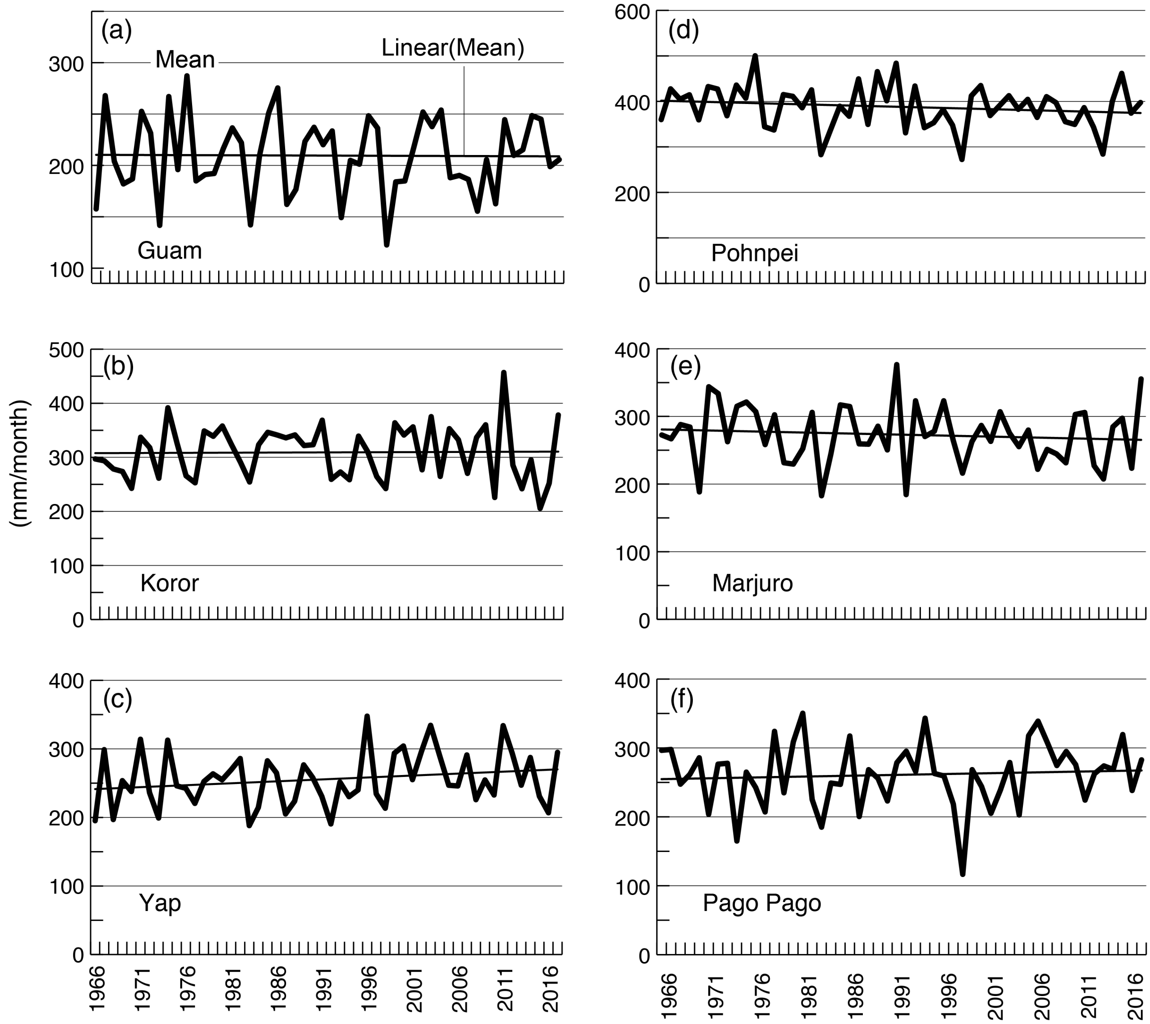

FIGURE 6 Interannual variability of observed monthly mean rainfall time series time series (1966–2017) and trend in some of the US-Affiliated Pacific Islands (USAPI) stations: Guam; Palau (Koror); Federated States of Micronesia (FSM) (yap, Pohnpei); Republic of Marshalls Islands (RMI) (Majuro); and American Samoa (Pago Pago) (*y*-axis is mm/month). The trend is denoted by a light black line. Source: National Climate Data Center (NCDC) (now National Center for Environmental Information—NCEI), National Weather Service (NWS) and https://www.weather.gov/peac/PEAC_Monthly_Call

interest. This could be a reason for this discrepancy which, at this stage, looks like a data-quality issue.

3.2.2 | Future projection

Like past trends, there was a strong uncertainty in rainfall projection for all periods as evidenced by the large spread of the precipitation change projections. The annual mean rainfall variation in the past and future as simulated by the GCMs shows that there is a slight increasing trend in NP rainfall (no noticeable trend in SP) towards the 2030s, 2050s and 2100s under RCPs 2.6–8.5 (Figure 7). However, a step increase in SP rainfall around 2070 can be seen (Figure 7). Table 2 shows the island-wide precipitation change projections (anomalies with respect to 1986–2005) at RCP8.5.

It is clear that, other than American Samoa, all other islands displayed increased rainfall in the future (Table 2). Guam and Palau showed an increase of about 12–25%, while FSM and RMI displayed about an 8–15% increase over the period of projections (2030s, 2050s and 2080s). The rainfall in winter (November–February) shows a higher percentage increase than in summer (May–August) for Guam and Palau. However, the increases for summer (May–August) are higher than winter (November–February) for FSM and RMI (Table 2). American Samoa, in contrast, displays no change in summer (November–February) rainfall, but only a 5% increase in winter (May–August) rainfall.

3.3 | Net water flux

According to the bulk parameterization scheme, evaporation is governed by the turbulent exchange co-efficient, wind speed and difference in water vapour mixing ratio at a surface height and saturation water vapour mixing ratio at the sea surface temperature. A warm climate is expected to spur more evaporation of water from the ocean to the atmosphere and can hold more water because the saturation water vapour pressure increases with warming, based on the Clausius–Clapeyron relationship.

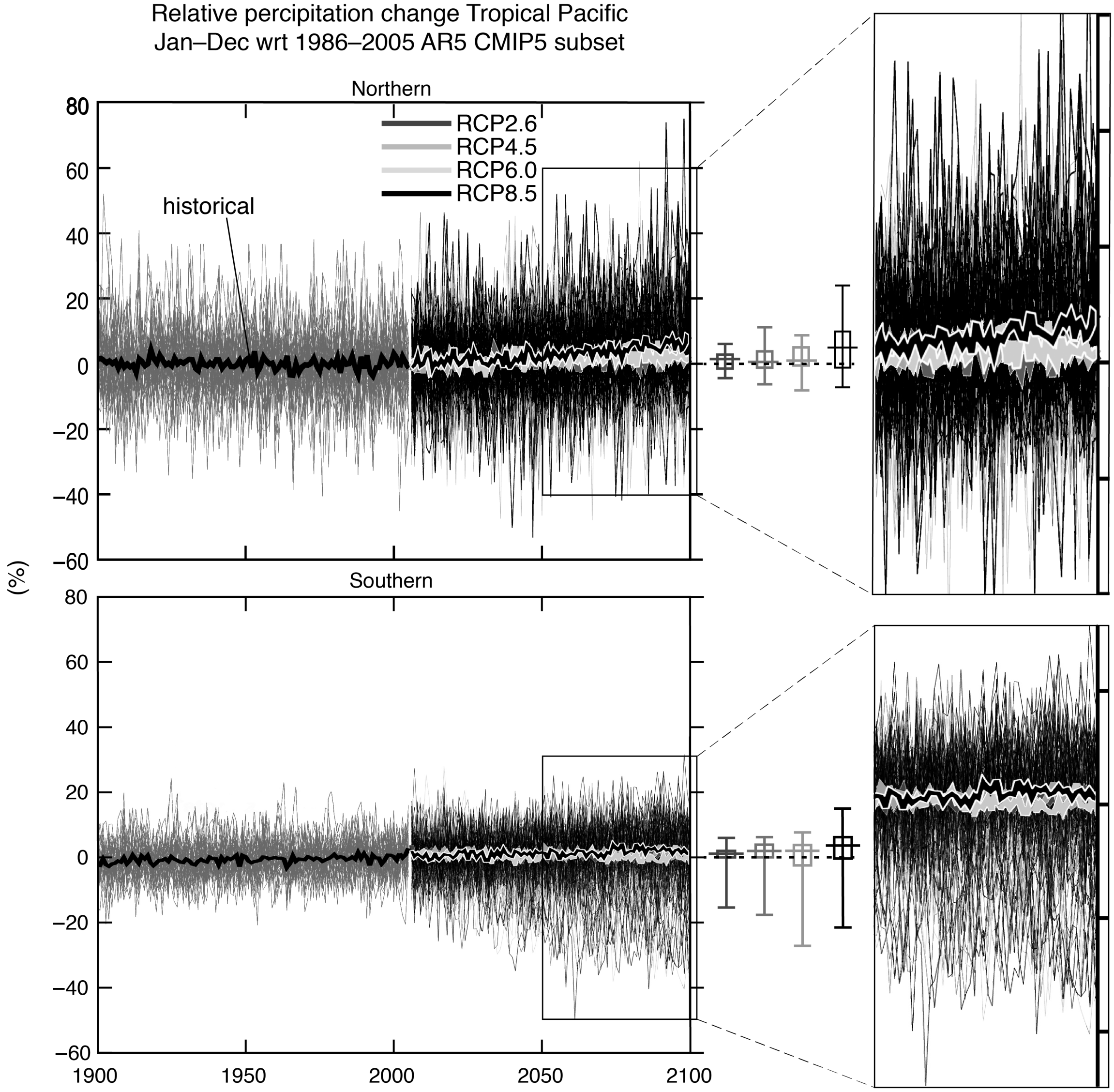

FIGURE 7 Same as for Figure 4, except for mean annual (January–December) relative precipitation change projections (anomalies with respect to the period 1986–2005) over North Pacific (NP) (top) and South Pacific (SP) (bottom) for representative concentration pathways (RCPs) 2.6 (dim grey), 4.5 (grey), 6.0 (light grey) and 8.5 (black) (*y*-axis is percentage change). The heavy black line denotes historical changes from 1900 to 2016. Box plots for RCPs 2.6, 4.5, 6.0 and 8.5 are also shown

TABLE 2 Island-wide mean relative precipitation change projections (mm/day) (anomalies with respect to 1986–2005) at representative concentration pathway (RCP) 8.5 for May–August (MJJA) and November–February (NDJF) during the 2030s, 2050s and 2080s

	Precipitation (mm/day) change projections at RCP8.5					
	2030s		**2050s**		**2080s**	
	MJJA	**NDJF**	**MJJA**	**NDJF**	**MJJA**	**NDJF**
Guam	1.5 (12)	1.3 (20)	1.6 (14)	1.4 (22)	1.8 (15)	1.5 (25)
Palau (Malakal)	1.6 (12)	1.4 (16)	1.8 (16)	1.8 (20)	2.0 (20)	2.0 (25)
FSM	1.4 (10)	1.2 (8)	1.6 (12)	1.4 (9)	2.0 (15)	1.5 (10)
RMI	0.8 (8)	1.0 (8)	0.9 (9)	1.0 (9)	1.0 (10)	1.0 (10)
American Samoa	Trace	0.5 (5)	Trace	0.5 (5)	Trace	0.5 (5)

Note: MJJA and NDJF are summer and winter in the North Pacific and opposite in the South Pacific (i.e. American Samoa). Numbers in parentheses are percentage change.
Source: Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Coupled Model Intercomparison Project Phase (CMIP5) subset.

Precipitation (P) minus evaporation (E) is usually referred to as the net flux of freshwater or the total freshwater in or out of the oceans. The (P-E) term strongly affects the salinity of the mixed layer of the ocean. The surface salinity is governed by the addition of water by precipitation and the removal of water by evaporation. Over land, it determines the sum of surface and subsurface run-off.

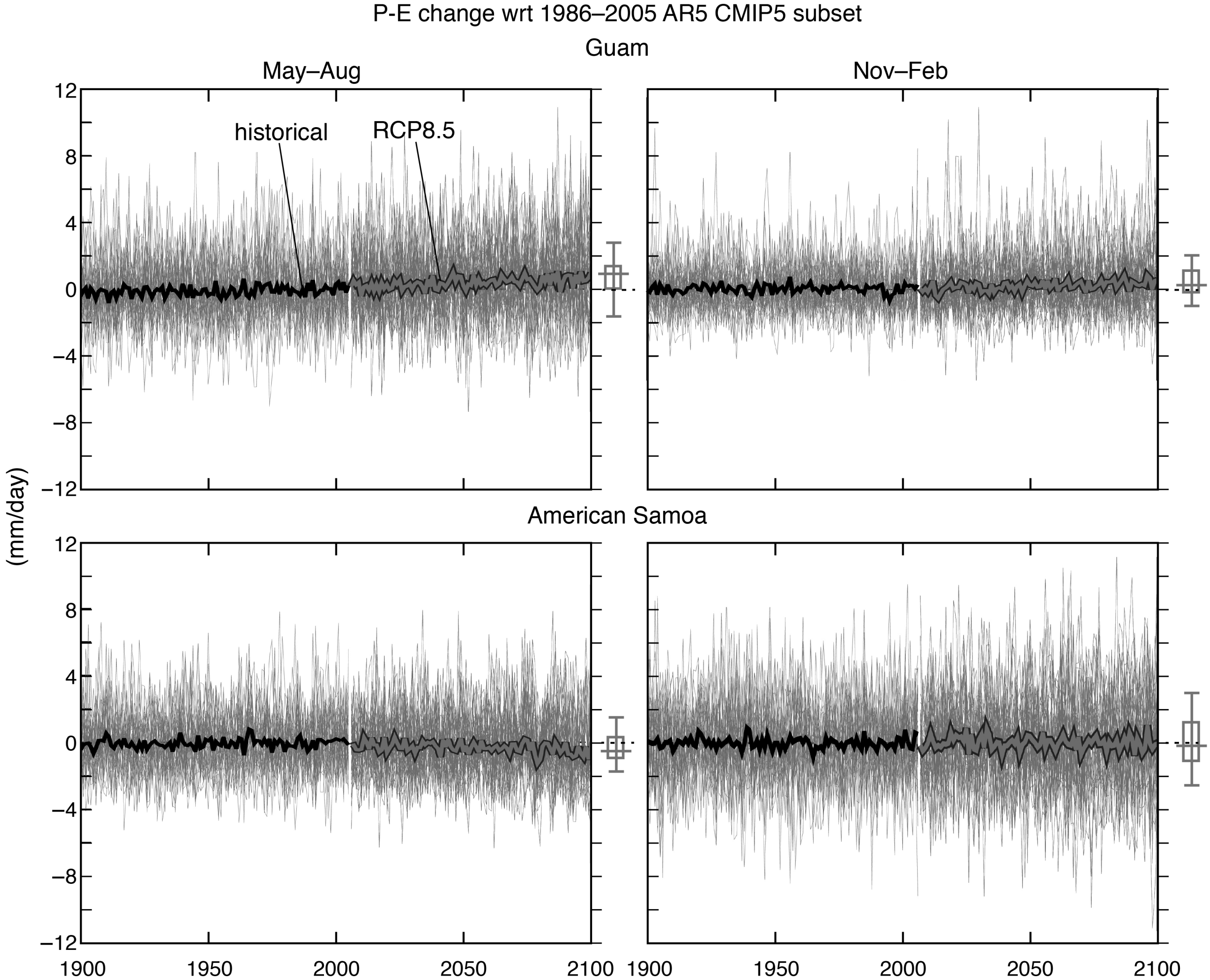

FIGURE 8 Mean relative net water flux (P-E) change projections at representative concentration pathway (RCP) 8.5 for May–August (MJJA; left) and November–February (NDJF; right) seasons for Guam (top) and American Samoa (bottom) during the period 1900–2100 (*y*-axis is mm/day). A box plot for RCP8.5 is also shown

TABLE 3 Island-wide mean relative P-E (net flux of freshwater; mm/day) change projections (anomalies with respect to 1986–2005) at representative concentration pathway (RCP) 8.5 for May–August (MJJA) and November–February (NDJF) during the 2030s, 2050s and 2080s

	P-E (net water flux change; mm/day) at RCP8.5					
	2030s		2050s		2080s	
	MJJA	NDJF	MJJA	NDJF	MJJA	NDJF
Guam	0.8	0.8	0.8	0.8	0.8	0.8
Palau (Malakal)	1.5	1.6	1.7	1.8	1.9	2.0
FSM	1.5	1.7	1.6	1.8	1.8	2.0
RMI	0.8	1.0	0.9	1.0	1.0	1.0
American Samoa	–0.5	0.7	–0.5	0.8	–1.0	1.0

Note: MJJA and NDJF are summer and winter in the North Pacific and opposite in the South Pacific (i.e. American Samoa). Other than Palau, the percentage of change ranges from 10 to 20% for all islands. In Palau, the range varies from 20 to 40%.
Source: Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Coupled Model Intercomparison Project Phase (CMIP5) subset.

Mean relative P-E (net flux of freshwater) change projections (anomalies with respect to 1986–2005) at RCP8.5 for Guam (NP) and American Samoa (SP) during 1900–2100s is shown in Figure 8. Table 3 summarizes island-wide mean relative P-E (mm/day) change for the May–August and November–February seasons. The net water flux rate in winter is generally higher than the summer flux for all USAPIs, except for Guam where there is no change in the net water flux (Table 3). While Guam and RMI display a 0.8–1.0 mm/day increase in net water flux change over the period of projections (2030s, 2050s and 2080s), Palau and FSM show a much higher rate of change (1.5–2.0 mm/day) (Table 3). The additional influx of freshwater into the tropics may affect the salinity of the

NP in future, if other processes remain constant. This will alter the stratification of the ocean and, thus, the thermodynamics and dynamics of the mixed layers.

American Samoa, in contrast, shows some interesting results: a decreasing (negative) trend of net water flux in austral winter and increasing trend in austral summer (Figure 8). Therefore, an increase in net water flux in austral summer (November–February) will be compensated by a decrease in flux in winter. However, the decreasing trend of P-E from the 2030s to the 2080s is expected to increase the likelihood of drought in American Samoa, particularly in any extreme El Niño year.

3.4 | ENSO variability and change: Current limitations

Clearly, improved longer term projections of the inter-annual El Niño variability are essential for managing (or adapting) to climate hazards in the USAPI region. However, currently the ENSO response to global warming differs strongly from model to model, and to some extent it remains uncertain. Nonetheless, the recent CMIP5 models have improved in their ability to simulate El Niño teleconnections (Karumuri and Yamagata, 2009). Based on CMIP3 and CMIP5 projections, there is an abundant literature available on the projected variability and change in the ENSO (Ashok and Yamagata, 2009; Boer, 2009; Lau *et al*., 2008; Müller and Roeckner, 2008; van Oldenborgh *et al*., 2005; Vecchi and Soden, 2007; Vecchi and Wittenberg, 2010; Weare, 2013; Wenju *et al*., 2014); therefore, this discussion is limited to a short review summary. Note that the PEAC Center does not generate ENSO information. As an applications climate centre, the tasks are mainly focused on producing operation climate products from the available ENSO information provided by the global ENSO research centres.

A summary of those GCMs-based results reveals that: (1) super El Niño events could double in frequency in future due to greenhouse warming; (2) extreme El Niño events could occur roughly every decade instead of every 20 years as at present; (3) El Niño will persist during the coming century; and (4) the recent CMIP5 models improved their ability to simulate El Niño teleconnections (Weare, 2013, *passim*). Weare (2013) attempted to understand the teleconnections associated with El Niño events in 20 CMIP5 climate models (see Supporting Information Appendix S2[2]) with reanalysis observations and concluded that the recent versions of earlier models have improved their ability to simulate El Niño teleconnections.

By analysing CMIP5 simulations, a recent study by Guojian *et al*. (2017) added that the frequency of extreme El Niño events doubles under the 1.5°C Paris target, and continues to increase long after global temperatures stabilize due to emission reductions. In contrast, extreme La Niña events see little change at either 1.5 or 2°C warming. Guojian *et al*. further added that the frequency of extreme El Niño events evolves linearly with the rising global mean temperature (GMT), conveying a simple but powerful message that any increase in CO_2 directly leads to a higher risk of increased frequency of extreme El Niño events. This linear relationship attributed to greenhouse forcing emerges because of various other factors that influence the frequency of extreme El Niño in each model, such as decadal natural variability and weather noise, which tend to be averaged out across an ensemble of models. The effects of these factors, other than greenhouse forcing, would be notable in a single realization, as in observation. Thus, the future frequency of extreme El Niño events increases due to greenhouse forcing in a single observed realization and will continue to be influenced by internal variability and stochastic forcing. The ultimate risk involves a continued increase in extreme El Niño frequency long after the GMT stabilization (Guojian *et al*., 2017).

4 | CURRENT LIMITATIONS OF THE GCMS

The climate in the Western Pacific is linked to a complex set of climatological features. In particular, the position of the Western Pacific Warm Pool and equatorial cold tongue influence large-scale patterns of circulation and precipitation (Brown *et al*., 2013). On seasonal time scales, the Western Pacific monsoon, monsoon trough and South Pacific Convergence Zone (SPCZ) vary in position and intensity. If models do not capture the monsoon trough and SPCZ, then the main rainfall and variability over countries in the Western Pacific will not be correctly reproduced. Based on the implications of CMIP3 model biases and uncertainties for climate projections in the Western tropical Pacific, Brown *et al*. (2013) concluded that while basin-scale projections for certain climate variables (e.g. temperature) can be done with high confidence, uncertainty remains prominent in precipitation projections (also see Brown *et al*., 2013, *passim*).

The CMIP5 models used here retain the same fundamental physical characteristics as the CMIP3. Despite several improvements in the simulation of CMIP5 (i.e. ENSO-like variability) over the previous CMIP3, there are still non-trivial biases in CMIP5. According to Grose *et al*. (2014), most CMIP5 models have an overly strong equatorial cold tongue and an incorrect shape for the eastern edge of the Indo-Pacific warm pool and biased strength and slope of the SPCZ. These biases, among others, lead to non-trivial biases in the spatial distribution and seasonality of rainfall in the USAPI region. Rainfall projection limitations were also observed in this study when the observed and CMIP5 multi-model ensemble mean did not correspond well.

An initiative by the Pacific climate change science program evaluated the CMIP3 model performance, which included quantitative assessment of three variables: temperature, precipitation and surface wind; three climate features:

SPCZ, ITCZ and the West Pacific Monsoon; as well as the ENSO, spurious model drift and long-term warming signal (Irving *et al*., 2011). It was difficult to identify a superior subset of models for the nine criteria and they ended up identifying poor performance models only. The GCMs limitations for Pacific region rainfall projections are not discussed further here as this has been well documented by Irving *et al*. (2011) and Grose *et al*. (2014), and what this means for climate projections is documented by Brown *et al*. (2013, *passim*).

A major concern of GCM is that there are many small-scale features that cannot be represented, even though they may significantly impact the local, regional or even global climate. The small size of some the islands (i.e. Majuro is only 8 square miles) in the USAPI region further complicates the problem. However, based on the current GCM evidence, the authors have confidence in their assessment of temperature change, but there still remain some challenges for rainfall assessments, although the results from station-based observed data are encouraging.

5 | CLIMATE VARIABILITY AND CHANGE IMPACTS ON THE USAPIS

Findings from long-term temperature and rainfall changes reveal that the Pacific island-wide temperature will increase (0.8–1.1, 1.3–1.8 and 3.0–3.6°C by the 2030s, 2050s and 2080s respectively) and the islands will likely face enhanced dry stress from the increasing temperature when combined with El Niño. From the real-time observed data (1966–2017), there was no trend in rainfall in the past (grid-based satellite data: 1950–2016 is also supportive), but, despite limitations in GCMs, an increase in rainfall in the future was clearly noticed. The P-E value has been positive all along, except for American Samoa where it displayed a slight decline in May–August (Austral winter). However, while there is no future rainfall deficit from a supply perspective, the major concern is whether the increasing rainfall will be able to meet the future demand for water in the USAPI region, as the water demand will increase due to population growth and increasing activities in different water-sensitive social and economic sectors. This is an open question for present and further research is needed to find a viable answer.

However, while the long-term trend for rainfall is not alarming for adaptations, the future concern lies in the increasing frequency of the ENSO. It is argued here that ENSO-based climatic disruption is the prime concern in the USAPI region (also see Power *et al*., 2017) and the long-term warming signal (Whan *et al*., 2013) can aggravate the problem. Therefore, El Niño-related drought and La Niña-related flooding are natural disruptions that some of the USAPIs will have to tackle in the face of changing climate. The La Niña-related flooding disruptions can further be aggravated due to rising sea level, particularly in any La Niña year when the sea level is higher than normal (Chowdhury *et al*., 2010). This is a major concern as the sea level in the USAPI region is highly sensitive to the ENSO, with low sea level during an El Niño year and a high sea level during a La Niña year (Chowdhury *et al*., 2007). A diagnostic discussion on the ENSO and sea level variability has been reported elsewhere (Chowdhury *et al*., 2007, 2010, *passim*), therefore, and not further discussed here. It can be concluded that the islands and the low-lying atolls in the FSM and RMI are particularly vulnerable to the ENSO-related heat stress and inundations. The following section provides an overview of rainfall variability in the regional and country-scale during El Niño and La Niña events.

5.1 | Impacts of the ENSO on Pacific rainfall

Seasonal rainfall in the western extremity of the Pacific is strongly influenced by the west Pacific monsoon, whose strength, timing and extent are also affected by the phase of the ENSO, particularly by the ENSO-related variations in trade winds (Collins *et al*., 2011). While Kug *et al*. (2009) classified El Niño events into three different types (e.g. a warm pool El Niño (WPE), a cold tongue El Niño (CTE) and a mixed El Niño (ME)), Murphy *et al*. (2014) identified that these three types produce different rainfall impacts across the tropical Pacific island countries, although CTE events are associated with the greatest rainfall impacts in most countries in the Pacific.

A recent study by Power *et al*. (2017) supported the fact that there is a tendency for the frequency of both El Niño and La Niña to increase in future and concluded that the multi-model mean (MMM) frequency of La Niña increases by 4% during the early 20th Century (E20C), 10% during the late 20th Century (L20C), 22% during the early 21st Century (E21C), and 9% during the late 21st Century (L21C) under the RCP8.5 scenario. Correspondingly, in E20C, L20C, E21C and L21C, 58, 63, 50 and 38% of models show an increase in the magnitude of the NINO3.4 SST anomaly respectively. During La Niña events, 71% models show a decrease in NINO3.4 SST anomaly in E20C, while 50, 58 and 67% of models show an increased NINO3.4 anomaly in L20C, E21C and L21C under the RCP8.5 scenario respectively (Power *et al*., 2017, *passim*).

5.2 | Impacts of the ENSO on country-scale rainfall

Recent research has emphasized the intensification of the ENSO-driven rainfall in the Pacific (Murphy *et al*., 2014, *passim*). The water resources sector in the USAPI region is already under stress and the ENSO is the primary factor of rainfall variability there. In order to evaluate the magnitude of disruption, an island-wide variation in rainfall response to the ENSO is provided in Figure 9. The paper only

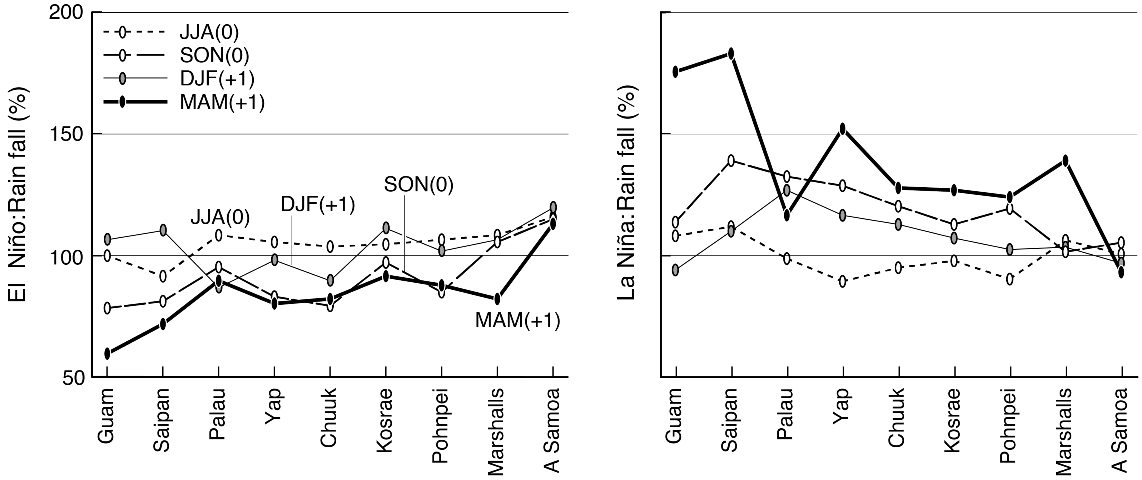

FIGURE 9 Seasonal rainfall variations (%) during El Niño (left) and La Niña (right) years (1966–2014) (source: Pacific ENSO Applications Climate's (PEAC) monthly conference call note; https://www.weather.gov/peac/PEAC_Monthly_Call, accessed March 21, 2018) (*y*-axis is percentage change during El Niño (EN) and La Niña (LN) years). Note that (0) represents the year of onset of El Niño or La Niña (dotted line) and (+1) represents the year following El Niño (0) or La Niña (0) (firm line). December–February (DJF), March–May (MAM), June–August (JJA) and September–November (SON) indicate winter, spring, summer and fall respectively (also note that DJF and JJA are austral summer and winter for American Samoa)

categorizes years into El Niño and La Niña (not into different El Niño types, which is a subject of further study) from 1966 to 2014.

It is evident that while the rainfall variability during the onset of El Niño (0) year is marginal, the variability abruptly changes during post El Niño (+1) year (Figure 9, left panel). Observations revealed that the NP islands experienced prolonged drought for two consecutive seasons (December–February to March–May) during the El Niño (+1) year. Guam, Saipan and Chuuk experienced the largest impacts. It is also noticeable that the El Niño signal lasts longer (up to June–August of El Niño (+1)) for Guam in the NP region (not shown). The rainfall variability in the SP islands (American Samoa) displays relatively less sensitivity to the El Niño signal. No major deviations in rainfall are observed during the El Niño (0) and El Niño (+) year. It is also clear from that most of the stations displayed fairly normal rainfall during the La Niña (0) year; however, rainfall increased during the La Niña (+1) year (Figure 9, right panel). Both the December–February and March–May season recorded higher than average rainfall, but the increase is significantly higher during the March–May season. The NP islands experienced wet conditions with possible inundations, and sometimes severe flooding, for two consecutive seasons (December–February to March–May) in the La Niña (+1) year. Guam, Saipan and Yap were severely impacted. It is also noticeable that the La Niña signal lasts longer for Guam and Saipan (up to June–August of La Niña (+1) year).

Recent research concluded that the frequency of disruptions to Pacific rainfall over the 21st Century associated with the ENSO will be much larger than it was during the 20th Century (Cai *et al*., 2014, 2015, 2015). The risk of major rainfall disruption has already increased and remains elevated for the remainder of the 21st Century, even if marked and sustained reduction in global greenhouse gas emissions are made (Power *et al*., 2017). Factors responsible for rainfall disruption are: (1) an increase in the frequency of El Niño and La Niña events; and (2) as the world warms up, an increase in precipitation anomalies arising from nonlinear interaction between unchanged ENSO-driven SST anomalies and background global warming (Brown *et al*., 2013; Power *et al*., 2013).

6 | SUMMARY OF THE FINDINGS AND CONCLUSIONS

The water resources in the US-Affiliated Pacific Islands (USAPI) region will be severely affected by the impacts of long-term temperatures and rainfall change, and the interannual El Niño–Southern Oscillation (ENSO) variability. Following an overview of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) General Circulation Models (GCMs) and ENSO projections, the uncertainty of the GCM simulations were found to be an important issue for future rainfall projections. A brief summary of findings and some improvement options are provided below.

- It has been found that the USAPI region will continue to see considerable increases in temperature and, relatively limited increases in rainfall and the rising greenhouse gas concentrations will drive the increasing frequency of El Niño, which will affect the variability of temperature, rainfall, drought, and flooding in the region.
- The risk of the ENSO-driven rainfall disruption has already increased in the Pacific and the risks remain elevated for the reminder of the 21st Century. The intensification of the ENSO-driven rainfall will cause more disruptions in the USAPI region. The impact of

increasing rainfall combined with future La Niña may cause intense flooding. In both cases of extreme events, the islands in Federated States of Micronesia (FSM) and Republic of Marshalls Islands (RMI) are particularly vulnerable.

- While the temperature projections by GCMs are promising for the USAPIs, the rainfall projection potentials are relatively limited (e.g. Coupled Model Intercomparison Project Phase (CMIP5) projects are more uncertain for rainfall). However, compared with the grid-based rainfall data, the real-time observed data provide an improved correspondence with the CMIP5 model-based information.
- To improve the current modelling (GCMs) limitations, future efforts should focus on Coordinated Regional Climate Downscaling Experiment (CORDEX) Regional Climate Models (RCMs) (http://www.cordex.org/), which is an improved framework for generating regional-scale climate projections for impact assessments. CORDEX is growing very quickly and many new regions and domains have been added recently. It is extremely important that the USAPI region, in collaboration with the international community, should strive to develop a RCM to support more detailed impact and adaptation assessment and planning.
- Apart from GCMs, there are also limitations in the ENSO forecasts and the fundamental question of how will the ENSO frequency, intensity and/or teleconnection properties change as the Earth warms still remains unanswered. However, the recent CMIP5 model-based study provided a strong message about the higher risk of extreme El Niño for future generations. For example, the frequency of extreme El Niño events doubles under the 1.5°C Paris target and continues to increase long after global temperatures stabilize due to emission reductions.

In conclusion, the temperature and rainfall change combined with future ENSO variability are likely to affect many important climate sensitive sectors in the USAPI region. Among others, the water resources sectors will be severely affected and the overall livelihoods of the most water-stressed countries in the FSM and RMI will be challenged. It is anticipated that greater knowledge about the ENSO and its impact on the global to regional scale will play an influential role in shaping and contributing to the critical climate change development capacity building efforts in the USAPI region. Therefore, further research on information products related to three types of El Niño-related (e.g. a warm pool El Niño (WPE), a cold tongue El Niño (CTE) and a mixed El Niño (ME)) impacts specific to the USAPI region is warranted. A climate information-based comprehensive water resources management plan for the 2030s is therefore essential with ENSO-related climate information, projections and the impacts in terms local residents can understand and respond to.

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ENDNOTES

[1] https://verc.enes.org/data/enes-model-data/cmip5/resolution

[2] See also: https://wiki.csiro.au/confluence/display/ACCESS/Home; www.ec.gc.ca/ccmac-cccma/default.asp?lang=En&n=3701CEFE-1; http://www.lasg.ac.cn/FGOALS/upfile/FGOALS-s2_13_aas.pdf; www.giss.nasa.gov/research/modeling; and ww.mri-jma.go.jp/Publish/Technical/ DATA/-VOL_64/tec_rep_mri_64_2.pdf/.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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