When El Niño Rages

How Satellite Data Can Help Water-Stressed Islands

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Hawaii and the United States Affiliated Pacific Islands (USAPI) are highly susceptible to extreme precipitation events such as drought and flooding (Schroeder et al. 2012). These extreme events directly influence the quality and the overall availability of freshwater resources utilized by island communities. Accessibility to freshwater is heavily dependent upon the amount and rate of precipitation that falls within a given season (Kruk et al. 2015). In fact, for many of the low-island coral atolls, using large rain tanks to collect and store rainfall is the only sustainable method. Due to the geographic location of the USAPI, many of the islands are vulnerable to heavy precipitation and drought during different phases of the El Niño–Southern Oscillation (ENSO). During strong warm ENSO phases, such as the 1997–98 El Niño event, extremes in precipitation distribution can induce significant socioeconomic impacts throughout the USAPI (Hamnett et al. 1999; Schroeder et al. 2012). The 1997–98 El Niño event in particular was responsible for crop losses across much of the USAPI; water rationing in the Marshall Islands and the Federated States of Micronesia; wildfires in Pohnpei, Chuuk, Yap, Palau, and Guam; and loss of livestock in the Northern Mariana Islands (Hamnett et al. 1999; Schroeder et al. 2012). Cool La Niña episodes generally have less severe widespread precipitation-related impacts; however, these events can negatively impact surface and groundwater availability through episodes of large surf and high sea levels (Schroeder et al. 2012). Furthermore, ENSO cycles affect tropical cyclone frequency and distribution in the region, adding more complexity to seasonal precipitation outlooks (Hamnett et al. 1999).

Established in 1994, the National Oceanic and Atmospheric Administration's (NOAA) Pacific ENSO Applications Climate (PEAC) Center works to provide climatological forecasts that relate to the management of climate sectors within the USAPI (Hamnett et al. 1999; Schroeder et al. 2012). PEAC collaborates with representatives from regional Weather Station Offices (WSOs) and NOAA's Climate Prediction Center (CPC) to create precipitation, tropical cyclone, and sea level outlooks (Schroeder et al. 2012). During active ENSO periods, precipitation outlooks are partly informed by an ENSO rainfall atlas assembled by NOAA's CPC (He et al. 1998). In that atlas, data from 66 in situ stations scattered throughout the USAPI from the years 1955–98 were used to generate a historical climatology for rainfall distribution across the region for various phases of the ENSO (He et al. 1998).

While that atlas is extremely useful, local island WSOs expressed the need for higher-resolution data, both spatially and temporally (NOAA 2015). Spatially, there are too few high-quality long-term rain gauges on the islands, and many of the islands are often 100 km or farther from the capital islands, where the primary rain gauges tend to be located (Sutton et al. 2015). The outer islands use high-frequency (HF) radio, or a system known as "Chatty Beetle", for data transmission and communication with the WSO, which at times is unreliable (Chip Guard 2014, personal communication). Temporally, forecasters could

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benefit from high-resolution satellite-derived rainfall estimates that can be blended and delivered to users every three hours (Center for Hydrometeorology and Remote Sensing; http://chrs.web.uci.edu/index.html). Due to the remoteness of the Pacific region, coupled with the expressed interest from island forecasters, it was evident that incorporating satellite data was a necessary compliment to the already present in situ data. The publicly available Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR; Ashouri et al. 2015), which offers a 30-year record of global, daily precipitation estimates at 0.25° resolution, was an ideal dataset to compliment the station data. Not only is the PERSIANN-CDR resolution ideal for this region, but it has also been used successfully in the past in areas with sparse station networks (see Miao et al. 2015).

Through a unique collaboration between the National Aeronautics and Space Administration (NASA) DEVELOP National Program and climatologists from NOAA's National Centers for Environmental Information (NCEI), a new satellite-derived rainfall atlas for Hawaii and the USAPI was produced. The NASA DEVELOP National Program (http://develop.larc.nasa.gov/) provides opportunities for young professionals to lead and participate in research that utilizes NASA Earth observations while under the guidance of NASA and partner science advisors. Over an intense 10-week period, the Pacific Water Resources team, composed of graduate and undergraduate students, successfully delivered a complete 30-yr ENSO climatology to forecasters within the Pacific region. This project culminated in the production of a 478-page climatic reference atlas (ftp://ftp.ncdc.noaa.gov/pub/data/coastal/ENSO_Rainfall_Atlas.pdf) that is used as a supplemental guide to help island forecasters increase confidence in their seasonal outlooks and better prepare their communities for extreme drought and heavy precipitation events commonly associated with El Niño conditions.

CDRS AND DATA ANALYSIS. NOAA's satellite Climate Data Records Program's mission is to provide global climate information from multiple weather satellites that have collected data during a time period of more than 30 years. NOAA's CDR program focuses on creating datasets that blend atmospheric and surface data to provide consistent, reliable, and stable long-term data records (National Research Council 2004). CDR applications provide scientists with insight into the dynamic nature of our climate system, especially at the regional scale (National Research Council 2004). Historically, the Global Precipitation Climatology Project (GPCP) has been utilized as the go-to global, long-term precipitation database. The GPCP merges multiple satellite and rain gauge data to provide global precipitation data at 2.5° resolution (Huffman et al. 1997; Schneider et al. 2008). However, at 2.5° spatial resolution, GPCP often struggles to accurately estimate rainfall extremes across regions of small spatial scale. This is particularly true with the Pacific Islands, where the average island size ranges from only 10 to 25 km^2. To address this resolution limitation, scientists created the PERSIANN-CDR, a multisatellite, high-resolution precipitation product. The PERSIANN-CDR uses the PERSIANN (Hsu et al. 1997; Sorooshian et al. 2000) model, which primarily relies on infrared (IR) satellite data from geostationary Earth orbiting satellites (GEOS). Particularly, it utilizes archived Gridded Satellite (GridSat-B1) IR data (Knapp 2008) as its primary input. To assure calibration consistency, the PERSIANN algorithm is pretrained using the National Centers for Environmental Prediction (NCEP) stage IV hourly precipitation data. The model parameters are then held steady, while the algorithm runs through the entire historical record of the GridSat-B1 data. To eliminate potential bias, the PERSIANN-CDR is adjusted using monthly GPCP 2.5° data. By doing so, the PERSIANN-CDR can still maintain its high resolution (temporally and spatially), but also remain consistent with GPCP monthly rainfall measurements (Ashouri et al. 2015). Although the PERSIANN-CDR resolution at 0.25° (~750 km^2) is still considerably larger than the size of an average Pacific island, it does offer an advantage in that its spatial resolution is much higher than most other long-term satellite precipitation datasets with at least 30-yr records. While other high-resolution satellite-derived precipitation datasets exist, the PERSIANN-CDR offers the 30-yr record, an advantage that allows for a higher sample of historical ENSO events that can be incorporated into the climatology. Additionally, with more than 30 years of data, the PERSIANN-CDR is of sufficient length to satisfy the World Meteorological Organization (WMO) requirements to be utilized in climatological studies (Burroughs 2003). Due to record length constraints, other high-resolution satellite-derived precipitation datasets are limited in their ability to capture a high sample of historical ENSO events and satisfy the WMO climatology 30-yr requirement. Therefore, the PERSIANN-CDR provides an enhanced opportunity to complement station data in the Pacific Islands by filling the spatial void left between smaller, stationless islands and their larger, station-located counterparts, and do so over a sufficient climatological record.

Global daily PERSIANN-CDR precipitation data were downloaded via ftp protocol from NOAA's NCEI CDR website (www.ncdc.noaa.gov/cdr/operationalcdrs.html). Once downloaded, the global precipitation data were formatted and analyzed using the R software (R Core Team 2013) and ArcGIS (ESRI 2011). Exclusive Economic Zone (EEZ) shape files were used to determine the spatial extent of each island chain within the USAPI. EEZs signify zones where the United States and other marine nations have authority over the natural resources located within those bounds. Six specific EEZs were used encompassing American Samoa, the Republic of the Marshall Islands (RMI), the Federated States of Micronesia (FSM), Guam and the Commonwealth of the Northern Mariana Islands (CNMI), the Republic of Palau, and Hawaii. Monthly precipitation from January 1985 through December 2014 was calculated from the daily estimates and was used to establish monthly, seasonal, and yearly averages.

To better understand the relationship between the in situ rain gauges and the satellite-derived rainfall estimates, a verification analysis was completed using daily precipitation data from the Global Historical Climate Network (Menne et al. 2012). Following the completeness of record standards for use in Pacific Island countries documented by Kruk et al. (2013), 36 high-quality, long-term stations were used in the analysis. A pixel-by-pixel analysis was performed, followed by an investigation of the average of the surrounding eight pixels to document the influence of neighboring pixels on an island's rainfall distribution. The results of the verification study indicated that specific amounts for days or months often varied between the stations and the PERSIANN-CDR. The stations found within the USAPI region that are used in the GPCP algorithm are sparse, potentially explaining some of the disagreement in the sensitivity analysis between the PERSIANN-CDR and station precipitation amounts. A higher-density GPCP in situ observations network would be needed to allow the PERSIANN-CDR to better capture precipitation amounts over such small pieces of land. For example, Miao et al. (2015) found that the largest errors in agreement between PERSIANN-CDR and station data were in areas of sparse rain gauge density, and that the error lessened with increasing density. Regardless, when comparing the ratios of the precipitation amounts between the stations and the PERSIANN-CDR, the results were almost always a close match. Thus, there was high confidence in using the PERSIANN-CDR to accurately represent ENSO-specific rainfall patterns across the USAPI.

The Oceanic Niño Index (ONI) monthly data were obtained from NOAA's CPC. The ONI is a 3-month

Table 1. ENSO phases and years used to make the rainfall atlas wet/dry anomalous maps. The years were classified based on the averaged Oceanic Niño Index values from September-October-November (SON) through January-February-March (JFM).

Mod-Strong La Niña $\text{ONI} \le -1.0$	Weak La Niña $-1.0 < \text{ONI} \le -0.5$	Neutral $-0.5 < \text{ONI} < 0.5$	Weak El Niño $0.5 \le \text{ONI} < 1.0$	Mod-Strong El Niño $\text{ONI} \ge 1.0$
88/89	84/85	85/86	94/95	86/87
98/99	95/96	89/90	04/05	87/88
99/00	00/01	90/91	06/07	91/92
07/08	05/06	92/93		97/98
10/11	08/09	93/94		02/03
11/12	96/97			09/10
	01/02			
	03/04			
	12/13			
	13/14			

running mean value of sea surface temperature (SST) anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W). ONI values were averaged over a period from September-October-November (SON) through January-February-March (JFM) to classify each year in the climatology to a specific ENSO phase. Table 1 provides the breakdown of years that correspond to each ENSO phase. Three-month anomalous wet and dry maps were created using ArcGIS to represent precipitation departure from normal during each specific ENSO phase. Based on this ONI-ENSO breakdown methodology, a range of sample sizes within each ENSO phase would be expected. Over the 30-yr record, ENSO events are somewhat rare, and most years fall within the neutral phase. Therefore, the remaining four phases have relatively small sample sizes. Nonetheless, when comparing these ENSO composites to the average, the resulting anomalous precipitation maps should represent the climatological trends found throughout the region relatively well. This is especially true for the moderate-strong El Niño, moderate-strong La Niña, and weak La Niña composites, each of which has at least five samples. However, with only three samples found in the weak El Niño composite, confidence in the anomalous maps derived from this phase would be lower.

THE ATLAS. The new satellite-derived rainfall atlas contains several different products, including wet/dry anomaly maps, time series figures, and percentage tables. Additionally, 3-month average precipitation maps are included. These maps highlight the spatial variation in precipitation found within and across the USAPI. This spatial variation fluctuates with the seasons, and a steep precipitation gradient is evident in some of the zones, such as in the Federated States of Micronesia and the Republic of the Marshall Islands. The PERSIANN-CDR also performs well at depicting the Inter Tropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ).

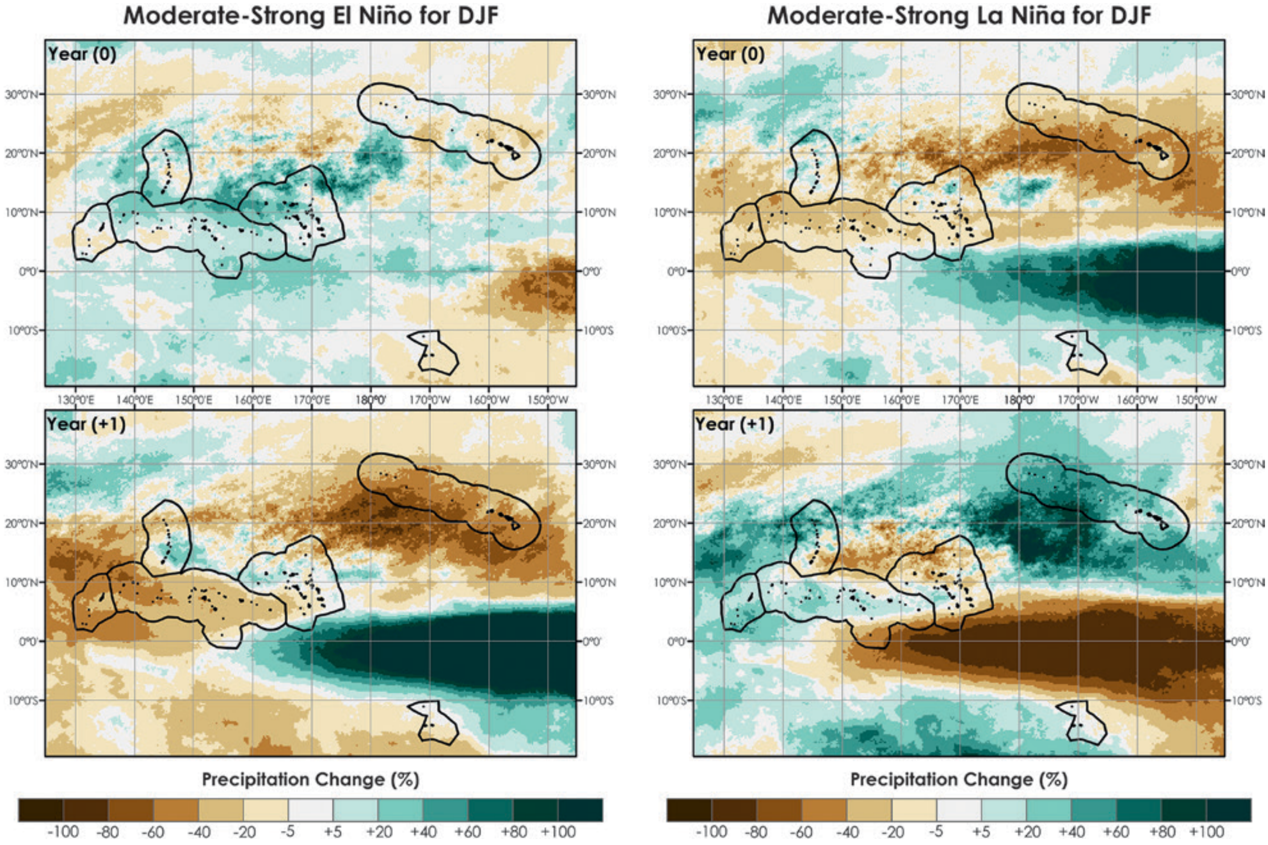

Fig. 1. PERSIANN-CDR comparison of anomalous wet (turquoise) and dry (brown) areas within and across the USAPI EEZs during (left) a moderate-strong El Niño phase and (right) a moderate-strong La Niña phase for the December-January-February (DJF) season. The top panels represent the onset year [Year (0)] of the ENSO phase while the bottom panels represent the year after onset [Year (+1)] of the ENSO phase.

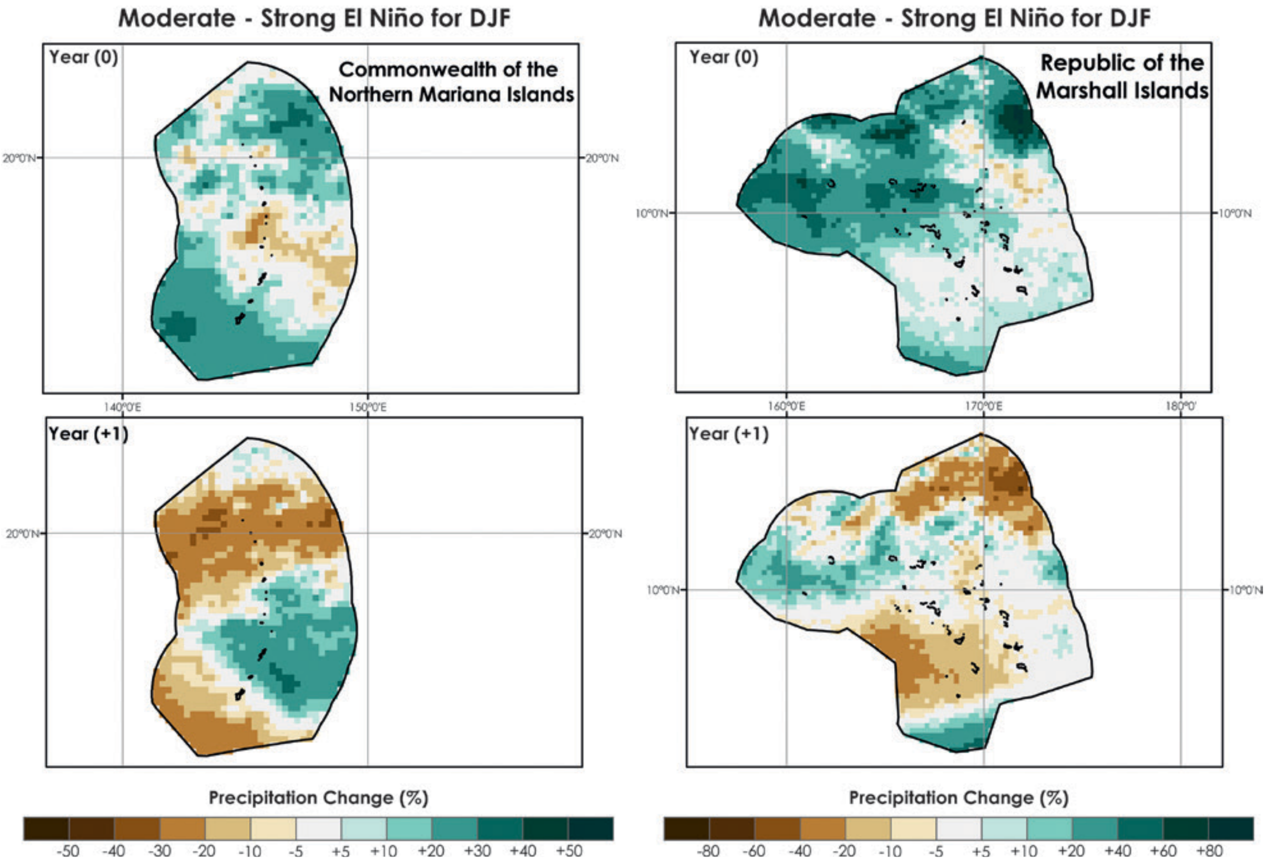

Fig. 2. PERSIANN-CDR comparison of anomalous wet (turquoise) and dry (brown) areas clipped down to USAPI EEZs during a moderate-strong El Niño phase for the December-January-February (DJF) season. The top panels represent the onset year [Year (0)] of a moderate-strong El Niño phase while the bottom panels represent the year after onset [Year (+1)] of a moderate-strong El Niño phase.

The atlas contains maps illustrating the percent departure from average for each 3-month season based on the defined ENSO phases. Since the ONI is a 3-month running average database, the maps were packaged by season and by whether the period was in the year of onset of a particular ENSO phase [Year (0)] or the year following the onset of an ENSO phase [Year (+1)]. This pre- versus post-ENSO phase distinction is important for a few reasons. First, ENSO phases typically last longer than one season, sometimes as long as 6 months to a year. In addition, the ONI is a lagging indicator, such that the impacts from an ENSO phase tend to occur before the ONI indicates the onset of the phase. Second, the variation in precipitation for a given season varies significantly between the year of onset [Year (0)] and the year after [Year (+1)] (Lander and Guard 2003; Lander 2004; Lander and Khosrowpanah 2004). For example, a regional comparison of the December–February (DJF) seasonal precipitation anomalies during a moderate-strong El Niño phase and a moderate-strong La Niña phase are shown in Fig. 1. Within each 2-panel map, the top map shows the average precipitation change for the 3-month season during the onset of the specific ENSO phase [Year (0)], and the bottom map shows the average precipitation change for the 3-month season following the onset of the specific ENSO phase [Year (+1)]. Figure 1 also highlights the expected shift in equatorial convection when comparing the DJF [Year (+1)] anomaly map for a moderate-strong El Niño phase with the DJF [Year (+1)] anomaly map for a moderate-strong La Niña phase. Interestingly, Fig. 1 suggests that the DJF [Year (+1)] moderate-strong El Niño season and the DJF [Year (+1)] moderate-strong La Niña season are almost—but not entirely—symmetrical.

Anomalous wet/dry maps for each ENSO phase were also “clipped” to each of the six EEZs. Figure 2 displays the DJF seasonal anomalies for a moderate-strong El Niño phase for two of the EEZs. The top maps in

Fig. 2 display the average precipitation change for the 3-month season during the onset of a moderate-strong El Niño phase [Year (0)], and the bottom map shows the average precipitation change for the 3-month season following the onset of a moderate-strong El Niño phase [Year (+1)]. The atlas also features time series graphs and percentage tables for stations throughout the USAPI showing precipitation anomalies for each ENSO phase. By providing PERSIANN-CDR-derived percentage tables for a given station location, forecasters can easily compare with station-derived percentages to help aid in assessing their own forecasting confidence (i.e., skill) in requesting water rations on specific islands or issuing drought statements.

The usefulness of this atlas is geared toward helping forecasters in the region with their own forecasting confidence by providing a spatially enhanced climatological reference tool. However, it is not expected that the atlas would be used as a stand-alone forecasting tool. Instead, it is expected that the atlas would be used in a combination with other meteorological tools and knowledge, including local knowledge of, and the seasonal outlook for, the frequency of potentially precipitation-skewing tropical cyclones. It is understood that a potential limitation to using the atlas is that one single tropical cyclone could skew the amount of precipitation in a given month, season, or year, but since the atlas is not meant to be a stand-alone forecasting tool, using it in combination with other meteorological forecasting tools still affords an enhanced opportunity to increase forecaster confidence in seasonal precipitation outlooks. This is especially true considering that in the past, forecasters were using the older, spatially limited station-based atlas as their only climatological reference tool.

The results of this project were shared with science advisors, partners, and end-users to highlight information about the effects of ENSO rainfall in the USAPI, as well as to view the seasonal maps and time series figures made by the NASA DEVELOP Pacific Water Resources team. This atlas can also be used for community outreach and education purposes to help local islanders better understand how the ENSO impacts their livelihoods, water resources, and adaptation/mitigation options. Access to the atlas can be found at this site: ftp://ftp.ncdc.noaa.gov/pub/data/coastal/ENSO_Rainfall_Atlas.pdf.

SUMMARY. In just 10 weeks, the NASA DEVELOP Pacific Water Resources team at NOAA's NCEI successfully downloaded and utilized the publicly available NOAA PERSIANN-CDR to create a new satellite-derived rainfall atlas for the USAPI and Hawaii. From the beginning, the vision for this project was to provide forecasters in the region with a supplementary satellite-derived ENSO precipitation climatology to help fill the in situ spatial void found within the region. The atlas was completed in late July 2015 and was immediately distributed to WSO forecasters throughout the USAPI. Initial feedback was tremendously positive, as many of the forecasters stated that they planned to heavily use the maps during the strong 2015–16 El Niño event. Forecasters were pleased with the greatly enhanced spatial component of the atlas, and alluded to its potential usefulness in making more accurate seasonal precipitation forecasts. Regional constituents plan to reference the atlas in the future to better understand precipitation patterns across their regions and utilize that knowledge to better prepare their communities for the inevitable return of drought and heavy-precipitation events. The success of this project further illustrates the usefulness of remotely sensed precipitation products in areas with sparse station networks. It also demonstrates the usefulness of blending in situ data with satellite data in helping decision makers identify new emergency policies and procedures. Finally, the results of the verification analysis between the PERSIANN-CDR and stations scattered throughout the USAPI solidified the ability of the high-resolution PERSIANN-CDR to be more than adequate for use in long-term precipitation climatology studies.

Interested readers can find more information about the project and watch a short video at *Earthzine*'s website (http://earthzine.org/2015/07/30/mapping-enso-precipitation-for-the-us-affiliated-pacific-islands/).

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FOR FURTHER READING

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