Trends and Variability in Droughts in the Pacific Islands and Northeast Australia

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ABSTRACT

Drought is a recurrent climate feature of the Pacific Islands and northeast Australia with meteorological and socioeconomic impacts documented from early European settlement. In this study, precipitation records for 21 countries and territories in the Pacific for the period 1951 to 2010 have been examined to identify trends in drought occurrence, duration, and magnitude. The strength of the relationships between the main climate drivers in the Pacific—El Niño–Southern Oscillation (ENSO), the interdecadal Pacific oscillation (IPO), and the Pacific decadal oscillation (PDO)—and precipitation has been also examined. Station-scale drought trends are largely positive, but the majority are statistically nonsignificant with the significant trends mainly in the subtropics. Spatially, trend patterns are largely heterogeneous. A significant relationship between the oceanic component of ENSO and precipitation is confirmed for a large part of the Pacific Islands and eastern Australia with a strong lagged relationship in the year after the El Niño onset at locations southwest of the South Pacific convergence zone (SPCZ) and north of the intertropical convergence zone (ITCZ). Similarly, a strong relationship was found with the IPO and PDO at most locations. Drought was found to be longer and more severe southwest of the SPCZ and north of the ITCZ during the positive phases of the IPO and PDO.

1. Introduction

Drought is a recurrent climate feature of the Pacific islands (Giambelluca et al. 1991; d'Aubert and Nunn 2012) and northeast Australia (Tapper and Hurry 1993; Anderson 2014) with meteorological and socioeconomic impacts documented from early European settlement. Paleoclimate research also points to periods of low rainfall over the last millennium with some events of greater magnitude and duration than those observed in the last century (Nunn 2007; Vance et al. 2014). While drought affects agriculture productivity on all of the Pacific islands, it is a particular problem on atolls because they have a fragile freshwater resource base that can be quickly depleted when precipitation drops (Barnett and Campbell 2010). Drought also affects the high islands and often causes serious losses in agricultural productivity (Barnett 2011), decreased electricity production (Sawlani 2015), disease (Singh et al. 2001), and nutritional deficiencies (World Bank 2000).

Recent severe and prolonged droughts have highlighted the Pacific islands' and Australia's vulnerability to prolonged periods of suppressed precipitation and their persistence and intensity have alerted the general

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public and governments to the many socioeconomic problems accompanying water storage and the need for drought mitigation measures. In mid-2011, the South Pacific nation of Tuvalu (population about 10 500) experienced a major water availability crisis. A drought that began in March 2009 on Funafuti atoll became the worst (in both duration and magnitude) in almost a century (Kuleshov et al. 2014). A state of emergency was declared in late September 2011 because of severe water shortages resulting in households on the islands of Funafuti and Nukulaelae being rationed to about 40 liters of fresh water a day. To exacerbate the situation Tuvaluans paid higher costs for imported food as local agricultural crops failed (Manhire 2011). The rainfall deficit caused contamination of the remaining groundwater supplies with the Red Cross declaring the water unsafe for human consumption (Benns 2011).

The drought in Tuvalu was associated with the 2010–12 La Niña, one of the strongest on record (Kuleshov et al. 2014), comparable in strength to the La Niña events of 1917/18, 1955/56 and 1975/76. The Southern Oscillation index (SOI) values in October and December 2010 and again in February and March 2011 were the highest for each month since records began (Australian Bureau of Meteorology 2012).

El Niño–Southern Oscillation (ENSO) is the largest source of climate variability in the Pacific on interannual time scales (McPhaden et al. 2006; Australian Bureau of Meteorology and CSIRO 2011). Its opposite phases, El Niño and La Niña, are accompanied by major changes in tropical sea surface temperatures (SST) and atmospheric pressure, thereby producing shifts and changes in wind patterns, convection (Folland et al. 2002; Chu and Chen 2005; Murphy et al. 2014; Salinger et al. 2014) and air temperatures (Power et al. 1998). There are also climate teleconnections beyond the Pacific region, such as suppressed convection over southern Africa and northern South America and excess convection in southeastern South America, eastern equatorial Africa, and the southern United States (Ropelewski and Halpert 1989; Allan et al. 1996).

Global-scale studies on trends in drought to date (e.g., Spinoni et al. 2014) present little information on the Pacific as the islands have little visibility at a global scale and Pacific data in global datasets are limited. Australia–Pacific studies on a regional scale are nonexistent with most work at national or subnational scales (e.g., Hennessy et al. 2008; Gallant et al. 2013). Results vary depending on the drought indicator and the time scale of drought considered. There is however, broad usage of the WMO/CLIVAR annual consecutive dry days (CDD) index in extreme precipitation studies across Australia and the Pacific. The CDD index is the maximum number of consecutive days in a calendar with precipitation <1 mm. As this typically occurs in the dry season, the index provides limited information on precipitation deficiency in the wetter months of the year when deficiencies are typically of greater importance. Nevertheless, these results are presented in the absence of an alternative.

For the 1950 to 2014 period, negative CDD trends exist across northern Australia with positive trends through the southern half of Queensland (QLD). Trends are smaller and mixed in New South Wales (NSW) and Victoria (Australian Bureau of Meteorology 2015). Similar patterns are presented in the Climate Change 2013 Working Group I report for the 1950–2010 period (IPCC 2013) and in Spinoni et al. (2014) using the 12-month Standardized Precipitation Index (SPI). The SPI is a normalized index representing the probability of occurrence of an observed precipitation amount when compared with the rainfall climatology at a certain geographical location. Negative SPI values represent precipitation deficit, whereas positive SPI values indicate precipitation surplus (McKee et al. 1993, 1995). CDD trends are largely positive and statistically significant for the Hawaiian Islands between 1950 and 2007 on all major islands (Chu et al. 2010). For the western Pacific, subregional CDD trends over 1951–2011 are nonsignificant with only two stations showing significant trends, in the Federated States of Micronesia (FSM) and French Polynesia (McGree et al. 2014).

There is a perception among Pacific island residents that the frequency and magnitude of drought has increased, particularly in the last couple of decades (Australian Bureau of Meteorology and CSIRO 2011). This would be of significant concern as agriculture and water storages on most Pacific islands are particularly sensitive to drought.

Considering the dearth of information on historical trends in drought and the importance of this subject, the objectives of this study are 1) to determine if there has been a statistically significant change in droughts occurrence, duration, and magnitude, and 2) to examine the strength of the relationship between the main climate drivers and Pacific and northeast Australia precipitation on regional and subregional scales.

Our study region covers the Pacific from 127°E to 130°W and 23°N to 32°S, excluding Indonesia and most of western and southern Australia. The paper is organized as follows. Section 2 provides a description of the data used and outlines the research methods. Section 3 presents the results of our research into drought trends and variability in the western Pacific and northeast Australia. A discussion of the results is presented in section 4 and conclusions in section 5.

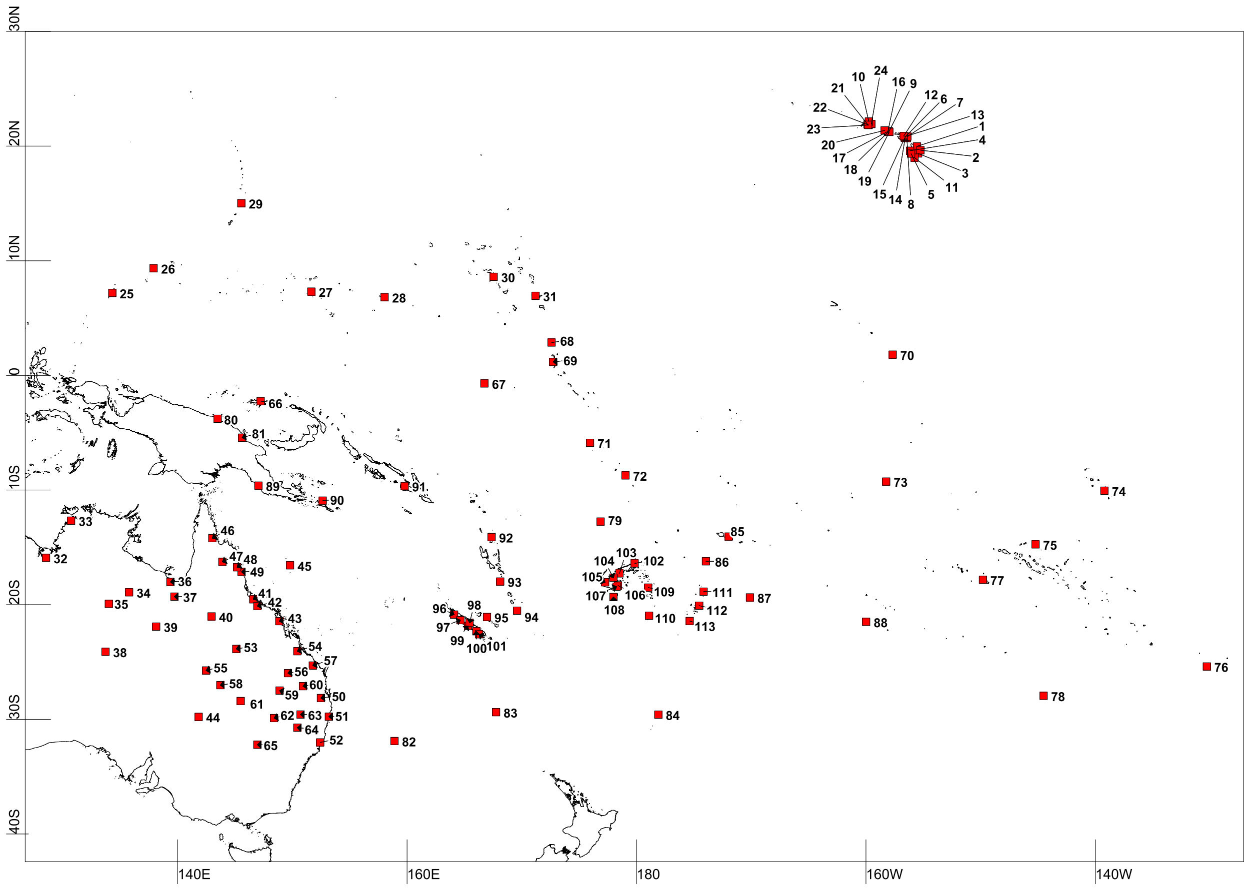

FIG. 1. Map of the Pacific and northeast Australia region showing the study region and station locations. Station numbers are associated with station names in Table A1.

2. Data and indices

a. Precipitation

Data for Australia (36 station records) were obtained from the Bureau of Meteorology climate change and variability pages (http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=site-networks) and are part of the Lavery et al. (1997) high-quality dataset. Data for the Hawaiian Islands (24 station records) were obtained from NOAA climate data online (http://www.ncdc.noaa.gov/cdo-web/search#t=secondTabLink) with station selection largely based on the work of Chen and Chu (2014) and Kruk et al. (2015). The Australian and Hawaiian stations are subsets of much larger precipitation observation networks. While additional Australian and Hawaiian stations could have been included, the authors chose not to overwhelm the limited records from the remaining Pacific islands. The latter comprise 53 station records for the Australian islands in the Pacific, the Cook Islands, the FSM, Fiji, French Polynesia, Kiribati, the Republic of the Marshall Islands (RMI), Nauru, New Caledonia, New Zealand, Niue, Palau, Papua New Guinea, Pitcairn Islands, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu. Details on the quality control and homogenization of these data are provided by McGree et al. (2014). Additional data were obtained for Fiji, French Polynesia, New Caledonia, the Commonwealth of the Northern Mariana Islands (CNMI), and Tuvalu to fill gaps in the historical record. The Pacific islands data were obtained from the respective national meteorological services.

Data for the period 1951 to 2010 are used in this study. While longer time series are available, the selected period provides the best temporal and spatial representation. Data quality requirements include no more than 10% missing data overall and no more than 5% missing data in the first and last decades. Overall, 113 station records are used in this study. The station names are presented in the appendix and locations are shown in Fig. 1.

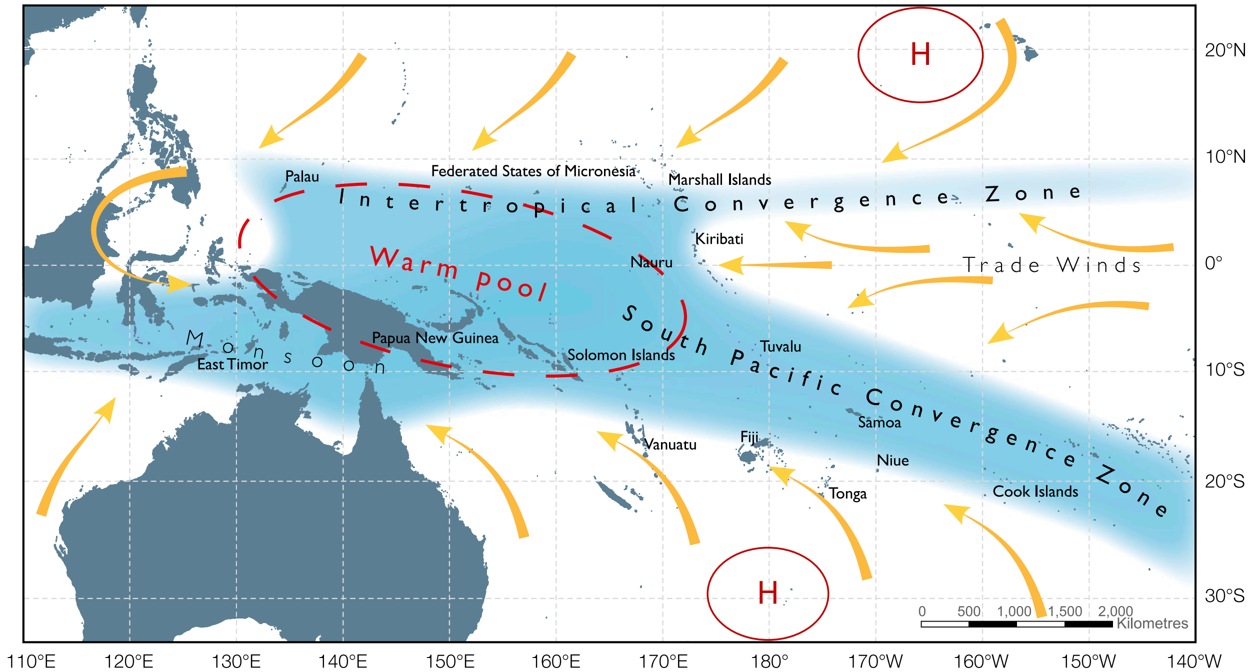

FIG. 2. Schematic of circulation in the Pacific. From Australian Bureau of Meteorology and CSIRO (2011).

b. ENSO index

Monthly Niño-3.4 SST anomalies are used as a representative indicator of ENSO behavior, in line with findings of Barnston et al. (1997). We have used the monthly ERSSTv4 dataset with a base period of 1981–2010. Data were obtained online at http://www.cpc.ncep.noaa.gov/data/indices/ersst4.nino.mth.81-10.ascii.

c. IPO index

The interdecadal Pacific oscillation (IPO) tripole index (TPI) (Henley et al. 2015) is used as the primary method for characterizing North and South Pacific low-frequency variability. We use the monthly HadISST2.1 unfiltered composite of 10 realizations version of the TPI with data from 1870 to 2010 (http://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/). The TPI is based on the difference between the SST anomaly (SSTA) averaged over the central equatorial Pacific and the average of the SSTA in the northwest and southwest Pacific. The regions used to calculate the index are defined as follows: region 1: 25°–45°N, 140°E–145°W; region 2: 10°S–10°N, 170°E–90°W; and region 3: 50°–15°S, 150°E–160°W. The base period is 1971–2000.

Interannual variability of ENSO and the strength of its climate teleconnections are modulated on decadal time scales (Power et al. 1999). The IPO is described as a natural ENSO-like pattern of Pacific SST anomalies that operates at decadal and interdecadal time scales. Changes in the phase of the IPO have been linked to significant changes in climate regimes across the Pacific. In the IPO negative phase, La Niña intensity is more strongly related to rainfall extremes in Australia than during IPO positive phases (Power et al. 1998; Cai and van Rensch 2012). The IPO also influences the SPCZ intensity and location (Folland et al. 2002; Salinger et al. 2001, 2014). The IPO and ENSO have fairly similar (but independent) influences on the SPCZ with the location of the SPCZ convergence maximum shifting southwest during negative IPO and La Niña episodes and northeast during positive IPO and El Niño episodes (Fig. 2). Positive IPO phases characterized the periods 1924–44 and 1977–98. These phases were separated by negative IPO phases from 1945 to 1976 and from 1999 to the present.

d. PDO index

The more widely known Pacific decadal oscillation (PDO) index of Mantua et al. (1997) is used as a secondary method for characterizing low-frequency variability (http://research.jisao.washington.edu/pdo/PDO.latest). This is the North Pacific manifestation of a Pacific-wide pattern encompassed by the IPO (Folland et al. 2002). The PDO is defined as the leading principal component of the monthly SSTA residuals (poleward of 20°N), whereas residuals are understood as the gridpoint anomalies after the global mean

TABLE 1. Classification used for the SPI.

SPI value	Class	Probability (%)
SPI ≥ 2.0	Extremely wet	2.3
1.5 ≤ SPI < 2.0	Severely wet	4.4
1.0 ≤ SPI < 1.5	Seriously wet	9.2
−1.0 < SPI < 1.0	Near normal	68.2
−1.5 < SPI ≤ −1.0	Seriously dry	9.2
−2.0 < SPI ≤ −1.5	Severely dry	4.4
SPI ≤ −2.0	Extremely dry	2.3

monthly SST is removed from every location (Zhang et al. 1997). Positive values of this index describe anomalously cold SSTAs around 45°N. Positive PDO phases prevailed from 1926 to 1946 and 1977 to 1998 and negative phases from 1947 to 1976 and over the decade from 1999.

While the TPI and PDO indices cover nearly identical sets of years, their relationship with precipitation is expected to be different as the PDO index is based on North Pacific SSTAs whereas the TPI encompasses both hemispheres.

e. *Standardized Precipitation Index*

Drought can be defined as meteorological, hydrological, agricultural, and socioeconomic. As a result there are numerous drought index parameters in the literature (Dracup et al. 1980; Wilhite and Glantz 1985; Lloyd-Hughes and Saunders 2002). While a study of drought using evapotranspiration and hydrological data would have been preferred, limited data availability constrains this study to a precipitation-only analysis of drought. Fortunately, indices based solely on precipitation data perform well when compared to more complex hydrological indices (Oladipo 1985).

The SPI ranks in the top positions among drought indicators for robustness and reliability (Heim 2002; Keyantash and Dracup 2002). The SPI is also recommended by the World Meteorological Organization and is likely to be the most frequently used drought indicator worldwide. The SPI is currently employed in more than 70 countries (WMO 2012).

The SPI is a statistical monthly indicator that compares the cumulated precipitation during a period of N months with the long-term accumulated rainfall distribution for the same location and accumulation period. This long-term record is fitted to a probability distribution (e.g., gamma distribution), which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee 1997).

McKee et al. (1993) used the classification system shown in Table 1 to define drought and wet period intensities. A drought occurs when SPI-N is continuously negative and reaches an intensity of −1.0 or less. The event ends when the respective SPI-N becomes positive. The positive sum of the SPI for all the months within a drought or wet period event is defined as the magnitude. Each event, therefore, has a duration defined by its beginning and end, and intensity for each month that the event continues.

The standardization of the SPI also allows the user to compare historical and current droughts between different climatic and geographic locations when assessing how rare, or frequent, a given drought event is.

f. *Defining drought and wet period events, including their frequency, duration, and magnitude*

To allow the comparison of the results from this study with those of Spinoni et al. (2014) we have selected the SPI-12 time scale and 1951 to 2010 study period. Spinoni et al. (2014) found that a medium-term accumulation period is more suitable to depict the various precipitation regimes than shorter (SPI-3, SPI-6) or longer periods (SPI-24, SPI-48), which may be too sensitive to extremes or miss relevant drought events. They also found comparable drought patterns on a spatial basis, both on global and continental scales, using SPI-6, SPI-12, and SPI-24.

Drought frequency (DF), total drought duration (TDD), and total drought magnitude (TDM) have been calculated for each station for 10-yr intervals between 1951 and 2010. TDD and TDM represent the sum of the durations and magnitudes of drought events that occurred in the considered period and they are expressed in the number of months for duration and in a dimensionless severity score for magnitude.

3. Methodology

a. *Linear drought trends*

Linear drought trends (DF, TDD, and TDM) are calculated over the six decades and the statistical significance of each trend is tested using a Student's t test with a confidence level of 95%. While this methodology is limited in that the trends have been computed using only six points, this method is preferred to the alternative, which is to calculate trends using the actual SPI values. For example an annual trend for 1951 to 2010 would involve a regression calculation using the December SPI-12 values for 1951 to 2010 (December SPI-12 covers the period January to December). The authors argue that the latter is a trend in standardized precipitation rather than drought.

b. Drought occurrence differences between individual decades and two 30-yr periods

The Kruskal–Wallis test (Kruskal and Wallis 1952) is a nonparametric alternative to a one-way analysis of variance (ANOVA), where ANOVA is used to determine if there are statistically significant differences between the means of two or more independent (unrelated) groups. The test does not require the data to be normal, but instead uses the rank instead of the actual data values for the analysis. The Kruskal–Wallis test is used to determine if the differences in the DF, TDD, and TDM medians of respective six decades are statistically significant. The null hypothesis is: H_0: the population medians are all equal.

The Mann–Whitney rank-sum test (Mann and Whitney 1947) is used to determine if there is a difference in the medians between the two 30-yr periods (first three decades and latter three decades). Like the Kruskal–Wallis test, the Mann–Whitney test uses the ranks of the sample data, instead of their specific values, to detect statistical significance. The null hypothesis is: H_0: $\eta_1 = \eta_2$, the median of the first population (η_1) equals the median of the second population (η_2) (Lattin et al. 2003).

c. Determining regions with homogeneous precipitation variability

Cluster analysis is widely used in climatology to divide precipitation for a single large region into homogeneous smaller regions of precipitation variability. Annual precipitation is scaled to a mean of zero and standard deviation of one. A hierarchical agglomerative clustering method is used to define clusters of precipitation stations. Each precipitation station is initially considered a separate cluster and, at each successive step, clusters are compared and the clusters with the smallest between cluster dissimilarities (a measure of the ''difference'' between clusters) merged until the desired numbers of clusters is reached. The average linkage method with a Euclidean distance measure was found to be the most desirable in the analysis of Australian district precipitation variability on seasonal time scales by Drosdowsky (1993). Ward's method has also been used to identify the main seasonal precipitation regimes in Australia (Chambers 2001, 2003) and Hawaii (Diaz et al. 2005) but has a tendency to produce clusters of similar numbers of observations, which is undesirable in this study as most of the precipitation stations are southwest of the SPCZ and therefore likely to be part of the same cluster. Salinger et al. (1995) applied cluster analysis to annual Pacific precipitation but did not describe the clustering method employed. A dendrogram delineates the level of association at which stations are grouped. The selection of the optimum number of clusters is complex, with no single criterion available to make an objective decision. A subjective choice of 10% of the total number of stations is suggested by Torok (1996). We have also considered the method of Lattin et al. (2003), which looks for a relatively wide range of distances over which the number of clusters in the solution does not change.

To confirm these groupings, year 0 and year +1 (lagged) annual precipitation and Niño-3.4 SSTA correlation coefficients are calculated and compared. A relationship is deemed to exist if the correlation coefficients are significant at the 95% level. Nonsignificant p values are >0.05.

d. Interdecadal variability

To detect low-frequency variability, a 13-yr running mean is applied to SPI-12 precipitation at a cluster level to remove interannual fluctuations and those on El Niño time scales. This method has been used previously by Power et al. (1999) to examine the strength of the relationships among Australian precipitation, temperature, river flow, and crop yield and the IPO and SOI on decadal time scales.

First, an annual time series of December SPI values over 1951 to 2010 is calculated as these are cumulative standardized totals of precipitation for the 11 preceding months including December. Cluster-scale annual time series are then calculated by averaging the station annual time series. The 13-yr running mean time series are produced from the cluster-scale annual time series. TPI and PDO 13-yr running means are also produced from the TPI and PDO time series. Finally correlation coefficients are calculated using the Spearman rank-order method. A relationship is deemed to exist if the correlation coefficients are significant at the 95% level.

It is possible the duration and magnitude of droughts differ between positive and negative phases of the IPO/PDO. If so, greater attention should be placed on drought during the IPO/PDO phase associated with longer and more intense droughts. We use the Mann–Whitney test to determine if the differences in median duration and magnitude occurrence are statistically significant. Drought magnitude at a station level (for each region) are aggregated over the 1951–77, 1999–2010, and 1978–98 periods and then compared. This also applies to drought duration.

4. Results

a. Trends in drought DF, TDD, and TDM on a station scale

The DF trends over 1951–2010 (Fig. 3a) are generally positive, indicating more frequent drought occurrence in recent decades, but mixed spatially and largely statistically nonsignificant at the 95% level (102 of 113 stations). There is some spatial consistency in parts of the study region; for example, the DF trends are largely positive in the Hawaiian Islands region. Positive DF trends are also mostly present, but smaller in size in the northwest Pacific, equatorial Pacific, and the South Pacific subtropics.

The results are similar for TDD (Fig. 3b) and TDM (Fig. 3c) in that a majority of the trends are positive, spatially mixed, and largely nonsignificant. Subregionally, spatial patterns are similar to that of DF with the addition of generally negative trends in north-central Australia and smaller negative trends in the eastern Australia. Figures 4a and 4b show mean TDD and TDM respectively for the Hawaiian stations. On a state scale the TDD and TDM trends over the six decades are positive but not significant.

Drought patterns in this study are comparable with those of Spinoni et al. (2014) for Australia. Both efforts show a decrease in TDD and TDM in the northern part of the NT and from northwest QLD southeast to NSW and an increase in TDD and TDM along the eastern Australia coast. Our results indicate largely nonsignificant trends for Australia whereas Spinoni et al. (2014) found significant trends for both TDD and TDM in the northern part of the NT. The differences may be due to station selection and/or the gridding technique used by Spinoni et al. (2014).

b. Difference in DF, TDD, and TDM medians

DF, TDD, and TDM medians for 1951–80 and 1981–2010 are presented in Table 2 and then compared using the Mann–Whitney test. The 1981–2010 DF, TDD, and TDM medians are larger than those for 1951–80 with the differences highly significant as shown by the p values.

The above results show that droughts have been more frequent, longer, and more intense since 1981. To determine if the trend is linear, the six decadal medians from 1951 are computed and then compared using the Kruskal–Wallis test. The p values at the bottom of Table 3 point to at least one of the decade medians being greater than the others with the difference significant at the 95% level. In the case of TDD and TDM, the 1991–2000 median is greater than all the other decade medians (as determined by the Mann–Whitney test) with the difference significant at the 95% level. For DF the 1981–90, 1991–2000, and 2001–10 medians are larger than that for 1951–60; also, the 1991–2000 median is greater than the median for 1971–80.

To display the occurrence of drought in the 1990s in comparison to the occurrence of drought in the remaining decades, drought hot spots are calculated and presented in Fig. 5. These are locations where decade TDM is ≥70.3 (the 90th percentile for the entire region and study period). As expected, TDM values for the 1990s dominate (25 of 69 station markers; the next highest decade has 12 markers). Most of the 1990s hot spot locations experience droughts during El Niño events.

c. Homogeneous regions of precipitation variability and association with ENSO

Cluster analysis has only been applied to the station records for the period 1955–2000 as data gaps prevent the use of the full study period. The cluster analysis was applied to the study region subdivided into the North Pacific, South Pacific, and northeast Australia. Allowance has been made for clusters that might traverse these geographic regions by including the closest stations in the neighboring geographic region in the multivariate analyses.

Eleven coherent precipitation regions were found—three in the North Pacific, six in the South Pacific, and two in northeast Australia (Fig. 6). We focus now on results of the cluster analysis and annual precipitation correlations with Niño-3.4 SSTA.

1) Region 1 (Hawaii Wet)

Cluster analysis divides the Hawaiian Islands into two regions defined as R1 (Hawaii Wet) and R2 (Hawaii Dry), respectively. This division is based on high (low) annual precipitation associated with the windward (leeward) sides of the islands.

An examination of the lag-0 relationship between annual precipitation in R1 and Niño-3.4 SSTA (see appendix A) reveals a largely nonsignificant precipitation relationship with ENSO, as only the correlation coefficient between Niño-3.4 SSTA and annual precipitation at Paauilo 221 is statistically significant. When annual precipitation is lagged by a year, there is an inclination toward negative and stronger relationships; however, the p values remain largely nonsignificant. This relationship is also reflected in the SPI-12 drought record for Hawaii Wet, where at least 50% of the droughts events between 1951 and 2010 are associated with El Niño events. Four DF trends in this cluster are positive with a fifth at Pauoa Flats also

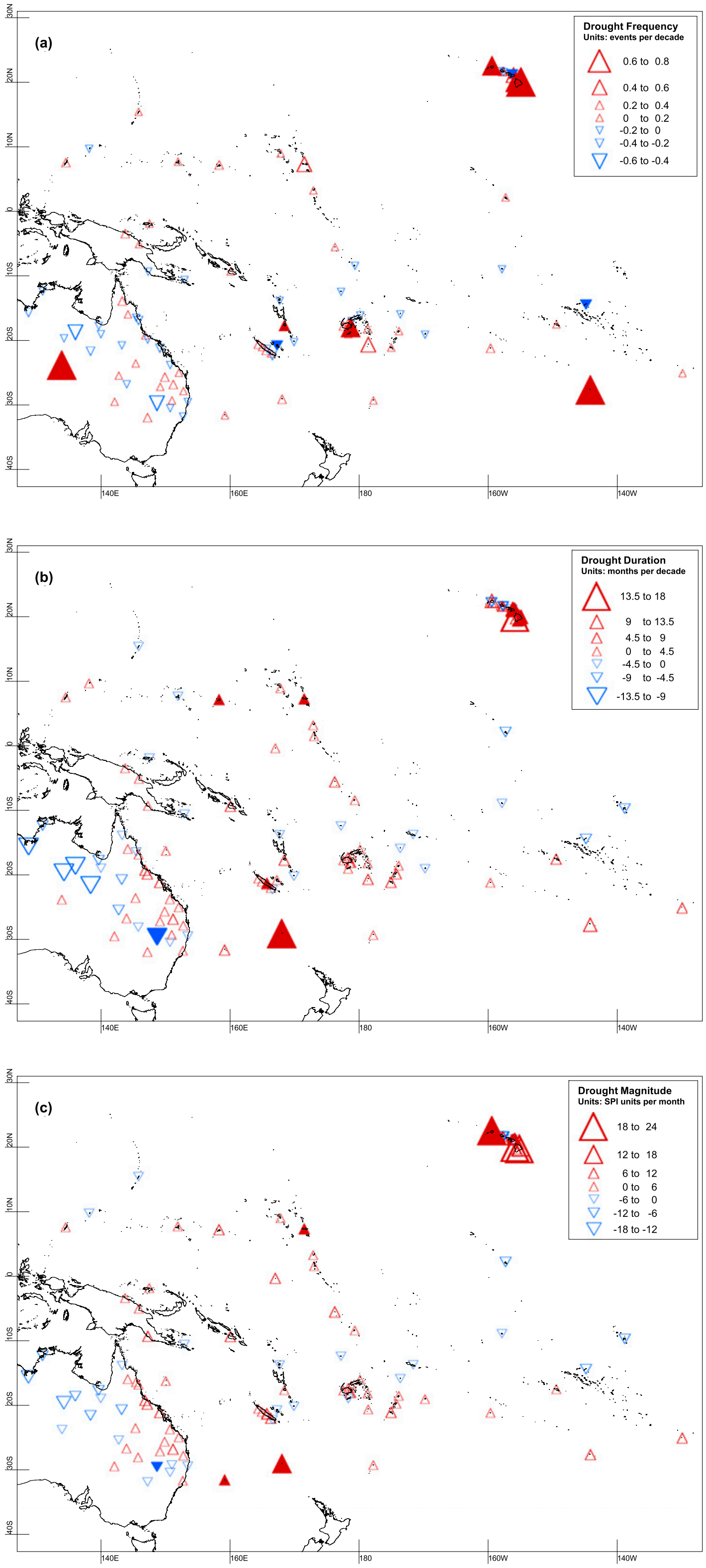

FIG. 3. Linear drought trends the period 1951–2010 (a) drought frequency, (b) total drought duration, and (c) and total drought magnitude. Filled triangles represent trends significant at the 95% level.

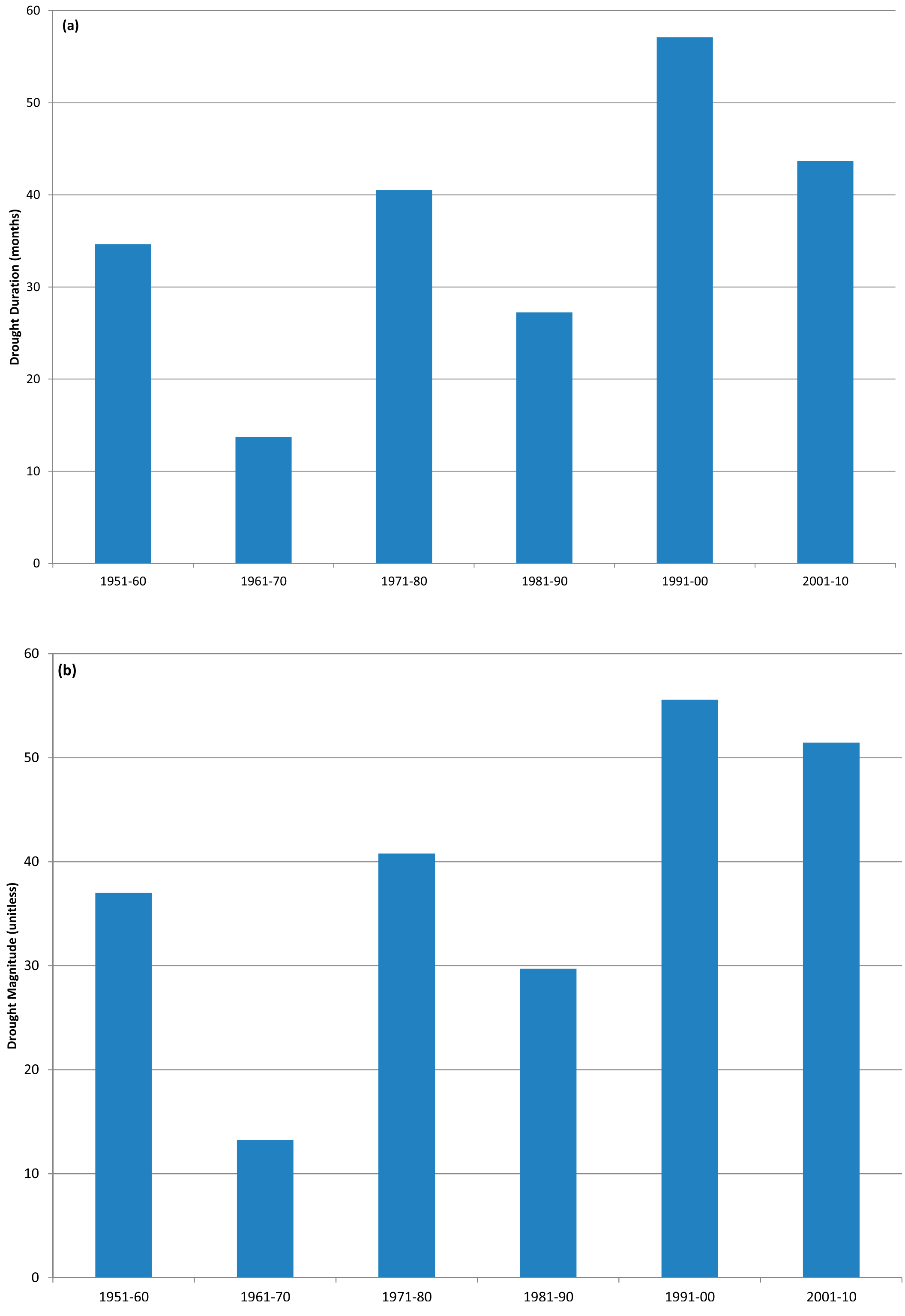

FIG. 4. Mean decadal total drought duration and total drought magnitude 1951–2010 for the selected Hawaiian stations: (a) TDD and (b) TDM.

TABLE 2. Median DF, TDD, and TDM over 1951–80 and 1981–2010.

	1951–80	1981–2010	p value
DF	5	6	0.0022
TDD	92	116	0.0000
TDM	96.9	121.8	0.0000

TABLE 3. Median DF, TDD, and TDM over individual decades between 1951 and 2010.

	DF median (average rank)	TDD median	TDM median
1951–60	2 (298.4)	27	26.9
1961–70	2 (337.3)	30	29.5
1971–80	2 (318.6)	28	29.5
1981–90	2 (357.2)	33	34.0
1991–2000	2 (375.8)	47	54.5
2001–10	2 (349.6)	34	35.0
p value	0.044	0.000	0.000

positive but only significant at the 90% level. For TDD, two on the Big Island and one on Maui show positive trends. The Haleakala Ranger Station on Maui and PH Wainiha on Kaua'i display positive trends but only at the 90% level. For TDM, there is a positive trend at PH Wainiha. Two stations on the Big Island and one on Maui also show positive trends, significant at the 90% level. DF, TDD, and TDM values over 1951–80 and 1981–2010 are presented in Table 4.

2) REGION 2 (HAWAII DRY)

As for Hawaii Wet, the lag-0 relationships between annual precipitation in R2 and Niño-3.4 SSTA are weak and nonsignificant. Lagged relationships produce stronger coefficient values that are statistically significant at five (on Kauai and Oahu) of 14 stations. The only significant drought trend is a DF negative trend at Puunene 396. This is supported by the small change in R2 DF, TDD, and TDM over the first and second 30-yr periods as shown in Table 4.

3) REGION 3 (NORTH ITCZ)

This region is made up of the CNMI, Palau, FSM, and RMI. Cluster analysis suggests this region can be divided into three subregions; Palau and FSM (R3a), CNMI (R3b), and the RMI (R3c). The lag-0 relationships between annual precipitation and Niño-3.4 SSTA are significant at three of four stations in R3a and at Majuro in R3c. The relationship becomes statistically significant at all the R3 stations when annual precipitation is lagged by a year. Most SPI-12 droughts are associated with El Niño. Only the following drought trends were statistically significant: R3a, the Majuro positive TDD and TDM trends, and R3c, the Pohnpei positive TDD trend. This is supported by larger R3 TDD and TDM medians over 1981–2010 when compared with 1951–80.

4) REGION 4 (NORTH AUSTRALIA)

This region includes the Kimberley Research Station in Western Australia (WA), five Northern Territory (NT) stations; Tibooburra Post Office (P.O.) in NSW, Willis Islands, and the QLD stations with the exception of the group between Rockley, south to the Harrisville P.O. near Brisbane and west to the Cunnamulla P.O. Cluster analysis suggests R4 can be divided into two subregions. R4a comprises most of R4 except Willis Island, Palmerville, Mossman South, Coen P.O., and Cairns Aero in northeast QLD, which form R4b. The relationship between the annual precipitation and Niño-3.4 SSTA is largely nonsignificant in the western part of the R4 and largely negatively correlated and significant to the east. Drought trends are largely nonsignificant in this part of Australia with the exception of the positive DF trend at the Alice Springs Airport. At the 90% level only the negative TDD trend at the Windorah P.O. and negative TDM trend at Brunette Downs are significant. Unlike Spinoni et al. (2014) we do not find significant negative TDD and TDM trends in the northern part of the NT; however we do find large negative nonsignificant trends in this region.

5) REGION 5 (EAST AUSTRALIA)

This region includes the QLD stations excluded in R4 and Collarenebri, Wallangra, Nyngan, Barraba P.O., Lorne, and Yamba Pilot Station in New South Wales. Cluster analysis suggests there are two subregions in R5; Lorne, Harrisville P.O., and Yamba Pilot Station in R5a with the remaining R5 QLD and NSW stations in R5b. Annual precipitation is negatively correlated with Niño-3.4 SSTA and statistically significant for most of the R5 stations. Unlike the North Pacific, lagged correlations by and large do not produce stronger relationships with the Niño-3.4 SSTA in Australia. Significant negative TDD and TDM trends are only present at Collarenebri in R5b.

6) REGION 6 (NEW GUINEA ISLANDS)

This cluster is made up of Momote Weather Office (W.O.) only, located on Manus Island north of the New Guinea mainland. The correlation coefficient between

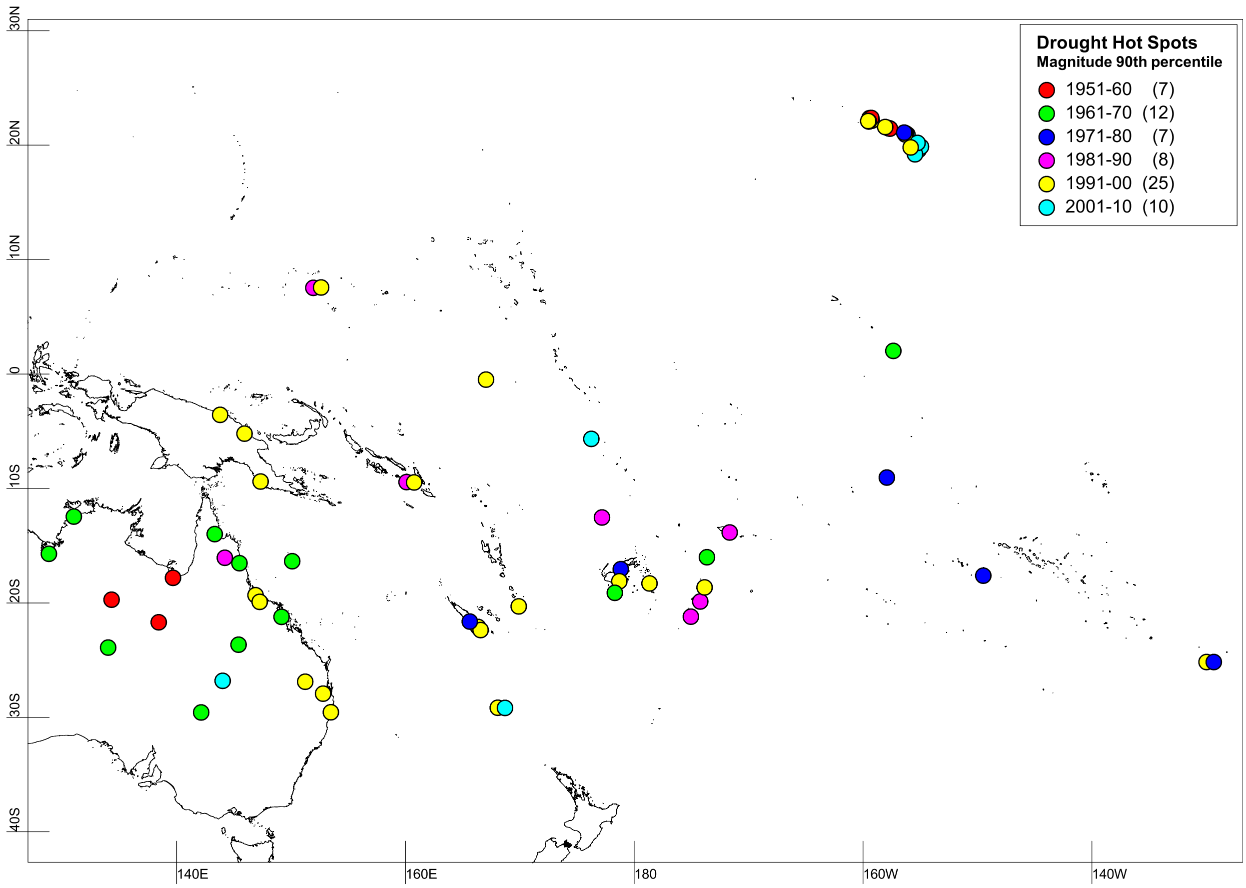

FIG. 5. Drought hot spots on decadal time scales 1951–2010. Numbers in parentheses refer to the number of stations for the respective decade.

Momote annual precipitation and Niño-3.4 SSTA is nonsignificant for both the concurrent and lagged relationships. Equal numbers of droughts for SPI-12 occur during El Niño and La Niña. DF, TDD, and TDM trends are nonsignificant. Kavieng rainfall on New Ireland shows a similar relationship with Niño-3.4 SSTA. Limited data prevents Kavieng from being included in this study.

7) REGION 7 (CENTRAL PACIFIC)

This region includes Nauru, Kiribati, Tuvalu, the northern Cook Islands, and the French Polynesia Tuamotu and Marquesas groups. These islands lie between the ITCZ to the north and SPCZ to the southwest. Annual precipitation is strongly related to the phase of ENSO and most droughts occur during La Niña. Cluster analysis suggests there are two subregions in R7, which are made up of Nauru and Kiribati (R7a) and Tuvalu, the northern Cook Islands, and northeast French Polynesia (R7b). Annual precipitation is strongly positively correlated with Niño-3.4 SSTs in R7a and to a lesser extent in R7b with the exception of the northernmost station in Tuvalu, which has a correlation coefficient more related to R7a. R7b stations have strong significant lagged relationships with the Niño-3.4 SSTA, which is not the case for R7a. With regards to drought trends in this region only the negative DF trend at Takaroa in R7b is statistically significant.

8) REGION 8 (PITCAIRN ISLANDS)

This region is composed solely of the Pitcairn Islands. Pitcairn has little seasonality in precipitation as it lies to the east of the SPCZ. Neither the concurrent nor lagged relationship between annual precipitation and Niño-3.4 SSTA are statistically significant. Two of the four SPI-12 droughts between 1954 and 2010 cover a total period of 122 months. Drought trends are not significant.

9) REGION 9 (SOUTHWEST FRENCH POLYNESIA)

This region is made up of Tahiti (Society Islands) and Rapa (Austral Islands) in French Polynesia at the

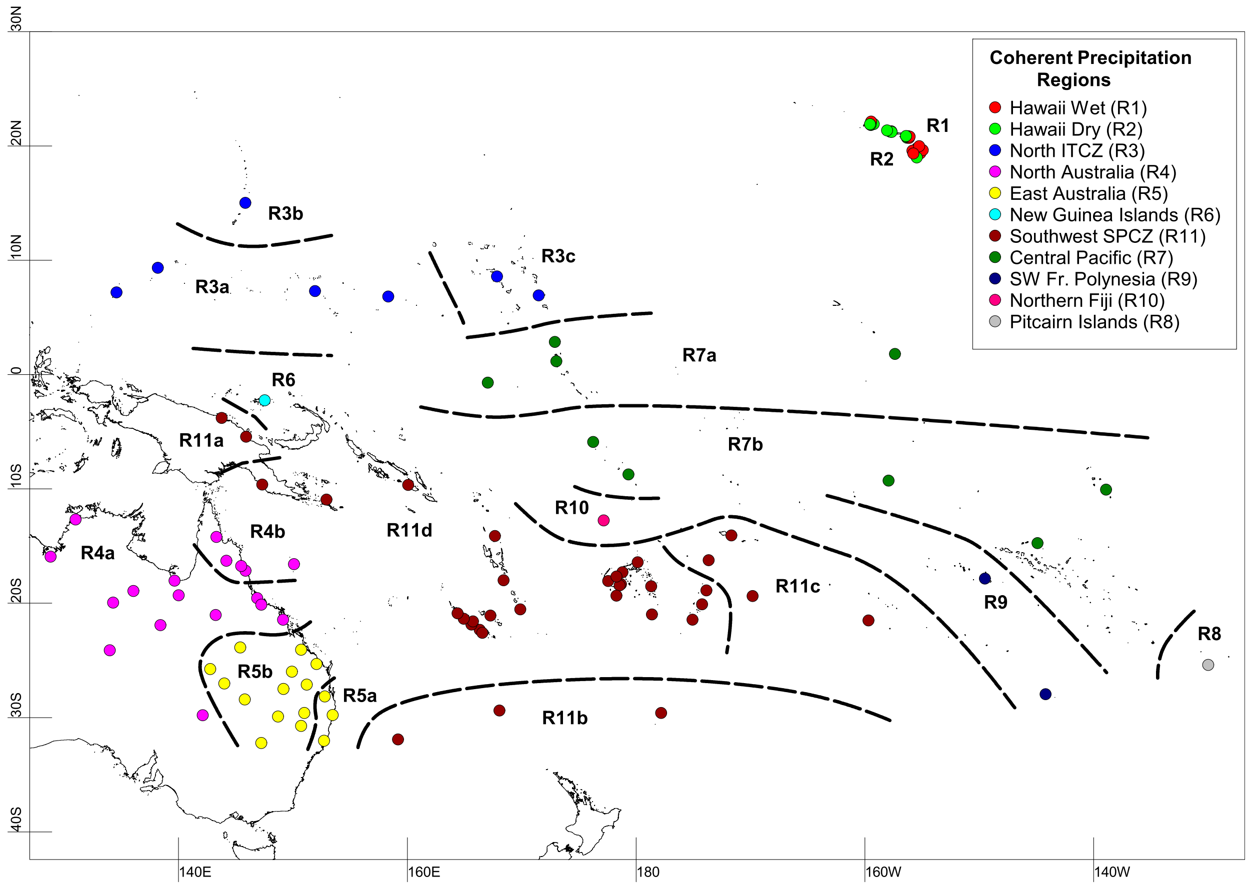

FIG. 6. Pacific Islands and northeast Australian coherent annual precipitation subregions as defined by cluster analysis.

eastern end of the diagonal portion of the SPCZ. Unlike R8, the presence of the SPCZ results in seasonality, but like Pitcairn the lag-0 annual precipitation and Niño-3.4 SSTA relationships are weak. La Niña marginally dominates the drought record for Tahiti and El Niño for Rapa. This is perhaps associated with stronger but nonsignificant lagged correlations with Niño-3.4 SSTA. Only the negative DF trend at Rapa is significant.

10) REGION 10 (NORTHERN FIJI)

This region comprises of Rotuma only, the northernmost Fiji Island, which is located under SPCZ for a large

TABLE 4. Station median DF, TDD, and TDM for 1951–1980 and 1981–2010.

Cluster	DF (No. of events)		TDD (months)		TDM (SPI units)	
	1951–80	1981–10	1951–80	1981–10	1951–80	1981–10
1. Hawaii Wet	5	7	71	153	71.4	152.8
2. Hawaii Dry	5	6	104	115	113.8	116.0
3. North ITCZ	6	7	71	116	68.8	139.1
4. North Australia	6	6	107	106	113.1	109.7
5. East Australia	7	7	107	116	107.3	117.9
6. New Guinea Islands	6	6	100	82	106.3	113.5
7. Central Pacific	5	5	117	89	124.3	116.9
8. Pitcairn	2	2	58	84	95.9	114.1
9. SW Fr. Polynesia	5	8	80	117	88.2	110.8
10. Northern Fiji	8	8	97	102	87.1	115.1
11. South SPCZ	5	7	83	120	88.1	138.8

TABLE 5. Correlation coefficients for TPI/PDO and annual standardized precipitation (columns 2 and 3). Median drought duration and drought magnitude for the TPI/PDO negative (−ve) phases (1951–77, 1999–2010) and TPI/PDO positive (+ve) phase (1978–98; columns 4–7). Correlation coefficients and medians differences statistically significant at the 95% level are presented in italics.

Cluster	TPI	PDO	DD IPO −ve	DD IPO +ve	DM IPO −ve	DM IPO +ve
1	2	3	4	5	6	7
1. Hawaii Wet	*−0.39*	*−0.58*	*15*	*12*	*15.8*	*10.8*
2. Hawaii Dry	−0.04	−0.23	14	16	14.6	14.7
3. North ITCZ	*−0.72*	*−0.81*	*11*	*16*	*12.2*	*21.7*
4. North Australia	*−0.35*	−0.08	14	13	16.9	12.9
5. East Australia	−0.26	−0.08	13	12	13.4	11.9
6. New Guinea Islands	*−0.32*	*−0.30*	13	14	16.5	22.7
7. Central Pacific	*+0.96*	*+0.92*	19	15	21.7	16.5
8. Pitcairn Islands	−0.22	*−0.44*	29	42	47.9	57.0
9. SW Fr. Polynesia	+0.10	−0.15	19	9	16.0	9.2
10. Northern Fiji	−0.22	*−0.37*	9	13	9.2	17.6
11. South SPCZ	*−0.95*	*−0.85*	*11*	*13*	*12.0*	*19.5*

part of the year. Both the lag-0 and lag-1 relationships between Rotuma precipitation and Niño-3.4 SSTA are nonsignificant. The climate of Rotuma is unique as droughts occur during El Niño and La Niña. La Niña results in SPCZ displacement toward Fiji but extreme southwest displacement leads to drought. Drought trends are not statistically significant. Supporting these results are data for Niulakita (not included in this study), the southernmost Tuvalu Island, located about 330 km to the northeast. Niulakita displays similar nonsignificant relationships with Niño-3.4 SSTA.

11) REGION 11 (SOUTHWEST SPCZ)

This region occupies the largest part of the study area: the PNG mainland, Solomon Islands, Vanuatu, New Caledonia, the main islands of Fiji, Tonga, Niue, the southern Cook Islands, and the Australian and New Zealand subtropical islands. With the exception of the stations on the northern coast of Papua New Guinea, the remaining stations lie to the southwest of the SPCZ and are affected by the subtropical high pressure belt. Cluster analysis suggests there are four subregions, which are Madang and Wewak in PNG (R11a); Lord Howe, Norfolk, and Raoul Islands in the subtropics (R11b); northern Tonga, Niue, Samoa, and the southern Cook Islands (R11c); and the remaining stations between southern Papua New Guinea and Tonga (R11d). There are significant lag-0 negative relationships between annual precipitation and Niño-3.4 SSTA at all 34 R11 stations. Stations in R11a, R11b, and R11c have nonsignificant lagged relationships with Niño-3.4 SSTA whereas most stations in R11d do have significant lagged relationships. Most droughts are associated with El Niño in R11.

In R11b, the Norfolk Island TDD and TDM trends are positive and significant. The DF trend is also positive and significant but only at the 90% level. The Lord Howe Island TDM trend is positive. Drought trends are mixed in the R11d. At Nausori Airport in Fiji and Port Vila–Bauerfield Airport in Vanuatu the DF trends are positive. The DF trend is negative at Chepenehe on Lifou Island in New Caledonia. At Houailou P. the TDD trend is positive and the TDM trends at Houailou P. and Kone are significant at the 90% level. Overall for R11, TDD and TDM are notably larger over 1981–2010 when compared with TDD and TDM for 1951–80.

d. *Drought variability on decadal time scales*

There is a negative relationship between 13-yr running average annual standardized precipitation and TPI/PDO in the Hawaii Wet, North ITCZ, North Australia (TPI only), New Guinea Islands, Pitcairn Islands (PDO only), Rotuma (PDO only), and Southwest Pacific regions and a strong positive relationship in the Central Pacific (Table 5). These results show there is decadal-scale variability in annual precipitation at these locations in phase with the IPO/PDO. On a Hawaiian Islands scale the PDO–precipitation relationship is statistically significant. The TPI–East Australia relationship is also significant but only at the 90% level.

Drought duration was longer and drought magnitude larger during the TPI/PDO negative phases in the Hawaii Wet region. Conversely, droughts were longer and more intense in the north ITCZ and southwest SPCZ regions during the TPI/PDO positive phase from 1978 to 1998 (Table 4).

5. Summary of regional findings

In this study we use the Standardized Precipitation Index (SPI-12 time scale) to examine the historical precipitation record for trends in drought frequency, duration, and magnitude over 1951–2010 using 113 station records for 21 countries and territories in western Pacific. This is followed by analyses to determine the strength of the relationship between precipitation and drivers of Pacific climate namely ENSO and the IPO/PDO.

Station-scale trends in drought are largely positive but nonsignificant (>90%) with spatially heterogeneous trends over 1951–2010, implying that there has been little change in meteorological drought occurrence for most of the study region over the last 60 years. Where trends are significant, they are also largely positive and located in the subtropics.

In the Hawaiian region, the positive drought trends complement earlier work that found an increase in CDD across the state over 1950–2007 (Chu et al. 2010). According to Chu and Chen (2005) the drying trends are associated with anomalous surface westerlies to the north of Hawaii, anomalously stronger and deeper sinking motions, and anomalously vertically integrated moisture flux divergence over Hawaii. These together with weakened northeast trade winds since the mid-1970s (Garza et al. 2012) provide unfavorable conditions for convection especially during the winter period. There are also a number of studies that suggest that the width of the tropical belt has changed (Seidel et al. 2008; Lu et al. 2007, 2009). Further, Li et al. (2011) show significant heat flux changes in the Pacific and suggest that the changes are closely linked to global warming forcing. In particular, Fig. 5 of the Li et al. (2011) paper suggests lower latent heat fluxes, particularly post-1990, in a broad region around and northeast of Hawaii, which may be associated with reduced precipitation in the Hawaiian Islands in recent decades (Diaz and Giambelluca 2012).

In the South Pacific subtropics, the significant positive TDD and TDM trends are supported by negative trends in total annual precipitation and annual days with rainfall >1 mm and >10 mm since 1951 (Jovanovic et al. 2012; McGree et al. 2014). Increasing trends in droughts in subtropical southern Australia (CSIRO 2012) and the Altiplano in South America (Morales et al. 2012), have previously been linked to changes in the Hadley circulation. As the Norfolk and Lord Howe Islands are adjacent to southern Australia it is likely that the intensification of the Hadley circulation and poleward shift of the subtropical dry zone are also responsible for the drying trends. The reason for the intensification is the subject of considerable debate, with some studies attributing the change to stratospheric ozone depletion (Min and Son 2013) while others favor increased surface global warming (Nguyen et al. 2015) or a combination of the two (Allen et al. 2014).

An alternative method of examining drought change over time is to compare the DF, TDD, and TDM medians for 1951–80 and 1981–2010. The 1981–2010 DF, TDD, and TDM medians are larger than those for 1951–80 with the differences in the median values highly significant. However, the change is nonlinear as discovered by comparing the six decadal medians since 1951. For all three measures of drought one of the decade medians is greater than the others with the difference being statistically significant. In the case of TDD and TDM, the 1991–2000 median is greater than all the other decade medians. This feature is notable in Fig. 6 which shows drought hot spots (TDM) for the study region. Station markers for the 1991–2000 period are in the majority (~35%). This was a period when a number of very strong El Niño events occurred, most notably the 1982/83 and 1997/98 events. The results of the study to this point suggest ENSO and possibly IPO influence on drought frequency, duration, and magnitude, which leads to the second part of the study where the aim is to investigate the strength of the relationship between precipitation and drivers of Pacific climate, especially in the tropical Pacific.

In the central North Pacific, El Niño events are associated with the upper-tropospheric jet stream extending eastward during the boreal winter. The Hawaiian Islands are located in the right exit region of the jet stream, in an area of upper-level convergence. The expected anomalous sinking motion resulting from upper-level convergence tends to hinder the development of subtropical cyclones, upper-level lows, and the passage of midlatitude frontal systems to the Hawaiian Islands. These features, together with reduced northeasterly trade winds, result in low wet season rainfall (Chu 1995; Chu and Chen 2005; Cao et al. 2007; Garza et al. 2012). In the northwestern tropical Pacific in the vicinity of the ITCZ, El Niño is associated with weakened trade winds (Lander 2004) and the ITCZ displaced on average closer to the equator and more intense within 0°–15°N and 160°E–120°W (Australian Bureau of Meteorology and CSIRO 2011), resulting in droughts in the islands immediately to the north (Fig. 2).

In the southwest Pacific, ENSO has a notable influence on the SPCZ and therefore on precipitation received in the countries nearby (Trenberth 1976; Vincent 1994; Folland et al. 2002; Vincent et al. 2011). Trenberth (1976) described the movement of the SPCZ as north and east during El Niño and south and west during La Niña. Asymmetric orientations of the SPCZ resulted in a near-parallel alignment with the equator (and in large displacement) for the very strong El Niño events of 1982/83 and 1997/98. There is also evidence that meridional Hadley circulation strengthens during El Niño

(Chu and Chen 2005; Lough et al. 2011) resulting in cooler, drier trade winds in the South Pacific.

In the Papua New Guinea and northeast Australian region the west Pacific monsoon (WPM; Fig. 2) is associated with a seasonal reversal of wind direction that brings heavy rainfall to northern Australia, and western tropical Pacific islands. Variations in the timing, position, intensity, longevity, and extent of the monsoon account for much of the rainfall variability in this region. ENSO causes some variability in the WPM. The two most extreme maximum eastern extents of the monsoon domain occurred during the strong El Niño events of 1982/83 and 1997/98 (Australian Bureau of Meteorology and CSIRO 2011). Although Australia is influenced by many climate drivers, El Niño and La Niña have perhaps the strongest influence on interannual rainfall variability. The shift in rainfall away from the western Pacific, associated with El Niño, means that Australian rainfall is usually reduced through winter–spring, particularly across the eastern and northern parts of the continent. The date of the monsoon onset in tropical Australia is generally 2–6 weeks later during El Niño years than in La Niña years. This means that precipitation in the northern tropics is typically well below average during the early part of the wet season for El Niño years (Nicholls 1984; Lo et al. 2007; Timbal and Drosdowsky 2013).

The literature survey demonstrates that precipitation variability is dissimilar across the study region and as such a simple regionally averaged precipitation time series would not be appropriate. In an effort to reduce the number of variables and reduce noise at a station level, multivariate analysis is applied to group the precipitation time series into coherent regions of variability. Eleven coherent precipitation regions of variability were found using cluster analysis: three in the North Pacific, two in northeast Australia, and six in the South Pacific. We confirm the cluster groupings and derive additional information by computing the strength of the ENSO (using Niño-3.4 SSTA) and precipitation relationship using correlation coefficients.

Cluster analysis divides the Hawaiian Islands into two regions based on high (low) annual precipitation largely associated with the windward (leeward) sides of the islands. Our investigation of the strength of the relationship between annual precipitation and Niño-3.4 SSTA finds a nonsignificant relationship at lag-0 across the state but a negative relationship at lag-1 at almost 50% of the stations on the leeward side of the islands and at one of 10 stations on the windward side.

Numerous studies have documented the negative correlation between equatorial Pacific SSTs and rainfall across most of Australia, including QLD (e.g., McBride and Nicholls 1983; Allan 1988; Lough 1991; Murphy and Ribbe 2004). There have also been a number of attempts to group northeastern Australian precipitation into coherent regions of variability (e.g., Drosdowsky 1993). Results vary depending on time period and data selected. Our results show two main clusters with the first covering the northeast WA, the NT, QLD with exception of the stations to the southeast, the northwest portion of NSW, and Willis Island off the coast of QLD. The second cluster covers the remaining portion of QLD and NSW. The annual precipitation relationship with Niño-3.4 SSTA is by and large nonsignificant in the monsoon-dominated portion of northern Australia but largely significant to the east. Unlike the North ITCZ and Southwest SPCZ clusters Niño-3.4 SSTA does not have a lagged relationship with northeast Australia precipitation.

We are only aware of one previous study (Salinger et al. 1995) beyond Australia and Hawaii that groups Pacific island precipitation time series into coherent regions of variability using statistical techniques. There are noteworthy differences between the results of Salinger et al. (1995) and this study. The northern Fiji cluster in this study does not include Samoa and the southern Cook Islands, partly because there is a significant inverse relationship between stations at these locations and Niño-3.4 SSTA whereas there is a weak relationship between the Northern Fiji cluster precipitation and Niño-3.4 SSTA. In Salinger et al. (1995) the Southwest SPCZ region is labeled ''Subtropical region.'' With a larger dataset the subtropical region expands in this study to include the PNG mainland, the Solomon Islands, the Australian Pacific subtropical islands, Samoa, and the southern Cook Islands.

Further, we present a lagged relationship between annual precipitation and Niño-3.4 SSTA for most of the stations between southern PNG and southern Tonga (southwest of the zonal portion of the SPCZ; Folland et al. 2002), which does not include the northern Tonga to southern Cook Islands portion (southwest of the diagonal portion of the SPCZ) of the Southwest SPCZ cluster. Grouping precipitation time series into coherent regions of variability has not been attempted for the north tropical Pacific. We have found a North ITCZ cluster that covers the CNMI, Palau, FSM and the RMI region. El Niño events correspond closely with increased risk of drought in the following year in this Micronesian region, with drought tending to be most extreme during the Northern Hemisphere winter and spring following an El Niño (Keener et al. 2012). We have found lag-0 relationships between annual precipitation and Niño-3.4 SSTA significant at four of six stations in the Palau-FSM and RMI subclusters. This relationship becomes statistically significant at all seven stations in the North ITCZ cluster when precipitation is lagged by a year.

Finally, we determine the strength of the relationship between the precipitation clusters and the IPO/PDO as well as determine whether droughts are longer and/or more severe during a particular phase of the IPO/PDO. The results show that during the IPO/PDO positive (negative) phase the Hawaii Wet, North ITCZ, North Australia (IPO only), New Guinea Islands, Pitcairn Islands (PDO only), Northern Fiji (PDO only), and Southwest SPCZ clusters were ‘‘drier’’ (‘‘wetter’’), with the reverse applying for the Central Pacific cluster. When the Hawaii Wet and Hawaii Dry clusters are merged, the 13-yr running average Hawaiian standardized precipitation and PDO relationship is found to be highly significant ($\rho = -0.369$, $p = 0.010$), in line with previous conclusions on the PDO and Hawaiian precipitation relationship (Mantua et al. 1997; Chu and Chen 2005). The above result for Hawaii Dry suggests that the PDO's influence on Hawaiian precipitation is stronger on the windward side of the islands.

For the North ITCZ and Southwest SPCZ clusters drier periods are associated with longer and more severe droughts. In the central Pacific and where the precipitation clusters and the IPO/PDO relationships were weaker (North Australia, New Guinea Islands, Pitcairn Island, Northern Fiji) there was no significant difference in median drought duration or magnitude. For Australia, this finding correlates with earlier work that found that during the earlier IPO positive phase ENSO and QLD rainfall became uncorrelated. During these years, QLD rainfall became less variable on interannual scales, presumably due to the lack of a large-scale climate driver (Lough 1991). Further, Power et al. (1999) found that the positive IPO phase resulted in a weakening of the ENSO–Australian rainfall teleconnection. Unexpectedly, drought duration and magnitude were found to be greater during Hawaii Wet ‘‘wet’’ phases. However, on a state scale the median differences are not statistically significant. It is possible the longer and more severe droughts in the Hawaii Wet cluster during PDO negative periods are the result of positive trends in drought at a number of stations in this cluster. This is supported by Frazier et al. (2011) and Diaz and Giambelluca (2012), who show some degree of negative correlation between PDO and Hawaiian winter precipitation prior to the late 1970s climate shift in the Pacific. However, since about 1980 the precipitation association with the PDO index has become much weaker or nonexistent.

There is a notable difference between the PDO and IPO (as defined by the TPI) with regard to their relationship with precipitation as shown in Table 5. This is in contrast to the findings of Folland et al. (2002), who found the PDO and IPO to be essentially equivalent in describing Pacific-wide variations in ocean climate. The relationship between the PDO and North Pacific precipitation (Hawaii Wet, Hawaii Dry, and North ITCZ clusters) is stronger than that of the TPI and Hawaiian precipitation whereas the reverse applies in the South Pacific (North Australia, East Australia, and Southwest SPCZ clusters). In the near-equatorial Pacific the relationships between the decadal indices and precipitation are nearly equivalent (Central Pacific and New Guinea Islands cluster). The weaker (as compared with the PDO) Northern Fiji and Pitcairn Islands cluster relationships with TPI are unexpected. This may be associated with weak to nonexistent relationships between precipitation and ENSO at these locations.

6. Conclusions

In response to the general perception among Pacific Islanders that the frequency of drought has increased, particularly in the last couple of decades, the results of this study show from a meteorological perspective drought frequency, duration, and magnitude for the Pacific islands and northeast Australia were greater during 1981–2010 than during 1951–80. The increase was not linear and was in a large part due to low-frequency variability, namely the positive phase of the IPO from 1977 to 1998. The switch to the negative phase of the IPO from 1999 resulted in a decade from 2000 with reduced drought activity. The subtropics of both hemispheres are notable exceptions. Here changes in the Hadley circulation resulted in a number of locations displaying positive drought trends that are statistically significant.

Overall, the IPO and ENSO were the dominant drivers of drought occurrence over the period 1951–2010 with the exception of the Pacific Ocean subtropics in recent decades.

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APPENDIX

Precipitation Observation Sites with Assigned Subclusters and Relationship with ENSO

In Table A1, the names and locations of the study sites are shown in columns 2-4. Homogeneous regions of precipitation variability are presented in column 5 and the strength of the relationship between annual Niño-3.4 SSTA and annual precipitation (lag-0) and Niño-3.4 SSTA and annual precipitation lagged by a year (lag-1) are presented in columns 6-7.

TABLE A1. Spearman rank correlation coefficients demonstrating the strength of the relationship between annual Niño-3.4 SSTA and annual precipitation (lag-0) and Niño-3.4 SSTA and annual precipitation lagged by a year (lag-1) on a station scale. Values in italics show correlation coefficients significant at the 95% level.

No.	Name	Latitude	Longitude	Cluster	Lag-0	Lag-1
1	Paauilo 221	20.1°N	155.4°W	1	*0.36*	0.13
2	Hilo Int. Airport	19.7°N	155.1°W	1	0.11	−0.23
3	Hawaii Vol. Nat. Park. HQ.	19.4°N	155.3°W	1	−0.13	*−0.35*
4	Lanihau 68.2	19.7°N	156.0°W	1	−0.16	*−0.48*
5	Honaunau 27	19.4°N	155.9°W	1	−0.07	−0.19
6	Hamakuapoko 485	20.9°N	156.4°W	1	0.17	−0.08
7	Kailua 446	20.9°N	156.2°W	1	−0.06	−0.19
8	Haleakala Ranger Stat. 338	20.8°N	156.3°W	1	0.10	−0.23
9	Pauoa Flats 784	21.4°N	157.8°W	1	0.10	−0.09
10	PH Wainiha 1115	22.2°N	159.6°W	1	−0.02	−0.21
11	Naalehu 14	19.1°N	155.6°W	2	−0.14	−0.15
12	Waihee Valley 482	20.9°N	156.5°W	2	0.15	−0.18
13	Puunene 396	20.9°N	156.5°W	2	0.12	−0.20
14	Keahua 410	20.9°N	156.4°W	2	0.28	−0.08
15	Kihei 311	20.8°N	156.4°W	2	0.05	−0.24
16	Moanalua 770	21.4°N	157.9°W	2	0.10	*−0.30*
17	Honolulu Int. Airport	21.3°N	157.9°W	2	0.05	*−0.34*
18	Punchbowl Crater 709	21.3°N	157.9°W	2	0.04	0.07
19	Wilhelmina Rise 721	21.3°N	157.8°W	2	0.28	−0.16
20	Waianae 798	21.4°N	158.2°W	2	−0.08	*−0.31*
21	Waimea 947	22.0°N	159.7°W	2	0.05	*−0.44*
22	Makaweli 945	21.9°N	159.6°W	2	0.03	*−0.40*
23	Eleele 927	21.9°N	159.6°W	2	−0.07	−0.27
24	Lihue WSO Airport	22.0°N	159.4°W	2	−0.02	−0.28
25	Koror	7.3°N	134.5°E	3a	*−0.32*	*−0.34*
26	Yap	9.5°N	138.1°E	3a	*−0.48*	*−0.50*
27	Chuuk	7.5°N	151.8°E	3a	*−0.40*	*−0.38*
28	Pohnpei	7.0°N	158.2°E	3a	−0.17	*−0.54*
29	Saipan Int. Airport	15.1°N	145.7°E	3b	−0.15	*−0.35*
30	Kwajalein	8.7°N	167.7°E	3c	−0.04	*−0.37*
31	Majuro	7.1°N	171.4°E	3c	*−0.29*	*−0.48*
32	Kimberley Res. Stat.	15.7°S	128.7°E	4a	−0.21	−0.07
33	Darwin Apt.	12.4°S	130.9°E	4a	−0.11	0.01
34	Brunette Downs	18.6°S	136.0°E	4a	*−0.36*	*−0.27*
35	Tennant Creek Airport	19.6°S	134.2°E	4a	−0.05	−0.20
36	Burketown P.O.	17.7°S	139.6°E	4a	*−0.37*	−0.10
37	Lorraine	19.0°S	139.9°E	4a	−0.20	−0.22
38	Alice Springs Airport	23.8°S	133.9°E	4a	−0.19	−0.15
39	Urandangi	21.6°S	138.3°E	4a	−0.26	−0.24
40	Richmond P.O.	20.7°S	143.1°E	4a	*−0.46*	*−0.30*
41	Townsville Aero	19.3°S	146.8°E	4a	*−0.31*	*−0.31*
42	Woodhouse	19.8°S	147.1°E	4a	*−0.29*	*−0.33*
43	Pleystowe Sugar Mill	21.1°S	149.0°E	4a	*−0.39*	−0.28
44	Tibooburra P.O.	29.4°S	142.0°E	4a	*−0.39*	−0.17
45	Willis Is.	16.3°S	150.0°E	4b	−0.17	−0.12
46	Coen P.O.	13.9°S	143.2°E	4b	*−0.35*	−0.08
47	Palmerville	16.0°S	144.1°E	4b	*−0.45*	−0.18

TABLE A1. (*Continued*)

No.	Name	Latitude	Longitude	Cluster	Lag-0	Lag-1
48	Mossman South	16.5°S	145.4°E	4b	−0.25	−0.18
49	Cairns Aero.	16.9°S	145.8°E	4b	*−0.29*	−0.27
50	Harrisville P.O.	27.8°S	152.7°E	5a	*−0.48*	−0.02
51	Yamba Pilot Stat.	29.4°S	153.4°E	5a	−0.26	−0.01
52	Lorne (Lorne Rd.)	31.7°S	152.6°E	5a	*−0.41*	−0.20
53	Barcaldine P.O.	23.6°S	145.3°E	5b	*−0.34*	−0.13
54	Rockley	23.8°S	150.6°E	5b	*−0.45*	−0.13
55	Windorah P.O.	25.4°S	142.7°E	5b	*−0.33*	−0.21
56	Taroom P.O.	25.7°S	149.8°E	5b	*−0.38*	0.16
57	Gin Gin P.O.	25.0°S	152.0°E	5b	*−0.45*	0.05
58	Whynot	26.7°S	143.9°E	5b	*−0.54*	−0.28
59	Surat	27.2°S	149.1°E	5b	*−0.43*	0.25
60	Jandowae P.O.	26.8°S	151.1°E	5b	*−0.32*	0.13
61	Cunnamulla P.O.	28.1°S	145.7°E	5b	*−0.42*	−0.03
62	Collarenebri	29.6°S	148.6°E	5b	*−0.32*	0.06
63	Wallangra Stat.	29.2°S	150.9°E	5b	*−0.33*	0.20
64	Barraba P.O.	30.4°S	150.6°E	5b	*−0.40*	0.08
65	Nyngan	31.9°S	147.1°E	5b	*−0.41*	0.06
66	Momote W.O.	2.1°S	147.4°E	6	0.01	0.19
67	Nauru Arc-2	0.5°S	166.9°E	7a	*0.78*	−0.06
68	Butaritari	3.0°N	172.8°E	7a	*0.68*	−0.04
69	Tarawa	1.4°N	172.9°E	7a	*0.82*	0.01
70	Kiritimati	2.0°N	157.5°W	7a	*0.70*	0.07
71	Nanumea	5.7°S	176.1°E	7b	*0.71*	*0.52*
72	Funafuti	8.5°S	179.2°E	7b	*0.38*	*0.58*
73	Penrhyn	9.0°S	158.1°W	7b	*0.53*	*0.60*
74	Atuona	9.8°S	139.0°W	7b	*0.33*	*0.49*
75	Takaroa	14.5°S	145.0°W	7b	*0.43*	*0.41*
76	Pitcairn	25.1°S	130.1°W	8	0.07	−0.04
77	Tahitii-Faaa	17.6°S	149.6°W	9	−0.05	0.12
78	Rapa	27.6°S	144.3°W	9	−0.07	−0.11
79	Rotuma	12.5°S	177.1°E	10	0.09	0.10
80	Wewak W.O.	3.6°S	143.7°E	11a	*−0.64*	0.05
81	Madang W.O.	5.2°S	145.8°E	11a	*−0.59*	−0.11
82	Lord Howe Is. Aero	31.5°S	159.1°E	11b	*−0.42*	0.10
83	Norfolk Is. Aero	29°S	167.9°E	11b	*−0.52*	0.18
84	Raoul Is.	29.3°S	177.9°W	11b	*−0.57*	−0.12
85	Apia	13.8°S	171.8°W	11c	*−0.50*	−0.09
86	Keppel	16.0°S	173.8°W	11c	*−0.31*	−0.01
87	Hanan Airport	19.1°S	169.9°W	11c	*−0.33*	−0.16
88	Rarotonga	21.2°S	159.8°W	11c	*−0.60*	−0.02
89	Port Moresby	9.4°S	147.2°E	11d	*−0.54*	*−0.37*
90	Misima W.O.	10.7°S	152.8°E	11d	*−0.61*	*−0.43*
91	Honiara	9.4°S	160.0°E	11d	*−0.29*	−0.26
92	Sola (Vanua Lava)	13.9°S	167.6°E	11d	*−0.42*	*−0.36*
93	Bauerfield (Efate)	17.7°S	168.3°E	11d	*−0.62*	*−0.33*
94	Aneityum	20.2°S	169.8°E	11d	*−0.62*	*−0.37*
95	Chepenehe	20.8°S	167.2°E	11d	*−0.54*	−0.15
96	Koumac	20.6°S	164.3°E	11d	*−0.44*	*−0.39*
97	Kone	21.1°S	164.8°E	11d	*−0.61*	*−0.31*
98	Houailou P.	21.3°S	165.6°E	11d	*−0.45*	−0.15
99	Bourail	21.6°S	165.5°E	11d	*−0.54*	−0.25
100	La Tontouta	22.0°S	166.2°E	11d	*−0.62*	−0.25
101	Noumea	22.3°S	166.5°E	11d	*−0.46*	*−0.35*
102	Udu Point	16.1°S	180.0	11d	*−0.52*	*−0.43*
103	Nabouwalu	17.0°S	178.7°E	11d	*−0.63*	*−0.54*
104	Penang Mill	17.4°S	178.2°E	11d	*−0.56*	*−0.51*
105	Nadi Airport	17.8°S	177.5°E	11d	*−0.59*	*−0.43*

TABLE A1. (*Continued*)

No.	Name	Latitude	Longitude	Cluster	Lag-0	Lag-1
106	Nausori Airport	18.1°S	178.6°E	11d	*−0.48*	−0.23
107	Suva	18.2°S	178.5°E	11d	*−0.41*	*−0.39*
108	Vunisea	19.1°S	178.2°E	11d	*−0.59*	*−0.36*
109	Lakeba	18.2°S	178.8°W	11d	*−0.48*	*−0.60*
110	Ono-i-Lau	20.7°S	178.7°W	11d	*−0.52*	*−0.45*
111	Lupepau'u	18.6°S	174.0°W	11d	*−0.55*	*−0.39*
112	Haapai	19.8°S	174.4°W	11d	*−0.46*	*−0.53*
113	Nuku'alofa	21.1°S	175.2°W	11d	*−0.50*	*−0.46*

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