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1 **Trends and variability in droughts in the Pacific Islands and**
2 **northeast Australia**

3

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PRELIMINARY ACCEPTED VERSION

ABSTRACT

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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 relationship between the main climate drivers in the Pacific – El Niño-Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO) and precipitation has been also examined. Station scale drought trends are largely positive but the majority are statistically non-significant 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 East 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 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 phase of the IPO and PDO.

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1. Introduction

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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 socio-economic impacts documented from

43 early European settlement. Paleoclimate research also points to periods of low
44 rainfall over the last millennium with some events of greater magnitude and duration
45 than those observed in the last century (Nunn 2007; Vance et al. 2014). While
46 drought affects agriculture productivity on all of the Pacific Islands, it is a particular
47 problem on atolls because they have a fragile freshwater resource base which can
48 be quickly depleted when precipitation drops (Barnett and Campbell 2010). Drought
49 also affects the high islands and often causes serious losses in agricultural
50 productivity (Barnett 2011), decreased electricity production (Sawhani 2015), disease
51 (Singh et al. 2001) and nutritional deficiencies (World-Bank 2000).

52 Recent severe and prolonged droughts have highlighted the Pacific Islands' and
53 Australia's vulnerability to prolonged periods of suppressed precipitation and their
54 persistence and intensity have alerted the general public and governments to the
55 many socio-economic problems accompanying water storage and the need for
56 drought mitigation measures. In mid-2011, the South Pacific nation of Tuvalu
57 (population about 10,500) experienced a major water availability crisis. A drought
58 that began in March 2009 on Funafuti atoll became the worst (both duration and
59 magnitude) in almost a century (Kuleshov et al. 2014). A state of emergency was
60 declared in late September 2011 due to severe water shortages resulting in
61 households on the islands of Funafuti and Nukulaelae rationed to about 40L of fresh-
62 water a day. To exacerbate the situation Tuvaluans paid higher costs for imported
63 food as local agricultural crops failed (Manhire 2011). The rainfall deficit caused
64 contamination of the remaining ground water supplies with the Red Cross declaring
65 the water unsafe for human consumption (Benns 2011).

66 The drought in Tuvalu was associated with the 2010–12 La Niña, one of the
67 strongest on record (Kuleshov et al. 2014), comparable in strength to the La Niña

68 events of 1917–18, 1955–56 and 1975–76. The Southern Oscillation Index (SOI)
69 values in October and December 2010, and February and March 2011, were the
70 highest for each month since records began (Australian Bureau of Meteorology
71 2012).

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

83 Global-scale studies on trends in drought to date e.g. Spinoni et al. (2014)
84 present little information on the Pacific as the islands have little visibility at a global
85 scale and Pacific data in global datasets are limited. Australia-Pacific studies on a
86 regional scale are non-existent with most work at national or subnational scales e.g.
87 Hennessy et al. (2008) and Gallant et al. (2013). Results vary depending on the
88 drought indicator and the time-scale of drought considered. There is however, broad
89 usage of the WMO/CLIVAR annual Consecutive Dry Days (CDD) index in extreme
90 precipitation studies across Australia and the Pacific. The CDD index is the
91 maximum number of consecutive days in a calendar with precipitation < 1 mm. As
92 this typically occurs in the dry season, the index provides limited information on

93 precipitation deficiency in the wetter months of the year when deficiencies are
94 typically of greater importance. Nevertheless, these results are presented in the
95 absence of an alternative.

96 For the 1950 to 2014 period, negative CDD trends exist across northern Australia
97 with positive trends through the southern half of Queensland (QLD). Trends are
98 smaller and mixed in New South Wales (NSW) and Victoria (Australian Bureau of
99 Meteorology 2015). Similar patterns are presented in the Climate Change 2013
100 Working Group I report for the 1950-2010 period (IPCC 2013) and in Spinoni et al.
101 (2014) using the 12-month Standardised Precipitation Index (SPI). The SPI is a
102 normalized index representing the probability of occurrence of an observed
103 precipitation amount when compared with the rainfall climatology at a certain
104 geographical location. Negative SPI values represent precipitation deficit, whereas
105 positive SPI values indicate precipitation surplus (McKee et al. 1993, 1995). CDD
106 trends are largely positive and statistically significant for the Hawaiian Islands
107 between 1950 and 2007 on all major islands (Chu et al. 2010). For the western
108 Pacific, sub-regional CDD trends over 1951-2011 are non-significant with only two
109 stations showing significant trends in the Federated States of Micronesia (FSM) and
110 French Polynesia (McGree et al. 2014).

111 There is perception amongst Pacific Island residents that the frequency and
112 magnitude of drought has increased, particularly in the last couple of decades
113 (Australian Bureau of Meteorology and CSIRO 2011). This would be of significant
114 concern as agriculture and water storages on most Pacific Islands are particularly
115 sensitive to drought.

116 Considering the dearth of information on historical trends in drought and the
117 importance of this subject, the objectives of this study are (i) to determine if there has

118 been a statistically significant change in droughts occurrence, duration and
119 magnitude, and (ii) examine the strength of the relationship between the main
120 climate drivers and Pacific and northeast Australia precipitation on regional/sub-
121 regional scales.

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

128

129 **2. Data and Indices**

130

131 *a. Precipitation*

132 Data for Australia (36 station records) were obtained from the Bureau of
133 Meteorology Climate Change and Variability pages
134 [http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=site-](http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=site-networks)
135 [networks](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
136 Hawaiian Islands (24 station records) were obtained from NOAA Climate Data
137 Online <http://www.ncdc.noaa.gov/cdo-web/search#t=secondTabLink> with station
138 selection largely based on the work of Chen and Chu (2014) and Kruk et al. (2015).
139 The Australian and Hawaiian stations are subsets of much larger precipitation
140 observation networks. While additional Australian and Hawaiian stations could have
141 been included, the authors chose not to overwhelm the limited records from the
142 remaining Pacific Islands. The latter is comprised of 53 station records for the

143 Australian islands in the Pacific, Cook Islands, FSM, Fiji, French Polynesia, Kiribati,
144 Republic of the Marshall Islands (RMI), Nauru, New Caledonia, New Zealand, Niue,
145 Palau, Papua New Guinea, Pitcairn Islands, Samoa, Solomon Islands, Tonga,
146 Tuvalu and Vanuatu. Details on the quality control and homogenisation of these data
147 are provided by McGree et al. (2014). Additional data were obtained for Fiji, French
148 Polynesia, New Caledonia, Commonwealth of the Northern Mariana Islands (CNMI)
149 and Tuvalu to fill gaps in the historical record. The Pacific Islands data has been
150 obtained from the respective national meteorological services.

151 Data for the period 1951 to 2010 are used in this study. While longer time-series
152 are available, the selected period provides the best temporal and spatial
153 representation. Data quality requirements include no more than 10% missing data
154 overall and no more than 5% missing data in the first and last decades. Overall, 113
155 station records are used in this study. The station names are presented in Appendix
156 1 and locations in Fig.1.

157

158 *b. ENSO Index*

159 Monthly NINO3.4 SST anomalies are used as a representative indicator of
160 ENSO behaviour, in line with findings of Barnston et al. (1997). We have used the
161 monthly ERSSTv4 dataset with a base period of 1981-2010. Data were obtained
162 from <http://www.cpc.ncep.noaa.gov/data/indices/ersst4.nino.mth.81-10.ascii>

163

164 *c. IPO Index*

165 The Tripole Index (TPI) for the Interdecadal Pacific Oscillation (IPO) (Henley et
166 al. 2015) is used as the primary method for characterising North Pacific and South

167 Pacific low frequency variability. We use the monthly HadISST2.1 unfiltered,
168 composite of 10 realisations version of the TPI with data from 1870 to 2010
169 (<http://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/>). The TPI is based on the
170 difference between the SST Anomaly (SSTA) averaged over the central equatorial
171 Pacific and the average of the SSTA in the Northwest and Southwest Pacific. The
172 regions used to calculate the index are: Region 1: 25°N–45°N, 140°E–145°W;
173 Region 2: 10°S–10°N, 170°E–90°W; Region 3: 50°S–15°S, 150°E–160°W. The base
174 period is 1971-2000.

175 **Interannual variability of ENSO and the strength of its climate teleconnections** are
176 modulated on decadal timescales (Power et al. 1999). The IPO is described as a
177 natural ENSO-like pattern of Pacific SST anomalies that operates at decadal and
178 interdecadal time scales. Changes in the phase of the IPO have been linked to
179 significant changes in climate regimes across the Pacific. In the IPO negative phase,
180 La Niña intensity is more strongly related to rainfall extremes in Australia than during
181 IPO positive phases (Power et al. 1998; Cai and van Rensch 2012). The IPO also
182 influences the SPCZ intensity and location (Folland et al. 2002; Salinger et al. 2001,
183 2014). The IPO and ENSO have fairly similar (but independent) influences on the
184 SPCZ with the location of the SPCZ convergence maximum shifting southwest
185 during negative IPO and La Niña episodes and northeast during positive IPO and El
186 Niño episodes (Fig. 2). Positive IPO phases characterised the periods 1924-44 and
187 1977-1998. These phases were separated by negative IPO phases from 1945-76
188 and 1999 to present.

189

190 *d. PDO Index*

191 The more widely known Pacific Decadal Oscillation (PDO) index of Mantua et al.
192 (1997) is used as a secondary method for characterising low frequency variability
193 (<http://research.jisao.washington.edu/pdo/PDO.latest>). This is the North Pacific
194 manifestation of a Pacific-wide pattern encompassed by the IPO (Folland et al.
195 2002). The PDO is defined as the leading principal component of the monthly SSTA
196 residuals (poleward of 20°N), whereas residuals are understood as the grid-point
197 anomalies after the global mean monthly SST is removed from every location (Zhang
198 et al. 1997). Positive values of this index describe anomalously cold SSTAs around
199 45°N. Positive PDO phase prevailed from 1926 to 1946 and 1977 to 1998 and
200 negative phases from 1947 to 1976 and over the decade from 1999.

201 While the TPI and PDO indices cover near-identical sets of years their
202 relationship with precipitation is expected to be different as the PDO index is based
203 on north Pacific SSTAs whereas the TPI encompasses both hemispheres.

204

205 *e. Standardized Precipitation Index*

206 Drought can be defined as meteorological, hydrological, agricultural and socio-
207 economical. As a result there are numerous drought index parameters in the
208 literature (Dracup et al. 1980; Wilhite and Glantz 1985; Lloyd-Hughes and Saunders
209 2002). While a study of drought using evapotranspiration and hydrological data
210 would have been preferred, limited data availability constrains this study to a
211 precipitation only analysis of drought. Fortunately, indices based solely on
212 precipitation data perform well when compared to more complex hydrological indices
213 (Oladipo 1985).

214 The SPI ranks in the top positions among drought indicators for robustness and
215 reliability (Heim 2002; Keyantash and Dracup 2002). The SPI is also recommended

216 by the World Meteorological Organization and is likely to be the most frequently used
217 drought indicator worldwide. The SPI is currently employed in more than 70
218 countries (WMO 2012).

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

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

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

235

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

238 To allow the comparison of the results from this study with those of Spinoni et al.
239 (2014) we have selected the SPI-12 timescale and 1951 to 2010 study period.

240 Spinoni et al. (2014) found that a medium term accumulation period is more suitable

241 to depict the various precipitation regimes than shorter (SPI-3, SPI-6) or longer
242 periods (SPI-24, SPI-48) which may be too sensitive to extremes or miss relevant
243 drought events. They also found comparable drought patterns on a spatial basis,
244 both on global and continental scales using SPI-6, SPI-12 and SPI-24.

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

251

252 3. Methodology

253

254 a. Linear drought trends

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

264

265 *b. Drought occurrence differences between individual decades and two 30-year*
266 *periods*

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

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

281

282 *c. Determining regions with homogeneous precipitation variability*

283

284 Cluster analysis is widely used in climatology to divide precipitation for a single
285 large region into homogeneous smaller regions of precipitation variability. Annual
286 precipitation is scaled to a mean of zero and standard deviation of one. A
287 hierarchical agglomerative clustering method is used to define clusters of
288 precipitation stations. Each precipitation station is initially considered a separate
289 cluster and, at each successive step, clusters are compared and the clusters with the

290 smallest between cluster dissimilarities (a measure of the 'difference' between
291 clusters) merged until the desired numbers of clusters is reached. The average
292 linkage method with a Euclidean distance measure has been found to be the most
293 desirable and has been used in the analysis of Australian district precipitation
294 variability on seasonal time-scales by Drosdowsky (1993). Ward's method has also
295 been used to identify the main seasonal precipitation regimes in Australia (Chambers
296 2001, 2003) and Hawaii (Diaz et al. 2005) but has a tendency to produce clusters of
297 similar numbers of observations which is undesirable in this study as most of the
298 precipitation stations are southwest of the SPCZ, therefore likely to be part of the
299 same cluster. Salinger et al. (1995) applied cluster analysis on annual Pacific
300 precipitation but the clustering method employed is not described. A dendrogram
301 delineates the level of association at which stations are grouped. The selection of the
302 optimum number of clusters is complex, with no single criterion available to make an
303 objective decision. A subjective choice of 10% of the total number of stations is
304 suggested by Torok (1996). We have also considered the method of Lattin et al.
305 (2003), which looks for a relatively wide range of distances over which the number of
306 clusters in the solution do not change.

307 To confirm these groupings, Year-0 and Year +1 (lagged) annual precipitation
308 and NINO3.4 SSTA correlation coefficients are calculated and compared. A
309 relationship is deemed to exist if the correlation coefficients are significant at the
310 95% level. Non-significant p-values are > 0.05 .

311

312 *d. Interdecadal variability*

313 To detect low frequency variability, a 13-yr running mean is applied to SPI-12
314 precipitation at a cluster level to remove interannual fluctuations and those on EI

315 Niño timescales. This method has been used previously by Power et al. (1999) to
316 examine the strength of the relationship between Australian precipitation,
317 temperature, river flow and crop yield and the IPO and SOI on decadal timescales.

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

327 It is possible the duration and magnitude of droughts differ between positive and
328 negative phases of the IPO/PDO. If so, greater attention should be placed on
329 drought during the IPO/PDO phase associated with longer and more intense
330 droughts. We use the Mann-Whitney test to determine if the differences in median
331 duration and magnitude occurrence are statistically significant. Drought magnitude at
332 a station level (for each region) are aggregated over the 1951-1977, 1999-2010 and
333 1978-1998 periods then compared. This also applies to drought duration.

334

335 **4. Results**

336

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

338 The DF trends over 1951-2010 (Fig. 3a) are generally positive indicating more
339 frequent drought occurrence in recent decades, but mixed spatially and largely

340 statistically non-significant at the 95% level (102 of 113 stations). There is some
341 spatial consistency in parts of the study region for example in the Hawaiian Islands
342 region where the DF trends are largely positive. Positive DF trends are also by large
343 present, but smaller in size in the northwest Pacific, equatorial Pacific and in the
344 south Pacific subtropics.

345 The results are similar for TDD (Fig. 3b) and TDM (Fig. 3c) in that a majority of
346 the trends are positive, spatially mixed and largely non-significant. Sub-regionally,
347 spatial patterns are similar to that of DF with the addition of generally negative trends
348 in north-central Australia and smaller negative trends in the eastern Australia. Fig.4a
349 and Fig. 4b show mean TDD and TDM respectively for the selected Hawaiian
350 stations. On a State-scale the TDD and TDM trends over the six decades are
351 positive but not significant.

352 Drought patterns in this study are comparable with those of Spinoni et al.
353 (2014) for Australia. Both efforts show a decrease in TDD and TDM in the northern
354 part of the NT and from northwest QLD southeast to NSW and an increase in TDD
355 and TDM along the eastern Australia coast. Our results indicate largely non-
356 significant trends for Australia whereas Spinoni et al. (2014) found significant trends
357 for both TDD and TDM in the northern part of the NT. The differences may be due to
358 station selection and/or the gridding technique used by Spinoni et al. (2014).

359

360

361 *b. Difference in DF, TDD and TDM medians*

362 DF, TDD and TDM medians for 1951-1980 and 1981-2010 are presented in
363 Table 2 then compared using the Mann-Whitney test. The 1981-2010 DF, TDD and

364 TDM medians are larger than those for 1951-1980 with the differences highly
365 significant as shown by the p-values.

366 The above results show droughts have been more frequent, longer and more
367 intense since 1981. In order to determine if the trend is linear, the six decade
368 medians from 1951 are computed then compared using the Kruskal-Wallis test. The
369 p-values at the bottom of Table 3 point to at least one of the decade medians being
370 greater than the others with the difference significant at the 95% level. In the case of
371 TDD and TDM, the 1991-2000 median is greater than all the other decade medians
372 (as determined by the Mann-Whitney test) with the difference significant at the 95%
373 level. For DF the 1981-1990, 1991-2000 and 2001-2010 decade, the medians are
374 larger than that for 1951-1960 and the 1991-2000 median is also greater than the
375 median for 1971-1980.

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

382

383 *c. Homogeneous regions of precipitation variability and association with ENSO*

384 Cluster analysis has only been applied to the station records for the period
385 1955-2000 as data gaps prevent the use of the full study period. The cluster analysis
386 was applied to the study region subdivided into the north Pacific, south Pacific and
387 northeast Australia. Allowance has been made for clusters that might traverse these

388 geographic regions by including the closest stations in the neighbouring geographic
389 region in the multivariate analyses.

390 Eleven coherent precipitation regions were found using cluster analysis -
391 three in the north Pacific, six in the south Pacific and two in northeast Australia (Fig.
392 6). From this point forward, we focus on results of the cluster analysis and annual
393 precipitation correlations with NINO3.4 SSTA.

394 *Region 1 (Hawaii Wet)*. Cluster analysis divides the Hawaiian Islands into two
395 regions defined as R1(Hawaii Wet) and R2 (Hawaii Dry), respectively. This division
396 is based on high (low) annual precipitation associated with the windward (leeward)
397 sides of the islands.

398 An examination of the lag-0 relationship between annual precipitation in R1
399 and NINO3.4 SSTA (Appendix 1) reveals a largely non-significant precipitation
400 relationship with ENSO, as only the correlation coefficient between NINO3.4 SSTA
401 and annual precipitation at Paauilo 221 is statistically significant. When annual
402 precipitation is lagged by a year, there is an inclination towards negative and
403 stronger relationships, however, the p values remain largely non-significant. This
404 relationship is also reflected in the SPI-12 drought record for Hawaii Wet, where at
405 least 50% of the droughts events between 1951 and 2010 are associated with El
406 Niño events. Four DF trends in this cluster are positive with a fifth at Pauoa Flats
407 also positive but only significant at the 90% level. For TDD, two on the Big Island and
408 one on Maui show positive trends. The Haleakala Ranger Station on Maui and PH
409 Wainiha on Kaua'i display positive trends but only at the 90% level. For TDM, there
410 is a positive trend at PH Wainiha. Two stations on the Big Island and one on Maui
411 also show positive trends, significant at the 90% level. DF, TDD and TDM over 1951-
412 80 and 1981-2010 are presented in Table 4.

413 *Region 2 (Hawaii Dry)*. As for Hawaii Wet, the lag-0 relationships between
414 annual precipitation in R2 and NINO3.4 SSTA are weak and non-significant. Lagged
415 relationships produce stronger coefficient values that are statistically significant at
416 five (on Kauai and Oahu) of 14 stations. The only significant drought trend is a DF
417 negative trend at Puunene 396. This is supported by the small change in R2 DF,
418 TDD and TDM over the first and second thirty year periods as shown in Table 4.

419 *Region 3 (North ITCZ)*. This region is made up of the CNMI, Palau, FSM and
420 the RMI. Cluster analysis suggests this region can be divided into three subregions;
421 Palau and FSM (R3a), CNMI (R3b), and the RMI (R3c). The lag-0 relationships
422 between annual precipitation and NINO3.4 SSTA are significant at three of four
423 stations in R3a and at Majuro in R3c. The relationship becomes statistically
424 significant at all the R3 stations when annual precipitation is lagged by a year. Most
425 SPI-12 droughts are associated with El Niño. Only the following drought trends were
426 statistically significant: R3a, the Majuro positive TDD and TDM trends and R3c, the
427 Pohnpei positive TDD trend. This is supported by larger R3 TDD and TDM medians
428 over 1981-2010 when compared with 1951-1980.

429 *Region 4 (North Australia)*. This region includes the Kimberley Research
430 Station in Western Australia (WA), five Northern Territory (NT) stations; Tibooburra
431 Post Office (P.O.) in NSW, Willis Is., and the QLD stations with the exception of the
432 group between Rockley, south to the Harrisville P.O. near Brisbane and west to the
433 Cunnamulla P.O. Cluster analysis suggests R4 can be divided into two subregions.
434 R4a comprises most of R4, except Willis Is., Palmerville, Mossman South, Coen
435 P.O. and Cairns Aero in northeast QLD which form R4b. The relationship between
436 the annual precipitation and NINO3.4 SSTA is largely non-significant in the western
437 part of the R4 and largely negatively correlated and significant to the east. Drought

438 trends are largely non-significant in this part of Australia with the exception of the
439 positive DF trend at the Alice Springs Airport. At the 90% level only the negative
440 TDD trend at the Windorah P.O. and negative TDM trend at Brunette Downs are
441 significant. Unlike Spinoni *et al.* (2014) we do not find significant negative TDD and
442 TDM trends in the northern part of the NT, however we do find large negative non-
443 significant trends in this region.

444 *Region 5 (East Australia).* This region includes the QLD stations excluded in
445 R4 and Collarenebri, Wallangra, Nyngan, Barraba P.O., Lorne and Yamba Pilot
446 Station in New South Wales. Cluster analysis suggests there are two subregions in
447 R5; Lorne, Harrisville P.O. and Yamba Pilot Station in R5a with the remaining R5
448 QLD and NSW stations in R5b. Annual precipitation is negatively correlated with
449 NINO3.4 SSTA and statistically significant for most of the R5 stations. Unlike the
450 north Pacific, lagged correlations by large do not produce stronger relationships with
451 the NINO3.4 SSTA in Australia. Significant negative TDD and TDM trends are only
452 present at Collarenebri in R5b.

453 *Region 6 (New Guinea Islands).* This cluster is made up of Momote W.O.
454 only, located on Manus Island north of the New Guinea mainland. The correlation
455 coefficient between Momote annual precipitation and NINO3.4 SSTA is non-
456 significant for both the concurrent and lagged relationships. Equal numbers of
457 droughts for SPI-12 occur during El Niño and La Niña. DF, TDD and TDM trends are
458 non-significant. Kavieng rainfall on New Ireland shows a similar relationship with
459 NINO3.4 SSTA. Limited data prevents Kavieng from being included in this study.

460 *Region 7 (Central Pacific).* This region includes Nauru, Kiribati, Tuvalu, the
461 northern Cook Islands, and the French Polynesia Tuamotu and Marquesas Groups.
462 These islands lie between the ITCZ to the north and SPCZ to the southwest. Annual

463 precipitation is strongly related to the phase of ENSO and most droughts occur
464 during La Niña. Cluster analysis suggests there are two subregions in R7 which are
465 made up of Nauru and Kiribati (R7a) and Tuvalu, northern Cook Islands and
466 northeast French Polynesia (R7b). Annual precipitation is strongly positively
467 correlated with NINO3.4 SSTs in R7a and to a lesser extent in R7b with the
468 exception of the northernmost station in Tuvalu which has a correlation coefficient
469 more related to R7a. R7b stations have strong significant lagged relationships with
470 the NINO3.4 SSTA which is not the case for R7a. With regards to drought trends in
471 this region only the negative DF trend at Takaroa in R7b is statistically significant.

472 *Region 8 (Pitcairn Islands).* This region is composed solely of the Pitcairn
473 Islands. Pitcairn has little seasonality in precipitation as it lies to the east of the
474 SPCZ. Neither the concurrent nor lagged relationship between annual precipitation
475 and NINO3.4 SSTA are statistically significant. Two of the four SPI-12 droughts
476 between 1954 and 2010 cover a total period of 122 months. Drought trends are not
477 significant.

478 *Region 9 (Southwest French Polynesia).* This region is made up of Tahiti
479 (Society Islands) and Rapa (Austral Islands) in French Polynesia at the eastern end
480 of the diagonal portion of the SPCZ. Unlike R8, the presence of the SPCZ results in
481 seasonality, but like Pitcairn the lag-0 annual precipitation and NINO3.4 SSTA
482 relationships are weak. La Niña marginally dominate the drought record for Tahiti
483 and El Niño for Rapa. This is perhaps associated with stronger but non-significant
484 lagged correlations with NINO3.4 SSTA. Only the negative DF trend at Rapa is
485 significant.

486 *Region 10 (Northern Fiji).* This region comprises of Rotuma only, the
487 northernmost Fiji Island which is located under SPCZ for a large part of the year.

488 Both the lag-0 and lag-1 relationships between Rotuma precipitation and NINO3.4
489 SSTA are non-significant. The climate of Rotuma is unique as droughts occur during
490 El Niño and La Niña. La Niña results in SPCZ displacement towards Fiji but extreme
491 southwest displacement leads to drought. Drought trends are not statistically
492 significant. Supporting these results are data for Niulakita (not included in this study),
493 the southernmost Tuvalu Island, located about 330 km to the northeast. Niulakita
494 displays similar non-significant relationships with NINO3.4 SSTA.

495 *Region 11 (Southwest SPCZ).* This region occupies the largest part of the
496 study area; PNG mainland, Solomon Islands, Vanuatu, New Caledonia, main islands
497 of Fiji, Tonga, Niue, southern Cook Islands and the Australian and NZ subtropical
498 islands. With the exception of the stations on the northern coast of Papua New
499 Guinea, the remaining stations lie to the southwest of the SPCZ and are affected by
500 the subtropical high pressure belt. Cluster analysis suggests there are four
501 subregions which are Madang and Wewak in PNG (R11a), Lord Howe, Norfolk and
502 Raoul Islands in the subtropics (R11b), northern Tonga, Niue, Samoa and the
503 southern Cook Islands (R11c) and the remaining stations between southern Papua
504 New Guinea and Tonga (R11d). There are significant lag-0 negative relationships
505 between annual precipitation and NINO3.4 SSTA at all 34 R11 stations. Stations in
506 R11a, R11b and R11c have non-significant lagged relationships with NINO3.4 SSTA
507 while most stations in R11d do have significant lagged relationships. Most droughts
508 are associated with El Niño in R11.

509 In R11b, the Norfolk Island TDD and TDM trends are positive and significant.
510 The DF trend is also positive and significant but only at the 90% level. The Lord
511 Howe Island TDM trend is positive. Drought trends are mixed in the R11d. At
512 Nausori Airport in Fiji and Port Vila-Bauerfield Airport in Vanuatu the DF trends are

513 positive. The DF trend is negative at Chepenehe on Lifou Island in New Caledonia.
514 At Houailou P. the TDD trend is positive and the TDM trends at Houailou P. and
515 Kone are significant at the 90% level. Overall for R11, TDD and TDM are notably
516 larger over 1981-2010 when compared with TDD and TDM for 1951-1980.

517

518 *d. Drought variability on decadal timescales*

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

527 Drought duration was longer and drought magnitude larger during the
528 TPI/PDO negative phases in the Hawaii Wet region. Conversely droughts were
529 longer and more intense in the North ITCZ and Southwest SPCZ regions during the
530 TPI/PDO positive phase from 1978-1998 (Table 4).

531

532 **5. Summary of Regional Findings**

533 In this study we use the Standardized Precipitation Index (SPI-12 timescale)
534 to examine the historical precipitation record for trends in drought frequency,
535 duration and magnitude over 1951-2010 using 113 station records for 21 countries
536 and territories in western Pacific. This is followed by analyses to determine the

537 strength of the relationship between precipitation and drivers of Pacific climate
538 namely ENSO and the IPO/PDO.

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

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

558 In the south Pacific subtropics, the significant positive TDD and TDM trends
559 are supported by negative trends in total annual precipitation and annual days with
560 rainfall > 1 mm and > 10 mm since 1951 (Jovanovic et al. 2012; McGree et al. 2014).
561 Increasing trends in droughts in subtropical southern Australia (CSIRO 2012) and

562 the Altiplano in South America (Morales et al. 2011), have previously been linked to
563 changes in the Hadley circulation. As the Norfolk and Lord Howe Islands are
564 adjacent to southern Australia it is likely the intensification of the Hadley circulation
565 and poleward shift of the subtropical dry zone are also responsible for the drying
566 trends. The reason for the intensification is the subject of considerable debate with
567 some studies attributing the change to stratospheric ozone depletion (Min and Son
568 2013), while others favour increased surface global warming (Nguyen et al. 2015) or
569 a combination of the two (Allen et al. 2014).

570 An alternative method of examining drought change over time is to compare
571 the DF, TDD and TDM medians for 1951-1980 and 1981-2010. The 1981-2010 DF,
572 TDD and TDM medians are larger than those for 1951-1980 with the differences in
573 the median values highly significant. However, the change is non-linear as
574 discovered by comparing the six decade medians from 1951. For all three measures
575 of drought one of the decade medians is greater than the others with the difference
576 statistically significant. In the case of TDD and TDM, the 1991-2000 median is
577 greater than all the other decade medians. This feature is notable in Fig. 6 which
578 shows drought hot spots (TDM) for the study region. Station markers for the 1991-
579 2000 period are in the majority (~35%). A period when a number of very strong El
580 Niño events occurred, most notably the 1982/83 and 1997/98 events. The results of
581 the study to this point suggest ENSO and possibly IPO influence drought frequency,
582 duration and magnitude which leads to the second part of the study where the aim is
583 to investigate the strength of the relationship between precipitation and drivers of
584 Pacific climate especially in the tropical Pacific.

585 In the central north Pacific, El Niño events are associated with the upper-
586 tropospheric jet stream extending eastward during the boreal winter. The Hawaiian

587 Islands are located in the right exit region of the jet stream, in an area of upper-level
588 convergence. The expected anomalous sinking motion resulting from upper-level
589 convergence tends to hinder the development of subtropical cyclones, upper-level
590 lows, and the passage of mid-latitude frontal systems to the Hawaiian Islands. These
591 features, together with reduced north-easterly trade winds result in low wet season
592 rainfall (Chu 1995; Chu and Chen 2005; Cao et al. 2007; Garza et al. 2012). In the
593 north-western tropical Pacific in the vicinity of the ITCZ, El Niño is associated with
594 weakened trade winds (Lander 2004) and the ITCZ displaced on average closer to
595 the equator and more intense between 160°E-120°W, 0°-15°N (Australian Bureau of
596 Meteorology and CSIRO 2011) resulting in droughts in the islands immediately to the
597 north (Fig. 2).

598 In the southwest Pacific, ENSO has a notable influence on the SPCZ and
599 therefore on precipitation received in the countries nearby (Trenberth 1976; Vincent
600 1994; Folland et al. 2002; Vincent et al. 2009). Trenberth (1976) described the
601 movement of the SPCZ as north and east during El Niño and south and west during
602 La Niña. Asymmetric orientations of the SPCZ resulted in a near-parallel alignment
603 with the equator (and in large displacement) for the very strong El Niño events of
604 1982/83 and 1997/98. There is also evidence that meridional Hadley circulation
605 strengthens during El Niño (Chu and Chen 2005; Lough et al. 2011) resulting in
606 cooler, drier tradewinds in the south Pacific.

607 In the Papua New Guinea and northeast Australian region the West Pacific
608 Monsoon (WPM) (Fig. 2) is associated with a seasonal reversal of wind direction that
609 brings heavy rainfall to northern Australia, and western tropical Pacific Islands.
610 Variations in the timing, position, intensity, longevity and extent of the monsoon
611 account for much of the rainfall variability in this region. ENSO causes some

612 variability in the WPM. The two most extreme maximum eastern extents of the
613 monsoon domain occurred during the strong El Niño events of 1982/83 and 1997/98
614 (Australian Bureau of Meteorology and CSIRO 2011). Although Australia is
615 influenced by many climate drivers, El Niño and La Niña have perhaps the strongest
616 influence on interannual rainfall variability. The shift in rainfall away from the western
617 Pacific, associated with El Niño, means that Australian rainfall is usually reduced
618 through winter–spring, particularly across the eastern and northern parts of the
619 continent. The date of the monsoon onset in tropical Australia is generally 2–6 weeks
620 later during El Niño years than in La Niña years. This means that precipitation in the
621 northern tropics is typically well-below-average during the early part of the wet
622 season for El Niño years (Nicholls 1984; Lo et al. 2007; Timbal and Drosowsky
623 2013).

624 The literature survey demonstrates precipitation variability is dissimilar across
625 the study region and as such a simple region averaged precipitation time-series
626 would not be appropriate. In an effort to reduce the number of variables and reduce
627 noise at a station level, multivariate analyses is applied to group the precipitation
628 time-series into coherent regions of variability. Eleven coherent precipitation regions
629 of variability were found using cluster analysis - three in the north Pacific, two in
630 northeast Australia and six in the south Pacific. We confirm the cluster groupings and
631 derive additional information by computing the strength of the ENSO (using NINO3.4
632 SSTA) and precipitation relationship using correlation coefficients.

633 Cluster analysis divides the Hawaiian Islands into two regions based on high
634 (low) annual precipitation largely associated with the windward (leeward) sides of the
635 islands. Our investigation of the strength of the relationship between annual
636 precipitation and NINO3.4 SSTA finds a non-significant relationship at lag-0 across

637 the State but a negative relationship at lag-1 at almost 50% of the stations on the
638 leeward side of the islands and at one of ten stations on the windward side.

639 Numerous studies have documented the negative correlation between
640 equatorial Pacific SSTs and rainfall across most of Australia, including QLD e.g.
641 McBride and Nicholls (1983); Allan (1988); Lough (1991); Murphy and Ribbe (2004).
642 There have also been a number of attempts to group northeast Australia
643 precipitation into coherent regions of variability e.g. Drosdowsky (1993). Results vary
644 depending on time-period and data selected. Our results show two main clusters
645 with the first covering the northeast WA, the NT, QLD with exception of the stations
646 to the southeast, the northwest portion of NSW and Willis Island off the coast of
647 QLD. The second cluster covers the remaining portion of QLD and NSW. The annual
648 precipitation relationship with NINO3.4 SSTA is by large non-significant in the
649 monsoon dominated portion of northern Australia but largely significant to the east.
650 Unlike the North ITCZ and Southwest SPCZ clusters NINO3.4 SSTA does not have
651 a lagged relationship with northeast Australia precipitation.

652 We are only aware of one previous study (Salinger et al. 1995) beyond
653 Australia and Hawaii that groups Pacific Islands precipitation time-series into
654 coherent regions of variability using statistical techniques. There are noteworthy
655 differences between results of Salinger et al. (1995) and this study. The Northern Fiji
656 cluster in this study does not include Samoa and the southern Cook Islands, partly
657 due to there being a significant inverse relationship between stations at these
658 locations and NINO3.4 SSTA whereas there is a weak relationship between the
659 Northern Fiji cluster precipitation and NINO3.4 SSTA. In Salinger et al. (1995) the
660 Southwest SPCZ region is labelled 'Subtropical region'. With a larger dataset the
661 'Subtropical region' is expanded in this study to include the PNG mainland, Solomon

662 Islands, Australian Pacific subtropical islands, Samoa and the southern Cook
663 Islands.

664 Further, we present a lagged relationship between annual precipitation and
665 NINO3.4 SSTA for most of the stations between southern PNG and southern Tonga
666 (southwest of the zonal portion of the SPCZ (Folland et al. 2002)) which does not
667 include the northern Tonga to southern Cook Islands portion (southwest of the
668 diagonal portion of the SPCZ) of the Southwest SPCZ cluster. Grouping precipitation
669 time-series into coherent regions of variability has not been attempted for the north
670 tropical Pacific. We have found a North ITCZ cluster that covers the CNMI, Palau,
671 FSM and the RMI region. El Niño events correspond closely with increased risk of
672 drought in the following year in this Micronesia region with drought tending to be
673 most extreme during the northern hemisphere winter and spring following an El Niño
674 (Keener et al. 2012). We have found lag-0 relationships between annual precipitation
675 and NINO3.4 SSTA significant at four of six stations in the Palau-FSM and RMI
676 subclusters. This relationship becomes statistically significant at all seven stations in
677 the North ITCZ cluster when the precipitation is lagged by a year.

678 Finally, we determine the strength of the relationship between the precipitation
679 clusters and IPO/PDO as well as determine whether droughts are longer and/or
680 more severe during a particular phase of IPO/PDO. The results show that during the
681 IPO/PDO positive (negative) phase the Hawaii Wet, North ITCZ, North Australia (IPO
682 only), New Guinea Islands, Pitcairn Is. (PDO only), Northern Fiji (PDO only) and
683 Southwest SPCZ clusters were 'drier' ('wetter') with the reverse applying for the
684 Central Pacific cluster. When the Hawaii Wet and Hawaii Dry clusters are merged,
685 the 13-year running average Hawaiian standardised precipitation and PDO
686 relationship is found to be highly significant ($\rho = -0.369$, $p = 0.010$) in line with

687 previous conclusions on the PDO and Hawaiian precipitation relationship (Mantua et
688 al. 1997; Chu and Chen 2005). The above result for Hawaii Dry suggests PDO's
689 influence on Hawaiian precipitation is stronger on the windward side of the islands.

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

709 There is a notable difference between PDO and IPO (as defined by the TPI)
710 their relationship with precipitation as shown in Table 5. This is in contract to the
711 findings of (Folland et al. 2002) who found PDO and IPO to be essentially equivalent

712 in describing Pacific-wide variations in ocean climate. The relationship between the
713 PDO and north Pacific precipitation (Hawaii Wet, Hawaii Dry and North ITCZ
714 clusters) is stronger than that of the TPI and Hawaiian precipitation while the reverse
715 applies in the south Pacific (North Australia, East Australia and Southwest SPCZ
716 clusters). In the near-equatorial Pacific the relationships between the decadal indices
717 and precipitation are near equivalent (Central Pacific and New Guinea Islands
718 cluster). The weaker (as compared with the PDO) Northern Fiji and Pitcairn Islands
719 cluster relationships with TPI are unexpected. This may be associated weak to non-
720 existent relationships between precipitation and ENSO at these locations.

721

722 **6. Conclusions**

723 In response to the general perception amongst Pacific Islanders that the
724 frequency of drought has increased, particularly in the last couple of decades, the
725 results of this study show from a meteorological perspective, drought frequency,
726 duration and magnitude for Pacific Islands and northeast Australia were greater over
727 1981-2010 as compared with 1951-1980. The increase was not linear and was in a
728 large part due to low frequency variability namely the positive phase of the IPO from
729 1977-1998. The switch to the negative phase of IPO from 1999 resulted in a decade
730 from 2000 with reduced drought activity. The subtropics of both hemispheres are
731 notable exceptions. Here changes in the Hadley Circulation resulted in a number of
732 locations displaying positive drought trends that are statistically significant.

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

736

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1020 TABLE 1. Classification used for the SPI

SPI value	Class	Probability %
$SPI \geq 2.0$	Extremely wet	2.3
$1.5 \leq SPI < 2.0$	Severely wet	4.4
$1.0 \leq SPI < 1.5$	Seriously wet	9.2
$-1.0 < SPI < 1.0$	Near normal	68.2
$-1.5 < SPI \leq -1.0$	Seriously Dry	9.2
$-2.0 < SPI \leq -1.5$	Severely dry	4.4
$SPI \leq -2.0$	Extremely dry	2.3

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1041 TABLE 2. Median DF, TDD and TDM over 1951-1980 and 1981-2010

	1951-1980	1981-2010	p-value
DF	5	6	0.0022
TDD	92	116	0.0000
TDM	96.9	121.8	0.0000

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1059 TABLE 3. Median DF, TDD and TDM over individual decades between 1951 and
 1060 2010

	DF Median (Ave 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
1991-00	2 (375.8)	47	54.5
2001-10	2 (349.6)	34	35.0
p-value	0.044	0.000	0.000

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1084 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

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1099 TABLE 5. Correlation coefficients for TPI/PDO and annual standardized precipitation
 1100 (columns 2-3). Median drought duration and drought magnitude for the TPI/PDO
 1101 negative phases (1951-1977, 1999-2010) and TPI/PDO positive phase (1978-1998,
 1102 columns 4-7). Correlation coefficients and medians differences statistically significant
 1103 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	<i>-0.39</i>	<i>-0.58</i>	<i>15</i>	<i>12</i>	<i>15.8</i>	<i>10.8</i>
2. Hawaii Dry	-0.04	-0.23	14	16	14.6	14.7
3. North ITCZ	<i>-0.72</i>	<i>-0.81</i>	<i>11</i>	<i>16</i>	<i>12.2</i>	<i>21.7</i>
4. North Australia	<i>-0.35</i>	-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	<i>-0.32</i>	<i>-0.30</i>	13	14	16.5	22.7
7. Central Pacific	<i>+0.96</i>	<i>+0.92</i>	19	15	21.7	16.5
8. Pitcairn Islands	-0.22	<i>-0.44</i>	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	<i>-0.37</i>	9	13	9.2	17.6
11. South SPCZ	<i>-0.95</i>	<i>-0.85</i>	<i>11</i>	<i>13</i>	<i>12.0</i>	<i>19.5</i>

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1115 TABLE A1. Spearman rank correlation coefficients demonstrating the strength of the
 1116 relationship between annual NINO3.4 SSTA and annual precipitation (lag-0) and
 1117 NINO3.4 SSTA and annual precipitation lagged by a year (lag-1) on a station scale.

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
1	Paauilo 221	20.1°N	155.4°W	1	0.36	0.13
2	Hilo Int. Apt.	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	Lanikai 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. Apt.	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

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
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 Apt.	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. Apt.	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 Apt.	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 Apt.	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

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
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
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

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
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

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
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 Apt.	17.8°S	177.5°E	11d	-0.59	-0.43
106	Nausori Apt.	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

No.	Name	Longitude	Latitude	Cluster	Lag-0	Lag-1
113	Nuku'alofa	21.1°S	175.2°W	11d	-0.50	-0.46

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1137 **FIG. 1.** Map of the Pacific and northeast Australia region showing the study region
1138 and station locations. Station numbers are associated with station names in Table
1139 A1.

1140

1141 **FIG. 2.** Schematic of circulation in the Pacific. From Australian Bureau of
1142 Meteorology, CSIRO. 2011.

1143

1144 **FIG. 3.** Linear drought trends the period 1951-2010 (a) drought frequency, (b) total
1145 drought duration, and (c) and total drought magnitude. Filled triangles represent
1146 trends significant at the 95% level.

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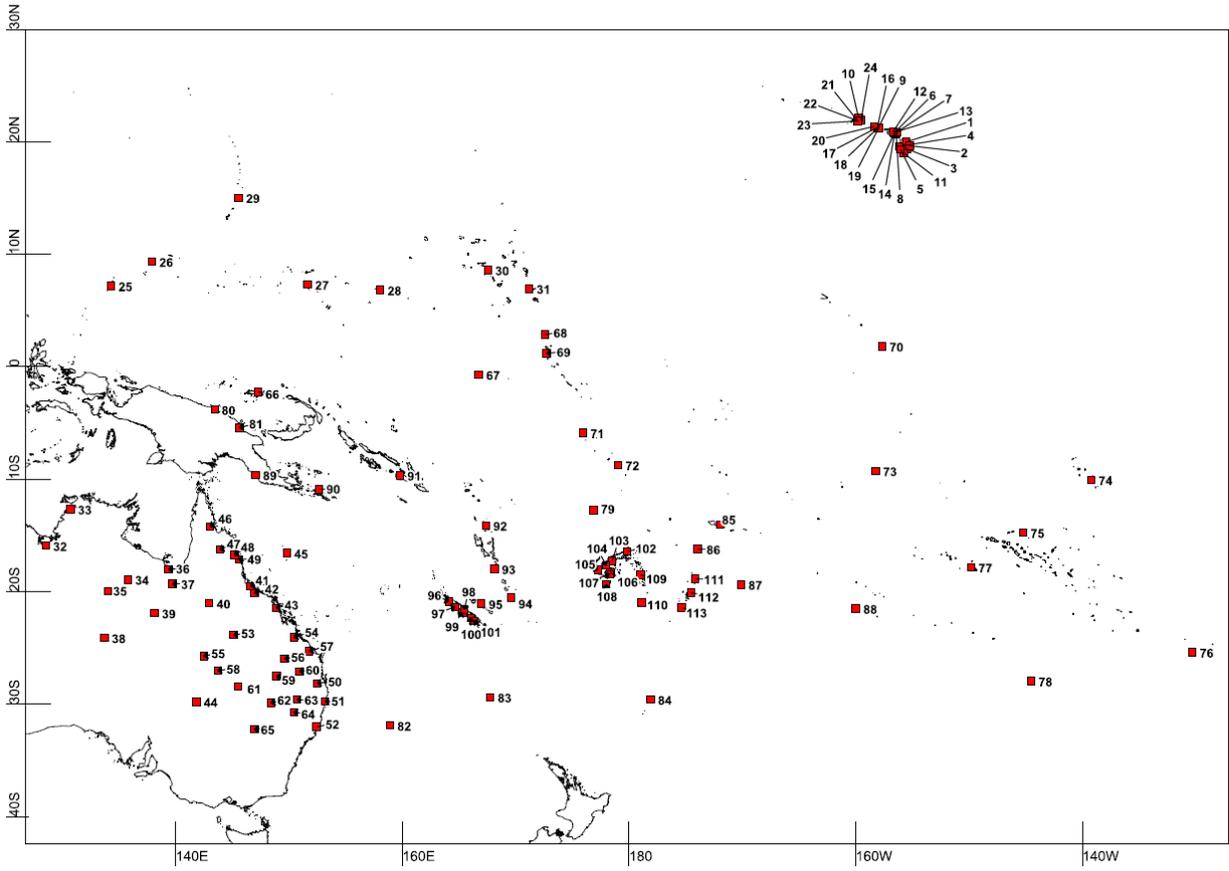
1148 **FIG. 4.** Mean decadal total drought duration and total drought magnitude 1951-2010
1149 for the selected Hawaiian stations (a) TDD (b) TDM.

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1151 **FIG. 5.** Drought hot spots on decadal time-scales 1951-2010. Numbers in
1152 parentheses refer to the number of stations for the respective decade.

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1154 **FIG. 6.** Pacific Islands and northeast Australian coherent annual rainfall subregions
1155 as defined by cluster analysis.

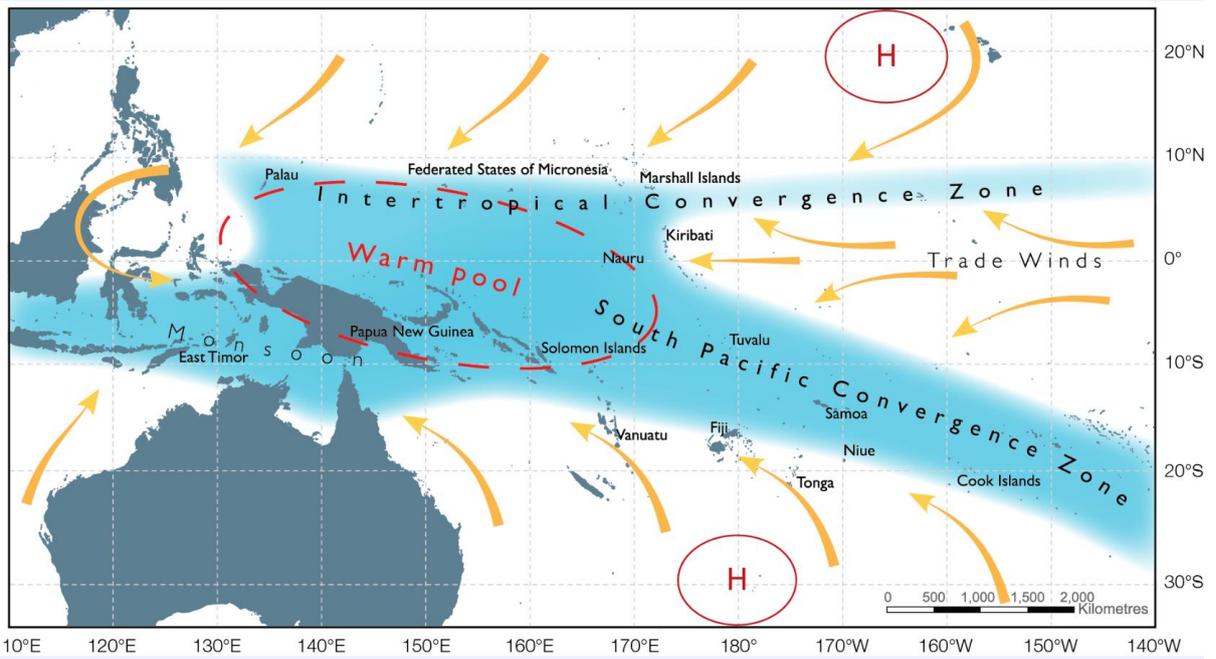


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1157 **FIG. 1.** Map of the Pacific and northeast Australia region showing the study region
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 1159 A1.

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FIG. 2. Schematic of circulation in the Pacific. The red broken line represents the

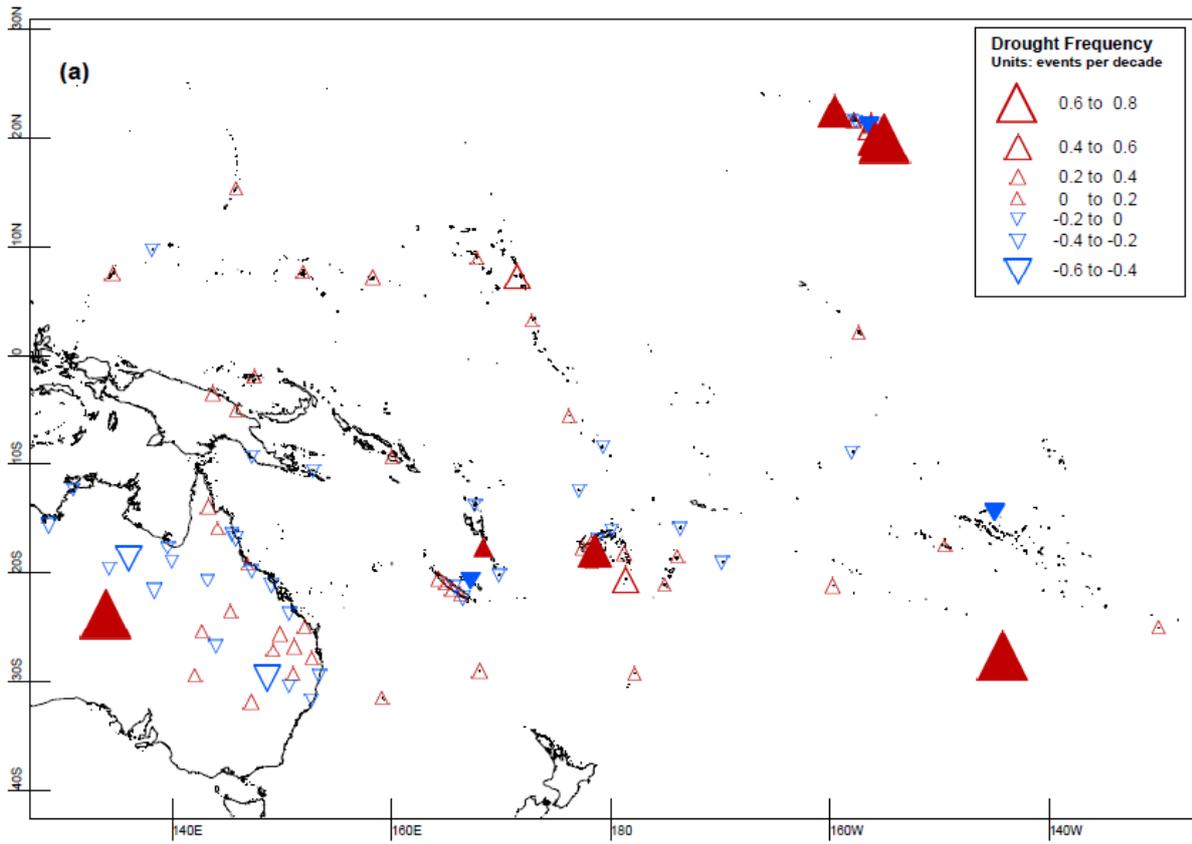
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bounds of the West Pacific Warm Pool. From Australian Bureau of Meteorology and

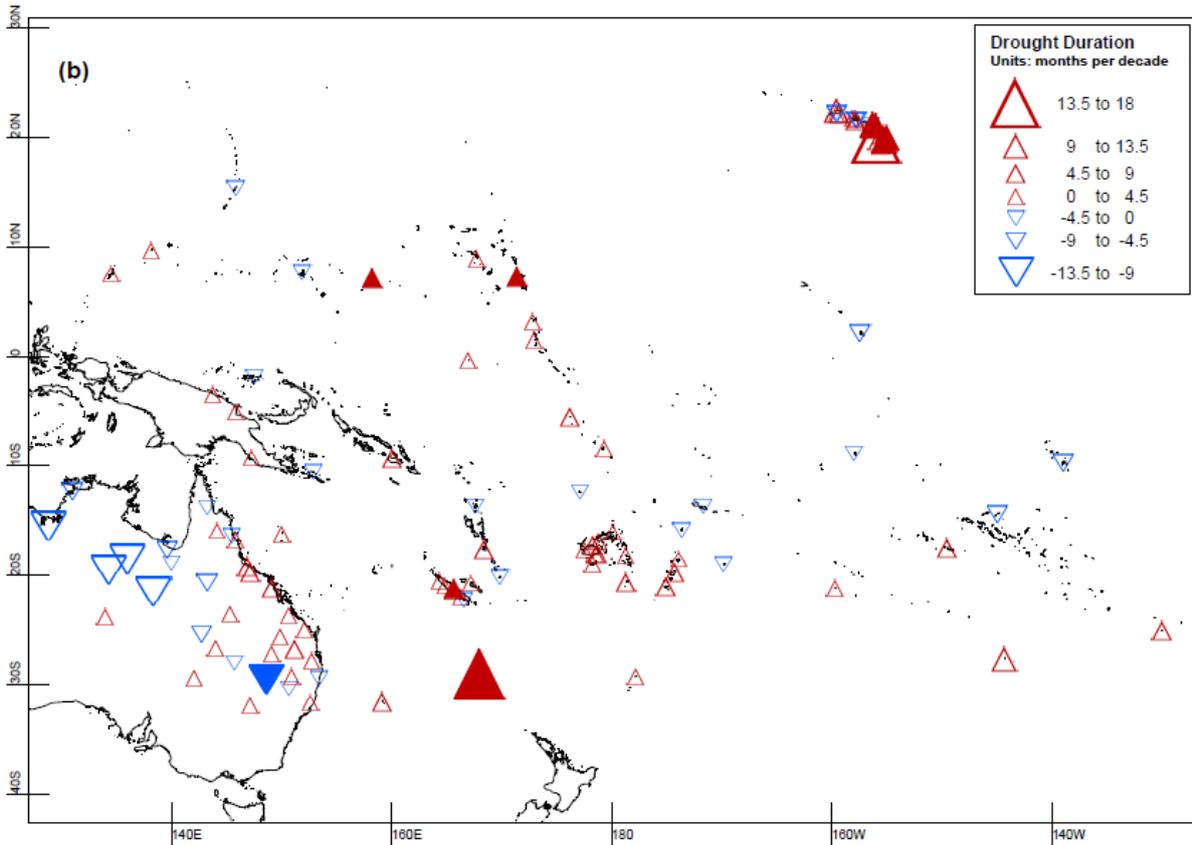
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CSIRO (2011).

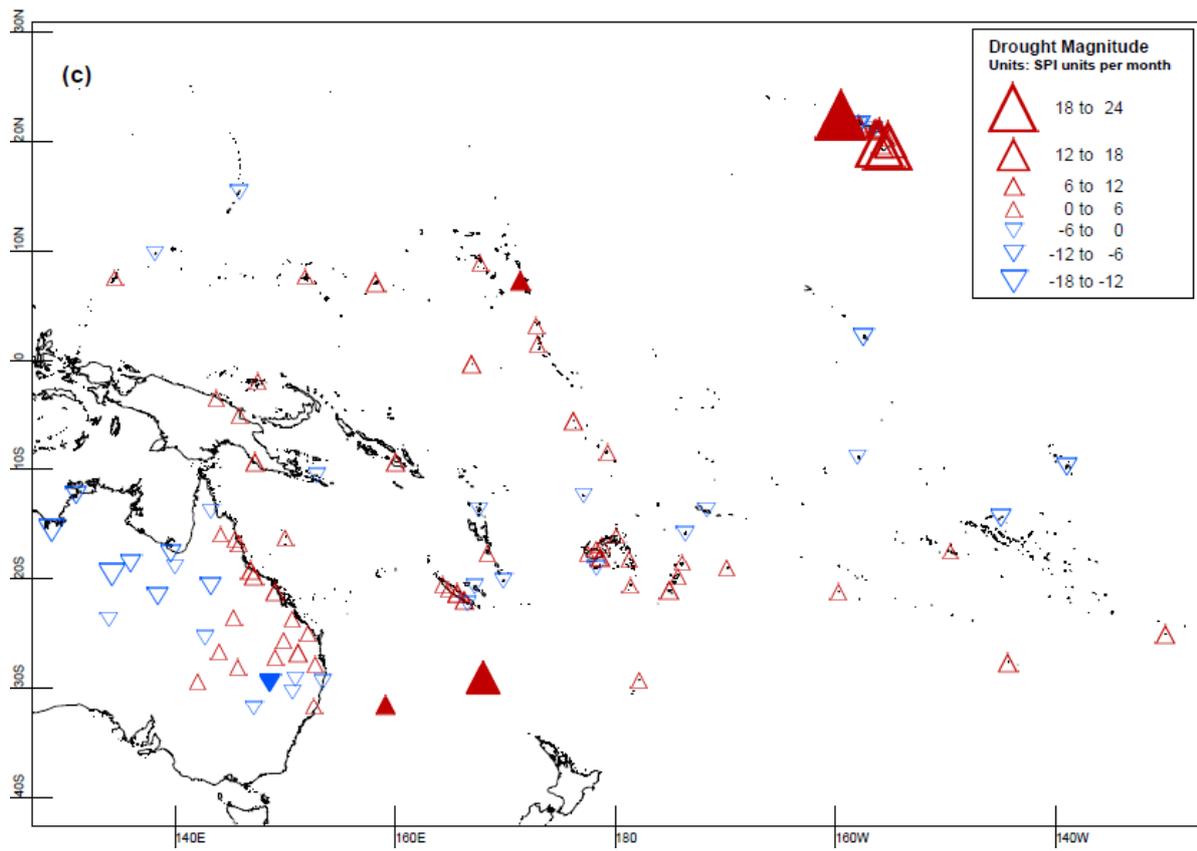
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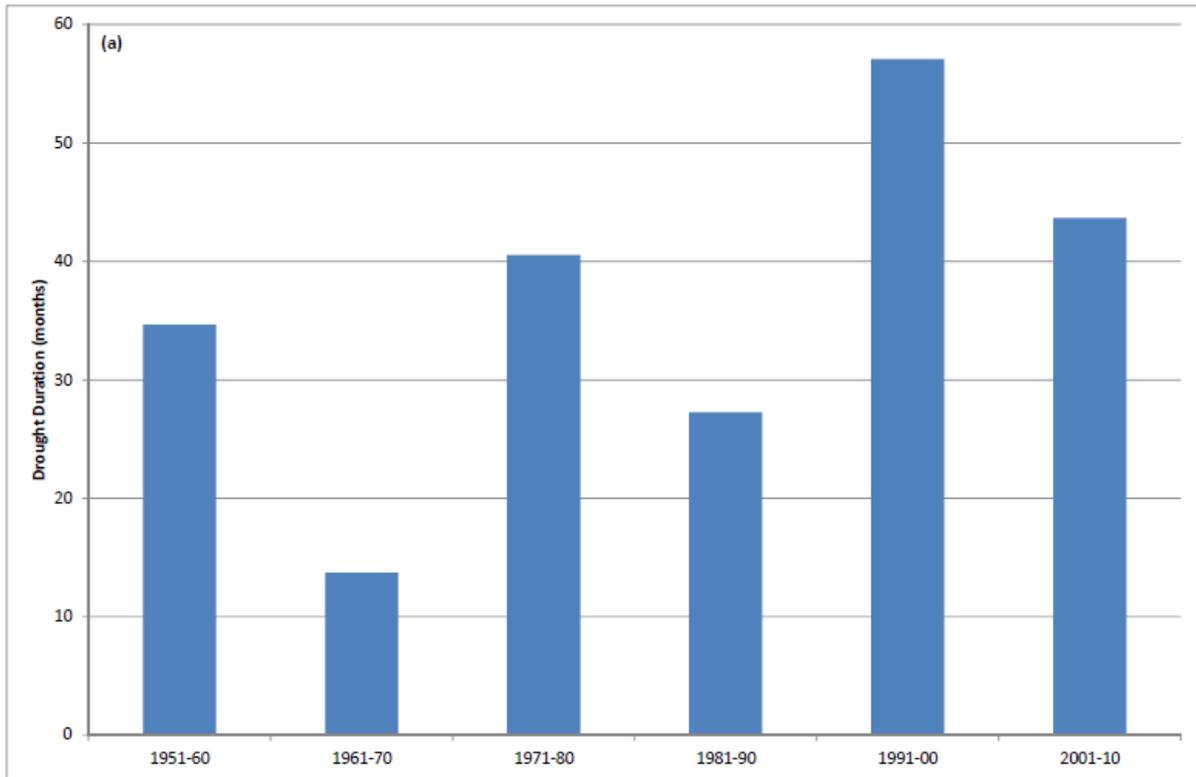
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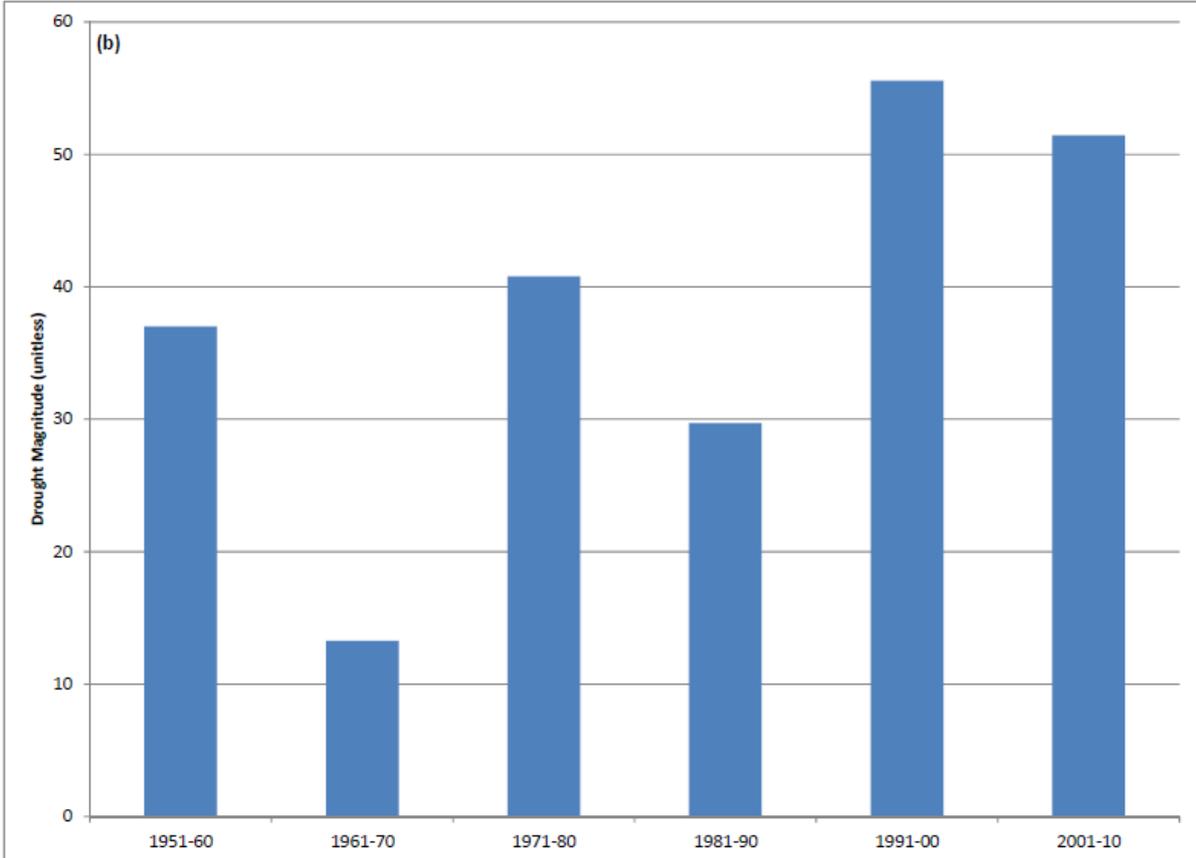
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1170 **FIG. 3.** Linear drought trends the period 1951-2010 (a) drought frequency, (b) total
 1171 drought duration, and (c) and total drought magnitude. Filled triangles represent
 1172 trends significant at the 95% level.

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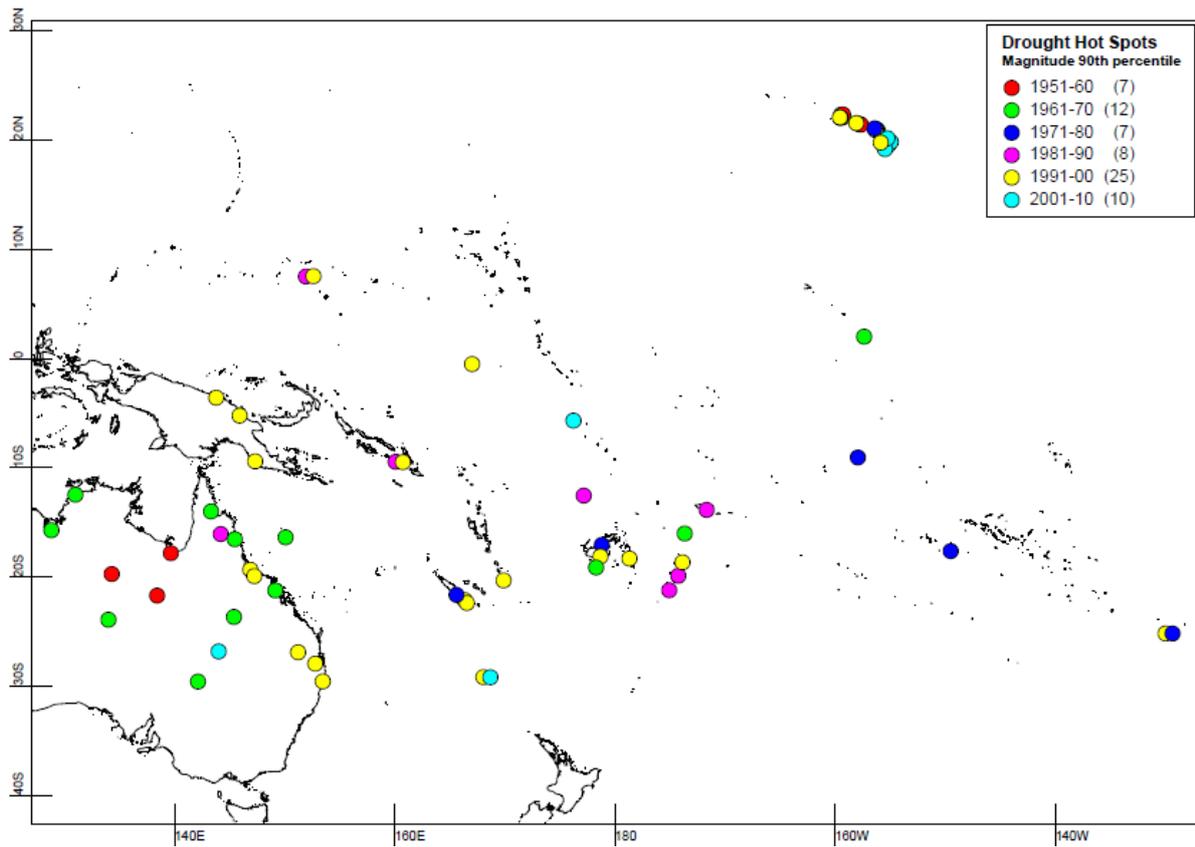
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1176 **FIG. 4.** Mean decadal total drought duration and total drought magnitude 1951-2010

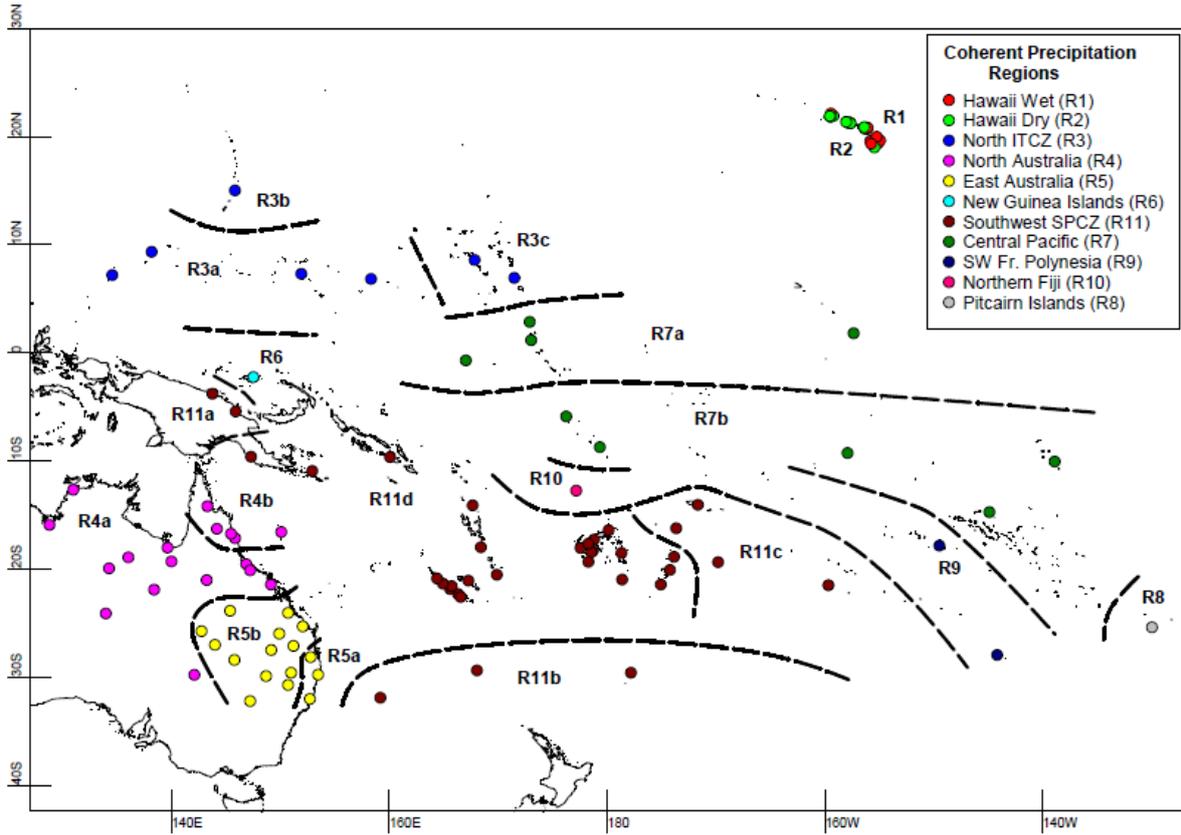
1177 for the selected Hawaiian stations (a) TDD (b) TDM.



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1179 **FIG. 5.** Drought hot spots on decadal time-scales 1951-2010. Numbers in

1180 parentheses refer to the number of stations for the respective decade.



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1182 **FIG. 6.** Pacific Islands and northeast Australian coherent annual rainfall subregions
 1183 as defined by cluster analysis.