An updated assessment of trends and variability in total and extreme rainfall in the western Pacific

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ABSTRACT: Rainfall records for 23 countries and territories in the western Pacific have been collated for the purpose of examining trends in total and extreme rainfall since 1951. For some countries this is the first time that their data have been included in this type of analysis and for others the number of stations examined is more than twice that available in the current literature. Station trends in annual total and extreme rainfall for 1961–2011 are spatially heterogeneous and largely not statistically significant. This differs with the results of earlier studies that show spatially coherent trends that tended to reverse in the vicinity of the South Pacific Convergence Zone (SPCZ). We infer that the difference is due to the Interdecadal Pacific Oscillation switching to a negative phase from about 1999, largely reversing earlier rainfall changes. Trend analyses for 1981–2011 show wetter conditions in the West Pacific Monsoon (WPM) region and southwest of the mean SPCZ position. In the tropical North Pacific it has become wetter west of 160°E with the Intertropical Convergence Zone/WPM expanding northwards west of 140°E. Northeast of the SPCZ and in the central tropical Pacific east of about 160°E it has become drier. Our findings for the South Pacific subtropics are consistent with broader trends seen in parts of southern and eastern Australia towards reduced rainfall. The relationship between total and extreme rainfall and Pacific basin sea surface temperatures (SSTs) has been investigated with a focus on the influence of the El Niño-Southern Oscillation (ENSO). We substantiate a strong relationship between ENSO and total rainfall and establish similar relationships for the threshold extreme indices. The percentile-based and absolute extreme indices are influenced by ENSO to a lesser extent and in some cases the influence is marginal. Undoubtedly, larger-scale SST variability is not the only influence on these indices.

KEY WORDS extreme climate indices; ETCCDI; SPCZ; IPO; Pacific Islands

Received 12 June 2013; Revised 21 October 2013; Accepted 23 October 2013

1. Introduction

More extreme climate events are likely to cause more societal or environmental damage (Zhang et al., 2011). Small Islands Developing States (SIDS) are amongst
the most vulnerable to extreme events as they are small in physical size and surrounded by large expanses of ocean. SIDS are also prone to natural disasters and extreme events, generally have poorly developed infrastructure, limited financial and human resources and lower levels of education and literacy (McCarthy et al., 2001). For many Pacific Islands (Figure 1), limited water collection and storage infrastructure lead to a dependence on regular rainfall for both domestic and agriculture purposes (Gawander, 2007), often relying on tanks or shallow aquifers and freshwater lenses (Falkland, 1991; White et al., 1999; Falkland, 2002). This nature of water supply means changes in mean and extreme rainfall have the potential to significantly impact Pacific Island society, for example, the 2011–2012 La Niña event in Tuvalu (population 10,500). Within a few months of drought conditions, rainwater tanks were depleted resulting in the Tuvalu Government declaring a state of emergency at the end of September 2011. This was followed by a declaration of national crisis for the capital atoll Funafuti and southern island of Nukulaelae (Sinclair et al., 2012) and most households being rationed to 40-L freshwater a day. A weekend before the New Zealand Government supplied two desalination plants and large containers, Tuvalu was left with just 2 days supply of water (RNZ, 2011). Drought conditions continued until May 2012.

Regional-scale studies on trends in total and extreme rainfall for the western Pacific Islands (e.g. Manton et al., 2001; Salinger et al., 2001; Griffiths et al., 2003) are limited geographically and temporally. Recent work has largely been on national or subnational scales (e.g. Koshy et al., 2006; Cavarero et al., 2012; Jovanovic et al., 2012) or part of neighbouring regional analyses (e.g. Choi et al., 2009; Caesar et al., 2011), often with dissimilar methodology and study periods.

The regional-scale studies have focussed mainly on the South Pacific where the effects of the South Pacific Convergence Zone (SPCZ, Figure 1) on mean rainfall regimes have been large in the past. Much of this variability is linked to the El Niño-Southern Oscillation (ENSO) or the Interdecadal Pacific Oscillation (IPO) (Salinger et al., 2001) and is directly attributable to shifts in the SPCZ (Folland et al., 2002). The mean position of the SPCZ extends from the Solomon Islands to southern French Polynesia and is composed of two parts which include a ‘zonal’ portion, normally located over the western Pacific ‘warm pool’ and a ‘diagonal’ portion orientated northwest-southeast lying east of the dateline (Vincent, 1994). There is significant movement around the SPCZ mean position seasonally, annually and on longer timescales. Trenberth (1976) described the movement of the SPCZ as north and east during El Niño events and south and west during La Niña events. The IPO is a natural Pacific-wide interdecadal signature with sea surface temperatures (SSTs) similar to those seen during ENSO events. When the IPO is in its positive (negative) phase, the mean SPCZ position is displaced north-east (southwest; Folland et al., 2002), consistent with the changes associated with ENSO. Folland et al. (2002) found that shifts in the position of the SPCZ were related to ENSO on interannual timescales, and the IPO on decadal timescales. These shifts appeared to be of similar magnitude and were largely linearly independent. Therefore, the SPCZ is located furthest north-east during El Niño events with a positive IPO, and furthest southwest during La Niña events with a negative IPO. The position of the SPCZ varies most strongly in the diagonal section of the SPCZ, between about 180° and 130°W, with the zonal section of the SPCZ showing slightly less latitude change under the effects of ENSO and the IPO (Folland et al., 2002). Since the late 1990s, the IPO has switched to a negative phase, and the SPCZ is currently displaced southwest of its mean position on a decadal timescale (ABOM-CSIRO, 2011).

Trends in rainfall have previously been examined for the period 1961–1998 and 1961–2000 for a number of stations in the South Pacific (Manton et al., 2001; Griffiths et al., 2003). Total annual rainfall showed a general decrease at locations to the southwest of the SPCZ and a general increase to the northeast of the SPCZ with the largest trends east of 160°W. Significant increases in total rainfall occurred at Penrhyn (Northern Cook Islands, about 500 mm decade$^{-1}$) and at Atuona (northern French Polynesia, about 250 mm decade$^{-1}$). Small but not statistically significant decreases occurred at Atuataki (Southern Cook Islands), Rapa (southern French Polynesia), Apia (Samoa), Nuku‘alofa (Tonga) and Raoul Island (New Zealand), but there was a statistically significant decline of 180 mm decade$^{-1}$ at Pitcairn Island. West of the dateline, trends were small and there were no obvious spatial patterns within the island groups of Tonga, Fiji, New Caledonia and Tuvalu. Here trends were incoherent and non-significant (Griffiths et al., 2003). Trends in the number of rain days were generally similar to those of total rainfall, with more (less) days typically associated with more (less) total rainfall (Manton et al., 2001; Griffiths et al., 2003). For the subtropical South Pacific, recent work by Jovanovic et al. (2012) showed non-significant negative trends in total rainfall at Norfolk Island (since 1915) and Lord Howe Island (since 1950) with stronger negative trends over the more recent 1970–2009 period. Little change was observed at Willis Island, in the Coral Sea, over 1924–2009.

Past changes in extreme rainfall in the Pacific have been analysed by frequency of extremes, intensity, proportion of total rain and dry spell length indices. Trends have tended to be consistent with those of total rainfall (Manton et al., 2001; Griffiths et al., 2003) and thus consistent with the diagonal SPCZ displacement (Folland et al., 2002).

There is little information available on the general climate and trends in total and extreme rainfall for East Timor, Papua New Guinea, Nauru and the Pacific Islands immediately north of the equator. In addition to ENSO, the major climate features that influence rainfall in these regions are the West Pacific Monsoon (WPM) and the Intertropical Convergence Zone (ITCZ) (Figure 1). The WPM is the southern extension of the
larger Asian–Australian Monsoon system that moves seasonally from the Northern Hemisphere into the tropical regions of the Southern Hemisphere during December to February (Australian Bureau of Meteorology and CSIRO, 2011). The WPM can be characterized as the seasonal reversal of prevailing winds (Kim et al., 2008) that brings heavy rainfall to the region north of Australia, extending from East Timor to the Solomon Islands. Much of the rainfall variability in this region can be attributed to variations in the timing, position, intensity, longevity and extent of the monsoon. Year-to-year variability is somewhat associated with ENSO (with the most extreme eastward extents occurring during the 1982–1983 and 1997–1998 El Niño events) and the extent of the monsoon-affected region is substantial, especially on the eastern edge, where it varies by more than 5000 km between maximum and minimum extent. The north–south variability of the western wind domain is much less pronounced (ABOM-CSIRO, 2011).

The ITCZ is located close to the equator and extends longitudinally across the tropical North Pacific for much of the year (Barry and Chorley, 1992). The ITCZ is one of the major features determining the climate of the tropical North Pacific, marked by the presence of a surface pressure trough, and formed by the convergence of moisture and heat-laden Northern and Southern Hemisphere trade winds. The upward branch of the Hadley Circulation cell in the Pacific sits over the ITCZ (ABOM-CSIRO, 2011). In the central and eastern Pacific, the ITCZ is narrow, whereas in the west the ITCZ becomes broad, due to strong monsoon flows, and the breadth of the ‘warm pool’ to the north and south. The position of the ITCZ in the central and eastern Pacific varies seasonally by approximately 5°. The ITCZ is closest to the equator from March to May, and furthest north from September to November, when it becomes broader, expanding both to the north and south (Waliser and Gautier, 1993). Rainfall totals in the ITCZ region peak in September–November at values around 50% higher than those of the (late) southern summer, January to March (ABOM-CSIRO, 2011).

Other meteorological features such as tropical cyclones have the potential to influence rainfall extremes in the non-equatorial parts of the western Pacific on longer timescales. Tropical cyclones (known as typhoons in the North Pacific) are often associated with brief periods of very heavy rain and it is known that their variability is related to factors such as ENSO (Dowdy et al., 2012). A comprehensive analysis of Southwest Pacific tropical cyclone best track data has shown no statistically significant trends in the total number of tropical cyclones over the period 1981–2007 nor in the overall number of intense tropical cyclones in the South Pacific Ocean (Kuleshov et al., 2010). Observation-based studies for the Northwest Pacific (Liu and Chan, 2008; Goh and Chan, 2010; Song et al., 2010) have not reached consensus with regards to the trends of tropical cyclones over the past few decades. It is important to note that the absence of overall trends for the South Pacific does not discount the possibility of subregional trends, noting for example evidence for a decline near the Australian coast (Callaghan and Power, 2010).

The aim of this study is to analyse past changes and variability in total and extreme rainfall in the western Pacific including East Timor. Secondary objectives are to further investigate possible causal mechanisms underlying observed trends and variability. This work is part of Pacific Climate Change Science Program (PCCSP, 2009–2011) and Pacific-Australia Climate Change Science and Adaptation Planning program (PACCSAP, 2012–2013), which sought to understand past climate
trends and variability and provide regional and national climate projections to partner countries (Power et al., 2011). The total and extreme trends presented here are based on updated and improved rainfall records developed in collaboration with the local National Meteorological Services in the region. Partner countries to the PCCSP/PACCSAP were the Cook Islands, East Timor, Federated States of Micronesia, Fiji, Kiribati, Marshall Islands, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu. In addition several other neighbouring states and territories collaborated at various times as described below.

This article is organized as follows: the observational data as well as the data quality control, homogenization, indices and trend calculation methodology are presented in Section 2. The total and extreme rainfall trends as well as relationship with ENSO analyses are presented in Section 3. The results are discussed and conclusions presented in Section 4.

2. Data, indices and methods

2.1. Station data

The primary mechanisms used to collate the regional rainfall dataset were research and training workshops followed by peer to peer exchanges and data exchange. The first workshop was held in Darwin, Australia, in June 2010 and second in Noumea, New Caledonia, in May 2012. The second workshop was modelled on the Expert Team on Climate Change Detection and Indices (ETCCDI) coordinated workshops designed to analyse trends in climate extremes at a regional level (Peterson and Manton, 2008). The ETCCDI is jointly sponsored by the World Meteorological Organisation (WMO) Commission for Climatology, the World Climate Research Programme on Climate Variability and Predictability (CLIVAR) and the Joint Commission for Oceanography and Marine Meteorology (JCOMM). Typically such workshops involve participants from several nations across a region coming together with data from their country to undertake analyses using standard definitions and methods. Not only does this allow direct cross-border comparisons, it also helps to build links between researchers across the region, and encourage data sharing beyond that which might happen under the auspices of the WMO. These types of workshops have proven highly successful in breaking down the barriers to data exchange, as well as leaving a legacy of improved local capacity for analysis. The workshops were attended by representatives of the National Meteorological Services of the 15 PCCSP/PACCSAP partner countries, American

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Table 1. List of the ETCCDI indices used.

| Group                  | ID | Indicator name                        | Units      |
|------------------------|----|---------------------------------------|------------|
| Absolute Indices       | RX1day | Max 1-day rainfall                    | mm         |
|                        | RX5day | Max 5-day rainfall                    | mm         |
| Threshold Indices      | R1mm | Days with 1 mm or more rainfall       | Days       |
|                        | R10mm | Days with 10 mm or more rainfall      | Days       |
|                        | R20mm | Days with 20 mm or more rainfall      | Days       |
| Duration Indices       | CDD  | Consecutive dry days                  | Days       |
|                        | CWD  | Consecutive wet days                  | Days       |
| Percentile-based Indices | R95p | Very wet days (above the 95th percentile of days with ≥ 1 mm rain, base period 1971–2000) | mm         |
|                        | R99p | Extremely wet days (above the 99th percentile of days with ≥ 1 mm rain, base period 1971–2000) | mm         |
| Other Indices          | SDII | Simple daily intensity index (average rainfall on days with ≥ 1 mm rain) | mm         |

Participants were asked to contribute monthly time series of temperature (maximum and minimum) and rainfall data from the best and longest climate station records in their country (ideally 1–3 stations for small countries, 5–7 for larger ones) that were at least 25 years long, and 80% complete. The expectation of insufficient daily and sub-daily data, complications with obtaining data and the anticipation of the PCCSP ending in mid-2011 resulted in only basic analysis of trends using monthly data being considered during the PCCSP. Additional funding under the PACCSAP program from July 2011 allowed for a specific project examining trends in climate extremes. At the Noumea workshop, participants were asked to contribute daily rainfall data for the same stations analysed in Darwin. Data collated at the workshops were supplemented with records sourced from Australian Bureau of Meteorology, NIWA and NOAA National Climatic Data Center archives, as well as data collected during in-country visits and sent to the lead authors after the workshops through e-mail. An examination of trends in western Pacific temperature extremes is presented in Whan et al. (in press). It is worth noting that this project included data for seven countries or territories (American Samoa, Guam, Palau, Federated States of Micronesia, Marshall Islands, Vanuatu, Wallis and Futuna) that had not previously been included in global or regional analyses. We have not used western Pacific observed rainfall data from other global archives as in some cases these records differ significantly from those in-country and in colonial archives. Quick comparisons found in-country and colonial archive records to be more akin to the original observations. Work is ongoing with regards to improving data quality and access with support from the Australian Bureau of Meteorology and NIWA. The authors anticipate that these modifications will be reflected in the global archives in the near future.

More than 100 stations were sourced from the 15 PCCSP/PACCSAP Partner Countries, American Samoa, the Australian Pacific Islands, French Polynesia, Guam, New Caledonia, New Zealand, Pitcairn Islands, Tokelau and Wallis and Futuna. All the data obtained are archived in the Pacific Climate Change Data Portal (http://www.bom.gov.au/climate/pccsp/). A unique feature of this data portal is the ability for countries to upload, analyse and manage their own data holdings remotely, meaning that while the data are centrally analysed and stored, full ownership and responsibility lies with the country of origin. Ideally, all data would be free and open, to facilitate data exchange between nations. However, in practice this is often not possible due to the costs associated with maintaining operational networks. By preserving ownership and control of data one is able to substantially, if not entirely, work around these issues.

2.2. Data quality and homogeneity

Some basic quality control of rainfall data was undertaken in-country and every effort has been made to ensure that the digitized data match the original paper-based observations. Further quality control was performed at and following the Darwin and Noumea workshops using the freely available software package: R ClimDex, which performs data quality control and calculates indices (Zhang and Yang, 2004, available at http://etccdi.pacificclimate.org/software.shtml). R ClimDex allows for the detection of outliers at daily timescales, allowing the setting of a range of thresholds for flagging suspect data. This quality information was manually interpreted for all stations, and suspect data were removed, disaggregated or re-entered from manual reports depending on the nature of the ‘data error’.

A key factor in any analysis of climate change is ensuring the data are fit for purpose and that artificial changes unrelated to climate factors are minimized (Trewin, 2010). To develop the homogeneous dataset, each data series was inspected visually to assess its suitability for homogenization. Some records were considered too short, incomplete or of insufficient quality to produce a viable homogeneous record. In some cases the earliest part of the raw data record was removed to avoid data where metadata indicated that observation practices...
Figure 3. Trends in Annual (January–December) Rainfall. 1961–2011 (top panel), 1981–2011 (middle panel), Blue circles represent positive trends and red circles negative trends. Solid circles represent trends significant at the 5% level. Reanalysis ERA-Interim gridded rainfall 1981–2011 (units mm decade$^{-1}$) (bottom panel).

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or instrumentation differed significantly from more recent practice. There are many scientific papers which discuss the need for, and application of homogenization including Peterson et al. (1998), Wang et al. (2010), Jovanovic et al. (2012) and Trewyn (2013).

Each series was then assessed for potential inhomogeneities using subjective and objective tests. This involved a combination of visual examinations, neighbour comparisons and the application of the RHTestV3 statistical test (Wang 2003, 2008a, 2008b). There are several data homogeneity tests available internationally (Reeves et al., 2007). The choice of RHTestV3 (available at http://etccdi.pacificclimate.org/software.shtml) was based on the software being freely available and the ability to run the software on a laptop or personal computer, making it particularly useful in developing countries and for application beyond the time frame of the current study. Reeves et al. (2007) also found that developments in the two-phase regression method since 1995, reflected in recent versions had substantially improved its performance. We acknowledge that well-established statistical methods for testing the homogeneity of daily resolution series are lacking (Wijngaard et al., 2003) and RHTestV3 is not the best homogeneity test even for monthly scale data (Venema et al., 2012). Based on expert advice (X. Wang 2012, pers. comm.) we have converted the daily records to monthly totals and tested the homogeneity of log-transformed monthly values. We use the latest versions of the RHTestV3 and RCLimDex (and the Fortran version, FClimDex) as of April 2012.

The power of a homogeneity test is increased if the candidate series can be compared against an independent, highly-correlated, homogeneous reference series (Peterson et al., 1998). A statistically significant change in the relationship between the two series over time is used to flag a potential discontinuity in the candidate series (i.e. that series which we seek to produce a homogenized version). This practice was applied to most station records with at least two neighbouring stations used as reference series. Due to the vast distances between some observation sites, the use of reference series is not always possible. Penrhyn (Cook Islands) and Kiritimati (Kiribati) for example are more than a 1000 km from the nearest neighbouring stations which were assessed to be of sufficient quality for use. The penalized maximal F test (Wang, 2008b) option in RHtestsV3 is used for these stations. Both the penalized t test (Wang et al., 2007) and maximal F tests were employed for stations with a viable comparison. In several cases where further analysis was required the RHtests_dlyPrcp package (Wang et al., 2010) was used as well in addition to referring to station metadata where available.

Monthly rainfall for 68 stations and daily rainfall for 57 stations were available for analysis (Figure 2; Appendix Table A1). Although the authors conclude that these data are largely homogeneous, it is possible that several inhomogeneities have escaped detection. Further work on refining the dataset is ongoing as addition data and metadata become available (See brief discussion on the history of observations in the Pacific Islands in Jones et al., 2013). The homogenized datasets used in this article are those that were in the Data Portal on 14 February 2013. It is hoped that the new dataset is not only suitable for monitoring and analysis of climate change, but will also lead to better validation and interpretation of regional climate projections, and help identify possible adaptation options for people living in the western Pacific. While there is currently sufficient data for analysis, the authors note with concern a decline in station numbers, metadata collection, data quality and the frequency of observations in almost all the countries in the western Pacific. Gaps are present in recent Cook Islands, Fiji, Kiribati, PNG and Tonga station records where prior to the mid-1990s data availability was greater than 95%.

2.3. Calculation of rainfall indices

Eleven of the 27 indices recommended by the ETCCDI are rainfall related while the others are associated with near surface air temperature. The rainfall indices were generated using daily rainfall data as described in Section 2.1. A full descriptive list of the indices can be obtained from http://etccdi.pacificclimate.org/list_27_indices.shtml (Karl et al., 1999; Peterson et al., 2001). The indices are chosen primarily for assessment of the many aspects of a changing global climate that include changes in intensity, frequency and duration of temperature and rainfall events. They represent events that occur several times per season or year, giving them more robust statistical properties than measures of extremes which are far enough into the tails of the distribution so as not to be observed during some years (Alexander et al., 2006). One weakness of the index approach is that it may not reveal the changing nature of the most extreme events.

For this study 10 rainfall indices have been used (Table 1). Nine are core indices defined within RCLimDex while the 10th is a user-defined index, ‘Annual count of days with PRCP ≥ nn mm’. We have selected ‘1 mm’ as our user-defined threshold (i.e. R1mm). All the indices are calculated via the Pacific Climate Change Data Portal that incorporates FCLimDex. The PRCP_TOT core index (annual total precipitation when PRCP ≥ 1 mm) has not been used as total rainfall is calculated from monthly values that are longer and more complete in most western Pacific countries. The rainfall indices are divided into five different categories as presented in Alexander et al. (2006).

2.4. Trend calculations and regional series

Not all indices are normally distributed, for example the frequency/count indices are bounded both below and above, so the use of simple linear least squares trend estimation is not appropriate (Alexander et al., 2006). The trends described here have been calculated using the nonparametric Kendall’s tau slope estimator which is available as an ‘autotrend’, R script developed by Environment Canada (Y. Fang and X. Wang, 2013). The power of a homogeneity test is increased if the candidate series can be compared against an independent, highly-correlated, homogeneous reference series (Peterson et al., 1998). A statistically significant change in the relationship between the two series over time is used to flag a potential discontinuity in the candidate series (i.e. that series which we seek to produce a homogenized version). This practice was applied to most station records with at least two neighbouring stations used as reference series. Due to the vast distances between some observation sites, the use of reference series is not always possible. Penrhyn (Cook Islands) and Kiritimati (Kiribati) for example are more than a 1000 km from the nearest neighbouring stations which were assessed to be of sufficient quality for use. The penalized maximal F test (Wang, 2008b) option in RHtestsV3 is used for these stations. Both the penalized t test (Wang et al., 2007) and maximal F tests were employed for stations with a viable comparison. In several cases where further analysis was required the RHtests_dlyPrcp package (Wang et al., 2010) was used as well in addition to referring to station metadata where available.

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As the stations cover a large geographical area and unique relationships exist with the major modes of variability and climate features, six subregional mean time series have been produced for each index (Figure 2). The subregions are the West Pacific Monsoon (WPM), North ITCZ (nITCZ), Southwest SPCZ (swSPCZ), Central tropics (CT), between the ITCZ and SPCZ) and South Pacific sub tropics (ST) and Far east SPCZ (feSPCZ). These subdivisions are based on the following general characteristics: CT significantly wetter during El Niño events; WPM significantly drier during El Niño years; swSPCZ and WPM significantly drier in El Niño+1 years with the wettest months December–February and July–August, respectively (Lough et al., 2011). Preliminary analyses showed the ST climate to be notably drier than that of the swSPCZ subregion with the wettest months from June–August. The feSPCZ could be included in the swSPCZ, but rainfall in this region has a weak relationship with the Southern Oscillation Index (SOI). For the purposes of this research the feSPCZ is treated as an individual subregion. Clearly, the exact boundaries of the climate feature are not unambiguously defined and the availability of stations requires some compromise about boundaries. As total rainfall and indices start dates are different and records are not available for every year we have adjusted the variance introduced by the changing number of data points available for each year taking into account the correlation between stations. This method has been employed in many works dealing with observational records (e.g. Jones et al., 2001; Brunet et al., 2007; Caesar et al., 2011).
of the negative IPO phase from 1999 on rainfall trends to become apparent. The period selected is a balance between minimizing the impact of interannual variability on the trend calculation and emphasizing the recent IPO phase. Previous studies (e.g. Griffiths et al., 2003) have found that interannual and decadal variability dominates long-term trends in western Pacific rainfall. We accept that short-term trends should not be taken as an indication of the future direction of change.

Hadley Centre SST and sea ice dataset (HadISST SST, Version 1.1 and HadISST ICE, Version 1.1) have been used to examine the relationship between total and extreme rainfall and SST patterns. HadISST is a combination of monthly globally complete fields of SST and sea ice concentration on a 1° latitude–longitude grid (Rayner et al., 2003) and is available from the Met Office Hadley Centre (http://www.metoffice.gov.uk/hadobs/). Pearson’s correlation coefficients were calculated between detrended subregional total and extreme rainfall and SST anomalies from the HadISST dataset over the period 1951–2011 to identify patterns of covariability. A similar methodology has been employed to examine the relationship between total and extreme rainfall and the annual average (January–December) of the SOI over the same period. SOI values were obtained from the Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/current/soihtm1.shtml). While significant relationships are possible with lagged correlations between ENSO and Pacific Island rainfall (e.g. Walsh et al., 2001), this aspect of the ENSO–rainfall relationship has not been examined in this article.

3. Results

3.1. Trends in total rainfall

Station trends over the 1961–2011 period are largely non-significant (approximately 95% of stations) and spatially heterogeneous except in the South Pacific subtropics where all the station trends are negative although not significant (Figure 3, top panel). Statistically significant trends (5% level) are limited to Kiritimati (+110.4 mm decade⁻¹) and Hihifo (−153.6 mm decade⁻¹).

A notable change in trend pattern is evident from 1981 (Figure 3, middle panel). Positive trends are observed across most of the WPM region, south and west of the SPCZ from Vanuatu to the Southern Cook Islands and in the west ITCZ region from Koror to Pohnpei in the North Pacific. North and east of the SPCZ negative trends are recorded at Nauru, Tarawa, Funafuti, French Polynesia and Pitcairn as well as north of the ITCZ at Guam and in the eastern ITCZ region in the Marshall Islands. Negative trends also exist in the South Pacific subtropics (except at Norfolk Island), at two sites in New Caledonia and at Willis Island off the Australian mainland. There are seven statistically significant trends (approximately 11% of stations) across the region: a negative trend at Funafuti and positive trends in the WPM (two), southwest of the SPCZ from Vanuatu to the Southern Cook Islands and in the Marshall Islands. Negative trends also exist in the South Pacific subtropics (except at Norfolk Island), at two sites in New Caledonia and at Willis Island off the Australian mainland. There are seven statistically significant trends (approximately 11% of stations) across the region: a negative trend at Funafuti and positive trends in the WPM (two), southwest of the SPCZ (three) and north of the ITCZ (one). There is remarkable spatial similarity between the observed rainfall trends for 1981–2011 and the annual mean (January–December) ERA–Interim reanalysis (Dee et al., 2011) trends for...
the same period (Figure 3, bottom panel). This suggests that these reanalyses (at least to first order) can be used for the description of rainfall trends in the region. However, reanalyses need to be used with caution when investigating trends in these types of indices. Reanalysis data prior to the 1981 should not be used for trends analysis (Sillmann et al., 2013). It is also worth noting that the ERA–Interim model reanalysis trend pattern is similar to the composite La Niña austral summer rainfall pattern (not shown), which is expected to be dominated by La Niña events from the late 1990s.

On a subregional scale, we have found the ST negative trend to be significant over 1951–2011 (Table 2A, Figure 4) and the WPM positive and feSPCZ negative trends to be significant over 1981–2011 (Table 2B). The decline in the ST rainfall is consistent with trends further west affecting south-eastern Australia where rainfall has decreased during autumn, particularly since the mid-1990s (Timbal, 2009). These declines are consistent with an expansion of the subtropical ridge in the southern subtropics together with an increase in intensity (Timbal and Drosdowsky, 2013; Whan et al., 2013). The subtropical ridge is the downward part of the Hadley Cell; a band of high pressure circling the globe at approximately 30° latitude in both the hemispheres.

3.2. Trends in rainfall indices

As for total rainfall, trends in the rainfall indices are largely spatially inconsistent in the extreme rainfall trends over 1961–2011 and the number of stations with significant trends is low (e.g. Figure 5, top panel). For R10mm, only the Lamap (−3.33 days decade−1) trend is significant (5% level). On a subregional scale, only the positive SDII trends in the WPM and negative R1mm and R10mm trends in the ST are significant (Table 2A).

For the period 1981–2011, trends in the threshold (e.g. R20mm, Figure 5, middle panel), percentile-based indices and CDD are similar to trends in total rainfall, consistent with a change across the mean position of the SPCZ. Based on these results, together with those of Murphy et al. (in press) we deduce that since 1999 the WPM has intensified, the SPCZ has been displaced south and extended northward west of 140°E. It should be stated however, that few of the station trends are significant for this shorter period. Trends in the absolute indices in the swSPCZ subregion are unlike those of the total rainfall, threshold indices and the percentile indices. Here the trend pattern in Max 1- (Figure 5, bottom panel) and 5-day rainfall are predominately negative, the reverse of the generally positive trend patterns in the total, threshold, CDD and percentile-based indices (the large positive trend for Nuku’alofa, Tonga which is also present in the Max 5-day rainfall plot (not shown) is likely to be an anomaly). These results, although not conclusive as most of the rainfall trends are not significant, suggest that the increase in rainfall since 1999 does not apply to the Max 1- and 5-day rainfall events. Further analysis of Nadi Airport, Fiji daily rainfall and tropical cyclone records over 1981–2011 reveals that 15 of 31 annual Max 1-day events are associated with tropical cyclones. Of these events 10 occurred between 1981 and 1993 meaning that the decline in Max 1-day rainfall is due to a similar reduction in tropical cyclones activity.

On a subregional scale, the positive trend in R1mm for 1951–2011 in the swSPCZ subregion is significant as are the negative trends in CDD (nITCZ), R20mm (feSPCZ) and SDII, Rx1day, Rx5day, R95p and R99p in the CT subregion (Table 2B). These results show that in the last 30 years the greatest changes in extreme rainfall have not been consistent across the western Pacific. They have been at the most extreme level in the CT subregion, whereas in the swSPCZ subregion the greatest change has been in the number of days with rainfall.

3.3. Relationship with SSTs and SOI

The total rainfall time series for the six subregions of the western Pacific (Figure 2) show substantial interannual variability (Figure 4) which is expected given the well-established role for variations in ENSO (as shown by the relationship with the SOI, Table 3) and the IPO in the region. In the CT subregion where variability is greatest, annual peaks (dips) are strongly associated with El Niño (La Niña) years or events. An inverse relationship exists between total rainfall and ENSO in the nITCZ, swSPCZ, ST and WPM subregions. In the swSPCZ subregion, greatest rainfall suppression is generally in the year after the El Niño event (e.g. 1998). The reason for this lag is uncertain at the present time.

Total rainfall is positively correlated with local SSTs in the CT (Figure 6, top panel), swSPCZ, WPM, nITCZ (eastern portion only) and ST (excluding Norfolk Is.) subregions but not in the feSPCZ and western portions of the nITCZ and ST subregions. With the exception of the CT (where local SSTs are central Pacific SSTs) there is generally an inverse relationship between total rainfall and central and eastern (CE) Pacific SSTs. Similar relationships exist for the threshold indices. In the case of the feSPCZ subregion, a relationship with CE Pacific SSTs that is not apparent for total rainfall is present for R1mm (Figure 6, middle panel) and to a lesser extent with R10mm. These findings are in general agreement with those in Table 3 where the strength of the relationship between the SOI and total rainfall and the extreme rainfall indices are presented.

There is a clear relationship between ENSO (both SOI and SSTs) and local SSTs and the percentile and absolute indices in the CT and ST subregions. ENSO also appears to have a moderate to strong influence on R95p in the swSPCZ subregion (Figure 6, bottom panel; greater R95p associated with La Niña events) and marginal influence (inverse relationship with the SOI) on R99p and Max 5-day rainfall in the nITCZ subregion. The SST plots (not presented) show this influence to mainly be in the western portion of the nITCZ region. The relationship...
Figure 5. Trends in annual rainfall indices. Number of rain days ≥ 10 mm (R10mm) 1961–2011 (top panel) Number of rain days ≥ 20 mm (R20mm) 1981–2011 (middle panel) Max 1-day rainfall (Rx1day) 1981–2011 (bottom panel). Blue circles represent positive trends and red circles negative trends. Solid circles represent trends significant at the 5% level.
Figure 6. Correlation of 1951–2011 regional annual series of HadISST with Total rainfall in the Central Tropics (top panel) Days with 1 mm or more rainfall (R1mm) in the Far east SPCZ (middle panel) and Very wet days (R95p) in the Southwest SPCZ (bottom panel). The linear trend has been removed from all series as a means to focus attention on the interannual covariability. Stippling marks significance at the 5% level. Green dots show the sites used for the correlations. The single green dot in the middle panel represents nine sites in the Society Islands, French Polynesia, as shown in Figure 2.
between ENSO and the percentile and absolute indices elsewhere is less noteworthy.

The results of the relationship between annual average SOI and total and extreme rainfall analysis (Table 3) also show that for some subregions (nITCZ, WPM, swSPCZ and ST) the threshold indices have a stronger relationship with the SOI than total rainfall. This generally does not apply to the more extreme (absolute and percentile) indices in these subregions.

### 4. Discussion and conclusions

As small island states are amongst the most vulnerable countries to extreme events (McCarthy et al., 2001), the analysis of past changes in total and extreme rainfall in the western Pacific is vital. Our findings complement efforts to model future rainfall changes, e.g. ABOM-CSIRO (2011) and are essential for effective climate change adaptation, as well as providing confidence for the use of future climate change projections. Through the PCCSP and PACCSP Program (Power et al., 2011), rainfall records for 23 countries and territories and the western Pacific have been collated for the purpose of examining trends in total and extreme rainfall. Of about 100 station records, 68 monthly and 61 daily records were found to be of sufficient length and homogeneous. A majority of the remaining records were too short or did not extend sufficiently over the analysis periods, which are from 1961 and 1981 on a station level and from 1951 and 1981 on a subregional level. A unique feature of this study is the collation of data in a single Internet portal, so that the trends and variability in mean and extreme indices can be kept up to date, and viewed through the World Wide Web.

We have found that trends in western Pacific total rainfall for 1961–2011 tend to lack spatial coherence north of the South Pacific subtropics and there are few significant trends – less than 5% of individual stations. On a subregional level only the negative trend in the South Pacific subtropics is statistically significant for the period 1951–2011. This relative lack of significant trends is perhaps not surprising as rainfall variability in the region is large, and recent estimates of the sensitivity of tropical Pacific rainfall to global warming suggests relatively small changes per degree of global warming (ABOM-CSIRO, 2011). Manton et al. (2001) and Griffiths et al. (2003) found that rainfall trends in the South Pacific were spatially consistent east of the dateline, with a break across the SPCZ over the 1961–1998 and 1961–2000 periods, respectively. It had become wetter to the north of the diagonal SPCZ and drier to the southwest. West of the dateline, a region influenced by the zonal portion of the SPCZ, trends were typically less coherent and not significant. These trends were associated with northeasterwards movement of the diagonal SPCZ since the late 1970s through to the 1990s, associated with a shift to a positive IPO phase.

In addition to longer and more reliable records, the primary reason our results are different from earlier analyses is the switch to a negative IPO phase from 1999 with a recent dominance of La Niña events. This is reflected in trends in total rainfall (both observed and reanalysis data) over 1981–2011. It has become wetter in the WPM region and southwest of the mean SPCZ position. In the tropical North Pacific it has become wetter west of 160°E with the ITCZ/WPM expanding northwards west of 140°E. Northeast of the SPCZ and in the central tropical Pacific east of about 160°E it has become drier. Our findings for the subtropical region are consistent with those of Jovanovic et al. (2012) and broader trends seen in parts of south-eastern Australia (Timbal, 2009), which are associated with an increase in intensity and expansion of the subtropical ridge of high pressure (Timbal and Drosdowski, 2013; Whan et al., 2013). We observe that although the relationship between ENSO and total rainfall in the South Pacific subtropics is significant, the negative IPO phase has not resulted in positive rainfall trends as observed in the Southwest SPCZ region.

Similar to trends in total rainfall, trends in extreme rainfall over 1961–2011 on a station level show little

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**Table 3. Relationship between annual average SOI and the variance adjusted subregional (annual) total rainfall and rainfall indices for the period 1951–2011.**

|               | North ITCZ | Central tropics | WPM | Southwest SPCZ | Far east SPCZ | South Pacific subtropics |
|---------------|------------|-----------------|-----|-----------------|---------------|--------------------------|
| Total rainfall| 0.334      | −0.828          | 0.585         | 0.710          | −0.149        | 0.481                    |
| Rx1day        | −0.242     | −0.473          | −0.150        | −0.001         | −0.123*       | 0.306                    |
| Rx5day        | −0.263     | −0.489          | −0.028        | 0.242          | −0.032*       | 0.420                    |
| R1mm          | 0.691      | −0.809          | 0.683         | 0.758          | 0.425*        | 0.535                    |
| R10mm         | 0.597      | −0.815          | 0.675         | 0.755          | 0.148*        | 0.654                    |
| R20mm         | 0.483      | −0.803          | 0.614         | 0.728          | −0.074*       | 0.568                    |
| CDD           | −0.410     | 0.629           | −0.553        | −0.722         | −0.109*       | −0.199                   |
| CWD           | 0.452      | −0.445          | 0.252         | 0.525          | 0.249*        | 0.138                    |
| R95p          | −0.157     | −0.723          | 0.229         | 0.482          | −0.177*       | 0.511                    |
| R99p          | −0.290     | −0.516          | −0.083        | 0.127          | −0.147*       | 0.383                    |
| SDII          | −0.121     | −0.732          | 0.179         | 0.417          | −0.365*       | 0.527                    |

Trends significant at the 5% level are shown in bold. *Data from 1961–2011.
spatial consistency and the number of stations with significant trends is low. On a subregional scale, only the positive SDII trends in the WPM and negative R10mm and R110mm trends in the subtropics are significant over 1951–2011.

The results from the ‘Relationship with SSTs’ analyses (Section 3.3.) confirm a strong relationship between ENSO and total rainfall and the threshold indices as found in the Southeast Asia region (Caesar et al., 2011). The percentile-based and absolute indices are influenced by ENSO to a lesser extent and in some cases the influence is negligible. Undoubtedly, larger-scale SST variability is not the only influence on these indices. The results of this study suggest the negative trends in Max 1-day rainfall southwest of the SPCZ over 1981–2011 are associated with reduced tropical cyclone occurrence near the dateline over the same period. Trends in South Pacific tropical cyclone frequency also show a negative trend but lack significance (Kuleshov et al., 2010).

The authors note a decline in station numbers, apparent data quality and the frequency of observations in almost all the countries in the western Pacific over the last two decades. As there is modest knowledge of climate in this region and the area covers approximately 8% of the earth’s surface, priority should be given to these countries with regards to improving observations and managing station data and metadata. Compared to earlier decades, little metadata is currently being documented and this will continue to hinder the homogenization of meteorological records in the future. While the PACCSAP program has recently contributed to data rescue efforts, a large amount of data continues to only be in hardcopy format (both in-country and in colonial archives), and further digitization of these data offer the possibility of extending the current analyses both temporally and spatially.

Acknowledgements
This study was fully funded by the Australian government’s International Climate Change Adaptation Initiative, and delivered through the Pacific Climate Change Science and Pacific-Australia Climate Change Science and Adaptation Planning Programs. It has only been made possible through the contributions of historical data and station history information from meteorological and climate organizations located in American Samoa, Cook Islands, East Timor, Federated States of Micronesia, Fiji, French Polynesia, Kiribati, Marshall Islands, Nauru, New Caledonia, New Zealand, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, the USA and Vanuatu. The authors thank the heads of these agencies for permitting access to their data and appreciate the assistance employees of these organizations have provided. Lisa Alexander’s contribution was supported by the Australian Research Council grant CE110001028. The authors are particularly grateful to Jim Salinger for metadata and personal knowledge about several Pacific island stations, and Blair Trewin, Xiaolan Wang, Yang Feng and Guomin Wang for assistance in training Partner Country representatives in data homogenization and providing the authors with advice, software and data. The authors wish to thank the Bureau of Meteorology internal reviewers and IJC anonymous reviewers for their comments and contributions.

APPENDIX

Table A1. List of stations used in this study together with the period of record.

| Country                    | Station       | Longitude | Latitude | Available daily record (start year or period of monthly record)* |
|----------------------------|---------------|-----------|----------|---------------------------------------------------------------|
| American Samoa             | Pagopago      | 170.71°E | 14.33°S  | 1957–2011                                                     |
| Australia                  | Willis Island | 149.98°E | 16.30°S  | 1924–2010                                                     |
|                            | Norfolk Island Aero | 167.94°E | 29.04°S  | 1915–2011                                                     |
|                            | Lord Howe Island Aero | 159.08°E | 31.54°S  | 1950–2011                                                     |
| Cook Islands               | Rarotonga      | 159.80°W | 21.20°S  | 1934–2011 (1899)                                             |
|                            | Penrhyn        | 158.05°W | 9.03°S   | 1937–2011                                                     |
|                            | Aitutaki       | 159.77°W | 18.83°S  | 1946–2011 (1939)                                             |
| East Timor                 | Dili Airport   | 125.57°E | 8.57°N   | 1970–2011 (1917)                                             |
| Federated States of Micronesia | Pohnpei     | 158.22°E | 6.97°N   | 1951–2011 (1949)                                             |
|                            | Yap            | 138.08°E | 9.48°N   | 1951–2011                                                     |
|                            | Chuuk          | 151.83°E | 7.45°N   | 1951–2011                                                     |
| Country            | Station                     | Longitude | Latitude | Available daily record (start year or period of monthly record)* |
|--------------------|-----------------------------|-----------|----------|---------------------------------------------------------------|
| Fiji Islands       | Rotuma                      | 177.05°E  | 12.50°S  | 1932–2011 (1912)                                             |
|                    | Nadi Airport                | 177.45°E  | 17.77°S  | 1942–2011                                                    |
|                    | Nausori Airport             | 178.57°E  | 18.05°S  | 1956–2011 (1882)                                             |
|                    | Laucala Bay, Suva           | 178.45°E  | 18.15°S  | 1942–2011                                                    |
|                    | Udu Point                   | 179.98°W  | 16.13°S  | NA (1946–2011)                                               |
|                    | Nabouwalu                   | 178.70°E  | 17.00°S  | 1949–2011                                                    |
|                    | Vunisea                     | 178.17°E  | 19.05°S  | 1947–2011                                                    |
|                    | Ono-i-Lau                   | 178.72°W  | 20.67°S  | NA (1948–2011)                                               |
| French Polynesia   | Rapa                        | 144.33°W  | 27.62°S  | NA (1951–2011)                                               |
|                    | Tahiti-Faa                  | 149.62°W  | 17.55°S  | 1961–2011 (1958)                                             |
|                    | Takaroa                     | 145.03°S  | 14.48°S  | NA (1951–2011)                                               |
|                    | Rikitea                     | 134.97°S  | 23.13°S  | NA (1980–2011)                                               |
|                    | Affaifiti3                  | 149.31°W  | 17.73°S  | 1961–2011                                                    |
|                    | Affaifiti4                  | 149.27°W  | 17.76°S  | 1961–2011                                                    |
|                    | Pirae1                      | 149.54°W  | 17.74°S  | 1961–2011                                                    |
|                    | Pueue1                      | 149.25°W  | 17.74°S  | 1961–2011                                                    |
|                    | Punauaia                    | 149.58°W  | 17.65°S  | 1961–2011                                                    |
| Guam               | Agana (Guam Int. Airport)   | 144.80°E  | 13.48°N  | 1957–2011                                                    |
| Kiribati           | Tarawa                      | 172.92°E  | 1.35°N   | 1947–2011                                                    |
|                    | Butaritari                  | 172.78°E  | 3.03°N   | NA (1931–2010)                                               |
|                    | Kirimiti                     | 157.48°W  | 1.98°N   | NA (1946–2011)                                               |
| Marshall Islands   | Kwajalein/Bucholz Aaf       | 167.73°E  | 8.73°N   | 1952–2011 (1945)                                             |
|                    | Majuro                      | 171.38°E  | 7.08°N   | 1954–2011                                                    |
| Nauru              | Nauru Arc-2                 | 166.92°E  | 0.52°N   | NA (1927–2011)                                               |
| Niue               | Hanan Airport               | 169.93°W  | 19.08°S  | 1915–2011 (1905)                                             |
| New Caledonia      | Kowmac                      | 164.28°E  | 20.57°S  | 1961–2011                                                    |
|                    | Ouanaham                    | 167.23°E  | 20.78°S  | 1961–2011                                                    |
|                    | Poindimie                   | 165.33°E  | 20.93°S  | 1965–2011                                                    |
|                    | LaTontouta                  | 166.22°E  | 22.02°S  | 1961–2011                                                    |
|                    | Noumea                      | 166.45°E  | 22.28°S  | 1961–2011 (1955)                                             |
| New Zealand        | Raoul Island                | 177.92°W  | 29.25°S  | 1937–2011                                                    |
| Palau              | Koror                       | 134.48°E  | 7.33°N   | 1947–2011                                                    |
| Papua New Guinea   | Wewak                       | 143.67°E  | 3.58°S   | 1951–2011                                                    |
|                    | Madang                      | 145.80°E  | 5.22°S   | 1916–2011                                                    |
|                    | Port Moresby                | 147.22°E  | 9.38°S   | 1945–2011                                                    |
|                    | Momote                      | 147.42°E  | 2.05°S   | 1951–2011                                                    |
|                    | Kavieng                     | 150.82°E  | 2.57°S   | 1918–2011                                                    |
|                    | Misima                      | 152.83°S  | 10.68°S  | 1951–2011                                                    |
| Pitcairn Islands   | Pitcairn                    | 130.10°W  | 25.07°S  | NA (1954–2011)                                               |
| Samoa              | Apia                        | 171.78°W  | 13.80°S  | 1961–2011 (1890)                                             |
| Solomon Islands    | Munda                       | 157.27°E  | 8.33°S   | 1962–2011                                                    |
|                    | Honiara                     | 159.97°E  | 9.42°S   | 1949–2011                                                    |
|                    | Henderson                   | 160.05°E  | 9.42°S   | 1975–2011                                                    |
|                    | Auki                        | 160.73°E  | 8.78°S   | 1962–2011                                                    |
|                    | Kirikira                    | 161.92°E  | 10.42°S  | 1964–2011                                                    |
|                    | Santa Cruz                  | 165.80°E  | 10.70°S  | NA (1972–2010)                                               |
| Tonga              | Keppel                      | 173.77°W  | 15.95°S  | 1947–2011                                                    |
|                    | Lupepau’u (Vava’u)          | 173.97°W  | 18.58°S  | 1947–2011                                                    |
|                    | Haapai                      | 174.35°W  | 19.80°S  | 1939–2011                                                    |
|                    | Nuku’alofa                  | 175.18°W  | 21.13°S  | 1938–2011                                                    |
| Tuvalu             | Funafuti                    | 179.22°E  | 8.50°S   | 1961–2011 (1927)                                             |
| Vanuatu            | Sola                        | 167.55°E  | 13.85°S  | 1948–2011                                                    |
|                    | Bauerfield Airport          | 168.30°E  | 17.70°S  | 1925–2011 (1905)                                             |
|                    | Lamap (Malekula)            | 167.80°E  | 16.42°S  | 1960–2011                                                    |
|                    | White Grass Airport         | 169.22°E  | 19.45°S  | 1967–2011                                                    |
|                    | Aneityum                    | 169.77°E  | 20.23°S  | 1948–2011                                                    |
| Wallis and Futuna  | Hihifo (Wallis)             | 176.18°W  | 13.25°S  | 1971–2010 (1964)                                             |

NA—not available. *For some stations, portions of the daily record are missing, yet to be digitized or have not been made available to the PACCSAP Program. These gaps have been filled with monthly records from reputable sources.

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