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Ocean Surface Warming and Long-Term Variability in Rainfall in Equatorial Pacific Atolls

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Abstract: Freshwater availability in Pacific equatorial atolls is highly variable because of the influence of El Niño–Southern Oscillation (ENSO) on rainfall. IPCC projections for the central and western tropical Pacific suggest annual rainfall (P_a) will increase as sea surface temperature (SST) rises. Future changes in ENSO frequency and intensity and in hydrological droughts, however, are uncertain. Here, trends in monthly, seasonal, annual, annual maximum, and minimum rainfall in two equatorial atolls in the eastern and central tropical Pacific are compared with trends in the SST of the surrounding Nino regions from 1951 to 2023. Significant increasing trends in the warm season, annual, and annual maximum SST in the Nino1 + 2, Nino3, and Nino4 regions were of order +1.0 °C/100 y. There were no significant trends in the cool season or annual minimum SST. Despite ocean warming, there were no significant trends in atoll P_a, in intra-annual or interannual variability over 7 decades for either SST or P_a, or in the relative strengths of warm/cool and wet/dry seasons. Extreme, large P_a only occurred after 1987, indicative of ocean warming. Extreme, small P_a happened throughout the period, suggesting no change in drought frequency. Correlations between 12-month P and SST were very strong, with historic rates of increases in P_a of around 1200 mm/y/°C, consistent with projections. The results indicate that the recharge of atoll groundwater will increase as oceans warm, but droughts will remain a major challenge.

Keywords: sea surface temperature; annual rainfall; Pacific atolls; trends; ENSO; extreme events; water security

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1. Introduction

Water resources in small island developing states are recognized internationally as being vulnerable to global change [1]. Those in equatorial Pacific atolls are especially vulnerable [2]. This is partly due to their unique hydrogeology and highly variable rainfall resulting from major ocean–atmosphere interactions such as El Niño–Southern Oscillation (ENSO) events, shifts in predominant rain bands, and changes in the phase of the interdecadal Pacific oscillation (IPO) [2] and also to the density of human settlement and development [3]. The susceptibility of shallow fresh atoll groundwater systems, a major source of freshwater supply, to climate change impacts is of increasing concern.

The Intergovernmental Panel on Climate Change (IPCC) projections for the central and western tropical Pacific indicate that mean annual rainfall is likely to increase as sea surface temperatures (SSTs) warm [4]. ENSO's influence on rainfall over the Indo–Pacific is projected with medium confidence to strengthen and shift eastward, but the projected changes in hydrological drought are less certain because of uncertainties in future ENSO frequency and intensity [4]. While increases in annual rainfall are an advantage to atoll water supplies, both groundwater and harvested rainfall are particularly at risk during prolonged ENSO-related droughts [5]. During the 2021–2023 triple La Niña event in June

2022, the government of Kiribati declared a State of Disaster because of severe water shortages and increasing salinity of groundwater.

By the end of this century, worst-case climate change projections are that SSTs in the equatorial Pacific could rise by 2 to 3 °C relative to 1981–2000 [6], injecting more water vapor into the atmosphere. However, the impacts ocean warming on the variability in ENSO and its attendant influences on the variability in SST, long-term rainfall, and droughts are uncertain [4]. Recent global circulation model (GCM) results [7] suggest that SST variability and ENSO event frequency and intensity have increased post-1960 because of anthropogenic impacts.

Current climate models do not account for ice sheet melting, which has the potential to slow down and eventually turn off the Atlantic Meridional Overturning Circulation (AMOC). Modeling indicates [8] that slowing down and turning off the AMOC will strengthen the Walker Circulation in the Pacific, causing a southward shift in the intertropical convergence zone (ITCZ). This will lead to an increased frequency of La Nina-like conditions. These studies imply increases in drought frequency and intensity in the equatorial Pacific region as the ocean warms. This projection is a major concern for atolls and small island nations in the region.

Analyses of trends in rainfall in the western Pacific concentrated on short-term extreme daily rainfall or days without rain and also examined trends in annual rainfall in Pacific islands for the period 1961 to 2011 [9]. Seasonal trends, important for rainwater harvesting, were not reported. Significant annual rainfall trends were largely absent, and it was suggested that this was due to a phase change in the interdecadal Pacific Oscillation (IPO) around 1999, resulting in a reversal of earlier significant annual trends [9].

Here, we focus on available SST since 1950 in the large Nino regions of the Pacific [10] and on rain gauge records in two equatorial atolls located within two of the Nino regions in the eastern and central tropical Pacific, which are subject to different climate drivers. We explore trends in seasonal, annual, annual maximum, and annual minimum monthly SST and rainfall in both atolls. Trends in the intra- and interannual variability in SST and P_a over 7 decades in the period 1951 to 2023 are investigated. This expands the time range considered in [9] and includes the record, very strong El Niño in 2015–2016 and two triple La Niñas in 1954–1956 and 2020–2022. The Nino SST regions and the two atolls are sensitive to ENSO-induced excursions of the South Pacific convergence zone (SPCZ), the ITCZ [11], and the Western Pacific Monsoon (WPM) [2], which may be modulated by the phase of the IPO [9]. In this work, we also examine the correspondence between longer-term rainfall and longer-term SST in the Nino regions.

The frequency, first appearance, and ranking of extreme, large (greater than the 95th percentile, P95) annual SST (SST_a) and annual rainfall (P_a) events and extreme, small SST_a and P_a events (less than the 5th percentile, P05) are examined for impacts of ocean warming. Possible relationships among 12-month rainfall, P_{12}, and 12-month SST, SST_{12}, in the Nino regions [12] are also explored. We focus on P_{12} and SST_{12} as well as seasonal rainfall relevant to rainwater harvesting, groundwater recharge [3], and water supply droughts in atolls [3,13]. Relationships between above-average (greater than the 70th percentile, P70), below-average (less than the 30th percentile, P30), and average (between tP30 and P70) P_a and SST are examined, and the possible impacts of trends on future groundwater supplies are discussed.

We seek to answer the following questions relevant to equatorial Pacific atoll water security:

1. What are the rates of SST increases in the Nino regions since 1951 and have they resulted in the expected increase in annual rainfall [4] in the equatorial Pacific?
2. Are the projected changes in ENSO frequency and intensity [4] evident in the SST and P records in the equatorial Pacific, particularly in terms of changes in variability or seasonality?
3. Are extreme annual events, especially droughts, increasing in frequency and intensity?
4. How significant are the relationships between P_{12} and SST_{12}?
5. What are the implications for atoll water security?

2. Materials and Methods

2.1. Study Locations

The two near-equatorial atolls chosen for this study are Kiritimati (1.98° N, 157.48° W) and Tarawa (1.35° N, 172.98° E), both in the Republic of Kiribati. The atolls are widely separated by 3300 km of the tropical Pacific, and both have continuous monthly rainfall records from at least January 1951 [14]. Kiritimati, in the central Pacific, borders the Pacific dry zone with annual rainfall influenced by the north–south migration of the ITCZ during ENSO events [2]. Tarawa, in the western Pacific, lies to the east of the Pacific warm pool and close to the confluence of the ITCZ and the SPCZ and can be impacted by the West Pacific Monsoon [2]. Annual rainfall there can vary with the north–south movement of the SPCZ during ENSO events. The differing atmospheric and oceanic factors operating in the regions are discussed in [2]. We chose to use measured rainfall data rather than satellite-derived data because of their direct relevance to atoll water supply. The locations of the atolls relative to the Nino regions are shown in Figure 1.

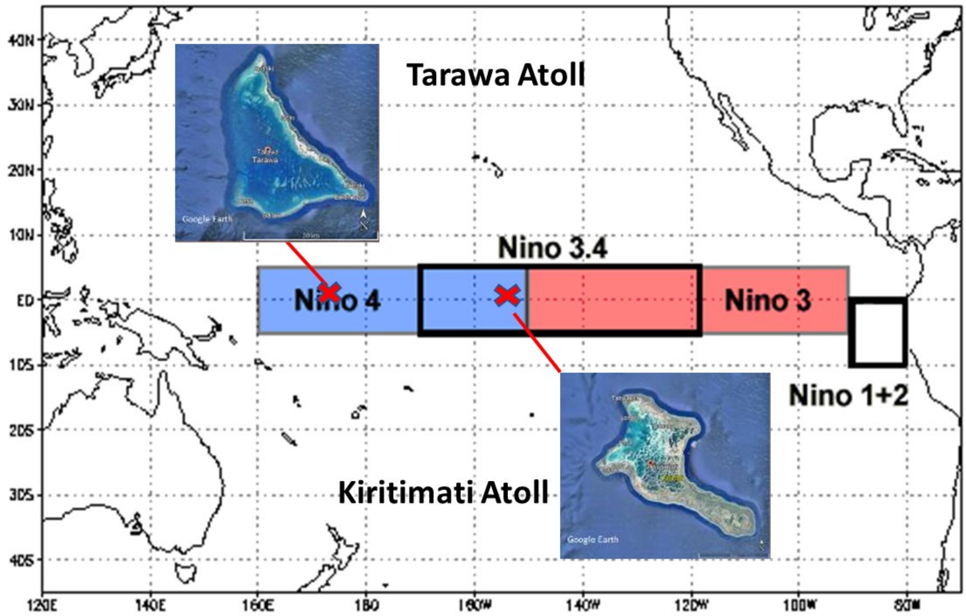

Figure 1. Location of Kiritimati and Tarawa atolls, Republic of Kiribati (red crosses), in relation to the Nino SST regions (modified from NOAA [12]).

Tarawa lies within the Nino4 region (5 N–5 S, 160 E–150 W) in the western Pacific, while Kiritimati lies on the eastern edge of the Nino4 region, just west of the Nino3 region (5 N–5 S, 150 W–90 W) and within the Nino3.4 region (5 N–5 S, 170 W–120 W) in the central Pacific. SST anomalies in the Nino3.4 region are used to identify the occurrence and strength of El Niño and La Niña events.

2.2. Data Sources

Continuous monthly rainfall data for Kiritimati (1951–2023) and Tarawa (1947–2023) were sourced from [14], the Kiribati Meteorological Service (KMS), and supplemented with recent data from [15]. Monthly SST data from 1950 to the end of 2023 for the four Nino regions were sourced from [16]. Actual SST data were used here, not SST anomaly data. Rainfall records for Tarawa were from the KMS headquarters on Betio, at the western edge of South Tarawa, while those for Kiritimati were for the KMS site at Cassidy International Airport, near Banana, or the northeastern side of the atoll. Because both atolls have low elevations, orographic effects on rainfall are expected to be small. On Tarawa, there is some evidence of small spatial variation in rainfall along the 30 km length of South Tarawa [17]. Spatial variation in monthly and longer period P has not been rigorously assessed in

Kiritimati, the world's largest atoll. Because of the shorter continuous rainfall record on Kiritimati, SST and P data were analyzed for the period January 1951 to December 2023.

2.3. Data Analysis, Autocorrelation, Homogeneity, Trends, and Correlations

Lag-1 autocorrelated data can produce false significant trends using the M-K method [9]. All time series were tested for lag-1 autocorrelation. Homogeneity tests on meteorological time series can reveal changepoints because of either measurement changes or changes in physical processes. Modeling has suggested an increase in ENSO frequency and intensity in the 1960s [7], which may result in significant changepoints in the SST or P time series. In addition, changes in the phase of the IPO [9] may also generate changepoints in SST or P data. To test for changepoints in the data, the homogeneity in monthly and annual SST and P data was examined using the non-parametric method of Pettitt [18] with the acceptance level for homogeneity set at $\alpha > 0.05$.

Temporal trends in seasonal and annual SST data are central to this work. Trends were examined using both linear regression and the non-parametric Mann [19]–Kendall [20] (M-K) trend test with Sen's [21] slope estimator. The significance level for the regression and non-parametric trend tests was set at $\alpha < 0.05$. Least square regression tends to be biased to start and end values of a data series and assumes a normal distribution of residuals [9]. While this may be the case for SST data, it is not for P_a. Here, we compare both methods of trend analyses. Regression analyses were performed using EXCEL, and all non-parametric tests were carried out using XLSTAT [22] with procedures for lag-1 autocorrelated data. Climate change projections [4,7] imply not only trends in SST and P but in their variability as well. To examine trends in intra-annual variability in monthly SST and P data, trends in the index of variability, IoV [23], were estimated using Equation (1),

$$\mathrm{IoV} = (\mathrm{P90} - \mathrm{P10})/\mathrm{M}, \tag{1}$$

where P90 and P10 are the 90th and 10th percentiles of monthly values in a year and M (=P50) is the median value. IoV does not assume normally distributed data [23]. Trends in interannual variability in SST and P were also examined by determining the IoV of annual values for each of the seven decades from 1951 to 2020.

A comparison was made between the timing and correspondence of extreme, large annual rainfalls (greater than P95) and extreme, large SST and between extreme, small P_a (less than P05) and extreme, low SST in the Nino regions to examine any changes in the frequency of extreme events between 1951 and 2023. These were compared with the reported strengths of ENSO events [24] assessed from SST anomalies in the Nino3.4 region.

Pearson correlations, R, between 12-month cumulative rainfall, P_{12}, and 12-month average SST in the Nino regions, SST_{12}, were calculated. The differing seasonality in monthly P and monthly SST data means that the strength of correlations depends on the start month of the 12-month period. The start month for each 12-month period was determined for rainfall in each atoll and SST in all four Nino regions. In addition, correlations between above-average (values greater than P70), average (values between P70 and P30), and below-average (values less than P30) P_a and the mean SST in the same year were also calculated. The results were used to estimate the past rate of change in annual precipitation with past ENSO-related excursions of SST in the Nino regions, $\partial P_{12}/\partial SST_{12}$.

Because atoll groundwater responds to long-term variations in rainfall, comparisons were made of the percentiles of 36-month cumulative rainfall with 36-month average SST to explore the similarities in very much above-average (values greater than P90) and very much below-average P and SST. Very much below-normal 36-month rainfalls often correspond to droughts in the equatorial Pacific atolls [13].

3. Results

3.1. Autocorrelations

The only significant lag-1 autocorrelation in seasonal time series was found for warm season SST in the Nino4 region. For annual time series, again, only SST_a for the Nino4 region had significant lag-1 autocorrelation. Both annual maximum and minimum monthly SST in the Nino4 and Nino3.4 regions had significant lag-1 autocorrelation. There were no significant lag-1 autocorrelations in any rainfall time series. The impact of removing lag-1 autocorrelation on trends determined by M-K was checked by removing data in even years and finding the trends for data only in odd years from 1951 to 2023. There was no effect of lag-1 autocorrelation on M-K trends determined using XLSTAT [22].

3.2. Homogeneity in the Time Series

Pettitt tests [18,25] of the homogeneity in seasonal data showed that the only significant changepoint was in warm season SST (SST_w) in the Nino3 ($\alpha < 0.05$) and Nino4 regions ($\alpha < 0.01$) for the year 1989 and wet season P in Tarawa in 1993 ($\alpha < 0.05$). Cool season SST (SST_c) in all regions and dry season P in both atolls as well as wet season P in Kiritimati were homogeneous. The absence of significant changepoints in cool season SST in both Nino3 and Nino4 regions showed seasonal asymmetry. For both regions, the mean SST_w was higher after 1989 than before it. For Tarawa, the mean P_w was less after 1993 than before. Surprisingly, the Nino3.4 region, which straddles the Nino3 and Nino4 (Figure 1), did not have a significant SST_w changepoint.

Annual rainfall time series in both atolls and $SST_{a,M}$ in all Nino regions except the Nino4 region were homogeneous. In the Nino4 region, a very significant changepoint also occurred in 1989 ($\alpha < 0.01$). $SST_{a,M}$ after the year 1989 was 0.4 °C warmer than before it. The year of the changepoint does not correspond to changes in the phase of the IPO, especially that in about 1999 [9]. There was a strong La Niña in 1988–1989 [24], coinciding with a major southward shift in the SPCZ [11].

3.3. Seasonal Variations in SST and Atoll Rainfall

The annual distributions of median monthly SST for the Nino regions over the period 1951 to 2023 in Figure 2 show the magnitude and progression of annual median warmer and cooler periods from the eastern to western Pacific Nino regions (Figure 1) as well as the shift in annual seasonality across the region. The increasing median temperatures and the longer duration of the warmer period from east to west are also apparent. The IoV of monthly SST for each region in Figure 2 is generally smaller in the warmer period than in the cooler period, but all IoVs are very low (IoV < 0.5 [23]). The IoV of annual SST in the Nino regions also decreases with the increase in median annual SST going from the eastern Pacific to the western Pacific (Table 1).

The seasonal distributions of median monthly rainfall for Kiritimati and Tarawa atolls over the period 1951 to 2023 are plotted in Figure 3 together with monthly IoVs of rainfall for each atoll. Kiritimati, in the eastern Pacific on the edge of the Pacific dry zone, has a distinct annual wet and dry season. In Tarawa, influenced by the high rainfall SPCZ and its proximity to the Pacific warm pool [2], the difference between the wet and dry seasons is less pronounced with a shorter average dry season. The onset of the Western Pacific Monsoon [2] is apparent in Tarawa with the increase in rainfall in December (Figure 3).

The IoVs of monthly rainfalls for both atolls in Figure 3 are high (1.25 < IoV < 1.5 [20]) for Tarawa and extreme (IoV > 2 [20]) for Kiritimati in contrast to the low IoV of SST in all Nino regions (Figure 2). Median annual rainfall in Kiritimati (Table 1) is less than 40% of that in Tarawa.

The median monthly values in Figures 2 and 3 together with attendant IoVs help identify the approximate duration of the median warmer and cooler periods in the Nino regions and wetter and drier seasons in the two atolls (Table 2). The duration of the wetter and drier periods in Kiritimati are identical to the warmer and drier periods in the Nino3 region lying to the east of Tarawa, perhaps because of the influence of the generally prevailing easterly trade winds [2]. The median wet and dry seasons in Tarawa, however, do not correspond to the warmer and cooler seasons in the easterly Nino3.4 region or the Nino4 region in which Tarawa is located.

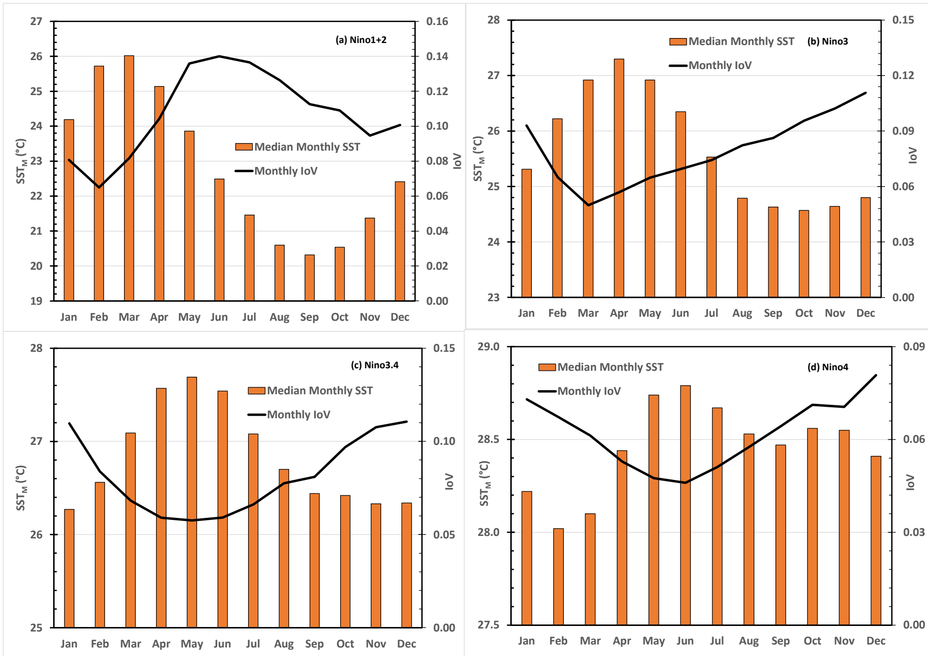

Figure 2. Annual distribution of median monthly sea surface temperatures, SST_M, in the Nino regions (Figure 1) for the period 1951 to 2023. (**a**) Nino1 + 2, (**b**) Nino3, (**c**) Nino3.4, and (**d**) Nino4. Also shown are the monthly indices of variability, IoV, for each region.

Table 1. Median annual SST in the Nino regions and median annual rainfall for Kiritimati and Tarawa together with the indices of variation over the period 1951 to 2023.

Region	SST_M (°C)	IoV	P_M (mm/a)	IoV
Nino1 + 2	22.8	0.26		
Nino3	25.8	0.13		
Nino3.4	27.0	0.10		
Nino4	28.5	0.065		
Kiritimati			782	2.1
Tarawa			1983	1.3

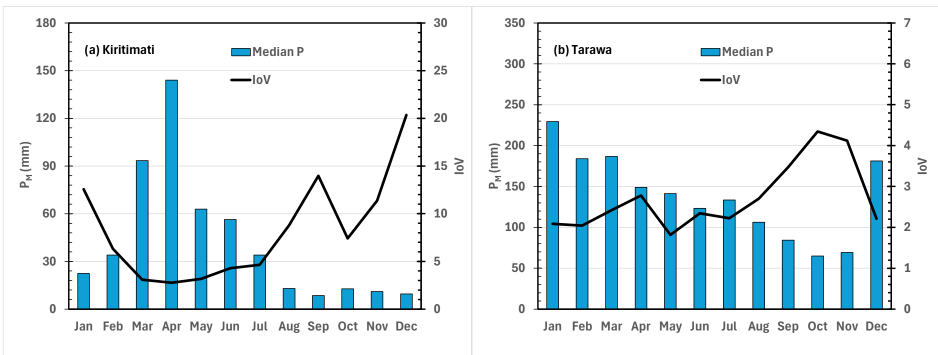

Figure 3. Annual distribution of medium monthly rainfall, P_M, for (**a**) Kiritimati and (**b**) Tarawa atolls for the period 1951 to 2023. Also shown are the monthly indices of variability for each atoll.

Table 2. Approximate duration of the warmer and cooler seasons in the Nino regions and the wetter and drier seasons in Kiritimati and Tarawa atolls. Abbreviated names for month are used.

Location	Duration of Seasons			
	Warmer	**Cooler**	**Wetter**	**Drier**
Nino1 + 2	Dec–Jun	Jul–Nov	-	-
Nino3	Jan–Jul	Aug–Dec	-	-
Nino3.4	Feb–Aug	Sep–Jan	-	-
Nino4	Apr–Dec	Jan–Mar	-	-
Kiritimati	-	-	Jan–Jul	Aug–Dec
Tarawa	-	-	Dec–Jul	Aug–Nov

3.3.1. Seasonal Ratios

The relative strengths of warm/cool SST and wet/dry P seasons over the period 1951 to 2023 are plotted in Figure 4 for the Nino3 and Nino3.4 regions. Figure 4 compares the annual ratio of the average warm season SST to the average cool season SST, $<SST_w>/<SST_c>$, with the annual ratio of the cumulative rainfall in the wet season to that in the dry season, P_w/P_d, for the two atolls between 1951 and 2023.

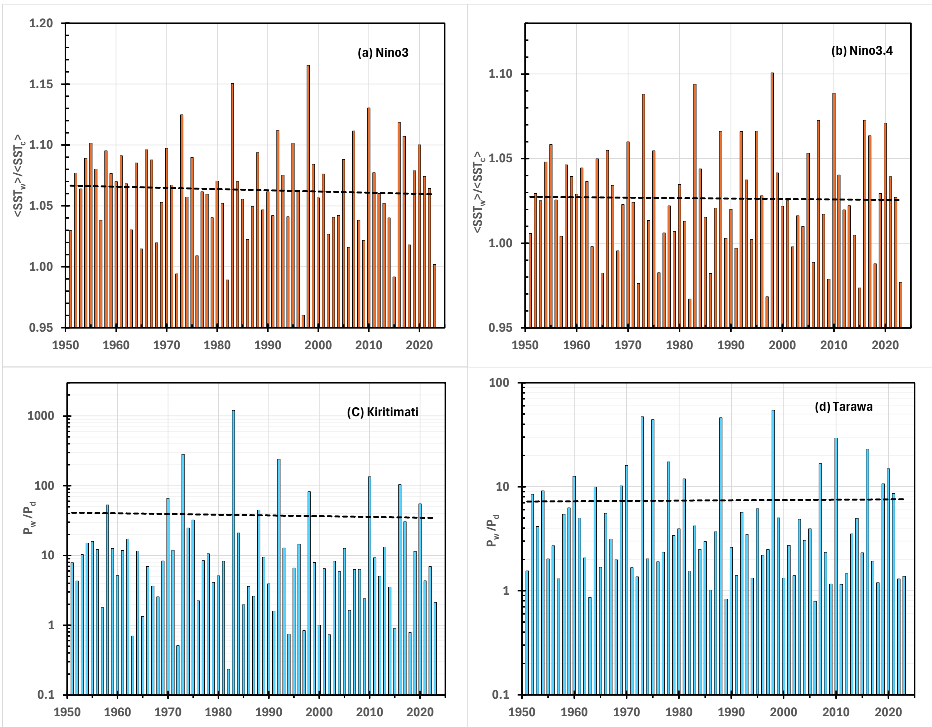

Figure 4. The ratio of the average SST in the annual warm season to that in the cool season $<SST_w>/<SST_c>$ for (**a**) the Nino3 region and (**b**) the Nino3.4 region over the period 1951 to 2023. Also plotted is the ratio of the rainfall in the wet season to that in the dry season for (**c**) Kiritimati and (**d**).Tarawa atolls over the same period (note the logarithmic scales for (**c**,**d**)). Dashed lines are non-significant trend lines. Ratios less than 1.0 show a reversal of seasons.

There are no significant trends in the relative strengths of warm and cool or wet and dry seasons in Figure 4 (or for the other two Nino regions). In some years, reversals of the magnitude of seasons are apparent. For both Nino3 and Nino3.4, average cool season SST sometimes exceeds average warm season SST ($<SST_W>/<SST_c> < 1.0$) and dry season rainfall periodically exceeds wet season rainfall ($P_w/P_d < 1.0$) in both atolls.

Moving from east to west across the Pacific Nino regions, in the eastmost Nino1 + 2 region, average warm season SST always exceeded cool season SST. In the Nino3 region, the Nino3.4

region (both in Figure 4), and the Nino4 region $<SST_w>$ were less than $<SST_c>$ in 4 years, 14 years, and 19 years, respectively, over the 72-year period. For the Nino3 region, the reversal of the seasonality of SST only occurred in either strong or very strong El Niño years [24]. For the Nino3.4 region, all reversals occurred in El Niño years with intensities ranging from weak to very strong. In contrast, in the Nino4 region, 14 of the 19 seasonal reversals of SST occurred in varying intensity La Niña years with the remaining 5 reversals taking place in El Niño years [24]. The increasing frequency of seasonal SST reversals from east to west may be due to ENSO-induced north–south migrations of the ITCZ in the east and the SPCZ [2,11] in the central and western Pacific, with only strong to very strong El Niños impacting the eastern Nino3 region.

The pattern of seasonal reversals for rainfall in the two atolls differs from that of seasonal SST in the Nino regions with the eastern atoll, Kiritimati had 9 years where $P_d > P_W$, while for Tarawa, there were only three years of seasonal P reversals. All seasonal P reversals in Kiritimati occurred during El Niño years [24]. The strong to very strong El Niño years, 1972, 1982, and 1997 [7], and the record 2015 caused seasonal reversals in both the Nino3 and Nino3.4 regions and produced seasonal P reversals in Kiritimati. In contrast, all three seasonal P reversals in Tarawa atoll in 1964, 1989, and 2006 occurred in moderate, strong, and weak, respectively, La Niña events when the SPCZ was displaced southward from November to April [11]. Seasonal reversals in Tarawa reflect the La Niña-dominated reversals in the Nino4 region but are much less frequent.

Periodic increases in the seasonal SST ratios in Figure 4 are associated with exponential increases in the seasonal ratios of P in both atolls (Figure 4). We conclude the relative strength of SST seasons in the Nino regions and P seasons in both atolls are highly variable because of ENSO-induced seasonal reversals but with no significant trend in time.

3.3.2. Trends in Seasonal Data

There were no significant temporal trends ($\alpha > 0.05$) in cool season SST_c for any Nino region or dry season P_d for both atolls over the period 1951 to 2023. Significant trends for warm season SST_w and wet season P_w are in Table 3.

Table 3. Trends in warm season SST_w in the Nino regions and wet season P_w in the two equatorial atolls, determined using linear regression and the non-parametric M-K method. Standard errors are shown for the linear regression analysis, and the significance level of the trends is indicated.

Data Series	Trend, $\partial SST_w/\partial t$ (°C/100 y)		Trend, $\partial P_w/\partial t$ (mm/100 y)	
	Linear Reg	M-K	Linear Reg	M-K
Nino1 + 2 SST_W	1.1 ± 0.5 *	1.1 **	-	-
Nino3 SST_W	0.7 ± 0.3 *	0.8 *	-	-
Nino3.4 SST_W	ns	ns	-	-
Nino4 SST_W	1.0 ± 0.3 ***	1.0 ***	-	-
Kiritimati P_w	-	-	ns	ns
Tarawa P_w	-	-	ns	ns

Significance level, * $\alpha < 0.05$ ** $\alpha < 0.01$, *** $\alpha < 0.001$, ns—not significant, $\alpha > 0.05$.

The significant trends in Table 3 identified by the two methods are identical within error. The trends in warm season SST_w for the Nino1 + 2, Nino3, and Nino4 regions are essentially identical, within error, although the Nino3 region trend is slightly smaller. Surprisingly, no significant warm season trends were found for the Nino3.4 region straddling the Nino3 and Nino4 regions. No significant trends in wet season P_w were found for either atoll despite the significant changepoint found for P_w for Tarawa atoll. There is an asymmetry between significant warm season SST_w trends in the Nino1 + 2, Nino3, and Nino4 regions and the absence of significant trends in cool season SST_c.

3.4. Annual Data

3.4.1. Annual Time Series and Intra-Annual Variability

Figure 5 compares the time series of annual rainfall, P_a, in Kiritimati and Tarawa atolls with median annual sea surface temperatures, $SST_{a,M}$, in the Nino3.4 region.

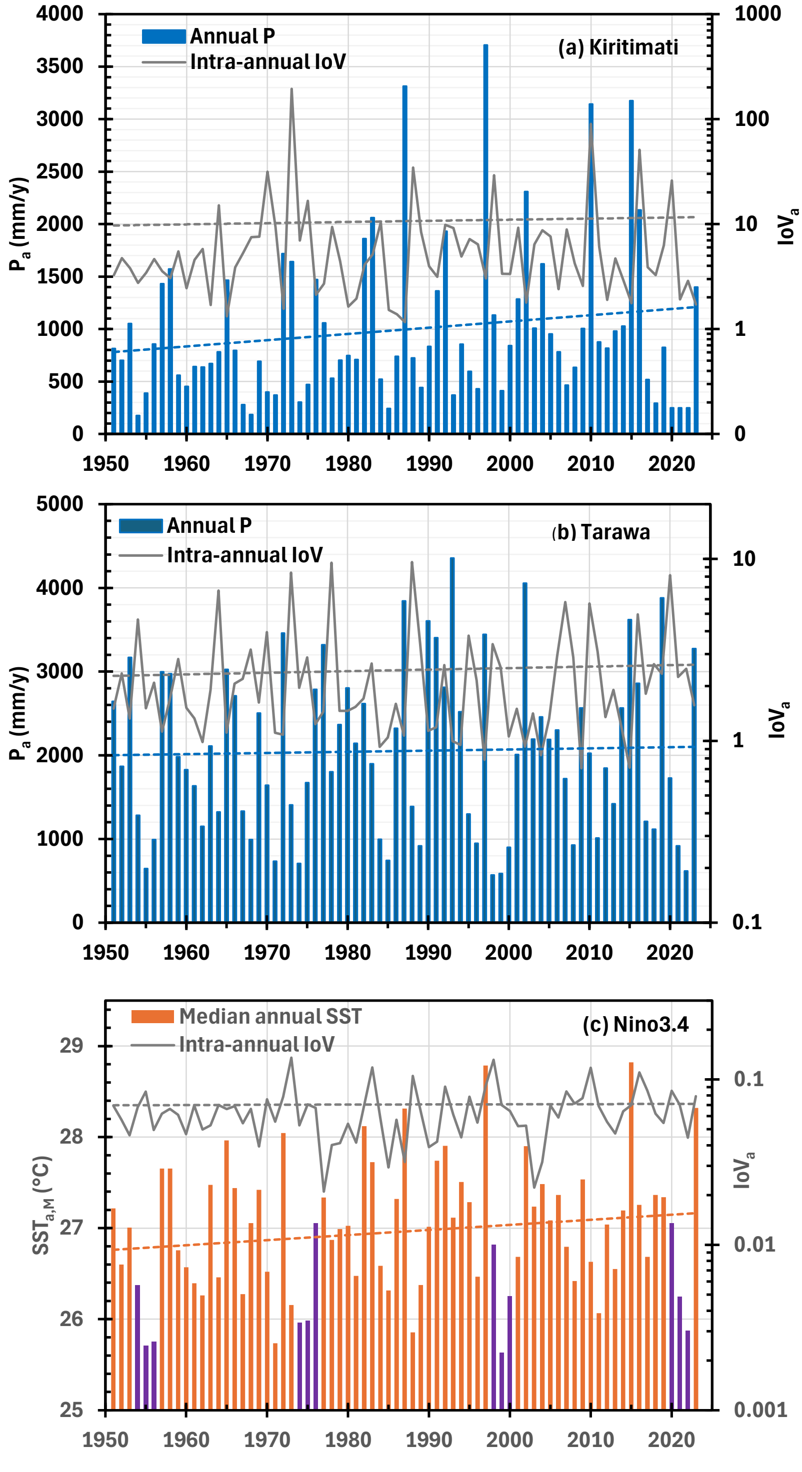

Figure 5. Annual rainfall, P_a, in (**a**) Kiritimati and (**b**) Tarawa compared with the median annual $SST_{a,M}$ in the Nino3.4 region. Also shown is the intra-annual index of variability in monthly P and SST. Dashed lines are non-significant trend lines. Triple La Niña years are shown by the purple shading in (**c**).

The intra-annual index of variation (Equation (1)) in monthly SST and P for each year, IoV_a, is also plotted in Figure 5 together with corresponding trend lines for P_a, IoV_a, and $SST_{a,M}$. The occurrences of the four triple La Niña events, 1954–1956, 1974–1976, 1998–2000, and 2020–2022, influential in major droughts in the equatorial atolls are identified in Figure 5c. The last two of these events resulted in emergency declarations in Tarawa atoll because of water shortages.

The intra-annual IoV_a of SST in the Nino3.4 region in Figure 5 and in all other Nino regions are very small compared with the strong to extreme IoV_a of rainfall in both atolls. Modest variations in SST are associated with very large changes in annual rainfall in the atolls.

3.4.2. Extreme Annual Events

The general correspondence between annual extremes in atoll rainfall and extremes in $SST_{a,M}$ in the Nino3.4 region is apparent in Figure 5. Table 4 summarizes the correspondence of extreme, large SST events greater than the 95th percentile (P95) with extreme (>P95) rainfall events in Kiritimati and Tarawa. The percentile ranking of events is also shown. For Kiritimati, P95 annual rainfall is 2643 mm, while for Tarawa, it is 3710 mm.

Table 4. Correspondence of extreme events greater than the 95th percentile, P95, for $SST_{a,M}$ in the Nino3.4 region and P_a in Kiritimati and Tarawa atolls. The estimated El Niño intensity of the year of the event determined by the Oceanic Nino Index (ONI) [24] and the rounded percentiles of events are also listed.

Year	El Niño Intensity [1]	Nino3.4 $SST_{a,M}$	Kiritimati P_a	Tarawa P_a
1982	Very strong	P96		
1987	Strong	P97	P99	P96
1993	Weak			P100
1997	Very strong	P99	P100	
2002	Moderate			P99
2010	Moderate		P96	
2015	Very strong	P100	P97	
2019	Weak			P97

[1] Very strong ONI > 2, strong 1.5 < ONI < 2, moderate, 1.0 < ONI < 1.5, weak, 0.5 < ONI < 1.0.

All extremely high Nino3.4 SST events in Table 4 only occur from 1982 onward, coincident with one of only three very strong El Niños to date [24]. This delayed occurrence of extreme, high SST happened for all Nino regions. For the Nino1 + 2, Nino3, and Nino4 regions, $SST_{a,M}$ greater than P95 first appeared in 1983, 1987, and 2002, respectively. In both atolls, a large P_a greater than P95 was only evident after 1987, coincident with a strong El Niño. This, together with the finding of a significant warm season and annual changepoint in 1989, indicates either increasing extreme, large events in both $SST_{a,M}$ and P_a or a step change after the early 1980s, consistent with the modeling suggestion of more severe El Niños since the 1960s [7].

For the Nino3.4 region in Table 4, the four extremely high SSTs occurred in all three very strong El Niño years together with a strong El Niño, as expected. In Kiritimati, extreme annual rainfalls (>P95) were evident in years with El Niño intensities from moderate to very strong, while those in Tarawa were in years with weak to strong El Niño intensities. There was only one case, i.e., the strong El Niño in 1987, when P95 events in the Nino3.4 region corresponded to extreme, large P_a in both atolls. Figure 6 shows the correspondence between monthly rainfalls in the atolls and monthly SST in the Nino3, Nino3.4, and Nino4 regions during the extreme 1987 event. The correspondence between extreme, large rainfall in both atolls and extreme, high SST, particularly in the Nino3 region, is evident in Figure 6. Interestingly, the maximum SST in the Nino3 region occurs two months before that in the Nino3.4 region and 6 months before that in the Nino4 region.

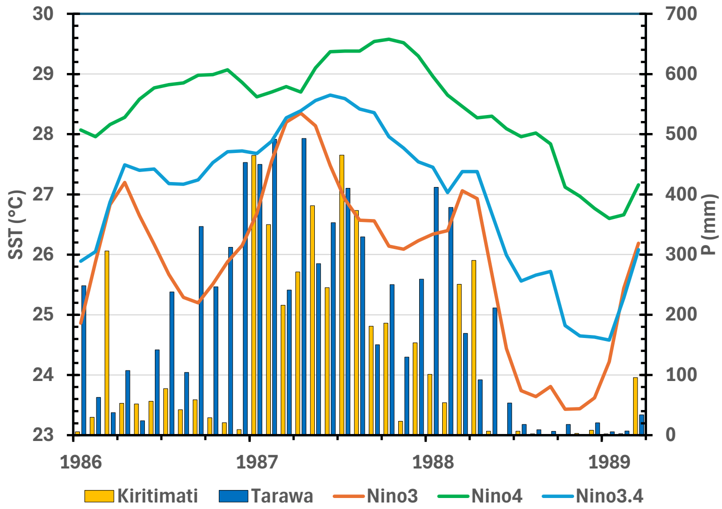

Figure 6. The 1987 extreme event (Table 4) showing the response of monthly rainfall to extreme high monthly SST in the Nino3, Nino3.4, and Nino4 regions.

The very strong El Niños in 1997 and the record 2015 El Niño resulted in extreme, large P_a in Kiritimati but not in Tarawa, although in Tarawa, both years corresponded to very much above-average P_a (P_a > P90). This demonstrates different rainfall responses to extreme, large SST in the eastern and central Pacific. None of the percentile rankings of rainfall in the atolls correspond to those of SST in the Nino3.4 region.

Table 5 summarizes the correspondence between extreme, small SST events, events less than the fifth percentile (P05) in the Nino3.4 region with extreme, small annual rainfalls in the atolls. The relation to the intensity of La Niña events [24] and the percentile ranking of events is also shown. The P05 annual rainfall for Kiritimati is 248 mm and that for Tarawa is 684 mm, indicating that the events in Table 5 are severe droughts.

Table 5. Correspondence of extreme events less than the 5th percentile, P05, for $SST_{a,M}$ in the Nino3.4 region and P_a in Kiritimati and Tarawa atolls. The estimated La Niña intensity of the year of the event determined by the ONI [24] and the rounded percentile of events (P00, P01, etc.) are also listed.

Year	La Niña Intensity [1]	Nino3.4 $SST_{a,M}$	Kiritimati P_a	Tarawa P_a
1954–1955	Weak	P00	P00	P04
1968	Weak		P01	
1971	Moderate	P04		
1975	Strong	P01		
1985	Weak		P03	
1998–1999	Strong	P03		P00 P01
2021–2022	Moderate		P04	P03

[1] Strong ONI < −1.5, moderate −1.5 < NI < −1.0, weak −1.0 < NI < −0.5.

In Table 5, extreme, low $SST_{a,M}$ (<P05) in the Nino3.4 region occurred in weak, moderate, and strong La Niña years. To date, there has not been a very strong La Niña event [24]. All low $SST_{a,M}$ occurred before the year 2000, consistent with ocean warming. The lowest on record occurred during the 1954–1956 triple La Niña; in contrast, the four extreme, small P_a values for both atolls spanned the period 1954 to 2022. While the lowest on record P_a in Kiritimati also occurred during the 1954–1956 triple La Niña, that for Tarawa occurred during the 2020–2022 triple La Niña. The continued occurrence of extreme, low annual rainfalls after 2000, despite the absence of extreme low $SST_{a,M}$, seems to indicate a decoupling of very small annual rainfalls and very small SST events. Apart from the 1954–1955 correspondence of the P00 event in Kiritimati and the Nino3.4 region, there was no correspondence in percentile rankings for events less than P05.

3.4.3. Trends in Annual SST and P

The trends in annual SST and rainfall are listed in Table 6. For the Nino regions, the trends determined by linear regression and non-parametric methods are again identical within error and are of order 1.0 °C/100 y, matching the trends for warm season SST in Table 3. There was again no significant annual SST trend ($\alpha > 0.05$) in $SST_{a,M}$ in the Nino3.4 region or in annual rainfall in both atolls.

Table 6. Linear regression (Reg) trends and M-K non-parametric temporal trends for annual median SST in the Nino regions and annual P in Kiritimati and Tarawa atolls over the period 1951 to 2023. Standard errors are given for the linear regression trends. Also indicated are the levels of significance.

Data Series	Trend, $\partial SST_{a,M}/\partial t$ (°C/100 y)		Trend, $\partial P_a/\partial t$ (mm/100 y)	
	Linear Reg	M-K	Linear Reg	M-K
Nino1 + 2 $SST_{a,M}$	1.1 ± 0.5 *	1.0 *	-	-
Nino3 $SST_{a,M}$	0.8 ± 0.4 *	0.7 *	-	-
Nino3.4 $SST_{a,M}$	ns	ns	-	-
Nino4 $SST_{a,M}$	0.9 ± 0.3 †	1.0 ***	-	-
Kiritimati P_a	-	-	ns	ns
Tarawa P_a	-	-	ns	ns

Significance level, * $\alpha < 0.05$, *** $\alpha < 0.005$, † $\alpha < 0.0005$, ns—not significant, $\alpha > 0.05$.

3.4.4. Trends in Annual Monthly Maxima and Minima

The trends in warm season SST_w suggest that there should also be significant trends in annual maximum monthly SST, SST_{max}. Table 7 shows the temporal trends in SST_{max} as well as the maximum annual monthly rainfall, P_{max}, in both atolls.

Table 7. Linear regression (Reg) trends and M-K non-parametric temporal trends for annual maximum monthly SST_{max} in the Nino regions and annual maximum monthly P_{max} in Kiritimati and Tarawa atolls over the period 1951 to 2023. Standard errors are given for the linear regression trends. Also indicated are the levels of significance.

Data Series	Trend, $\partial SST_{max}/\partial t$ (°C/100 y)		Trend, $\partial P_{max}/\partial t$ (mm/100 y)	
	Linear Reg	M-K	Linear Reg	M-K
Nino1 + 2 SST	0.9 ± 0.5 *	1.0 *	-	-
Nino3 SST	0.8 ± 0.3 *	0.7 *	-	-
Nino3.4 SST	ns	ns	-	-
Nino4 SST	1.0 ± 0.3 †	1.0 †	-	-
Kiritimati P	-	-	ns	ns
Tarawa P	-	-	ns	ns

Significance level, * $\alpha < 0.05$, † $\alpha < 0.0005$, ns—not significant, $\alpha > 0.05$.

The trends for SST_{max} in Table 7 are identical, within error, to the annual trends in Table 6. Again, there is no significant trend in SST_{max} for the Nino3.4 region despite the significant trends in the Nino3 and Nino4 regions that it straddles. There is also no significant trend in P_{max} for both atolls. For the Nino4 region, the increasing trend in SST_{max} is very highly significant ($\alpha > 0.0005$), consistent with the very significant ($\alpha < 0.01$) changepoint found in the annual data for the year 1989. Trends in SST in the Nino4 region are easier to detect because the IoV of SST in this region is the lowest of all the Nino regions (Table 1).

In contrast to maximum annual data, no significant temporal trends ($\alpha > 0.05$) in minimum annual monthly data, SST_{min}, in any Nino region or in P_{min} for either atoll were discovered. This is consistent with the asymmetry found between significant warm season SST trends in the Nino1 + 2, Nino3, and Nino4 regions and the absence of significant cool season trends in these regions.

3.4.5. Trends in Intra-Annual Variability

The significant increasing trends in warm season SST and annual maximum monthly SST but not in cool season SST and minimum annual monthly SST in the Nino1 + 2, Nino3, and Nino4 regions between 1951 and 2023 suggest that annual variability in SST may be increasing as the ocean warms. The strong to extreme intra-annual variability in P in the two atolls and the Nino3.4 region is shown in Figure 5. Linear regression and M-K analyses of trends in the IoV (Equation (1)) intra-annual monthly SST for all Nino regions as well as the IoV of intra-annual monthly P in both atolls were carried out.

No significant trends ($\alpha > 0.05$) in the intra-annual IoV of SST in any of the Nino regions or in P in either atoll were found, as evident in Figure 5. There was the hint of a weakly significant ($\alpha < 0.07$) increasing linear regression trend in IoV of $0.017 \pm 0.009/100$ y for the Nino4 region, but the M-K analysis similar trend of 0.016/100 y was even less significant ($\alpha < 0.11$).

3.4.6. Trends in Interannual Variability over Seven Decades

Figure 7 compares the interannual IoV of Pa for the two atolls with the IoV of mean annual SST for the Nino3 and Nino4 regions over seven decades between 1951 and 2020.

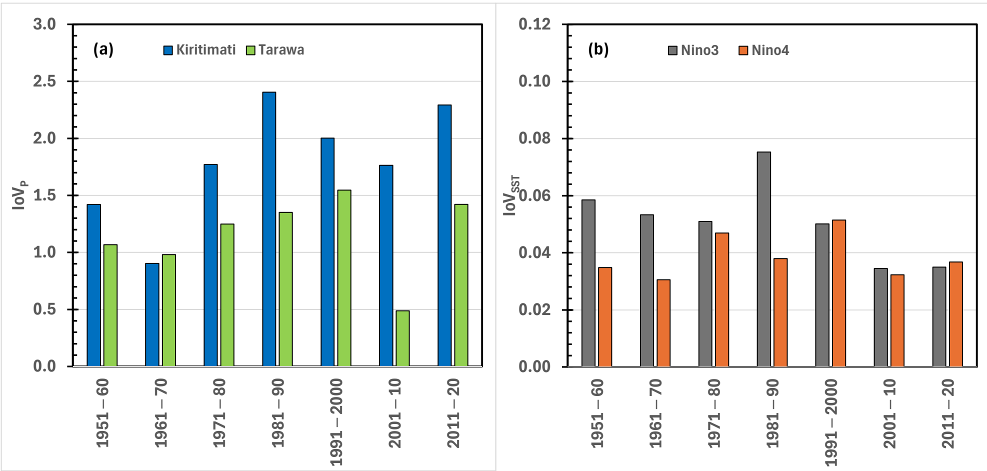

Figure 7. Interannual IoV of annual rainfall, IoV_P, and mean annual SST, IoV_{SST}, over seven decades since 1951: (**a**) IoV_P for Kiritimati and Tarawa atolls and (**b**) IoV_{SST} for the Nino3 and Nino4 regions.

There were no significant trends in the decadal interannual IoV_{SST} in any Nino region or in IoV_P in either atoll. The maximum decadal IoV_P at Kiritimati in Figure 7 was over the decade 1981 to 1990 as was the maximum IoV_{SST} in the Nino3 region. The maximum IoV_P for Tarawa was over the decade 1991 to 2000, which was also the decade of maximum IoV_{SST} for the Nino4 region. During the decade 1981 to 1990, three moderate, one strong, and a very strong El Niño occurred, interspersed with two consecutive weak and a strong La Niña. Over the decade 1991–2000, there was a moderate, a strong, and a very strong El Niño and one moderate and two consecutive strong La Niñas [24].

The minimum IoV_P for Kiritimati and minimum IoV_{SST} for the Nino4 region were in the decade 1961 to 1970, while the minimum IoVp for Tarawa and for the Nino3 region occurred between 2001 and 2010. In the decade 1961 to 1970, there was a weak, a moderate, and a strong El Niño and two weak and one moderate La Niñas. Over the decade 2001 to 2010, there were two weak and two moderate El Niños and two weak and one strong La Niñas [24]. It appears that maximum IoVs arise in decades in which both strong El Niños and strong La Niñas occur. There was no significant correlation between the IoV_P of the atolls and the IoV_{SST} of the Nino regions. Figure 7 shows the strong contrast in decadal interannual variability between atoll rainfall and ocean SST; IoV_P is about 30 times the magnitude of IoV_{SST}.

3.5. Correlation of 12-Month Rainfall with 12-Month Sea Surface Temperature

This section examines the correlation between measured 12-month rainfall in Kiritimati and Tarawa atolls and 12-month average SST in the Nino regions. Because of the difference in the seasonality of SST in the Nino regions (Figure 2) and the seasonality in P in the two atolls (Figure 3), as well as the episodic seasonal occurrence of ENSO events, correlations between P_{12} and SST_{12} depend on the start month of the 12-month period. The correlations of cumulative P data in the two atolls with mean SST data in the Nino regions for 12-month periods starting at different months of the year are shown in Figure 8, and the maximum correlations are in Table 8.

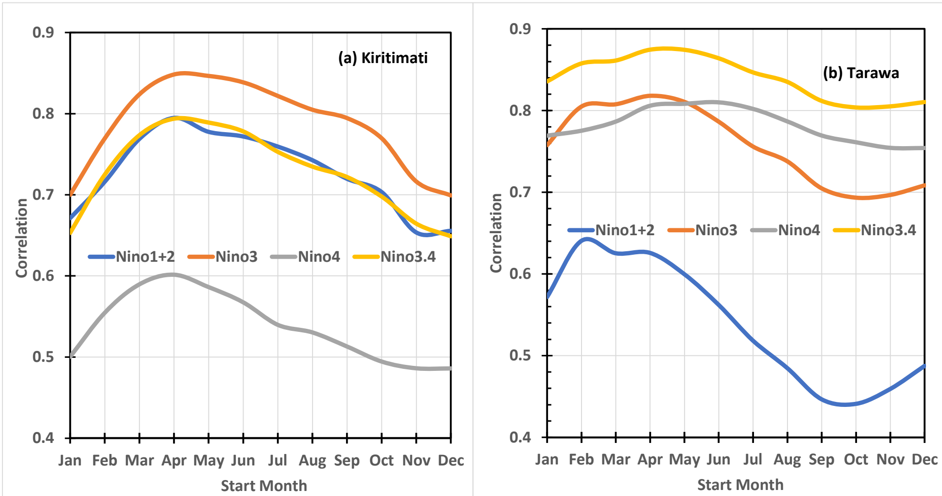

Figure 8. Pearson correlation between 12-month cumulative rainfall and 12-month mean SST in the four Nino regions for 12-month periods with different starting months for (**a**) Kiritimati atoll and (**b**) Tarawa atoll.

Table 8. Maximum correlations between 12-month cumulative P in Kiritimati and Tarawa atolls and 12-month mean SST in the Nino regions for the period 1951 to 2023. The start month of the 12-month period is also indicated.

Region	**Maximum Correlation**	
	Kiritimati P_{12}	**Tarawa P_{12}**
Nino1 + 2 SST_{12}	0.795 [1]	0.641 [2]
Nino3 SST_{12}	0.848 [1]	0.818 [1]
Nino3.4 SST_{12}	0.794 [1]	0.874 [1]
Nino4 SST_{12}	0.602 [1]	0.810 [3]

Start month of the 12-month period, [1] April, [2] February, [3] June.

For Kiritimati atoll in Figure 8a, maximum correlations arise when the 12-month period starts in April for all the Nino regions. Although Kiritimati lies just inside the Nino4 region (Figure 1), the correlation between P_{12} and SST_{12} of Nino4 is the least of any region. The correlation between P_{12} in Kiritimati and SST_{12} in the remote Nino1 + 2 region, however, is essentially identical to the correlation for the Nino3.4 region in which Kiritimati is located. The maximum correlation between P_{12} at Kiritimati and with SST_{12} is with SST_{12} in the Nino3 region lying to the east of the atoll (Figure 1). This is also apparent in the correspondence between monthly P in Kiritimati and monthly SST in Figure 6.

For Tarawa atoll in Figure 8b, the correlations are different. Maximum correlations occur for the April start month with the Nino3 and Nino3.4 regions; however, the maximum correlation for the Nino1 + 2 is with a February start month and for Nino4 and with a June start month for the 12-month period. The lowest correlation of P_{12} in Tarawa with SST_{12} is with the remote Nino1 + 2 region, while those for the Nino4 and Nino3 regions are comparable. The maximum correlation, however, is with the Nino3.4 region, which also lies to the east of Tarawa atoll (Figure 1).

3.5.1. Relations between 12-Month Rainfall and 12-Month Average SST

We found temporal trends in seasonal, annual, and annual maximum SST in the Nino1 + 2, 3, and 4 regions of order 1.0 °C/100 y for the period 1951–2023 but no significant trends in atoll P over the same period. Detecting trends in equatorial atoll rainfall is challenging because of the extreme rainfall variability imposed by ENSO (Figure 5). Historic annual mean SST in the Nino regions, however, have varied by between 2.5 °C (Nino4) and 4.5 °C (Nino1 + 2) over this period. The strong relation between atoll rainfall P and SST over monthly timescales is exemplified in Figure 6 for the 1987 extreme SST and P events. In this section, we examine the impact of historic 12-month mean SST variations on variations in 12-monthly cumulative rainfall in Kiritimati and Tarawa.

The robust, highly significant correlations between P_{12} in both atolls and SST_{12} in the Nino regions eastward of the atolls in Table 8 suggest strong relationships exist between P_{12} and SST_{12}. Linear relationships are plotted in Figure 9 for P_{12} in Kiritimati verses SST_{12} in the Nino3 region and P_{12} in Tarawa verses SST_{12} in the Nino3.4 region, all with April as the start month of the 12-month periods.

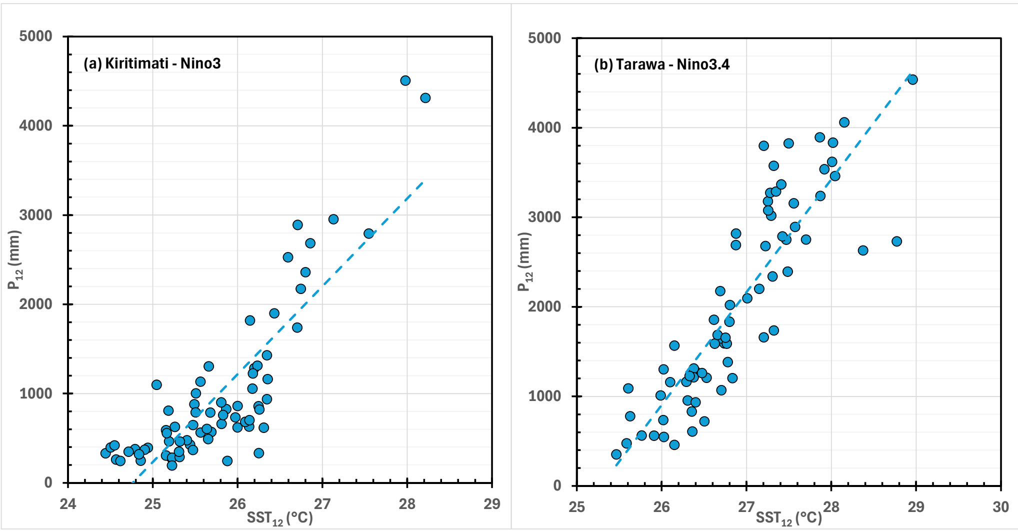

Figure 9. Relationships between P_{12} and SST_{12} (points) for (**a**) Kiritimati and Nino3 and (**b**) Tarawa and Nino3.4. For all data, the start month for the 12-month period is April. Dashed lines are significant regression fits to data.

While the linear relationship between P_{12} and SST_{12} in the Nino3.4 region for Tarawa atoll adequately describes the variations (Figure 9b), the linear relationship between Kiritimati and SST_{12} in the Nino3 region does not fit the two extreme rainfall events that occurred during the two very strong El Niño events in 1997–1998 and 2015–2016 (Figure 9a). Table 9 summarizes the values of the slopes of the linear regression, $\partial P_{12}/\partial SST_{12}$, found for both atolls and all the Nino regions together with their standard errors.

All linear relationships in Table 9 were extremely significant ($\alpha << 0.00001$). The rate of change in P_{12} with SST_{12} for the remote southeastern Nino1 + 2 region, where the intra-annual temperature range is twice as large as those in the equatorial Nino regions (Figure 2), is lower than for the equatorial Nino regions. For the equatorial Nino regions, Table 9 indicates that 12-month rainfall in Kiritimati increases by about 940 mm for every 1.0 °C rise in SST_{12}, while that in Tarawa increases by about 1300 mm for every 1.0 °C rise in SST_{12} in the equatorial Nino regions. The response of P_{12} in Kiritimati in Figure 9a, however, suggests a non-linear response to SST_{12} in the Nino3 region, which is explored in the following section

Table 9. The slopes of linear regressions between 12-month rainfall in Kiritimati and Tarawa atolls and 12-month SSTs in the Nino regions. Also shown are the standard errors in estimated slopes and the coefficient of determination, R^2, for the relationships. Start months for the 12-month data are also indicated.

Region	Kiritimati		Tarawa	
	Slope (mm/y/°C)	R^2	Slope (mm/y/°C)	R^2
Nino1 + 2	820 ± 75 [1]	0.63	720 ± 102 [2]	0.41
Nino3	980 ± 73 [1]	0.72	1140 ± 109 [1]	0.61
Nino3.4	940 ± 86 [1]	0.63	1290 ± 86 [1]	0.76
Nino4	910 ± 145 [1]	0.36	1500 ± 130 [3]	0.65

Start month for the 12-month data [1] April, [2] February, [3] June.

3.5.2. Response of above-Average, Average, and below-Average Rainfall to SST_{12}

Figure 9a suggests that above-average, average, and below-average 12-month rainfalls P in Kiritimati may respond differently to changes in SST_{12} in the equatorial Nino regions. Figure 10 separates the data in Figure 9 into the dependence of above-average ($P_{12} > P70$), average ($P30 < P_{12} < P70$), and below-average ($P_{12} < P30$) 12-month rainfalls on SST_{12} in the Nino3 and Nino3.4 regions for both atolls.

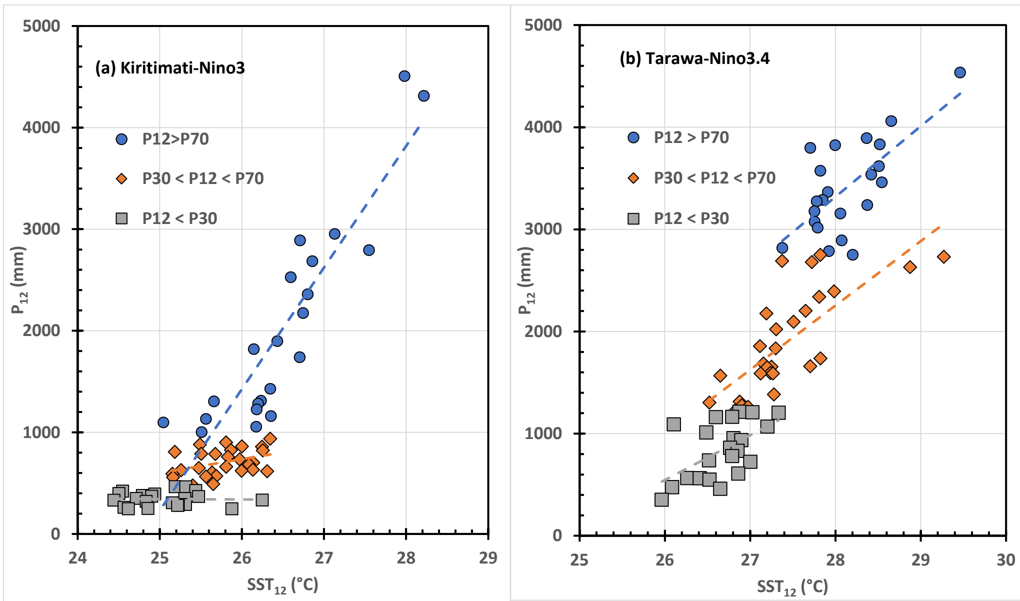

Figure 10. The response of above-average, average. and below-average 12-month rainfalls to changing SST_{12} (as shown in the legend) (**a**) in Kiritimati atoll, with P_{12} responding to SST_{12} in the Nino3 region and (**b**) in Tarawa atoll, with P_{12} responding to SST_{12} in the Nino3.4 region. The start month of the 12-month period for all data is April. Dashed lines are the color-coded regression fits for above average (blue), average (brown) and below average (grey).

In Figure 10a, for Kiritimati, only above-average P_{12} responded significantly to changing SST_{12} in the Nino3 region. Average and below-average 12-month rainfalls are statistically independent of SST_{12} in the Nino3 region. In contrast, for Tarawa atoll, in Figure 10b, above-average, average, and below-average 12-month rainfalls all respond similarly to increasing SST_{12} in the Nino3.4 region. Table 10 summarizes the values of the slope $\partial P_{12}/\partial SST_{12}$ for the three percentile ranges in Figure 9 for Kiritimati and Tarawa and both the Nino3 and Nino3.4 regions.

Table 10. Slopes of the linear regression relations between above-average (P_{12} > P70), average (P30 < P_{12} < P70), and below-average (P_{12} < P30) 12-month rainfalls in Kiritimati and Tarawa atolls and 12-month sea surface temperatures in the Nino3 and Nino3.4 regions. Also listed are the standard errors of the slopes, the coefficient of determination, R^2, and the level of significance of the relationship. The start month for all 12-month values is April.

Region	P_{12} Percentile Range	Kiritimati		Tarawa	
		Slope (mm/y/°C)	R^2	Slope (mm/y/°C)	R^2
Nino3	Above average	1200 ± 130 ‡	0.81	630 ± 150 †	0.47
	Average	ns	0.14	430 ± 100 †	0.39
	Below average	ns	0.003	450 ± 150 **	0.33
Nino3.4	Above average	1160 ± 170 ‡	0.70	690 ± 170 †	0.46
	Average	ns	0.04	650 ± 110 ‡	0.58
	Below average	ns	0.04	440 ± 140 **	0.32

Significance level: ** $\alpha < 0.01$, † $\alpha < 0.0005$, ‡ $\alpha << 0.0001$, ns—not significant $\alpha > 0.05$.

Table 10 reveals that above-average 12-month rainfalls in Kiritimati and Tarawa have extremely significant linear relationships with SST_{12} for both the Nino3 and Nino3.4 regions. For the eastern atoll, Kiritimati, the rate of change in above-average P_{12} with increasing SST_{12}, of about 1200 mm/°C, is almost twice that of the western atoll, Tarawa, of about 660 mm/°C, although it is equal to the rate for Tarawa over the full range of rainfall (Table 9). For average and below-average P_{12}, the results in Table 10 emphasize that average and below-average P_{12} are statistically independent of SST_{12} for Kiritimati. In contrast, the results for Tarawa show that average and below-average P_{12} are very significantly related to SST_{12}, with slopes either almost equal to or slightly less than those of above-average rainfall. These results suggest a different response of 12-month rainfalls in the eastern and central Pacific to variations in SST_{12}.

While correlations do not necessarily indicate a causal link, the results above suggest a strong dependence of above-average 12-month rainfall on 12-month average SST in the equatorial Nino regions, but the response of average and below-average rainfalls depends on atoll location.

3.6. SST Dependence on Rainfall and Atoll Water Security

The results in Figures 6 and 10 and Table 10 indicate complex, spatially dependent past relationships between rainfall in Kiritimati and Tarawa atolls and SST in the equatorial Pacific, which have significant implications for atoll water security. Groundwater is the predominant source of water in these atolls [3], and groundwater responds to variations in rainfall over longer terms than annual [13,17]. Figure 11 compares the percentiles of running 36-month cumulative precipitation in Kiritimati and Tarawa atolls with the percentiles of running 36-month average SST in the Nino3 and Nino3.4 regions. Also shown are the limits of very much above-average (values greater than P90) and very much below-average (values less than P10) P and SST over 36-month periods.

Figure 11 shows the general correspondence between 36-month rainfall percentiles in Kiritimati (Figure 10a) and 36-month average SST in the Nino3 region (Figure 11c) and the good correspondence between the rainfall percentiles for Tarawa atoll (Figure 11b) and the SST percentiles for the Nino 3.4 region (Figure 11d). There are, however, some significant differences.

For Kiritimati, very much above-average 36-month rainfalls (>P90) are only evident after 1997. For the Nino3 and Nino3.4 regions, very much above-average events were first apparent in 1983, after a very strong El Niño [24]. In contrast, for Tarawa, very much above-average rainfalls were evident first in 1960 and 1980. Although no significant trends were found in annual SST data for the Nino3.4 region or in annual P data for Kiritimati, the data in Figure 11a,c show that very much above-average events only occurred after 1983 and 1997, respectively.

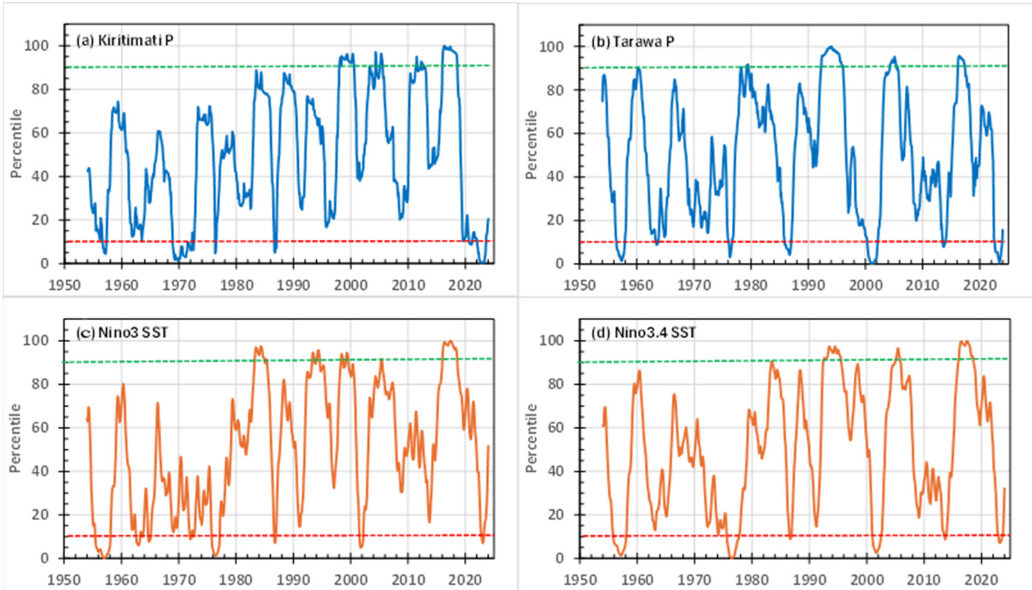

Figure 11. Percentiles of 36-month running cumulative rainfall in (**a**) Kiritibati and (**b**) Tarawa atolls compared with those of 36-month running mean SST in (**c**) the Nino3 region and (**d**) the Nino3.4 region for the period 1951 to 2023. Also shown are the percentile limits for very much above average (values greater than P90, green dashed lines) and very much below average (values less than P10, red dashed lines).

For Tarawa atoll, while very much above-average 36-month rainfall events occurred as early as 1960 and in 1978 and 1979, extreme 36-month rainfalls (>P95) are only evident from 1992. Very much above-average and extreme 36-month rainfalls correspond to periods of high groundwater recharge, and, in some circumstances, local flooding as water tables rise to the ground surface.

The very much below-average (<P10) rainfalls in Figure 11a,b correspond to major water supply droughts that have threatened water security, particularly for urban South Tarawa. Figure 11 shows that these occurred episodically throughout the period 1951 to 2023, although there was a hiatus in Kiritimati between 1986 and 2022. The lowest 36-month average SST on record occurred in 1957 for the Nino3 region and in 1976 for the Nino3.4 region, both at the end of triple La Niñas (Figure 5) and both in the first half of the SST time series. In contrast, in Tarawa, the lowest 36-month rainfall on record occurred in 2001–2002, and that in Kiritimati occurred in 2022, both again following triple La Niñas, but both in the last half of the record. The data in Figure 11, however, do not appear to support the suggestion of increasing drought frequency after the 1980s, as very much below-average events occur throughout the period 1951 to 2023.

The hiatus in very much below-average 36-month rainfalls in Kiritimati between 1986 and 2022 means that rainfall in Kiritimati did not respond to the extreme, low 36-month SST in 2001–2002 in Figure 11c,d, in contrast to Tarawa, which had the lowest 36-month rainfall on record in 2001–2002. This lack of response may be a manifestation of the surprising SST independence of average and below-average annual rainfall in Kiritimati (Figure 10 and Table 10) and evidence of different dependencies in the eastern and central tropical Pacific.

Both Kiritimati and Tarawa atolls are located within the Nino4 region. Figure 12 shows the 36-month average SST percentiles for the Nino4 region, which has highly significant trends in the warm season (Table 3), median annual (Table 6), and annual maximum SST (Table 7). It has been suggested that SST in the Nino4 region may be a better indicator of ENSO events [10]. The increasing intensity of large 36-month SST Nino4 events with time region is apparent in Figure 12. Very much above-average events only occur from 1992, and there are no very much below-average SST events after 2000, despite the 2020 to 2022 triple La Niña that resulted in very much below-average annual rainfall at both Kiritimati and

Tarawa (Table 5). Increasing the minimum 36-month SST in the Nino4 region surrounding the atolls, between 1951 and 2023, did not decrease drought severity in either atoll.

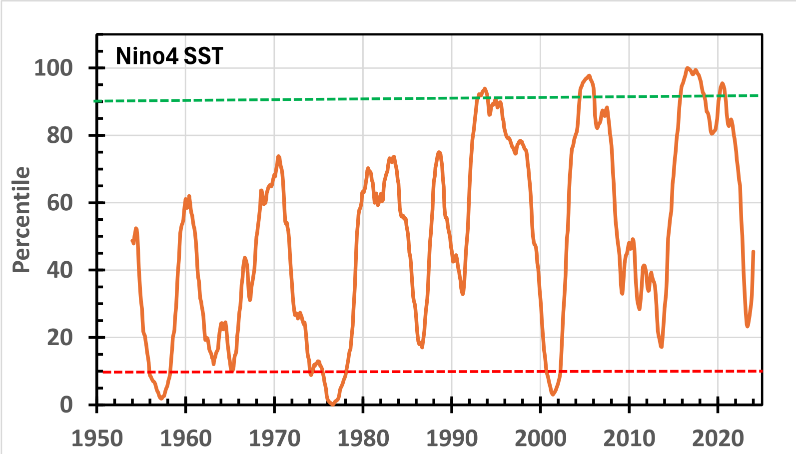

Figure 12. Percentiles of 36-month running mean SST in the Nino4 for the period 1951 to 2023. Also shown are the percentile limits for very much above average (values greater than P90, green dashed line) and very much below average (values less than P10, red dashed line).

4. Discussion

Three critical issues for atoll water security are the changes in the availability, variability, and quality of water as surrounding ocean surface temperatures increase and sea levels rise. Here, we concentrated on changes in longer-term rainfall and its variability relevant to atoll water security.

Prompted by IPCC projections for the western and central Pacific [4] and results from global circulation models (GCM) that the frequency of strong El Niño and La Niña events has increased since 1960 [7], we sought to find answers to the five following questions for the period 1951 to 2023 using rain gauge records and SST records in the extensive Nino regions:

1. What are the rates of SST increases in the Nino regions since 1951 and have they resulted in the expected increase in annual rainfall [4] in the equatorial Pacific?
2. Are the projected changes in ENSO frequency and intensity [4] evident in the SST and P records in the equatorial Pacific, particularly in terms of changes in variability or seasonality?
3. Are extreme annual events, especially droughts, increasing in frequency and intensity?
4. How significant are the relationships between P_{12} and SST_{12}?
5. What are the implications for atoll water security?

All data series were first checked for significant lag1 autocorrelation because of its potential interference with trend identification using the M-K method [9]. Autocorrelation was mainly limited to the SST series in the Nino4 region and did not influence the magnitude of trends. The homogeneity in the SST and P data series was then examined to discover if there were significant, consistent changepoints coincident with major ocean–atmosphere events.

4.1. Homogeneity in the Data and Changepoints

A previous modeling study [7] found more frequent strong El Niño and La Niña between 1960 and 2020 relative to the period 1901 to 1960 linked to greenhouse warming. All very strong El Niños since 1950 occurred from 1982–1983 onwards, while strong La Niñas appeared from 1973–1974 onwards [24]. While the period covered here, 1951 to 2023, is shorter than in [7], a search for changepoints in the SST and P data series was carried out to examine possible changes in SST and P time series because of major ENSO events or reversal in phases of the IPO [9,26].

The time series of cool season SST (Figure 2) for all Nino regions and of dry season P (Figure 3) in both atolls were homogeneous. The only significant seasonal changepoints found were in 1989 for warm season SST in both the Nino3 and Nino4 region and in 1993 for wet season P in Tarawa atoll. Mean SST in both Nino regions was greater after the changepoint than before, consistent with a warming tropical Pacific, but mean wet season P in Tarawa decreased after the 1993 changepoint. Because Tarawa is located within the Nino4 region (Figure 1), the decrease in P_w following the changepoint as Nino4 SST increased appears paradoxical. Results from climate change modeling using an ensemble of global circulation models (GCMs) [27], however, project decreasing trends in rainfalls in the region around Tarawa as the ocean warms. The absence of a changepoint in warm season SST in the Nino3.4 region is also puzzling since it straddles the Nino3 and Nino4 regions (Figure 1).

The time series of annual P for both atolls were homogeneous. Only the annual median SST for the Nino4 region had a significant changepoint, again in 1989, identical to the warm season SST changepoint for this and the Nino3 region. The 1989 changepoint corresponded to a strong La Niña in 1988–1989 [24], with significant southward displacement of the SPCZ [11] and northward displacement of the ITCZ [28].

The change in the phase of the IPO around 1999, thought to be responsible for changes in the trends in rainfall in some Pacific Island countries [11], did not generate an SST changepoint. The relationship between the long-term phases of the IPO and shorter-term ENSO events is an area of active research [29]. Additionally, the dramatic episodic northward shifts and mergers of the SPCZ with the ITCZ [26] in the strong and very strong El Niños in 1982–1983, 1991–1992, and 1997–1998 did not generate SST changepoints.

The key conclusion here is that switches in the phase of the IPO were not linked to changepoints in SST and that changepoints in SST do not correspond to changepoints in atoll rainfall, possibly because of the large variability in the P time series imposed by ENSO events.

4.2. Trends in SST and P

4.2.1. Errors in Trends

Although the identified regression trends in SST in Tables 3, 6 and 7 were significant or highly significant, they were associated with large statistical standard errors. These standard errors scale with the relatively modest IoVs of the Nino region SST time series (Table 1) so that the trend in SST in the Nino4 region has the smallest standard error and is highly significant. These variations are driven by episodic ENSO events. Despite an apparent trend in rainfall in Kiritimati (Figure 5a), the extremely large IoVs of longer-term rainfall in both atolls (Table 1), which are also driven by ENSO events, preclude any statistically significant trends. Here, we showed that a modest 1.0° in annual SST produces about 1200 mm variation in annual rainfall in the atolls.

4.2.2. Significant Trends

Understanding temporal trends and changes in rainfall is central to the future management of scarce water resources in atolls [3,16,30]. Here, we used both linear regression and nonparametric M-K analyses to identify trends in SST in the Nino regions and P in the atolls over the period 1951 to 2023. This period covers several positive and negative phases of the IPO [9,29,31,32] as well as 27 El Niño and 25 La Niña events [24]. It includes three very strong El Niño events and seven strong La Niña as well as three triple La Niña events. The criterion for identifying a significant trend was that both methods showed a trend of similar magnitude at a significance level of at least $\alpha < 0.05$. In all cases, the identified significant trends in SST by both methods were identical within error (Tables 3, 6 and 7).

There were no significant trends in median cool season SST in any Nino region or in the wet or dry season P in either atoll. There were, however, significant trends in the median warm season SST in the Nino1 + 2, Nino3, and Nino4 regions of order 1.0 °C/100 y (Table 3) but with the trend in the easterly equatorial Nino3 region being about 80% of that in the other two regions. The difference in trend behavior between the warm and cool seasons suggests that intra-annual variability may be increasing. Surprisingly, there was no significant trend in the warm season SST for the Nino3.4 region.

The seasonal trend results prompted an examination of trends in annual maximum and minimum monthly SST and P. There were no significant trends in P_{max} or P_{min} in either atoll or significant trends in SST_{min} in any of the Nino regions. The significant trends in SST_{max} in the Nino1 + 2, Nino3, and Nino4 regions (Table 7) were identical within error to the trends found for warm season SST for these Nino regions, but again, there was no significant trend in SST_{max} for the Nino3.4 region. The different trend behavior between maximum and minimum annual monthly SST is consistent with that between warm and cool season SST, again implying that intra-annual variability may be increasing and showing asymmetric behavior.

Significant increasing trends ($\alpha < 0.05$) in median annual SST (Table 6) were found for the Nino1 + 2 and Nino3 regions and a highly significant ($\alpha < 0.005$) trend for the western Nino4 region adjacent to the neutral position of the Pacific warm pool [2]. All were of order 1.0 °C/100 y, with the eastern Nino3 region being less, by about 0.8 °C/100 y. There was, however, no significant trend in annual SST in the Nino3.4 region and no significant trends in annual P in either atoll, consistent with the lack of significant trends in the warm season and maximum annual monthly P despite projections of increased annual rainfall in the western and central Pacific as oceans warm [4].

Table 1 and Figures 5 and 7 assist in understanding the absence of significant trends in longer-term rainfall in the atolls despite warming trends in the surrounding ocean. Episodic ENSO events sweep the Pacific warm pool back and forth along the equatorial Pacific with attendant north–south excursions of the predominant Pacific rain bands, the ITCZ [26], and the SPCZ [2,11,31,32]. The index of variability in all SSTs listed in Table 1 and shown in Figures 5 and 6, however, is very low (IoV << 0.5) because of the enormous temperature buffering of the Pacific Ocean. In contrast, the intra-annual (Figure 5) and decadal interannual variability in P (Figure 7) in the atolls, because of the same ENSO events, is high (1.0 < IoV < 1.25) to extreme (IoV > 2). Frequent ENSO cycles perhaps coupled with longer-term phases of the IPO [11,26,29,31,32] impose extreme variability in longer-term P in the central and western Pacific. Detecting significant trends in highly variable rainfall records is problematic with relatively short time series. However, variability cannot be used to explain the absence of significant trends in the Nino3.4 SST time series. The IoV of SST in the Nino3.4 region (Table 1, Figures 5 and 7) is low and smaller than those of the Nino1 + 2 and Nino3 regions, which have significant trends.

Previous work on rainfall trends between 1961 and 2011 in the western Pacific [9] found a significant increasing trend ($\alpha < 0.05$) in annual P in Kiritimati of between 800 and 1200 mm/100 y, but not in Tarawa. Over a shorter period, from 1981 to 2011, they found no significant trends in annual P in either atoll, which was attributed to a change in phase of the IPO around 1999. Here, we extended the period covered in both atolls, from 1951 to 2023. This period includes two additional triple La Niña events (Figure 5c), 1954–1956 and 2020–2022, and the strongest El Niño to date, 2015–2016 [Table 4]. The absence of trends found in Kiritimati over the longer period from 1951 to 2023 seems to be a result of the extreme variability imposed by strong ENSO events, especially triple La Niña events. For atoll groundwater management, the key knowledge gap is not so much the progressive trend in mean annual rainfall but the change in the occurrence frequency of strong ENSO events as oceans warm [7].

4.3. Trends in Intra-Annual and Interannual Variability and Seasonality

The uncertainty in IPCC projections of the impacts of global warming on the frequency and intensity of ENSO events [4] has raised concerns about the possible increasing variability in SST and P in the equatorial Pacific [7]. GCM modeling has pointed to increases in ENSO-related variability, which are different in the central and eastern Pacific [28] and should have been evident from the 1960s onward [7]. Our finding indicating the difference between significantly increasing trends in SST_w and SST_{max} and the absence of significant trends in SST_c and SST_{min} suggests that intra-annual variability in the tropical central and eastern Pacific may be increasing.

There were no significant trends in the intra-annual IoV (Figure 5) or interannual variability over 7 decades (Figure 7) of SST in any of the Nino regions or P in either atoll for the period 1951 to 2023. There was, however, the hint of a very weakly significant increasing trend of $0.017 \pm 0.009/100$ y ($\alpha < 0.07$ and $\alpha < 0.11$) in the intra-annual IoV of SST for the western Nino4 region. Previous GCM modeling found that ENSO variability in the tropical Eastern and Central Pacific responds differently to global warming [27]. Increased ENSO SST variability was projected to emerge in the eastern Pacific by 2030 ± 6, a decade earlier than the central Pacific. The absence of any trends in intra-annual or decadal interannual SST variability in either central or eastern Pacific between 1951 and 2023 is therefore unsurprising. The weak trend in intra-annual SST in the Nino4 region appears counter to the prediction that ENSO variability should first emerge in the eastern Pacific.

Changes in seasonal rainfall affect rainwater harvesting in atolls [3]. We looked for changes in the relative strength of seasons by considering trends in the ratio of warm season to cool season SST and the ratio of wet to dry season P (Figure 4). No significant trends in SST_w/SST_c in any Nino region or in P_w/P_d in either atoll were uncovered. Episodic reversals of annual seasons with $SST_w < SST_c$ and $P_W < P_d$ were a feature of the seasonal ratios. The number of reversals increased from zero in the eastern Nino1 + 2 region to 19 in the western Nino4 region between 1951 and 2023. Surprisingly, there were nine seasonal reversals in Kiritimati, the easternmost atoll, but only three in Tarawa, located within the Nino4 region. Seasonal reversals in the Nino3 and Nino3.4 regions and in Kiritimati occurred in El Niño years, whereas most of those in the Nino4 region and all reversals in Tarawa occurred in La Niña years. These reversals appear following movements of the Pacific warm pool and shifts in the SPCZ and the ITCZ during ENSO events, with only strong to very strong El Niño events extending to the Nino3 region and to Kiritimati accompanied by major southward shifts in the ITCZ [28].

4.4. Extreme Annual P95 and P05 SST and Rainfall Events

GCM predictions of increases in the frequency of strong El Niño and La Niña events since 1960 [7] prompted our examination of the occurrence of extreme annual events, taken here to be annual data greater than the 95th percentile or less than the 5th percentile. Tables 4 and 5 show the less-than-perfect correspondence between P95 and P05 annual median SST in the Nino3.4 region and those for annual P in the atolls. There was almost no one-to-one correspondence between the percentile rankings of extreme SST events and extreme P_a events, although all P95 events coincided with El Niños and all P05 events corresponded to La Niña events, as expected [2].

The significant feature of Table 4 is extreme, high SSTs in the Nino3.4 region were only evident from 1982 onward, while extreme, large P in both atolls only occurred from 1987 onward. In the Nino3 and Nino4 regions, P95 SST only appeared from 1987 and 2002, respectively. These are consistent with the impacts of increasing SST and with the model projections of increased frequency of strong El Niño events post-1960 [7].

In contrast, in Table 5, all extreme, low P05 SST events in the Nino3.4 region occurred before 1999, consistent with rising ocean temperatures, but extreme, low rainfalls in the atolls occurred throughout the record, from the triple La Niña in 1954–1956 to the triple La Niña in 2020–2022. This suggests a decoupling of extreme, low rainfalls from extreme, low SST.

In terms of atoll water security, for Kiribati, the P05 annual rainfall is only 248 mm, while that for Tarawa is 684 mm. The P05 rainfall events in Table 5 represent severe droughts that challenge atoll water security, particularly in urban atolls. The data in Table 5 does not appear to support the suggestion that severe droughts in the equatorial Pacific are increasing with time [4]. The lowest annual rainfall on record in Kiritimati occurred in 1954, while that in Tarawa occurred in 1998, both in triple La Niñas. When summed over 36 months, however, the lowest cumulative rainfall for Kiritimati was in

2022, while that for Tarawa was in 2002. The linkage between ENSO events, identified by the SST anomaly in the Nino3.4 region, and island rainfalls across the western is very well known [2] and is used routinely to inform three-month forecasts of water stress for Pacific Island countries [33].

4.5. The Relationships between Twelve-Month Rainfall and Historic SST Excursions

Despite significant increasing trends of order 1.0 °C/100 y in annual median SST in the Nino1 + 2, Nino3, and Nino4 regions, we did not find accompanying significant trends in annual rainfall in the two equatorial study atolls. Can past influences of annual SST excursions on annual rainfall provide a guide to future influences?

Annual average SSTs in the Nino regions, between 1951 and 2023, varied by 2.5 to 4.5 °C, driven by ENSO cycles. This range is of the same order or larger than the projected climate-change-driven increase in SST in the equatorial Pacific at the end of this century [6]. Here, we explored the relationships between 12-month rainfall in the atolls and 12-month average SST in the Nino regions. On monthly time scales, the relationships are apparent but complex (Figure 6).

The maximum correlation between P_{12} and SST_{12} for each of the atolls occurred with the Nino region to the east of the atoll (Figure 8 and Table 8), for Kiritimati with the Nino3 region, and for Tarawa with the Nino3.4 region, but not with the Nino regions within which they are located (Table 8). One possible explanation for this is the impact of the persistent easterly Pacific trade winds sweeping water vapor from the ocean to the east of the atoll. The correlations with all Nino SST_{12} values were extremely significant ($\alpha << 0.00001$). The maximum correlations between P_{12} and SST_{12} (Table 8) show that a simple linear relation between P_{12} in Kiribati and SST_{12} in the Nino3 region (Figure 8) explains 72% of the variance. For P_{12} in Tarawa and SST_{12} in the Nino3.4 region, 76% of the variance is explained by the linear relationship.

Taking the simplest assumption that P_{12} is linearly dependent on SST_{12} (Figure 9), we found that the rate of increase in 12-month rainfall in Kiritimati with increasing 12-month SST in the Nino3 regions is about 940 mm/°C, while for Tarawa and the Nino3.4 region, the rate of increase is about 1300 mm/°C (Table 9).

For Kiritimati, the assumption of linear dependence is questionable (Figure 9a). Examination of above-average (12-month rainfalls greater than the 70th percentile), average (12-month rainfalls between the 30th and 70th percentile), and below-average (12-month rainfalls less than the 30th percentile) 12-month rainfalls, however, appears to resolve the apparent non-linearity (Figure 10a). For Kiribati, above-average rainfalls have increased by about 1200 mm for every 1.0 °C rise in SST_{12} in the Nino3 region but, surprisingly, average, and below-average rainfalls are statistically independent of SST_{12} (Figure 10a and Table 10).

For Tarawa, the situation is quite different (Figure 10b and Table 10). Above-average, average, and below-average rainfalls all increased with increasing SST_{12} in the Nino3.4 region. Above-average and average rainfalls increased at about the same rate, by about 670 mm/°C, while below-average rainfalls increased at about two-thirds of that rate.

One possible explanation for the difference in behavior between the two atolls is that the eastern location of Kiritimati atoll borders the Pacific dry zone [2]. In strong to very strong El Niño events with higher SST in the equatorial Pacific, the ITCZ moves southward over the atoll [26], causing extreme, high annual rainfalls (Table 6). Moderate and weaker El Niños have a much smaller influence on annual rainfall. Tarawa, to the west, lies closer to the neutral location of the Pacific warm pool and has higher median annual rainfall and lower variability than Kiritimati (Table 1). Tarawa also has less pronounced seasonality than Kiritimati (Figure 3) and is influenced by the Western Pacific Monsoon [2]. Weaker and moderate El Niños have more influence in Tarawa because of the northward displacement of the SPCZ, which mostly does not affect Kiritimati.

Recent GCM model projections [27] identified a difference in SST response to ENSO cycles in the eastern and central tropical Pacific. In the eastern Pacific, there are strong warm events and weaker cool events, while in the central Pacific, there are strong cool events and weaker warm events. Kiritimati borders the eastern Pacific, so the lack of dependence of average and below-average P_{12} on SST_{12} (Figure 10a, Table 10) compared to the significant dependence of all P_{12} values on SST_{12} in Tarawa (Figure 10b, Table 10), which borders on the central Pacific, may be consistent with these projections. Additionally, the asymmetry between warm season/maximum annual SST with significant temporal trends and cool season/minimum SST with no significant trends may be a manifestation of these differences.

GCM projections [27] also suggest rainfall increases relative to pre-industrial levels in the eastern equatorial Pacific at the location of Kiritimati under a high greenhouse gas emission scenario of about 1200 to 2000 mm/y/°C of global warming, of the same order as the historic rate of change in above average rainfall in Kiritimati (Table 10). For the western equatorial Pacific, however, in the vicinity of Tarawa, the projections suggest rainfall decreases of about −600 mm/y/°C of global warming, which is at odds with the historic increasing trend for Tarawa (Table 10).

4.6. Implications for Future Water Security in Atolls

The finding that extreme, large rainfall events in both atolls only appeared from 1987 onward suggests that an episodic increase in groundwater recharge in both atolls has happened since 1987. The data in Table 4, however, does not provide evidence that the intensity of extreme events is increasing with time despite the increasing intensity of extreme, high SST in the Nino3.4 region (Table 4).

Atoll groundwater constantly discharges to the surrounding sea [3,17,30], so the influence of increased episodic recharge on groundwater security depends on the frequency, severity, and duration of intervening droughts [13]. For the two atolls in this study, this depends on the timing and strength of La Niña events (Table 5). Even though the lowest 36-month rainfalls in both atolls occurred after the year 2000, Figure 11a,b do not suggest increases in drought frequency or duration since 1951.

GCM model projections suggest that increased ENSO-related variability may only emerge around 2030 [27]. Two of the lowest extreme annual rainfalls in Tarawa and all four in Kiritimati (Table 5) occurred during triple La Niña events (Figure 5c), which have occurred regularly about every 20 years since 1951. These had major impacts on water security, particularly in urban South Tarawa. Any increase in the frequency of triple La Niñas is a major threat to future water security in these equatorial atolls.

If the past influences of SST on rainfall in the atolls is a guide, the results in Figure 10 and Table 10 suggest that above-average rainfall in Kiritimati may increase by about 1200 mm for every 1.0 °C rise in SST, while above-average and average rainfall in Tarawa may increase by about 660 mm/°C. For Kiritimati, below-average 12-month rainfalls were independent of SST, while below-average 12-month rain in Tarawa increased by 450 mm/°C. With projected SST rises in the equatorial Pacific of 2 to 3 °C, the past behavior suggests that both Kiritimati and Tarawa will experience increased groundwater recharge and local flooding, while droughts in Tarawa will be less severe because of increasing below-average rainfall. Droughts in Kiritimati, however, may remain unchanged because of the independence of below-average rainfall on SST. Finding strategies for supplying reliable and safe water during extreme droughts in atolls with increasing populations remains a priority challenge.

An often-mentioned threat to atoll groundwater security is the threat of rising sea levels because of global warming. A study of 30 atolls in the Indian and Pacific Oceans over the past decades and up to a century found that no atoll has decreased in land area despite sea level rises of up to 5 mm/year [34]. Islands over 10 ha in area either remained stable or increased in area. Faced with the projected magnitude of sea level rise by 2100, however, there is no guarantee that the accumulation of reef debris will continue to keep pace with rising sea levels [35].

5. Conclusions

Because of the long-recognized vulnerability of atoll freshwater supplies, this work focused on the influences of SST in the vast surrounding ocean on longer-term rainfall and its variability in two widely separated atolls in the central and western equatorial Pacific where warming seas are projected to increase annual rainfall [2,4] and variability [7,27]. The atolls are in regions subject to quite different large-scale atmosphere–ocean interactions [2], but both are dominated by ENSO events. Our understanding of the dynamics of ENSO events is currently incomplete [4], and GCM projections of their future frequency and intensity are uncertain.

Between 1951 and 2023, we found warm season, annual monthly maximum, and annual SST in the Nino1 + 2, Nino3, and Nino 4 regions increased significantly at a rate of order 1.0 °C/100 y, in accordance with GCM projections for high greenhouse gas emissions [28]. There is, however, an asymmetry between the increasing trends in the warm season and maximum annual SST in the Nino regions and the absence of significant trends in cool season and annual minimum annual SST. This asymmetry suggests annual variability should have increased, in line with GCM projections [7], but no significant trends were detected in intra-annual or interannual variability in SST over 7 decades in any of the Nino regions. Recent projections suggest that ENSO-related variability may only emerge in the eastern tropical Pacific after 2030 and a decade later in the central Pacific [28].

Although SST in the equatorial Pacific has increased significantly, we found no significant trends in seasonal, annual maximum, annual minimum, or annual rainfalls or in intra- or interannual rainfall variability over 7 decades for the two atolls located in this region. This is in accordance with a previous analysis over a 20-year shorter period than analyzed here [9]. They attributed the general lack of significant trends in rainfall between 1961 and 2011 to a change in the phase of the IPO around 1999 [9]. Here, we propose that the strong to extreme variability in P_a in both atolls because of frequent ENSO events masks any significant trends in longer-term rainfall.

We found evidence of the impact of rising SST on rainfall by analyzing the appearance of extreme, large annual events (greater than the 95th percentile) post-1951. Extreme, large annual SST events appeared from 1982 onward and extreme, large P_a only appeared from 1987 onward, in line with GCM projections [4,7,26]. While extreme, large SST_a events increase in magnitude with time, extreme, large rainfalls in both atolls do not. We cannot, therefore, conclude that extreme, large P_a are increasing in intensity, only that they were first evident from 1987 onward.

Our results for extreme, small annual events (less than the fifth percentile) again show asymmetry. There have been no extreme, small SST_a, (SST_a < P05) since 1999 in any of the Nino regions, consistent with the warming ocean trend. In contrast, extreme, low P_a in both atolls occur episodically between 1954 and 2021, an apparent decoupling of the linkage between small P_a and small SST_a. For 12-month rainfalls, the smallest P_a on record in both atolls occurred prior to the year 2000, at odds with suggestions of increasing drought severity with global warming. Cumulative rainfall over 36 months, relevant to atoll groundwater recharge, however, showed that the lowest 36-month rainfall on record in both atolls occurred after 2000, following triple La Niñas. Triple La Niñas have occurred approximately every 20 years since 1951, accompanied by severe droughts. Their future frequency and severity are of vital importance for atoll water security.

Here, we proposed that the past response of cumulative rainfall over 12 months, P_{12}, in the equatorial atolls to ENSO-induced fluctuations in 12-month average SST, SST_{12}, may be a guide for future responses to the warming ocean. The maximum, highly significant correlations between P_{12} in the atolls and SST_{12} occurred with SST_{12} of the Nino regions to the east of the atolls and not with those of the Nino regions surrounding the atolls. We suggest this is due to the prevailing easterly trade winds. Assuming linear relations, the rate of change in P_{12} with SST_{12} was about 900 to 1300 mm/°C. For Kiritimati, bordering on the eastern tropical Pacific, this is consistent with the range of rate of change in GCM projections for a high emission scenario. However, the projections for Tarawa, in the central western Pacific, which project decreasing annual rain with increasing global temperatures, [27] are inconsistent with the historically increasing trend.

For Kiritimati, the response of P_{12} to SST_{12} appears exponential, as expected from the increase in water vapor pressure with rising SST. When rainfall is portioned into above-average, average, and below-average P_{12}, the increasing trend was resolved but a surprising difference between the atolls emerged. In Kiritimati, only above-average P_{12} rainfall was significantly related to SST_{12} with a rate of change of about 1200 mm/°C, whereas average and below-average P_{12} was independent of SST_{12}. In contrast, for Tarawa, all three percentile ranges were significantly related to SST_{12}. We suggest that the different responses of the atolls are due to their locations in the eastern and western tropical Pacific and the spatially different impacts of ENSO events on the migrations of the SPCZ, the ITCZ, and the WPM in those locations. Recent GCM projections found different responses of the eastern and central Pacific to ENSO cycles under global warming [27].

If the past historic responses of longer-term rainfalls in the atolls to ENSO-induced changes in SST are guides to what may happen with 2°C to 3 °C of warming by the end of this century, then groundwater recharge and local flooding may increase markedly in both atolls by 2100. In Tarawa, droughts may become less severe as average and below-average rainfalls increase with rising SST. In Kiritimati, however, the past independence of average and below-average rainfalls on SST implies that droughts will be as severe as they have been in the past. A critical uncertainty in projecting future water security in equatorial Pacific atolls is the frequency and severity of triple La Niña events. An increase in the frequency of triple La Nina occurrences with warming SST would be a severe threat to atoll water security.

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