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Revisiting the association between sea surface temperature and the epidemiology of fish poisoning in the South Pacific: Reassessing the link between ciguatera and climate change

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ABSTRACT

The most detailed dataset of ciguatera intensity is that produced by the South Pacific Epidemiological and Health Information Service (SPEHIS) of the Secretariat of the Pacific Community. The SPEHIS fish poisoning database has been previously analysed yielding statistically significant correlations between the Southern Oscillation Index (SOI) and ciguatera case numbers in several countries raising concerns this affliction will increase as oceans warm. Mapping of the SPEHIS records and other data hints at ciguatera not only being restricted to warm waters but that the Indo-Pacific Warm Pool, a body of water that remains hot throughout much of the year, may inhibit ciguatera prevalence. A qualitative assessment of ciguatera intensity and sea surface temperature (SST) behaviour within the EEZ of selected South Pacific nations supported the notion that ciguatera intensity was highest when SST was between an upper and lower limit. Many more climate and SST indices beyond the SOI are now available, including some that measure the above-mentioned phenomenon of oceanic warm pools. Statistically significant, positive and negative cross-correlations were obtained between time series of annual ciguatera case rates from the SPEHIS dataset and the Pacific Warm Pool Index and several ENSO related indices which had been lagged for up to 2 years before the ciguatera time series. This further supports the possibility that when considering the impact of climate change on ciguatera, one has to consider two thresholds, namely waters that remain warm enough for a long enough period can lead to ciguatera and that extended periods where the water remains too hot may depress ciguatera case rates. Such a model would complicate projections of the effects of climate change upon ciguatera beyond that of a simple relationship where increased SST may cause more ciguatera.

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1. Introduction

It is often stated that ciguatera is a tropical and sub-tropical disease. This generalisation is not strictly true as it is not pan-tropical and where it does occur, it does so with variable intensity, ranging from severe at times to non-existent at others. This is evident if one looks at the

distribution of reported ciguateric fish and ciguatera poisonings (Fig. 1).

Ciguatera arises after people eat fish that have bioaccumulated ciguatoxins. A key contributing factor to ciguatera prevalence in a human population is the amount of ciguatoxin within the food web where they are the top-level consumer. Toxicity of individual fish depends upon the time spent bioaccumulating toxins and the amount of bioavailable toxin in the source organism, epiphytic dinoflagellates in the *Gambierdiscus* genus (Chinain et al., 1999a; Holmes, 1998; Lewis and Holmes, 1993). Dinoflagellate

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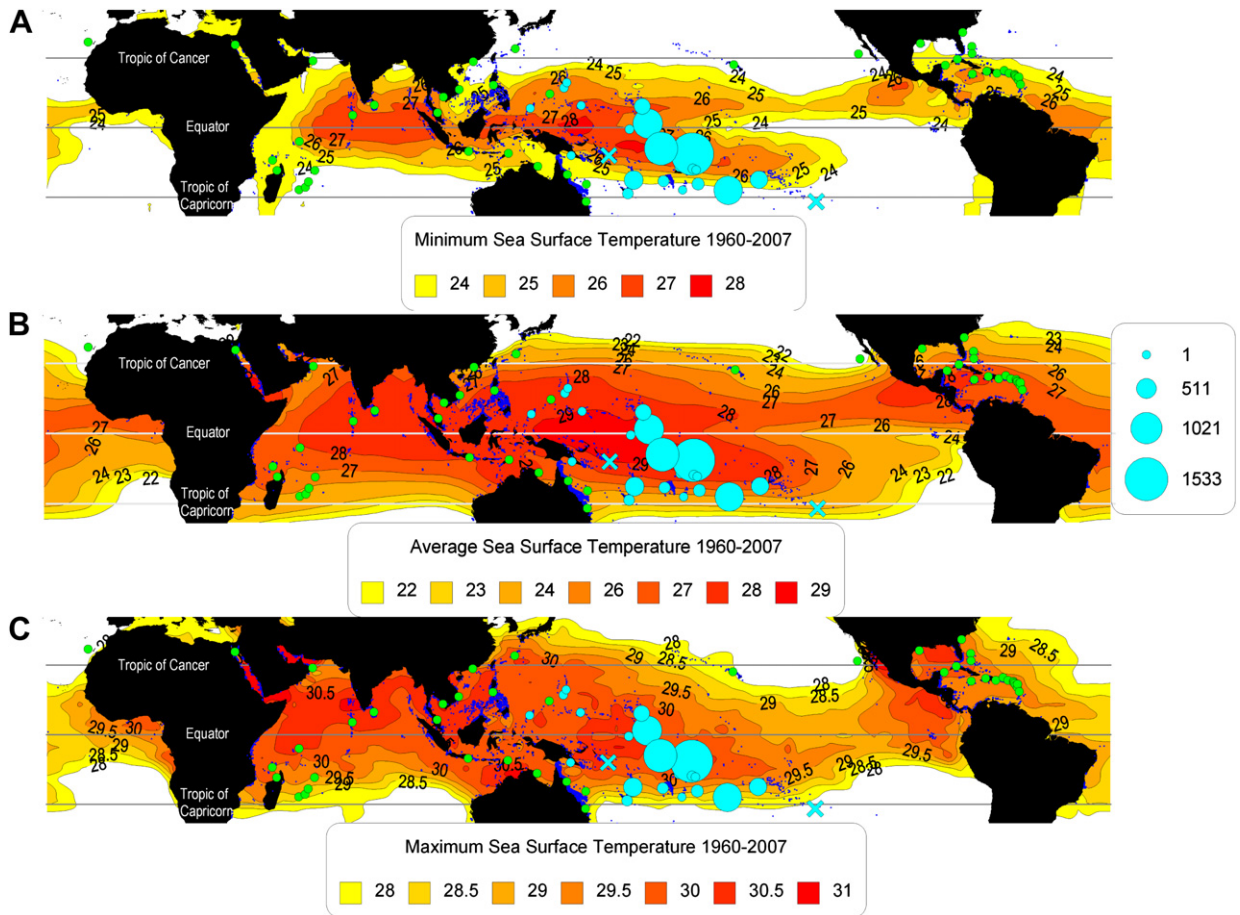


Fig. 1. Global distribution of ciguatera and ciguateric fish relative to (A) minimum, (B) average and (C) maximum sea surface temperatures for the period 1960–2007 from the HadISST dataset. Light blue circles depict annual case rate of fish poisoning from the SPEHIS dataset (1988–1996) with circle size indicating the case rate as per the legend to the right. The two light blue crosses indicate the Solomon Islands and Pitcairn Island where zero cases of ciguatera were recorded in the SPEHIS dataset. Small green circles indicate reported locations of ciguatera or capture of ciguateric fish from the primary scientific literature as well as quality testing reports for various major fish markets (eg Japan, Hong Kong). Blue dots locate coral reefs obtained from the Worldfish Center Reefbase (www.reefbase.org).

population size is also seasonal such as the winter blooms of *Gambierdiscus toxicus* reported in the Atimaono barrier reef in Tahiti (Chinain et al., 1999b).

For a microscopic organism, the littoral oceans can be paradise, providing nutrients and trace elements, substrates upon which they can settle and colonise, as well as sunlight for photosynthesising organisms. The oceans also provide a watery medium by which they can be transported between suitable living locations and by which thermal energy can be transferred to the organism. Unlike the controlled laboratory environment, these conditions fluctuate with the seasons and are subject to long term trends in the scale and limits of these fluctuations. It is this latter point that underlies the concerns that long-term changes in climactic conditions may affect the prevalence of ciguatera and the geographic range of its occurrence.

Data from the South Pacific Epidemiology and Health Information Service (Dalzell, 1993) has been previously used to identify a correlation between sea surface temperatures (SST), the Southern Oscillation Index (SOI) as a measure of El

Nino-Southern Oscillation (ENSO) events and numbers of reports of fish poisoning in different South Pacific nations (Hales et al., 1999). This study has informed much thinking about future ciguatera risk within South Pacific nations, most notably by the Intergovernmental Panel on Climate Change (Mimura et al., 2007) and in projections for Kiribati that “a rise in temperatures is expected to increase the incidence of ciguatera poisoning from 35–70 per thousand people in 1990 to about 160–430 per thousand by 2050” (Papua New Guinea and Pacific Islands Country Unit, 2000). There must be caution however about a simple model of increasing SST’s leading to increased ciguatera because surface waters do not have an infinite capacity to warm. Feedback mechanisms can suppress unlimited SST increases in open oceans, a phenomena called the tropical ocean thermostat, although the thermostat threshold may itself be subject to change (Kleypas et al., 2008).

In the past decade, continued mining of global climate datasets has delivered climatological indices of relevance to the Pacific beyond the SOI (Table 1). Within the past decade

or so, there has also been recognition of the existence and importance of the Indo-Pacific (Huang and Mehta, 2004) and Western Pacific Warm Pools (Wang and Enfield, 2001), large bodies of seawater whose SST mostly remains above 28.5 °C. Given this expansion in climate indices that attempt to describe complex oceanic behaviour relevant to tropical Pacific nations, it is timely to revisit possible relationships between climate measures and the SPEHIS fish poisoning dataset, especially in light of how it has shaped widespread thinking about links between climate change and ciguatera risk.

2. Materials and methods

Fish poisoning statistics were obtained from the South Pacific Epidemiological and Health Information Service (SPEHIS) of the Secretariat of the Pacific Community which provides monthly data for most of the South Pacific nations for 1988–1996. It should be noted that reporting accuracy for the different nations can vary considerably because these are developing nations and territories with sparse resources which may be concentrated within urban centres. Furthermore, they can be geographically widespread (eg Kiribati, Cook Islands, French Polynesia) affecting communication from outlying areas. Annual ciguatera case rates were calculated using population data from the United Nations global population database (Anonymous, 2007a,b), which is provided on a 5 yearly basis. Populations in intervening years were calculated using a linear relationship between the 5 yearly values.

Table 1

Cross-correlation coefficients between annual fish poisoning case rates for South Pacific nations (1973–1996) and average annual (January–December) climatology indices. Climate index time series were lagged up to 2 years prior to the ciguatera case rate time series. Cross-correlation values are only shown for statistically significant relationships ($p < 0.001$). A climate index is listed only if there was a statistically significant relationship for 3 or more countries for at least one of the time series. The right hand column is the number of statistically significant relationships that exist between ciguatera case rate time series for the 9 listed countries and the listed climate index at the stated time lag.

	Lag (years)	American Samoa	Fiji	French Polynesia	Kiribati	New Caledonia	Tokelau	Tuvalu	Vanuatu	Western Samoa	Number statistically significant relationships
Southern Oscillation Index	0			0.46				−0.51		−0.43	3
	1					0.51	−0.47			−0.50	3
	2	−0.33				0.54		−0.45			3
Pacific Warm Pool	0	0.33	0.54		0.34	−0.68			0.51		5
	1		0.48		0.68	−0.65	0.37		0.46		5
	2		0.55		0.66	−0.49		0.51	0.51		5
Pacific Decadal Oscillation	0					−0.33	0.38				2
	1	0.32	0.36			−0.45			0.37		4
	2		0.49		0.41	−0.44			0.51		4
Tropical Pacific EOF	0	0.33		−0.41			0.32	0.41			4
	1					−0.51	0.45			0.39	3
	2				0.32	−0.44			0.40		3
Nino 3.4	0			−0.42				0.46			2
	1					−0.40	0.36			0.45	3
	2					−0.40			0.33		2
Nino 4	0		0.41	−0.49	0.32			0.61		0.39	5
	1					−0.53	0.34			0.55	3
	2	0.32				−0.50			0.47		3
Bivariate ENSO	0			−0.46				0.49		0.38	3
	1					−0.44	0.38			0.50	3
	2					−0.47			0.38		2
Trans Nino	0		−0.45					−0.50	−0.37	−0.38	4
	1		−0.44		−0.35			−0.35	−0.42	−0.50	5
	2	−0.50				0.38			−0.32		3
Multivariate ENSO Index	0			−0.42				0.44		0.33	3
	1					−0.56	0.46			0.47	3
	2				0.34	−0.49			0.44		3

Annual case rate time series were extended to 1973–1996 by combining this dataset with previously published annual case rates from the same data source (Lewis, 1986). This generated time series spanning 23 years for nine countries (Table 1).

Climate indices and their annual (January–December) averages were sourced from the Climate Prediction Center, National Centers for Environmental Prediction, National Oceanic and Atmospheric Administration (NOAA) and National Weather Service of the USA (www.cdc.noaa.gov/data/climateindices/list).

Sea surface temperatures (SST) were obtained from the Hadley Centre Sea Ice and SST dataset (HadISST) (Rayner et al., 2003). When necessary, it was sub-divided into the South Pacific nations Exclusive Economic Zones (EEZ) by identifying all $1^\circ \times 1^\circ$ grid squares that were >50% in a nation's EEZ using maritime boundaries as calculated by the Flanders Marine Institute (Anonymous, 2005).

All cross-correlations, auto-correlation and partial auto-correlation calculations between time series of ciguatera case rates, and their lags, and climate indices were conducted using R (R Development Core Team, 2008).

3. Results

3.1. Qualitative analysis

Mapping South Pacific national ciguatera case rates from the SPEHIS database along with other locations where ciguatera and ciguateric fish have been reported, shows this

syndrome is most prevalent in regions where SST's do not go far below 24 °C (Fig. 1A). The intensity of ciguatera in the South Pacific increases dramatically where average SST's are at least 28–29 °C (Fig. 1B). For example, the three largest circular symbols which depict the highest ciguatera case rates in Figs. 1A–C, represent Tokelau, Tuvalu and Kiribati all of whom had an average SST for the period 1960–2007 greater than 29 °C. The fourth largest symbol represents the Cook Islands. The Cook Islands is a very geographically dispersed nation with its capital Raratonga located only two degrees of latitude north of the Tropic of Capricorn but with most of its territory, and therefore fishing grounds, stretching 15 degrees north of Raratonga towards the equator (Fig. 2). Most of the Cook Islands territory has an average SST greater than 28 °C. The next three largest symbols represent case rates for Marshall Islands, Vanuatu and French Polynesia. Like the Cook Islands, French Polynesia possesses a very large sovereign territory (Fig. 2) much of it extending north into a region that experienced an average SST more than 28 °C (1960–2007). The Marshall Islands experienced an average SST greater than 28 °C during 1960–2007 and Vanuatu is predominantly located within a region with an average SST ranging between 27 and 28 °C.

Exceptions exist however to the above observation that ciguatera intensity is highest in regions where the average SST is greater than 28–29 °C. This includes north-western Australia and the Solomon Islands which are not renowned for

ciguatera. Notably these locations are regions where the SST can become very warm (Fig. 1C). Similarly, the Red Sea and the Arabian Gulf are tropical locations not renowned for ciguatera and these enclosed seas can also become very warm.

A phenomenon that exists within the western Pacific along the Equator is the West or Indo-Pacific Warm Pool (IPWP). This is a body of water whose temperature remains above 28–28.5 °C. Fig. 2 depicts the same case rates shown in Fig. 1 but focussing on the equatorial Indo-Pacific region and the South Pacific nations covered by the SPEHIS dataset. It also depicts that body of water whose SST remained above 28 °C all year round and during the four seasons in the years spanned by the SPEHIS dataset (1988–1996). Apart from a few locations, this warm pool corresponds to areas with low or negligible ciguatera intensity based on our current knowledge. This observation coupled with the increase in ciguatera intensity with warmer water, indicates that ciguatera occurrence and intensity may have both a lower and upper threshold.

This potential interaction between seawater being either too hot or too cold for ciguatera production is exemplified in Fig. 3. This figure depicts annual case rates for Kiribati using SPEHIS data used here coupled with previously published annual case rates from the same source (Lewis, 1986). The figure shows the percentage of the Kiribati EEZ that was below, between and above an SST band of 28 and 30 °C. Ciguatera case rates are presented in

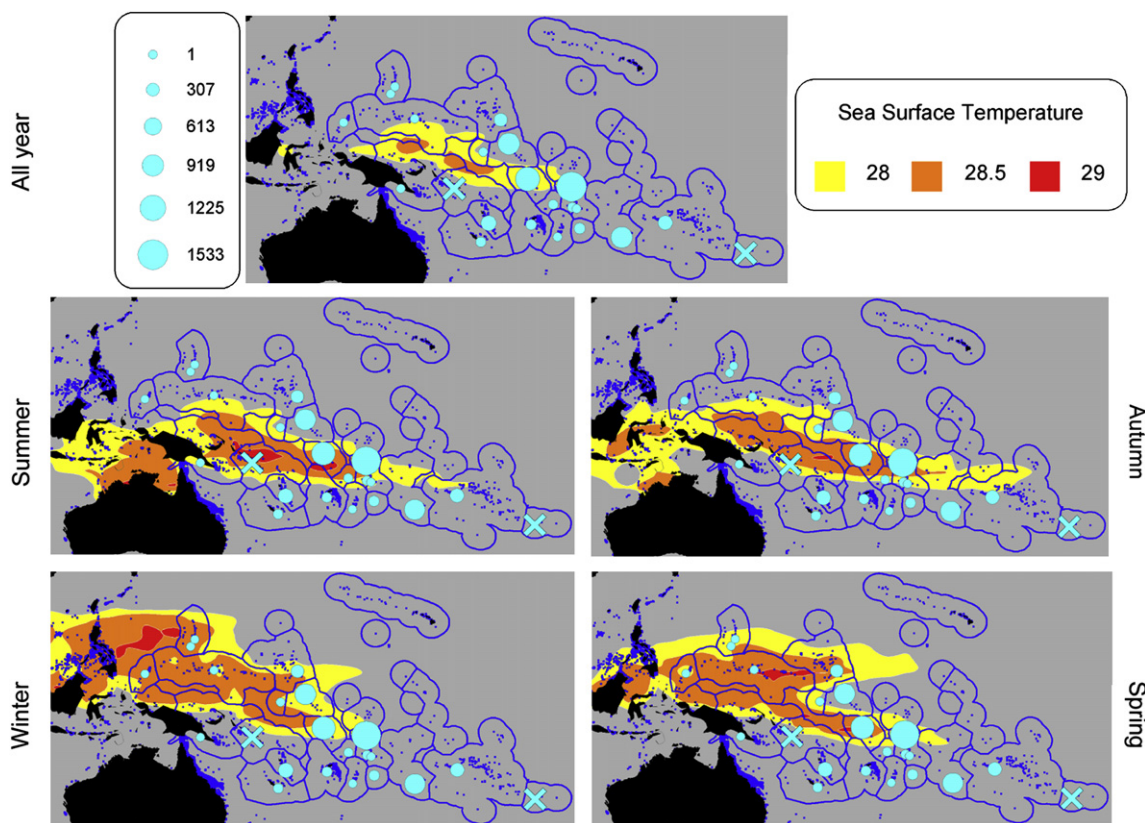


Fig. 2. Annual case rates for ciguatera from the SPEHIS dataset and proximity to the Indo-Pacific Warm Pool based on SST values from the HadISST dataset for the period 1986–1996, which is the same time period covered by the SPEHIS dataset in addition to the previous 2 years to account for potential lag of effects. Blue borders depict Exclusive Economic Zones as calculated by the Vlaams Instituut voor de Zee (Anonymous, 2005).

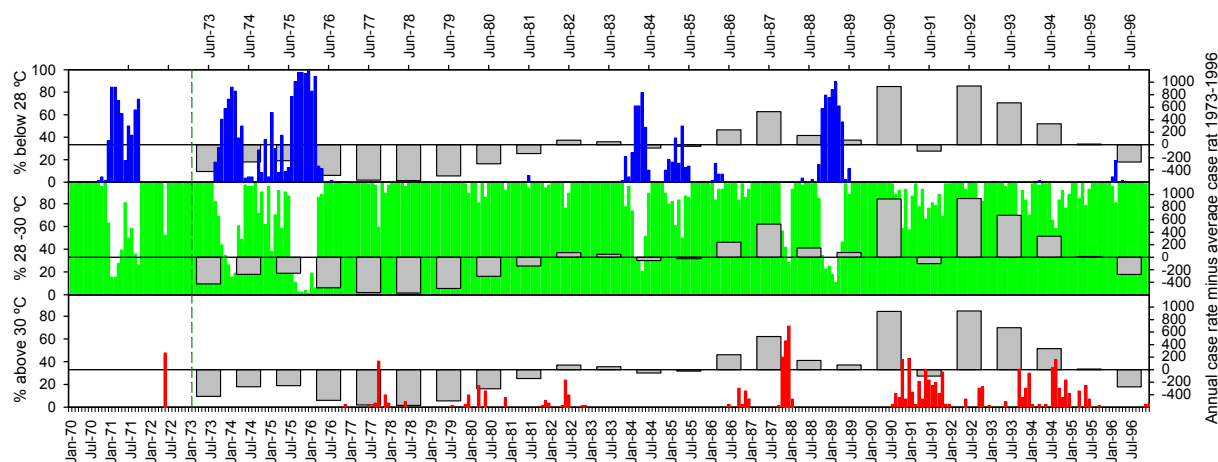


Fig. 3. Annual case rates for ciguatera for Kiribati and SST dynamics for the Kiribati EEZ. Ciguatera case rates are presented by subtracting the long term average of the dataset from each annual case rate value (Grey histogram bars). This shows the variations in ciguatera intensity around the average ciguatera load for Kiribati. Overlaid upon the ciguatera case rate series is the percentage of the Kiribati EEZ that was below, between and above the SST band of 28 and 30 °C (blue, green and red bars, respectively). SST data is for the period 1970–1996 and ciguatera case rate data was from 1973 to 1996.

a similar manner as SST anomalies by subtracting the long term average of the dataset from each annual case rate value. This more clearly visualises variations in ciguatera intensity around what might be considered the expected ciguatera load for Kiribati. The period 1971–1976 was quite cool and likewise, the ciguatera intensity was low. From 1977 to 1983, SST remains mostly between 28 and 30 °C and the rate of ciguatera increased to the long term average. A mild cool period in 1984 and 1985 corresponds to a stop in the rate of increase of ciguatera intensity before it starts to increase again when waters were again predominantly in the 28–30 °C band. A short period of hot water in late 1987 followed by a cold period in 1988–1999 corresponded to a decrease in ciguatera until 1990. Seawater temperature increased above 30 °C in 1990–1991 and saw a drop in ciguatera reports after which they increased again when the hot water disappeared. From 1992 onwards, warm water greater than 30 °C again regularly appeared and there was a rapid year-on-year decline in ciguatera case rates.

3.2. Time series cross-correlations

Prior to computing cross-correlations between time series of climate indices and ciguatera case rates, they were assessed for autocorrelation which is where a data series is significantly correlated to itself when it is lagged by one or more steps. (Chatfield, 2003), a property most obvious in seasonal time series. Autocorrelation and seasonality can render a time series non-stationary which can compromise cross-correlation analyses. Autocorrelation and partial autocorrelation coefficients were calculated for all time series and none were significantly auto-correlated.

Table 1 lists statistically significant cross-correlations between annual ciguatera case rate time series from South Pacific countries and climate indices. Only those indices are listed where three or more countries exhibited a significant relationship. The strongest relationships were the negative cross-correlation between the Pacific Warm

Pool index and New Caledonia ciguatera case rates (-0.68) when there was no time lag and the positive relationship between Pacific Warm Pool Index (lagged 1 year) and Kiribati ciguatera intensity. The Pacific Warm Pool Index had statistically significant relationships with 5 of the nine countries for each of the cases where there were time lags of 0, 1 year and 2 years. Of the ENSO indices, the strongest positive relationship observed was 0.61 between Tuvalu and Nino 4 when there was no time lag. The strongest negative relationship was -0.56 between the Multivariate ENSO Index (lagged 1 year) and New Caledonia ciguatera case rate. Nino 4 also had statistically significant relationships with 5 of the 9 countries when there was no time lag but the cross-correlation values were generally less than that obtained using the Pacific Warm Pool Index.

4. Discussion

Ciguatera epidemiology is subject to significant uncertainty and depends upon victims presenting themselves to medical professionals, ciguatera being correctly diagnosed and for cases to be reported to public health authorities. Ciguatera occurs mostly within developing tropical nations (IMF, 2009) with limited public health funds, expertise and facilities. Many of these countries also possess remote populations without access to medical care and communication tools for reporting events when they occur. These limitations are not unique to ciguatera epidemiology however (Pocock et al., 2004; Stallknecht, 2007) and despite these reservations for many datasets, public health authorities and resource managers seek to improve their decision-making by mining available data for patterns.

The largest dataset of ciguatera occurrence is that provided by the South Pacific Epidemiology and Health Information Service (Dalzell, 1993). From it, statistically significant correlations were reported to exist between sea surface temperatures (SST), ENSO events and fish poisoning levels in different South Pacific nations (Hales et al., 1999).

There is a logical rationale underlying the potential link between changing climate to ciguatera prevalence and distribution. Ambient temperature may affect ciguatoxin production by altering growth rates of toxic organisms (Chinain et al., 1999b) and rates of toxin production (Ashton et al., 2003). Different temperature may also alter accumulation, metabolism and detoxification kinetics in fish vectors much like it can for tetrodotoxin (Matsumoto et al., 2007) and organic pollutants (Hop et al., 2002). More complicated mechanisms may exist however. It has been shown that a model reef fish takes up dietary nutrients less effectively at higher seawater temperatures (Munday et al., 2008). This may be paralleled by a reduced ability to bioaccumulate toxins from their diet. Similarly, the range inhabited by various fish species, and hence toxin vectors, may change with altered climactic conditions as has been shown in the North Sea (Perry et al., 2005). It has also been suggested that increased fatal coral bleaching events, which can occur when seawater gets too hot (Gleeson and Strong, 1995; Goreau and Hayes, 1994), may lead to an increased available surface area for macroscopic algal growth and therefore also for toxic dinoflagellates (Lehane and Lewis, 2000).

As our understanding of the global climate increases and computation power enables improved mining of global datasets, more and more measures have emerged of regional oceanic phenomena. This includes recognition of regions referred to as warm pools, one of which is in close proximity to the South Pacific nations, the Indo-Pacific Warm Pool (IPWP) (Fig. 3). Notably, nations in close proximity to the IPWP have low or negligible ciguatera even though they are located within the tropics, widely regarded as the home of ciguatera. Enclosed tropical seas such as the Red Sea and Arabian Gulf, which can attain SST's near 35 °C in some parts, also have negligible ciguatera reputations. Coupled with the observation that SST must be reasonably warm for ciguatera to occur (Fig. 1), the following hypothesis can be generated:

- SST needs to be above a lower threshold long enough to generate enough ciguatoxin in the ecosystem for ciguatera to be widely observed in a human population;
- If SST exceeds an upper limit long enough, ciguatera occurrence decreases.

Qualitative examination of the behaviour of SST within the EEZ's of South Pacific nations and their changes in their ciguatera intensity (Fig. 3) support this notion that

ciguatera rates decrease when seawater gets either too cold or too warm. Time lags between seawater conditions and responses by *Gambierdiscus* spp. populations have also been observed (Chateau-Degat et al., 2005). This further complicates the potential link between seawater conditions and ciguatera by the need to accommodate the possibility that it may take some time for the ciguatoxin load within an ecosystem to increase to a threshold above which we observe increased ciguatera within the human population.

Climate indices convert complex phenomena into a simple numerical representation to visualise patterns of change, usually through time. The Pacific Warm Pool Index was the most successful climate measure in terms of having statistically significant relationships to ciguatera intensity in five South Pacific nations for the period 1973–1996. This index summarises the behaviour of the Indo-Pacific Warm Pool and covers a geographic region close to many of the nations analysed here (Fig. 4). Several ENSO indices also exhibited robust relationships with ciguatera case rate time series with Nino 4 being the most successful. This may not be surprising given its close geographic proximity to many of the South Pacific nations examined here (Fig. 4). A statistical relationship has been previously observed by Hales et al. (1999) to ENSO-related phenomena. They reported that annual case rates (1973–1994) for Tuvalu, Western Samoa and Kiribati were correlated to annualised values for SOI and local SST. The SOI is calculated from atmospheric pressure differences between Tahiti and Darwin, Australia and does not cover a geographic region. Statistically significant relationships between SOI and ciguatera were also observed here with ciguatera in Western Samoa and Tuvalu but not for Kiribati at either 0, 1 or 2 year time lags. French Polynesia (no time lag), New Caledonia (1 and 2 year lag) and Tokelau (1 year lag) had statistically significant relationships with the SOI. The Nino 3.4 (Table 1), Nino 3 (data not shown) and Nino 1 + 2 (data not shown) indices had only a few, if any, statistically significant relationships with ciguatera intensity. These indices cover regions increasingly distant from the South Pacific nations listed in Table 1.

Cross-correlation analysis supports the possibility that warming seawater may have both a positive and negative impact upon ciguatera case rates. This points to the requirement for SST to remain within a band of temperature long enough for ciguatera to become prevalent. Such a phenomenon complicates projections of the effects of climate change upon ciguatera beyond a simple

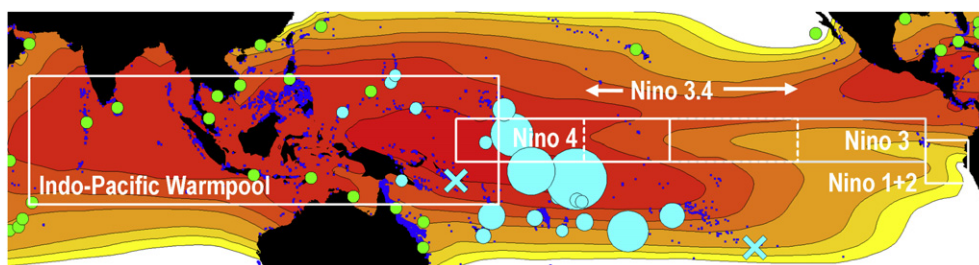


Fig. 4. Map showing geographic extent for the Nino and Indo-Pacific Warm Pool indices derived from large spatial areas. The underlying map depicts average SST and ciguatera intensity as per Fig. 1B.

relationship of increased SST causing more ciguatera. If there is an upper and lower threshold to SST and its impact upon ciguatera intensity, then there will be a need to identify both of these limits for increased ciguatera risk and ascertain whether they vary between regions. Also in terms of projecting risk maps for future ciguatera, then one has to consider not only when a region may enter the ciguatera friendly conditions in terms of the seawater becoming warm enough to promote ciguatera but also when it may become too warm for ciguatera to occur. There is an obvious analogy that can be made to another seawater temperature dependent dinoflagellate phenomena, namely coral bleaching (Gleeson and Strong, 1995; Goreau and Hayes, 1994). Coral and zooxanthellae exist in a symbiosis which can collapse at both elevated (Glynn and D'Croz, 1990) and cool sea surface temperatures (Hoegh-Guldberg et al., 2005).

While the SPEHIS dataset is valuable for analysing ciguatera epidemiology, more ciguatera data with increased robustness is required as well as a need to adopt more sophisticated analyses. Climate and other SST indices may need to be purpose-designed for ciguatera forecasting by targeting specific geographic regions. Analyses may also need to include multivariate models that link several independent climate measures with ciguatera intensity. The model presented here is just such a case where measures of both upper and lower temperature thresholds may need to be combined to provide leading indicators of ciguatera prevalence.

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Conflict of interest

There are no competing interest.

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