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Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies☆

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ABSTRACT

Ciguatera fish poisoning (CFP) is a circumtropical disease caused by ingestion of a variety of reef fish that bioaccumulate algal toxins. Distribution and abundance of the organisms that produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with water temperature. Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP. This concern prompted experiments on the growth rates of six G*ambierdiscus* species at temperatures between 18 °C and 33 °C and the examination of sea surface temperatures in the Caribbean and West Indies for areas that could sustain rapid *Gambierdiscus* growth rates year-round. The thermal optimum for five of six *Gambierdiscus* species tested was ≥29 °C. Long-term SST data from the southern Gulf of Mexico indicate the number of days with sea surface temperatures ≥29 °C has nearly doubled (44 to 86) in the last three decades. To determine how the sea surface temperatures and *Gambierdiscus* growth data correlate with CFP incidences in the Caribbean, a literature review and a uniform, region-wide survey (1996–2006) of CFP cases were conducted. The highest CFP incidence rates were in the eastern Caribbean where water temperatures are warmest and least variable.

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1. Introduction

Ciguatera fish poisoning (CFP) occurs in tropical regions worldwide and, globally, is the most common non-bacterial food-borne illness associated with consumption of fish (Baden et al., 1995; Ansdell, 2009). The toxic organisms most commonly associated with CFP are benthic dinoflagellates in the genus *Gambierdiscus*. These dinoflagellates are reported to produce ciguatoxins (Yasumoto et al., 1979; Durand-Clement, 1987; Lewis and Holmes, 1993) which bioconcentrate in marine food chains, reaching their highest levels in top predators such as barracuda and other tropical reef fish. Ciguatoxins have been found in more than 400 fish species, including groupers, snappers, jacks, mackerels, trigger fish and surgeonfish (Halstead, 1978; Bagnis et al., 1980). Consumption of tainted fish can lead to gastrointestinal distress followed by neurological and cardiovascular symptoms and, in rare cases, death. Chronic symptoms of CFP can persist for weeks, months or years (Freudenthal, 1990; Chateau-Degat et al., 2007) and repeated exposure to ciguatoxins exacerbates the symptoms (Bagnis et al., 1979; Pottier et al., 2001).

While CFP is a threat to public health throughout tropical areas, it is generally managed by local, traditional knowledge of the native fishers, who may warn each other about areas where ciguatoxic fish are known to occur. However, local knowledge of ciguatoxic reefs and seasonality of occurrence

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may no longer be accurate due to changing environmental conditions (Tosteson, 2004). Tosteson (2004) reported a seasonal correlation between the abundance of toxic, benthic dinoflagellates, the toxicity of barracuda and incidences of CFP in Puerto Rico from 1985 to 1988. Data collected from the southwest coast of Puerto Rico from 1990 to 2000 showed a gradual loss of seasonality and a significant increase in the fraction of toxic barracuda (Tosteson, 2004). He argued these changes were due to increasing periods of elevated sea surface temperatures in the Caribbean. While considerable evidence exists that ciguatoxicity does vary seasonally (Carlson and Tindall, 1985; Bomber et al., 1988; Chinain et al., 1999; Tester et al., 2009), not all studies reflect this (de Fouw et al., 2001). Some suggest there may be cultural practices that cause CFP incidences to mimic seasonal patterns (Tosteson, 2004; Morrison et al., 2008), especially when holiday meals include large reef fish.

One of the objectives of this study was to characterize the relationships between sea surface temperatures (SSTs) and CFP incidence rates in the Caribbean and West Indies, hereafter referred to as the Caribbean. This was done in tandem with a series of experiments designed to determine the effects of temperature on the growth rate of organisms responsible for CFP. Growth rates of five species of *Gambierdiscus* isolated from the Caribbean and the U.S. South Atlantic Bight (Litaker et al., 2009; Litaker et al., in press) and *G. pacificus* isolated from Moorea, Society Islands in the Pacific were determined at temperatures between 18 °C and 33 °C. The thermal growth optima for the six species were compared with seasonal sea surface temperatures derived from thermal imagery and longer term temperature trends (1977–2007) from buoy data for the Caribbean and southern Gulf of Mexico. These data provide information about which regions of the Caribbean are hospitable to *Gambierdiscus* growth and which areas could support maximal growth year-round.

To characterize and evaluate information on CFP throughout the Caribbean, data were requested from public health officials and fisheries managers from 24 island nations and territories in the Caribbean, as well as the nine mainland countries surrounding the Caribbean, to determine the frequency of CFP incidences from 1996 through 2006. To better understand CFP distributions in the Caribbean versus the Pacific, these incidence rates were compared with those from literature reports from both the Caribbean and the tropical Pacific, including data published after our primary data collection had been completed.

2. Materials and methods

2.1. Incidence rates of ciguatera fish poisoning between 1996 and 2006 in the Caribbean

Based on published cases and self-reporting, it appeared that CFP was most prevalent in the West Indies (Stinn et al., 2000) with the highest number of CFP cases centered in the Bahamas. It is important to point out that Stinn et al. (2000) were reporting cases of CFP and not incidence rates. To better assess where CFP was most prevalent or if "hot spots" could be identified in the Caribbean, the case reports needed to be normalized in a systematic way. The most commonly used method for normalizing CFP data is to divide the CFP cases by the population of the reporting area for the same year the CFP cases were reported. In this way CFP cases are translated to CFP incidence per 10,000 population per year and can be compared among different areas and studies. This is the approach used in the current study to examine patterns of CFP occurrence and compare those with water temperature data.

To examine CFP distribution patterns, an active method was used to query public health officials and fisheries managers about the occurrence of CFP from 1996 through 2006 in 24 Caribbean island nations and territories and 9 mainland countries bordering the Caribbean. This time period was selected, in part, to overlap with data from earlier studies that compiled Caribbean CFP data through 2006 (Tosteson, 2004; G. Luber and L. Backer, personal communication). Fisheries and public health officials in each country were contacted separately and asked for compiled data on occurrence of CFP by month. One or both agencies could be involved in the surveillance of and response to CFP, though often within different administrative units. The survey questions used in this study were vetted by experts with experience in designing human health surveys (see Acknowledgements; Tester et al., 2009).

Initial contact was made with public health and fisheries department staffs by phone. Introductory conversations were conducted in English, Spanish, or French, depending on the preference of the officials. Introductory information was provided by phone. Once a contact was identified, written information was provided in the appropriate language (or languages, as some participants received the information in both Spanish and English or French and English). Health and fisheries officials from the following countries were contacted: Anguilla, Antigua and Barbuda, Aruba, the Bahamas, Barbados, Belize, the British Virgin Islands, the Cayman Islands, Colombia, Costa Rica, Cuba, Dominica, the Dominican Republic, Grenada, Guadeloupe, Guatemala, Honduras, Jamaica, Martinique, Mexico, Montserrat, the Netherlands Antilles, Nicaragua, Panama, Puerto Rico, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, the U.S. Virgin Islands, and Venezuela. Until 2007, Saint Martin and Saint Barthélemy were both administratively attached to Guadeloupe, an overseas region and department of France. The Netherlands Antilles is comprised of Curaçao and Bonaire, just off the Venezuelan coast, and Sint Eustatius, Saba, and Sint Maarten, located southeast of the Virgin Islands. Efforts to establish contacts in Haiti were unsuccessful.

2.2. Literature searches

For the Caribbean most of the data identified through literature searches were obtained from the Caribbean Epidemiology Centre (CAREC, 2009) and the Pan American Health Organization (PAHO, 1998, 2002) websites and annual reports. Other government and health department websites for each country were searched for epidemiological data. Additional data and case reports were found through an extensive literature search using Google Scholar© (2009) and ISI Web of Science© (2009). Annual population data for the total populations in the areas of interest were obtained from the CIA World Factbook (2008) and were supplemented with data from CAREC (2009), the Caribbean Community Secretariat (CARICOM, 2009) and the United Nations Statistics Division (2009).

For the Pacific, some compiled data on CFP cases were found online from the South Pacific Epidemiological and Health Information Services (SPEHIS, 2005) and the Secretariat of the Pacific Community (SPC, 2009). As in the Caribbean, data were also identified by searching government and health department websites for epidemiological data. Information for French Polynesia was obtained by personal communication (T. Darius). Population data used to calculate incidence rates of CFP were obtained from SPEHIS annual reports and from the CIA World Factbook (2008). Population data for Hawaii were obtained from the State of Hawaii Department of Business, Economic Development and Tourism (2006).

2.3. Remote sensing and buoy data

Sea surface temperature (SST) data were downloaded from the National Data Buoy Center (2009) website. Buoys were selected based on their proximity to the study area and the length of the period of data availability. There was a 30 year record for NDBC Station 42003 (25.966 N, 85.594 W) in the southeastern Gulf of Mexico. In addition, 3 year records were available from the Yucatán buoy 42056 (19.874 N, 85.059 W) in the western Caribbean and station CHAV3 at the tip of the British Virgin Islands (18.335 N, 64.92 W) in the eastern Caribbean. Hourly buoy data were filtered to limit the data to one record per day at local noon to correspond to the daytime satellite SST information.

Sea surface temperature data for 2002–2007, derived from satellites, were downloaded from the National Aeronautic and Space Administration Giovanni website (NASA, 2009). Temperature data used in this study were derived from 9-km resolution data from the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite, representing sea surface temperatures (as derived from the 11 micron wavelength, during the daytime). Data were downloaded as monthly, time-averaged latitude–longitude maps. Digital data at 1.0° resolution were also downloaded for 2002–2007. Temperature data for each month were averaged over 5 years to produce five-year average monthly SSTs maps that were plotted using ArcMap version 9.2© (ESRI, Redlands, CA). An inverse distance weighted interpolation was applied to create the temperature contour lines in 1 °C increments. These maps facilitated an examination of the spatial relationship between SST and the incidence of CFP.

2.4. *Gambierdiscus* growth rates at temperatures between 18 °C and 33 °C

Each of six species of *Gambierdiscus* (*G. carolinianus*, *G. pacificus*, *G. ruetzleri*, *G. belizeanus*, *G. caribaeus*) and *Gambierdiscus* Ribotype 2) (Litaker et al., 2009; Litaker et al., in press) was grown in a series of five replicate 275-ml vented tissue culture flasks containing 150 ml of sterile modified K medium (salinity = 33, no TRIS, no Cu, no Si, no NH_4^+, 2 × NO_3^-) (Keller et al., 1987). Each flask was incubated under 100 μE m^{-2} s^{-1} of irradiance (12:12 light/dark cycle) and held at a constant temperature ranging from 18 °C to 33 °C (Durand-Clement, 1987; Ballantine et al., 1988). Approximately 40 ml of each culture was aseptically transferred to a sterile screw-capped test tube and *in vivo* fluorescence was measured using a Turner model 10 fluorometer (Turner Designs, Inc., Sunnyvale, California). Growth rates were calculated as the slope of the fluorescence vs. time curve using a series of 3–5 sequential fluorescence measurements. The mean growth rate for each species was then calculated using the slope of each replicate ($n = 5$).

3. Results

3.1. Ciguatera fish poisoning incidence rates during 1996–2006 in the Caribbean

All countries and island nations responded to the request for information on ciguatera fish poisoning except one (32 of 33, 97%). No response was received from Haiti because no appropriate Haitian contacts could be reached. A total of 35 of 66 surveys from health and fisheries departments relating to CFP were completed (53% of those sent to the health and fisheries departments queried from the 33 countries and territories included in the study). Another set of respondents indicated that they did not plan to submit information because either they did not collect any data about CFP or they were not aware of CFP cases in their jurisdictions during the survey period. This group of respondents was comprised of 20 departments (30% of the fisheries and health agencies targeted) representing fisheries or health agencies in 17 countries (52% of the total countries and territories contacted). Summing the agencies that completed surveys and instances when officials stated they did not plan to submit information, 54 agencies responded affirmatively or negatively to requests for information (82% of those targeted), and these agencies represented 32 countries or territories (97% of the 33 included in this study). The data were accepted as provided. In the survey, no specific instructions were included about recording zeros, leaving blanks in the data table or recording that no data were available for a given year. Since blanks on the survey form could mean either no data or zero (no incidence), we questioned the two respondents who left blanks in their data and resolved the issue. Years for which no data were provided were not used in calculations of the average number of CFP cases. However, if a dataset chronicling multiple years indicated there were zero cases in a given year those were included in the average incidence rate calculations. There was no attempt to identify bias or normalize these data except to report all information as number of CFP cases per 10,000 population annually (Fig. 1).

3.2. Literature searches

Comparative CFP incidence rates for the Caribbean and tropical Pacific were compiled from online data clearinghouses and a variety of literature reports. Incidence rates were calculated based on the number of CFP cases per year

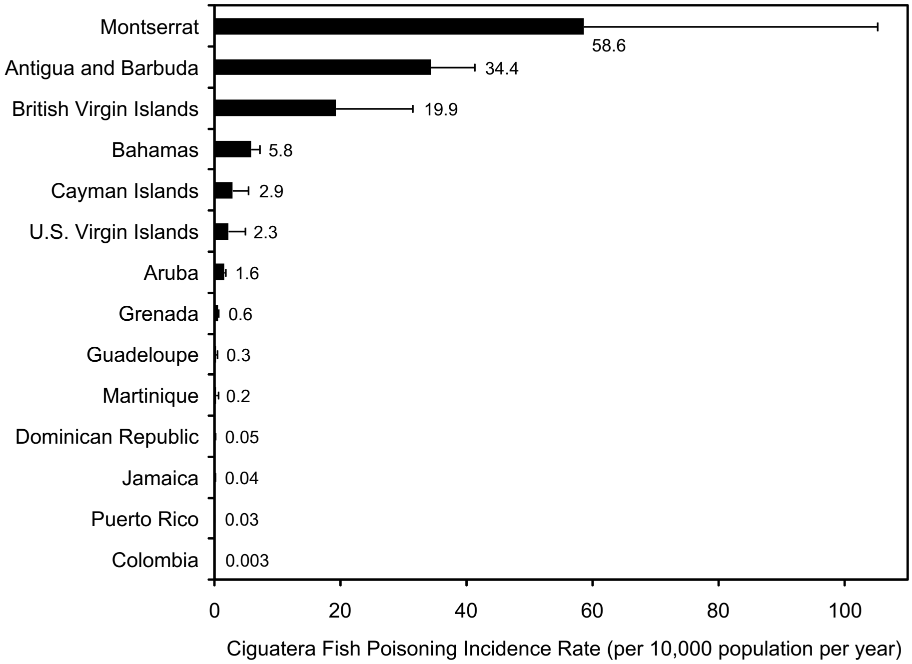

Fig. 1. Average number and standard deviation of ciguatera fish poisoning cases per 10,000 population per year in the Caribbean from 1996–2006, as reported on questionnaires returned by health and fisheries departments. Limited data were available for this survey from the US Virgin Islands, representing only St. Croix. Fourteen countries reported either no cases of ciguatera fish poisoning during the study period or that no data were available.

divided by the population of the country, territory or island for that year. Annual CFP incidence rates were averaged over all years and reported as cases per 10,000 population per year when data were available for more than 1 year (Table 1).

3.3. Sea surface temperatures

The CFP incidence rates were plotted on contour maps of average annual sea surface temperatures (Fig. 2), the average temperatures during the coldest month (February, Fig. 3), and the average temperatures during the warmest month (September, Fig. 4) based on data from 2002 through 2007. These maps help characterize patterns of occurrence of CFP and suggest thermal thresholds for *Gambierdiscus* occurrence. Data from this study for the last decade substantiate that CFP occurrences were most prevalent in the warmest regions of the Caribbean, and all CFP cases occurred where annual average temperatures were ≥ 25 °C (Fig. 2). Even during the coldest month of the year, February, most of the Caribbean basin south of the Greater Antilles (Cuba to Puerto Rico) still had average temperatures above 25 °C (Fig. 3). In September, the hottest month of the year, the 25 °C isotherm was north of 35° N (off Cape Hatteras, North Carolina, USA) and water temperatures in nearly all areas in the Gulf of Mexico and the Caribbean were $\geq$29 °C (Fig. 4).

3.4. Gambierdiscus growth rates at temperatures between 18 °C and 33 °C

Using a temperature range of 18–33 °C, we conducted growth experiments for five *Gambierdiscus* species isolated from the Caribbean to North Carolina (Litaker et al., 2009; Litaker et al., in press) (Fig. 5) and one from the Pacific. In this study *Gambierdiscus carolinianus* had the lowest temperature ($\sim$25 °C) requirement for maximum growth. Not surprisingly, this species is found at the most northerly location, near 34° N. The other five species (*G. belizeanus*, *G. caribaeus, G. pacificus, G. ruetzleri* and *Gambierdiscus* Ribotype 2) all had positive or maximum growth rates $\geq$29 °C. This correlates well with the optimal growth temperature (29 °C) reported for a single isolate of *Gambierdiscus* by Morton et al. (1992). *Gambierdiscus caribaeus*, the most widely distributed *Gambierdiscus* species (Litaker et al., in press), had positive growth between 18 °C and 33 °C, the entire temperature range tested.

Because of the association of *Gambierdiscus* with macrophytes in coral reef habitats, it is important to note the relationship between elevated water temperatures and the proliferation of macroalgae, the preferred habitat for *Gambierdiscus* (Cruz-Rivera and Villareal, 2006). Temperatures >30 °C can cause coral bleaching with subsequent degradation of reef habitats and a “phase shift” from abundant coral to abundant macroalgae (Hoegh-Guldberg, 1999; McCook, 1999). Such a phase shift could provide more macroalgal habitat for *Gambierdiscus* at temperatures highly favorable for their growth.

These growth data were put in context by examining the thermal data available from the National Data Buoy Center’s (2009) stations in the Gulf of Mexico and Caribbean (Fig. 6a). Using 29 °C as a reference point that represents a favorable temperature for *Gambierdiscus* growth, a 30 year record from buoy 42003 was queried for the number of days per year that exceeded 29 °C (Fig. 6b).

Table 1
Ciguatera fish poisoning incidence (CFP) rates in the Caribbean and West Indies (dark grey shaded) and Pacific. Incidence rates were calculated from the number of CFP) cases per year divided by the population of the country, territory or island for that year. Annual CFP incidence rates were averaged over all years and reported as cases per 10,000 population per year. Countries, territories and islands are listed from those with the highest reported incidence rate to those with the lowest incidence rate. Where available, incidence rates from multiple sources are listed, as referenced.

Country or Territory	CFP incidence	Source(s) and other notes
US Virgin Islands	440, 120, 73, 23, 2.31	McMillan et al., 1980 (data from a direct household canvass on St. Thomas, late 1970s); Hanno, 1981 (data from emergency room reports for 1981); Morris et al., 1982 (reporting for 1977–1981); Bagnis, 1981[c] (data for 1981); This study[b] (data for St. Croix only, 2000–2006)
Tokelau	188.81, 65.3	SPEHIS, 2005 (data for 1988–1995); Lewis (1986)[a]
Culebra, Puerto Rico	121.6	G. Luber, personal communications, 2008 (reporting cases for 2005–2006)
Tuvalu	108.6, 43.9	SPEHIS, 2005 (data for 1988–1996); Lewis (1986)[a]
St. Martin	100	Bagnis, 1981[c] (data for 1981)
Kiribati	93.92, 32.4	SPEHIS, 2005 (data for 1988–1996); Lewis (1986)[a]
Cook Islands	85.89, 0.1	SPEHIS, 2005 (data for 1988–1996); Lewis (1986)[a]
Montserrat	58.63, 42, 33.33	This study[b] (data for 1999–2006); Bagnis, 1981[c] (data for 1981); CAREC, 2006, 2008a (data for 1980–2006)
French Polynesia	54.5, 40.11, 26.3–41.9	Lewis (1986)[a]; SPEHIS, 2005 (data for 1988–1996); Chateau-Degat et al., 2007 (reporting cases for 1992–2001)
Guadeloupe	5–55, 1.5, 0.27	Czernichow et al., 1984 (reporting cases for 1960–1980 as 30 ± 25); Bagnis, 1981[c] (data for 1981); This study[b] (data for 2004–2006)
FL, Miami Dade Co.	5–50(est)	Lawrence et al., 1980 (reporting cases for 1972–1976)
Vanuatu	47.78, 2.9–6.5, 2.5	SPEHIS, 2005 (data for 1988–1996); Goodman et al., 2003 (reporting cases for 1986–1995 on Santo and Ambae islands); Lewis, 1986
British Virgin Islands	40, 25.98, 19.38	Bagnis, 1981[c] (data for 1981); CAREC, 2008a (data for 1980–2005); This study[b] (data for 2000–2004)
Antigua and Barbuda	34.43, 25.38, 6	This study[b] (data for 1996–2006); CAREC, 2006, 2008a (data for 1980–2006); Bagnis, 1981[c] (data for 1981)
Marshall Islands	31.87	SPEHIS, 2005 (data for 1988–1996)
New Caledonia	20, 10.37	Lewis (1986)[a]; SPEHIS, 2005 (data for 1988–1996)
Niue	16.45, 13.0	SPEHIS, 2005 (data for 1989–1996); Lewis (1986)[a]
Fiji	12.86, 1.6	SPEHIS, 2005 (data for 1988–1994, 1996); Lewis (1986)[a]
Anguilla	11.71	CAREC, 2006, 2008a (data for 1980–1996, 1999–2006)
Puerto Rico	11, 0.14, 0.2, 0.03, 0.023	Escalona de Motta et al., 1986 (data from emergency room reports 1980–1982); Holt et al., 1984 (reporting cases for 1982 only); Bagnis, 1981[c] (data for 1981); This study[b] (data for 1996–2006); Tosteson, 1995 (calculated from data for 1980–1989)
American Samoa	8.7, 2.56	Lewis (1986)[a]; SPEHIS, 2005 (data for 1988–1994)
Northern Mariana Islands	8.3	SPEHIS, 2005 (data for 1988–1994)
Bahamas	5.82, 2.31	This study[b] (data for 1996–2006); CAREC, 2006, 2008a (data for 1980–2006)
Samoa	5.75, 5.4	SPEHIS, 2005; Lewis (1986)[a]
Cayman Islands	5.71, 2.94	CAREC, 2006, 2008a (data for 1980–2006); This study[b] (data for 1996–2007)
Wallis and Futuna	5.57, 0.9	SPEHIS, 2005 (data for 1990, 1992–1994, 1996); Lewis (1986)[a]
St. Kitts and Nevis	5.5, 0.04, Yes	Bagnis, 1981[c] (data for 1981); CAREC, 2006, 2008a (data for 1980–1996, 1998–2006 with no cases reported until 1996); This study[b]
Turks and Caicos	4.25	CAREC, 2006, 2008a (data for 1980–2006 with no cases reported until 1991)
Nauru	2.55, 0.7	SPEHIS, 2005 (data for 1990, 1994); Lewis (1986)[a]
Tonga	2.1, 0.37	Lewis (1986)[a]; SPEHIS, 2005 (data for 1989–1994, 1996)
Jamaica	1.8, 0.07, 0.04	Bagnis, 1981[c] (data for 1981); CAREC, 2006, 2008a (data for 1980–2006); This study[b] (data for 1997, 1999, 2002–2006)
Aruba	1.61	This study[b] (reported as an estimated 15 cases per year for 1996–2006)
Dominica	1.2, Yes, 0	Bagnis, 1981[c] (data for 1981); Taylor, 1984 (reporting cases for 1980); CAREC, 2006, 2008a (data for 1980–1996, 1998–2006)
Martinique	1.15, 0.9, 0.23	PAHO, 1998 (data for 1995–1996); Bagnis, 1981[c] (data for 1981); This study[b] (data for 1997–2007)
Guam	1.04, 0.8	SPEHIS, 2005 (data for 1988–1996); Lewis (1986)[a]
Fed. States of Micronesia	0.91	SPEHIS, 2005 (data for 1990, 1992–1996)
Bermuda	0.75	CAREC, 2006, 2008a (data for 1980–2006 with no cases reported until 1992)
Grenada	0.58, 0	This study[b] (data for one incident where multiple people exhibited symptoms of CFP in 2004); CAREC, 2008a (data for 1994–2005)
Papua New Guinea	0.56	SPEHIS, 2005 (data for 1989 only)
Hawaii	0.44	Hawai'i Department of Health Communicable Disease Division, 2003 (reporting cases for 1998–2002)
Barbados	0.43	CAREC, 2008a, b (data from 1980–1993, 2006 with no cases reported until 2006)
Haiti	0.4, 0.008	Bagnis, 1981[c] (data for 1981); Poli et al., 1997 (data for six cases reported in 1995)
Palau	0.4	SPEHIS, 2005 (data for 1994–1996)
Cuba	0.3, 0.04	Bagnis, 1981[c] (data for 1981); IPK, 2006 (data for 1997–2006)
Solomon Islands	0.2, 0	Lewis (1986)[a]; SPEHIS, 2005 (data for 1995 only)
Dominican Republic	0.05	This study[b] (data for 1996–2006)
Belize	0.04, 0	CAREC, 2006, 2008a (data for 1980–2006 with no cases reported until 1992); This study[b] (data for 1996–2006)
Colombia	0.003, 0.001	This study[b] (data from 2007 only); Alvarez, 1999 (reporting cases for 1999)

Table 1 (*continued*)

Country or Territory	CFP incidence	Source(s) and other notes
Trinidad and Tobago	0.002, 0	CAREC, 2006, 2008a (data for 1980–2006 with no cases reported until 1999); Bagnis, 1981[c] (data for 1981)
Mexico	Yes	This study[b] (data provided on cases only in the state of Quintana Roo, 1997–2002)
Netherlands Antilles	Yes	This study[b]
Venezuela	Yes	This study[b]
Honduras	Unknown	This study[b] (suspected cases reported in 2008)
Costa Rica	0	This study[b]
Guatemala	0	This study[b]
Nicaragua	0	This study[b]
Panama	0	This study[b]
Pitcairn Island	0	SPEHIS, 2005 (data for 1988–1996)
St. Lucia	0, 0	This study[b]; CAREC, 2006, 2008a (data for 1980–1993, 1998–1999, 2006)
St. Vincent and the Grenadines	0, 0	This study[b]; CAREC, 2006, 2008a (data for 1980–2006)

[a] SPEHIS data compiled from 1973 to 1983.
[b] Data requested for 1996–2006. A few respondents also provided 2007 data.
[c] Data from Table 1, Tosteson (1995). Adapted from Bagnis: The incidence of Ciguatera in the Caribbean Region, 1981. A Report of the Intergovernmental Oceanographic Commission (IOC) of the United Nations.

In only three decades, beginning in 1977, the average number of days where SST was >29 °C nearly doubled from 44 to 86. Again using 29 °C as a reference temperature, the data from buoy 42003 in the southeastern Gulf of Mexico was compared with data from buoys off the Yucatán (42056) and to the east at the tip of the British Virgin Islands (CHAV3) (Fig. 6c). Even with many fewer records from the latter two buoys, water temperatures generally increased from 2005 through 2007. Data from the station in the eastern Caribbean (CHAV3) included more days above 29 °C than the western Caribbean location. As might be expected, both Caribbean stations reported more days with SSTs above 29 °C than the Gulf of Mexico station to the north (42003). This echoes Tosteson's (2004) observations on the southwest coast of Puerto Rico where the number of days exceeding 29.5 °C increased from 31 per year in 1985–1988 to 43 per year between 1990 and 1995.

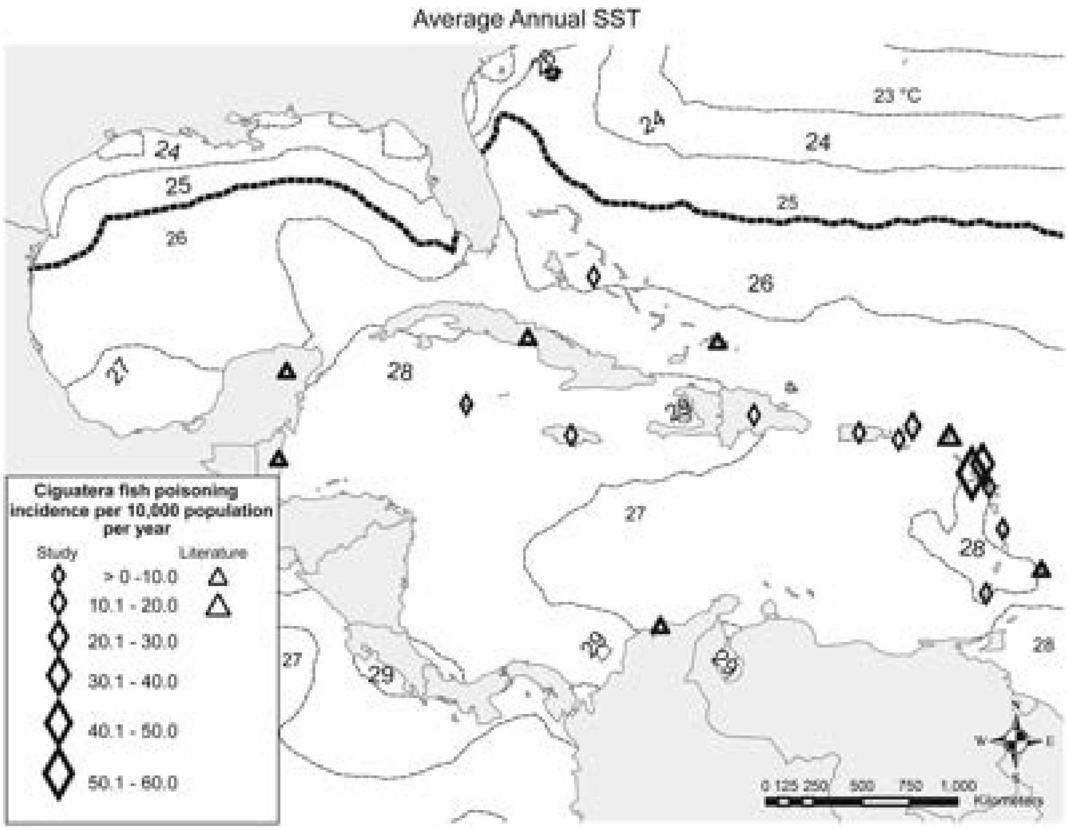

Fig. 2. Average ciguatera fish poisoning incidence rates per 10,000 population per year from 1996–2006 across the Caribbean, plotted with temperature contours (°C) from annual average sea surface temperatures from 2002–2007.

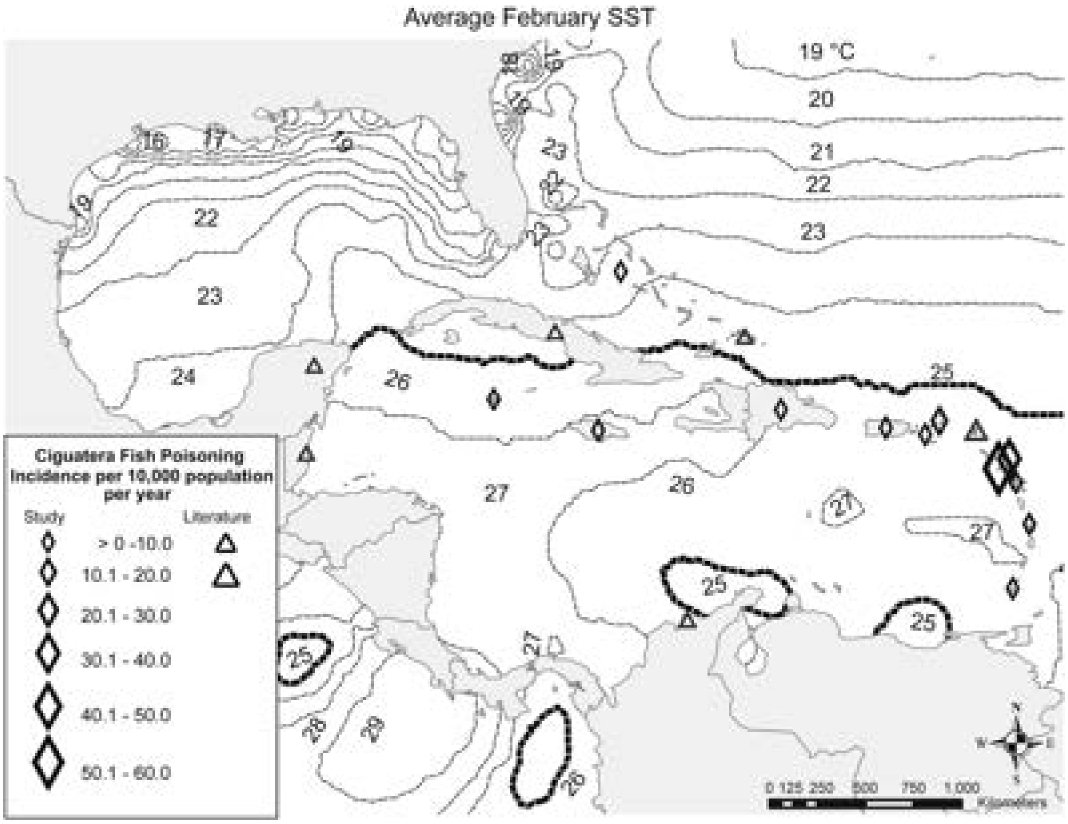

Fig. 3. Average ciguatera fish poisoning incidence rates per 10,000 population per year from 1996–2006 across the Caribbean, plotted with temperature contours (°C) from annual average sea surface temperatures for February, the coldest month of the year from 2002–2007.

4. Discussion

4.1. Incidence rates of ciguatera fish poisoning from 1996 to 2006 in the Caribbean

The highest rates of CFP from 1996 through 2006 reported as part of this study were identified in the Lesser Antilles, the easternmost part of the Caribbean where 34 and 59 cases per 10,000 population per year were reported in Antigua-Barbuda and Montserrat, respectively (Fig. 1). These high CFP incidence rates co-occur with the warmest water temperatures in the Caribbean and where annual temperatures are least variable (Figs. 2–4) (Goreau et al., 1992). There appears to have been an increase in CFP incidence for Antigua-Barbuda and Montserrat in the Lesser Antilles since 1981, when Bagnis as cited in Tosteson (1995) reported 6 and 42 cases per 10,000 population respectively, though no cases were reported at that time to the Caribbean Epidemiology Center in either jurisdiction (CAREC, 2008a, b).

Data from the survey indicated there were seven island nations where an average of one or more cases of CFP per 10,000 population per year occurred during the period 1996–2006 (Fig. 1). Six of the seven (all but the Cayman Islands) are between 12.5° N and 25° N and in the eastern Caribbean. However, the Cayman Islands had a six-fold increase in the number of CFP cases between 2002 and 2007 ($n = 131$) compared to 1996–2001 ($n = 22$). This could document an actual increase in new cases of CFP associated with the warming trend noted in the Caribbean (Fig. 6b, c) and reflect a 0.4–0.8 °C positive temperature anomaly in the Caribbean during 2001–2005 (relative to the 1951–1980 base period) (Hansen et al., 2006).

When asked, public health officials in the Cayman Islands attributed this increase to population growth. The Cayman Islands have experienced a doubling of the population in the last 20 years, in part because they have one of the highest per capita immigration rates in the world (CIA, 2008). So, as the population has grown, so too has the demand for fish. This could result in an increased number of people exposed to CFP, especially those who are not familiar with it. A contact at the Cayman Islands Department of the Environment indicated that native islanders are somewhat more aware and concerned about CFP and the types of fish that might be ciguatoxic than are new residents. Also, increased reports of CFP cases in the Cayman Islands could be due to increased reporting rates because of heightened awareness in the last 5–6 years.

While it is generally agreed across the Caribbean, as in other endemic areas, that CFP has been underreported (Tosteson, 1995), there are other difficulties associated with establishing robust measures of incidence rates. For example, there can be variability in the extent to which the population or their medical providers can identify CFP or in

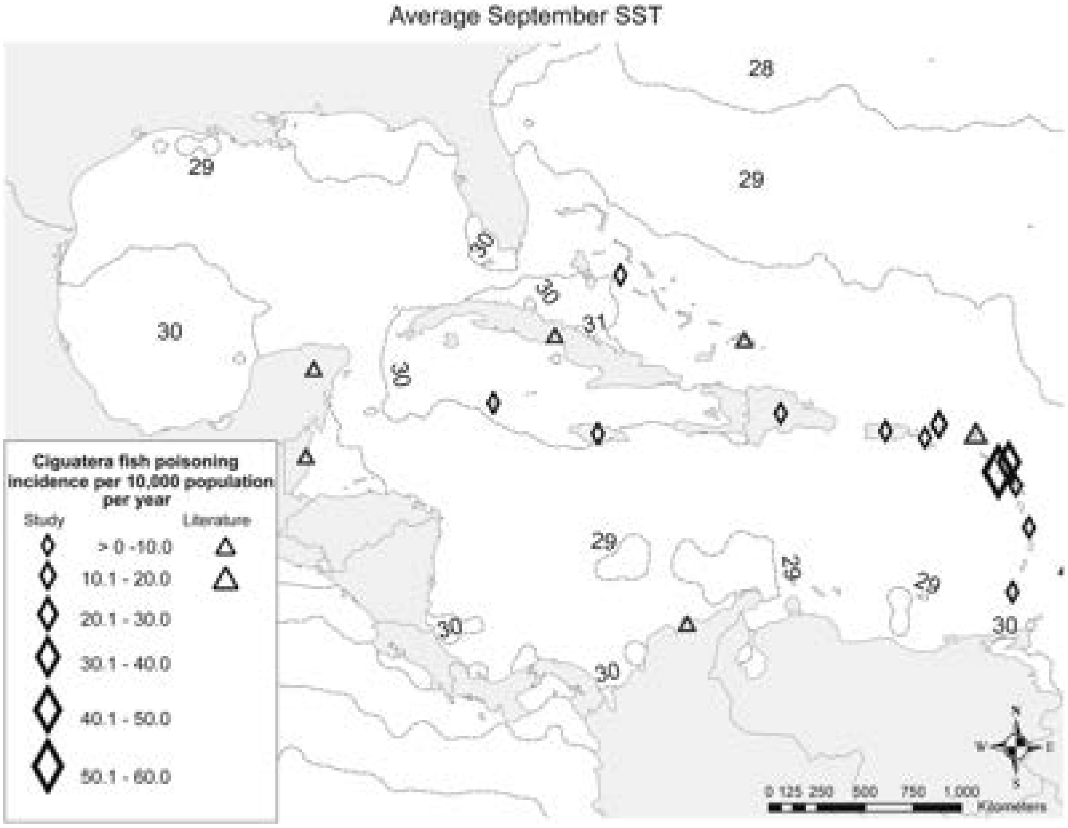

Fig. 4. Average ciguatera fish poisoning incidence rates per 10,000 population per year from 1996 to 2006 across the Caribbean, plotted with temperature contours (°C) from annual average sea surface temperatures for September, the warmest month of the year from 2002 to 2007.

the consistency of reporting CFP to public health authorities. Incidence rates can be affected by variability in regulations across the Caribbean that prohibit selling or trading large, commonly ciguatoxic reef fish. Ciguatera fish poisoning incidence rates also depend on the extent to which the population relies upon locally-caught seafood as their primary source of protein, the extent to which fishers communicate about areas where ciguatoxic fish have been caught, as well as other factors like mandatory or voluntary reporting requirements.

Frequently, it is difficult to resolve causative environmental factors from sociological ones. However, Hales et al. (1999) documented a significant relationship between the number of CFP cases on four tropical Pacific islands and positive SST anomalies. Under the influence of the West Pacific Warm Pool (WPWP), an area of the highest mean annual sea surface temperatures, conditions are highly favorable for *Gambierdiscus* growth year-round. This pattern of the highest incidence rates co-occurring in the warmest part of the Pacific (Fig. 7) mirrors our results for the Caribbean (Fig. 4).

4.2. Literature searches

Across the tropics, where CFP is endemic, it should be noted that small differences or inconsistencies in reporting, or different binning of sparse data, could cause an area to appear to be a “hot spot” for CFP. In the Pacific, high CFP incidence rates were reported after localized blooms of *Gambierdiscus* (Nakajima et al., 1981; Withers, 1984; Chinain et al., 1999; Darius et al., 2007), possibly triggered by favorable environmental conditions (Hales et al., 1999). Data from both the Pacific and Caribbean collated from the literature, and the results of the current Caribbean

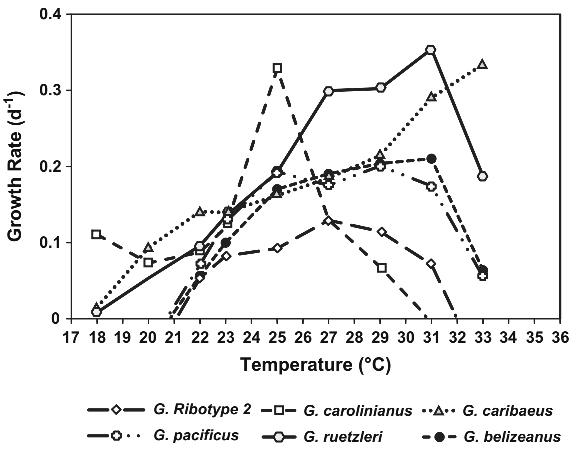

Fig. 5. Growth rates of six species of *Gambierdiscus* measured in the laboratory at temperatures from 18 °C to 33 °C.

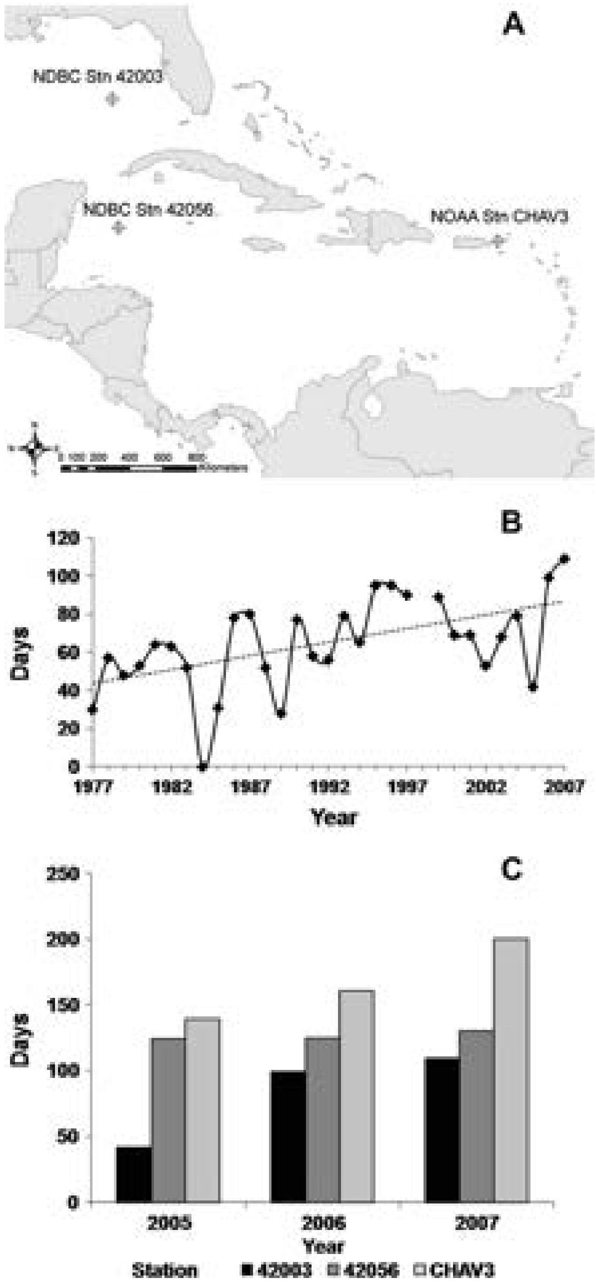

Fig. 6. (a) The National Oceanic and Atmospheric Administration's National Data Buoy Center station locations in the Gulf of Mexico and the Caribbean Sea. (b) Number of days per year exceeding 29 °C at buoy 42003, in the southeastern Gulf of Mexico over three decades. No data were available for 1998. (c) Number of days per year exceeding 29 °C in the Gulf of Mexico (42003) and at the recently deployed data buoys in the western Caribbean (42056) and the eastern Caribbean (CHAV3), from 2005 through 2007.

survey, documented that high incidence rates (e.g., over 100 incidences per 10,000 population per year) occur in both the Pacific and Caribbean, albeit with high variability (Table 1). There was no clear trend in the high incidence rates that pointed to significant differences among islands in the Pacific compared to those in the Caribbean. It is important to remember these high incidence rates, while widely reported, represent only a small subset of the data for either the Pacific or Caribbean. Most annual incidence rates from both regions fell well below the 100 incidences per 10,000 population per year. Average CFP incidences (excluding the door to door and telephone survey results discussed below) were 2-fold higher in the tropical Pacific (24 per 10,000 population per year) compared to the Caribbean (12 per 10,000 population per year). These data would seem to corroborate the common assumption that the tropical Pacific has higher CFP incidence rates than the Caribbean. However, Pacific and Caribbean average incidence rates were not statistically different because of the high variability (two-tailed t-test, $t = 1.86$, $df = 105$, ns).

Spatially intensive studies provide informative examples of how CFP incidence rates are driven by both sociological and environmental factors. Tosteson (1995) cites two studies; both were done in St. Thomas, U.S. Virgin Islands at about the same time. The first was a telephone survey by Tacket reported in a U.S. Center for Disease Control and Prevention (CDC) report of households from 1975 to 1980. The CFP incidence rate in this study was 72.4 cases per 10,000 population per year. The second study reported 440 cases per 10,000 population per year (McMillan et al., 1980) and was the product of a direct household canvass. Tosteson (1995) explained the difference by pointing out the telephone survey excluded lower income households that represented "regular consumers of seafood caught in the immediate area".

In one recent study, G. Luber and L. Backer (personal communication) conducted a door to door survey of households in Culebra, Puerto Rico, in 2005–2006 and found the annual incidence rates of CFP on this small island were between 73.6 and 169.5 per 10,000 (actually reported as 7.36 to 16.95 per 1000) of the island's population. In another study, Morrison et al. (2008) offered some valuable insight into CFP incidence rates in Cuba during the decade between 1993 and 2002. They report 4086 CFP victims in Cuba, or an average annual rate of 0.37 cases per 10,000 population. However, when Morrison et al. (2008) examined data from communities on the northwest coast of Cuba, adjacent to Cuidad de la Habana (Havana City), and used the local population estimates rather than the total population of Cuba to determine annual CFP incidence rates, they found CFP rates varied from 159.11 per 10,000 population per year in Mariel to 1.85 per 10,000 population per year in Santa Cruz del Norte. Mariel, known for its industrial pollution, had the highest rate of CFP in Cuba and one of the most seriously degraded coral reef areas in the country. This community also suffered disproportionally during the collapse of the Cuban economy in the early 1990s when severe shortages caused illegal fishers to thrive, and there was little accountability from black marketers. On the other hand, Santa Cruz de Norte, a traditional fishing village with a strong sense of community, had an active fishermen's federation coupled with a high awareness of CFP (Morrison et al., 2008) that helped protect local residents. There, the CFP incidence rate was lower and close to the rate reported for the adjacent island group having similar thermal habitat, the Cayman Islands (2.9 incidences per 10,000 population).

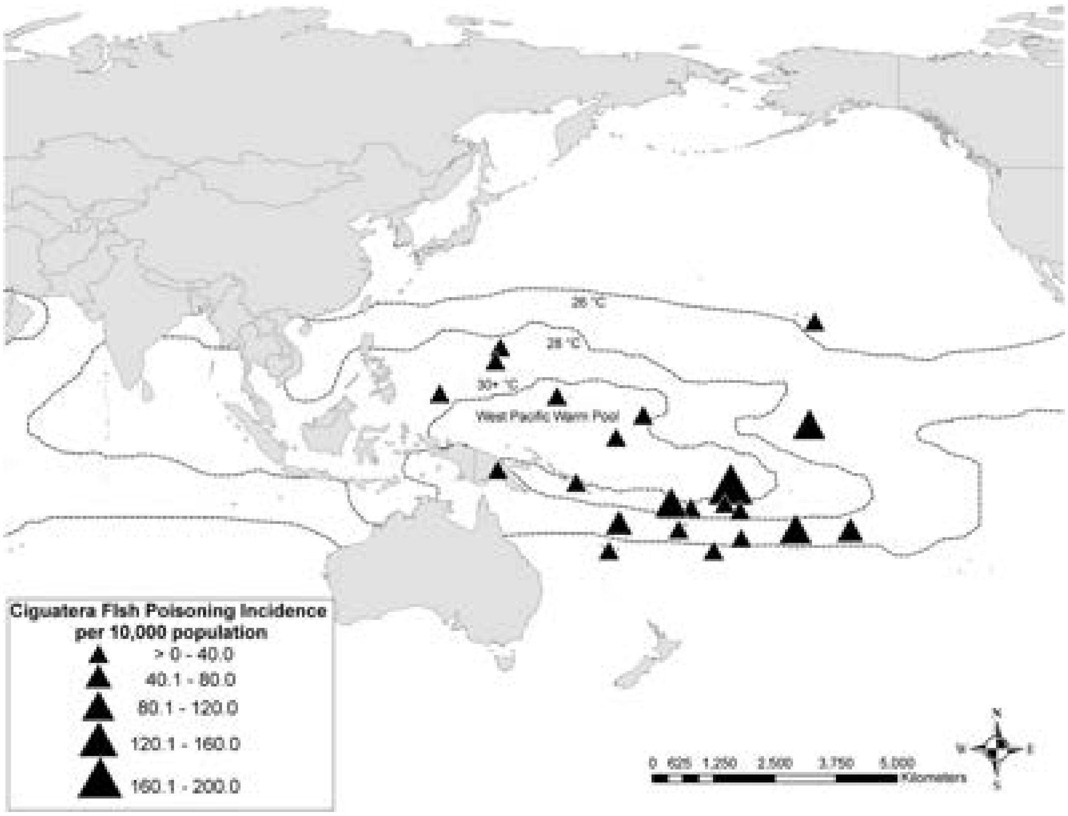

Fig. 7. Average ciguatera fish poisoning incidence rates per 10,000 population per year, from 1988–1996, mapped on 2 °C temperature contours in the south Pacific. Ciguatera fish poisoning data are from SPEHIS (2005), and the thermal data are after Kleypas et al. (2008).

A noteworthy finding from the literature was that CFP seems to have been detected in Trinidad and Tobago only within the last decade. In his study of the Caribbean, Bagnis (as cited in Tosteson (1995)) did not report CFP in Trinidad-Tobago in 1981. There were no CFP cases reported there until 1999, however, from 2000–2006 zero to two cases per year were reported to CAREC (2006, 2008a).

4.3. *Gambierdiscus and temperature*

The autecology of *Gambierdiscus* predicts that many of the species will respond favorably to global climate change (Tester, 1994). Studies of *Gambierdiscus* indicate that many of the species will have wider distributions and increased growth rates. The lower thermal threshold of 25 °C should be considered "permissive" for year-round *Gambierdiscus* growth while temperatures of ≥29 °C permit maximum growth (Figs. 2–4 and 5). An example of range extension consistent with these criteria was discovered by Villareal et al. (2007). They found that numerous oil rigs in the northern Gulf of Mexico support macroalgal populations and now harbor *Gambierdiscus* species. There, lower wintertime temperatures (Fig. 3) still limit overall cell abundance, but this is likely to change as ocean temperatures warm. *Gambierdiscus* species have been found as far north along the U.S. east coast as North Carolina, where the outer continental shelf is over washed by the Gulf Stream (Langley et al., 2009; Litaker et al., 2009). This habitat is characterized by rocky outcrops, rich in seaweeds, and it generally conforms to all the *Gambierdiscus*-permissive environmental conditions (Litaker et al., in press).

The temperature contours on the Pacific coasts of Mexico and Central America also show potentially hospitable areas for *Gambierdiscus* (Figs. 2–4). There has been one report of a ciguatera-like outbreak off the coast of Mexico at a location called Alijos Rocks, 300 miles off Southern Baja California, at 24°57′N, 115°45′W in 1993 (Lechuga-Devéze and Sierra-Beltrán, 1995). There have been other recent, confirmed reports of ciguatoxic fish caught outside endemic areas, such as amberjack (*Seriola rivolinan*) from the Canary Islands in 2004 (Pérez-Arellano et al., 2005), barracuda (*Sphyraena barracuda*) and snapper (*Lutjanus* sp.) from Cameroon, West African (Bienfang et al., 2008), rabbitfish (putatively *Siganus* sp.) caught in Haifa Bay in the eastern Mediterranean basin (Raikhlin-Eisenkraft and Bentur, 2002) and fish reportedly carrying ciguatoxins from Crete in 2007 (Aligizaki et al., 2008). These CFP occurrences may be attributed to range extensions for *Gambierdiscus* into higher latitudes in response to climate change, as predicted by Tester (1994).

We generally learn of exotic CFP occurrences from literature reports that lag behind the events by at least one to several years. Even in endemic areas like the

Caribbean, our survey found that CFP incidence data were not collected uniformly or consistently by country or territorial governments. Another interesting finding of this study was the wide range in the levels of concern and knowledge among Caribbean populations and the extent to which CFP is monitored there. Some government agencies mandate central reporting of CFP cases, while other agencies acknowledged a potential problem exists, but have been hampered by insufficient resources to initiate an organized monitoring system. Some health departments reported making progress toward bringing CFP surveillance programs online, sometimes in response to recent outbreaks of CFP. A few agencies asserted that CFP did not occur in their jurisdictions, an assertion that was not always consistent with the findings of the literature searches. This underscores the need for public health and fisheries professionals to receive up to date information about regional CFP occurrences. The absence of a uniform reporting procedure for CFP cases and a universal location where data could be stored has hampered regional understanding of the scope of this important public health issue. Our future efforts will focus on developing a standardized reporting protocol and website where CFP data can be uploaded. In addition the CFP website will be linked to near real time environmental data. If data on CFP episodes are uploaded as soon as they occur on a website that displays geographic locations and links to environmental variables such as sea surface temperature, this could help provide timely warnings for local residents, physicians and public health officials across the Caribbean island nations and the surrounding mainland countries.

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Conflict of interest

None.

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