Doctoral Thesis

博士論文

Ciguatera Fish Poisoning and Its Association with Climate Change and Food Choice in the Pacific: Implications for Surveillance and Response Systems

(太平洋諸島におけるシガテラ中毒の気候変動および食料選択との関連性：サーベイランスと対応策への示唆)

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ABSTRACT

The Pacific is in fact without a doubt one of the most vulnerable regions when it comes to several challenges due to climate change, particularly in many of the remote outer islands. Such challenges may affect local communities' health, sustenance, livelihood and economic activities. For instance, local prevalence of "fish poisoning" has adversely affected the food and public health systems of many Pacific island countries. One most common form of fish poisoning is called ciguatera. Ciguatera fish poisoning (CFP) is caused by ingestion of a wide spectrum of coral reef fish that contains bio-accumulated neurotoxins. These toxins, produced by the toxic dinoflagellate *Gambierdiscus*, accumulate and transform as they pass up the marine food web from herbivorous to carnivorous fish, and subsequently to human. CFP is an endemic disease across all Pacific Island countries and territories. It is estimated over 500,000 Pacific islanders might have suffer from CFP in their life time while the true incidence rate remains difficult to be verified due to underreporting and misdiagnosis.

Since toxic dinoflagellates are sensitive to various climate factors, scientist community reckons that climate change and its subsequent anomalous weather events represent a serious threat of CFP. Existing studies assessing the relationship between climate factors and CFP are very limited, and only a few studies consider the time interval between environmental parameters and CFP events, all basing on old data or suffering for significant limitations. Meanwhile, an important gap remains in the field of socioeconomic impact of CFP, particularly in small island communities where fish provides primary source of food and dietary protein for the local people. This study

contributes to fill the research gaps and unfold the nexus between climate change, CFP and food security in the Pacific using meteorological, epidemiological and original household survey datasets. In particular, I analyze the relation between climate change and occurrence of CFP, quantitatively exploiting the time series data in two Pacific countries and examine how CFP incidences are affecting food choice and utilization of indigenous people based on primary cross-sectional data in Fiji. It is expected that the results of this study have important policy implications which could improve the current health surveillance and response system in many small island countries under the context of climate change.

After the introduction in Chapter 1, Chapter 2 reviews the existing literature regarding the effects of climate change and climate variability on ciguatera, as well as the health and socio-economic impacts of ciguatera. Chapter 3 discusses the overall prevalence of CFP, current reporting schemes and attempted intervention programs in the Pacific Island countries and territories.

In Chapter 4, I conduct time-series analysis to postulate the climatic effects on CFP incidence at macro-level. Cross-correlation analysis and auto-regressive integrated moving-average (ARIMA) model have been used to develop predictive models of ciguatera incidence rate in Cook Islands and French Polynesia, two long-lasting endemic territories in the Pacific. The monthly CFP incidence rate evolved in close lagged correlation to several variables that are associated with sea surface temperatures in the Economic Exclusive Zones of these two countries, with a 12-month lag in Cook Islands and 32-month lag in French Polynesia. Results of model validation proved extreme weather-related variables (e.g. sea surface temperature anomaly) as significant predictors of CFP incidence, indicating the possible relevance between extreme seawater temperature and disturbances of coral reefs system.

In Chapter 5, I assess how ciguatera as a local disease challenges the health and food choice of indigenous communities and seek to explain their food consumption behavior under the risk of fish poisoning at micro-level, using the original survey data collected from 239 households in 12 villages in a remote Fijian island in 2019. My case study has found that CFP incidences result in the temporal to permanent dietary change, and as a natural source of protein, fish has been replaced with an increased consumption of other food sources, including processed foods. A number of factors were found to have been important for the consumption of risky species – on household level, food and income diversity could be essential coping mechanism in response to potential food shock of CFP; and on individual level, the role of taste, risk perception and optimistic bias are shown to contribute to food aversion of risky species.

Taking the analyses results from the above two Chapters, Chapter 6 presents the policy implications for surveillance and response on future risk of CFP. For example, the time-lagged correlations between climate variables and CFP incidences found in the time series analyses would allow health authorities to take appropriate actions by evaluating and refining strategies for disease control, to avoid or limit the epidemic risk, especially on high-risk climate scenarios; findings of case study in Fiji have referential significance for designing and developing interventions with higher effectiveness and efficacy on food safety and health behavior to reduce the negative impacts of fish poisoning for the small island communities. In addition, limitations of my studies point to the importance of better data management to reduce the under-reporting and misdiagnosis rate of CFP, as well as more communications among countries and international organizations about CFP epidemiology.

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LIST OF ABBREVIATIONS

AIC	Akaike Information Criterion
ACF	Auto-Correlation Function
ARIMA	Auto-Regressive Integrated Moving-Average
CFP	Ciguatera Fish Poisoning
CTXs	Ciguatoxins
CCF	Cross-Correlation Function
ENSO	El Niño Southern Oscillation
EEZ	Exclusive Economic Zone
FJD$	Fiji Dollar
IRD	Institute of Research for Development
NOAA	National Oceanic and Atmospheric Administration
NZD$	New Zealand Dollar
PICTs	Pacific Island Countries and Territories
PACF	Partial Auto-Correlation Function
RMSE	Root Mean Square Error
SST	Sea Surface Temperature
SSTTC	Sea Surface Temperature along the Tropic of Capricorn
SSTA	Sea Surface Temperature Anomaly
SPC	Secretariat of the Pacific Community
SPEHIS	South Pacific Epidemiological and Health Information Service
SOI	Southern Oscillation Index
USD$	United States Dollar

1. INTRODUCTION

1.1 Ciguatera Fish Poisoning and Ciguatoxins

The Pacific Islands are especially vulnerable to challenges arising from climate change. One of the challenges is the risk of Ciguatera Fish Poisoning (CFP). Unlike other frequently mentioned problems such as increasing drought, water scarcity, coastal flooding and erosion, CFP poses threats facing Pacific Islanders on everyday basis, potentially imposing substantial health and economic costs.

CFP is a type of food poisoning caused by ingestion of a wide spectrum of tropical and subtropical fish and marine invertebrates that contain ciguatoxins (CTXs). CTXs are lipid-soluble polycyclic polyether compounds with ladder-like structure involving 13 to 14 ether rings (see Figure 1.1).

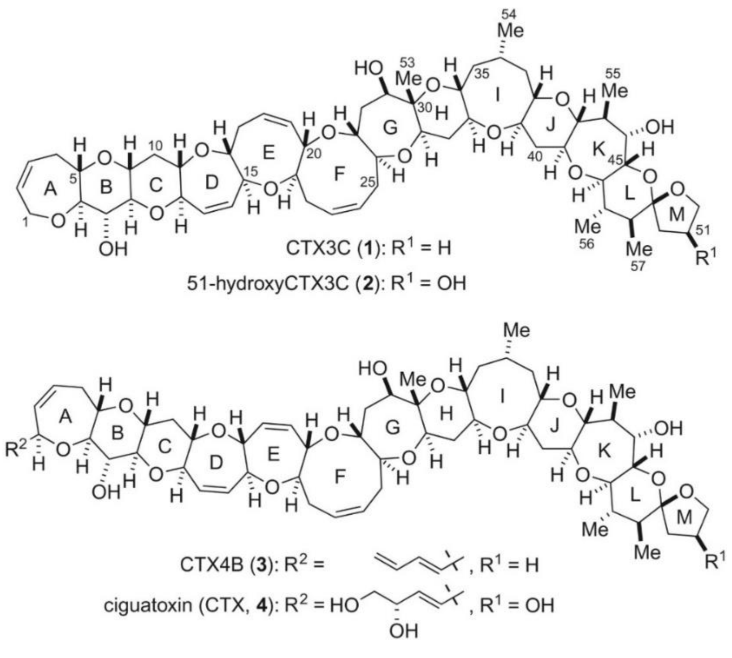


Figure 1. 1 Structure of Pacific (P) and Caribbean (C) CTXs

Source: Inoue et al., 2004

CTXs and their precursor are produced by the toxic dinoflagellate called *Gambierdiscus*. These dinoflagellates typically grow in macro-algae and turfs that mainly crawl on host substrate such as seaweeds and damaged corals (see Figure 1.2). Since the toxins bio-accumulate and concentrate as they pass up the marine food web surrounding the coral reef system, and subsequently to human (Lewis, 2001), fish and marine invertebrates in the higher food web tend to have higher concentration of CTXs than fish (mainly herbivorous) in the bottom of food web; and those who acquire nutrition from coastal food webs are more susceptible to CFP than those in open and pelagic waters (Friedman et al., 2017).

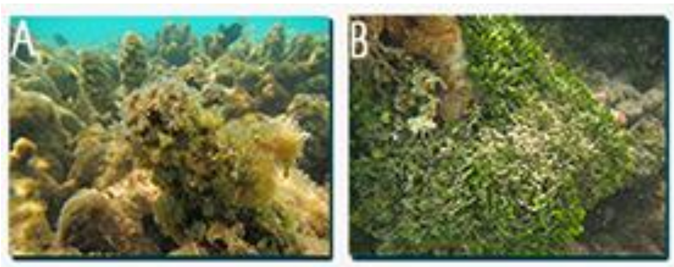


Figure 1. 2 Example of *Gambierdiscus*' "support-algae". (A) Turbinaria ornate; (B) Halimeda spp.

Source: Louis Malardé Institute, 2014

Unlike other toxins, CTXs are odorless, tasteless and cannot be eliminated and destroyed by conventional cooking and freezing. Hence, contaminated fish do not show distinctive signs and therefore cannot be identified by inspection, appearance, smell, taste, or textures (Food and Agriculture Organization of the United Nations (FAO), 2004).

More than 400 seafood species are found susceptible to be ciguatoxic. Selected common fish species associated with CFP is listed below (see Table 1.1).

Table 1. 1 Examples of fish species associated with CFP

Species
Lined surgeonfish (*Acanthurus linearis*)
Bonefish (*Albula vulpes*)
Gray triggerfish (*Balistes carolinensis*)
Gaucereye porgy (*Calamus calamus*)
Horse-eye jack (*Caranx latus*)
Whitetip shark (*Carcharinus longimanus*)
Humphead wrasse (*Cheilinus undulatus*)
Heavybeak parrotfish (*Chlorurs gibbus*)
Red groupper (*Epinephelus morio*)
Giant moray (*Gymnothorax javanicus*)
Hogfish (*Lachnolaimus maximus*)
Northern red snapper (*Lutjanus campechanus*)
Tarpon (*Megalops atlanticus*)
Narrow-head gray mullet (*Mugil capurri*)
Yellowtail snapper (*Ocyurus chrysurus*)
Spotted coralgrouper (*Plectropomus maculatus*)
Blue parrotfish (*Sparus coeruleus*)
Spanish mackerel (*Scomberomorus maculatus*)
Lesser amberjack (*Seriola fasciata*)
Great barracuda (*Sphyraena barracuda*)
Chinamanfish (*Symphorus nematophorus*)
Swordfish (*Xiphias gladius*)

Note: Common name and scientific name in parentheses

Source: FAO, 2004

1.2 Clinical Features and Health Risk

Once ingested CTX-contaminated fish, the onset of the early symptoms could appear in 30 minutes in case of severe intoxications. In some milder cases, symptoms were occasionally delayed for more than 24 to 48 hours (Wong & Lewis, 2017). It is worth noting that patterns of symptom vary in the Pacific, Caribbean Sea and other regions, depending on the main congeners of CTXs identified in each region (Lewis, 2000). There are 175 symptoms mentioned in literature, classified into four categories: gastrointestinal, neurological, cardiovascular and neuropsychological symptoms (see Table 1.2).

Table 1. 2 Clinical characteristics of CFP

Category of clinical manifestations	Symptom	Incubation period	Duration
Gastrointestinal	Diarrhea, vomiting, nausea, abdominal pain	6 – 12 hours	1 – 4 days (typically less than 24 hours
Neurological	Paresthesia-extremity, reversal of temperature sensation, tingling, muscle pain, dental pain	About 24 hours	Weeks to months
Cardiovascular	Hypotension, hypertension, bradycardia, tachycardia	About 6 hours	1 – 3 days
Neuropsychological	Vertigo/dizzy, reduced memory, hallucination, depression, balance disturbance	Days after the initial illness	Weeks to months

Source: Friedman et al., 2017; Kim, 2015

The early symptoms can be either gastrointestinal (e.g. diarrhea, vomiting, nausea) or neurological (e.g. reversal of temperature perception, tingling, muscle pain). Gastrointestinal symptoms account for 50 percent of the cases. They generally appear 6 to 12 hours after the consumption of toxic fish and can last for one to four days, while neurological symptoms come later (within two days) but often last longer than gastrointestinal symptoms (Friedman et al., 2017). In fact, some of the neurological symptoms such as reversal of temperature perception, and numbness and tingling in lips, hands and feet, are the pathognomonic features for the diagnosis of CFP (Bagnis et al., 1979; Glaziou & Legrand, 1994).

Cardiovascular signs (including hypotension and bradycardia) generally become apparent in the early stage of the illness, after the onset of early symptoms. They often come in combination with the above two categories of clinical manifestations (Chateau-Degat et al., 2007). In certain cases, neuropsychological symptoms could also manifest in days and weeks after the initial acute features. Such symptoms include hallucination, reduced memory, anxiety and difficulty of concentration, disrupting the patients' cognitive capability (Friedman et al., 2007).

Ciguatera symptoms normally last for several weeks to several months, depending on the toxin dose, the type of fish consumed and quality of medical care. In a small percentage of cases (less than 5 percent), certain symptoms may persist for a number of years (FAO, 2004). Death is uncommon, with a low fatality rate of less than one percent (Kim, 2015; Lehane, 2000).

During the recovery phase, victims could develop adverse reaction which are reminiscent of the originally experienced symptoms to certain food items such as seafood, caffeine, peanuts and alcohol (Thompson et al., 2017). It is recommended by the public health authorities to avoid the consumption of all fish species (including freshwater fish) for three to six months after recovering from CFP or until all the ciguatera-like symptoms have resolved (Friedman et al., 2017).

As CFP has caused severe problems in some endemic regions, some predicted that the risk of CFP will drive local people to rely on more imported food and elevate the rate of non-communicable diseases (Lewis, 1983). According to Skinner et al. (2011), public health departments in seven Pacific countries reported changes in diet as a result of CFP; seven reported secondary health problems as a result of CFP; and five reported both dietary changes and CFP-induced secondary health issues.

1.3 Medical Treatment and Remedies

There is no known antidote for ciguatera and no blood tests available to confirm the poisoning with CTX (Copeland et al., 2014). Many treatments have been used for the poisoning and mostly are case-by-case symptomatic supports for gastrointestinal and cardiovascular manifestations (Chinain et al., 2019).

Intravenous mannitol is long thought to be the only pharmacotherapy treatment that confirmed by many clinical trials and has shown promise especially for moderating neurological symptoms during the acute phase of CFP. However, recent randomized controlled trials cast more doubts from medical experts, that mannitol fails to confirm its efficacy for ciguatera compared with normal saline, and causes other side effects (Schnorf et al., 2002).

In some rare cases, ondansetron or other anti-emetic medicine may be used for reducing nausea and vomiting; and endotracheal intubation and mechanical ventilation are required for respiratory failure and/or airway protection (de Fouw et al., 2001). Oral activated charcoal, if administered early, can also prevent further toxin absorption to the other organs (Friedman et al., 2017).

Since specific antidotes and medical supports are lacking particularly in many remote islands, people who have developed fish poisoning symptoms might leave them untreated, or use traditional herbal medicines and remedies (Skinner et al., 2011). The traditional remedies are various and complex in kinds as they associate with the multiplicity of the CFP symptoms. For example, in Vanuatu, there are at least 90 plant species used as herbal medicines for CFP according to the survey (Laurent et al., 1993). Several of the plant species have emetic, laxative, diuretic and diaphoretic functions that could rid the body of toxins. They are usually water-based and being processed through decoction and infusion of different parts of the plant including leaves, barks, roots and latex (Kumar-Roiné et al., 2011). One typical plant species called Argusia Argentea (*H. foertherianum*) has been commonly used in many Pacific islands as preferred remedies for ciguatera. A sample survey of 500 persons in Noumea, New Caledonia revealed that 40% of the sample population used Argusia Argentea for ciguatera (Laurent et al., 1992). Other herbal medicine, such as *E. hirta, V. trifolia and Vitex sp.*, commonly found in the South Pacific countries, are also used for the treatments of CFP (Kumar-Roiné et al., 2011).

1.4 Geographic Distribution

Globally, CFP endemic regions overlaps with the coastal areas covered with coral reefs, mainly confined to small-islands communities in tropical and subtropical areas between 35°N and 35°S latitude. Populations in the Caribbean Basin, Indo-Pacific Ocean and Indian Ocean are particularly at risk (Louis Malardé Institute, 2014). Even among the endemic areas, CFP has been more prevalent on islands than continental coasts, interpreted by the hypothesis that the coral reef system around the islands has higher exposure to oceanic currents which could stimulate the growth of dinoflagellates (Botana, 2008). Different strains of *Gambierdiscus*, the ciguatera-causing dinoflagellate, has been discovered from Gulf of Mexico, Caribbean Sea, Atlantic Ocean, Pacific Ocean, Indian Ocean and Southeast Asia (Litaker et al., 2010). Difference of the dominating strains in each region also determines the geographic distributions of clinical features of CFP. It appears ciguatera intoxications in South Pacific and Australia has a higher probability to contact neurological symptoms including acral paresthesia and temperature reversal; while cases in Miami and US Virgin Islands have a higher proportion of gastrointestinal symptoms including diarrhea and vomiting (Botana, 2008).

Evidences have shown that CFP risk has been expanding to more temperate regions (see Figure 1.3). In the past 15 years, *Gambierdiscus* species have been newly reported in West Africa, Mediterranean Sea, Gulf of Red Sea, Hong Kong, Thailand and Korea, etc. (Jeong et al., 2012; Pérez-Arellano et al., 2005).

Scientist community reckons that climate change is altering the patterns of environmental factors including seawater temperature and cyclone events, which act as accelerators for *Gambierdiscus* abundance, expansion and toxin growth and hence a higher CFP risk (Gingold et al., 2014). Since 1990s, cases of CFP or CTX-contaminated fish have been reported in new regions including Canary Islands, North Carolina, the main island of Japan, Baja California of Mexico and India (Barton et al., 1995; Friedman et al., 2017; Morris et al., 1990; Rajeish et al., 2016). These incidences reflect a widening of ciguatera risk at a global scale.

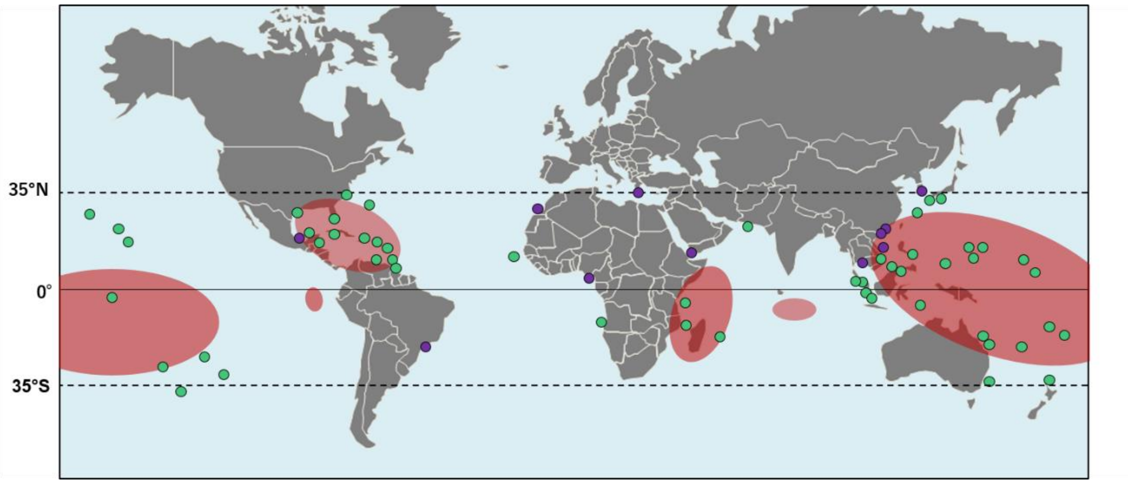


Figure 1. 3 Geographic distribution of ciguatera risk

Note: Red areas indicate disease endemic areas of ciguatera, green dots indicate known distribution of Gambierdiscus, and purple dots indicate locations where Gambierdiscus was newly discovered from 2004 to 2016 (based on data from Pérez-Arellano et al., 2005; Richlen et al., 2012; Friedman et al., 2017).

Furthermore, globalization of international trade and international tourism have brought ciguatera fish and CFP incidence to novel locations in which ciguatera is non-endemic, such as the continental U.S., Canada and Europe (FAO, 2004).

1.5 Research Objectives

While ciguatera is increasingly attracting greater attention among the general public and within the community of food safety and public health experts, oceanographers, meteorologists and marine economists, related studies in the non-medical field are still limited or premature. Further, the climatic effect on CFP outbreaks remains unclear, and the potential risks of CFP on food choice and utilization, both in individual and household-level are yet to be defined. To address the issue of CFP in a more comprehensive manner and improve upon the relevant public health policies, more detailed evidences based on quantitative data are now called for.

Given this background, this thesis seeks to disentangle the links among CFP, climate change, and food security using quantitative methods, with a focus on the Pacific – a long-lasting endemic region with high reliance on fishery resources and shortage of professional health support in most of its territories. In particular, I examined (1) how climate factors influence CFP incidence in Cook Islands and French Polynesia using time series analysis, and (2) how the risk of CFP impacts the food choice and utilization of indigenous communities in Fiji based on original data. The results could contribute to develop/improve and maintain a climate-resilient health surveillance and response system, particularly in many small island communities.

To achieve the above objectives, this thesis takes the following outline. Chapter 2 reviews the existing studies and research regarding effects of environmental factors and climate change on ciguatera, as well as the risk factors, potential health and socio-economic impacts of ciguatera. Chapter 3 discusses the overall incidence and prevalence of CFP, current reporting schemes, intervention programs, and ciguatera-related import and export restrictions in the Pacific.

In Chapter 4, time series analysis has been performed to postulate the climatic effects on CFP incidence at macro-level. Cross-correlation analysis and auto-regressive integrated moving-average (ARIMA) model are used to elicit the important climate indicators and time interval of bioaccumulation, and develop predictive models of ciguatera incidence rate in Cook Islands and French Polynesia, two ciguatera-endemic territories in the Pacific. Utilizing the original survey data collected from a remote island in Fiji, Chapter 5 explores how ciguatera as a local disease challenges the health and food choice of indigenous communities, and explains their food consumption behavior and risk-coping mechanisms under the risk of CFP. Based on the analysis results and limitations of research from the above two studies, Chapter 6 concludes the thesis by presenting the policy implications for surveillance, reporting and response in the context of climate change, and pointing out the directions and strategies for future research (see Figure 1.4)

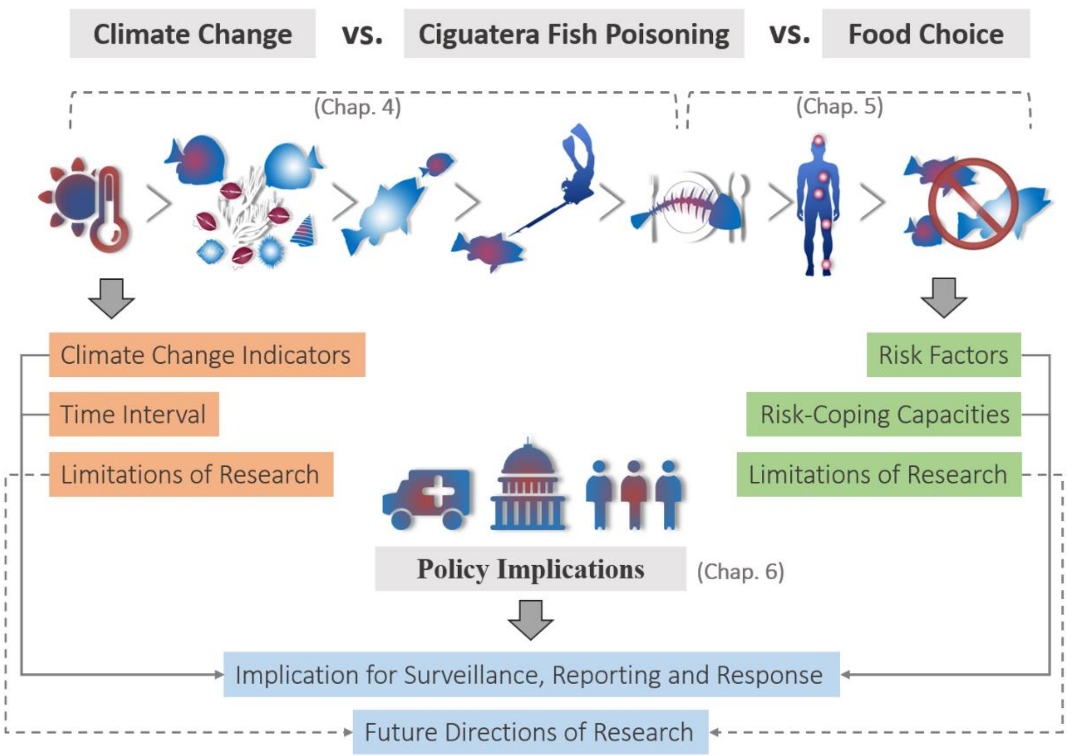


Figure 1. 4 Framework of the thesis

2. LITERATURE REVIEW

2.1 Climate Impacts on CFP

A number of studies have explored the effect of climate change and its related weather events on the onset of human health, particularly for vector-borne diseases (Hamlet et al., 2018; Jing et al., 2018; Wangdi et al., 2010). Though not being formally classified as vector-borne disease, CFP has a vector nature that the marine environment facilitates the growth and accumulation of the toxin and hence could be affected by climate change. In fact, past research has already linked the increase of ciguatera incidences or occurrence of CFP to climate change (Chateau-Degat et al., 2005; Gingold et al., 2014; Kibler et al., 2015; Tester et al., 2010).

In order to assess the correlations between climate factors and CFP, a thorough understanding of the environmental dynamics that influence ciguatera toxin and the disease is necessary. On-going research assessing the correlations of climate and ciguatera has been mainly conducted under the perspective of two mechanisms – seawater environment and disturbances to coral reef systems.

2.1.1 Environmental Factors and *Gambierdiscus* Abundance

The first mechanism is related to the impact of climate change on seawater environment. Climate change may alter the patterns of environmental factors including temperature, precipitation, water salinity and so on, and these factors can accelerate the growth and abundance of *Gambierdiscus*. In the last three decades, several experiments provided substantial evidence in this regard by measuring *Gambierdiscus* cells growth rate while controlling climate change-sensitive variables. These studies have, among others, confirmed that *Gambierdiscus* cells respond to different environmental conditions and show a linear or non-linear correlation between its growth rate and temperature, salinity, light irradiance, etc. (see Table 2.1).

Table 2. 1 Studies of factors potentially affecting *Gambierdiscus* abundance

First author, Year	Region	Climate factor			
		Temperature	Light	Salinity	Wind velocity
Parsons, 2010	Hawaii, USA	+/-	+	+/-	
Xu, 2016	Multiple locations	+/-	+	+/-	
Bomber, 1988	Florida, USA	+/-	+	-	
Morton, 1992	Florida, USA	+/-	+/-	+/-	
Chinain, 1999	French Polynesia	+		0	
Delgado, 2006	Cuba	+		-	-
Kibler, 2013	Multiple locations		+/-		

Note: + : positively associated; - : negatively associated; +/- : positive association first and then negative after reaching a threshold; 0: unrelated

Seawater temperature has been proven the most indicative factor for the growth of *Gambiediscus*. Lab tests traced back to 1980s have already shown that the division rate of *Gambiediscus* reacts positively in warmer seawater environment (Bomber et al., 1988; Morton et al., 1992). However, these studies also revealed a non-linear correlation, which at a threshold level the growth rate may be suppressed when the temperature goes too high. The species tend to grow well within the temperature range between 24 to 31°C (Bomber et al., 1988; Morton et al., 1992). The thermal tolerance typically reaches the highest around 25 to 30°C, with slight differences for varying *Gambiediscus* species and locations where the species sample were collected. For example, in Xu's (2016) study, *G. belizeanus*, a species of *Gambierdiscus* collected from US Virgin Islands, reaches its maximum growth rate at 27°C and begins to drop in temperature above 27°C; while the growth rate of another species *G. pacificus* collected from Kiribati, remains steady around 27 to 31°C and drops thereafter.

Other environmental factors, albeit associated with seawater temperature, were also demonstrated significant to the growth and abundance of *Gambierdiscus* in a series of laboratory experiments and field studies. Light/irradiance penetration through the water could facilitate the primary production in the ocean but also limit the distribution of benthic dinoflagellates, including *Gambierdiscus*. In most studies, the growth rate of the species follows a non-linear positive curve with the increase of irradiance level (Bomber et al., 1988; Kibler et al., 2013; Morton et al., 1992; Parsons et al., 2010; Xu et al., 2016).

The species are often assumed to be extremely sensitive to subtle changes in salinity since they normally reside in coral reef environments far away from continental coasts (Kibler et al., 2012). Generally *Gambierdiscus* species are mostly adapted to stable oceanic salinities between 34 to 38‰. However, unlike temperature, the association between *Gambierdiscus* growth and salinity appeared to be more complicated and lack of unity. In previous literature, the growth curve is either nonlinear positive, negative, or uncorrelated, depending on strains of the species (Bomber et al., 1988; Chinain et al., 1999; Delgado et al., 2006; Morton et al., 1992; Parsons et al., 2010; Xu et al., 2016). In most studies, the curve appeared to be a parabola going downwards with a steep peak (Morton et al., 1992; Parsons et al., 2010; Xu et al., 2016). In a test performed by Parsons & Preskitt (2007), one species called *O. Ovata* was found to be negatively correlated with salinity, while in the field experiment conducted by Chinain et al. (1999), salinity did not show any correlation with the seasonal abundance of *Gambierdiscus*.

In addition to the above factors, Delgado (2006) found wind velocity is negatively related to the abundance of *Gambierdiscus*, since strong winds produce heavy waves, and ocean currents could limit the growth of the species. Apart from the environmental parameters reviewed in Table 2.1, dissolved nutrients and substrate availability could also affect the proliferation of *Gambierdiscus* (Kibler et al., 2013).

2.1.2 Disturbances to Coral Reef Systems

The second mechanism on how climate change affects the incidence of CFP is related to the impact of climate change on coral reefs, which are habitats of *Gambierdiscus*. The overall abundance of *Gambierdiscus* is considered as a function of algal cover on coral reefs, for which even subtle environmental change in reef ecosystems can potentially cause a massive ciguatera outbreak. *Gambierdiscus* cells are benthic and grow preferably on macroalgae, despite the fact that they can occasionally show free-swimming behavior (Nakahara et al., 1996; Parsons et al., 2011). These macroalgae "turf", as epiphytes, predominately crawl on host substrates such as, dead or damaged corals (Kaly & Jones, 1994). According to Richlen et al. (2012), filamentous or calcareous macroalgae, the preferred host substrate of the dinoflagellate, can rapidly colonize the coral surfaces once the corals are bleached or dead. Climate change is related to warmer seawater temperature causing extensive coral bleaching in some regions, and higher frequency of tropical storm or cyclones activities that contributes to coral reef damages. Both can allow macroalgae to become more prolific over a wider range, and thereby, create more habitat for *Gambierdiscus* (Diaz-Pulido et al., 2009; Dubinsky & Stambler, 2011). Other anthropogenic damages to coral reefs from boat channels, ship wrecks and military activities can also lead to an increased CFP incidence or outbreaks (Bagnis, 1994; Ruff, 1989).

Unlike the impacts of environmental factors to ciguatera, studies assessing the impacts of coral reef disturbances on ciguatera came with varied conclusions. After collected algae sample from US Virgin Islands and British Virgin Islands, Kohler and Kohler (1992) found that the dead sections of bleached corals have been colonized by filamentous algae sheltering *Gambierdiscus toxicus*. Fish species in the sampling areas were observed preying on the algae covering on dead corals. Though the study did not further examine the toxicity of the fish, it was expected that an increase of ciguatoxic fish may occur around areas with major coral mortality. Turquer et al. (2001) found that the sustainable rise in seawater temperature, led by El Niño abnormalities had caused coral bleaching in Mayotte Island in the Indian Ocean, subsequently offered good substrate conditions and available nutrients in the ocean. However, contamination to the human food web remained low and no CFP outbreaks were notified. In a field study conducted in three communities in Cuba, CFP has been linked to the state of coral reef, that poor-conditioned coral reefs blanketed with macroalgae have possibly contributed to the large number of local CFP outbreaks (Morrison et al., 2008).

Some studies revealed no associations between physical disturbances to coral reefs and ciguatera, but most of them have significant limitations. In a survey targeting on public health institutions in 18 Pacific countries, a positive correlation was found between ciguatera incidence and occurrence of coral bleaching, cyclone incidence and perceived reef condition. However, no statistical significance was found between the average number of incidence and the three types of environmental disturbances, probably due to the small number of sample countries (Skinner et al., 2011). In Tuvalu, scientists found that no consistent effects of new boat channels on the *Gambiediscus* abundance and fish toxicity were detected, although they argued that further research is needed as temporal monitoring is limited (Kaly & Jones, 1994).

On all accounts, physical disturbances to coral reef system may or may not cause ciguatera. Whether or not ciguatera can be induced by disturbances depends highly on their intensity, timing, frequency and scale (Kaly & Jones, 1994). But climate change will almost certainly beget an increase of ciguatera outbreaks. Under the scenarios of rising ocean temperature, the impact of coral disturbances on the habitats for *Gambierdiscus* and impact of environmental factors on the proliferation of *Gambierdiscus* could have joint effects to a larger incidence rate and distribution globally.

2.1.3 Climate Change Indicators and Time Interval of Bioaccumulation

After the dynamics of toxin growth and accumulation became increasingly clear, several studies have attempted to explore how environmental factors affect the number of poisoning cases under the context of climate change. These studies, mainly using time series analysis as methodologies, have identified and developed indicators that could reflect the changing climate or hypothetical extreme climate scenarios. Among all, sea surface temperature (SST), in some studies also referred as seawater temperature, is one of the most commonly used indicators. Some studies applied multiple explanatory variables (e.g. maximum SST, minimum SST, SST anomaly) extracted from the same SST dataset in order to raise the goodness of fit (Gingold et al., 2014; Hales et al., 1999).

In addition, recent studies associate ciguatera with El Niño Southern Oscillation (ENSO) events. It is expected that during ENSO events, the modification of tropical cyclones activity will lead to abnormal changes in ciguatera outbreak in certain regions (Sharkov & Sharkov, 2012).

With the use of Pearson correlation analysis, Hales et al. (1999) found that the annual number of ciguatera cases in most South Pacific islands between 1973 – 1994 is negatively related to Southern Oscillation Index, indicating fish poisoning is likely to occur during El Niño conditions. Further, they found statistically significant relationships between the local SST anomalies and annual ciguatera cases in four islands including Western Samoa, Kiribati, Tuvalu and Rarotonga of Cook Islands. In French Polynesia, Chateau-Degat et al. (2005) found positive linear associations between seawater temperature, *Gambierdiscus* abundance, as well as the peak of CFP incidence from 1993 to 2001. Llewellyn (2010) assessed the association between SST and annual ciguatera cases from 1988 – 1996 in the equatorial Indo-Pacific regions, and discovered that ciguatera cases appear to be highest in areas with average SST above 28°C. He also discovered several positive or negative ENSO-related variables that are significantly indicative of CFP cases in nine Pacific countries, and argued that the positive/negative signs of coefficients indicate a lower and upper threshold for the intensity and occurrence of CFP.

Using the epidemiological data collected from health and fisheries departments from 32 Caribbean countries and territories, Tester et al., (2010) found that CFP incidence tends to be higher in areas with warmer SST. Many of them have an average SST well above 29°C in September. The authors acknowledged the inconsistent reporting schemes from the sample countries and territories could possibly bias the estimation. Gingold et al.

(2014) observed that the number of CFP outbreaks in the United States was positively correlated to minimum regional SST and seasonality. They also discovered the positive association between CFP and tropical storms. Other spatial variables such as maximum and minimum latitude of a certain isotherm were also included in the analysis but did not show major significance. However, the study suffered from significant limitations, since it assumed all cases in the continental United States come from the Caribbean, and therefore used regional climate indicators in the Caribbean as explanatory variables.

The dependence of ciguatera events on environmental parameters is rarely instantaneous. As the blooms of *Gambierdiscus* develop slowly, a significantly long time interval may be required for the dinoflagellate to reach the sufficient cell biomass and toxins production level for CTXs to bio-accumulate in the food chain and lead to ciguatera outbreaks (Kibler et al., 2015). Nevertheless, only a few studies have considered the time-lags between environmental parameters and CFP events. Bagnis et al. (1992) concluded the highest densities of *Gambierdiscus* were reached after three to four months after the onset of coral bleaching events in French Polynesia, while Chinain et al. (1999) suggested a 7-month lag between major reef mortality events and an increased ciguatera risk in Tahiti. Kaly and Jones (1994) observed a roughly one-year lag between *Gambierdiscus* abundance and peaks of fish toxicity in Niutao, Tuvalu albeit utilizing minimal data. Rongo and van Woesik (2011) have also discovered one- to two-year lag between the ciguatera case and the ENSO phase. Chateau-Degat et al. (2005) have estimated a 13- to 17-month lag between seawater temperature and *Gambierdiscus* growth, and 3-month lag between the peak of *Gambierdiscus* abundance and the peak of CFP cases from 1993-1999. Llewellyn (2010) has linked the annual number of CFP to the ENSO indices and observed lag times of up to 2 years. Gingold et al. (2014) have found that the monthly

CFP cases in the continental U.S. were associated with higher tropical storms frequency in Caribbean with 18-month lag. Contradictorily, multiple studies have not shown any seasonality pattern (Chateau-Degat et al., 2005; Hokama et al., 1996).

Thus, in my analysis that follows, I examine how CFP incidence reacts to a series of lagged variables related to SST following a time interval. By using the monthly incidence rate as response variable, I am able to capture the potential seasonality within the time series.

2.2 Impacts of CFP on Food Choice and Utilization

2.2.1 CFP and Dietary Shift

Empirical research is lacking on the relationship between fish/food poisoning and food choice, though research from other disciplines have provided supplementary evidences on this topic.

Archaeological evidence suggested that historically, elevated risk of ciguatera had kept Polynesians purposely avoiding certain types of fish, and eventually led to waves of emigration from their homelands (Rongo et al., 2009). By studying a group of pregnant women in an outer island of Fiji, cultural anthropologists concluded that the risk of fish poisoning has led to aversions of certain fish species, and some fishes are even regarded as taboo to consume especially among pregnant women (Henrich & Henrich, 2010).

It has been assumed that island communities with extensive CFP experience may undergo dietary shift away from fresh reef fish (Lewis, 1983), because this rise of CFP risk may increase the tendency for the remote islands communities to rely more on imported food such as canned fish, meat and other processed, fat and carbohydrate intense foods (Lewis, 1986). Two studies investigating the protein consumption preference in Rarotonga, Cook Islands have recorded a 15% to 50% decrease of per-capita fresh fish consumption, possibly due to ciguatera outbreaks. However, further evidence was lacking to directly support this causal relation (Rongo & van Woesik, 2012; Solomona et al., 2009). Skinner et al. (2011) found that the per capita incidence of ciguatera was associated with dietary change in seven Pacific Island countries based on the voluntary report from the health departments of 17 Pacific countries, though the paper did not mention what food products, which direction and to what extent the Pacific Islanders' diets are switching for. The extent of dietary change may vary according to contextual factors, such as the availability of processed foods, toxin prevalence, fishery dependence, social customs, and demographic trends (Friedman et al., 2017). Lewis (1986) had warned the potential effects on the islanders' nutritional status as the disease patterns emerged in the Pacific mirror those of western countries with increasing rates of diabetes, hypertension and cardiovascular diseases. Same observations were also revealed by Skinner et al. (2011).

Moreover, the dietary change to alternative protein sources depends on the economic status of the community and perhaps households. For instance, in the main island of French Polynesia, while having the political and economic ties with Metropolitan France, local diet tends to draw closer to frozen meat including chicken, beef and lamb. In contrary, ciguatera-affected populations in Cook Islands tend to show dietary change toward processed food, because the freezing facilities are limited (Rongo & van Woesik, 2012). In an empirical study of disasters and food shocks, one's ability to withstand a food shock is determined largely by their resilience capacity including food and livelihood diversity, asset ownership and external connection (Smith & Frankenberger, 2018). And lower income individuals may rely on locally caught fish and have less capability to afford other protein alternatives, therefore are more susceptible to higher risk (Radke et al., 2013).

2.2.2 Factors Associated with Food Avoidance and Food Aversion

When economists analyze people's food choices, they assume rationality and utility maximization of a fully informed agent. And their food choice has been traditionally viewed as a function of a series of food attributes including taste, appearance, nutrition, convenience, hedonic effect and price over the items they consume (Shepherd, 1999). Recently, the role of risk perception towards food with risk and uncertainty has been widely studied, and proved to be strong determinant of food choice when a health threat is perceived to be direct result (Brug & van Assema, 2001; Petrolia, 2016). Besides, optimistic bias has been identified for people who are aware of the potential risk of food items but still make risky food choices, because they view others as more at risk of danger than themselves (Knox, 2000). In addition, risk preference, often measured by lottery-choice experiments and considered consistent over different contexts, has also been used to explain individual's consumption of food products in question such as raw seafood, genetically-modified food, etc. (Bruner et al., 2011; Lusk & Coble, 2005).

Though empirical investigations on the effect of fish poisoning on food aversion is particularly limited, health behavioral research has shown that food aversion may result from motion sickness susceptibility. The aversion occurs mainly on food products related to disgust reactions such as nausea and vomiting, which are highly likely in the clinical presentations of CFP, or/and food products with high bacterial contamination risk such as meat, fish and other seafood (Egolf et al., 2018). Two surveys revealed that nausea and vomiting are positively correlated with conditioned food aversions, especially on female (Fessler & Arguello, 2004).

2.3 Research Gaps

Most of existing research investigating how ciguatera incidences or outbreaks respond to climate factors based their analyses on old data or suffered for significant gaps in terms of the plausibility of their findings. For instance, in the Pacific where my case study focuses on, past literature has mostly utilized the epidemiological data from 1980s to 1990s. The latest one was up to 2010 (Chateau-Degat et al., 2005; Kaly & Jones, 1994; Llewellyn, 2010; Rongo & van Woesik, 2011; Skinner et al., 2011). A lot of time series analyses based on annual counts of ciguatera cases and annual climate data, therefore did not reflect the seasonality features of ciguatera incidences, even though seasonal pattern actually occurred to the ciguatera incidence in some Pacific countries and CTX toxicity in certain fish species (Lewis, 1992). Finally, existing research mostly failed to control for external factors affecting local CFP incidence, such as tourism, fish imports, local food habits, economic situation of the country, how CFP data are collected, etc. (Gingold et al., 2014).

To fill the gaps of existing research, in this thesis, I examine the effects of climate variables on CFP incidence in two ciguatera-endemic countries, using the latest epidemiological data and taking seasonality into account.

For the socio-economic impacts of CFP, the majority of existing studies have been conducted in the settings of urban health while it also matters on the rural areas. The social epidemiology in low socioeconomic groups and in small island communities has been too little explored. In addition, little is known about how fish poisoning affects food consumption, and how food choice and utilization are made under the risk of fish poisoning. Food choice research has focused almost exclusively upon attempting to elicit individual's willingness-to-pay for various food and health outcomes by presenting a series of choice sets to respondents (Dannenberg, 2009; Lagerkvist & Hess, 2011). But this approach could not be applied to the context of small island communities where the food intakes of indigenous population are mainly supplied by self-harvests from traditional farming and subsistence fishing.

Given all these research gaps, in the thesis, I examine how the experience and risk of CFP affect the health and food consumption of indigenous islanders. Food choice and utilization are represented by the number of food aversion on household-level and food avoidance on individual-level.

3. OVERVIEW OF CIGUATERA FISH POISONING IN THE PACIFIC ISLANDS

3.1 History and the Present Situation

The presence of ciguatera in the Pacific Ocean has been known over the centuries, but the origin of the toxicity was long time unknown until the past few decades. The incidence of poisoning was described as early as 1600s in Vanuatu, and an apparent outbreak in New Caledonia was first reported by British navigator James Cook (Kiple & Ornelas, 2001). Ciguatera has long existed in the dietary culture of local communities of Pacific Islands. The islanders have developed certain food taboos, food preparation strategies and traditional medicine all associated with ciguatera (Boyd, 2017). Until 1970s, marine scientists collected the samples of toxic dinoflagellates on the surface of dead coral in Gambier Islands of French Polynesia and found the samples are correlated to the toxin abundance in the viscera content of reef fish. The newly-identified dinoflagellate was named *Gambierdiscus toxicus* after the place where it was first discovered (Legrand et al., 1991).

Ciguatera is one of the most common food-borne illnesses and the most common seafood-borne disease in the Pacific. It accounts for 96% of fish poisoning in Fiji, 37% in American Samoa, 51% in Hawaii, and the majority of fish poisoning cases in Kiribati and Marshall Islands (Lewis, 1992). Incidences of CFP have been reported in almost every Pacific Island Countries and Territories (PICTs). It is estimated that over 500,000 Pacific islanders might have suffered from CFP at least once in their lifetime (Skinner et al., 2011). However, estimation of the number of confirmed cases is difficult since CFP is often misdiagnosed and underreported globally and more so in the Pacific (Friedman et al., 2008).

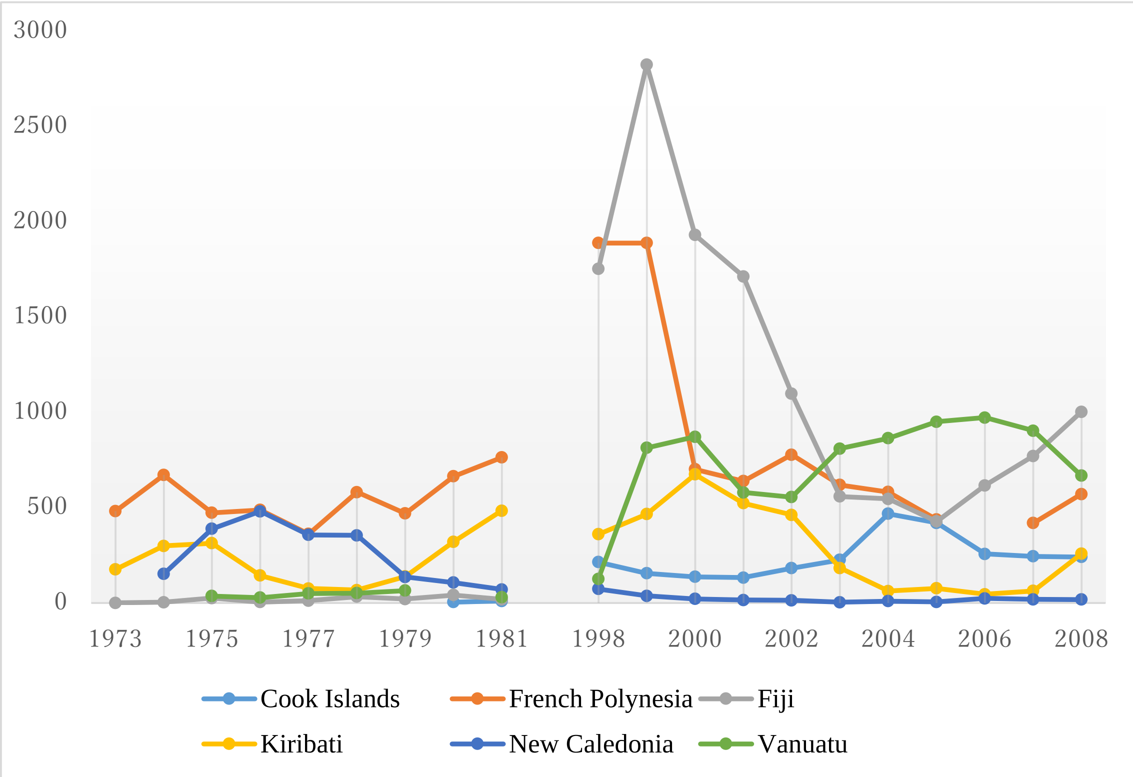


Figure 3. 1 Comparison of ciguatera incidences in two surveys in six selected PICTs

Source: Lewis, 1983; Skinner et al, 2011

Combining the results of two separate surveys conducted at different times, Figure 3.1 shows a substantial increase of CFP cases in the past decades, with the annual incidence of CFP increased by 60% from 1973 – 1981 to 1998 – 2008.

Regarding the epidemiology in Cook Islands, Fiji and French Polynesia, three endemic countries of my case study, the numbers of incidences have remained steady or slightly increased over the last few years (see Figure 3.2). Fiji has the highest incidence number among all three countries, followed by French Polynesia, while Cook Islands might be subjected to the highest incidence rate per capita for its relatively smaller population scale. However, direct comparison among the epidemiological data across countries has sometimes failed to be objective and accurate given that each countries have different reporting rate under their independent reporting systems.

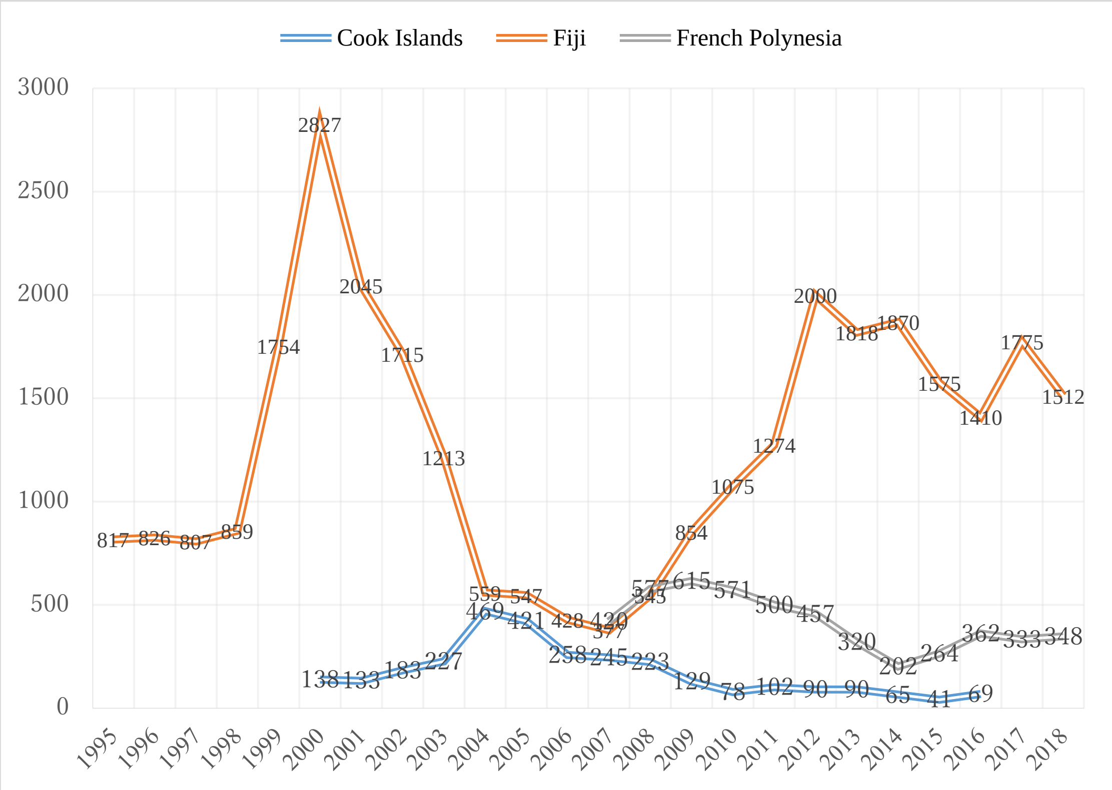


Figure 3. 2 Number of ciguatera incidence in Cook Islands, Fiji and French Polynesia (1995 – 2018)

Note: Data of Fiji sum up the numbers under the categories of "fish poisoning" and "ciguatera fish poisoning"

Source: Cook Islands Ministry of Health; Fiji Ministry of Health; Louis Malardé Institute

3.2 Public Health and Socio-Economic Impacts

Ciguatoxic fish is not only the source of intoxication to human beings, which leads to serious public health hazard, but also responsible for the great socio-economic loss in many PICTs where fish delivers primary source of food and dietary protein (Gillett & Tauati, 2018).

The most significant cost derived from CFP is the public health cost, which includes fees for hospitalization and medication, hospital and staff time involved in the treatment of ciguatera, and loss of labor productivity due to the sickness (Rongo & van Woesik, 2012). The health-related cost varied case by case, which could occasionally be as high as the annual income of an adult individual. In Moorea Island of French Polynesia, health-related costs charged to CFP were estimated to be around USD \$1613 for each reported case and USD \$749 for unreported case (Morin et al., 2016). Another study in Rarotonga of Cook Islands had estimated a total health-related cost of NZD \$2090 (≈ USD \$1330) for each individual (Rongo & van Woesik, 2012). Ciguatera victims could also be subjected to a loss of food sources through avoidance of reef fish and dietary shifts toward western processed foods that can exacerbate the risks of diabetes, hypertension and cardiovascular diseases. Because the alternative sources of protein are often intense in fat, salt and carbohydrate (Lewis, 1992).

The health risk of CFP is even higher in many isolated outer Pacific islands. Local islanders are highly dependent on marine sources and hard to alternate with other sources of protein. Meanwhile, low medical professional level and long distance from medical facilities disallow them to receive treatment for severe cases (Lewis, 1986). There have been sporadic cases of death in remote Pacific islands due to a lack of medicine and prompt medical treatment. For example, in 2017, four people died in an outbreak occurred in Gau Island of Fiji, with a total of 21 people poisoned (Aguilar, 2017; Bolanavanua, 2017).

Other major costs that Pacific islanders have to pay for CFP are loss to fishing markets and industries due to import bans and refined market regulation, loss of tourism from other countries, depopulation through emigration to avoid increasing risk of ciguatera, cost of program monitoring and management for disease control and prevention, etc. (Lewis, 1986; Lewis, 1992; Morin et al., 2016; Rongo & van Woesik, 2012). In French Polynesia, the estimation of potential economic loss, including loss of fisheries trade and labor productivity, is up to USD $1 million per year (Bagnis et al., 1992).

3.3 Reporting Schemes, Interventions and Regulatory Frameworks

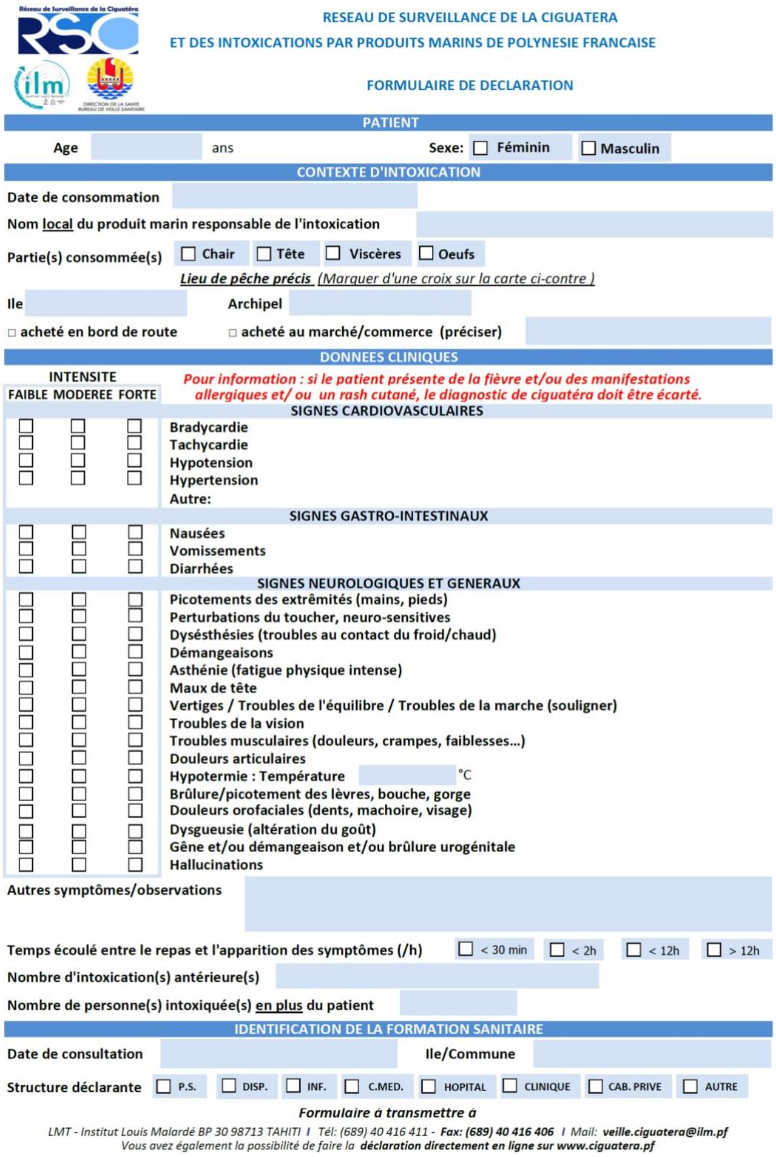
The major hurdle for ciguatera data collection is the constant underreporting and misdiagnosis, partly because CFP has highly variable clinical manifestations. Majority of islanders feel indifferent to seek professional medical support and report the disease that is apparently commonplace in their culture. Instead, they prefer or have to treat themselves with herbal medicine or leave the disease untreated (Chinain et al., 2010; Parsons et al., 2010). Most physicians do not realize CFP is reportable and in many countries it is not even enforced to be a reportable disease (Friedman et al., 2008). In 1998, a formal scheme for collecting fish poisoning records was established by South Pacific Epidemiological and Health Information Service (SPEHIS) for PICTs. The scheme was considered limited as it failed to include within-country distribution of the diseases, failed to differentiate CFP from other types of fish poisoning, and it only required voluntary report on annual basis (Lewis, 1992). As a result, few PICTs have continued to report their epi-data to SPEHIS (Dalzell, 1993; Goater et al., 2011). Currently in the Pacific, accurate and well-organized data reporting and management systems are only developed in Australia, French Polynesia and Hawaii (Goater et al., 2011). For instance, in French Polynesia, the epi-data collection is operated by Louis Marladé Institute in Tahiti. Medical doctors, clinicians and health workers are solicited to fill the incidence declaration form with explicit date, food source, incubation period, symptoms and personal information of the patients, and submit to the Institute (see Figure 3.3). Other countries such as Fiji have not possessed health information system targeting on CFP. From my observation during the field research, local health workers in remote outer islands are more inclined to report the name and dosage of medicine they prescribed to the patients rather than report the case under the disease name. This can be attributed to the nature of various symptoms of CFP and common practices of case-by-case symptomatic supports.

Few interventions have been initiated to mitigate the epidemiology from the downstream. Most of interventions are the release of brochures, leaflets and placement of warnings, but rarely actual educational programs directly delivering to at-risk populations (Botana, 2008). In Cook Islands and Fiji, warnings have been issued by the public health agency routinely to avoid risky fish for the potential threats of fish poisoning (Aguilar, 2017; Hajkowicz, 2006). In 2006, the Secretariat of the Pacific Community (SPC) and the Institute of Research for Development (IRD) have jointly released a field reference guide reviewing knowledge and practices of CFP (Laurent et al. 2005). The guide has also highlighted the methods and logical steps to assess and reduce the CFP risk in the South Pacific, but how extensive this information disseminated to the general public is unclear. On the other hand, a few educational and community outreach interventions were implemented in French Polynesia and resulted a significant reduction in CFP incidences

(Chinain et al., 2019). One problem of the initiation and launch of the intervention programs is the absence of reliable surveillance data. Goater et al. (2011) pointed out the complex mutuality between data collection and interventions – lack of available data provides little information for health intervention to base upon, and lack of effective means of disease prevention makes the continuation of data collection meaningless.

Globally, very few regulations and measures are being taken specifically for the inspection of CTXs. In some areas, regulations have been imposed for securely consuming suspected ciguatera fish or banning the sales of certain seafood products. In the Pacific, such restrictions have been enforced in American Samoa, Australia, French Polynesia, Fiji and Hawaii (FAO, 2004). For example, in Queensland, Australia, the capture of Spanish Mackerel and barracuda, and the sales of moray eel, chinaman, red bass and paddletail fish have been prohibited in order to reduce the ciguatera risk (de Fouw et al., 2001).

However, few of these regulations are associated with market access and fishery import and export, particularly in PICTs. For import inspection of fishery products, mouse bioassay vivo tests are the gold standard and the most commonly used method in many importing regions such as European Union (European Commission, 2015), but as it is expensive and time consuming, and it is unlikely to be implemented in endemic communities. Import refusals of seafood products from the Pacific happened occasionally and brought with economic consequences. In 1999, an CFP outbreak in Hong Kong allegedly caused by fish imported from Kiribati, had eventually led to the closure of live reef food fish trade in Kiribati, equivalent to annual revenue loss of a quarter million dollars (Yeeting, 2009).



RESEAU DE SURVEILLANCE DE LA CIGUATERA
ET DES INTOXICATIONS PAR PRODUITS MARINS DE POLYNESIE FRANCAISE

FORMULAIRE DE DECLARATION

PATIENT

Age ans Sexe: ☐ Féminin ☐ Masculin

CONTEXTE D'INTOXICATION

Date de consommation

Nom local du produit marin responsable de l'intoxication

Partie(s) consommée(s) ☐ Chair ☐ Tête ☐ Viscères ☐ Oeufs

Lieu de pêche précis (Marquer d'une croix sur la carte ci-contre)

Ile Archipel

☐ acheté en bord de route ☐ acheté au marché/commerce (préciser)

DONNEES CLINIQUES

INTENSITE
FAIBLE MODEREE FORTE

Pour information : si le patient présente de la fièvre et/ou des manifestations allergiques et/ ou un rash cutané, le diagnostic de ciguatéra doit être écarté.

SIGNES CARDIOVASCULAIRES

☐ ☐ ☐ Bradycardie
☐ ☐ ☐ Tachycardie
☐ ☐ ☐ Hypotension
☐ ☐ ☐ Hypertension
Autre:

SIGNES GASTRO-INTESTINAUX

☐ ☐ ☐ Nausées
☐ ☐ ☐ Vomissements
☐ ☐ ☐ Diarrhées

SIGNES NEUROLOGIQUES ET GENERAUX

☐ ☐ ☐ Picotements des extrêmités (mains, pieds)
☐ ☐ ☐ Perturbations du toucher, neuro-sensitives
☐ ☐ ☐ Dysésthésies (troubles au contact du froid/chaud)
☐ ☐ ☐ Démangeaisons
☐ ☐ ☐ Asthénie (fatigue physique intense)
☐ ☐ ☐ Maux de tête
☐ ☐ ☐ Vertiges / Troubles de l'équilibre / Troubles de la marche (souligner)
☐ ☐ ☐ Troubles de la vision
☐ ☐ ☐ Troubles musculaires (douleurs, crampes, faiblesses...)
☐ ☐ ☐ Douleurs articulaires
☐ ☐ ☐ Hypotermie : Température °C
☐ ☐ ☐ Brûlure/picotement des lèvres, bouche, gorge
☐ ☐ ☐ Douleurs orofaciales (dents, machoire, visage)
☐ ☐ ☐ Dysgueusie (altération du goût)
☐ ☐ ☐ Gêne et/ou démangeaison et/ou brûlure urogénitale
☐ ☐ ☐ Hallucinations

Autres symptômes/observations

Temps écoulé entre le repas et l'apparition des symptômes (/h) ☐ < 30 min ☐ < 2h ☐ < 12h ☐ > 12h

Nombre d'intoxication(s) antérieure(s)

Nombre de personne(s) intoxiquée(s) en plus du patient

IDENTIFICATION DE LA FORMATION SANITAIRE

Date de consultation Ile/Commune

Structure déclarante ☐ P.S. ☐ DISP. ☐ INF. ☐ C.MED. ☐ HOPITAL ☐ CLINIQUE ☐ CAB. PRIVE ☐ AUTRE

Formulaire à transmettre à

LMT - Institut Louis Malardé BP 30 98713 TAHITI / Tél: (689) 40 416 411 - Fax: (689) 40 416 406 / Mail: veille.ciguatera@ilm.pf
Vous avez également la possibilité de faire la déclaration directement en ligne sur www.ciguatera.pf

Figure 3. 3 Sample of ciguatera incidence declaration form in French Polynesia

Source: Louis Malardé Institute, 2014

For local level, since currently there is no test kit that are commercially available for the detection of ciguatoxic fish with high accuracy, rapidity, and cost effectiveness, in the Pacific and other parts of the world (Bienfang et al., 2011), local Pacific islanders have developed certain strategies by looking into the size, limpness, redness (fish with heavy bleeding), combined with their traditional knowledge to screen toxic fish species, though these methods were proved inefficient and sometimes inaccurate (Chinain et al., 2016; Gaboriau et al., 2014).

4. EFFECT OF CLIMATE VARIABILITY ON CIGUATERA INCIDENCE: EVIDENCE FROM TIME SERIES ANALYSIS

4.1 Research Questions

In this chapter, I attempt to answer my first research objective of analyzing the effects of climate change on the CFP incidence as discussed in Section 1.5. In particular, I use cross-correlation analysis and auto-regressive integrated moving-average (ARIMA) model to examine the eventual time-lag correlation between several variables related to SST and CFP incidence rates in two South Pacific countries, Cook Islands and French Polynesia.

Based on the literature review conducted in Section 2.1, the questions I seek to answer are: (1) How and to what extend climate factors affect the incidence of CFP? (2) What is the time interval of bio-accumulation from environmental change to the onset of CFP? (3) What could be the future CFP incidence pattern under the context of climate change?

My goal is to improve the knowledge of relationships between climate factors and CFP by taking seasonality into consideration as seasonality has not been considered in existing studies despite its importance; and to develop predictive models of ciguatera incidence to identify significant time-lag relationships between ciguatera incidences and local weather or regional climate predictors.

4.2 Study Areas

The geographical locations of both countries are shown in Figure 4.1. Cook Islands is a self-governing country in free association with New Zealand, comprised of 15 islands distributed over two million square kilometers on the Pacific Ocean (United Nations Development Program (UNDP), 2009). French Polynesia is a French overseas country spread over a territory as wide as Europe, composed of 118 islands divided into five archipelagos, Society, Tuamotu, Australes, Marquesas and Gambier Archipelagos (Adjeroud, 1997).

Cook Islands and French Polynesia are both located in the South Pacific Ocean, with a tropical-subtropical climate divided in two seasons: the cool/dry season from May to October, and warm/wet season from November to April. The average temperature is 24.4°C in Rarotonga (main island of Cook Islands) and 26.5°C in Tahiti (main island of French Polynesia). As South Pacific is particularly vulnerable to climate change, both countries are likely to face a rising of temperature and decreasing rainfall (Bell et al., 2011).

Cook Islands and French Polynesia have been chosen for case study for three reasons.

Firstly, CFP is highly endemic and common in both countries. As Skinner et al. (2011) stated, Cook Islands and French Polynesia are among the top five with the highest CFP incidence in all 18 PICTs where marine and lagoon products represent an important part of food habits of the local population, providing primary source of food and dietary protein for the local islanders (Gillett, 2016). Annual fish consumption per capita in Cook Islands and French Polynesia are 59.6 and 65.5 kilograms respectively, far above the world average of 19.8 kilograms (FAO, 2019). Due to the consumption pattern, effects of external factors on CFP incidences is very limited in the case of both countries. Imported fish mainly concern pelagic or freshwater fish that comes from non-endemic regions which excludes the introduction of external CFP risks. As a consequence, all CFP cases recorded in both countries can be considered indigenous.

Secondly, the CFP rates in these two countries are considered to be more accurate relative to other areas. While CFP is universally under-reported and under-diagnosed, the CFP cases in the South Pacific are more likely to be reported (with a rate of 10 to 20 percent of the true incidence), compared to the U.S. (2 to 10 percent) (Richlen et al., 2012). A study conducted in Moorea Island of French Polynesia indicates an under-reporting rate of 54%, meaning approximately 46% of actual cases are reported (Morin et al., 2016). And in Rarotonga, Cook Islands, a reporting rate of 34% was estimated by Rongo and van Woesik (2011). In fact, in both countries, special efforts were made each year by their health authorities to update and inform their general public about their epidemiological data.

Thirdly, over the period of study, both countries have not undergone major economic upheavals that could lead to deep modifications in the consumption habits of the population. Indeed, in a period of major crisis or high unemployment, the proportion of people returning to a subsistence fishing, is likely to increase and lead to a higher risk to be exposed to the ciguatoxic risk.

4.3 Data Source and Processing

Monthly number of CFP cases in Cook Islands from January 2000 to December 2016 was taken from *National Health Information Bulletin 2016*, compiled by the Cook Islands Ministry of Health (2018) through its Health Information Unit. CFP cases in French Polynesia (available from January 2007 to December 2016) were acquired through personal communication with the CFP surveillance program, managed by the Louis Malardé Institute and Health Directorate of French Polynesia. These epidemiological data were then converted into monthly incidence rate per 10,000 population using population data from United Nations' World Populations Prospects (2019).

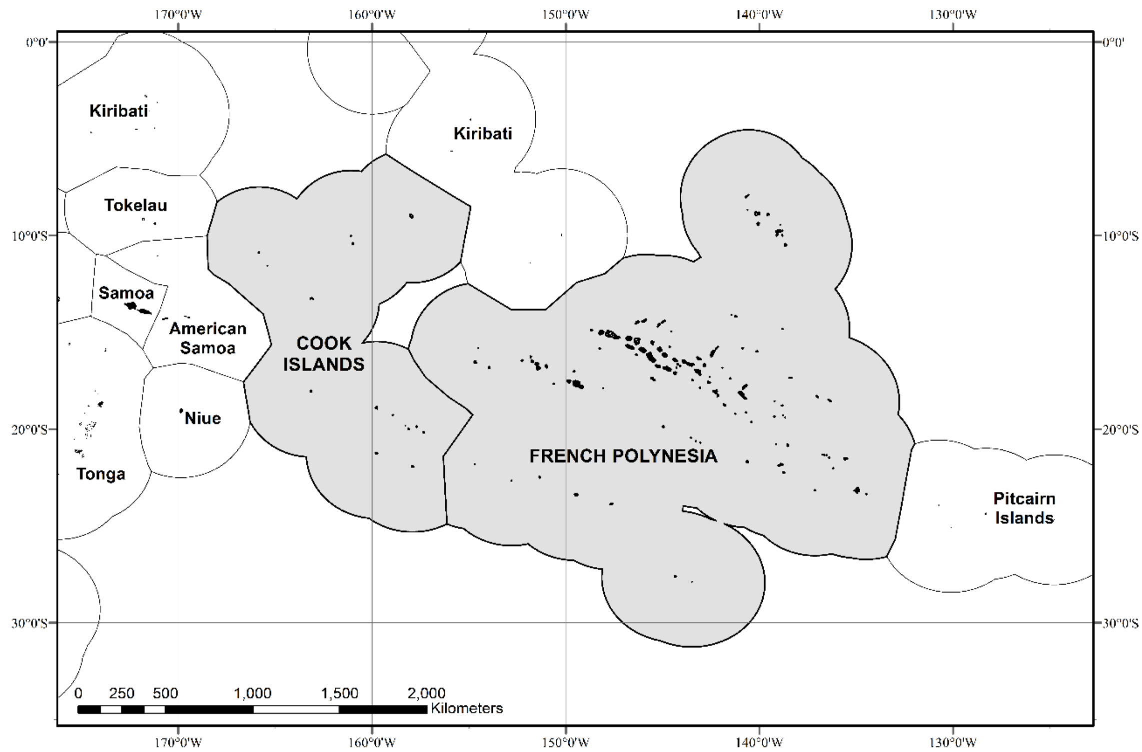


Figure 4. 1 Locations of Cook Islands and French Polynesia and their Exclusive Economic Zones (EEZs)

SST data in monthly 1°×1° gridded formats, contained in Reynolds and Smith OISST ver.2 SST dataset were downloaded from National Oceanic and Atmospheric

Administration (NOAA) (2019). Masking was applied to remove all data outside the Economic Exclusive Zones (EEZs) of Cook Islands and French Polynesia (Figure. 4.1), in which their own inhabitants can fish legally. In order to maximize the predictive power of the model, I extracted and created seven candidate variables from the dataset. Monthly SST anomaly (SSTA) was calculated with respect to the 1971-2000 climatology. The other six variables are the mean (SST_{mean}), maximum (SST_{max}) and minimum SST (SST_{min}) within each country's EEZ, and mean ($SSTTC_{mean}$), maximum ($SSTTC_{max}$) and minimum SST ($SSTTC_{min}$) along the Tropic of Capricorn (latitude 23.5°N) within their EEZ, all of which are in monthly formats. While SST_{mean}, SST_{max} and SST_{min} are variables that conventionally employed in similar research that mirror high or low seawater temperature, SSTA and SSTTC are actually indicators directly reflected ocean warming. SSTA, showing SSTs' Celsius degrees above or below the historical average value, has been considered an important predictor of harm algal blooms, levels of marine toxins, and fisheries catches (Hales et al., 1999; Lluch-Cota et al., 2017; Vandersea et al., 2018). As the Tropic of Capricorn passes through the southern part of both countries, SSTTC could potentially mark the ocean thermal expansion within each EEZ. Similar indicators like SSTTC were also created and used in Gingold et al.'s research (2014).

However, using variables all related to SST does not suggest temperature is the sole predictor to *Gambierdiscus* and CFP incidence. Though temperature has been considered the most significant factor, *Gambierdiscus* reacts to different environmental factors including salinity, light, wind velocity, as mentioned in Chapter 2. Since these environmental factors are largely inter-correlated, the inclusion of other variables may cause the problem of collinearity and biases of result interpretation.

4.4 Methodology

4.4.1 Cross-Correlation Analysis

Cross-correlation analysis is a measure to identify time lags of input series that might be statistically significant to predict output series. Given that both SSTs and CFP incidence rate are individually auto-correlated, a prewhitening process needs to be undertaken prior to the cross-correlation analysis for preventing spurious correlations. First I detrended the SSTs, then fitted with a time series model. The “white-noise” residuals of this model were used as the prewhitened SSTs series. At the same time, estimated coefficients from this model were extracted to filter the series of CFP incidence rate (Shumway & Stoffer, 2016). I then examined the cross-correlation function (CCF) between the prewhitened SSTs and the filtered CFP incidence rate with a maximum lag number of 48 months. The significant lags of each candidate variable with highest cross-correlation coefficients were retained for the next step of the analysis. CCF plots before and after the prewhitening are shown in Appendices.

4.4.2 ARIMA Modeling

The ARIMA method was first advocated by Box and Jenkin (Box et al., 2015), and has been widely used to predict climate-sensitive diseases, such as dengue (Jing et al., 2018), malaria (Wangdi et al., 2010) and leptospirosis (Chadsuthi et al., 2012). The model is generally classified as ARIMA(p, d, q) where p is the order of the auto-regressive terms, d is the order of differencing for producing a stationary time series, and q is the order of the moving-average process.

A simplified ARIMA model is expressed in the following form:

$$Y_t = \mu + \frac{\theta_q(L)}{\phi_p(L)} \varepsilon_t$$

where Y_t is the CFP incidence rate at time t, μ is the mean term, $\theta_q(L)$ is the auto-regressive polynomial, $\phi_p(L)$ is the moving-average polynomial, and ε_t is the error term. L represents the lag operator, defined as $LY_t = Y_{t-1}$ for all t>1.

As I hypothesized that the CFP incidence rate is related to the past lags of SSTs, here the model is modified to include explanatory variables, and is equivalent to:

$$Y_t = \mu + \frac{\theta_q(L)}{\phi_p(L)} \varepsilon_t + v(L)X_t$$

where $v(L)X_t$ denotes the transfer function which allows X_t to influence Y_t through a distributed lag. In case of a seasonal pattern observed in the time series, seasonal auto-regressive order P, seasonal differencing order D and seasonal moving-average order Q will also be inserted to capture the potential seasonality.

The time series dataset on both countries were divided into two subsets. The first 192 months (from January 2000 to December 2015) on Cook Islands, and first 108 months (from January 2007 to December 2015) on French Polynesia were used as training sets for model fitting; the last 12 months (from January 2016 to December 2016) on both countries were used as test sets for model validation.

I first checked the stationarity of training sets by their auto-correlation function (ACF) plot and Dickey-Fuller test. For non-stationary series, a higher order of differencing (d) is necessary. I then inferred the p and q orders by using cutoff time lag of ACF and partial auto-correlation function (PACF). Ljung-Box test was employed to check if the residuals of models are white-noise. For seasonal ARIMA model, same procedures were applied. I also incorporated the significant time lags of each explanatory variable, identified by cross-correlation analysis, into the ARIMA model.

Numerous candidate models were developed with different explanatory variables as well as different p, d, q, and P, D, Q orders. Coefficients of the model were estimated by maximum likelihood method. The goodness of fit was determined through Akaike information criterion (AIC), root mean square error (RMSE) and P-value of regression coefficients.

To measure the model accuracy, best-fitting models were used for validation by predicting the CFP incidence rate 12 months ahead, and comparing the predicted values to the actual values.

Time series analysis and data visualization were performed by using the R software (version 3.5.3, The R Foundation for Statistical Computing) with TSA, lmtest, forecast and ggplot2 packages.

4.5 Results

A total of 2,961 CFP cases were officially reported in Cook Islands from 2000-2016, and 4,284 cases were declared in French Polynesia from 2007-2016. Figure 4.2 represents the trend of monthly CFP cases, both showing a seasonal pattern with a nadir of median number of CFP cases in July or August, and a high occurrence season between September to May. In terms of temporal distribution, the number of cases in French Polynesia reached its highest level around 2009/2010, then receded, and increased again since 2014.

Whereas the number in Cook Islands peaked around 2004/2005, and began to flatten thereafter.

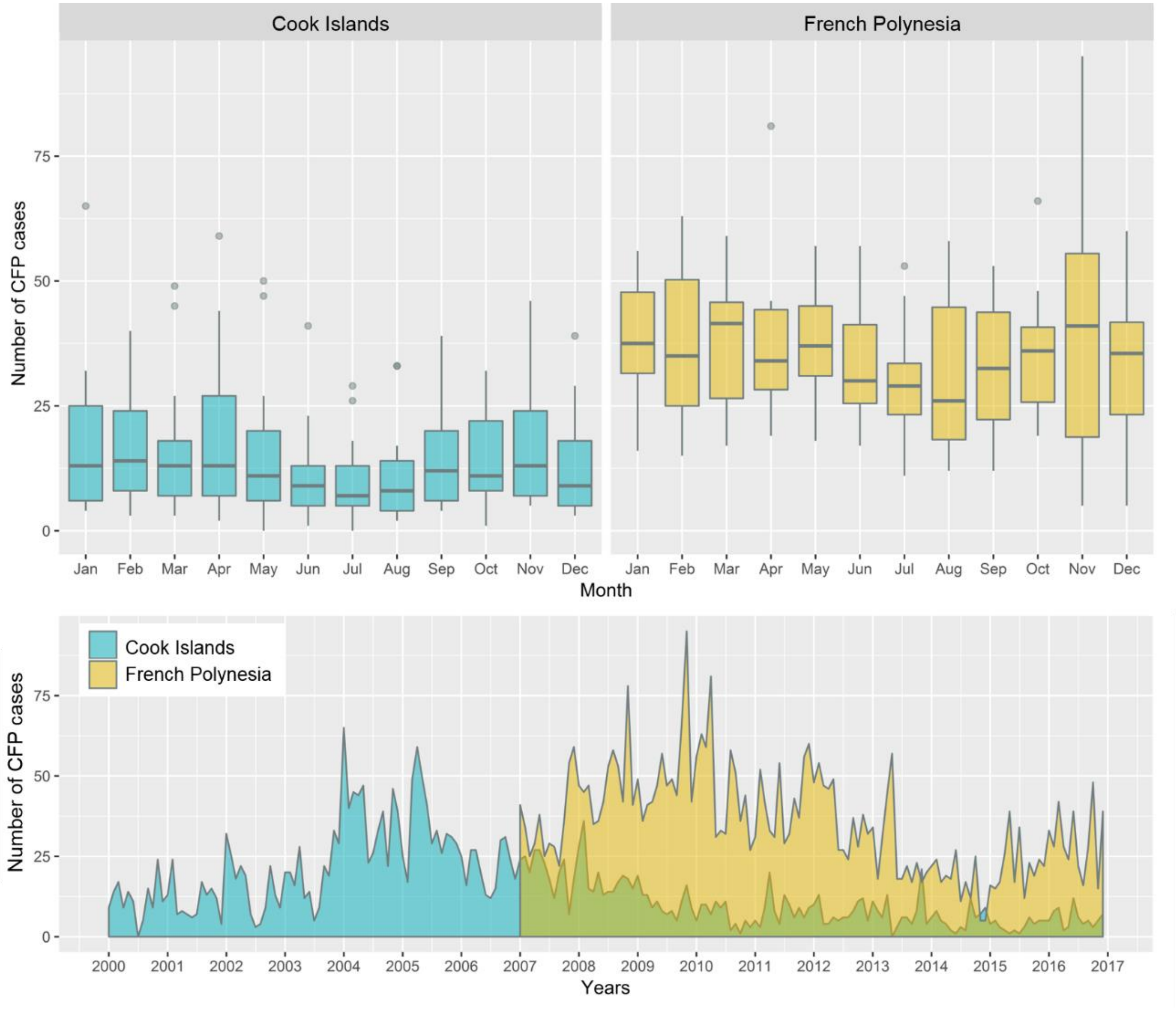


Figure 4. 2 Monthly number of CFP cases in Cook Islands (2000-2016) and French Polynesia (2007-2016)

To better control the external effects of population change during the studied period, monthly number of CFP cases were converted into monthly CFP incidence rate per 10,000 population, for which I used it as response variable in time series analysis.

4.5.1 Cook Islands

Table 4.1 presents the cross-correlations between the prewhitened candidate explanatory variables and the filtered CFP incidence rate. Maximum cross-coefficients occurred at lags of 12 months for SSTA and SST_{mean}, 4 months for SST_{min}, $SSTTC_{mean}$, and $SSTTC_{min}$, and 16 months for $SSTTC_{ma}$, respectively. It is also worth noting that although seasonal auto-correlations were greatly removed after prewhitening, the CCFs still exhibit weak periodicities corresponding to a 4 to 8-month interval that cycles between warm and cool seasons. Here I only took the lags of each candidate variable with peak cross-correlations to the ARIMA model analysis.

After stepwise selection, I finalized the model to ARIMA(2, 1, 3)$(1, 0, 0)_{12}$ and separately incorporated each explanatory variable at the time-lag characterized by the highest coefficient. Table 4.2 summarized the candidate models and their statistics of goodness of fit. The models with SSTA (lag12) and with SST_{mean} (lag12) as explanatory variables achieved relatively lower RMSEs (3.653 and 3.634 respectively), while model with $SSTTC_{max}$ (lag16) had the lowest AIC (975.040). In terms of P-value, the model with SSTA (lag12) have shown statistical significance for most of its coefficients. Henceforward, SSTA (lag12), SST_{mean} (lag12) and $SSTTC_{mean}$ (lag12) were combined in three pairs, and each pair was inputted again in the ARIMA(2, 1, 3)$(1, 0, 0)_{12}$ model.

As presented in Table 4.3, all three models enhanced their performance by getting lower AICs and RMSEs. ARIMA model comprised of both SSTA (lag12) and $SSTTC_{mean}$ (lag16) had the lowest AIC (964.919), whereas the one with both SSTA (lag12) and SST_{mean} (lag12) had RMSE of 3.564, the least among all models.

Table 4. 1 Cross-correlations between the prewhitened SSTs, and filtered CFP incidence rate in Cook Islands

Variable	Lag (month)								
	0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**
SSTA	0.018	0.019	0.017	0.000	0.001	0.079	0.202	0.134	0.053
	.	.	.	.	.	.	+	.	.
SST_{mean}	0.129	0.020	-0.106	-0.078	-0.049	0.114	0.200	0.040	-0.073
	.	.	.	.	.	.	+	.	.
SST_{max}	0.091	-0.108	0.019	-0.008	-0.125	0.086	0.084	-0.035	0.040
	.	.	.	.	.	.	.	.	.
SST_{min}	0.138	0.040	-0.193	-0.070	-0.027	0.041	0.110	0.086	-0.116
	.	.	-	.	.	.	.	.	.
$SSTTC_{mean}$	0.115	0.053	-0.170	-0.078	-0.019	0.060	0.143	0.075	-0.115
	.	.	-	.	.	.	+	.	.
$SSTTC_{max}$	0.109	0.047	-0.161	-0.012	0.018	0.137	0.002	-0.005	-0.180
	.	.	-	.	.	.	.	.	-
$SSTTC_{min}$	0.111	0.047	-0.179	-0.063	-0.040	0.052	0.149	0.067	-0.108
	.	.	-	.	.	.	+	.	.

Note: '+', positive statistical significance; '-', negative statistical significance; '.', no statistical significance. For simplicity, only even-numbered month lags between 0 and 16 are displayed.

Table 4. 2 Summary of fitted ARIMA models on CFP incidence rate in Cook Islands (1)

Model	AIC	RMSE	Variables	Coef.	S.E.	P-value
ARIMA(2,1,3)(1,0,0)$_{12}$	1072.895	3.842				
			ar1	-1.191	0.138	<0.001 ***
			ar2	-0.808	0.110	<0.001 ***
			ma1	0.647	0.140	<0.001 ***
			ma2	0.006	0.122	0.963
			ma3	-0.637	0.081	<0.001 ***
			sar1	0.164	0.074	0.026 *
ARIMA(2,1,3)(1,0,0)$_{12}$ with SSTA	992.311	3.653				
			ar1	-1.071	0.082	<0.001 ***
			ar2	-0.767	0.082	<0.001 ***
			ma1	0.582	0.087	<0.001 ***
			ma2	0.026	0.104	0.801
			ma3	-0.689	0.071	<0.001 ***
			sar1	0.229	0.077	0.003 **
			SSTA (lag12)	4.340	1.241	<0.001 ***
ARIMA(2,1,3)(1,0,0)$_{12}$ with SST_{mean}	989.157	3.634				
			ar1	-1.086	0.081	<0.001 ***
			ar2	-0.759	0.090	<0.001 ***
			ma1	0.575	0.080	<0.001 ***
			ma2	0.006	0.100	0.954
			ma3	-0.676	0.065	<0.001 ***
			sar1	0.147	0.079	0.064 .
			SST_{mean} (lag12)	1.856	0.469	<0.001 ***
ARIMA(2,1,3)(1,0,0)$_{12}$ with SST_{min}	1044.012	3.759				
			ar1	-0.924	0.788	0.241
			ar2	-0.468	0.938	0.618
			ma1	0.392	0.717	0.585
			ma2	-0.208	0.509	0.683
			ma3	-0.491	0.546	0.368
			sar1	0.156	0.083	0.062 .
			SST_{min} (lag4)	-0.680	0.206	<0.001 ***
ARIMA(2,1,3)(1,0,0)$_{12}$ with $SSTTC_{mean}$	1042.577	3.738				
			ar1	-1.174	0.118	<0.001 ***
			ar2	-0.789	0.083	<0.001 ***
			ma1	0.611	0.112	<0.001 ***
			ma2	-0.030	0.096	0.757
			ma3	-0.669	0.067	<0.001 ***
			sar1	0.120	0.075	0.111
			$SSTTC_{mean}$ (lag4)	-0.749	0.208	<0.001 ***
ARIMA(2,1,3)(1,0,0)$_{12}$ with $SSTTC_{max}$	975.040	3.718				
			ar1	-1.057	0.122	<0.001 ***
			ar2	-0.696	0.106	<0.001 ***
			ma1	0.560	0.116	<0.001 ***
			ma2	0.001	0.106	0.990
			ma3	-0.643	0.071	<0.001 ***
			sar1	0.140	0.080	0.080 .
			$SSTTC_{max}$ (lag16)	-0.541	0.226	0.017 *
ARIMA(2,1,3)(1,0,0)$_{12}$ with $SSTTC_{min}$	1042.086	3.733				
			ar1	-1.173	0.121	<0.001 ***
			ar2	-0.791	0.082	<0.001 ***
			ma1	0.609	0.115	<0.001 ***
			ma2	-0.028	0.096	0.773
			ma3	-0.670	0.067	<0.001 ***
			sar1	0.120	0.075	0.110
			$SSTTC_{min}$ (lag4)	-0.766	0.208	<0.001 ***

*Note: AIC, Akaike Information Criterion; RMSE, root mean square error; Coef., coefficient; S.E., standard error; ar#, auto-regressive order; ma#, moving-average process order; sar#, seasonal auto-regressive order. *** P<0.001, **P<0.01, *P<0.05, .P<0.1*

Table 4. 3 Summary of fitted ARIMA models on CFP incidence rate in Cook Islands (2)

Model	AIC	RMSE	Variables	Coef.	S.E.	P-value
ARIMA(2,1,3)(1,0,0)$_{12}$ with SSTA and SST_{mean}	985.667	3.564				
			ar1	-1.090	0.076	<0.001 ***
			ar2	-0.791	0.074	<0.001 ***
			ma1	0.585	0.078	<0.001 ***
			ma2	0.023	0.092	0.807
			ma3	-0.707	0.067	<0.001 ***
			sar1	0.158	0.079	0.046 *
			SSTA(lag12)	3.024	1.296	0.020 *
			SST(lag12)	1.516	0.483	0.002 **
ARIMA(2,1,3)(1,0,0)$_{12}$ with SSTA and $SSTTC_{max}$	964.919	3.582				
			ar1	-1.048	0.084	<0.001 ***
			ar2	-0.721	0.080	<0.001 ***
			ma1	0.559	0.083	<0.001 ***
			ma2	0.005	0.093	0.961
			ma3	-0.688	0.065	<0.001 ***
			sar1	0.180	0.081	0.027 *
			SSTA (lag12)	4.297	1.207	<0.001 ***
			$SSTTC_{max}$ (lag16)	-0.498	0.231	0.031 *
ARIMA(2,1,3)(1,0,0)$_{12}$ with SST_{mean} and $SSTTC_{max}$	965.719	3.597				
			ar1	-1.061	0.101	<0.001 ***
			ar2	-0.706	0.090	<0.001 ***
			ma1	0.554	0.094	<0.001 ***
			ma2	-0.015	0.093	0.873
			ma3	-0.674	0.065	<0.001 ***
			sar1	0.142	0.083	0.085 .
			SST_{mean} (lag12)	1.794	0.543	<0.001 ***
			$SSTTC_{max}$ (lag16)	-0.175	0.246	0.478

*Note: AIC, Akaike Information Criterion; RMSE, root mean square error; Coef., coefficient; S.E., standard error; ar#, auto-regressive order; ma#, moving-average process order; sar#, seasonal auto-regressive order. *** P<0.001, **P<0.01, *P<0.05, .P<0.1*

4.5.2 French Polynesia

Though a much more significant cross-correlation exhibited between raw series of both datasets due to seasonal components and structural dependency, the significance of CCF between all SST-related variables and CFP incidence rate in French Polynesia was largely removed after prewhitening. As presented in Table 4.4, only SSTA at the time-lag of 32 months appeared to be positively significant, while other variables did not display significant correlations at any time-lags up to 48 months with CFP incidence rate.

Therefore, SSTA (lag32) was used as the only explanatory variable for the next-step analysis.

Table 4. 4 Cross-correlations between the prewhitened SSTs, and filtered CFP incidence rate in French Polynesia

Variable	Lag (month)								
	20	**22**	**24**	**26**	**28**	**30**	**32**	**34**	**36**
SSTA	-0.071	-0.024	-0.037	-0.037	0.133	-0.027	0.204	0.101	0.059
	.	.	.	.	.	.	+	.	.
SST_{mean}	-0.04	-0.002	0.035	-0.003	-0.004	-0.075	0.041	0.018	0.075
	.	.	.	.	.	.	.	.	.
SST_{max}	-0.102	0.021	0.068	-0.069	0.028	-0.025	-0.053	0.06	0.083
	.	.	.	.	.	.	.	.	.
SST_{min}	0.059	-0.033	-0.011	0.061	-0.06	0.011	0.053	-0.008	0.029
	.	.	.	.	.	.	.	.	.
$SSTTC_{mean}$	-0.012	-0.01	0.017	0.018	-0.013	-0.111	0.087	0.02	0.045
	.	.	.	.	.	.	.	.	.
$SSTTC_{max}$	-0.071	0.054	-0.026	0.028	0.002	-0.152	0.065	0.05	0.064
	.	.	.	.	.	.	.	.	.
$SSTTC_{min}$	0.004	-0.111	0.076	0.001	-0.019	-0.041	0.047	0.018	0.073
	.	.	.	.	.	.	.	.	.

Note: '+', positive statistical significance; '-', negative statistical significance; '.', no statistical significance. For simplicity, only even-numbered month lags between 20 and 36 are displayed.

After comparing the diagnostic test results of models with different p, d, q and P, D, Q values, I narrowed the ARIMA models to three candidate models. Table 4.5 displays the summary of the three models. Model of ARIMA(0,1,1)$(1,0,0)_{12}$ with SSTA (lag32) produced smallest AIC (104.350), while ARIMA(4,1,0)$(0,1,1)_{12}$ with the same explanatory variable had lower RMSE (0.441) and gotten statistical significance for all its coefficients. The ARIMA(0,1,1)$(1,0,0)_{12}$ model without an explanatory variable resulted in an increase of both AIC (150.480) and RMSE (0.460).

Table 4. 5 Summary of fitted candidate ARIMA models on CFP incidence rate in French Polynesia

Model	AIC	RMSE	Variables	Coef.	S.E.	P-value
ARIMA(0,1,1)(0,1,1)$_{12}$	150.480	0.460	ma1	-0.710	0.084	<0.001 ***
			sma1	0.739	0.116	<0.001 ***
ARIMA(0,1,1)(1,0,0)$_{12}$ with SSTA	104.350	0.454	ma1	-0.780	0.078	<0.001 ***
			sar1	0.081	0.143	0.572
			SSTA (lag32)	0.448	0.226	0.048 *
ARIMA(4,1,0)(0,1,1)$_{12}$ with SSTA	109.480	0.441	ar1	-0.667	0.133	<0.001 ***
			ar2	-0.537	0.142	<0.001 ***
			ar3	-0.508	0.134	<0.001 ***
			ar4	-0.318	0.132	0.016 *
			sma1	-0.663	0.172	<0.001 ***
			SSTA (lag32)	0.586	0.260	0.024 *

Note: AIC, Akaike Information Criterion; RMSE, root mean square error; Coef., coefficient; S.E., standard error; ar#, auto-regressive order; ma#, moving-average process order; sar#, seasonal auto-regressive order; sma#, seasonal moving-average process order.
**** P<0.001, **P<0.01, *P<0.05*

4.5.3 Model Validation

The predicted values of best-fitted models and actual incidence rates in Cook Islands and French Polynesia from January to December 2016 were plotted in Figures 4.3 and 4.4. Overall, predicted values tend to be consistently below the actual values, partly because the models captured the downward trends of time series in both countries, or the models failed to accommodate the extreme observations. And yet some models still demonstrated a good ability to predict the CFP incidence rate. For example, predictions by model with SSTA (lag12) and model with $SSTTC_{max}$ (lag16) shared a relatively similar pattern with the observed incidence rate in Cook Islands. Although models with double explanatory variables gave similar predictions, models with single variable seemed more appropriate for forecasting.

For candidate models in French Polynesia, ARIMA(4,1,0)(0,1,1)$_{12}$ model with SSTA (lag32) seemed to give a more directionally correct forecast.

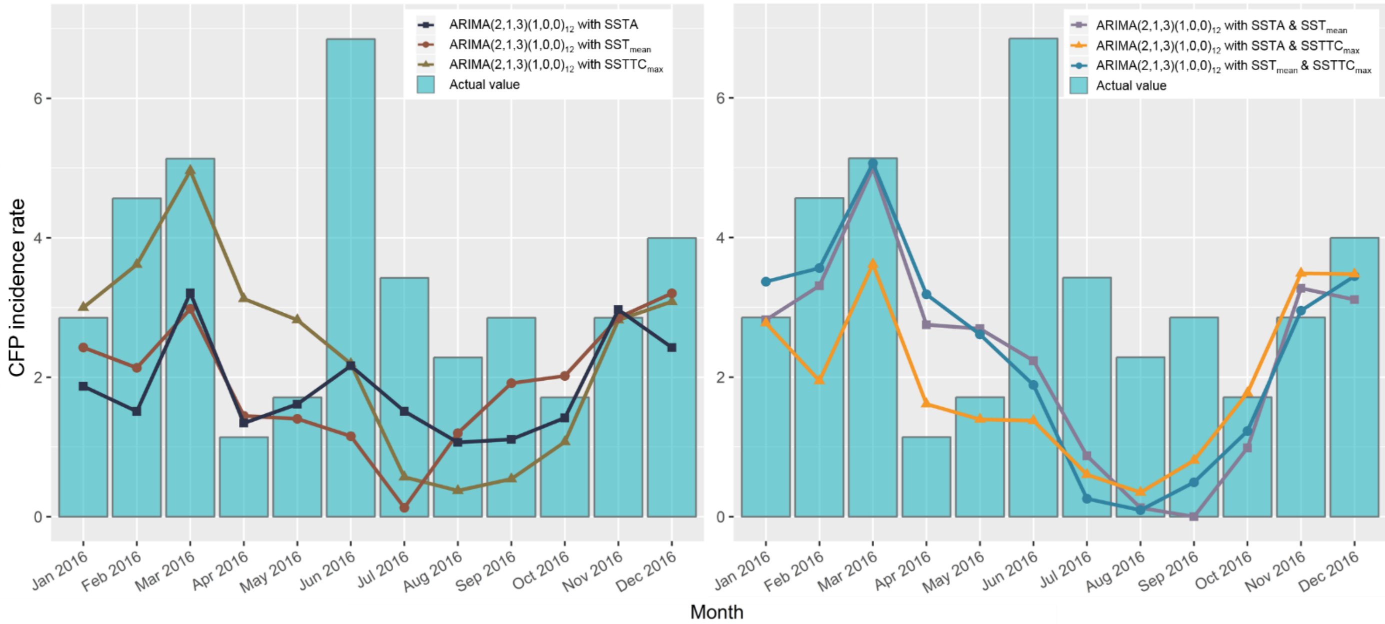


Figure 4. 3 Cross-validation for testing monthly CFP incidence rate in Cook Islands

Note: The actual observed incidence rates from January 2016 to December 2016 plotted in histogram are shown in both panels; predictions of ARIMA models with single explanatory variables plotted in line charts are shown in the left panel; predictions of ARIMA models with double explanatory variables plotted in line charts are shown in the right panel.

For a better visualization of the predicted values matching the actual observations, I added a secondary axis to both charts (see Figures 4.5 and 4.6), where the actual observations plotted against the left y-axes. As displayed in Figure 4.5, model with SSTA (lag12) shares a relatively similar pattern with the actual patterns of incidence rate; and for ARIMA(4,1,0)(0,1,1)$_{12}$ model with SSTA (lag32) in Figure 4.6, the initial two peaks of predictions and actuals are one-month staggered, but overall the model shows a similar pattern of peaks and nadirs as the actuals.

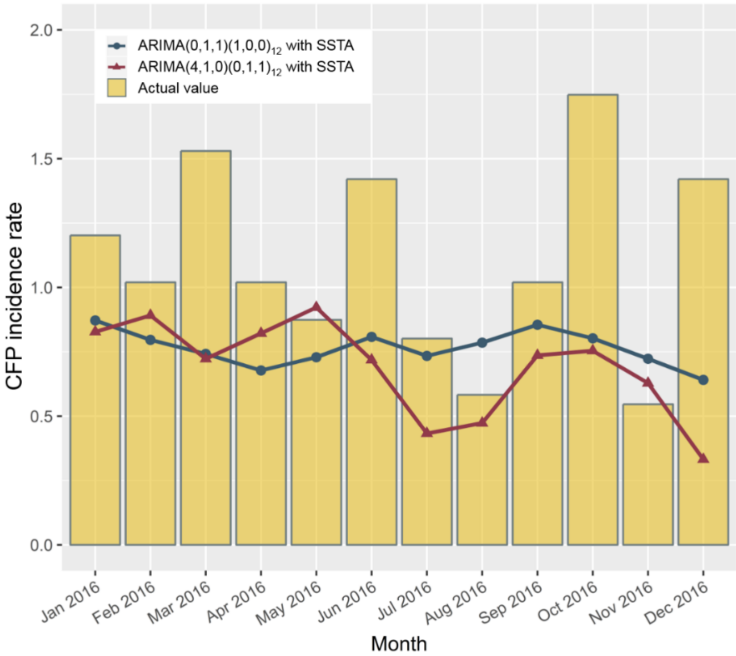


Figure 4. 4 Cross-validation for testing monthly CFP incidence rate in French Polynesia

Note: The actual observed incidence rates from January 2016 to December 2016 are plotted in histogram; predictions of ARIMA models are plotted in line charts.

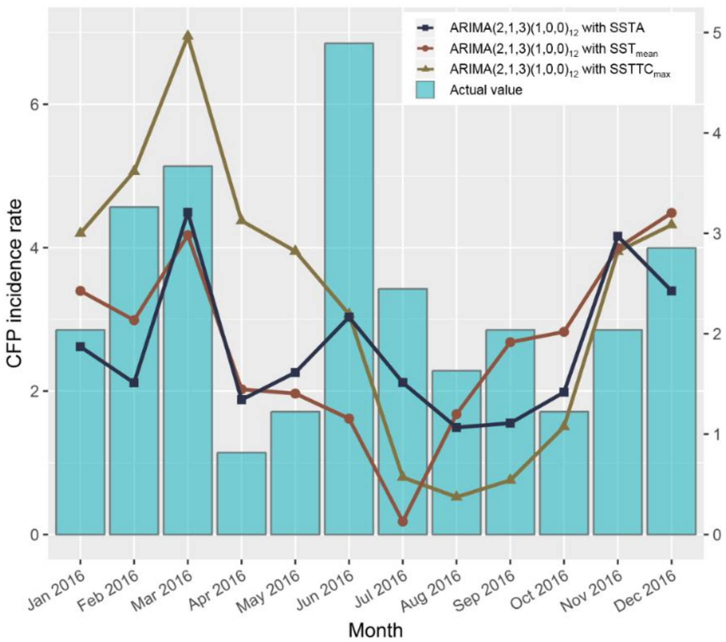


Figure 4. 5 Cross-validation for testing monthly CFP incidence rate in Cook Islands (dual axes)

Note: The actual observed incidence rates from January 2016 to December 2016 are plotted in histogram to the left y-axis; predictions of ARIMA models are plotted in line charts to the right y-axis.

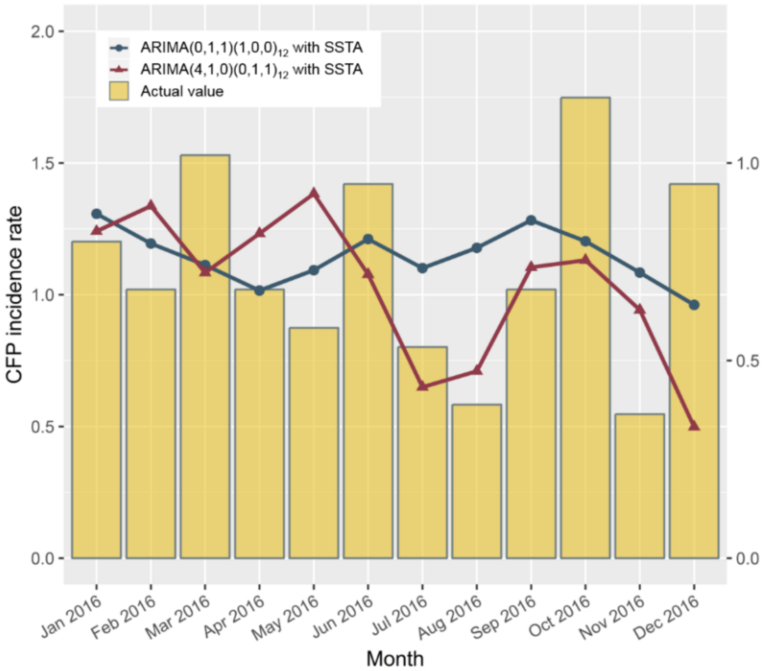


Figure 4. 6 Cross-validation for testing monthly CFP incidence rate in French Polynesia (dual axes)

Note: The actual observed incidence rates from January 2016 to December 2016 are plotted in histogram to the left y-axis; predictions of ARIMA models are plotted in line charts to the right y-axis.

4.6 Discussion

This study sought to develop predictive models of ciguatera events, based on the cases of Cook Islands and French Polynesia, two long-lasting endemic territories in the South Pacific (Bagnis, 1968; Rongo and van Woesik, 2011). Incorporating SSTs with time-lagged effects, I found that the monthly CFP incidence rate evolved in close relation to SST-related variables. In particular, SSTA (lag12) and SST_{mean} (lag12) have shown positive significant effects on CFP incidence rate in Cook Islands, whereas SSTA (lag32) is positively correlated with the CFP incidence in French Polynesia. Results of model validation have demonstrated that ARIMA models associated with SSTA are most appropriate to predict the incidence rate in both countries.

Analysis of the relationship between climate variables and the onset of CFP incidence represents a unique challenge. Unlike other vector-borne diseases such as dengue and malaria, CFP is a response to a long-consuming accumulation of toxins along the food web from the toxic dinoflagellates *Gambierdiscus* to coral reef fish and marine invertebrates that consumed by humans. The process can take a considerable long time. Apart from climatic factors, the geographical location, the strains of *Gambierdiscus*, the coral reefs adaptability to environmental changes, the fish species distribution, as well as human activity pressures, all may influence the time interval between dinoflagellates proliferation, toxin production and human poisonings.

Previous works have described a heterogeneity in response time interval between climate variables and CFP events. For example, between several ENSO-related indices and CFP incidence rates, empirical studies suggest a 1- to 2-year lag in Cook Islands (Rongo and van Woesik, 2011), and a 0-year lag in French Polynesia (Llewellyn, 2010), both with yearly time series data utilized; Chateau-Degat et al. (2005) suggest an approximately 16- to 20-month lag between seawater temperature and the peak of ciguatera events in French Polynesia. In my study of Cook Islands, maximum correlations for SSTA and SST_{mean} versus CFP occurred at 12-month lag, which is consistent with previous work. Indeed, for other variables including $SSTTC_{mean}$ and $SSTTC_{min}$, despite being excluded in the final model, significant associations were also found around the time-lags of 12 months. For French Polynesia, the time-lag (32 months) suggested by my results is far longer than the case of Cook Islands and those observed in other studies. Results variability recorded among the cases and all previous studies can be explained by the difference in methodology, the period of study, geographical and socio-economic factors of the study areas, but also I cannot rule out other environmental factors. For example, the thresholds at which different strains of *Gambierdiscus* reach their maximum growth rate or stop growing are varied when reacting to a changing temperature (Xu et al., 2016). The species composition of *Gambierdiscus* in two different regions could lead to different time intervals of bioaccumulation. Besides, the instability of water motion in some areas, which may cause the cells of *Gambierdiscus* disappeared or washed away, can extend the time interval (for destruction and recolonization) in certain areas (Nakahara et al., 1996). All above are only speculations at this point but long term prospective multifactorial studies that take all these parameters into consideration should allow a better understanding of the heterogeneity observed and consolidate correlation findings.

Though statistical significance revealed at the time lag of 12 months for Cook Islands and 32 months for French Polynesia, this does not mean that I insist that the time intervals of bioaccumulation are precisely 12 and 32 months. Since the CCFs between SSTs and CFP incidence rate have shown significance over an extending number of lags, and the "prewhitened" cross-correlation analysis only captured the most significant time lags that were retained for the model fitting. I suggest that time lags, which are roughly equivalent to 12 months for Cook Islands and 32 months for French Polynesia, can be seen as a possible determining cursor for CFP incidence prediction. If these time-lags are confirmed and refined by more investigations, such models could be useful early warning tools for future occurrence of CFP.

The proven significance of SSTA in predicting CFP incidence comes in line with Hales et al.'s findings (1999), where they found a linear relationship between SSTA and number of annual ciguatera cases in four Pacific islands. It may suggest that the occurrence of CFP during my studied period is more closely linked to the availability of suitable benthic habitats for *Gambierdiscus*, than the seasonal variabilities of *Gambierdiscus* abundance. SSTA has been constantly associated with the disturbances of coral reef systems and is a major indicator to determine coral reefs that are at risk of bleaching (NOAA, 2020). Oceanographic research reveals that high intensity and high frequency of anomalous temperature promote physical disturbances of coral reefs including coral mortality and bleaching (Ferreira et al., 2013; Sully et al., 2019), followed by the colonization of host macroalgae which provides substrate for *Gambierdiscus* (Hales et al., 2000). This finding raises a cautionary flag regarding the potential effect of regional or global warming which will eventually lead to a higher CFP risk in future.

4.7 Limitations

ARIMA modeling (along with cross-correlation analysis) has been extensively applied to develop predictive models for managing climate-sensitive health risk (Jing et al., 2018; Wangdi et al., 2010), and there are associated strengths and weaknesses in its application (see Table 4.6).

The primary advantage of the ARIMA modeling is that it can be extended to handle trends and seasonal variations of the original time series. In my analysis, the combination of cross-correlation analysis and seasonal ARIMA models enabled the identification of time-lags between environmental change and ciguatera events, which in turn could predict possible high-risk periods in the near future. In addition, the meteorological data is rather easy to be accessed and obtained by researchers and health officials and used as explanatory variables in the model.

Table 4. 6 Strengths and weaknesses of ARIMA modeling and forecasting

	Strengths	Weaknesses
Data necessity	• Easy access to downloadable meteorological data	• Difficulty to include social-economic factors; • Incapability to forecast short series
Modeling and estimation	• Taking into account the auto-regressiveness of time series data; • Inclusion of seasonal components; • Perfect for the short run	• Lack of accuracy for long term prediction; • Incompetence to accommodate extreme values
Application to actual policies	• Possibility to roughly confirm the time-lags between environmental factors and potential outbreaks; • Possibility to identify high-risk period with potential spikes of cases;	• Limited capability to predict absolute epidemiological levels

However, some underlying limitations must be acknowledged.

First of all, the modeling in my analysis was not able to include social-economic factors except population change (e.g. importance of turn-over and changes in reporting habits of health professionals, prevalence of population who prefers to treat itself rather than consult a medical facility, economic crisis, evaluation and quantification of anthropogenic damage to the coral reef system, etc.), as they are hard to quantify over a long period and in such geographically dispersed territories. I assumed that all these factors remained constant during the studied period.

Secondly, the model may not work well with short time series. For testing purposes, there should be enough sample size to allow some observations to be withheld. In my case, while I managed to trace the monthly epidemiological data as early as possible, the length of the time series, especially on French Polynesia, could bias my estimates.

Thirdly, while the model makes relatively accurate prediction in short run, it is complicated to obtain confident forecast for longer term due to the randomness of time series data. Past studies with the use of ARIMA model tend to have one to two years forecasting with moderate confidence intervals (Gingold et al., 2014; Jing et al., 2018), and in my study, predictions were generated 12 months ahead.

Past studies also revealed its incompetence to deal with outliers efficiently (Chadsuthi et al., 2012). In Section 4.5.3, the predicted values were consistently lower than the actual CFP incidence rate and mismatched with the extreme observations.[1] Alternatively, using monthly number of CFP outbreaks might be able to overcome this estimation bias.

Moreover, past studies have employed other indicators by collecting the water/fish sample and measuring the *Gambierdiscus* density or toxin level in fish (Chateau-Degat et al., 2005; Kaly & Jones, 1994)). These kinds of direct measurement may be effective and can provide more concrete evidence but at the expense of shortened time series. In my case, I considered the monthly CFP incidence rate as an indicator of the level of toxin biomass in marine ecosystem at a given time point, because using monthly CFP incidence rate as response variable allows a longer time frame, which is more favorable to time series analysis. In future, joint efforts from multiple disciplines shall allow a better

[1] The extreme observations might be explained by the nature of epidemiological data monthly CFP incidence rate) used in the study. Since a toxic fish (or a batch of toxic fish) can poison more than one individual, monthly incidence number could be the results of double-counting or overestimation of the actual number of CFP outbreaks.

estimation of time intervals and explanation for the bioaccumulation process.

To conclude, this chapter used cross correlation analysis and ARIMA modeling to postulate the lagged effects of SSTs on CFP incidence rate in Cook Islands and French Polynesia. The results supported the idea that CFP reacts to SSTs positively over an extended period of time. Although more investigations are needed to confirm the time intervals and address the underlying limitations of the model, important policy implications of can be drawn from the findings, which will be thoroughly elaborated in Chapter 6.

5. IMPACT OF CIGUATERA ON FOOD CHOICE IN SMALL ISLAND COMMUNITIES: EVIDENCE FROM HOUSEHOLD SURVEYS

5.1 Research Questions

As mentioned in Section 2.3, since most socio-economic studies on CFP were carried out with an urban health setting, the real impacts of CFP on remote islands remain largely unknown. While these areas are generally having a limited access to any medical facilities and a heavy reliance on marine resources, such particular case raises the questions – (1) what is the past and present status of fish poisoning in these communities? (2) How fish poisoning outbreaks have affected the health and food systems of indigenous communities? (3) What factors contribute to their consumption behavior under the risk of CFP? (4) Most importantly, what can be done to enhance local food security to withstand the increasing risk of food shock if climate change persists? Questions (1) and (2) will be answered by the summary statistics of the primary survey results. To answer Questions (3) and (4), econometric analysis will be conducted and discussion will be made based on the results of analysis.

To fill the gaps of existing research, my study focuses on Gau Island, a remote island in Fiji. Past works and efforts pertaining to CFP in the Pacific have been conducted in Cook Islands, French Polynesia, Hawaii, Tuvalu, etc. As one of PICTs with the highest number of ciguatera incidence (Skinner et al., 2011), Fiji has rarely been a case study object. And similar to many other small island communities in the Pacific, Gau highly rely on marine and lagoon products and is distant from formal medical care facilities. For local people, any consumption of fish species must be weighed against the risk of CFP, particularly under the background that four Gau islanders died of CFP in 2017 (Bolatiki

& Aguilar, 2017).

This chapter aimed to assess the present situation of fish poisoning in Gau island and impacts of fish poisoning on their food consumption behavior including food avoidance and aversion, as well as dietary shift to alternative food products. I used quantitative methods to investigate the determinants of fish consumption behavior among the local population despite being well aware of the potential risk. I further explore risk-coping capacities that can reduce the likelihood of risky fish consumption. Such results could contribute to a better understanding of the peculiarity and vulnerability of indigenous communities' food system, and assist to develop effective intervention programs pertaining to food safety as well as climate-resilient livelihoods.

Moreover, given the current paucity of information on micro-level food security in Pacific, my study could offer a glimpse into food availability and utilization in small island communities, and provide supplementary evidence and policy frameworks to tackle the food insecurity issue worldwide.

5.2 Study Area

Fish poisoning (termed *ika gaga* in Fijian language) is an endemic disease all throughout Fiji Islands. Data shows that incidence rate of CFP has significantly increased over the last few decades. The annual average number of reported incidences in Fiji moved from 97 between 1973 and 1983 to 1,205 between 1998 and 2008 (Lewis, 1986; Skinner et al., 2011). Between 2012 and 2018, the number rose to 1,709.[2] Although the

[2] The epidemiological data (2012 – 2018) was obtained from the Ministry of Health in Fiji through private contact. The number combines cases under the category of "fish poisoning" and "ciguatera fish poisoning".

explosion in incidence rate can be partially explained by an improved reporting rate and population growth, it cannot be concealed that CFP has expanded its presence and exposure in Fiji.

My case study was carried out in Gau Island, Fiji, a remote island situated to the east of the main island Viti Levu. It has a land area of 190 square kilometres and a coastline of 66 kilometres. The island is surrounded by a ring of extensive barrier reef like many other islands in the Pacific (see Figure 5.1), which provides a rich habitat for marine life of all kinds.

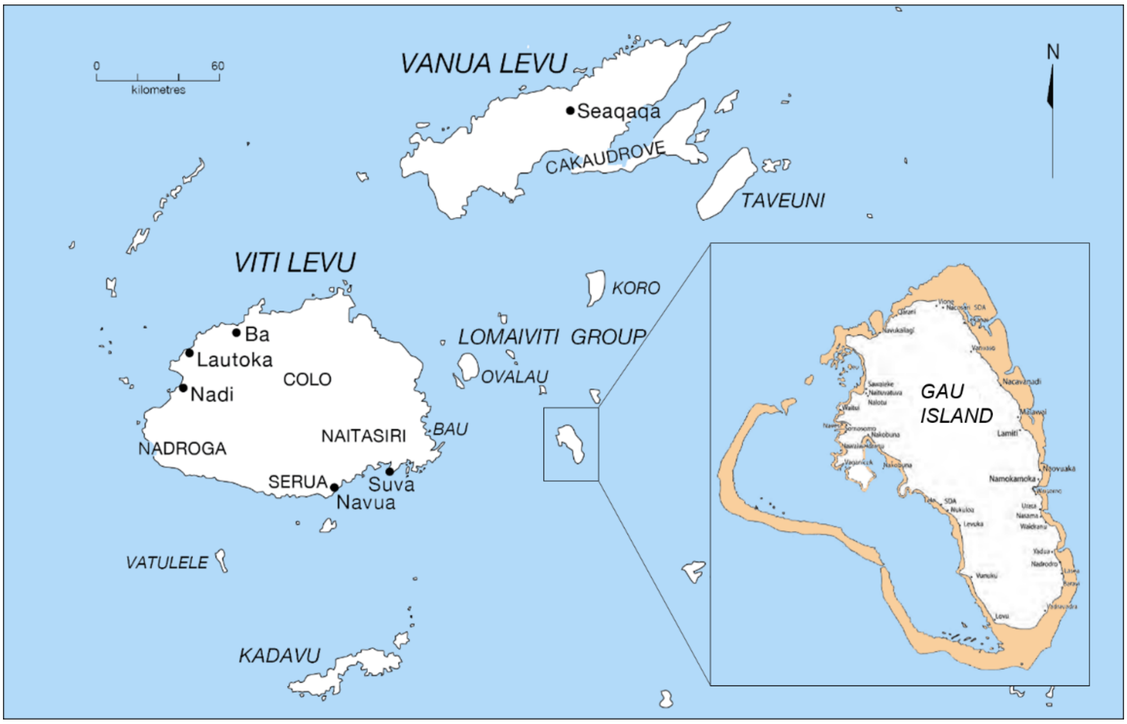


Figure 5. 1 Map of Fiji and location of Gau Island

Note: white areas indicates lands of the islands and orange areas indicate barrier reefs.

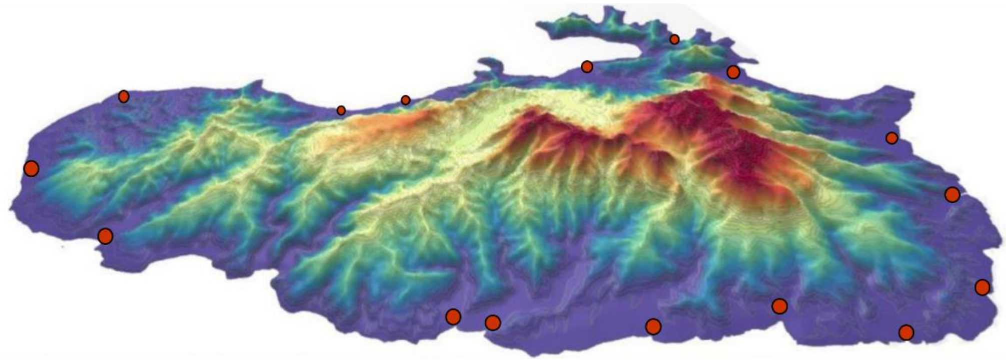


Figure 5. 2 Relief map of Gau Island

Note: red dots indicate location of villages

Since the interior part of Gau Island is rugged and mountainous, an estimated resident population of over 3000 are all residing in 16 different villages and 11 settlements scattered on the coastal area (World Wide Fund for Nature (WWF), 2011) (see Figure 5.2). Indigenous Fijian people made up 100 percent of the population. Almost all of them engage in traditional farming and subsistence fisheries. The nearest hospitals are about 90 kilometres away from the island, in either Ovalau Island or the capital city, Suva. However, there are three nursing stations and one health centre on the island that provide basic medical consultation and common drugs. While a few adjacent villages are mutually accessible through dirt roads or paths during low tide, the most common form of transportation between villages and settlements or to other islands is by fiberglass boat.

Fish poisoning has been commonly occurred to local people for decades. Recently in January 2017, two massive outbreaks of fish poisoning have stricken Gau Island, induced by consumption of *Herklotsichthys quadrimaculatus* (bluestripe herring) in Somosomo village and *Gymnothorax undutus (*moray eel) in Lovu village, involving 31 persons in total and causing four deaths (Aguilar, 2017; Bolanavanua, 2017). The outbreaks were later confirmed by Ministry of Health in Fiji as ciguatera (Fiji Government, 2017).

Throughout the years, local people have developed certain strategies to lower their exposure to CFP. The application of traditional knowledge is involved to certain extent in deciding fishing sites, selecting and cooking potentially poisonous fish, and treating ciguatera-like symptoms with herbal medicine.

5.3 Materials and Method

Original survey data was gathered through household interviews, reviews of community health notes, key informant interviews, and focus group discussions from June 2018 to June 2019. Households were randomly selected from sampled kin groups in 12 villages. The selection of interviewees is only confined to long-term residents of the indigenous communities, excluding civil servants, teachers, and medical workers on the islands who are usually temporary residents on the islands. The sample size is 239 households across 12 villages in Gau Island.

Key variables are categorized into medical history, consumption pattern of risky species and household characteristics. In addition, adult household members were asked about their preference for food attributes on sample fish species risk perception and risk preference for individual-level analyses. Details of key variables are presented in Table 5.1. The complete content of questionnaire can be seen in Appendices.

Table 5. 1 Description of key variables

Category	Description
Medical history	Medical history includes episodes of fish poisoning, time of occurrence, suspect fish species, incubation period, symptoms and their duration, etc. Medical history of household members below 18 years old were reported by their legal guardians or other adult members in the same household.
Avoidance and aversion of risky fish species	Variable "avoidance of bluestripe herring" is a dummy variable based on the following question. *"Have you avoided consuming bluestripe herring after the outbreak occurred in January 2017?";* Variable "level of aversion to risky fish" is created on the basis of the following question. *"How many fish species from the list you and your households have avoided to eat during the past 12 months?"* The list of 20 fish sample, identified by Ministry of Fisheries in Fiji as high-risk fish for CFP (see Appendices). The number of aversion to risky species was converted to categorical variable "level of aversion to risky fish " for five levels: aversion to less than two species = 1, two to three species = 2, four to six species = 3, seven to nine species = 4, and more than nine species = 5.
Household characteristics	The respondents reported their household characteristics such as age, education, household size, the variety of crops and livestock they grow and possess, as well as number of sources of income including crop sales, weaving, fishing, remittance, business, salary/pension, and others. Variety of crops and livestock was converted to "food diversity ratio", a categorical variable for five levels: less than four types of crops and livestock = 1, four to five types = 2, six to seven types = 3, eight to 11 types = 4, more than 11 types = 5; The number of sources of income was directly used as "income diversity".
Food attributes	By showing the image sample of bluestripe herring, respondents were asked to rank from 1 to 10 for three attributes: nutrition, taste and preciousness. Picture of bluestripe herring is presented in Appendices.
Risk perception and Optimistic bias	Three questions were asked to elicit the respondents' risk perception. *(1) "How possible do you think consuming certain fish would cause fish poisoning to you" by following a 10-point scale;* *(2) "Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than neighbors in your village?";* *(3) "Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than people in your neighboring villages?".* Questions (2) and (3) measure the optimistic biases in village level and external level, respectively.
Risk preference	Risk preference is elicited by a payroll game using Eckel and Grossman's measure (2008). The measure asks respondents to make one choice from the presented 6 gambles. The game is designed so that risk-averse respondents would choose those with a lower standard deviation (Game 1 – 4), risk-neutral ones should choose the gamble with the higher expected return (Game 5), and those who are risk-seeking should choose Game 6 (see Appendices).

After the CFP outbreak occurred on Gau Island in January 2017, many local islanders started to avoid consuming the suspect species *Herklotsichthys quadrimaculatus* (bluestripe herring, termed *daniva* in Fijian) for differing length of time.

In order to understand the determining factors of individual's fish avoidance after the outbreak, I first used pairwise Pearson coefficients to confirm the correlations between food avoidance of bluestripe herring, the response variable and other explanatory variables such as self-perceived food attributes, risk preference and risk perception (including optimistic bias). Significant variables were retained for the logistic regression analysis while avoiding potential collinearity. The logistic regression models were controlled for individual and household characteristics. Within the 239 household surveys covering a population of 959, I was able to extract 575 adult individual samples for the econometric estimation.

I then attempted to explore, for each household, whether their risk-coping capacity could affect their level of food aversion. For this purpose, multivariate regression analysis was performed. Again, I conducted Pearson correlation analysis and selected the variables with statistical significance for the regression. Since the distribution of number of risky species aversion is skewed, the categorical variable was created to reflect the degrees of food aversion (see Table 5.1). The regression models thus used the level of aversion to risky fish species as response variable and household characteristics including food expenditure, food diversity, total income, and income diversity as independent variables.

The econometric analysis is implemented in STATA 14.

5.4 Descriptive Statistics

Among the sample population, 24% of them have suffered from fish poisoning at least once in lifetime whilst the overall incidence rate is 31 cases per 100 people.

Table 5.2 gives the age and sex distributions of fish poisoning among the sample population. For people who experienced CFP in lifetime, male islanders accounts for 58% of the total cases while female accounts for 42%. In terms of the number of total incidences (where more than one episode of fish poisoning can occur to one person), the share of male islanders is slightly higher than the share of males in the number of individuals. The incidence rates of male islanders are also substantially higher than those of females, particularly in age groups of 40 – 49 and 50 – 59. This implicates that men are more likely to engage in risky decision-making on fish consumption than women.

Table 5. 2 Age and sex distribution of individuals experienced with CFP

Age group (years)	Number of individuals who had experienced CFP			Number of total incidences of CFP			Incidence rate		
	Male No. (%)	Female No. (%)	Total No. (%)	Male No. (%)	Female No. (%)	Total No. (%)	Male	Female	Overall
0 – 19	3 (1)	7 (3)	10 (4)	3 (1)	7 (2)	10 (3)	1%	4%	3%
20 – 29	11 (5)	10 (4)	21 (9)	14 (5)	11 (4)	25 (8)	29%	31%	29%
30 – 39	25 (11)	22 (9)	47 (20)	32 (11)	28 (9)	60 (20)	55%	45%	50%
40 – 49	35 (15)	22 (9)	57 (25)	44 (15)	31 (10)	75 (25)	65%	48%	56%
50 – 59	34 (15)	20 (9)	54 (23)	50 (17)	26 (9)	76 (26)	85%	46%	66%
≥ 60	26 (11)	17 (7)	43 (19)	32 (11)	20 (7)	52 (17)	51%	43%	48%
Totals	134 (58)	98 (42)	232 (100)	175 (59)	123 (41)	298 (100)	35%	27%	31%

Note: Incidence rate is the ratio of number of incidences to the sample population of each age group.

Majority of fish poisoning victims are distributed within the above 30-year-old population with a much higher incidences rates (over 50%) than those from the younger age groups. A part of the reasons is that a longer duration and more severe symptoms are associated with increasing age; and as stated in existing literature, many of the sample households reported restriction on their children's consumption of suspect fish in order to minimize the risk of CFP on children (McKerracher et al., 2016).

Table 5.3 summarizes important details regarding cases of CFP. The number of incidences has drastically increased over the last decade.[3] 35% of victims have visited public health facilities including hospital, health center and nursing station. Hence the overall reporting rate of CFP is estimated to be 35% or lower. There is some geographical variation of reporting rates in different villages as some villages have better accessibility to nursing stations or health center. Traditional remedies and herbal medicine are most commonly used for post-poisoning care, as much as 62% of victims in my sample, and sometimes as supportive care after receiving treatment from medical facilities. I also note that 12% of victims do not practice any of these treatments.

Most fish poisoning victims developed neurological manifestations including burning sensations when touching water (hot and cold reversal (66%)), tingling in hands and feet (82%), and numbness of other body parts (26%). Similar to other forms of food poisoning, diarrhea and vomiting appear to be common symptoms as well (50% and 24%, respectively). The longest duration of symptoms lasted for two years while in some cases with mild symptoms the illness only lasted for two days.

Numerous species are reported by respondents as high-risk species. Most of them are typical predator fish residing near the coral reefs including snapper, grouper, and

[3] It should be noted that the increasing trend of CFP might be biased since people tend to report the most recent cases, and only cases with both confirmed date and suspect fish species are included in the statistics.

moray eel. 67% of victims reported a temporal to long-term avoidance of seafood consumption for preventing recurrence of ciguatera-like symptoms while 33% of them reported no fish aversion (see Table 5.3). In some cases, the restriction of food consumption has extended to tinned fish and seaweed. The length of food aversion varied from three days to one year, according to the severity of poisoning. During this period, most people have an increase consumption of leafy greens and root crops. Processed foods such as canned meat and instant noodle were also reported to be consumed in a more frequent basis. Thus, a rise in food expense is seen in many households after one or some of their household members have suffered from fish poisoning.

During the interview, the respondents were asked to point out the fish species they considered potentially toxic but still have consumed over the last 12 months, from the list of 20 highly risky fish species (see Appendices). 100% of households have consumed at least one risky species, and the number of risky fish consumption appeared to be astoundingly high. On average, households have consumed about 15 risky species over the past 12 months.

Table 5. 3 Descriptive statistics of CFP incidences within sample households

	Number of incidences	Percent of total incidences (n=298)
Period of occurrence		
2010 - 2019	175	59%
2000 - 2009	59	20%
Before 2000	63	21%
Main fish species involved		
Two-spot red snapper (*bati*)	74	25%
Moray eel (*dabea*)	71	24%
Camouflage grouper (*kawakawa*)	35	12%
Brown-marbled grouper (*delabulewa*)	14	5%
Leopard coral grouper (*donu*)	13	4%
Rivulated snapper (*regurawa*)	11	4%
Porcupine fish (*sokisoki*)	10	3%
Gold spot herring (*daniva*)	8	3%
Long-face emperor (*dokonivudi*)	6	2%
Medical treatment		
Herbal medicine	184	62%
Treatment from medical facilities	104	35%
Other over-the-counter medicine	4	1%
Untreated	36	12%
Typical sign or symptom		
Tingling in hands and feet	243	82%
Reversal of hot and cold sensation	197	66%
Diarrhea	150	50%
Numbness around mouth and tongue	76	26%
Vomiting	73	24%
Joint pain	52	17%
Main dietary change after poisoning		
Replaced fish with root crops	104	35%
Replaced fish with leafy greens	185	62%
Replaced fish with processed food	84	28%
No aversion of fish	98	33%

Note: Fish species are labeled in the form of common name along with local name in parentheses

5.5 Regression Results

After the destructive CFP outbreak occurred in Somosomo Village in January 2017, about half of the surveyed population have started to avoid the consumption of bluestripe herring, which is the species associated with the outbreak. However, reasons of fish aversion varied. In order to assess the important self-perceived determinants of islanders' decision-making on food under the risk of CFP, the regression used their post-outbreak fish avoidance behavior as dependent variables and food attributes, risk perception and preference, and optimistic biases as independent variables. Table 5.4 provides summary statistics and variable definition used in the individual-level regression. With an age range of 18 to 98, 53% of sample individuals have avoided consuming bluestripe herring after the outbreak. 39% of them have experienced fish poisoning at least once in lifetime, while 9% have suffered from severe symptom during their last episode of fish poisoning.

Table 5.5 shows the Pearson correlation coefficients for the food avoidance dummy and predictor variables. As displayed, the food avoidance dummy was significantly correlated with one's fish poisoning experience (including the dummy, total episodes, and the occurrence of severe symptoms). Taste, risk preference and risk perception (including optimistic bias) on bluestripe herring all show statistical significance to different level.

Table 5. 4 Summary Statistics of individual-level analysis

Variable	Mean	Std. Dev.	Min	Max
Avoidance of bluestripe herring (=1 if yes)	0.53	0.50	0	1
Age (years)	45.47	15.45	18	98
Sex (=1 if female)	0.47	0.50	0	1
Episodes of fish poisoning in lifetime (times)	0.51	0.76	0	5
Fish poisoning experience (=1 if yes)	0.39	0.49	0	1
Severe symptoms in the last episode (=1 if yes)	0.09	0.28	0	1
Food attribute - Nutrition (1-10, 10 highest)	4.45	1.53	1	9
Food attribute - Taste (1-10, 10 highest)	5.15	2.15	1	10
Food attribute - Preciousness (1-10, 10 highest)	3.65	1.56	1	10
Risk preference (1-6, 1 most risk averse)	2.70	1.43	1	6
Risk perception (1-10, 10 perceive most risky)	4.15	1.95	1	9
Optimistic bias (village-level) (=1 if yes)	0.46	0.50	0	1
Optimistic bias (external) (=1 if yes)	0.53	0.50	0	1
Distance to the center of CFP outbreak (FJD$)	69.83	41.82	0	150
N	575			

Note: Distance to the center of outbreak is measured by the fuel cost of the minimum distance to Somosomo Village, the center of the outbreak from each village by fiberglass boat. Severe symptoms in the last episode refers to people experienced symptoms for more than 30 days during the last CFP episode.

Table 5. 5 Pearson correlation coefficients for avoidance of bluestripe herring and predictors

		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Avoidance of bluestripe herring (=1 if yes)	-													
2	Age (years)	0.0369	-												
3	Sex (=1 if female)	0.0605	-0.0333	-											
4	Episodes of fish poisoning in lifetime (times)	0.0930**	0.0837**	-0.0930**	-										
5	Fish poisoning experience (=1 if yes)	0.0931**	0.0919**	-0.0987**	0.836***	-									
6	Severe symptoms in the last episode (=1 if yes)	0.276***	0.0165	-0.0158	0.356***	0.381***	-								
7	Food attribute – Nutrition (1-10, 10 highest)	0.00928	-0.0301	0.0525	-0.0740*	-0.0754*	-0.0777*	-							
8	Food attribute - Taste (1-10, 10 highest)	-0.136***	-0.0104	0.00360	0.0273	0.0474	-0.0566	-0.0216	-						
9	Food attribute - Preciousness (1-10, 10 highest)	0.00296	0.0444	-0.0193	0.00996	0.0147	0.0772**	-0.00041	-0.0281	-					
10	Risk preference (1-6, 1 most risk averse)	-0.0718*	0.0406	-0.0972**	-0.0458	-0.0561	-0.0178	-0.0527	0.0537	0.0244	-				
11	Risk perception (1-10, 10 perceive most risky)	0.291***	0.0683	-0.00957	0.0165	0.0708*	0.0887**	-0.0574	-0.0220	-0.0361	-0.0369	-			
12	Optimistic bias (village-level) (=1 if yes)	0.0305	0.0503	-0.00903	-0.0999**	-0.0649	0.0166	-0.00871	-0.0109	-0.0159	0.0170	-0.00058	-		
13	Optimistic bias (external) (=1 if yes)	-0.0753*	0.0496	-0.0299	-0.0409	-0.0553	-0.0384	0.00951	-0.0257	-0.0201	-0.00699	0.00137	0.0311	-	
14	Distance to the center of CFP outbreak (FJD$)	0.0236	0.000720	0.0298	-0.0512	-0.0487	-0.00469	0.00831	-0.0963**	-0.00709	-0.0972**	0.169***	-0.0921**	-0.119***	-

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

I then retained the non-self-perceived variables for the logistic regression. Estimated coefficients and marginal effects were displayed along with standard errors. Table 5.6 displays the results of logistic regression. Clustering of household was applied to all models for fixing the within-cluster correlation of standard errors. To avoid collinearity, fish poisoning dummy, total episodes, and the occurrence of severe symptoms were each included in separated models, all of which shown statistical significance. These confirm that fish poisoning experience leads to avoidance of fish. The dummy "severe symptoms in the last episode" shows highest significance and the magnitude, which could be interpreted as people experienced severe symptoms (lasting for more than 30 days) in their last CFP episode are particularly cautious in consuming bluestripe herring this time.

I ran the logistic regressions by including the self-perceived attributes. In Table 5.6 (Model (4)), all variables except risk preference that shown statistical significance in the Pearson correlation analysis still demonstrated their significance in the model controlling for individual characteristics. The results show that higher risk perception increases the probability of food avoidance, controlling for the level of risk preference. On the other hand, if risk perception is controlled for, risk preference per se does not determine food avoidance behavior. In addition, attribute of taste affects food avoidance negatively, showing that if perceived tastier, people tend to consume even risky food.

Table 5. 6 Results of regression analysis for the association between avoidance of bluestripe herring and social-economic factors

	Dummy =1 if avoided bluestripe herring after the CFP outbreak											
	(1)			**(2)**			**(3)**			**(4)**		
Variables	**Coef.**	**ME**	**(Std. Err.)**	**Coef.**	**ME**	**(Std. Err.)**	**Coef.**	**ME**	**(Std. Err.)**	**Coef.**	**ME**	**(Std. Err.)**
Age	0.004	0.001	(0.006)	0.004	0.001	(0.006)	0.005	0.001	(0.006)	0.002	0.000	(0.006)
Sex	0.286	0.070	(0.198)	0.285	0.070	(0.197)	0.285	0.065	(0.196)	0.301	0.061	(0.119)
Fish poisoning experience	0.410**	0.101**	(0.181)									
Episodes of fish poisoning in lifetime				0.272***	0.067**	(0.115)						
Severe symptoms in the last episode							3.943***	0.901***	(0.992)	3.983***	0.807***	(0.936)
Distance to the center of CFP outbreak	0.001	0.000	(0.003)	0.001	0.000	(0.003)	0.001	0.000	(0.003)	-0.002	-0.000	(0.003)
Food Attributes												
Nutrition										0.059	0.012	(0.061)
Taste										-0.130***	-0.026***	(0.047)
Preciousness										-0.023	-0.005	(0.062)
Optimistic bias												
Village-level										0.156	0.032	(0.196)
External										-0.386**	-0.078**	(0.185)
Risk Preference										-0.087	-0.176	(0.071)
Risk Perception										0.357***	0.072***	(0.050)
Constant	-0.450		(0.380)	-0.431		(0.379)	-0.495		(0.371)	-0.738		(0.667)
N	575			575			575			575		
R-squared	0.0110			0.0111			0.0759			0.1567		

Note: Coef.,coefficient; ME, marginal effects; Std. Err., standard errors. Standard error adjusted for clustering of households for all models.
**** p<0.01, ** p<0.05, * p<0.1*

I further attempted to examine the effect of income and other risk-coping capacities on household-level consumption of risky species. Table 5.7 displays the summary statistics of all candidate variables. The heads of target households have an average age of 53 and 9.5 years of formal education. 13% of them are female. The average income per year is FJD$ 4166. Among 239 sample households, 66% have experienced fish poisoning for at least one of their household members.

Table 5.8 presents the Pearson coefficients for the degree of food aversion and explanatory variables. Female-headed households are more likely to practice safer diet by limiting the number of risky fish intake, which is consistent with the existing literature that women are more selective in consuming risky species to minimize risks for the fetuses and infants, as well as other minors in their family (McKerracher et al., 2016). Income diversity, food diversity ratio, and per-capita food expenditure are all positively related to aversion to risky food.

Table 5. 7 Summary Statistics of household-level analysis

Variable	Mean	Std. Dev.	Min	Max
Level of aversion to risky fish (1-5, 5 most averse)	2.58	1.24	1	5
Age of HH head (years)	52.88	13.70	25	82
Female headed HH (=1 if yes)	0.13	0.33	0	1
Education of HH head (years)	9.51	2.44	0	16
HH size (#)	4.00	1.87	1	11
Episodes of fish poisoning within HH (times)	1.31	1.39	0	8
Fish poisoning experience (=1 if yes)	0.66	0.47	0	1
Income diversity (1-7, 7 most diverse)	3.49	1.43	1	7
Total income (FJD$)	4166.23	1551.14	960	9100
Food diversity ratio (1-5, 5 most diverse)	2.70	1.03	1	5
Per capita expenditure on food (FJD$)	29.64	22.99	3.33	160
Cell phone ownership (=1 if yes)	0.42	0.49	0	1
N	239			

Table 5. 8 Pearson correlation coefficients for level of aversion to risky fish and explanatory variables

		1	2	3	4	5	6	7	8	9	10	11	12
1	Level of aversion to risky fish (1-5, 5 most averse)	-											
2	Age of HH head (years)	0.0588	-										
3	Female headed HH (=1 if yes)	0.314***	0.181***	-									
4	Education of HH head (years)	0.0676	-0.377***	-0.100	-								
5	HH size (#)	-0.0745	-0.152**	-0.115*	-0.0276	-							
6	Episodes of fish poisoning within HH (times)	0.144**	-0.0155	-0.132***	0.0804	0.195***	-						
7	Fish poisoning experience (=1 if yes)	0.0986	-0.0100	-0.0756	0.114*	0.118*	0.680***	-					
8	Income diversity (1-7, 7 most diverse)	0.125*	-0.0277	0.0901	-0.00509	-0.116*	-0.0318	0.00614	-				
9	Total income (FJD$)	0.0819	-0.0140	0.0581	0.0695	-0.0475	0.0489	0.0786	0.657***	-			
10	Food diversity ratio (1-5, 5 most diverse)	0.125*	-0.00603	0.170***	-0.0946	0.0131	0.0214	-0.0434	-0.0141	-0.0160	-		
11	Per capita expenditure on food (FJD$)	0.151**	0.0706	0.0433	0.107	-0.584***	0.0712	0.121*	0.128**	0.0636	-0.0682	-	
12	Cell phone ownership (=1 if yes)	0.00178	0.0557	0.0627	0.0799	0.0182	0.0161	0.0160	0.0928	0.0221	-0.0600	0.107*	-

Note: * *p < 0.1,* ** *p < 0.05,* *** *p < 0.01*

To assess the effect of risk-coping capacities to divert away from risky fish consumption, regression analysis is conducted by using the level of aversion to risky fish as dependent variable. Risk-coping capacitiy indicators including food diversity ratio and per-capita food expenditure were further retained in the multivariate models. Total annual income and income diversity were purposely put in separate models to prevent collinearity. Village fixed effects were used to control differences between villages. Results are shown in Table 5.9.

Table 5. 9 Results of regression analysis for the association between level of aversion to risky fish and household risk-coping capacities

Variables	**(1)**	**(2)**	**(3)**	**(4)**
Income diversity	0.094* (0.055)	0.100* (0.054)		
Total income			0.000 (0.000)	0.000 (0.000)
Food diversity ratio	0.163** (0.076)	0.093 (0.076)	0.164** (0.076)	0.094 (0.076)
Per capita expenditure on food	0.008** (0.003)	0.006* (0.003)	0.008** (0.003)	0.007* (0.003)
N	239	239	239	239
Other HH controls	No	Yes	No	Yes
R-squared	0.053	0.220	0.046	0.210

*Note: Standard errors in parentheses; Model (2) and (4) are controlled for age of HH head, female headed HH, years of education of HH head, and episodes of fish poisoning within HH. Village-fixed effects were applied. *** p<0.01, ** p<0.05, * p<0.1*

Of the risk-coping capacities, food diversity ratio and food expenditure are of significance in two unadjusted models respectively, meaning households with more diverse supply of and higher per-capita expense on food tend to consume less of risky fish. However, the statistical significance level both decreased after adjusted with household characteristics variables. Income diversity is also positively related to degree of food aversion and sustained to be significant in the adjusted model. Overall, the results revealed that households with higher risk-coping capacity are more inclined to practice safe consumption behavior.

5.6 Discussion

The beginning of this chapter has set four research questions. (1) what is the past and present status of CFP in these communities? (2) How CFP outbreaks have affected the health and food systems of indigenous communities? (3) What factors contribute to their consumption behavior under the risk of CFP? And (4) what can be done to enhance local food security to withstand the increasing risk of food shock? Though estimation bias could occur, CFP incidences in Gau have increased drastically over the past ten years. Besides acute to chronic clinical symptoms, the incidences also resulted in the temporal to permanent dietary change, including the increase consumption of imported processed foods. A number of factors were found to have been important for the consumption of risky species such as food and income diversity on household level, taste and risk perception on individual level. The following discussion will further elaborate the findings and shed light on what to do to achieve the last objective.

As discussed in the previous chapters, fish poisoning, predominantly ciguatera, is directly affected by seawater temperature and the stability of coral reef system. Climate change and its subsequent events are altering the usual pattern of marine toxin and thus leading to a greater risk of fish poisoning. With a heavy reliance on marine resource, the Pacific islanders, specifically those who reside on small island communities are particularly at risk. Many respondents during the interviews reflected that abrupt and unexpected fish poisonings in the past years, caused by species previously perceived safe. Therefore, it becomes particularly important for local islanders to minimize their risk and exposure to fish poisoning and improve preparedness for potential disastrous events.

Official warnings and notices to the islanders had been sent by government authorities as well as NGOs for multiple times before and after the outbreaks of fish poisoning (see Figure 5.3), but proved ineffective (Aguilar, 2017). Repetitive consumption of risky species is still common.

From the results of analyses, risk perception (including optimistic bias) showed significant positive correlations with the consumption of risky fish species. In contrary, risk preference, albeit slightly significant in terms of Pearson coefficient, became insignificant in the final model by controlling all other factors. Multiple reasons could explain the irrelevance between the food avoidance and risk preference. First, there might be a correlation between risk preference and sex dummy variable as female are more risk aversion and female (or female-headed households) are also more inclined to avoid risky fish, therefore the female dummy may be capturing most of the effects. Second, there might be lack of rigor during the risk preference elicitation experiment. For instant, the experiment was conducted in a hypothetical manner without actual payment. Certain subjects might fail to understand the procedure and did not give their innermost response. Another factor not to be neglected is, these money-based risk preference experiments tend to reflect financial risk-taking of the subjects but are not accurate for measuring risky behavior in other disciplines (Charness et al., 2013).

While it remains difficult to change one’s risk preference, risk perception could be transformed by the provision of information and education. There have been community-based intervention programs which successfully reduced perceived health risk while local perception and indigenous knowledge play an important role before and after the interventions (Tate et al., 2003). In this sense, launching educational programs on the risk of fish poisoning and significance of food safety practices could be of help to change their risk perception and foster healthy life behavior. Furthermore, the results of analysis revealed that people with experience of fish poisoning or severe clinical symptoms tend to consciously avoid risky fish. This could offer a glimpse on the evaluation of programs, which could be more targeted on potentially high-risk populations such as male adults, unaffected population, or those with mild symptoms during their previous poisonings, for a better dissemination and adoption rate.

Figure 5. 3 Poster for ciguatera prevention (left); Goods sold in two different stores in the village (right)

Meanwhile, my analysis in this chapter showed that a substantial number of CFP victims will need to consume canned food on an increasing frequency during the phase of post-poisoning; and households who developed a food aversion tend to have a higher expenditure on buying food products. The geographical and financial constraints of the islanders determine they have to occasionally rely on processed foods, because those are easy to ship and carry, and non-perishable. In fact, almost all food products sold in the community stores and private stores on the island are processed foods (Figure 5.3). It is worrying that increasing risk of fish poisoning may alter islanders' dietary pattern – to replace fish, the natural source of protein, with more imported and processed foods that are energy dense and nutrient poor – and subsequently increase their financial burden as well as risk of non-communicable diseases. It has been already confirmed that the increasing reliance on processed food among many Pacific communities has led to higher risk of diabetes, which is already of high prevalence in the Pacific (Lutz & Strobel, 2014).

Traditional Pacific diet consists of a wide range of root crops (cassava, taro, yam), coconuts, leafy greens, fruit, fish and other seafood (Dignan et al., 2004). In the last few decades, as a result of the country's policies on export promotion and import substitution, a number of non-traditional crops have been introduced to the indigenous communities in Fiji, including lettuce, cucumbers, rice, and cash crops such as sugar and cocoa (Snowdon & Thow, 2013). The proportion of meat and poultry also increased, with chicken being the main species reared (Diarra, 2017). In Gau island, although chicken and pigs are common livestock species, the small-scale "family poultry" pattern with minimal inputs has significantly limited the production level and hence the frequency of consumption. Chicken and pork are regarded as valuable commodities and only consumed in festive occasions. Rarely did the fish poisoning victims replace fish with chicken or pork during the phase of post-poisoning. On the other hand, fish may have become increasingly risky but for most islanders, given their heavy reliance on fishery resources, a complete avoidance of fish consumption is impossible and implausible. The fact that households with less consumption on risky fish have higher food diversity ratio gives important policy implications – projects and initiatives aiming for increasing the diversity of food or protein source may provide a way out of the life-threatening conundrum for the islanders to lower the risk and unpredictability of CFP outbreaks on the food system of the communities.

Based on the results of analyses, another important factor associated with the consumption of risky fish species is household income diversity. The logic behind this association could be explained by (1) households with more diverse income sources earn higher total income and depend less on self-harvested fisheries as sustenance, and/or (2) their extra income-generating activities are also food-related (e.g. opening their own grocery stores, selling crops, vegetable or livestock, etc.), which can in return provide them with simple and quick food source. Therefore, strengthening different types of livelihoods for local households could possibly offset the adverse food shocks brought by CFP. Previously, intervention programs with similar missions have already proved successful in many developing countries for enhancing household food security and disaster-coping resilience (Smith & Frankenberger, 2018).

In conclusion, this chapter explored the islanders' decision-making on risky fish species under threat conditions in small island communities. The regression analyses revealed the significant role of risk perception on aversion to risky fish after controlling for fish poisoning experience and other factors. It also indicated households with higher risk-coping capacity tend to avoid more risky fish species and practice safer consumption behavior. The results of this study could contribute to better understand the vulnerability of indigenous islanders' food systems, and develop more effective intervention programs on disease prevention and capacity building. More specific implications will be discussed in Chapter 6.

5.7 Limitations

My study has also limitations. Since the regression was run with the use of cross-sectional data, the results may not suggest a strong causality between the key variables and food aversion, but only showing suggestive correlations. Another limitation is the study assumed no major variance in the distribution of bluestripe herrings among the sample villages. Although I have learnt it is a common species all around the island, additional ecological data would help clarify its actual abundance across different villages. Future studies could be more multi-faceted and multi-disciplinary to close this gap.

6. SURVEILLANCE AND RESPONSE TO A CHANGING CLIMATE

The objectives of this thesis are to investigate how climate change affects CFP as a local disease in the Pacific and evaluate the impacts of health and food systems of indigenous communities and seek to explain their food consumption behavior under the risk of CFP.

Results of time series analysis reveal the significant time-lagged associations between the monthly CFP incidence rate and a series of indicators relating to SST. In particular, significant time intervals of 12 months for Cook Islands and 32 months for French Polynesia were found and used to develop the predictive models. SSTA was proved a strong positive predictor of an increased ciguatera incidence for both Cook Islands and French Polynesia.

My case study in Fiji found that CFP incidences resulted in the temporal to permanent dietary change, with an increased consumption of other food sources including imported processed foods. A number of factors were found to be associated with the consumption of risky species – on household level, food and income diversity are essential coping mechanism in the face of CFP risk; and on individual level, the role of risk perception and optimistic bias increase the probability of aversion to risky species.

Based on the findings of this thesis, in this chapter I will provide policy implications on what can be done to establish/improve the surveillance networks to solve the problems of under-reporting and misdiagnose; and to design and develop interventions with higher effectiveness and efficacy on food safety and health behavior to reduce the negative impacts of CFP for the small island communities.

6.1 Implications for Surveillance, Reporting and Response

The cross-correlation analysis and ARIMA modeling in Chapter 4 showed a lagged effect along the delivery and accumulation of the ciguatera-induced toxin. Based on the findings and the limitations of my research, these could provide forceful evidence to the development of decision support tools, which health officials and local communities could benefit by making use of the lagged effect of climate variables and taking proper actions in advance especially on high-risk scenarios (see Figure 6.1).

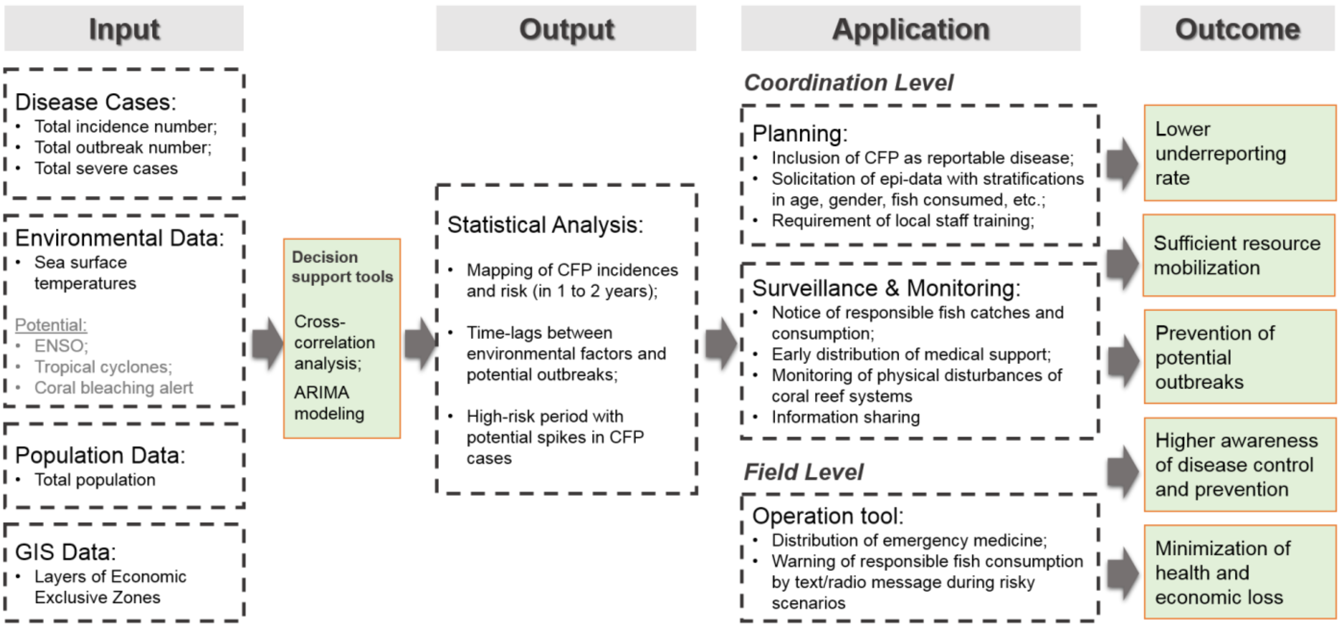


Figure 6. 1 Framework of decision support system for CFP control and prevention

Note: The framework is adapted from Wangdi et al. (2016).

For a more specific elaboration, the climate-based forecasting takes the forms of counts of CFP incidences or outbreaks. Open data repositories such as IRI/LDEO Climate

Data Library[4], NOAA Physical Sciences Laboratory[5], and other national meteorological agencies could provide all types of climatic data with high-resolution. It is also essential to obtain population data to control the effect of exogenous demographic change. The model forecasting could inform relevant units about the anticipated high-risk period with potential spikes in ciguatera events and the approximate time intervals for them to take appropriate actions, after certain environmental disturbances and extreme weather conditions. Such actions include regulating fishing industry and private catches, noticing the high-risk communities for responsible captures and consumption, and informing the local medical structures and other response systems to strengthen the medical capacity and remain connected for the potential CFP outbreaks.

The correlation between SSTA and CFP incidence is a cautionary warning that among all the possible mechanisms enabling climate factors to influence the abundance of ciguatera toxins, the physical conditions of coral reef systems may hold the most essential cause for the increases of CFP incidences and outbreaks. Since one of the main and direct consequences of climate change in the Pacific is the rising frequency and expanding area of coral bleaching and mortality, local residents in the Pacific become particularly in danger of ciguatera risk. In fact, according to "Coral Reef Watch Satellite Monitoring", a project launched by NOAA (2020), a significant part of EEZs of Cook Islands and French Polynesia are under "warning" or "alert level" in terms of the risk of coral bleaching. Scientists and researcher communities should pay close attention to the coral mortality and coral bleaching events in the adjacent areas. Efforts should be made under the collaboration between marine biologists, public health researchers as well as government authorities, facilitating the sharing of information and expertise.

[4] https://iridl.ldeo.columbia.edu/
[5] https://www.psl.noaa.gov/data/gridded/

Most importantly, it is crucial to implement long-term ciguatera surveillance programs, implicating not only health, fisheries, environment authorities but also meteorologists and social scientists, and encourage countries to communicate more about CFP epidemiology. Concerted efforts should be prompted to reduce the underreporting rate, particularly in remote islands, for a better monitoring and data analysis. For instance, for non-hospitalized patients, it is necessary to establish a reporting channel for them to report their fish poisoning experience by confirming the date, number of infections, suspect food source, and clinical presentations. Certain incentives could be provided for promoting the voluntary reporting of epidemics. In villages where health professionals with medical qualifications such as doctors and nurses are not presented, it is better to appoint and train locally-based health workers to document and report the epidemiology of CFP. Addition of CFP to the list of reportable diseases could also improve CFP surveillance, but above all, reinforce the information dissemination among healthcare workers and the general public, prevent at-risk consumption behaviors and minimize the potential health and economic loss.

In Chapter 5, I confirmed the changing dietary pattern after the CFP incidences and outbreaks. Such changes do not only apply to victims and their households, but also to individuals and households that were not directly affected. I also observed the importance of possible risk-coping capacities such as food and income diversity to households to withstand food shocks. As thoroughly discussed in Section 5.6, efforts to increase the diversity of food source and strengthen different types of livelihoods for local communities are beneficial not only to the wellbeing of indigenous households, but also their capability in times of disaster and crisis. Thus I recommend the vulnerable communities to engage in community-based capacity building for prevention and response to CFP.

As the risk perception plays an important role in risky consumption behavior, intervention programs aiming to change knowledge, attitudes and perception of fish poisoning could help to foster health behavior in indigenous communities. Also, as processed foods are being consumed more frequently in the Pacific, government authorities should consider implementing regulations on the nutrient content of processed food products and developing interventions on healthy dietary habits. In addition, similar to the recommendations based on Chapter 4, an early warning surveillance network and emergency response plan must be implemented in the high-risk regions in case of potential outbreaks.

6.2 Implications for Future Research and Collaboration

More investigations are necessary to confirm the time interval of bioaccumulation by utilizing various models, indicators, and datasets of different regions. These could contribute to the explanation and interpretation of differences of time intervals recorded in different regions and in different studies. More dynamic models can also improve the predictability while taking into account the social-economic factors such as evaluation and quantification of anthropogenic damages to the coral reef system.

In addition to the betterment of date reporting, a better segmentation of data and information could be also applied to the process of data collection. For example, to collect breakdown data such as differentiating CFP incidence and outbreak, victims with mild or severe symptoms, and to report a more specific location rather than to include them under the umbrella of an administrative unit.

Finally, I stress the importance of constructing coordinated regional surveillance networks to promote inter-governmental and inter-organizational partnerships. In fact, a multiplication of international initiatives has been undertaken in recent years, including the "EuroCigua" project (Spanish Agency for Food Safety and Nutrition (AECOSAN), 2015), the "Global Ciguatera Strategy 2015-2019" (Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), 2015), the "CiguaWatch" project (French Research Institute for Exploitation of the Sea (IFREMER), 2017), the FAO/WHO Ciguatera Experts Meeting (FAO, 2018), and the launch of the Ciguatera-Online website by the Louis Malardé Institute (2014). Such efforts could ultimately contribute to promote collaboration and information sharing between endemic and non-endemic countries, and raise public awareness worldwide, especially on suspected newly at-risk regions. Moreover, they will eventually lead to a better ciguatera risk management and improve studies aiming at the projection of global CFP incidences evolution in the context of climate change.

REFERENCES

Adjeroud, M. (1997). Long-term changes of epibenthic macrofauna communities in a closed lagoon (Taiaro Atoll, French Polynesia): 1972-1994. *Hydrobiologia*. https://doi.org/10.1023/A:1003052515305

Aguilar, M. (2017). 10 Hit by New Case of Fish Poisoning. Internet site: https://fijisun.com.fj/2017/01/25/10-hit-by-new-case-of-fish-poisoning/. (Accessed March, 2019)

Bagnis, R. (1968). Clinical aspects of ciguatera (fish poisoning) in French Polynesia. *Hawaii Medical Journal.* 28(1), 25.

Bagnis, R. (1994). Natural versus anthropogenic disturbances to coral reefs: comparison in epidemiological patterns of ciguatera. *Memoirs - Queensland Museum*.

Bagnis, R. Kuberski, T., & Laugier, S. (1979). Clinical observations on 3,009 cases of ciguatera (fish poisoning) in the South Pacific. *American Journal of Tropical Medicine and Hygiene*. https://doi.org/10.4269/ajtmh.1979.28.1067

Bagnis, R., Spiegel, A., Nguyen, L., & Plichart, R. (1992). Public health, epidemiological and socioeconomic patterns of ciguatera in Tahiti. In *Proceedings of the Third International Conference on Ciguatera Fish Poisoning* (Vol. 30, pp. 157-168). Polyscience Publications Quebec.

Barton, E. D., Tanner, P., Turchen, S. G., Tunget, C. L., Manoguerra, A., & Clark, R. F. (1995). Ciguatera fish poisoning: A Southern California epidemic. *Western Journal of Medicine*.

Bell, J.D., Johnson, J.E., Ganachaud, A.S., Gehrke, P.C., Hobday, A.J., Hoegh-Guldberg, O., Le Borgne, R., Lehodey, P., Lough J.M., Pickering, T., Pratchett, M.S. & Waycott, M. (2011) Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change: Summary for Pacific Island Countries and Territories. Secretariat of the Pacific Community, Noumea, New Caledonia.

Bienfang, P., DeFelice, S., & Dowling, A. (2011). Quantitative Evaluation of Commercially Available Test Kit for Ciguatera in Fish. *Food and Nutrition Sciences*, *02*(06), 594–598. https://doi.org/10.4236/fns.2011.26083

Bolanavanua, S. (2017). Suspected Fish Poisoning Story Will Always Be Remembered. Internet site: https://fijisun.com.fj/2017/01/09/suspected-fish-poisoning-story-will-always-be-remembered/. (Accessed March 2019)

Bolatiki, M., & Aguilar, M. (2017). 4 Dead, 9 Under Observation. Internet site: https://fijisun.com.fj/2017/01/06/4-dead-9-under-observation/. (Accessed March 2019)

Bomber, J. W., Guillard, R. R. L., & Nelson, W. G. (1988). Rôles of temperature, salinity, and light in seasonality, growth, and toxicity of ciguatera-causing

Gambierdiscus toxicus Adachi et Fukuyo (Dinophyceae). *Journal of Experimental Marine Biology and Ecology*. https://doi.org/10.1016/0022-0981(88)90189-X

Botana, L. M. (2008). *Seafood and freshwater toxins: Pharmacology, physiology, and detection, second edition*. *Seafood and Freshwater Toxins: Pharmacology, Physiology, and Detection, Second Edition*.

Boyd, R. (2017). *A different kind of animal: How culture transformed our species* (Vol. 46). Princeton University Press. Retrieved from http://www.ghbook.ir/index.php?name=های رسانه و فرهنگ نوین&option=com_dbook&task=readonline&book_id=13650&page=73&chkhashk=ED9C9491B4&Itemid=218&lang=fa&tmpl=component

Brug, J., & van Assema, P. (2001). Beliefs About Fat Why do we Hold Beliefs About Fat and why and how do we Study these Beliefs? In *Food, People and Society*. https://doi.org/10.1007/978-3-662-04601-2_4

Chadsuthi, S., Modchang, C., Lenbury, Y., Iamsirithaworn, S., & Triampo, W. (2012). Modeling seasonal leptospirosis transmission and its association with rainfall and temperature in Thailand using time-series and ARIMAX analyses. *Asian Pacific Journal of Tropical Medicine*, *5*(7), 539–546. https://doi.org/10.1016/S1995-7645(12)60095-9

Charness, G., Gneezy, U., & Imas, A. (2013). Experimental methods: Eliciting risk preferences. *Journal of Economic Behavior and Organization*. https://doi.org/10.1016/j.jebo.2012.12.023

Chateau-Degat, M. L., Chinain, M., Cerf, N., Gingras, S., Hubert, B., & Dewailly, É. (2005). Seawater temperature, Gambierdiscus spp. variability and incidence of ciguatera poisoning in French Polynesia. *Harmful Algae*, *4*(6), 1053–1062. https://doi.org/10.1016/j.hal.2005.03.003

Chateau-Degat, M. L., Dewailly, E., Cerf, N., Nguyen, N. L., Huin-Blondey, M. O., Hubert, B., Laudon, F., & Chansin, R. (2007). Temporal trends and epidemiological aspects of ciguatera in French Polynesia: A 10-year analysis. *Tropical Medicine and International Health*. https://doi.org/10.1111/j.1365-3156.2006.01798.x

Chinain, M., Gatti, C. M., Roué, M., & Darius, H. T. (2019). Ciguatera poisoning in French Polynesia: insights into the novel trends of an ancient disease. *New Microbes and New Infections*, *31*, 100565. https://doi.org/10.1016/j.nmni.2019.100565

Chinain, M., Germain, M., Deparis, X., Pauillac, S., & Legrand, A. M. (1999). Seasonal abundance and toxicity of the dinoflagellate Gambierdiscus spp. (Dinophyceae), the causative agent of ciguatera in Tahiti, French Polynesia. *Marine Biology*, *135*(2), 259–267. https://doi.org/10.1007/s002270050623

Chinain, Mireille, Darius, H. T., Gatti, C. M., & Roué, M. (2016). Update on ciguatera research in French Polynesia. *Fisheries Newsletter*, *150*, 42–51.
Chinain, Mireille, Darius, H. T., Ung, A., Fouc, M. T., Revel, T., Cruchet, P., Pauillac, S., & Laurent, D. (2010). Ciguatera risk management in French Polynesia: The case study of Raivavae Island (Australes Archipelago). *Toxicon*, *56*(5), 674–690. https://doi.org/10.1016/j.toxicon.2009.05.032
Cook Islands Ministry of Health, (2018). Health Statistics Bulletin. Internet site: https://www.health.gov.ck/resources/publications/health-statistics-bulletin/ (Accessed October 2019).
Copeland, N. K., Do, W. R. P., & Bienfang, P. K. (2014). Ciguatera Fish Poisoning in Hawai ‘ i and the Pacific, *73*(11), 24–27.
Dalzell, P. (1993). The South Pacific Commission’s database on ciguatera and other seafood poisoning. *Papua and New Guinea Medical Journal*.
Dannenberg, A. (2009). The dispersion and development of consumer preferences for genetically modified food - A meta-analysis. *Ecological Economics*. https://doi.org/10.1016/j.ecolecon.2009.03.008
de Fouw, J. C., van Egmond, H. P., & Speijers, G. J. A. (2001). Ciguatera fish poisoning: a review. *RIVM Report*.
Delgado, G., Lechuga-Devéze, C. H., Popowski, G., Troccoli, L., & Salinas, C. A. (2006). Epiphytic dinoflagellates associated with ciguatera in the northwestern coast of Cuba. *Revista de Biologia Tropical*, *54*(2), 299–310.
Diarra, S. S. (2017). Poultry industries in the South Pacific region: issues and future direction. *World's Poultry Science Journal*, 73(2), 293-300.
Diaz-Pulido, G., McCook, L. J., Dove, S., Berkelmans, R., Roff, G., Kline, D. I., Weeks, S., Evans, R. D., Williamson, D. H., & Hoegh-Guldberg, O. (2009). Doom and Boom on a Resilient Reef: Climate Change, Algal Overgrowth and Coral Recovery. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0005239
Dignan, C., Burlingame, B., Kumar, S., & Aalbersberg, W. (2004). *The Pacific Islands food composition tables*. Rome: Food and Agriculture Organization of the United Nations.
Dubinsky, Z., & Stambler, N. (2011). *Coral reefs: An ecosystem in transition*. *Coral Reefs: An Ecosystem in Transition*. https://doi.org/10.1007/978-94-007-0114-4
Eckel, C. C., & Grossman, P. J. (2008). Forecasting risk attitudes: An experimental study using actual and forecast gamble choices. *Journal of Economic Behavior and Organization*. https://doi.org/10.1016/j.jebo.2008.04.006
Egolf, A., Siegrist, M., & Hartmann, C. (2018). How people’s food disgust sensitivity shapes their eating and food behaviour. *Appetite*, *127*(April), 28–36. https://doi.org/10.1016/j.appet.2018.04.014

European Commission, 2015. CIGUALERT Report Summary. Internet site: <http://cordis.europa.eu/result/rcn/186388_en.html>. (Accessed March 2020)
Ferreira, B. P., Costa, M. B. S. F., Coxey, M. S., Gaspar, A. L. B., Veleda, D., & Araujo, M. (2013). The effects of sea surface temperature anomalies on oceanic coral reef systems in the southwestern tropical Atlantic. *Coral Reefs*. https://doi.org/10.1007/s00338-012-0992-y
Fessler, D. M. T., & Arguello, A. P. (2004). The relationship between susceptibility to nausea and vomiting and the possession of conditioned food aversions. *Appetite*, *43*(3), 331–334. https://doi.org/10.1016/j.appet.2004.10.001
Fiji Government, (2017). Fijian Minister for Health response on fish poisoning on Gau Island [Video File]. Retrieved from https://www.youtube.com/watch?v=JzpLsJlDZdI/.
Food and Agriculture Organization of the United Nations (FAO), (2004). Marine biotoxins. *FAO Food and Nutrition Paper 80*, 278. https://doi.org/10.1046/j.1365-2672.1998.0840s141S.x
Food and Agriculture Organization of the United Nations (FAO), (2018). Experts meet for deep dive on ciguatera fish poisoning. Internet site: http://www.fao.org/fao-who-codexalimentarius/news-and-events/news-details/en/c/1173604/ (Accessed November 2019).
Food and Agriculture Organization of the United Nations (FAO), (2019). FishStatJ - Software for Fishery and Aquaculture Statistical Time Series. Internet site: http://www.fao.org/fishery/statistics/software/fishstatj/en (Accessed November 2019).
French Research Institute for Exploitation of the Sea (IFREMER), 2017. Le programme de recherche CIGUAWATCH. Internet site: https://wwz.ifremer.fr/umr_eio/Vie-scientifique/Programmes/CIGUAWATCH (Accessed November 2019).
Friedman, M. A., Arena, P., Levin, B., Fleming, L., Fernandez, M., Weisman, R., Bernstein, J., Schrank, K., Blythe, D., Backer, L., & Reich, A. (2007). Neuropsychological study of ciguatera fish poisoning: A longitudinal case-control study. *Archives of Clinical Neuropsychology*. https://doi.org/10.1016/j.acn.2007.03.003
Friedman, M. A., Fernandez, M., Backer, L. C., Dickey, R. W., Bernstein, J., Schrank, K., Kibler, S., Stephan, W., Gribble, M. O., Bienfang, P., Bowen, R. E., Degrasse, S., Flores Quintana, H. A., Loeffler, C. R., Weisman, R., Blythe, D., Berdalet, E., Ayyar, R., Clarkson-Townsend, D., Swajian, K., Benner, R., Brewer, T. & Fleming, L. E. (2017). An Updated Review of Ciguatera Fish Poisoning: Clinical, Epidemiological, Environmental, and Public Health Management. *Marine Drugs*, 15(3), 72. https://doi.org/10.3390/md15030072

Friedman, M. A., Fleming, L. E., Fernandez, M., Bienfang, P., Schrank, K., Dickey, R., Bottein, M. Y., Backer, L., Ayyar, R., Weisman, R., Watkins, S., Granade, R., & Reich, A. (2008). Ciguatera fish poisoning: treatment, prevention and management. *Marine Drugs*, 6(3), 456–479. https://doi.org/10.3390/md20080022

Gaboriau, M., Ponton, D., Darius, H. T., & Chinain, M. (2014). Ciguatera fish toxicity in French Polynesia: Size does not always matter. *Toxicon*, *84*, 41–50. https://doi.org/10.1016/j.toxicon.2014.03.006

Gillett, R. (2016). Fisheries in the Economies of Pacific Island Countries and Territories. Pacific Community, New Caledonia.

Gillett, R., & Tauati, M. I. (2018). Fisheries of the Pacific Islands: Regional and national information. *FAO Fisheries and Aquaculture Technical Paper*.

Gingold, D. B., Strickland, M. J., & Hess, J. J. (2014). Ciguatera fish poisoning and climate change: Analysis of national poison center data in the United States, 2001-2011. *Environmental Health Perspectives*, *122*(6), 580–586. https://doi.org/10.1289/ehp.1307196

Glaziou, P., & Legrand, A. M. (1994). The epidemiology of ciguatera fish poisoning. *Toxicon*. https://doi.org/10.1016/0041-0101(94)90365-4

Goater, S., Derne, B., & Weinstein, P. (2011). Commentary Critical Issues in the Development of Health Information Systems in Supporting Environmental Health : A Case Study of Ciguatera, *119*(5), 585–590. https://doi.org/10.1289/ehp.1002575

Hajkowicz, S. (2006). Cost scenarios for coastal water pollution in a small island nation: A case study from the Cook Islands. *Coastal Management*. https://doi.org/10.1080/08920750600860233

Hales, S., Kovats, S., Woodward, A. (2000). What El Niño can tell us about human health and global climate change. Global Change and Human Health, 1(1), 66-77.

Hales, S., Weinstein, P., & Woodward, A. (1999). Ciguatera (Fish Poisoning), El Nino, and Pacific Sea Surface Temperatures. *Ecosystem Health*, *5*(1), 20–25. https://doi.org/10.1046/j.1526-0992.1999.09903.x

Hamlet, A., Jean, K., Perea, W., Yactayo, S., Biey, J., Van Kerkhove, M., Ferguson, N., & Garske, T. (2018). The seasonal influence of climate and environment on yellow fever transmission across Africa. *PLOS Neglected Tropical Diseases*, *12*(3), e0006284. https://doi.org/10.1371/journal.pntd.0006284

Henrich, J., & Henrich, N. (2010). The evolution of cultural adaptations: Fijian food taboos protect against dangerous marine toxins. *Proceedings of the Royal Society B: Biological Sciences*, *277*(1701), 3715–3724. https://doi.org/10.1098/rspb.2010.1191

Hokama, Y., Ebesu, J. S. M., Asuncion, D. A., & Nagai, H. (1996). *Growth and cyclic studies of Gambierdiscus toxicus in the natural environment and in culture*.

Harmful and Toxic Algal Blooms.
Inoue, M., Miyazaki, K., Uehara, H., Maruyama, M., & Hirama, M. (2004). First- and second-generation total synthesis of ciguatoxin CTX3C. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.0401684101
Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), (2015). IOC/IPHAB Global Ciguatera Strategy 2015-2019, for Adoption at the 12th Session of UNESCO-IOC's Intergovernmental Panel on Harmful Algal Blooms. Internet site: http://hab.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=15111 (Accessed November 2019).
Jeong, H. J., Lim, A. S., Jang, S. H., Yih, W. H., Kang, N. S., Lee, S. Y., Yoo, Y. D., & Kim, H. S. (2012). First report of the epiphytic dinoflagellate Gambierdiscus caribaeus in the temperate waters off Jeju Island, Korea: Morphology and molecular characterization. *Journal of Eukaryotic Microbiology*. https://doi.org/10.1111/j.1550-7408.2012.00645.x
Jing, Q. L., Cheng, Q., Marshall, J. M., Hu, W. B., Yang, Z. C., & Lu, J. H. (2018). Imported cases and minimum temperature drive dengue transmission in Guangzhou, China: evidence from ARIMAX model. *Epidemiology and Infection*, *146*(10), 1226–1235. https://doi.org/10.1017/S0950268818001176
Kaly, U., & Jones, G. (1994). Test of the effect of disturbance on ciguatera in Tuvalu. *Memoirs of the Queensland Museum. Brisbane*.
Kibler, Litaker, R. W., Vandersea, M. W., Holland, W. C., & Tester, P. A. (2013). *Effect of Light Intensity on Five Species of Gambierdiscus*. *Proceedings of the 14th International Conference on Harmful Algae.*
Kibler, S. R., Litaker, R. W., Holland, W. C., Vandersea, M. W., & Tester, P. A. (2012). Growth of eight Gambierdiscus (Dinophyceae) species: Effects of temperature, salinity and irradiance. *Harmful Algae*, *19*, 1–14. https://doi.org/10.1016/j.hal.2012.04.007
Kibler, S. R., Tester, P. A., Kunkel, K. E., Moore, S. K., & Litaker, R. W. (2015). Effects of ocean warming on growth and distribution of dinoflagellates associated with ciguatera fish poisoning in the Caribbean. *Ecological Modelling*, *316*, 194–210. https://doi.org/10.1016/j.ecolmodel.2015.08.020
Kim, S. K. (2015). *Springer handbook of Marine biotechnology*. *Springer Handbook of Marine Biotechnology*. https://doi.org/10.1007/978-3-642-53971-8
Kiple, K. F., & Ornelas, K. C. (2001). The Cambridge World History of Food. *Food Service Technology*. https://doi.org/10.1046/j.1471-5740.2001.00006.x
Knox, B. (2000). Consumer perception and understanding of risk from food. *British Medical Bulletin*, *56*(1), 97–109. https://doi.org/10.1258/0007142001903003

Kohler, S. T., & Kohler, C. C. (1992). Dead bleached coral provides new surfaces for dinoflagellates implicated in ciguatera fish poisonings. *Environmental Biology of Fishes*. https://doi.org/10.1007/BF00004993

Kumar-Roiné, S., Taiana Darius, H., Matsui, M., Fabre, N., Haddad, M., Chinain, M., Pauillac, S., & Laurent, D. (2011). A review of traditional remedies of ciguatera fish poisoning in the pacific. *Phytotherapy Research*, *25*(7), 947–958. https://doi.org/10.1002/ptr.3396

Lagerkvist, C. J., & Hess, S. (2011). A meta-analysis of consumer willingness to pay for farm animal welfare. *European Review of Agricultural Economics*. https://doi.org/10.1093/erae/jbq043

Laurent, D., Bourdy, G., Amade, P., Cabalion, P., & Bourret, D. (1993). La gratte ou ciguatera : ses remèdes traditionnels dans le Pacifique Sud. *SANTE PUBLIQUE*.

Lehane, L. (2000). Ciguatera update. *Medical Journal of Australia*. https://doi.org/10.5694/j.1326-5377.2000.tb125546.x

Lewis, N. (1983). Ciguatera - Implications for Nutrition and Marine Resource Development in the Pacific Islands. *Journal de La Société Des Océanistes*, *39*(77), 89–104. https://doi.org/10.3406/jso.1983.2791

Lewis, N. (1986). Epidemiology and impact of ciguatera in the Pacific : a review. *Marine Fisheries Review*.

Lewis, R. J. (1992). Socioeconomic impacts and management ciguatera in the Pacific. *Bulletin de La Société de Pathologie Exotique (1990)*.

Lewis, R. J. (2000). Ciguatera Management. *SPC Live Reef Fish Information Bulletin*, (7), 11–13.

Lewis, R. J. (2001). The changing face of ciguatera. *Toxicon*. https://doi.org/10.1016/S0041-0101(00)00161-6

Litaker, R. W., Vandersea, M. W., Faust, M. A., Kibler, S. R., Nau, A. W., Holland, W. C., Chinain, M., Holmes M. J., & Tester, P. A. (2010). Global distribution of ciguatera causing dinoflagellates in the genus Gambierdiscus. *Toxicon*, *56*(5), 711–730. https://doi.org/10.1016/j.toxicon.2010.05.017

Llewellyn, L. E. (2010). 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. *Toxicon*, *56*(5), 691–697. https://doi.org/10.1016/j.toxicon.2009.08.011

Lluch-Cota, S. E., Salvadeo, C., Lluch-Cota, D. B., Saldívar-Lucio, R., & Díaz, G. P. (2017). Impacts of Climate Change on Mexican Pacific Fisheries. In *Climate Change Impacts on Fisheries and Aquaculture*. https://doi.org/10.1002/9781119154051.ch9

Louis Malardé Institute, 2014. Ciguatera Fish Poisoning (CFP). Internet site:

https://www.ciguatera.pf/index.php/en/nos-services/en-quelques-mots (Accessed November 2019).

Lusk, J. L., & Coble, K. H. (2005). Risk perceptions, risk preference, and acceptance of risky food. *American Journal of Agricultural Economics*. https://doi.org/10.1111/j.1467-8276.2005.00730.x

Lutz, B., & Strobel, F. (2014). Trade as a structural driver of dietary risk factors for noncommunicable diseases in the Pacific: an analysis of household income and expenditure survey data. *Globalization and Health*. https://doi.org/10.1186/1744-8603-10-48

McKerracher, L., Collard, M., & Henrich, J. (2016). Food Aversions and Cravings during Pregnancy on Yasawa Island, Fiji. *Human Nature*, *27*(3), 296–315. https://doi.org/10.1007/s12110-016-9262-y

Morin, E., Gatti, C., Bambridge, T., & Chinain, M. (2016). Ciguatera fish poisoning: Incidence, health costs and risk perception on Moorea Island (Society archipelago, French Polynesia). *Harmful Algae*, *60*, 1–10. https://doi.org/10.1016/j.hal.2016.10.003

Morris, P. D., Campbell, D. S., & Freeman, J. I. (1990). Ciguatera fish poisoning: An outbreak associated with fish caught from north carolina coastal waters. *Southern Medical Journal*. https://doi.org/10.1097/00007611-199004000-00005

Morrison, K., Aguiar Prieto, P., Castro Domínguez, A., Waltner-Toews, D., & Fitzgibbon, J. (2008). Ciguatera fish poisoning in la Habana, Cuba: A study of local social-ecological resilience. *EcoHealth*, *5*(3), 346–359. https://doi.org/10.1007/s10393-008-0188-7

Morton, S. L., Norris, D. R., & Bomber, J. W. (1992). Effect of temperature, salinity and light intensity on the growth and seasonality of toxic dinoflagellates associated with ciguatera. *Journal of Experimental Marine Biology and Ecology*, *157*(1), 79–90. https://doi.org/10.1016/0022-0981(92)90076-M

Nakahara, H., Sakami, T., Chinain, M., & Ishida, Y. (1996). The role of macroalgae in epiphytism of the toxic dinoflagellate Gambierdiscus toxicus (Dinophyceae). *Phycological Research*. https://doi.org/10.1111/j.1440-1835.1996.tb00385.x

National Oceanic and Atmospheric Administration (NOAA), (2019). NOAA Optimum Interpolation (OI) Sea Surface Temperature (SST) V2. Internet site: https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html (Assessed June 2019).

National Oceanic and Atmospheric Administration (NOAA), (2020). Coral Reef Watch Satellite Monitoring and Modeled Outlooks. Internet site: https://coralreefwatch.noaa.gov/satellite/index.php. (Accessed March 2020)

Parsons, M. L., & Preskitt, L. B. (2007). A survey of epiphytic dinoflagellates from the coastal waters of the island of Hawai'i. *Harmful Algae*, *6*(5), 658–669. https://doi.org/10.1016/j.hal.2007.01.001

Parsons, M. L., Settlemier, C. J., & Ballauer, J. M. (2011). An examination of the epiphytic nature of Gambierdiscus toxicus, a dinoflagellate involved in ciguatera fish poisoning. *Harmful Algae*. https://doi.org/10.1016/j.hal.2011.04.011

Parsons, M. L., Settlemier, C. J., & Bienfang, P. K. (2010). A simple model capable of simulating the population dynamics of Gambierdiscus, the benthic dinoflagellate responsible for ciguatera fish poisoning. *Harmful Algae*, *10*(1), 71–80. https://doi.org/10.1016/j.hal.2010.07.002

Petrolia, D. R. (2016). Risk preferences, risk perceptions, and risky food. *Food Policy*. https://doi.org/10.1016/j.foodpol.2016.09.006

Pérez-Arellano, J. L., Luzardo, O. P., Brito, A. P., Cabrera, M. H., Zumbado, M., Carranza, C., Angel-Moreno, A., Dickey, R. W., & Boada, L. D. (2005). Ciguatera fish poisoning, Canary Islands [8]. *Emerging Infectious Diseases*. https://doi.org/10.3201/eid1112.050393

Radke, E. G., Grattan, L. M., Cook, R. L., Smith, T. B., Anderson, D. M., & Morris, J. G. (2013). Ciguatera incidence in the US Virgin Islands has not increased over a 30-year time period despite rising seawater temperatures. *American Journal of Tropical Medicine and Hygiene*, *88*(5), 908–913. https://doi.org/10.4269/ajtmh.12-0676

Rajeish, M., Shekar, M., Madhushree, H. N., & Venugopal, M. N. (2016). Presumptive case of ciguatera fish poisoning in Mangalore, India. *Current Science*. https://doi.org/10.18520/cs/v111/i9/1543-1547

Richlen, M. L., Parsons, M. L., & Anderson, D. M. (2012). Ecology and Impacts of Ciguatera on Coral Reef Ecosystems. *Advances in Environmental Research. Volume 26*, (January 2012), 41–75.

Rongo, T., & van Woesik, R. (2011). Ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae*, *10*(4), 345–355. https://doi.org/10.1016/j.hal.2010.11.005

Rongo, T., & van Woesik, R. (2012). Socioeconomic consequences of ciguatera poisoning in Rarotonga, southern Cook Islands. *Harmful Algae*, *20*, 92–100. https://doi.org/10.1016/j.hal.2012.08.003

Rongo, T., Bush, M., & Van Woesik, R. (2009). Did ciguatera prompt the late Holocene Polynesian voyages of discovery? *Journal of Biogeography, 36*(8), 1423–1432. https://doi.org/10.1111/j.1365-2699.2009.02139.x

Ruff, T. A. (1989). CIGUATERA IN THE PACIFIC: A LINK WITH MILITARY ACTIVITIES. *The Lancet*. https://doi.org/10.1016/S0140-6736(89)91212-9

Schnorf, H., Taurarii, M., & Cundy, T. (2002). Ciguatera fish poisoning: A double-blind randomized trial of mannitol therapy. *Neurology*.

https://doi.org/10.1212/WNL.58.6.873
Sharkov, E. A., & Sharkov, E. A. (2012). Regional tropical cyclogenesis. In *GLOBAL TROPICAL CYCLOGENESIS*. https://doi.org/10.1007/978-3-642-13296-4_3
Shepherd, R. (1999). Social determinants of food choice. In *Proceedings of the Nutrition Society*. https://doi.org/10.1017/S0029665199001093
Shumway, R. H., & Stoffer, D. S. (2016). Time series analysis and its applications With R Examples EZ Edition. *Springer Texts in Statistics EZ Edition*.
Skinner, M. P., Brewer, T. D., Johnstone, R., Fleming, L. E., & Lewis, R. J. (2011). Ciguatera fish poisoning in the pacific islands (1998 to 2008). *PLoS Neglected Tropical Diseases*, *5*(12), 1–7. https://doi.org/10.1371/journal.pntd.0001416
Smith, L. C., & Frankenberger, T. R. (2018). Does Resilience Capacity Reduce the Negative Impact of Shocks on Household Food Security? Evidence from the 2014 Floods in Northern Bangladesh. *World Development*, *102*, 358–376. https://doi.org/10.1016/j.worlddev.2017.07.003
Snowdon, W., & Thow, A. M. (2013). Trade policy and obesity prevention: challenges and innovation in the P acific I slands. Obesity reviews, 14, 150-158. https://doi.org/10.1111/obr.12090
Solomona, M. D., Tuatai, T., Vuki, V., & Metusela, K. (2009). Decadal changes in subsistence fishing and seafood consumption patterns on Rarotonga, Cook Islands. *SPC Women in Fisheries Information Bulletin*, *19*. Retrieved from http://earth.google.com
Spanish Agency for Food Safety and Nutrition (AECOSAN), (2015). FRAMEWORK PARTNERSHIP AGREEMENT GP/EFSA/AFSCO/2015/03 “Risk characterization of ciguatera food poisoning in Europe”. Internet site: http://www.aecosan.msssi.gob.es/AECOSAN/web/ciguatera/seccion/the_project.htm (Accessed November 2019).
Sully, S., Burkepile, D. E., Donovan, M. K., Hodgson, G., & van Woesik, R. (2019). A global analysis of coral bleaching over the past two decades. *Nature Communications*. https://doi.org/10.1038/s41467-019-09238-2
Tate, R. B., Fernandez, N., Yassi, A., Canizares, M., Spiegel, J., & Bonet, M. (2003). Change in health risk perception following community intervention in Central Havana, Cuba. *Health Promotion International*. https://doi.org/10.1093/heapro/dag401
Tester, P. A., Feldman, R. L., Nau, A. W., Kibler, S. R., & Wayne Litaker, R. (2010). Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. *Toxicon*, *56*(5), 698–710. https://doi.org/10.1016/j.toxicon.2010.02.026
Thompson, C. A., Jazuli, F., Taggart, L. R., & Boggild, A. K. (2017). Ciguatera fish

poisoning after Caribbean travel. *CMAJ*. https://doi.org/10.1503/cmaj.151207
Turquer, J., Quod, J.-P., Ten-Hage, L., Dahalanr, Y., & Wendling, B. (2001). *Example of a Gambierdiscus toxicus flare-up following the 1998 coral bleaching event in Mayotte Island (Comoros, south-west Indian ocean). Harmful Algal Blooms 2000.*
United Nations Development Program, (2009). Cook Islands Country Presentation PACC. Retrieved February 29, 2020, from https://www.adaptation-undp.org/sites/default/files/downloads/pacc_cook_islands_inception_meeting_presentation_-_july_2009.pdf
United Nations, (2019). World Population Prospects 2019. Internet site: https://population.un.org/wpp/ (Accessed October 2019).
Vandersea, M. W., Kibler, S. R., Tester, P. A., Holderied, K., Hondolero, D. E., Powell, K., Baird, S., Doroff, A., Dugan, D., & Litaker, R. W. (2018). Environmental factors influencing the distribution and abundance of Alexandrium catenella in Kachemak bay and lower cook inlet, Alaska. *Harmful Algae*. https://doi.org/10.1016/j.hal.2018.06.008
Wangdi, K., Banwell, C., Gatton, M. L., Kelly, G. C., Namgay, R., & Clements, A. C. (2016). Development and evaluation of a spatial decision support system for malaria elimination in Bhutan. *Malaria Journal*, *15*(1), 180. https://doi.org/10.1186/s12936-016-1235-4
Wangdi, K., Singhasivanon, P., Silawan, T., Lawpoolsri, S., White, N. J., & Kaewkungwal, J. (2010). Development of temporal modelling for forecasting and prediction of malaria infections using time-series and ARIMAX analyses: A case study in endemic districts of Bhutan. *Malaria Journal*, *9*(1), 1–9. https://doi.org/10.1186/1475-2875-9-251
Wong, Y. C., & Lewis, R. J. (2017). *Analysis of Food Toxins and Toxicants*. *Analysis of Food Toxins and Toxicants*. https://doi.org/10.1002/9781118992685
World Wide Fund for Nature (WWF), (2011). Sawaieke- Gau Island-Fiji. Internet site: http://d2ouvy59p0dg6k.cloudfront.net/downloads/gau_email_1.pdf. (Accessed June 2019).
Xu, Y., Richlen, M. L., Liefer, J. D., Robertson, A., Kulis, D., Smith, T. B., Parsons, M. L., & Anderson, D. M. (2016). Influence of Environmental Variables on Gambierdiscus spp. (Dinophyceae) Growth and Distribution. *PLoS ONE*. 11(4), e1053197. https://doi.org/10.1371/journal.pone.0153197
Yeeting, B. (2009). Ciguatera-like fish poisoning from giant clams on Emao Island, Vanuatu. . *SPC Fisheries Newsletter*, *129*(August), 13–16.

APPENDICES

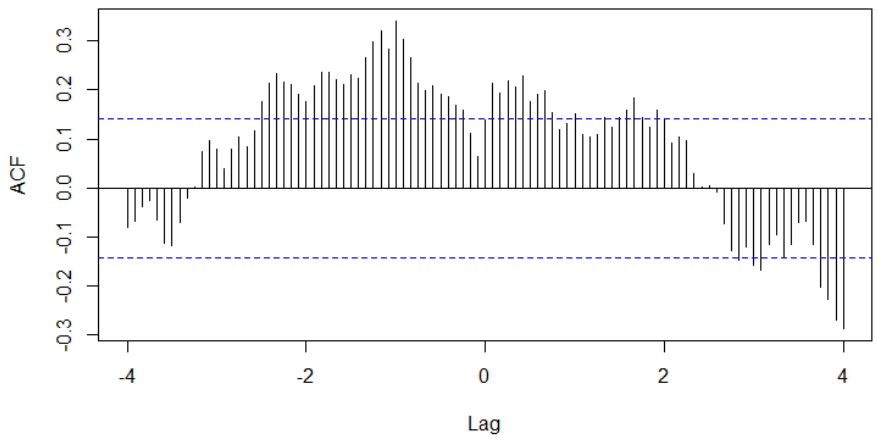


Figure 1A. CCF plot between SSTA and CFP incidence rate in Cook Islands

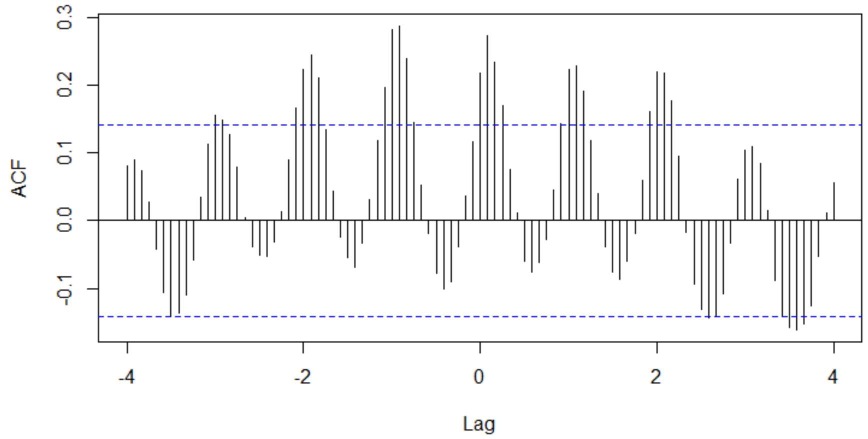


Figure 1B. CCF plot between SST_{mean} and CFP incidence rate in Cook Islands

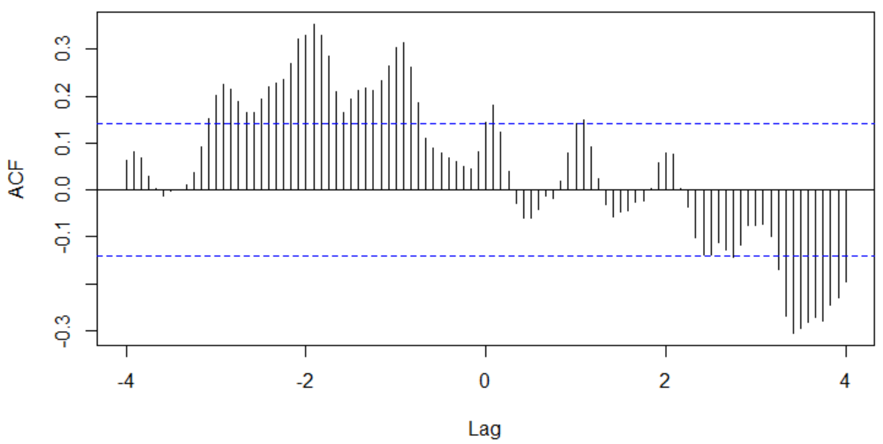


Figure 1C. CCF plot between SST_{max} and CFP incidence rate in Cook Islands

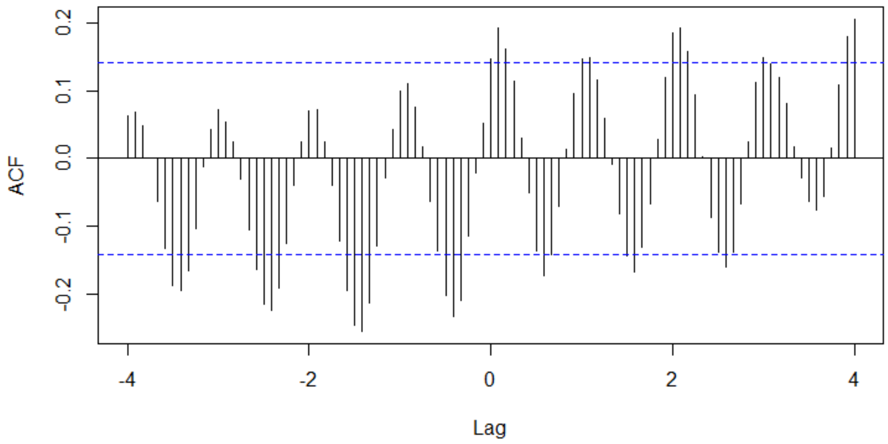


Figure 1D. CCF plot between SST_{min} and CFP incidence rate in Cook Islands

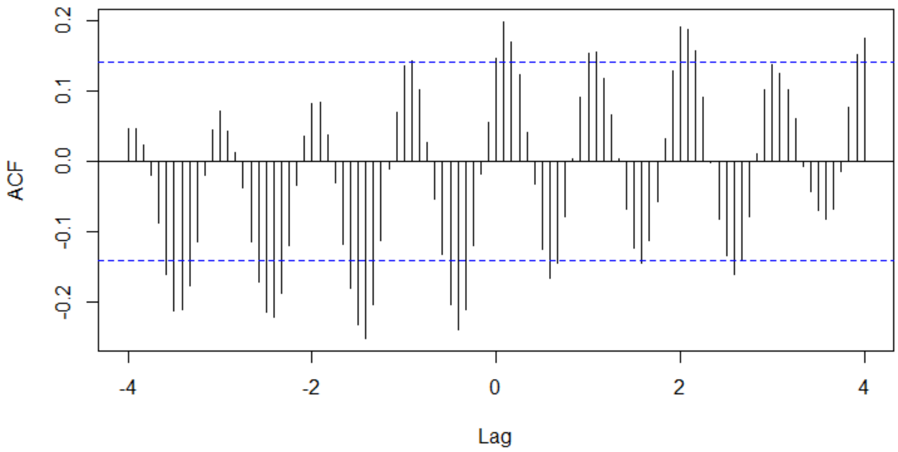


Figure 1E. CCF plot between $SSTTC_{mean}$ and CFP incidence rate in Cook Islands

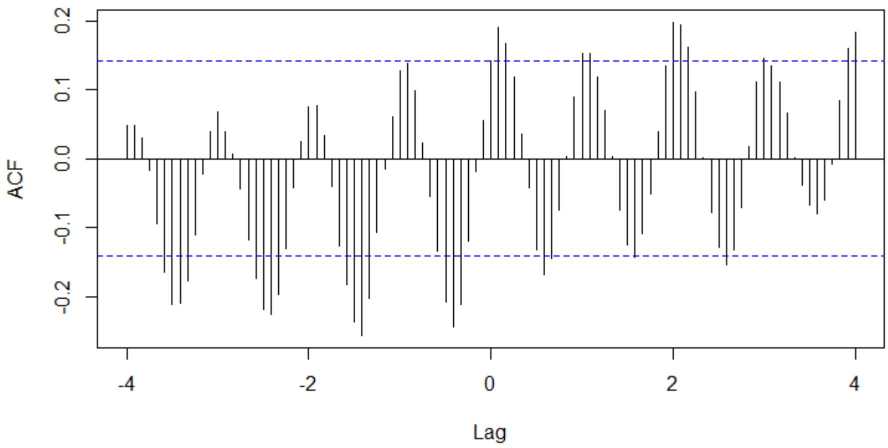


Figure 1F. CCF plot between $SSTTC_{max}$ and CFP incidence rate in Cook Islands

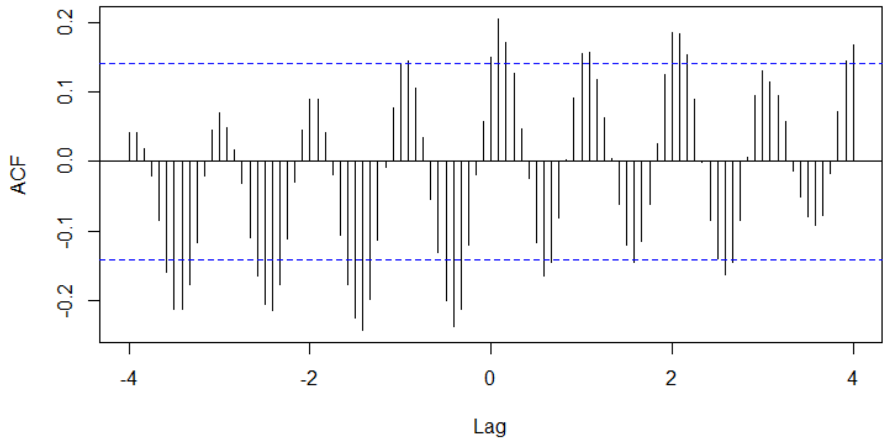


Figure 1G. CCF plot between $SSTTC_{min}$ and CFP incidence rate in Cook Islands

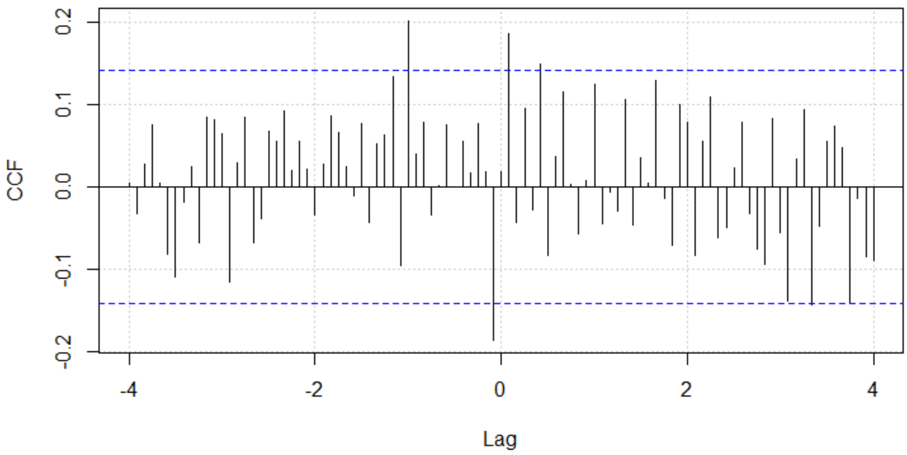


Figure 1H. CCF plot between prewhitened SSTA and filtered CFP incidence rate in Cook Islands

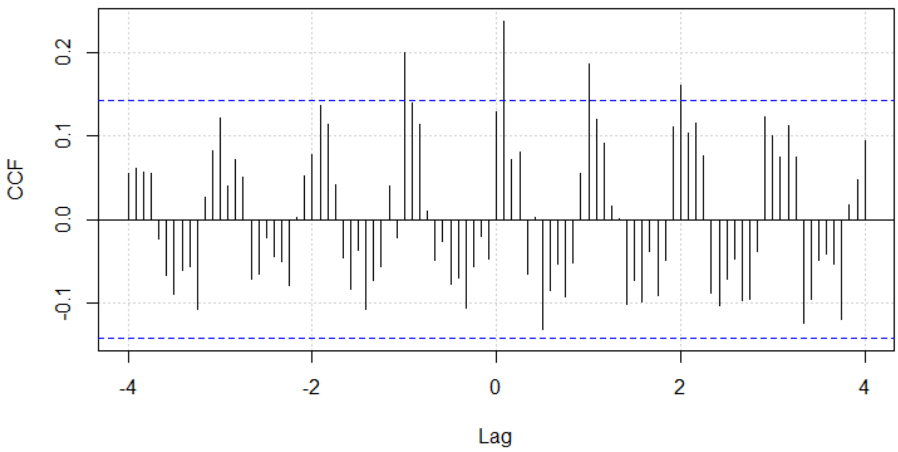


Figure 1I. CCF plot between prewhitened SST_{mean} and filtered CFP incidence rate in Cook Islands

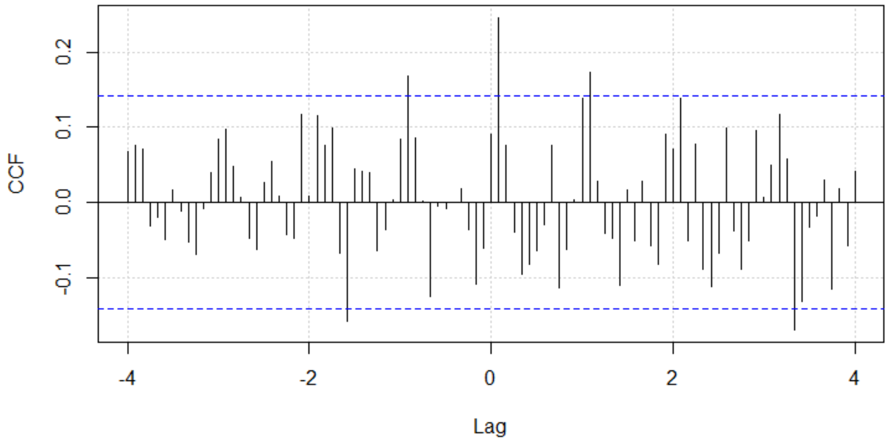


Figure 1J. CCF plot between prewhitened SST_{max} and filtered CFP incidence rate in Cook Islands

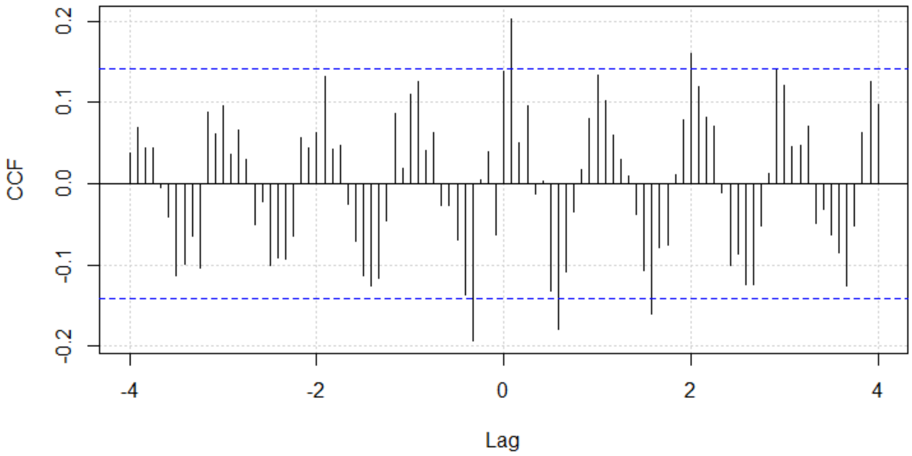


Figure 1K. CCF plot between prewhitened SST_{min} and filtered CFP incidence rate in Cook Islands

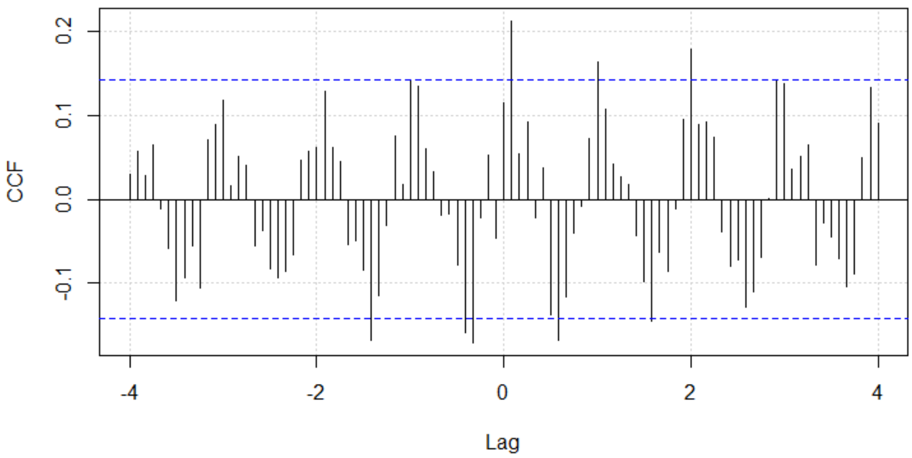


Figure 1L. CCF plot between prewhitened $SSTTC_{mean}$ and filtered CFP incidence rate in Cook Islands

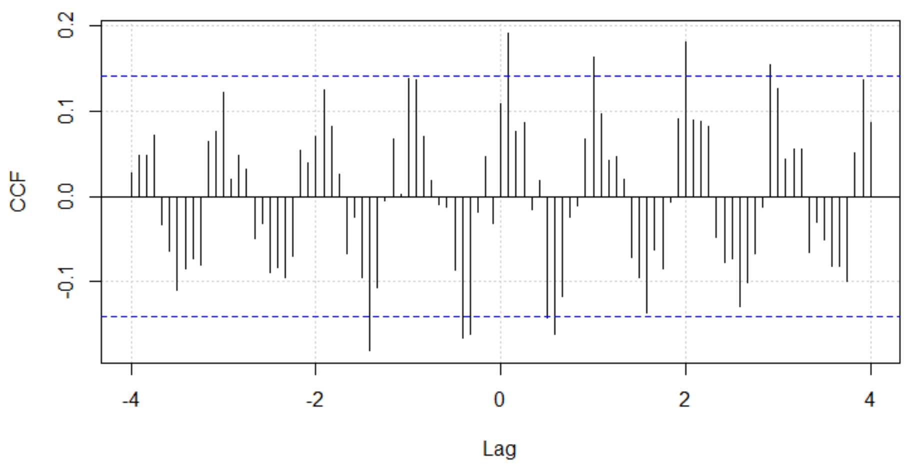


Figure 1M. CCF plot between prewhitened SSTTC$_{max}$ and filtered CFP incidence rate in Cook Islands

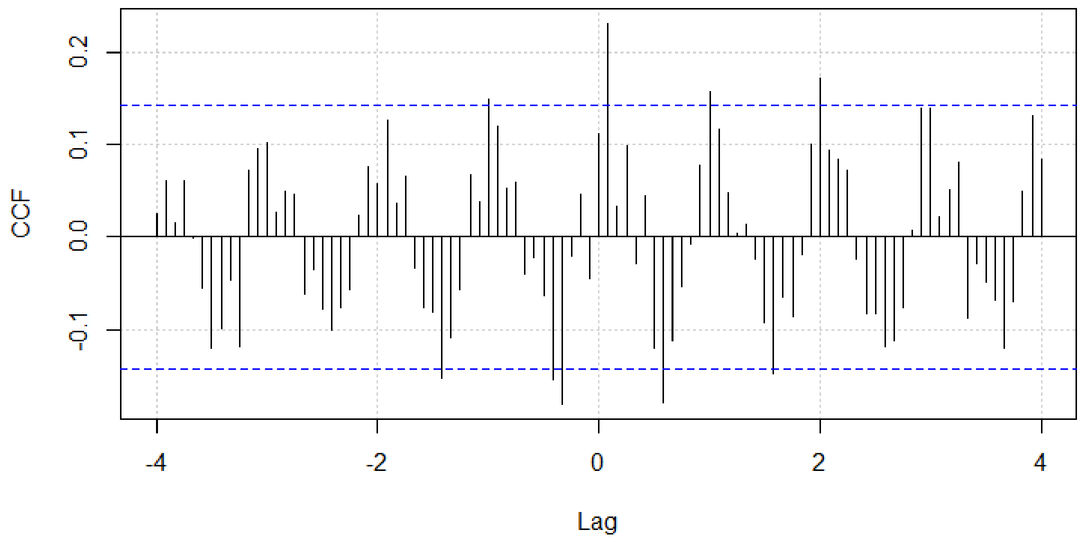


Figure 1N. CCF plot between prewhitened SSTTC$_{min}$ and filtered CFP incidence rate in Cook Islands

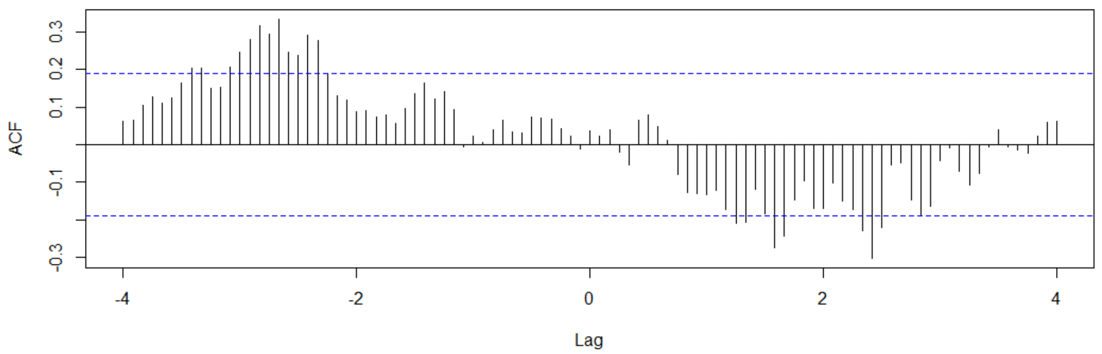


Figure 2A. CCF plot between SSTA and CFP incidence rate in French Polynesia

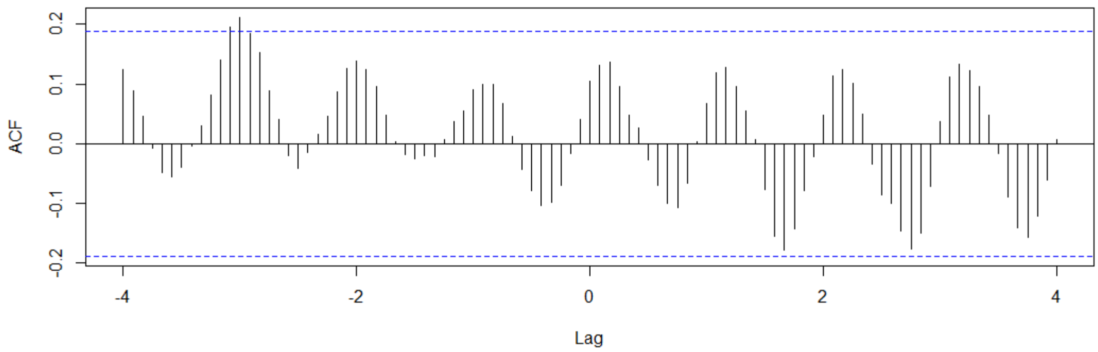


Figure 2B. CCF plot between SST_{mean} and CFP incidence rate in French Polynesia

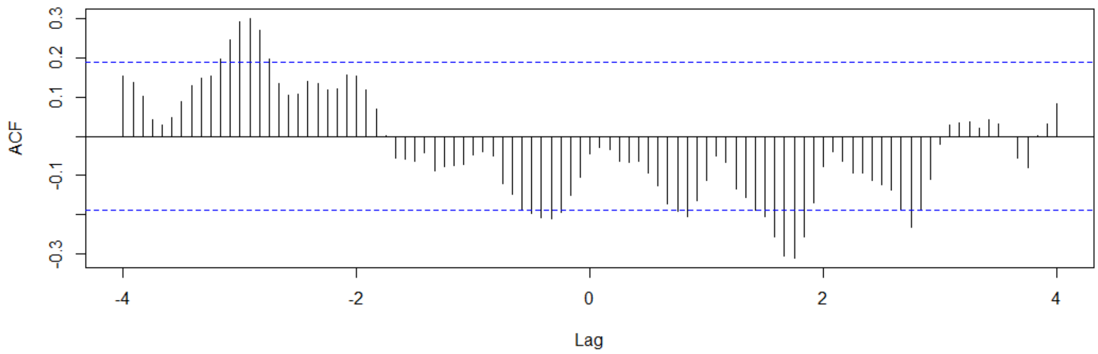


Figure 2C. CCF plot between SST_{max} and CFP incidence rate in French Polynesia

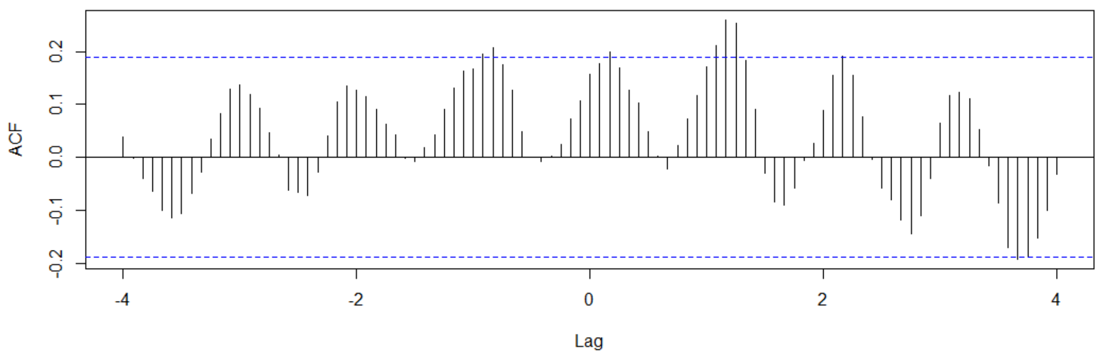


Figure 2D. CCF plot between SST_{min} and CFP incidence rate in French Polynesia

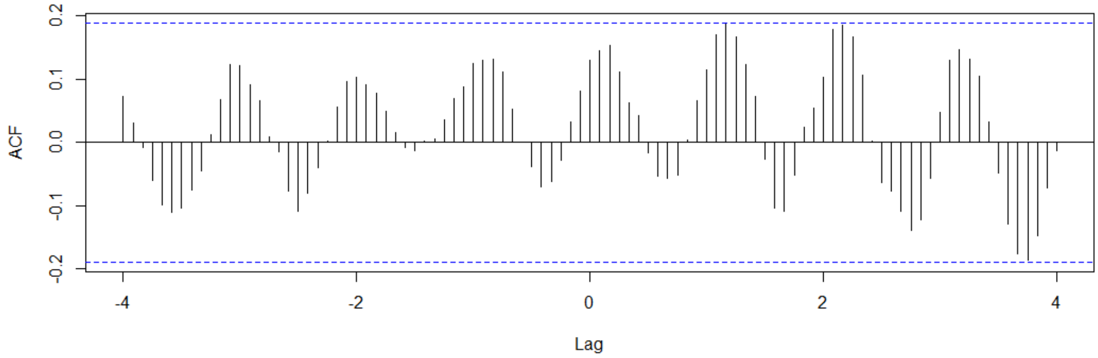


Figure 2E. CCF plot between SSTTC$_{mean}$ and CFP incidence rate in French Polynesia

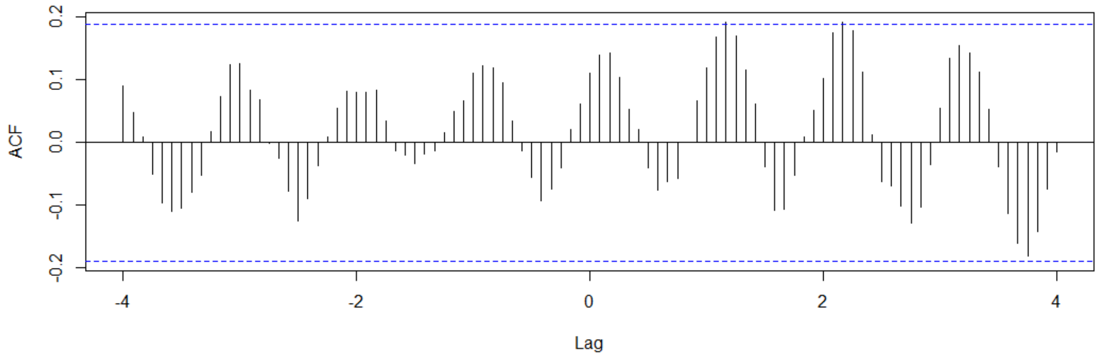


Figure 2F. CCF plot between SSTTC$_{max}$ and CFP incidence rate in French Polynesia

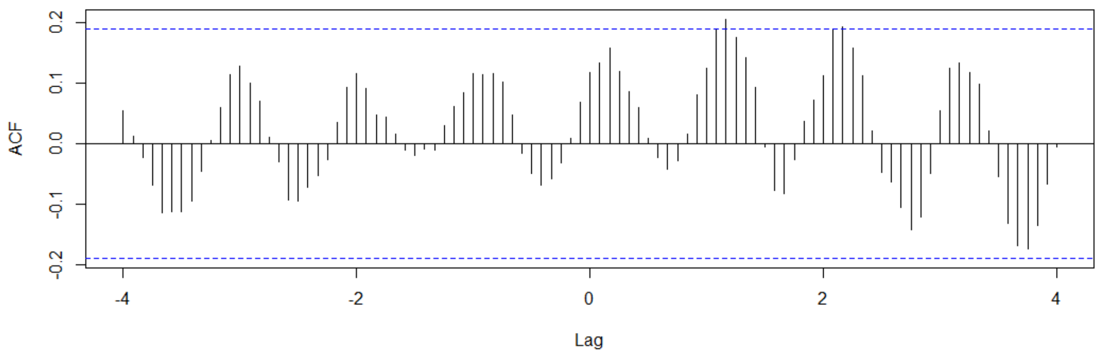


Figure 2G. CCF plot between SSTTC$_{min}$ and CFP incidence rate in French Polynesia

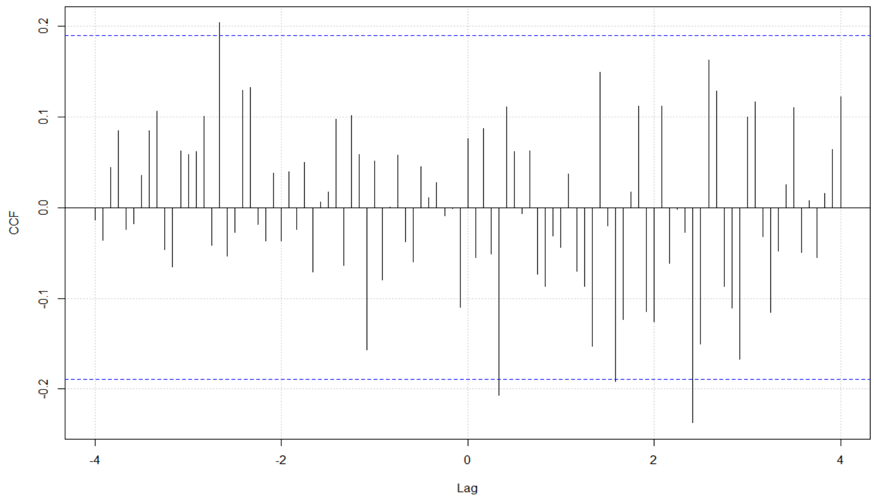


Figure 2H. CCF plot between prewhitened SSTA and filtered CFP incidence rate in French Polynesia

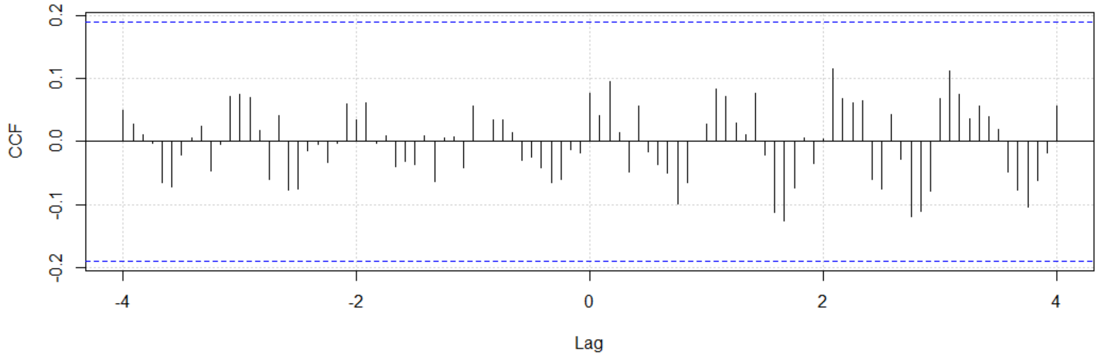


Figure 2I. CCF plot between prewhitened SST_{mean} and filtered CFP incidence rate in French Polynesia

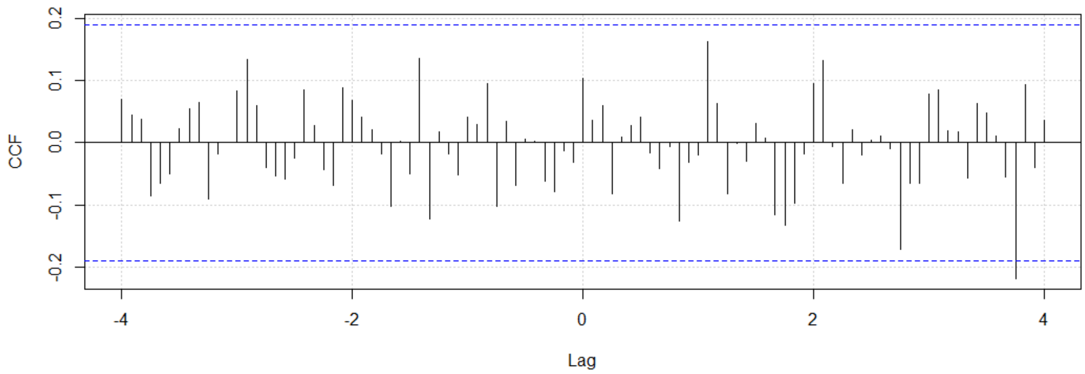


Figure 2J. CCF plot between prewhitened SST_{max} and filtered CFP incidence rate in French Polynesia

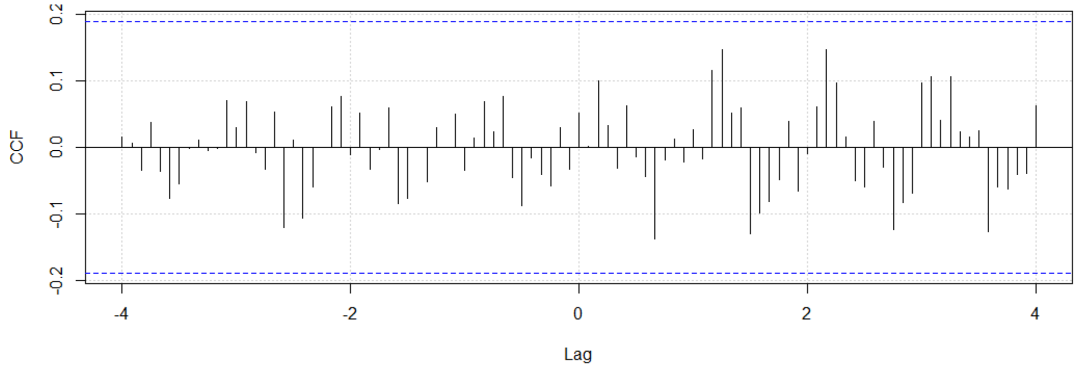


Figure 2K. CCF plot between prewhitened SST_{min} and filtered CFP incidence rate in French Polynesia

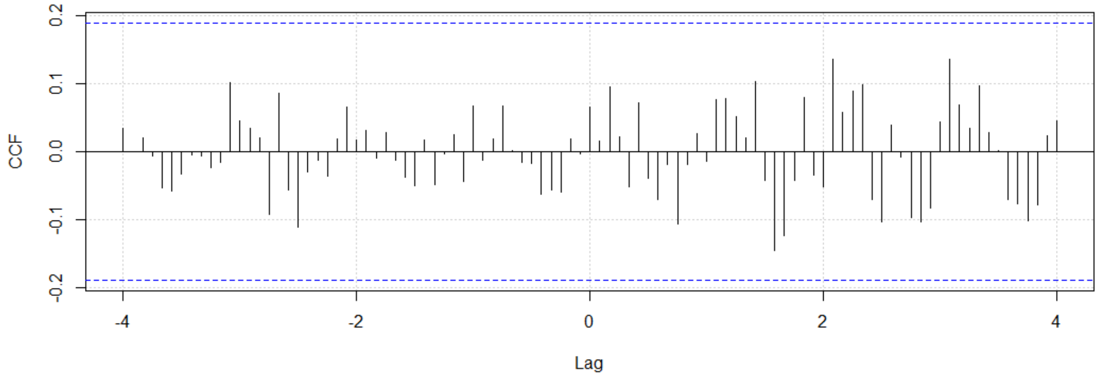


Figure 2L. CCF plot between prewhitened $SSTTC_{mean}$ and filtered CFP incidence rate in French Polynesia

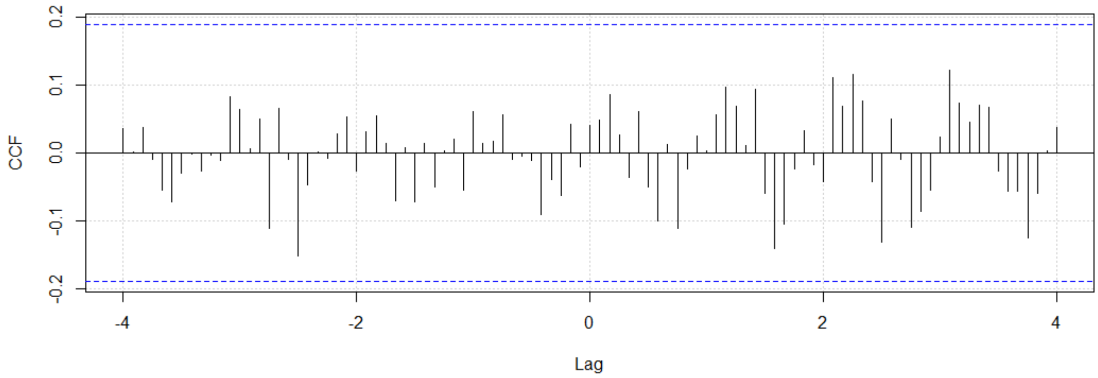


Figure 2M. CCF plot between prewhitened $SSTTC_{max}$ and filtered CFP incidence rate in French Polynesia

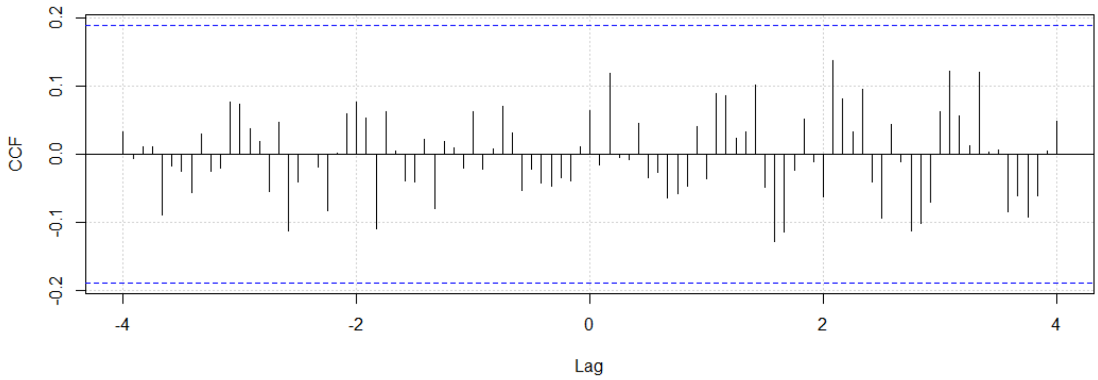


Figure 2N. CCF plot between prewhitened SSTTC$_{min}$ and filtered CFP incidence rate in French Polynesia

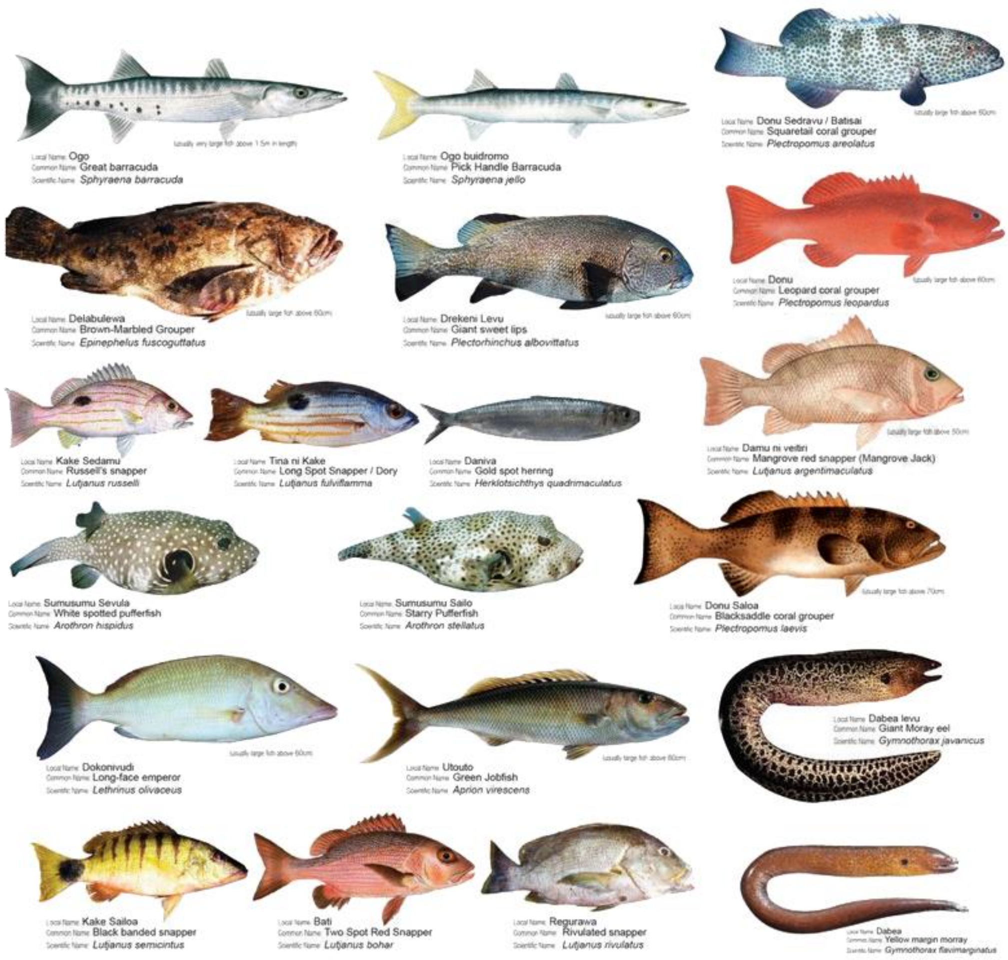


Figure 3A. Sample of 20 risky fish species presented during the survey

Figure 3B. Bluestripe herring (Fijian: *daniva*)

Table 1A. The Eckel and Grossman measure of risk preference elicitation

Choice (50/50 Game)	Low payoff	High payoff	Expected return	Standard deviation	Implied risk attitude
Game 1	28	28	28	0	risk-averse
Game 2	24	36	30	6	risk-averse
Game 3	20	44	32	12	risk-averse
Game 4	16	52	34	18	risk-averse
Game 5	12	60	36	24	risk-neutral
Game 6	2	70	36	34	risk-seeking

Selected questions in survey on "Ciguatera Fish Poisoning and Food Choice and Utilization in Gau"

HH ID (XYYZZZ**,** X=Sub-regency/District code (1-3), YY= Farmers group code (1-12), ZZZ=household code (1-60)) **HH ID** __________|

HH0d Is this household available for an interview?
1. Yes, 2. No (refused), 3. No (no contact), 4. No (no head or influential person) 5. No (Other reason)

HH0e If you are not the household head, what is your relationship to the household head?
1. Wife, 2. Children, 3. Parents, 4. Parents in law, 5. Siblings, 6. Others

HH0e____________

Section 1a. Demography

[Enumerator] I would like to ask you some questions about your household members. We consider someone a member of the household if they usually live and eat in the household for <u>at least one month in the last 12 months.</u> Thus, any son or daughter who is living outside the house (for example, in a different village or town) is not a member of the household.

ID	Name [Note to Enumerator] Write the name of the respondent in the first row.	Sex 1=Male 2=Female	Relation to household head 0=Head 1=Spouse 2=Parent (in law) 3=Child (in law) 4=Grand-child (in law) 5=Other relative 6=Non-relative	Age	Place of birth 1=Same village 2=Other villages in Gau (specify) 3=Other islands in Fiji (specify) 4=Other country	Highest grade completed (or currently enrolled in) 0= Don't/didn't go to school 1= Year 1 2= Year 2 3= Year 3 4= Year 4 5= Year 5 6= Year 6 7= Year 7 8= Year 8 9= Form 3 10= Form 4 11= Form 5 12= Form 6 13= Form 7 14= Undergrat dropout 15= Undergrad 16= Post-grad 17= vocational school	Is this person ...? 1=Working full-time (farming) 2=Working full-time (house work) 3= Working part-time (farming) 4= Working part-time (house work) 5=Student 6=Not in the labor force 7=Other	Days of farming per week	Frequency of fishing per week	Type of the non-farm (non-agriculture) activity (If the person is engaged in more than one activities, please choose only one from which the person gains most.) 1= None 2= Self-employed (store, handicraft) 3= Employed in manufacturing (e.g., tailor, metal work, furniture, pottery) 4= Employed in non-manufacturing (e.g., small shop, restaurant, driver) 5= Civil Service (government) 6=Others	Is this person currently pregnant? If Sex = 2
ID	**NAME**	**D1**	**D2**	**D3**	**D4**	**D5**	**Dn1**	**Dn2**	**Dn3**	**Dn4**	**Dn5**
1											

2											
3											
4											
5											
6											
7											
8											
9											
10											
11											

Section 1b. Income, expenditure, and family asset
[Enumerator] Could you please tell us about your household's annual income, expenditure, and the value of family asset.

ID	Source of Income	Db1	Type of Expenditure	Db2	Family Asset	Quantity (Db3)	Year of Purchase (Db4)
1	Sales of crops (yagona)		Food		Toilet		
2	Fishing		Education		Kitchen		
3	Weaving		Church		TV		
4	Sales of Livestock		Health		Vehicle		
5	Remittances		Business		Stereo		
6	Personal business		Community		Solar light		
7	Social welfare		Other (specify)		Boat		
8	Salaried or waged labor				Kerosene stove		
9	Other (specify)				Carpentry tools		
10					Cell phone		
11					Other (specify)		
12							
13							
14							

Section 1c. Crops and livestock
Please specify the amount of crops and livestock you have grown in your farm.

ID	Crops	Acre	Livestock	Amount
1	Yaqona		Pig	
2	Cassava		Chicken	
3	Yam		Cattle	
4	Taro		Goat	
5	Rourou		Duck	
6	Bele		Other (specify)	
7	Cucumber			
8	Chili			
9	Other vegetable (specify)			
10	Kumala			
11	Watermelon			
12	Tivoli			
13	Ginger			
14	Cabbage			
15	Papaya			
16	Eggplant			
17	Pumpkin			
18	Pineapple			
19	Other (specify)			

Section 1d. Fish poisoning

[Enumerator] Now, I will ask about the medical history about you and your household members.

ID	Name	Age	Frequency of eating locally caught fish 1= Every day 2=five days a week 3=two to four days a week 4=once a week 5=less than once a week 6=Never	How many total episodes of fish poisoning have you had in lifetime?	In what month and year did you have fish poisoning (last episode and/or other episodes)?	What type of fish did you believe cause your symptoms (last episode and/or other episodes)?	Which part of fish that you consumed (last episode)? 1.flesh 2.head 3.entails 4.viscera 5.other	How many fish did you consumed (last episode)?	Are you the first on in family to eat the fish? 1=yes 0=no	Symptoms 1.Abdominal Pain 2.Diarrhea 3.Hot and cold reversal 4.Tingling/ numbness in hands or feet 5.Weakness 6. Vomit 7. Pain on joint and feet 8.Other (specify) 9.Don't know	How soon after you ate the fish did your first symptoms of fish poisoning appear?	How did you treat your symptoms from fish poisoning? 1.health clinic 2.contact community nurse 3.Benadryl 4.Brown sugar 5.Bush tea 6.Charcoal 7.Mauby Bark 8.Other over-the-counter medicine (specify) 9.Other herbal medicine (specify)	Did your trip to the emergency room, doctor, or clinic cost you any money? And how much?	Can you recall how many people got poisoned from the same fish (last episode and/or other episodes)?
ID	**NAME**	**D3**	**Dm1**	**Dm2**	**Dm3**	**Dm4**	**Dm5**	**Dm6**	**Dm7**	**Dm8**	**Dm9**	**Dm10**	**Dm11**	**Dm12**
1														

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11														

Section 1d. Fish poisoning (continued)

ID	Name	Age	How many days did the symptoms last for?	How many days did you stay in bed?	How many days of work did you miss?	Do you know where the fish was caught?	What kind of herbal medicine you use as secondary support? 1.Coconut 2.Bread tree leaves 3.Tree heliotrope 4.Other (specify)	What did you use to replace fish during post-poisoning period? 1.Canned food (specify) 2.Root crop (specify) 3.Still consuming fish 4.Reducing intake without replacement 5.Other (specify)	How long did it take you return to your regular diet?	How many days after poisoning you start to consume the same species again?	Do you have other chronic diseases? 1. Diabetes 2. Cancer 3. Stroke 4. Kidney disease 5. Heart problem 6. High blood pressure 7. Jaundice or hepatitis 8. Other (specify)	Have you avoided Daniva after January 2017?	How often do you drink containing alcohol? 1.Never; 2. Once a month; 3.two to four times a month; 4. two to three times a week; 5. four or more times a week; 6. Other	Do you currently smoke tobacco? 1=yes 0=no	Do you believe fish poisoning could be a punishment from God?
ID	**NAME**	**D3**	**Dm13**	**Dm14**	**Dm15**	**Dm16**	**Dm17**	**Dm18**	**Dm19**	**Dm20**	**Dm21**	**Dm22**	**Dm23**	**Dm24**	**Dm25**
1															
2															
3															
4															
5															

6															
7															
8															
9															
10															
11															

Section 2a. Perception on risky fish

Please tell us your risk perception in consuming *Daniva* fish:

Item	Definition	Answer (ID1)	Answer (ID2)	Answer (ID3)	Answer (ID4)
Item 1	"How possible do you think consuming certain fish would cause fish poisoning to you" by following a 10-point scale. 1 = strongly disagree; 10 = strongly agree				
Item 2	"Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than neighbors in your village?". higher=1, same=2, lower=3				
Item 3	"Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than people in your neighboring villages?". higher=1, same=2, lower=3				
Item 4	"Do you believe the toxin in certain fish can be removed if treated properly?" Yes=1				

Please tell us your risk perception in consuming *Dabea* fish:

Item	Definition	Answer (ID1)	Answer (ID2)	Answer (ID3)	Answer (ID4)
Item 1	"How possible do you think consuming certain fish would cause fish poisoning to you" by following a 10-point scale. 1 = strongly disagree; 10 = strongly agree				
Item 2	"Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than neighbors in your village?". higher=1, same=2, lower=3				
Item 3	"Do you think the risk of fish poisoning for consuming certain fish is higher, same, or lower than people in your neighboring villages?". higher=1, same=2, lower=3				
Item 4	"Do you believe the toxin in certain fish can be removed if treated properly?" Yes=1				

Please tell us the food attributes in consuming *Daniva* fish: response to scale questions.

Item	Definition	Answer (ID1)	Answer (ID2)	Answer (ID3)	Answer (ID4)
Item 1	"Do you think certain fish species is nutritious (or healthy) to consume?" 1 = strongly disagree; 10 = strongly agree				
Item 2	"Do you think certain fish species are tasty/delicious?" 1 = strongly disagree; 10 = strongly agree				
Item 3	"Do you think certain fish species are precious or rare to find?" 1 = strongly disagree; 10 = strongly agree				

Please tell us the food attributes in consuming *Dabea* fish: response to scale questions.

Item	Definition	Answer (ID1)	Answer (ID2)	Answer (ID3)	Answer (ID4)
Item 1	"Do you think certain fish species is nutritious (or healthy) to consume?" 1 = strongly disagree; 10 = strongly agree				
Item 2	"Do you think certain fish species are tasty/delicious?" 1 = strongly disagree; 10 = strongly agree				
Item 3	"Do you think certain fish species are precious or rare to find?" 1 = strongly disagree; 10 = strongly agree				

Section 2b. Risk preference

Please make one choice from the presented 6 gambles.

Choice (50/50 Gamble)	Low payoff	High payoff	Expected return	Your choice (ID1)	Your choice (ID2)	Your choice (ID3)	Your choice (ID4)
Gamble 1	28	28	28				
Gamble 2	24	36	30				
Gamble 3	20	44	32				
Gamble 4	16	52	34				
Gamble 5	12	60	36				
Gamble 6	2	70	36				

Section 3. Knowledge and behavior on fish poisoning

ID	Name	How many of the following fish species that you have known?	How many of the following fish species could be poisonous?	How many of the following fish species that you have avoided to eat with your family in the past 12 months?	Why fish is poisoned in your opinion?	Which part of fish is more toxic? 1.Head 2.Flesh 3.Gut 4.Other 5. Don't know	Is there a season when fish are more likely to be poisonous?	Is there any way to tell if a fish might be poisonous ?	What is the most obvious symptoms of fish poisoning?	Do you have a less preferred place to fish because there could be toxic fish?	Have you avoided consuming *Daniva* after the outbreak occurred in January 2017? Yes=1 No=0	How many days have you avoided consuming *Daniva* after the outbreak occurred in January 2017? If Dk10=1
ID	**NAME**	**Dk1**	**Dk2**	**Dk3**	**Dk4**	**Dk5**	**Dk6**	**Dk7**	**Dk8**	**Dk9**	**Dk10**	**Dk11**
1												
2												
3												
4												
5												
6												
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8												
9												
10												
11												