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Effects of ocean warming on growth and distribution of dinoflagellates associated with ciguatera fish poisoning in the Caribbean

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ABSTRACT

Projected water temperatures at six sites in the Gulf of Mexico and Caribbean Sea were used to forecast potential effects of climate change on the growth, abundance and distribution of *Gambierdiscus* and *Fukuyoa* species, dinoflagellates associated with ciguatera fish poisoning (CFP). Data from six sites in the Greater Caribbean were used to create statistically downscaled projections of water temperature using an ensemble of eleven global climate models and simulation RCP6.0 from the WCRP Coupled Model Intercomparison Project Phase 5 (CMIP5). Growth rates of five dinoflagellate species were estimated through the end of the 21st century using experimentally derived temperature vs. growth relationships for multiple strains of each species. The projected growth rates suggest the distribution and abundance of CFP-associated dinoflagellate species will shift substantially through 2099. Rising water temperatures are projected to increase the abundance and diversity of *Gambierdiscus* and *Fukuyoa* species in the Gulf of Mexico and along the U.S. southeast Atlantic coast. In the Caribbean Sea, where the highest average temperatures correlate with the highest rates of CFP, it is projected that *Gambierdiscus caribaeus*, *Gambierdiscus belizeanus* and *Fukuyoa ruetzleri* will become increasingly dominant. Conversely, the lower temperature-adapted species *Gambierdiscus carolinianus* and *Gambierdiscus* ribotype 2 are likely to become less prevalent in the Caribbean Sea and are expected to expand their ranges in the northern Gulf of Mexico and farther into the western Atlantic. The risks associated with CFP are also expected to change regionally, with higher incidence rates in the Gulf of Mexico and U.S. southeast Atlantic coast, with stable or slightly lower risks in the Caribbean Sea.

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1. Introduction

Ciguatera fish poisoning (CFP) is a pantropical illness caused by the bioconcentration of algal toxins, known as ciguatoxins (CTXs), in marine food webs. CTXs are produced by benthic and/or substrate-associated dinoflagellates in the genus *Gambierdiscus* (and potentially, *Fukuyoa*, see below). There is a consensus that CTXs enter marine food webs primarily via ingestion by herbivorous and surface-feeding fish and invertebrates (Bagnis et al., 1980, 1985; Chinain et al., 2010; GEOHAB, 2012). Growth, distribution and abundance of CFP-associated dinoflagellates are largely temperature driven and expected to shift in response to climate induced changes as ocean temperatures rise (Tester et al., 2010; Kibler et al., 2012). Historically, CFP has been more prevalent at low latitudes (∼35° N–35° S), but recent evidence indicates some *Gambierdiscus* species also occur in subtropical-temperate locations where their abundance will likely increase as ocean temperatures rise (Litaker et al., 2009; Nascimento et al., 2010; Nishimura et al., 2013, 2014). In the Atlantic, CFP is most common in the Greater Caribbean Region (GCR), a broad area bounded by the coastlines of the Gulf of Mexico, Caribbean Sea, the tropical western Atlantic adjacent to the Bahamas, and the southeastern coast of the United

Abbreviations: CFP, ciguatera fish poisoning; CTX, ciguatoxins; GCR, Greater Caribbean Region; μ, growth rate; GCM, global climate model.

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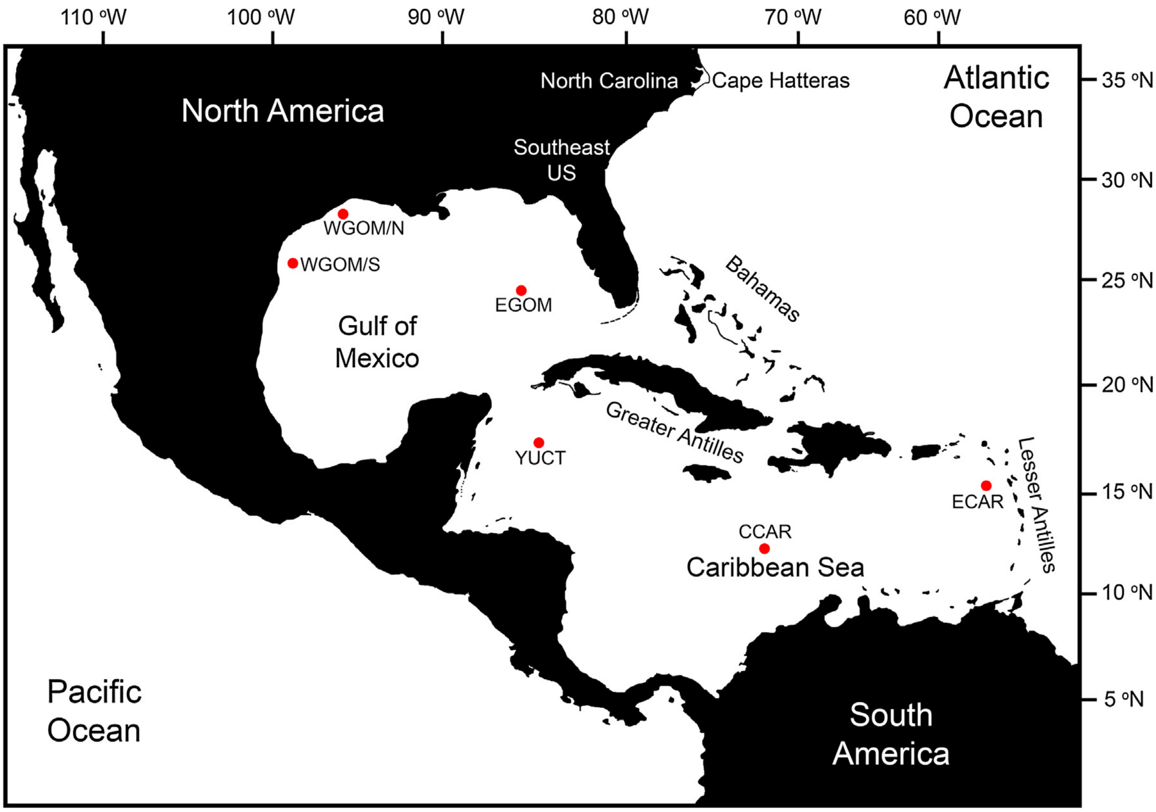

Fig. 1. Map of Caribbean region showing the six buoy sites (●) where temperature and growth were projected through the end of the 21st century. Details for each site are given in Table 1.

States as far north as Cape Hatteras, North Carolina (after Gledhill et al., 2008) (Fig. 1). Average sea surface temperatures are highest and most stable in the eastern Caribbean Sea (~24 to 29 °C), very near the optimum growth temperatures for Caribbean *Gambierdiscus* and *Fukuyoa* species (25–30 °C; Gordon, 1967; Bomber et al., 1988a; Morton et al., 1992; Gallegos, 1996; Tester et al., 2010; Kibler et al., 2012). The highest CFP incidence rates also occur in the eastern Caribbean, supporting the hypothesis that CFP occurrence is associated with optimal growth conditions for *Gambierdiscus* and *Fukuyoa* cells (Tester et al., 2010; Radke et al., 2013).

Although systematic data on cell distribution across the GCR are scarce, a review of historical records indicates *Gambierdiscus* and *Fukuyoa* cell densities tend to be greatest in warm, shallow bays and where temperatures are high and relatively stable throughout the year (Taylor and Gustavson, 1985; Bomber et al., 1989; Faust et al., 2005; Okolodkov et al., 2014; Tester et al., 2014). The case is similar in the Pacific, where CFP incidences are positively correlated with water temperatures and are highest when temperatures remain at 28–30 °C (Hales et al., 1999; Chateau-Degat et al., 2005; Llewellyn, 2010). However, the temperature–CFP relationship weakens at temperatures >30 °C, suggesting an upper thermal limit may restrict *Gambierdiscus* occurrence (Llewellyn, 2010). An upper threshold is supported by experimental data showing a precipitous decline in *Gambierdiscus* and *Fukuyoa* growth rates at temperatures approaching ~31 °C (Kibler et al., 2012). Like many tropical organisms, these dinoflagellates exhibit maximum growth rates within ~5–10 °C of their upper thermal growth limits, T_u, the point at which temperatures are too high to support cellular growth. This means that even small (1–2 °C) increases in ocean temperatures may yield relatively large increases in *Gambierdiscus/Fukuyoa* growth rates, but more substantial warming may cause cell mortality (Kibler et al., 2012). Such lethal temperatures are unlikely in oceanic waters, where evaporative and convective processes prevent temperatures from exceeding ~31 °C (i.e., the ocean thermostat; Kleypas et al., 2008). However, water temperatures may approach or exceed T_u in protected coastal environments with limited vertical circulation, and coincidently, where *Gambierdiscus* and *Fukuyoa* cells reach highest abundances (Carlson, 1984; Faust et al., 2005; Tester et al., 2014).

To better understand how rising water temperatures may affect the distribution and abundance of *Gambierdiscus* and *Fukuyoa* species in the GCR, we used experimental temperature vs. growth data in combination with projected water temperatures at six representative sites to predict how the growth rates of these species will change as oceans warm through the 21st century. Specifically, we examined the effect of rising ocean temperatures on growth of five dinoflagellate species common across the GCR (Vandersea et al., 2012): *Gambierdiscus belizeanus*, *Gambierdiscus caribaeus*, *Gambierdiscus carolinianus*, *Gambierdiscus* ribotype 2 (undescribed), and the closely related species *Fukuyoa ruetzleri* (formerly *Gambierdiscus ruetzleri*; Gómez et al., 2015). Because these species co-occur and may produce toxins causing CFP, henceforward they will be collectively referred to as CFP-associated dinoflagellates. Experimental growth data were compiled from the study by Kibler et al. (2012), together with our unpublished temperature vs. growth data from a variety of experiments completed over the last decade. Global climate model projections indicate ocean temperatures in the GCR will rise by 1–3 °C by 2100 (Good et al., 2007; Strong et al., 2008; Chollett et al., 2012). *Gambierdiscus* species are sensitive to even small increases in temperature; therefore it is likely that ocean warming will prompt changes in species abundance, diversity and distribution. It is hypothesized these changes will include (1) northward progression of species currently restricted to lower latitude environments, (2) increased abundance of species already present in subtropical to temperate areas, and (3) reduced occurrence of some species in the Caribbean Sea as temperatures exceed