

Assessment and management of seafood safety and quality

Current practices and emerging issues



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Current practices and emerging issues

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5.2 IMPACTS OF CLIMATE CHANGE ON HARMFUL ALGAL BLOOMS AND SEAFOOD SAFETY (GUSTAAF HALLEGRAEFF)

5.2.1 Introduction

In a strict sense, harmful algal blooms are completely natural phenomena that have occurred throughout recorded history. However, even non-toxic algal blooms can have devastating impacts when they lead to kills of fish and invertebrates by generating anoxic conditions in sheltered bays. Other algal species, although non-toxic to humans, can produce exudates that can cause damage to the delicate gill tissues of fish (raphidophytes *Chattonella*, *Heterosigma*, and dinoflagellates *Karenia*, *Karlodinium*). Whereas wild fish stocks are free to swim away from problem areas, caged fish in intensive aquaculture operations are trapped and, thus, can suffer devastating mortalities. Of greatest concern to human society are algal species that produce potent neurotoxins that can find their way through shellfish and fish to human consumers where they evoke a variety of gastrointestinal and neurological illnesses. One of the first recorded fatal cases of food poisoning after eating contaminated shellfish happened in 1793, when Captain George Vancouver and his crew landed in British Columbia (Canada) in an area now known as Poison Cove. He noted that, for local Indian tribes, it was taboo to eat shellfish when the seawater became bioluminescent due to algal blooms by the local dinoflagellate *Alexandrium catenella/tamarense*, which is now known to be a causative organism of PSP. The increase in shellfish farming worldwide is leading to more reports of PSP, DSP (first documented in 1976 in Japan), NSP (reported from the Gulf of Mexico as early as 1844) and ASP (first identified in 1987 in Canada). The explorer Captain James Cook already suffered from the tropical illness of CFP from fish when visiting New Caledonia in 1774. Worldwide, almost 2 000 cases of food poisoning from consumption of contaminated fish or shellfish are reported each year. Some 15 percent of these cases prove fatal. If not controlled, the economic damage through the slump in local consumption and exports of seafood products can be considerable. Whales and porpoises can also become victims when they receive toxins through the food chain via contaminated zooplankton or fish. In the United States of America, poisonings of manatees in Florida via seagrasses and, in California, of pelicans and sea lions via contaminated anchovies have also been reported (Hallegraeff, Anderson and Cembella, 2003).

In the past three decades, harmful algal blooms seem to have become more frequent, more intense and more widespread. Four explanations for this apparent increase in algal blooms have been proposed: (i) a greater scientific awareness of toxic species; (ii) the growing utilization of coastal waters for aquaculture; (iii) the stimulation of plankton blooms by domestic, industrial and agricultural wastes and/or unusual climate conditions; and (iv) the transportation of algal cysts either in ships' ballast water or associated with moving shellfish stocks from one area to another (Hallegraeff, 1993).

Few long-term records exist of algal blooms at any single locality; ideally, at least 30 consecutive years of data would be needed. Therefore, whether or not the apparent global increase in harmful algal blooms represents a real increase is a question that will probably not be answered conclusively for some time to come.

The growing interest in using coastal waters for aquaculture is leading to a greater awareness of toxic algal species. People responsible for deciding quotas for pollutant loadings of coastal waters, or for managing agriculture and deforestation, should be made aware that one probable outcome of allowing polluting chemicals to seep into the environment will be an increase in harmful algal blooms. In countries that pride themselves on having disease- and pollution-free aquaculture, every effort should be made to quarantine sensitive aquaculture areas against the unintentional introduction of non-indigenous harmful algal species. Nor can any aquaculture industry afford not to monitor for an increasing number of harmful algal species in water and for an

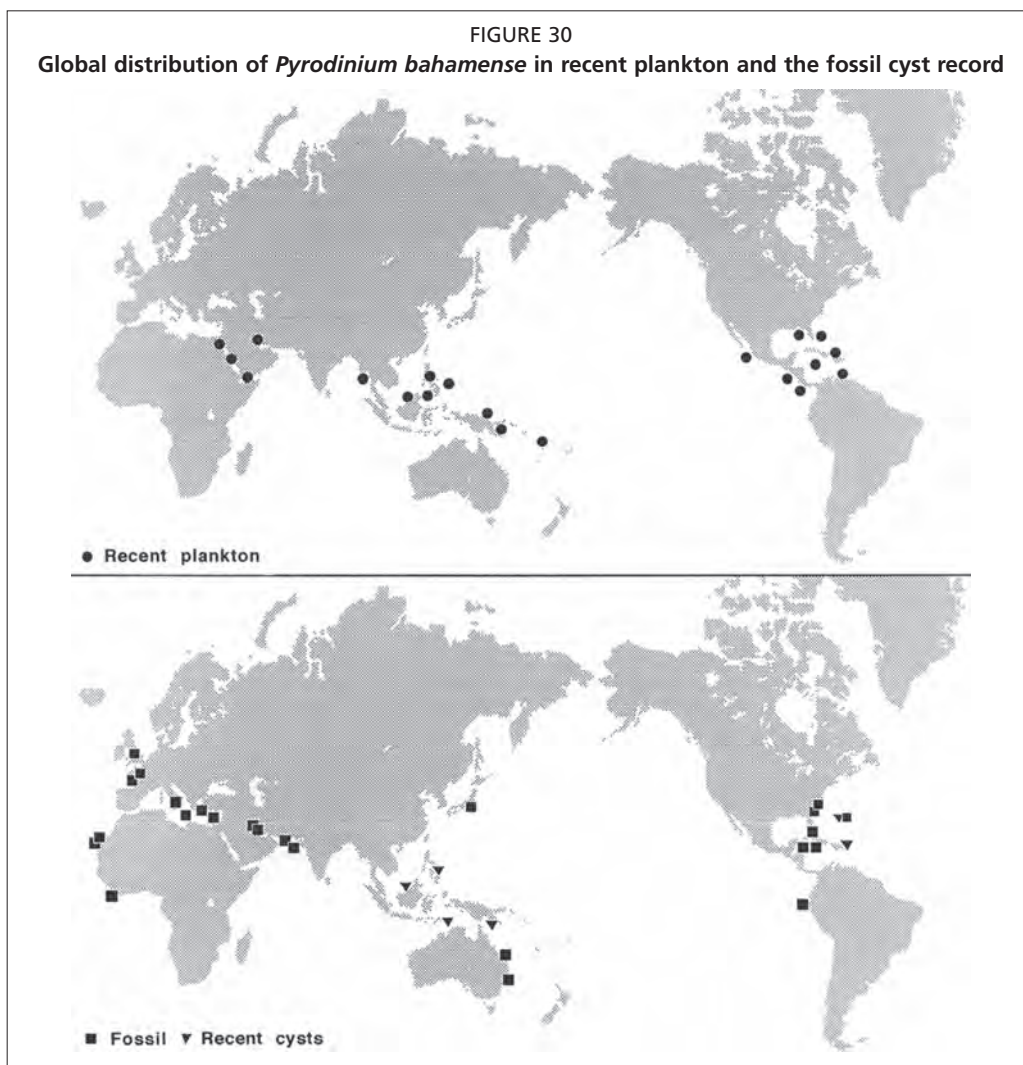
increasing number of algal toxins in seafood products – using increasingly sophisticated analytical techniques such as LC-MS (see Section 3.2.5). Last, global climate change is adding a new level of uncertainty to many seafood safety monitoring programmes, as are range extensions of harmful algal bloom species through their being transported in ships' ballast water and as a consequence of increases in sea surface temperatures (Hallegraeff, 2010).

5.2.2 Range extensions by transport in ships' ballast water

Ballast water is seawater that has been pumped into a ship's hold or dedicated ballast tanks to steady it by making it heavier and thus less likely to roll; the water is released when a ship enters port. Ballast water on cargo vessels was first suggested as a means of dispersing marine plankton more than 100 years ago (Ostenfeld, 1908). However, it was only in the 1980s that the problem sparked considerable interest, after evidence was brought forward that non-indigenous toxic species such as the PSP dinoflagellate *Gymnodinium catenatum* had been introduced into sensitive aquaculture areas of Australian waters, with disastrous consequences for commercial shellfish farms (McMinn *et al.*, 1997). Similarly, the PSP dinoflagellate *Alexandrium catenella*, of a diagnostic temperate Asian ribotype, has appeared on French and Spanish Mediterranean coasts in the past two decades (Lilly *et al.*, 2002). Ecosystems disturbed by pollution or climate change are more prone to ballast water invasions (Stachowicz *et al.*, 2002).

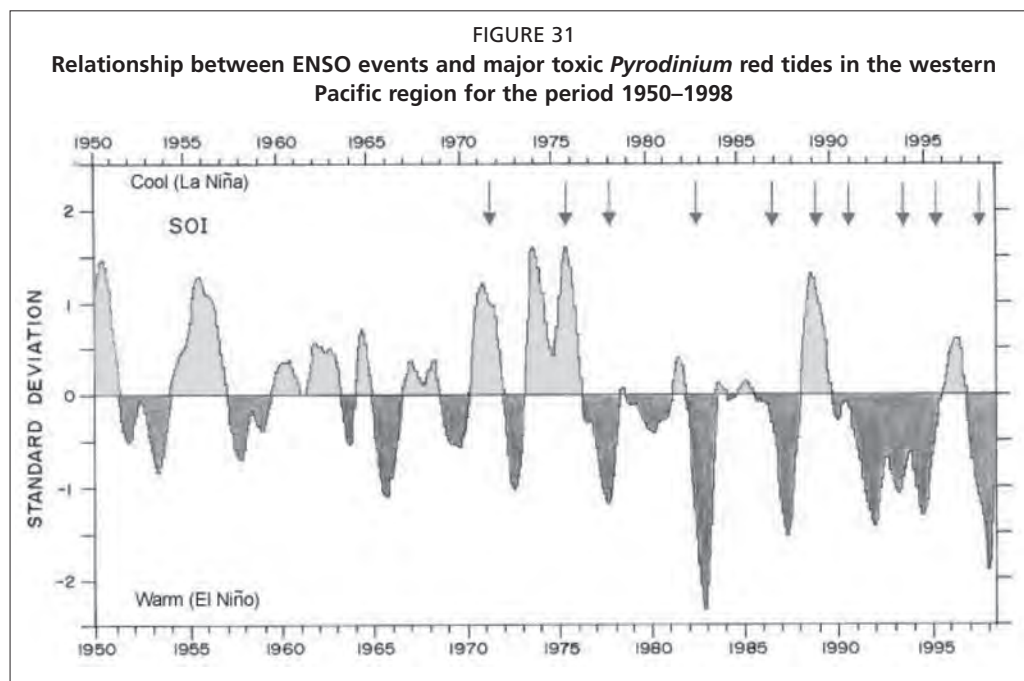
5.2.3 Algal bloom range extensions and climate change

The dinoflagellate *Pyrodinium bahamense* is currently confined to tropical, mangrove-fringed coastal waters of the Atlantic and Indo-West Pacific. A survey of cyst fossils (named *Polysphaeridium zoharyi*) going back to the warmer Eocene 50 million years ago indicates a much wider range of distribution in the past. For example, in the Australasian region at present, the alga is not found farther south than Papua New Guinea, but, some 100 000 years ago, the alga ranged as far south as what is now Sydney Harbour, Australia (McMinn, 1989). There is concern that, with an increased greenhouse effect and warming of the oceans, this species may return to Australian waters (Figure 30). In the tropical Atlantic, in areas such as Bahia Fosforescente in Puerto Rico and Oyster Bay in Jamaica, the glowing red-brown blooms of *Pyrodinium* are a major tourist attraction. At first considered harmless, *Pyrodinium* blooms gained a more sinister reputation in 1972 in Papua New Guinea after red-brown water discolorations coincided with the fatal food poisoning (diagnosed as PSP) of three children in a seaside village. Since then, these toxic blooms have apparently spread to Brunei Darussalam and Sabah, Malaysia, (1976), the central (1983) and northern Philippines (1987) and North Maluku, Indonesia. There is strong circumstantial evidence of a coincidence between *Pyrodinium* blooms and weather perturbations linked to the ENSO (Figure 31). *Pyrodinium* is thus a serious public health and economic problem for these tropical countries, all of which depend heavily on seafood for protein. In the Philippines alone, *Pyrodinium* has now been responsible for more than 2 000 human illnesses and 100 deaths resulting from the consumption of contaminated shellfish, sardines and anchovies (Hallegraeff and MacLean, 1989; Azanza and Taylor, 2001). Erickson and Nishitani (1985) reported exceptional PSP episodes by *Alexandrium tamarense/catenella* in the Pacific Northwest during 7 out of 9 ENSO events between 1941 and 1984.



Source: Hallegraeff (1993).

Until recently, NSP by the dinoflagellate *Karenia brevis* was considered to be endemic to the Gulf of Mexico and the east coast of Florida, the United States of America, where red tides had been reported as early as 1844. An unusual feature of NSP is the formation by wave action of toxic aerosols, which can lead to respiratory asthma-like symptoms in humans. In 1987, a major Florida bloom was dispersed by the Gulf Stream northward into the waters of North Carolina, the United States of America, where it has since persisted (Tester *et al.*, 1991; Tester, Geesey and Vukovich, 1993). In early 1993, more than 180 human NSPs were reported from New Zealand. Most likely, this mixed bloom of *Karenia mikimotoi* and related species was again triggered by the unusual weather conditions at the time, including higher than usual rainfall and lower than usual temperature, which coincided with an El Niño event (Chang *et al.*, 1998; Rhodes *et al.*, 1993).

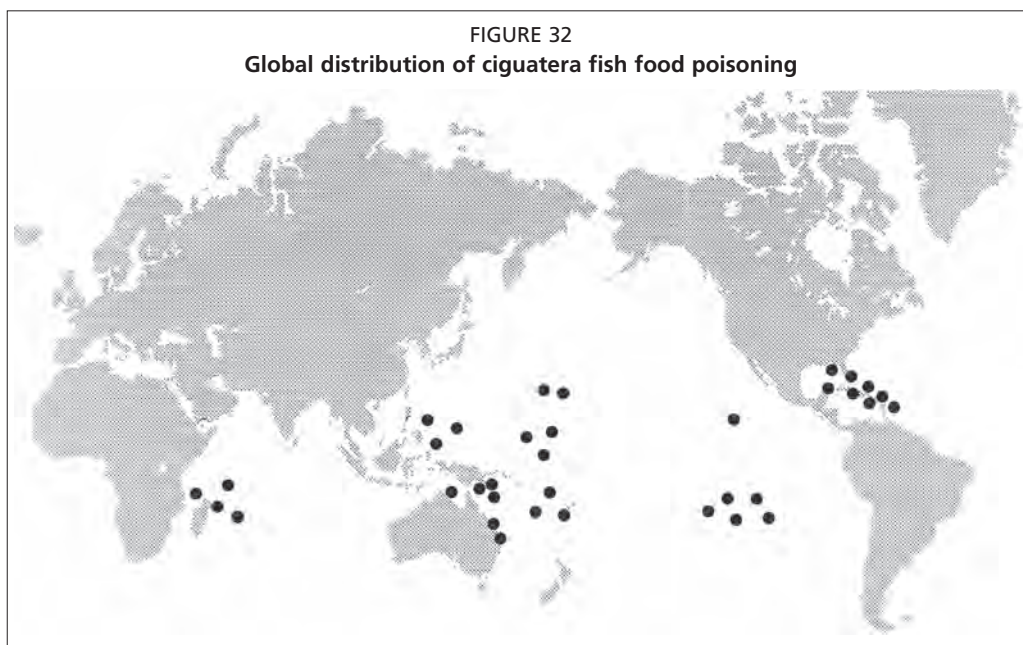


Notes: The Southern Oscillation Index (SOI) values are based on readings taken in Tahiti (French Polynesia), Hawaii (the United States of America) and Darwin (Australia). Arrows indicate years when *P. bahamense* red tides occurred in the Philippines and Malaysia.

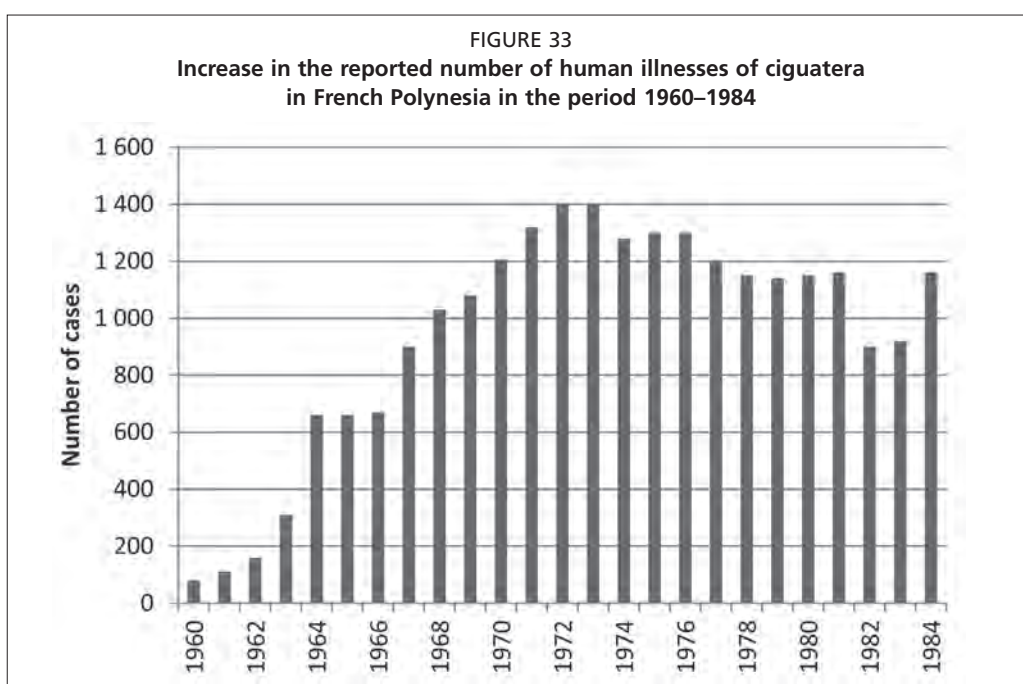
Source: Azanza and Taylor (2001).

Ciguatera caused by the benthic dinoflagellate *Gambierdiscus toxicus* is a tropical food poisoning syndrome well-known in coral reef areas in the Caribbean, Australia and, in particular, French Polynesia (Figure 32). Whereas, in a strict sense, this is a completely natural phenomenon, from being a rare disease two centuries ago, ciguatera has now reached epidemic proportions in French Polynesia. From 1960 to 1984, more than 24 000 patients were reported from this area, which is more than six times the average for the Pacific as a whole. Evidence is accumulating that reef disturbance by hurricanes, military activities and tourist developments (Bagnis, Bennett and Barsinas, 1985), as well as coral bleaching (linked to global warming) and perhaps, in future, increasing coral damage due to ocean acidification (Hoegh-Guldberg, 1999) are increasing the risk of ciguatera (Figure 33). Ciguatera dinoflagellates are predicted to become one of the winners from climate change (Tester *et al.*, 2010).

In the Australian region, *Gambierdiscus* dinoflagellates are well-known from the tropical Great Barrier Reef and southwards down to just north of Brisbane. However, in the past five years, this species has exhibited an apparent range extension into southeast Australian seagrass beds as far south as Melbourne, aided by a strengthening of the East Australian Current. In the same region, the red-tide dinoflagellate *Noctiluca scintillans* (known from the Sydney region as early as 1860) has, since 1994, expanded its range into southern Tasmanian waters, where it has caused problems for the salmonid fish farm industry (McLeod *et al.*, 2012). In the North Sea, an analogous northward shift of warm-water phytoplankton has occurred as a result of regional climate warming (Hays, Richardson and Robinson, 2005; Edwards and Richardson, 2004; Richardson and Schoeman, 2004).



Source: Hallegraeff (1993).



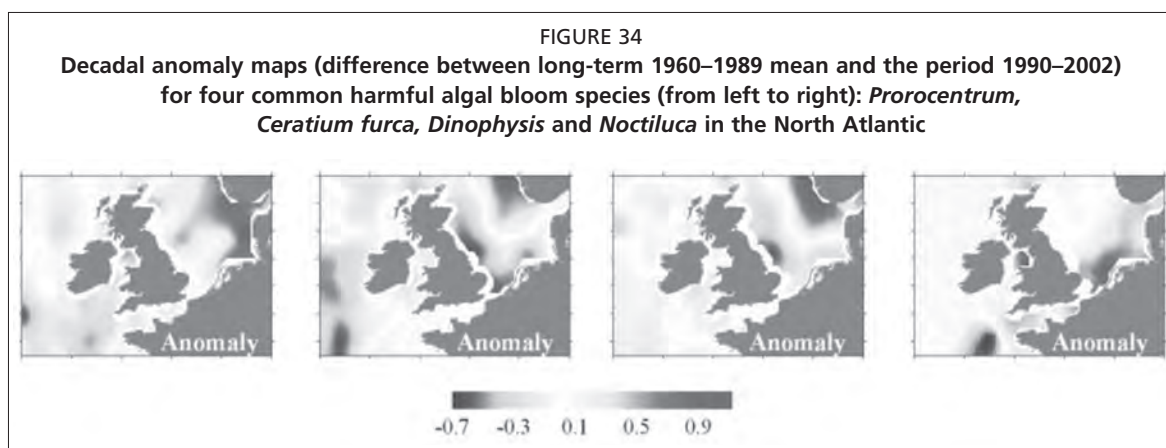
Note: Increased reef damage by coral bleaching or ocean acidification is predicted to stimulate ciguatera.
Source: Bagnis, Bennett and Barsinas (1985).

5.2.4 Predicted impact of climate change on phytoplankton abundance

Phytoplankton play a central role in several global biogeochemical cycles. Through the process of photosynthesis, they are also a major consumer of carbon dioxide. The ability of the oceans to act as a sink for anthropogenic carbon dioxide largely relies on the conversion of this gas by phytoplankton into particulate organic matter, and subsequent partial loss to the deep ocean (the so-called “biological pump”). Phytoplankton also have important feedback effects on climate. Some species (e.g. *Phaeocystis*) are producers of dimethylsulphonium propionate, a precursor of dimethylsulphoxide, which in the atmosphere is oxidized into sulphate, which forms

condensation nuclei for clouds (Charleson *et al.*, 1987). Therefore, phytoplankton can indirectly affect albedo and precipitation and, hence, coastal runoff, salinity, water column stratification and nutrient supply. Increased temperature, enhanced surface stratification, nutrient upwelling, stimulation of photosynthesis by elevated CO₂, changes in land runoff and nutrient availability, and altered ocean pH may produce contradictory species- or even strain-specific responses. Complex factor interactions exist, and ecophysiological experiments rarely take into account genetic strain diversity and physiological plasticity.

Predicting the impact of global climate change on harmful algal blooms is fraught with uncertainties. However, important lessons can be learned from the dinoflagellate cyst fossil record (Dale, 2001) and from the few long-term data sets available (such as the Continuous Plankton Recorder surveys; Hays, Richardson and Robinson, 2005; Figures 34 and 35). The climate on our planet has been forever changing, from scales of millions of years (glacial to interglacial periods) to short-term oscillations of tens of years (ENSO, and the North Atlantic Oscillation). Even in the past 1 000 years, the planet has gone through episodes much warmer than present (the Medieval Warm Period of 550–1300 AD) or much colder than now (the Little Ice Age 1300–1900 AD). Because of their short generation times and longevity, many phytoplankton can respond to climate change with only a very small time lag. They can spread quickly with moving water masses into climatic conditions that match the requirements of a species in terms of temperature, salinity, land runoff and turbulence.



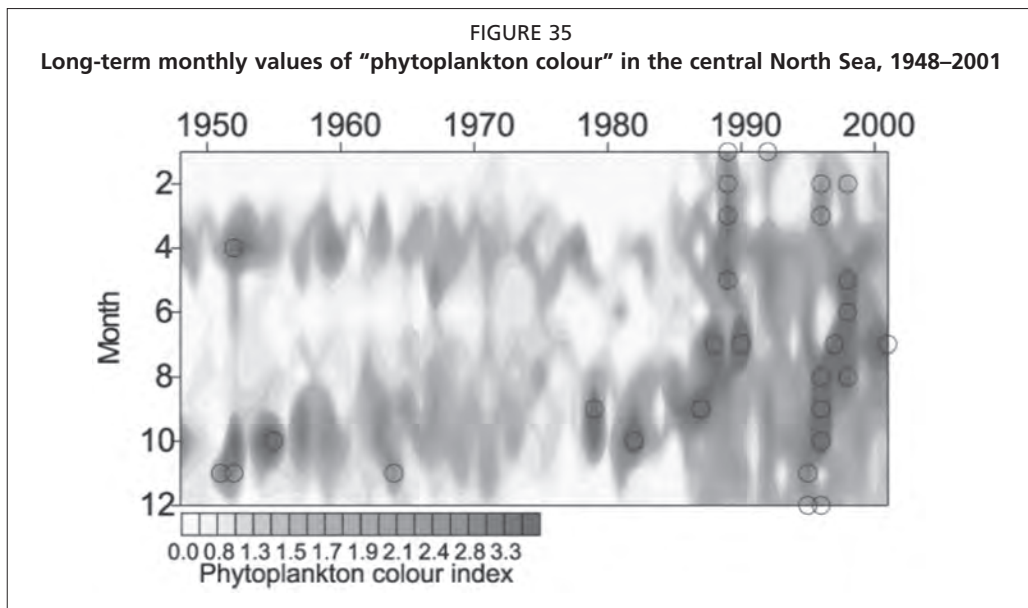
Note: Note the increase in *Prorocentrum*, *Ceratium furca* and *Dinophysis* along the Norwegian coast and increase in *Noctiluca* in the southern North Sea.

Source: Edwards *et al.* (2008).

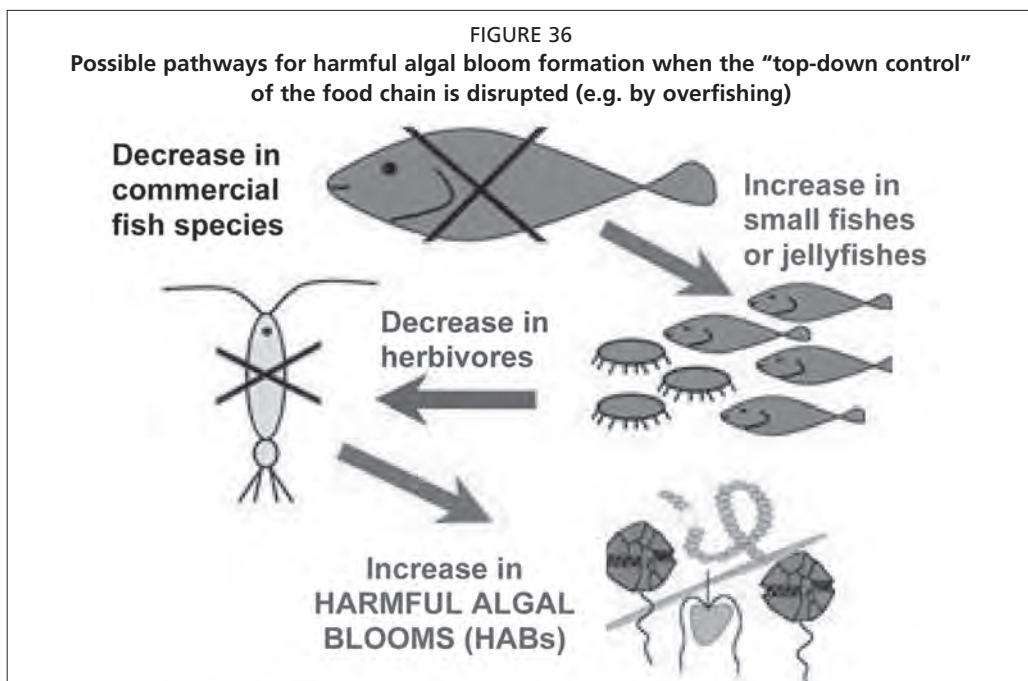
5.2.5 Impact of global warming and sea surface temperature change

Phytoplankton grow over a range of temperatures characteristic of their habitat, and growth rates are usually higher at higher temperature but considerably lower beyond an optimal temperature (Eppley, 1972). Natural populations of phytoplankton are often found at temperatures that are suboptimal for photosynthesis, and it is believed that this is designed to avoid risking abrupt declines in growth associated with the abrupt incidence of warmer temperatures (Li, 1980). Temperature effects on phytoplankton growth and composition are more important in shallow coastal waters, which experience larger temperature fluctuations than oceanic waters. Increasing sea surface temperature may shift the community composition towards species adapted to warmer temperatures, as observed in the temperate North Atlantic (Edwards and Richardson, 2004). Seasonal timing of phytoplankton blooms is now occurring up to 4–5 weeks earlier in the North Sea in relationship to regional climate warming (Figure 35). However, not all trophic levels are responding to the same extent. Where

zooplankton or fish grazers are differentially affected by ocean warming, this may have cascading impacts on the structure of marine food webs (Figure 36).



Notes: Circles denote > 2SD above the long-term monthly mean (from Edwards, 2004). Note an apparent shift towards earlier spring and autumn phytoplankton blooms.

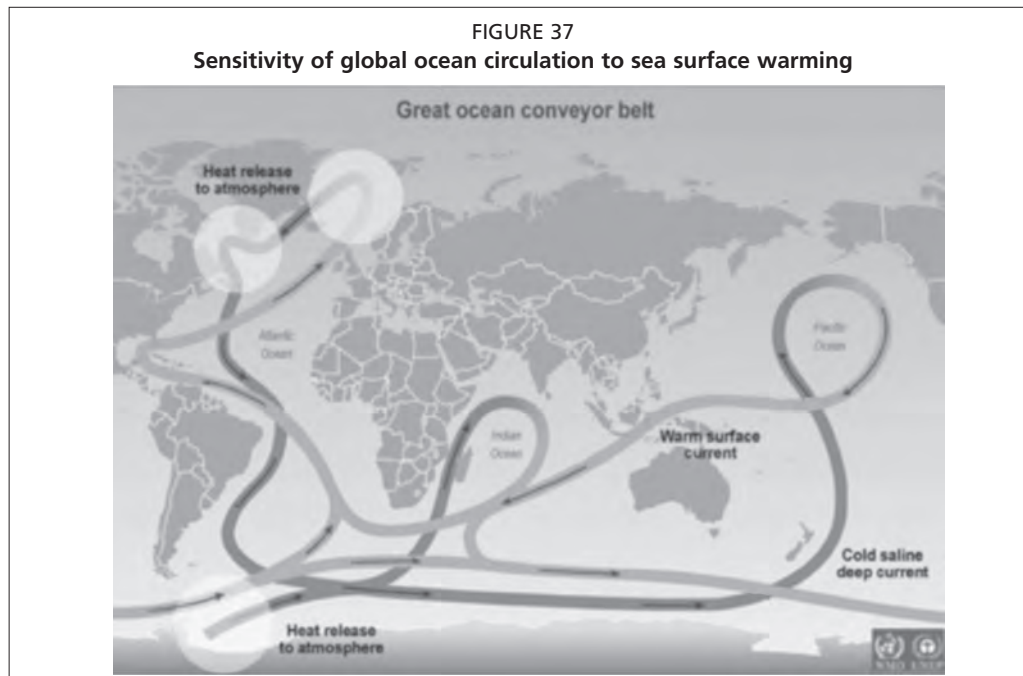


Note: Differential impacts of climate change on zooplankton or fish grazers can produce similar stimulation of harmful algal blooms.

Source: Turner and Graneli (2006).

5.2.5.1 Sea-level rise, wind and mixed-layer depth

Increasing sea surface temperature and water column stratification (shallowing of the mixed layer) can be expected to have a strong impact on phytoplankton because of the resource requirements and temperature ranges to which species are adapted. Wind determines the incidence of upwelling and downwelling, which in turn strongly affect the supply of macronutrients to the surface (recognized as drivers of *Gymnodinium catenatum* blooms off Spain [Fraga and Bakun, 1990]). Broad changes in ocean circulation such as those comprising the deep-ocean conveyor belt (Figure 37) can cause displacements to existing upwelling areas and associated algal bloom phenomena. Wind-driven currents may also transport phytoplankton away from a region, and affect the size and frequency of formation of mesoscale features such as fronts and eddies. Locally, wind intensity strongly influences the depth and intensity of vertical mixing in the surface layer, thereby affecting phytoplankton access to nutrients, light availability for algal photosynthesis and phytoplankton exposure to potentially harmful UV-B radiation. Finally, winds can influence the supply of iron to the surface ocean through aeolian transport of dust from land to sea, contributing micronutrients such as iron, which can stimulate *Karenia brevis* blooms off Florida (Walsh and Steidinger, 2001). Extreme climate events such as hurricanes are known to expand the existing distribution of cyst-producing toxic dinoflagellates (e.g. *Alexandrium tamarense* in New England, the United States of America, after a 1972 hurricane [Anderson, 1997]). Sea-level rise has the potential to increase the extent of continental-shelf areas, providing shallow, stable water columns favouring phytoplankton growth. The proliferation of coccolithophorids in the geological period the Cretaceous has been partially explained on this basis.



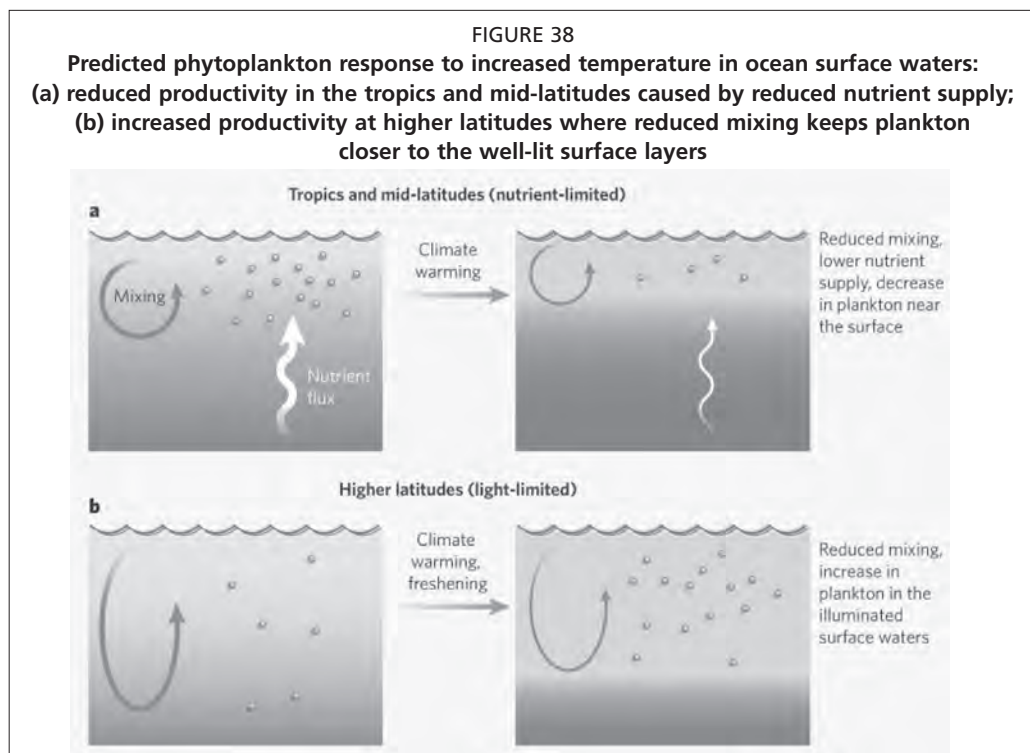
Source: Rahmstorf (2002).

5.2.5.2 Impact of heavy precipitation events and flash floods

Changes in the amount or timing of rainfall and river runoff affect the salinity of estuaries and coastal waters. Salinity is relatively constant throughout the year in most oceanic waters and in coastal areas that receive little freshwater input. Coastal phytoplankton is subject to more variation in salinity than phytoplankton in oceanic

waters. While some species grow well over a wide range of salinities, other species grow best only at salinities that are low (estuarine), intermediate (coastal) or high (oceanic species). Freshwater also modifies the stratification of the water column, thereby affecting nutrient resupply from below. While diatoms seem to be negatively affected by the decrease in nutrient concentrations associated with river discharge, dinoflagellates often benefit as this usually increases stratification and the availability of humic substances (Doblin *et al.*, 2005). PSP dinoflagellate blooms of *Gymnodinium catenatum* (in Tasmania, Australia [Hallegraeff, McCausland and Brown, 1995]) and *Alexandrium tamarense* (off Massachusetts, the United States of America [Anderson, 1997]) tend to be closely associated with land runoff events. In Hiroshima Bay, Japan, blooms of the fish-killing raphidophyte *Chattonella marina* followed typhoon-induced accretion of nutrient-rich land runoff (Kimura, Mizokami and Hashimoto, 1973).

Increased temperatures driven by climate change are predicted to lead to enhanced surface stratification, more rapid depletion of surface nutrients and a decrease in replenishment from deep nutrient-rich waters (Figure 38). This in turn will lead to a change in phytoplankton species, with smaller nanoplankton and picoplankton cells with higher surface-area:volume ratios (better able to cope with low nutrient levels) favoured over larger cells. Mixing depth affects sea surface temperature, the supply of light (from above) and nutrients (from below), and affects phytoplankton sinking losses within the surface layer. Climate models predict changes in the mixed-layer depth in response to global warming for large regions of the global ocean. In the North Pacific, decadal-scale climate and mixed-layer variability (Hayward, 1997), and, in the North Atlantic, longer-term changes in wind intensity and stratification since the 1950s have also been related to considerable changes in the phytoplankton community (Richardson and Schoeman, 2004). Similarly, in high-latitude regions with relatively deep mixing and sufficient nutrients, decreasing mixing depth has resulted in higher phytoplankton biomass because of increased light availability. In contrast, in regions with intermediate mixing depth, increased stratification has resulted in decreased phytoplankton biomass owing to reductions in nutrient supply.



Source: Doney (2006).

5.2.5.3 Ultraviolet radiation

Ultraviolet (UV) can negatively affect several physiological processes and cellular structures of phytoplankton, including photosynthesis, nutrient uptake, cell motility and orientation, algal life span, and DNA (Häder, Worrest and Kumar, 1991). Whereas shorter wavelengths generally cause greater damage per dose, inhibition of photosynthesis by ambient UV increases linearly with increasing total dose. In clear oceanic waters, UV-B radiation can reach depths of at least 30 m. Although some phytoplankton may acclimate to, compensate for, or repair damage by, UV, this involves metabolic costs, thereby reducing the energy available for cell growth and division. Raven, Finkel and Irwin (2005) suggest that UV intensity affects the size ratio in phytoplankton communities because small cells are more prone to damaging UV, and have comparatively high metabolic costs to screen it out. Many surface-dwelling red-tide species of raphidophytes and dinoflagellates possess UV-absorbing pigments, which give them a competitive advantage over species lacking such UV protection (Jeffrey *et al.*, 1999).

5.2.5.4 Ocean acidification

It is widely predicted that increasing CO₂ will lead to ocean acidification, which can potentially have an adverse impact on calcifying organisms, the most important of which in terms of biomass and carbon sequestration is the coccolithophorid *Emiliana huxleyi* (Riebesell *et al.*, 2000). Calculations based on CO₂ measurements of the surface oceans indicate that uptake by the oceans of approximately half the CO₂ produced by fossil-fuel burning has already led to a reduction in surface pH by 0.1 units. Under the current scenario of continuing global CO₂ emissions from human activities, average ocean pH is predicted to fall by 0.4 units by 2100 (Orr *et al.*, 2005). Such a pH is lower than has been experienced for millennia and, critically, this rate of change is 100 times faster than ever experienced in the known history of the planet (Royal Society, 2005). Experimental manipulations of pH in *Emiliana huxleyi* cultures have both produced reduced (Riebesell *et al.*, 2000) and enhanced calcification and growth (Iglesias-Rodriguez *et al.*, 2008). This has been partially attributed to differences in analytical procedures as well as strain-specific responses, while increasingly the potential for adaptive evolution to gradual environmental changes is now also being recognised (Lohbeck, Riebesell and Reusch, 2012).

Decreasing pH to < 8.0 has been observed to have a negative effect on nitrification in marine bacteria. Therefore, it could potentially reduce nitrate availability for plankton algae. However, the nitrogen-fixing tropical cyanobacterium *Trichodesmium* may be a beneficiary of ocean acidification (Hutchins *et al.*, 2007). Decreasing pH has also been found to increase the availability of toxic trace elements such as copper. Because the relative consumption of HCO₃⁻ and CO₂ differs between phytoplankton species, changes in their availability may affect phytoplankton on the cellular, population and community level. Most harmful algal bloom species tested thus far lack carbon-concentrating mechanisms and, hence, they may benefit from increased atmospheric CO₂, whereas diatom species such as *Skeletonema*, for which photosynthesis is already CO₂-saturated, will remain constant (Beardall and Raven, 2004).

5.2.6 Mitigation of the probable impacts on seafood safety

Our limited understanding of marine ecosystem responses to multifactorial physicochemical climate drivers, as well as our poor knowledge of the potential of marine microalgae to adapt genetically and phenotypically to the unprecedented pace of current climate change, are emphasized. Some species of harmful algae (e.g. those benefitting from increased water column stratification or increased water temperatures) may become more successful, while others may diminish in areas currently impacted (Hallegraeff, 2010). The greatest problems for human society will be caused by being

unprepared for significant range extensions of harmful algal bloom species or an increase in algal biotoxin problems in currently poorly monitored areas. While, for example, ciguatera contamination would be expected and monitored for in tropical coral-reef fish, with the apparent range extension of the causative benthic dinoflagellate into warm-temperate seagrass beds of southern Australia, other coastal fisheries could unexpectedly be at risk. Similarly, incidences of increased surface stratification in estuaries or heavy precipitation or extreme storm events are all warning signs that call for increased vigilance in monitoring seafood products for algal biotoxins, even in areas not currently known to be at risk.