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REVIEW

Harmful algal blooms (red tide): a review of causes, impacts and approaches to monitoring and prediction

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Abstract

Red tide, an impermanent natural phenomenon including harmful algal blooms, causes changing the color of the sea generally to red or almost brown, and has a serious impact on environment along the coast and aquatic ecosystem. Due to recent extensive steady harmful algal blooms events that cause adverse impacts on human healthsome, aquaculture and tourism industry, and the entire economy of the coastal region, the need of society for realizing these phenomena is much greater than the past. In the recent decades, consideration of algal blooms and determination of bloom-former species and fundamental researches about dynamics of blooms are increased worldwide. Development in technology has increased our abilities in monitoring oceans and has provided new opportunities for blooms identification as well as defining the biological, physical and chemical parameters that lead to algae beginning, expansion and disappearance. In spite of these rapidly developing observational capabilities, harmful algal blooms' proceedings will carry on to be undersampled for the foreseeable future, due to their spacious spaced and temporal coverage. Therefore, reliance on models to help interpreting observations is necessary. To watch red tides, there are different methods: field observation and using sampling data, satellite-based studies, laboratory studies, modeling. (This item includes complex numerical models, conceptual models, simple analytic formula, semi-empirical models and aggregated box models or zero-dimensional models.) This paper proposes different observation and prediction methods ever used worldwide.

Keywords Algal bloom · Harmful algal blooms · Phytoplankton · Red tide

Introduction

Non-native plant or animal species in a host environment are known as an invasive species and have an inclination to propagate to a level believed to be harmful to the environment, economy or public health. Sometimes, despite not being native, they are known as the dominant species in the region and in some cases due to the expansion in the world without having destructive effects, they may not be known as invader anymore. Introducing into the sea involving bays, or into freshwaters, harmful aquatic organisms and pathogens may endanger the environment, human healthsome, property or resources and impair biodiversity or in contrast to other legal usages of such zones (IMO-BWM 2014a, b).

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Generally, origins of invasive species include: ships' ballast waters, trade species in order to establishment and development of aquarium industry, entering species to the ecosystem for reproduction, biological control and entering a new species for controlling other species, releasing organism as live food for fishing, changing and manipulation water resources in order to expand their use including the construction of water channels between two different water bodies, establishment of aquaculture farms, doing some research regardless of related side effects (Kiyani Moghadam et al. 2014).

Some examples of aquatic bio-invasions are *Vibrio cholera*, *Cercopagis pengoi*, *mitten crab, harmful algal bloom or red tide, Asterias amurensis, Carcinus maenas, Dreissena polymorpha, Mnemiopsis leidyi, Undaria pinnatifida, Caulerpa taxifolia and Sabella spallanzanii* (IMO-AIS 2014; Raaymakers and Gould 2014). Some of the outcomes of invaders on introduced environment are disrupting complex ecosystems, reducing biodiversity, degrading habitats, and increasing human health impacts and economic impacts (Kiyani Moghadam et al. 2014).

As we know, land-sourced marine pollution, overexploitation of alive marine stocks, habitat ruination and foreign species introduction to new environment had been considered as the major hazards to the oceans. Unlike oil pollution and other marine pollution caused by ships, invaders cannot be removed from or absorbed by the ocean, so their effects on the environment are irreversible (IMO-BWM 2014a, b).

Red tide is an invasive species caused by algae bloom. Algal bloom can be harmful or non-harmful. In other words, blooms and their environmental effects on aquatic areas depend on the species involved, their biological and ecological features, scale of this phenomenon, and hydrological and topographical status of environment where they are found (Bahrami Rad 2013). If this event is temporary and transient and comes from non-toxic species, it is not so alarming. But if it becomes permanent, it may cause irreparable damages to the aquatic species and ecosystem (Hamzeie 2012). Algal blooms which accompany with the natural toxin production, dissolved oxygen depletion or other negative impacts are defined as harmful algal blooms (HABs) in general. *Cyanobacteria, dinoflagellates* and *diatoms* are three main algal classes that cause HABs. *Cyanobacteria*, also called blue–green algae, are blooming species in freshwater lochs and flows, or at estuaries. The other kinds of algae which include *diatoms* and *dinoflagellates*, generally called red tides, are found mainly in marine environments, like coastlines or estuaries (Wikipedia—harmful algal bloom 2017b).

According to recent extensive steady red tide events and their adverse effects on human health, aquaculture and tourism industry, and the entire economy of the coastal region around the world, the need of society for realizing these phenomena and its causes is much greater than the past. In addition, knowing about controlling and decreasing measure and prediction methods can be effective for controlling its adverse effects. In the following, different observation and prediction methods ever used worldwide are proposed in this paper.

Red tide

Red tide used as a conversational term for one of the natural phenomena known as harmful algal bloom (rapid increase or accumulation in the population of microalgae) happens in estuarine, marine or freshwater. In this event, algae increase in the water column rapidly and cause surface water coloration, varying from purple to nearly pink, yellow, brown and normally being red or green. Since this phenomenon is occurred due to red phytoplankton bloom for the first time, it is called red tide; however, it has various colors. Also, due to the fact that this phenomenon is not uniform and its intensity changes like tide in the sea, the tide word is following the red color. These algae are not native to specific area; in other words, they have various species with broad ranges (Malaei Tavana et al. 2008; Mohammadi 2008; Wikipedia—red tide 2017a). Of 5000 + microscopic algae species or phytoplankton exist worldwide, about 300 species can cause high concentration of red tides. Only one-fourth of this amount is known to be harmful or toxic which include *dinoflagellates, diatoms, Haptophyceae, Cyanophyceae* and some of *cycloflagellate* (Malaei Tavana et al. 2008; Wikipedia—red tide 2017a, b). Many of the HAB species have complex life cycles, and physiologically, they are categorized into single-celled, colonies, resistant cyst and temporary cyst. Having different shapes and properties increases their resistance against harsh environmental condition. Approximately 75% of HAB species and about 50% of red tide species are *dinoflagellates*, and many of their toxic species form resistant cysts (Mohammadi 2008; Bahrami Rad 2013). Studies indicate the presence of 21 bloom-former species is potentially toxic, in *Persian Gulf* (Malaei Tavana et al. 2008). Some blooms may be identified by water coloration due to high level of pigmented cell density. Some *dinoflagellates* have bioluminescence property and produce living light, while the others are the cause for red tide (Wikipedia—red tide 2017a, b). By photosynthesis and reproduction of these single-celled algae, converting dissolved nutrients and uncomplicated into plant biomass, and small population of grazing zooplankton and aquatic species, bloom is enlarged. It seems that their population is affected not only by their growth rate, but also by wind or ocean currents that bring them to the water surface (Anderson 1994; Malaei Tavana et al. 2008).

Two major contributing factors to the growth of phytoplankton are temperature and nutrients, especially phosphorus and nitrogen. Phytoplankton live in the depth of 100 meters or more. The depth is limited by the light accessibility. Photosynthesis can occur in 1% of the light level and phytoplankton have their optimal growth, not just on the surface, but deep down, about 100 meters subsurface, since the water is nutrient-rich, such as nitrogen, phosphorus and iron (Wikipedia—red tide 2017a, b).

The dominant mode of reproduction is simple asexual fission. Different phytoplankton species have different growing rates. Measures are taken pursuant to which we can evaluate the average daily growth rate. The average daily growth rate of *dinoflagellates* is almost 0.3 per day with a three-day period for regeneration. *Diatoms* have a daily growth rate more than *dinoflagellates*; 40% of them have regeneration period less than 3 days (Malaei Tavana et al. 2008; Taghavi and Abbaspour 2012). The algae cells' population can grow fast when there is no shortage of nutrients or light, or wide grazing by tiny zooplankton that consume the algae. Sometimes, a milliliter of seawater can hold tens or hundreds of thousands of algal cells (Anderson 1994; Malaei Tavana et al. 2008; Vahedi 2009). Due to high growth rate of phytoplankton population, they determine the carbon level in the ocean. The issue can also affect climate change (Wikipedia—red tide 2017a, b).

When nutrients are in short supply, some species did sexual reproduction by producing thick-walled dormant cells, called cysts. If these circumstances are not changed by natural and physical forces, they can settle on the seabed and remain there for years. During upwelling phenomenon, cooler and typically nutrient-rich water has driven toward the surface. Along with the water, cysts deposited on the seafloor come up. The nutrient-rich water along with the appropriate conditions of temperature, salinity and light increases the growing rate and reproduction of cysts. In fact, this favorable growth condition causes cyst germination and swimming cells. If the appropriate conditions remain, the cells continue to divide and reproduce so that a single cell can be multiplied into thousand cells in 2 weeks and can fill the water with swimming cells that cause bloom. However, not all algae species create cysts, many do, and this change describes main aspects of their ecology and biology. The time and location of a bloom can depend on time of sprouting cysts and the position of their settling, respectively. Also cyst production eases species dispersion. A considerable example of natural dispersion happened in 1972, when a huge bloom reaching from *Maine* to *Massachusetts* due to a September hurricane (Anderson 1994; Taghavi and Abbaspour 2012).

Dinoflagellates and *cyanobacteria* are motile species and undergo daily vertical migration. They can swim at speeds of more than 10 m/day and pass thermocline layer. This property is a great advantage for them. They are exposed to sun bathers on water surface during daytime and then swim down to the *pycnocline* to receive nutrients during night. So, blooms can unexpectedly appear on water surface that are nutrient-free and seemed to be unable to support such abundant growth. *Dinoflagellates* do their migration by flagella, while *cyanobacteria* alter their depth by varying their floating cells. This advantage can be useful only when the water column is stable. So red tide usually cannot be developed unless the water column surface is stable or phytoplankton population is trapped near a density gap (cut or distance) of water (Anderson 1994; Astani and Agah 2012).

Cullen and MacIntyre (1998) showed that since solar radiation and inorganic nutrients are the main material sources for autotrophic phytoplankton, vertical processes have main roles in algal growth. Margalef (1978) indicated that in nutrient-rich turbulent waters, nutrient stock is less restricting and the fast-growing diatoms will become dominating *("r-strategy")*. However, nutrient influx for *dinoflagellates* can be much more useful than *diatoms* in nutrient-free classified waters *("K-strategy")* (Wong et al., 2007). Also, Azov (1986) and Zingone et al. (1995) showed that *diatoms* are dominant phytoplankton community in nutrient-rich waters (coastal waters). *Dinoflagellates* are less dependent on nutrients than *diatoms*. On the other hand, *dinoflagellates* are so sensitive to changes in salinity (Sadeghi Mazidi et al. 2011). Wong (2004), with the field measurement of chlorophyll-A (CHL-A) in different depths, showed the fact that, unlike *dinoflagellates* which can migrate vertically in a daily pattern, *diatoms* are dispersed in the water and depend on passive advection

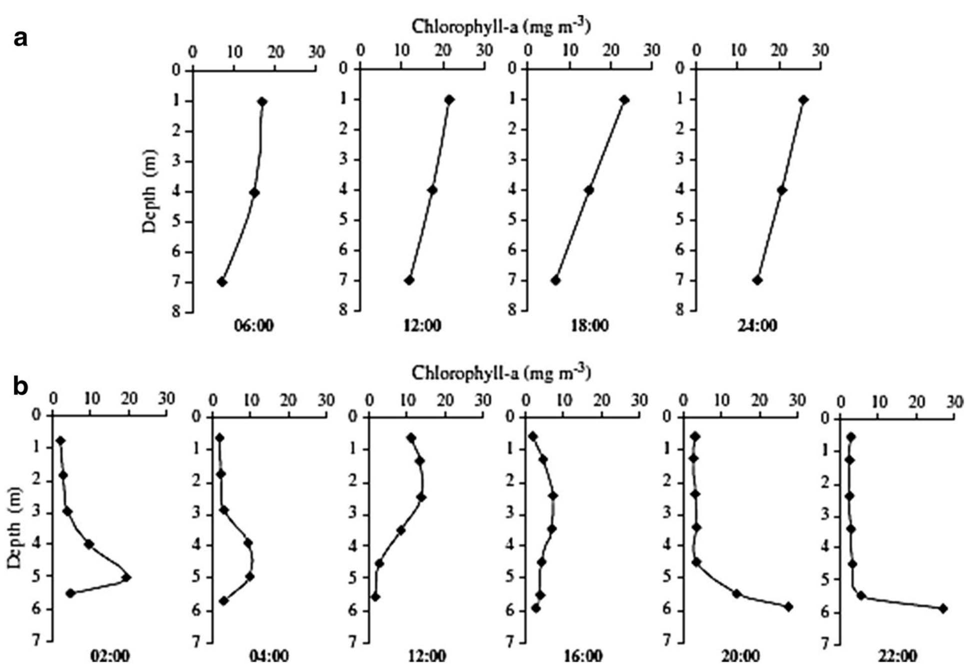

Fig. 1 **a** Observed diatom concentration profile in Lamma Island, August 2000, and **b** observed dinoflagellate concentration profile in Kat O, March 2001 (Wong et al. 2007)

and dispersion to receive their nutrient stock. These general features are shown in Fig. 1 (Wong et al. 2007).

Red tide causes

In general, the causes of red tide occurrence are divided into two categories: human activities and natural factors.

- Human activities:

1. Enrichment coastal water (eutrophication) by influx of industrial, urban, agricultural runoff and intensive animal farming fertilizers, which run into the sea by wind or running water (Malaei Tavana et al. 2008; Zarei and Arjmandi 2014): Two major nutrients in algal bloom are nitrogen and phosphorus. NH4, NO3 and PO4, which are found in industrial and urban sewage, are the best available forms (Heller et al., 1995). The amount of phosphate in the coastal waters is 15 times higher than the usual. These nutrients can increase both toxic and non-toxic phytoplankton (Malaei Tavana et al. 2008). *Theodor J. Smayda* brings the nutrient ratio supposition related to toxic bloom phenomena. He argues that human activities have changed the relative accessibility of certain nutrients in coastal waters in favor of toxic forms (Anderson 1994). Some of the studies, such as Peinert et al. (1982), Vollenweider (1992), Hodgkiss and Ho (1997), Glibert et al. (2010), showed eutrophication is a main contributor in HAB development in their growth period (Wong et al., 2007; McGillicuddy, 2010; Sadeghi Mazidi et al., 2011). Long-term studies carried out at the regional level revealed when coastal nutrients increased, algal bloom concentration is generally raised. When the pollution around *Tolo Harbor* in *Hong Kong* increased sixfold in 1976 till 1986, red tides raised eightfold (Anderson 1994; Malaei Tavana et al. 2008). The phytoplankton nutrient consumption depends on temperature and the nitrogen-to-inorganic phosphorus ratio. Optimal growth is provided in a value around 9:1. If the value is significantly different, the nutrient shortage can act as a restricting factor in algae growth (Heller et al. 1995).
2. Accumulated foods in aquaculture pools, such as shrimp and fish, cause increase in phytoplankton amount (Malaei Tavana et al. 2008).
3. Discharge of ships' ballast waters: Some studies estimated that 300 billion dinoflagellates can be transferred through ship's ballast water tanks. *G.M. Hallegraeff* of the *University of Tasmania* proved this transfer by sampling sediments accumulated in ship ballast tanks. At the time of red tide occurrence in *Persian Gulf* in 2008, *Kuwait*'s sources of news presented that the discharge of ballast waters in the shipping route between *Qatar* and *Kuwait* was the reason for that (Anderson 1994; Malaei Tavana et al. 2008; Hamzeie 2010).
4. Oil spills from ships or offshore structures: Oil spills result in increasing growth of *Noctiluca dinoflagellate* which cause red tide (Malaei Tavana et al. 2008).
5. Discharge of ships' sewage: Wastewater discharges pathogens and nutrients into water and results in increasing eutrophication and algal growth rate, and also decreasing water-soluble oxygen (Ospar Commission 2009).

- Natural factors:

1. Water surface temperature: Water temperature causes phytoplankton growth. Polat et al. (2005) showed that there is a positive correlation between temperature and phytoplankton number. Usually, effective temperature range for phytoplankton growth is 25–30 degrees Celsius (Malaei Tavana et al. 2008; Sadeghi Mazidi et al. 2011; Seddigh Marvasti et al. 2012; Zarei and Arjmandi 2014).
2. Enormous climatic oscillations: Some enormous climatic fluctuations like *El Niño* event cause coastal waters' algal bloom in *Pacific Ocean*. In other words, this atmospheric phenomenon, which happens every 3–5 years, changes the wind direction and increases temperature, and eventually results in the world climate change (Malaei Tavana et al. 2008; Bahrami Rad 2013).
3. Salinity: Gasiunaite et al. (2005) showed that salinity has a significant role in forming *diatom* community. They reported that the maximum concentration of *dinophysis* happens in water with over 5 ppt salinity and in the spring (Sadeghi Mazidi et al. 2011). Effective salinity range for *Cochlodinium polykrikoides* growth is 15–50 psu in *Korea* coastal waters and is 32–34 psu in the *Persian Gulf* (Hamzeie 2010; Ebrahimzade and Hajizade Zaker 2012).
4. Current systems: A study in *North Carolina* showed that toxic species are passing on from an area to another by ocean currents, and this process can be studied by remote sensing methods, for example transporting *dinoflagellate G. breve* cells by a warm water mass of the Gulf Stream from *Gulf of Mexico* toward *North Carolina*'s narrow continental shelf (Anderson 1994; Malaei Tavana et al. 2008).
5. Turbulence: Vertical turbulent mixing affects dynamics of phytoplankton mass in the water column. Turbulence causes the increase in *diatoms, and dinoflagellate* population, unlike when there is water stratification (Taghavi and Abbaspour 2012).

6. Vitamins: More red tide species need solved B12 vitamin to be in the range of 2-5 ng/ml. In this concentration, red tide algae species can retain their growth compared to other phytoplankton. In eutrophic regions, due to entry of contaminated river flow and organic wastewater, which include more than 10 ng/L of vitamin B12 concentration, the growth rate is maximum (Mohammadi 2008; Bahrami Rad 2013; Zarei and Arjmandi 2014).
7. Wind: Wind effect on upwelling, which brings nutrients from the seafloor to the water surface and causes increase in phytoplankton growth, is important (Malaei Tavana et al. 2008; Seddigh Marvasti et al. 2012).
8. Dust storms: Iron-rich dust with the wind blowing over large desert areas like *Sahara* enters grains to the sea, so nutrients are increased. Iron restriction is often presented as a controlling agent for red tide events alongside the eastern coast of *North America* (Malaei Tavana et al. 2008; Seddigh Marvasti et al. 2012; Zarei and Arjmandi 2014).
9. Upwelling: The most productive areas of the world are in the upwelling zones. All researchers are sure that red tide occurs after upwelling is stopped. However, it does not seem that nutrients that come from deep water to the surface are the direct cause of algal blooms by itself. *Arabian Sea, Oman Sea* and the coasts of *Peru* are the most important areas of upwelling phenomenon in the world. Upwelling along the coasts of Hong Kong waters, due to the flooding of the rivers and *Manson* winds, resulted in several hundred red tide events during the summer of the years 1998–2004 (Malaei Tavana et al. 2008; Taghavi and Abbaspour 2012; Bahrami Rad 2013).
10. Changes in water temperature: Increasing the water temperature above the average value is one of the reasons for the increase in algal bloom (Malaei Tavana et al. 2008).
11. Rainfall: Rainfall with increasing nutrients flows to the sea, especially in temperate regions such as the *Caspian Sea* and the *Black Sea*, and causes algal bloom. Many of the phytoplankton blooms occur after a heavy rain period like the Texas coast in 1935 (Malaei Tavana et al. 2008; Taghavi and Abbaspour 2012; Zarei and Arjmandi 2014).
12. Light: Phytoplankton are alive so they need light to grow and for photosynthesis phenomenon. Therefore, the depth of light and light penetration and light intensity, day and night, are important in this phenomenon. A period of sunny and warm days is often observed before the occurrence of red tide (Malaei Tavana et al. 2008; Seddigh Marvasti et al. 2012).
13. The lack of hunters or consumers of red tide algae (Malaei Tavana et al. 2008).
14. Climate change: Since climate change results in increasing global warming and also sea and ocean temperature affects changing in air circulation patterns, so it causes developing algal blooms. Also dust storms and strong winds and intense rainfalls due to climate change increase nutrient flow to the waters. Based on Australian scientists' studies, global warming is a major driving force for blooms in the southern hemisphere (Zangi Abadi 2011; Wikipedia—harmful algal bloom 2017a, b).
15. Low water levels in inland waterways and lakes: This phenomenon results in reducing water flow and increasing water temperatures (Wikipedia—harmful algal bloom 2017b).
16. Earth activities like earthquake in seabed and volcano: These phenomena cause heat generation due to earth layer friction and also increase the possibility of dissolving materials like iron and mineral compounds in water, acknowledged by some *NASA* scientists. On the other hand, earthquake occurrence can cause upwelling. This condition in *Qeshm* earthquake resulted in an excessive algal blooming due to nutrient dispersion. In 2010, iron-dissolved ash from the *Eyjafjallajökull* volcano created an algal bloom in the *North Atlantic* (Rezaee and Kabiri 2009; Wikipedia—algal blooms 2018).
17. Ocean eddies: Eddies, as hydrodynamic phenomena, have a great influence on ecosystem changes and algal blooms. In general, they are divided into 3 types: cyclonic, anticyclonic and mode water. Each of them results in different ecological responses in the region, due to their effects on water layers and the density displacement in the lower layers. According to studies in *BATS* region of *Sargasso Sea*, chlorophyll is increased in areas affected by cyclone and mode water eddies and decreased in areas affected by anticyclonic eddies. In addition, mutual satellite studies of surface temperature and chlorophyll show an increase in chlorophyll concentration in cold eddies and a reduction in warm eddies (Seddigh Marvasti 2016).

In this regard, recognizing thermocline layer is important because enough nutrients and light are in this layer. Also, current, wind, tides, water stratification, etc. are important factors. The growth rate of phytoplankton with hydrodynamic conditions is important. For example, in one place there is a growth rate, but the strong current in that place transports phytoplankton by itself to another place. But in another hydrodynamics condition, the same growth rate is proper for red tide occurrence (Seddigh Marvasti 2016).

Notable occurrences

While harmful or harmless kinds of red tide has been reported from all over the world, harmful red tide occurred more in countries such as *Brazil, Korea, China, Japan, Chile, Canada, UK, France, Hong Kong, India,* the countries of the *Black Sea* and the *Mediterranean Sea* and recently the *Persian Gulf* and the *Caspian Sea* (Malaei Tavana et al. 2008; Seddigh Marvasti et al. 2012). The red tide prior occasion occurred in *Florida Gulf Coast,* 1530 (FDACS 2017).

Many species can make the red tide phenomenon happen. These species, due to their kind and creation of destructive masses and depletion of dissolved oxygen and production of toxins or mucus, cause marine mortalities, coastal pollution and damage to environment and tourism industry. Sometimes consuming poisonous shellfish leads to illness or death in humans (Vahedi 2009; Astani and Agah 2012) (Table 1; Fig. 2).

According to the date of mentioned events, the number of HABs, the scale and complexity of this natural phenomenon, the economic damages, the kinds of affected supplies and the variety of toxins have all increased. Indeed, there is a belief among several experts about expanding. Is this true expansion? Is it a worldwide outbreak? Is it connected to human activities, like increasing contamination along the coast? Or is it due to developed scientific grasp and better supervision or analytical abilities? Possible reasons for the increase may include the following: natural mechanisms of dispersal of species (marine currents and tides), a group of phenomena related to human activities such as enrichment water, climate change, and transferring harmful algal species by ships' ballast water (Anderson 1994; Malaei Tavana et al. 2008; Wikipedia—red tide 2017a, b).

Effects of red tides

Physical and chemical conditions of water (appropriate temperature, nutrient-rich water specially phosphates and nitrates) and increasing pollution of sea cause explosive growth of single-celled plants and create appropriate environment for flagellates' growth. Red tides are often accompanied by large-scale marine mortalities occurrences in fish, seabirds, sea turtles, marine mammals and other organisms. In fact, its cycle is like this; algae produce toxins and shellfish like oysters use them. So, the algal toxins accumulate in their body and transfer to organs of certain fish that consumes it. Finally, through the marine food web, these toxins are entered to human bodies. Hence, the above phenomenon causes serious illness and economic harm (Mohammadi 2008; Zarei and Arjmandi 2014; Wikipedia—red tide 2017a, b).

In general, damages caused by red tides are divided as follows:

- Direct poisoning for aquatic animals and humans: Some toxins produced by red tide are so strong that they can kill marine animals and cause illness in people directly. The most famous of toxins is neurotoxin which causes paralyzing the central nervous system of fish and resulting in asphyxiation (like the *dinoflagellate Gymnodinium breve* in the *Gulf of Mexico*). Also they can cause respiratory and skin irritation for beach-goers due to swimming or touching the water and inhaling the toxin from the spray of wind or waves. Some phytoplankton species produce polyunsaturated fatty acids and galactolipids which result in destroyed blood cells. This effect would describe the ruptured gills, hypoxia and edema in dead fish. Some algae also create these hemolytic compounds and neurotoxins. The combination can greatly decrease a fish's heart rate, leading to decrease in blood flow and a dangerous reduction in oxygen amount.
- Indirect poisoning for aquatic animals and humans: based on the National Oceanic and Atmospheric Administration (NOAA), non-toxic blooms can cause indirect marine mortalities by oxygen depletion and uncomplicated blockage in the water when flourishing and while rotting after they die. In other words, they create dead zone as a result. There were 49 dead zones in the 1960s which is increased to 405 by 2008 all over the world. The produced toxins can also enter the aquatic species' body through feeding. Then, consumption of these species by other species such as birds, marine mammals and even humans causes illness and death. Indirect poisoning in humans happen by eating shellfishes contaminated with red tide toxin, because they feed the algae and keep the toxins in their digestive system. Some of the examples are: over 150 dead manatees on *Sanibel Island, Florida,* in 1996; 14 dying humpback whales in *Cape Cod Bay, Massachusetts,* in 1987; dying pelicans due to amnesic shellfish poisoning (ASP) in *Monterey Bay* in 1991; and fish kill more than 34 tones in *Hormozgan* waters, *Persian Gulf* in 2008(Anderson 1994; Rezaee and Kabiri 2009; PGTMRC 2014). Human shellfish poisoning syndromes caused by HABs are as follows: *amnesic shellfish poisoning (ASP)* like Canadian outbreak in 1987, *ciguatera fish poisoning (CFP)* predominantly in tropical and subtropical islands (*ciguatera* toxins is soluble in fishes' tissues), *diarrheic shellfish poisoning (DSP), paralytic shellfish poisoning (PSP), neurotoxic shellfish poisoning (NSP)* like *North Carolina* episode, *azaspiracid shellfish poisoning (AZP)*. About 60,000 poisonings in the world each year have been documented due to algal toxins (Anderson 1994; Biello 2008; Malaei Tavana et al. 2008; PGTMRC 2014; Zarei and Arjmandi 2014; Peebles, 2016; Wikipedia—harmful algal bloom 2017b).
- Discolor coastal waters and harm water quality: This issue results in damaging desalination systems and equip-

Table 1 Some of the red tide notable occurrences (Anderson 1994; Wong et al. 2007; Shams 2009; Hamzeie 2010; Farman Ara et al. 2012; Daily Express 2013; NOAA 2016; The press democrat 2015; Ecowatch 2016; EPA 2017; IHABDC 2016; Novascotia 2017; Wikipedia—harmful algal bloom 2017a, b; Wikipedia—algal blooms 2018; Milstein 2015)

1793	**Species**: red tides contained with paralytic shellfish poisoning (PSP) Some of the red tide notable occurrences (*British Columbia*, *Canada*) Damages: a sailor of Captain *George Vancouver's* ship was died by eating mussels	1998	**Species**: *Karenia digitata* Area: Hong Kong **Damages**: Above 3400 tones (80 percent) of fish stock ruined, about HK$312 million economic loss
1840	**Species**: *Karenia brevis* **Area**: *Florida* **Damages**: Respiratory irritation (coughing, sneezing and tearing) due to transferring its toxic aerosol onshore by winds blow, itching and burning due to swimming in high-concentration red tide regions	2001	**Species:** 3 red tide species (*Pyrodinium bahamense*, *Gymnodinium catenatum* and *Gyrodinium impudicum*) and *Streptococcus agalactiae* bacteria **Area**: *Kuwait* **Damages**: Large-scale fish kill
1972	**Species**: A*lexandrium (Gonyaulax) tamarense* **Area**: *New England* **Damages**: Lead to PSP due to consuming toxic shellfish (contained *saxitoxin* and *gonyautoxins*)	2002	**Species**: *Prorocentrum minimum* **Area**: *Philippines* **Damages**: About 120 thousand dollars economic loss
1972 –1973	**Species**: Several red tide species **Area**: *Port Moresby Harbour* **Damages**: 2 death and harmed a Japanese pearl farm	2005	**Species:** *Canadian HAB* **Area**: From *Maine* and *Massachusetts* to *Long Island*, *NY* **Damages**: Closed shellfish beds, destroyed the area's fishing and shellfish industry, menaced tourism industry
1976	**Species**: *Pyrodinium bahamense (var. compressum)* **Area**: *Sabah, Malaysian Borneo* **Damages**: 202 suffering and 7 deaths due to PSP	2007	**Species**: *Noctiluca* **Area**: *British Columbia* **Damages**: 260 tons of salmon loss in a fish farm
1983	**Species**: *Pyrodinium bahamense* **Area**: *Samar sea, Philippines* **Damages**: 700 cases of acute poisoning and 70 death in humans and about 500 thousand dollars economic loss	2008	**Species**: *Cochlodinium polykrikoides* **Area**: *Chesapeake Bay* and close branches like *the James River* **Damages**: Millions of dollars economic loss and many beach closures
1985	**Species**: *P. parvum (golden algae)* **Area**: *Pecos River, Texas* **Damages**: Affected 33 reservoirs alongside main river systems, about 27 million fish mortality and tens of millions of dollars economic loss	2009	**Species**: Green algal boom **Area**: *Brittany, France* **Damages**: a human unconsciousness and 3 animal mortalities due to lethal rotting gas emissions
1987	**Species**: *Alexandrium tamarense* **Area**: *Cape Cod Bay, Massachusetts* Damages: 14 died humpback whales due to consuming mackerel contained with saxitoxin, 3 death and 105 poisoning case, respiration problems and eye irritation, diarrhea, dizziness, vomiting, abdominal cramps and other symptoms showing neurotoxic poisoning, and permanent short-term memory loss due to eating mussels *from Prince Edward Island*	2013	**Species**: *Red tide* **Area**: *Sarasota* beach, *Florida* **Damages**: Fish and manatee mortality, respiratory problems for beach-goers, harmed tourism industry
		2013	**Species**: *Pyrodinium bahamense (var. compressum)* **Area**: *Sabahw* east coast, *Malaysian Borneo* **Damages**: Two death due to consume a toxic shellfish
		2015	**Species**: Red tides containing PSP **Area**: *Bohol* **Damages**: 12 people suffered
1991	**Species**: *Pseudonitzschia* **Area**: *Monterey Bay, California* **Damages**: Sick/death brown pelicans and cormorants, consuming anchovies contained domoic acid	2015	**Species**: Reddish brown algae **Area**: *Katwijk and Scheveningen, the Netherlands* **Damages**: Public warning for not swimming because of skin irritation and respiration problem

Table 1 (continued)

1995	**Species**: *Cochlodinium polykrikoides* **Area**: *Korea* Damages: About 95 million dollars damage in fishery during 8-week period	2016	**Species**: toxic algal bloom **Area**: *Chile* **Damages**: 23 million salmon mortality in a farm, about $800 million economic loss
1995	**Species**: *Gymnodinium and Phaeocystis spp.* **Area**: *Persian Gulf (Kuwait)* **Damages**: Fish kill about several tones	2016	**Species**: Several harmful genera of algae **Area**: *Florida* **Damages**: Closed several beaches like Palm Beach

ment, ships and shore facilities. For instance, *Toledo* water treatment plant could not treat the water to safe level in 2014, so authorities gave hints to its 500,000 residents to not to drink tap water. *Kenya* in 2004, *China* in 2007 and *Australia* in 2016 experienced similar incidents.

- Economic and social harms and a sharp decrease in tourism industry: based on a report in 2016, economic loss includes the costs come from lost business; damages to human healthsome, fisheries, tourism and recreation; healthcare organization studies like water sampling and testing, and marking affected areas by warning signs; and also monitoring and management of flourishing areas. *NOAA* had declared that some of these estimated costs are caused by different blooms in recent years: $10.3 million loss at *Texas* oyster farm in 2011; $2.4 million loss in *Pacific Northwest*; and $40 million loss at *Washington State* due to fishery closures in 2015.
- Formation of fetid foam with unpleasant smell: This foam is created due to the decomposition of bacteria when they reach to a growth degree, and result in harm to beachgoers and sharp drop in coastal traffic. In 2009, northern *Brittany* beaches were covered by tones of potentially lethal rotting green algae and a horse died by fumes emitted from them.
- Severe damage to light-dependent aquatic (especially coral) ecosystems: Suffocation and reduction in light penetration due to the formation of gelatinous mass after the death of algae and sediment on the seafloor blooms have damaging effect on benthic organisms and coral reefs. Severe damage to coral reefs in *Hormozgan* waters, around northern part of *Lark Island*, southeast part of *Qeshm Island* and eastern part of *Faror Island* in 2008, is one of these cases (Vahedi, 2009; Taghavi and Abbaspour 2012; NOAA 2016; Wikipedia—harmful algal bloom 2017b) (Fig. 3).

Controlling and decreasing methods for red tide

The best time to control bloom is before the time of bloom development. Preventing the sewage, animal waste and urban runoff entry to the sea; establishment of the equipped refinery and complete wastewater treatment in order to control the nitrogen-to-phosphorus ratio; preventing the dangerous change in the water temperature; rectification of farming methods like utilizing fertilizer at the proper time for decreasing potential runoff (applying fertilizer drip irrigation system as an alternative to wide dispersion due to keeping fertilizer to be washed away); establishing barrier areas of bush and wetlands to help remove the phosphorus before reaching water; and applying conservation tillage, changing crop rotations and reinstating wetlands are the solution for preventing HABs.

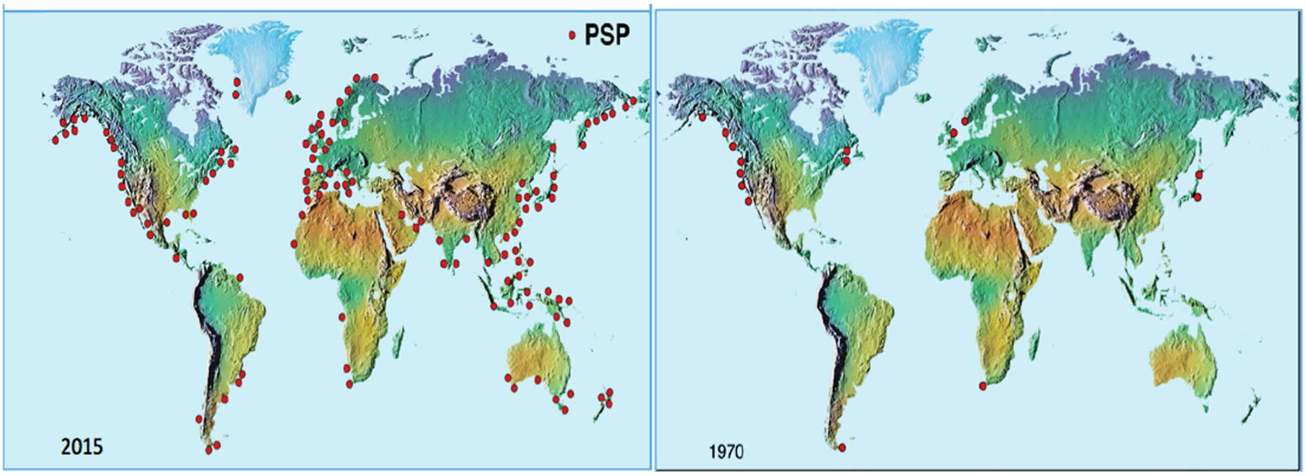

Fig. 2 Comparison outbreak of red tides in 1970 and 2015 (WHOI 2015)

After the outbreak of algal bloom, some of the proposed methods to control and decrease growth of red tides, including physical, chemical and biological, are as follows:

- Physical methods: These methods include decreasing sources of nutrient entry like industrial and urban sewage; treating wastewater by cultivating algal in purification ponds; reducing the salinity conditions of ecosystem; changing the water rotation to prevent red algae dispersion; spraying phosphate-free clay (powder or liquid); controlling ships' ballast waters before discharge by preventing untreated ballast waters entry into the sea; using floating anchorages as well as using it to prevent oil spill development at sea; collecting dead fish in coastal waters and burying them; and suctioning water contaminated with red tide and returning it to the sea after proper filtering. Among these methods, using clay to eliminate algae, although not acceptable, increases the risk of marine pollution, but due to its high performance in eliminating algae, low cost and availability, and also having minimal impact on aquatic organisms and the environment, it has been introduced as the safest and most effective method for eliminating algal bloom. About 25 years ago, preliminary data about using clay to deal with this phenomenon in affected countries such as *Japan, South Korea* and *Australia* were obtained and they began to spray clay for controlling the algae bloom. Clay can cause flocculation and sedimentation of algal cells rapidly or can reduce this phenomenon by chemical or physical interactions with the cells. Due to accumulation of clay on the algal cells on the seafloor, there is a possibility of cell death.

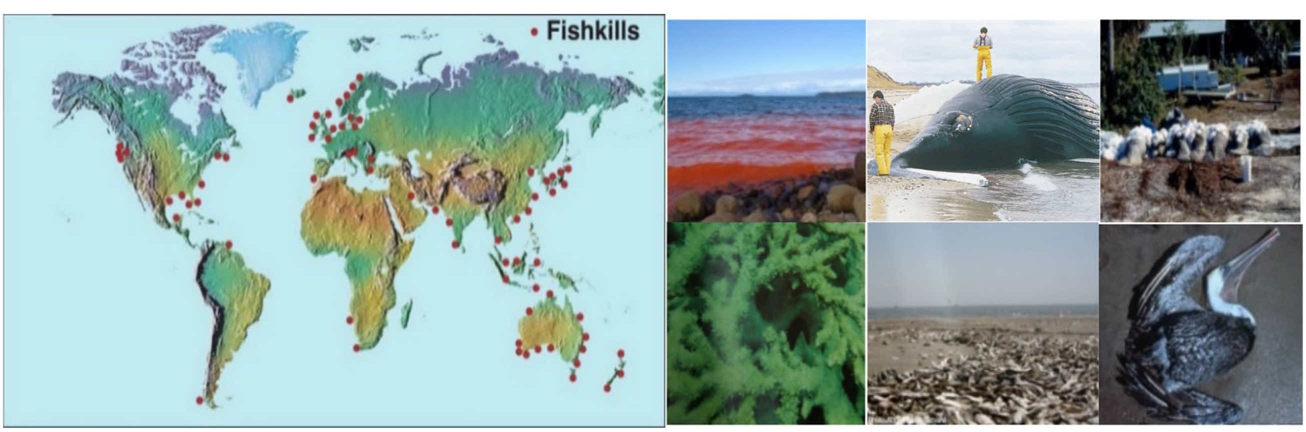

Fig. 3 Fish kill plan due to red tide 2014 and some damages caused by red tides (dead manatees on *Sanibel Island;* water discoloration in *British Columbia*; dying humpback whales in *Cape Cod Bay;* dying pelicans in *Monterey Bay*; fish kill and bleaching staghorn coral in *Persian Gulf*) (Anderson 1994; Rezaee and Kabiri 2009; PGTMRC 2014)

- Biological methods: Biological methods use living organisms such as grass-fed aquatic birds and domestic animals, microorganisms causing rotting, and bacteria and viruses to control phytoplankton' population. Although using biological method is common and acceptable, it must be admitted that it cannot be easily used by other organisms in the marine environment. New animal login to the marine environment is likely to change or even destruct the current ecosystem. The first research studies determine the biological species include viruses, bacteria and parasites that could affect harmful algal bloom species. At first, for biological control, we must do some research to determine the viruses, bacteria and parasites that could have harmful effect on algal bloom species. Also the environmental effect of releasing non-native species must be investigated before any biological control.
- Chemical methods: Chemical method is done regularly by using systemic pesticides and herbicides in small bodies of water. This method is expensive and risky because of its negative effects on marine wildlife but affects very soon. In chemical methods, materials such as silver nitrate, copper sulfate, ozone, potassium permanganate can be used in ponds and aquaculture centers. Of course, at first, this method should be carefully tested in laboratory conditions. Also, using sodium hypochlorite solutions, generated by electrolysis of seawater at a rate of 4.0 grams per cubic meter, is one of the most useful chemical methods for decreasing the population of *Cochlodinium*, dominant red tide species in the *Persian Gulf*. (Nabi Zadeh et al. 2009; Asadi, 2011; Astani and Agah 2012; Taghavi and Abbaspour 2012; Zarei and Arjmandi 2014; Wikipedia—harmful algal bloom 2017a, b) (Fig. 4).

Red tide observation and prediction methods

Development in technology has increased our abilities in monitoring oceans and has presented new opportunities for bloom identification as well as defining the physical, chemical and biological parameters that lead to algae beginning, expansion and disappearance. In spite of these rapidly developing observational abilities, HABs' proceedings will carry on to be undersampled for the foreseeable future, due to their extensive spatial and temporal coverage. In addition to creativeness and innovation of explorers in developing new models and methods, future improvements in this field depend deeply on cooperation of physical and biological researchers struggling with plankton populations. For example, a HAB problem on the *West Florida Shelf* was studied by one of the early coupled physical–biological models of plankton dynamics, considering growth and diffusion effects (Skellam 1951; Kierstead and Slobodkin 1953). By predicting red tide events and fast provision of mitigation activity, reducing the loss of HABs will be possible (McGillicuddy 2010; Park et al. 2013).

To watch red tides, there are different methods: field observation and using sampling data, satellite-based studies, laboratory studies and modeling (this item includes complex numerical models, conceptual models, simple analytic formula, semi-empirical models and aggregated box models or zero-dimensional models) (McGillicuddy 2010; Seddigh Marvasti et al. 2012). Also, autonomous underwater vehicles (AUVs) can be used for data collecting. In 2003, a robot glider, equipped with miniature sensors which could record temperature, salt and plankton levels, was released into the *Gulf of Mexico* by *Gary Kirkpatrick* team of *Rutgers University* to help forecast and study red tides. Furthermore, it

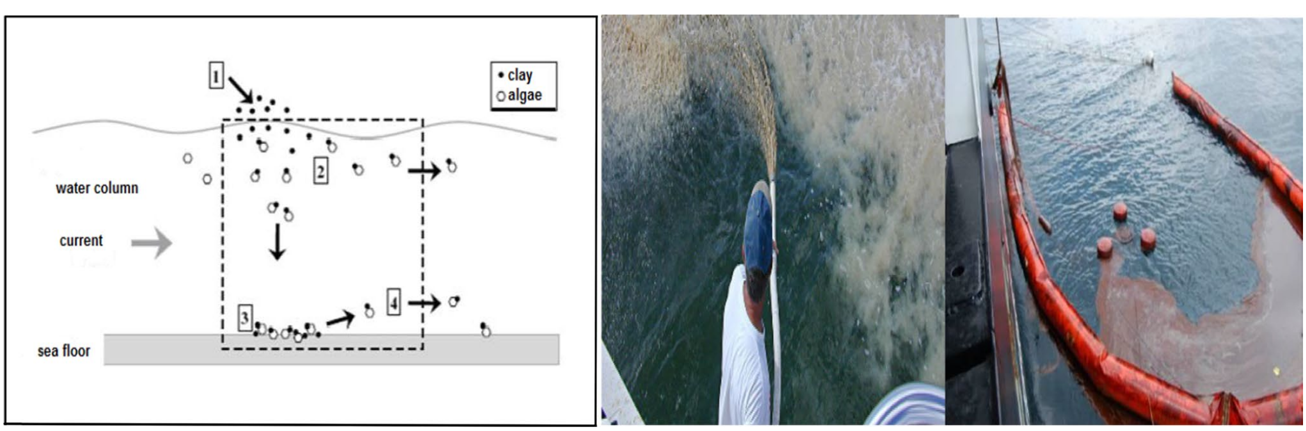

Fig. 4 Use of clay and floating inhibitor to control algal bloom; plan for suspended mass of clay/algae, deposition and resuspension (Astani and Agah 2012; Zarei and Arjmandi 2014)

can help researchers for finding out key information about causes of red tide formation. The glider transmitted its positions and data to *Kirkpatrick*'s team through satellite prior to set up a new course based on a GPS system and began again its underwater voyages. It could swim for 15–20 km a day (Clarke 2003).

Statistical method such as manual method, pattern recognition and case-based reasoning (CBR) are applied in field studies. Examination of prior red tide events, marine environment and coast area databases is done using manual methods in direct way for forecasting algal blooms. *Smaydam* (2000) manually analyzed former algal bloom occurrence database to forecast its happening by considering a 38-year time series according to weekly sampling in *Narragansett Bay*. In CBR method, a database of cases of red tide incidents is applied to identify same patterns and use the reasoning process for prediction algal bloom. The *K-nearest neighbor (kNN), support vector machines (SVM), neural network, naive bayesian classification, decision trees*, and *fuzzy* methods are the basis of the pattern recognition methods (Li and Smaydam 2000; Park et al. 2013) (Table 2).

The fact that phytoplankton are strongly influenced by the optical properties of natural waters and discolored or murky waters were caused by high concentration of algae leads to the detection by using biosensor methods. Satellite remote sensing is a proper method for phenomena that occur in waters and land surface. In red tide detection, the amount and extent of the red tide can be calculated by using standard estimation algorithm of chlorophyll, phytoplankton absorption determination, checking turbidity and light penetration changes in seawater and spectral study of different wavelengths by remote sensing methods. Ocean color remote sensing method is a useful tool for assessing HAB phenomenon, measuring amount and quality of light reflected from the sea surface. These ocean sensors are installed on the satellite to detect changes in ocean waters and mainly provide useful information through the radiation transport equations. This tool provides increase in regular and extensive monitoring of coastal waters and developing our ability to determine the presence of HABs, their distribution and tracking them quickly (Hamzeie 2010, 2012; Seddigh Marvasti et al. 2012). In 1979, the first satellite detection of HABs was done by Coastal Zone Color Scanner (CZCS) satellite in the world's waters, initially using simple changes in water color and then using hybrid algorithms (Hamzeie 2010).

In addition to conceptual models being practical in their own right, they are basis of all other types of models. In HAB modeling, empirically based algorithms are playing a progressively main role, and preparing a significant connection between conceptual and dynamical modeling methods. Aggregated box models, in other words zero-dimensional models, are used more for various targets, from exploratory theoretical and conceptual model development to applications in real systems with HAB phenomenon (McGillicuddy 2010) (Table 3).

For numerical modeling of this phenomenon, physical and biological equations of it must be coupled together and we must examine different scenarios. One-dimensional modeling of this phenomenon can be done by one-dimensional software such as *GOTM, PROBE*, and for two-dimensional and three-dimensional modeling, software such as *Coherence* and *MIKE* can be used (Seddigh Marvasti et al. 2012). Examples of related work, carried out in each branch of study, are presented in Table 4.

Conclusion

Due to recent extensive steady HAB events that cause adverse impacts on human healthsome, aquaculture and tourism industry, and the entire economy of the coastal region, the need of society for realizing these phenomena is much greater than the past. By forecasting red tide occurrence and immediate mitigation activity preparation, reducing the loss of HABs will be possible. Development in technology has increased our abilities in monitoring oceans and has provided new opportunities for blooms identification as well as defining the biological, physical and chemical parameters that cause algae emergence, expansion and disappearance. Therefore, reliance on models to help interpreting observations is necessary. In addition to creativeness and innovation of explorers in developing new models and methods, future improvements in this field depend deeply on cooperation of physical and biological researchers struggling with plankton populations. Based on studies, field observation and laboratory studies are difficult and time-consuming methods. Also, they are weak for spatial and temporal observation. Further, satellite-based studies have limitations such as the superficiality of satellite data. Conceptual models, although the basis

Table 2 Laboratory studies and field observations and using the measured data

2004	**Researcher**: *Wong Tse-man, Ken* **Research location**: *Hong Kong* subtropical waters **Reference**: (Wong 2004) **Accomplished task**: Applied online field monitoring system at *Kat O* and *Lamma* Island from 2000 till 2003 to monitor some parameters variation and *Lagrangian* modeling for forecasting algal blooms **Assessed parameter**: Dynamics of algal biomass, dissolved oxygen (DO) and some major hydrometeorological variations **Conclusion**: Considered the water turbulence and nutrient significance on species choice and bloom control; found the various vertical structure of CHL and DO for diatom and dinoflagellate blooms; obtained growth and sinking rate, and migration speed from one steady in situ data during the blooms
2005	**Researcher**: *Lee* et al. **Research location**: *Hong Kong* **Reference**: (Lee et al. 2005; Wong et al. 2007) **Accomplished task**: Carried out a real-time algal bloom observations by an early warning system and bringing up a real-time telemetric monitoring system at two different hydrographic and pollution loading feature mariculture areas: *Kat O* and *Lamma* Island (depth about 10 m) by observing the following parameters at period of 10-14 days **Assessed parameter**: CHL, DO and water temperature data at three depths; sunlight, wind speed and direction, tidal current, water transparency; vertical profiles of salinity and temperature; and nutrient (phosphate, mineral nitrogen) concentration **Conclusion**: Evaluated and interpreted hydrobiological factors throughout a bloom in an integrated system; facilitated the forecasting model development of various bloom; proved the relationship between CHL concentration and values of assessed parameters in the previous week
2006	**Researcher**: *Lee* et al. **Research location**: *Jinhae Bay, South Korea* **Reference**: (Park et al. 2013) **Accomplished task**: Studied marine environment impact on the algal blooms occurrence by analyzing the following parameters 10 days prior to the red tide blooms due to reaching the red tide density alert after 10 days of red tide beginning **Assessed parameter**: Temperature, rainfall and solar radiation **Conclusion**: Marine environmental and weather variables, 10 days before the red tide event, are a main reason of red tide blooms
2006	**Researcher**: *Rong* et al. **Research location**: *South Korea* **Reference**: (Park et al. 2013) **Accomplished task**: Red tide forecast according to fuzzy neural network **Conclusion**: Showed that their method has better prediction result than a back propagation (BP) network and radial basis function (RBF) network **Limitation**: Not enough accuracy in the prediction results due to utilizing small amount of data for the experiment of the method
2010	**Researcher**: *Blauw* et al. **Research location**: *Dutch* coastal waters **Reference**: (Blauw et al., 2010; McGillicuddy, 2010) **Accomplished task**: Applied fuzzy logic for relating nuisance foam occurrences to Phaeocystis globosa blooms, measuring their correlation with environmental parameters like mixed layer irradiance and access to nutrient; **Assessed parameter**: salinity; nutrients, Phaeocystis; CHL-A; extinction coefficient; images of foam on the beach; fluorescence; wind speed; wind direction; solar irradiance data of 1991–2007 (some data sources like Waterbase, ARGUS, Smartbuoy, KNMI) **Conclusion**: Predicted about 90 percent of viewed foam happens at the period 2003–2007 correctly; however, there were many false positives; communicated current realization of foam origination; increased the probability of forecasting these events, established a basis for more detailed modeling efforts
2010	**Researcher**: *Wang* et al. **Research location**: Southwest of *Luzon Strait* **Reference**: (McGillicuddy, 2010; Wang and Tang 2010) **Accomplished task**: Applied empirical orthogonal function analysis by using satellite ocean color database for the identification of winter phytoplankton blooms, related their reasons to subsurface upwelling and mixed layer entrainment via statistical analysis of both remotely sensed and in situ observations **Assessed parameter**: Remote sensing database of CHL-A, surface temperature and winds, and in situ observations database of DO, nutrients (nitrate, phosphate and silicate), and physical oceanographic parameters like mixed layer depth, Ekman pumping velocity and entrainment velocity at the period of 2000–2006 **Conclusion**: Showed Ekman pumping-driven upwelling (observed at about 50 m subsurface) and upper mixed layer entrainment as the main reasons for winter bloom, and the relation between the seasonal bloom variation and monsoonal wind forcing
2010	**Researcher**: *Raine* et al. **Research location**: *Bantry Bay, southwestern Ireland* **Reference**: (McGillicuddy, 2010; Raine et al., 2010) **Accomplished task**: Recognized a chain of visible events like physical forcing of wind-driven two-layer oscillatory flow that result in HAB occurrences in coastal waters, assess capability of HAB predictions methods in both hindcast and forecast modes **Assessed parameter**: Wind index, water temperature, HAB cell No. per liter **Conclusion**: Wind-driven exchange is the main cause of HAB events in the bay due to phytoplankton populations transfer

Table 2 (continued)

2010	**Researcher**: *Flynn*	**Research location**: UK	**Reference**: (Flynn, 2010; McGillicuddy, 2010)
	Accomplished task: Applied comprehensive physiological models to study external nutrient access effects on internal cellular nutrient stores; provided the complex nonlinear processes engaged in phytoplankton response to various environmental states; ran the model through a fixed optical depth system (1, 5 or 10 m), assuming cells homogeneous in the water column **Assessed parameter**: Dissolved inorganic N or P, N-to-P ratio, growth rate, light limitation **Conclusion**: Represented the difficulties of attempting to recognize the restricting nutrient by refer to nutrient accessibility and nutrient ratios because of the implications of nutrient stress for trophic dynamics and toxicity in HABs, and of eutrophication for ecosystem management; showed the majority of nutrient concentrations of source acquisition in phytoplankton bloom, and not ratios of those nutrients; defined the source ratio role in forming plankton ecology; considered proper model definition for simulations as important as for theoretical studies		
2010	**Researcher**: *Roiha* et al.	**Research location**: *Baltic Sea*	**Reference**: (McGillicuddy, 2010; Roiha et al., 2010)
	Accomplished task: issued an example about using ensemble methods in an ecosystem model with multiple phytoplankton functional types for forecasting cyanobacterial blooms **Assessed parameter**: Weather parameters (wind, temperature, surface solar radiation and surface thermal radiation), nitrate, phosphate and cyanobacteria concentration **Conclusion**: Showed the importance of stable conditions in establishing more unanimous ensembles prediction; defined the spring-time phosphorus fields as a fine forecaster for the spatial, basin-scale propagation of HABs in the summer; and defined the major effect of weather conditions on beginning time, period and severity of HABs		
2010	**Researcher**: *Song* et al.	**Research location**: *Korea*	**Reference**: (Park et al., 2013)
	Accomplished task: Outlined a red tide watching system using case-based reasoning, case base monitoring of prior occurrence and retrieved the most related case using the KNN classification method **Limitation**: Hasing restriction in forecasting the numerical data, for example an algae density **Conclusion**: This uncomplicated method can clearly categorize the red tide occurrence using a high likeness case of past events		
2013	**Researcher**: *Park* et al.	**Research location**: *South Korea*	**Reference**: (Park et al., 2013)
	Accomplished task: Predicting red tide using ensemble method, providing a modified composite model by applying a combination of models to improve the accuracy of the resulting classifier and predictor based on decision tree. Output variables include numerical and categorical variable. Normalization of categorical output parameters is done in the ensemble method by using a value between -1 and 1 for the red tide density. The numerical output variable data for fuzzy reasoning are determined by dividing the algae density by 1000 **Assessed parameter**: Water and sea surface temperature and rainfall data 10 days prior to red tide occurrence and algal intensity **Conclusion**: Displayed forecast correctness as high as 92.39% by utilizing experimental data of HABs in nine years in South Korea waters		
2015	**Researcher**: *Ebrahimi*	**Research location**: *Persian Gulf* and *Oman Sea, Iran*	**Reference**: (Ebrahimi, 2015)
	Accomplished task: Monitoring algal growth data of 11 stations in Hormozgan coastal waters in 2012 to investigate the monthly changes of phytoplankton, zooplankton and the environmental (physical and chemical) factors by sampling monthly using CTD **Assessed parameter**: Water temperature, salinity, DO, PH, CHL-A **Conclusion**: Defined average changes of above factors during the course and identified the dominant groups of phytoplankton and zooplankton in various seasons; Results of Spearman correlation test showed the positive and significant correlation between total amount of phytoplankton and physicochemical parameters		
2018	**Researcher**: *Huang* et al.	**Research location**: *Tolo Harbour, Hong Kong*	**Reference**: (Huang et al., 2018)
	Accomplished task: Studied the relationship between dinoflagellate and diatom red tides and meteorological factors by using a 32-year time series of frequent red tide events from 1983 to 2014 **Assessed parameter**: Wind speed and direction, rainfall, air temperature, cloud cover, hours of solar radiation **Conclusion**: Presented the optimum temperature, cloud cover, rainfall and hours of solar radiation range for dinoflagellate and diatom red tides. Warming air temperatures in spring and moderate northeasterly winds are favor for the dinoflagellate red tides generation, while precipitation prevents them. The amount of brightness does not affect dinoflagellate blooms, but diatom blooms need a specified amount of bright uncomplicated		

Table 3 Conceptual models

1995	**Researcher**: *Peter Struss* et al.	**Research location:** *Rio, Brazil*	**Reference**: (Heller et al., 1995)
	Accomplished task: A simplified qualitative modeling, which consists of the upstream, the downstream and the bay compartment, without external pollution to algal bloom prediction was applied by researcher from *Brazil, Germany* and *France*; the process ontology of *Forbus* (1984), describing the system with a set of state parameters and processes acting on them, was considered in this modeling. A modeling assumption is that all the state variable changes are caused by the effects of processes. It contains instinctive conceptual entities (e.g., processes), instead of complex formalisms and coding		
	Assessed parameters: Phytogrowth, nitrification, advection and dispersion, photosynthesis, acidity reaction, dissociation, intoxication, predation and respiration		
	Limitation: Ignoring the light conditions and oxygen equilibrium		
	Conclusion: Presented a first step of the SIGMA system development, a proposed framework for environmental decision support systems		
2010	**Researcher**: *Xu* et al.	**Research location:** *Hong Kong*	**Reference**: (McGillicuddy, 2010; Xu et al., 2010)
	Accomplished task: Apply first conceptual models for explaining 22-year time series data (1986–2007) in Tolo and Victoria harbors to show that different hydrodynamic circulation and mixing are the main reasons for different eutrophication impacts in those specific areas		
	Assessed parameters: Stratification index, salinity, temperature, nutrient concentration, DO, CHL-A		
	Conclusion: Demonstrate the importance of understanding the physical processes role in forecasting the effectiveness of sewage management strategies in decreasing eutrophication effects		
2010	**Researcher**: *Llebot* et al.	**Research location:** *Mediterranean* estuarine bay	**Reference**: (Llebot et al., 2010; McGillicuddy, 2010)
	Accomplished task: Apply a zero-dimensional ecological model to find out the effect of nutrient budget on phytoplankton growth in five scenarios simulations, compare constructed sensitivity experiments with accessible observations owing to evaluating the plausibility of a variety of nutrient sources and mechanisms for delivery, and demonstrate the significance of DOP to bloom nutrition, in spite of the hydrodynamic simplifications innate in the zero-dimensional formulation		
	Assessed parameters: Dissolved organic phosphorus (DOP), phytoplankton biomass and CHL		
	Conclusion: Demonstrated the DOP main role in establishing a phosphorus source that allows drawdown of nitrate and buildup of phytoplankton biomass; showed that sediment resuspension is not a key source of phosphorus, and just has some effect during the low nitrogen load periods		
2010	**Researcher**: *Hense*	**Research location:** *Hamburg, Germany*	**Reference**: (Hense, 2010; McGillicuddy, 2010)
	Accomplished task: Establish guidance to conceptualization of phytoplankton life cycles consist of resting stages, vegetative growth and sexual reproduction in both Eulerian and Lagrangian frameworks		
	Assessed parameters: For each life cycle stage, consider nutrient demands (e.g., uptake of dissolved inorganic nitrogen versus nitrogen fixation), motility (e.g., sinking versus rising), tolerance for physical factors (e.g., salinity, temperature, light and turbulence), mortality, respiration and growth		
	Conclusion: Defining the factors affected the growth rate and loss rate for using in numerical models		
2015	**Researcher**: *Jeong* et al.	**Research location:** *Korea*	**Reference**: (Jeong et al., 2015)
	Accomplished task: Categorized red tide outbreak mechanisms into conceptual models (GM1–GM4) according to red tide organisms' feeding manners and their biological interactions; the simplest one, GM1, assumed phototrophic red tide without migration ability in vertical direction and considered nutrient concentrations N and light intensity I for photosynthesis as significant driving forces. Vertical migration and mixotrophy, which considered in GM2 and GM3, respectively, allow red tides outbreaks in nutrient-poor offshore and coastal waters. Since GM4 includes direct biological interactions, like prohibition by chemical effect or physical contact, and indirect biological interactions like getting sources faster than others, it can show the dominant red tide species under specified conditions		
	Assessed parameters: Required parameters depend on selected model like nutrient concentration, irradiance intensity, the abundance of the red tide species, the abundances of its potential heterotrophic predators, mortality of the red tide species, etc.		
	Conclusion: Accurate red tide forecasting and consuming time and costs depend on choosing proper GMs according to dominant species; using GM4, due to providing more accurate predictions, needs much greater cost and time than using GM1. So GM1 is proper for fast-growing red tide diatoms in eutrophic, shallow coastal waters, while GM4 should be utilizing for slow-growing but fast-swimming mixotrophic red tide dinoflagellates like Cochlodinium polykrikoides offshore		

Table 4 Numerical modeling

1949	**Researcher**: *Riley* et al.	**Research location:** *Georges Bank, Western North Atlantic ocean*	**Reference**: (Sverdrup, 1953; Di Toro, 1974; Wong et al., 2007)
	Accomplished task: Using the vertical mass transport equation for analyzing the stability of a quasi-steady vertical algal concentration profile in a water column of big depth		
	Assessed parameters: Distribution of phytoplankton biomass in spring of 1941		
	Limitation: Not addressing the short-term bloom forecasting, absence of direct link between environmental forcing variables (e.g., tidal flow) and field data of algae blooms, no clear quantitative frame to set the model variables or test them, just assuming the phytoplankton are purely sinking (not motile)		
	Conclusion: Provide a correlation between plankton and stability		
1953	**Researcher**: *Sverdrup*	**Research location:** Weather Ship "M" (66°N., 2°E. Gr.)	**Reference**: (Sverdrup, 1953; Wong et al., 2007)
	Accomplished task: Provided the classic critical depth model to forecast algae blooms when the mixing layer depth is less than the critical depth		
	Assessed parameter: Depth, phytoplankton numbers per liter, thickness of top mixed layer		
	Limitation: Not addressing the short-term bloom forecasting, absence of direct link between environmental forcing variables (e.g., tidal flow) and field data of algae blooms, no clear quantitative frame to set the model variables or test them, just assuming the phytoplankton are purely sinking (not motile)		
	Conclusion: Found a notable agreement between the hydrographic conditions and the plankton communities' development		
1974	**Researcher**: *Di Toro*	**Research location:** *Central Lake Erie, Lake Ontario, Onondaga Lake, Margaret's Bay*	**Reference:** (Di Toro, 1974; Wong et al., 2007)
	Accomplished task: Developed *Riley* et al.'s idea to evaluate velocity of algal sedimentation from field data of blooms during long time scales (several months) together with their interaction with vertical dispersion and eutrophic zone depth		
	Assessed parameters: Investigate the relative importance of algal deposit, vertical mixing, light penetration and algal growth		
	Limitation: Not addressing the short-term bloom forecasting, absence of direct link between environmental forcing variables (e.g., tidal flow) and field data of algae blooms, no clear quantitative frame to set the model variables or test them, just assuming the phytoplankton are purely sinking (not motile)		
	Conclusion: Present an asymptotic eigenvalue analysis for vertical interaction in phytoplankton		
1999	**Researcher**: *Huisman* et al.	**Research location:** Gulf of Maine	**Reference:** (Huisman et al., 1999; Wong et al., 2007)
	Accomplished task: Applied a numerical model according to the critical depth idea, to represent the compatibility of various habitats for algal growth		
	Assessed parameter: Critical turbulence, background turbidity, critical depth, phytoplankton population density		
	Limitation: Not addressing the short-term bloom forecasting, absence of direct link between environmental driving force variables (e.g., tidal flow) with field data of algal blooms, no clear quantitative framework to determine the model parameters or to test the models, just assuming the phytoplankton are purely sinking (not motile)		
	Conclusion: Showed that two different mechanisms for bloom development (critical depth and critical turbulence) lead to a difference in species composition as well		
2005	**Researcher**: *WHOI*[a] *Dennis McGillicuddy* and *Ruoying He)*	**Research location:** *New England*	**Reference:** (Carlowicz, 2006)
	Accomplished task: Created a mathematical model including physical and biological factors of *Alexandrium* dynamics; combination with other computer models explaining water-borne nutrients, sunlight and large-scale motions in the *North Atlantic Ocean*; verifying model by utilizing field observation database of 2005 bloom		
	Assessed parameters: Ocean currents, speeds and directions, water temperature and salinity, winds, surface heat exchanges, tides, river runoff and *Alexandrium* cell distribution in the water and in seafloor sediments		
	Limitation: Not predicting the end of the bloom due to not knowing enough about mortality in *Alexandrium*		
	Conclusion: Successfully predict the *Alexandrium* bloom in 2005 in accordance with winds and river runoff; the team was encouraged to track the 2006 season as it occurs		

Table 4 (continued)

2007	**Researcher**: *Wong* et al.	**Research location:** *Hong Kong*	**Reference:** (Wong et al., 2007)
	Accomplished task: Expanded a uncomplicated mathematical model for predicting coastal algal blooms according to field observations at two coastal areas, and similar hypothesis with the classical *Riley* et al. (1949) and *Di Toro* (1974) which considered algal growth, decay, disposal and vertical turbulent mixing; the goal of this model is to achieve practical metrics for interpretation the complex myriad of field observations and to create a first-order model for evaluating the probability of bloom occurrence		
	Assessed parameter: Algal growth parameters, and minimum field water column transparency and nutrient concentration, and maximum algal growth rate of the motile and non-motile species requires as input		
	Limitation: Forecast phytoplankton blooms just in semi-surrounded coastal waters like *Kat O* and *Lamma* Island		
	Conclusion: Presented a vertical stability criterion, $E < \frac{4\mu L^2}{\pi^2}$ (where E, μ and L are the vertical turbulent diffusivity, algal growth rate and euphotic layer depth, respectively) and a minimum nutrient limen concentration are main parameters for happening algal blooms. Also, due to nutrient competitiveness, the bloom type (motile or non-motile species) can be categorized. Also by utilizing 3D hydrodynamic circulation models, simple correlations are derived to examine the vertical mixing coefficient as a function of tidal range, wind speed and density stratification. Further, the significance of vertical turbulent mixing in managing nutrient supplier resources to both type of species is examined too		
2011	**Researcher**: *Savvidis* et al.	**Research location:** *Thermaikos Gulf (NW Aegean Sea)*	**Reference:** (Savvidis et al., 2011)
	Accomplished task: Development and application of the hydrobiological mathematical model to investigate the growth and dispersion of HABs during January 2000 at the period of 21 days; described hydrodynamic and biological processes such as displacement, dispersion, growth and death of cells by using conservative of mass/momentum equation and random walk or tracer model simulation of particles motion; applied real data of 2005 for model verification		
	Assessed parameter: Temperature, light, nutrients, growth rate, hydrodynamics conditions		
	Conclusion: Showed HAB distribution in the Thermaikos Gulf for various wind conditions (the prevailing winds of the north, northwest and southeast) and various bloom sources		
2012	**Researcher**: *Seddigh Marvasti*	**Research location:** *Persian Gulf* and *Oman Sea*	**Reference:** (Seddigh Marvasti et al. 2012)
	Accomplished task: Applied one-dimensional numerical simulation using PROBE software to investigate red tide dispersion; considered two types of plankton (the growth of type I depends on phosphate and nitrate, and the growth of type II depends on phosphate, temperature and salinity) and solved physical and biological equations at the same time		
	Assessed parameter: Input data include weather parameters (air temperature, wind speed, cloudiness and relative humidity); output data include temperature, salinity, phosphate and nitrate amount, phytoplankton concentrations of type I and II		
	Limitation: Unable to model the phytoplankton concentration amount in stations of the Hormuz Strait due to the high mixing and interference of inlet and outlet flows		
	Conclusion: Showed a positive correlation between temperature, salinity and nutrients with plankton concentration; and also showed the amount of phytoplankton type II concentration is higher than the type I		
2012	**Researcher**: *Farman Ara* et al.	**Research location:** *Persian Gulf*	**Reference:** (Farman Ara et al., 2012)
	Accomplished task: Numerical simulation of the effects of subsurface currents on the red tide development by using three-dimensional Coherence model; considered the physical, hydrodynamical and biological aspects of this phenomenon; and simulated the development and dispersion of phytoplankton by tracking particle transfer in lagrangian framework in three different depths		
	Assessed parameter: Weather parameters (wind, air temperature, humidity, cloudiness and rainfall) and sea surface temperature		
	Conclusion: Showed that surface particles entered the Persian Gulf through the Strait of Hormuz. However, less volume of particles in middle layers entered the Persian Gulf. Deep sea layer particles transfer from the Persian Gulf to the Oman Sea and the Indian Ocean		
2017	**Researcher**:*Mahin Abdollahzadeh* et al.	**Research location:** *Oman Sea, Iran*	**Reference:** (Mahin Abdollahzadeh et al., 2017)
	Accomplished task: Examined the distribution of HAB cells due to hydrodynamic factors by utilizing *MIKE 3-FM* and *ECOLab*, including hydrodynamics and quality simulation as well as the chlorophyll-a distribution. Model validation is done by root mean-square deviation (RMSE)		
	Assessed parameter: CHL-A concentration, nitrate, phosphate, water temperature, DO and salinity		
	Conclusion: Provided a benefit prediction tool for developing several scenarios concerning the HAB spread within aqueous ecosystems		

Woods Hole Oceanographic Institution

for other models, do not prepare early and wide detection. So, using numerical modeling, due to low costs and the possibility to consider different parameters, has great benefits.

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