

1 HARMFUL ALGAL BLOOMS

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1.1 ALGAL BLOOMS

Oceans and freshwater rivers, lakes, and streams teem with microscopic plants called algae that capture the sun's energy with their pigments and grow and proliferate in illuminated surface waters, typically through simple cell division. These increases in abundance over background levels are termed "blooms", analogous to the growth and flourishing of terrestrial plants. Many algal species are non-motile and thus their distributions are simply determined by the movements of water. Even species that swim are not powerful enough to control their location in most situations, so they too are generally dominated by the motion of waves, currents, and tides (though the combination of swimming behaviour and water movement can lead to dense cell aggregations and other spatial features (see section 1.5.3.6)). The microscopic algae are called phytoplankton (drifting, single celled plants), to be distinguished from their close relatives, the multi-cellular macroalgae or seaweeds. Algae of both types are critical to life on earth, as they produce half of the oxygen we breathe and represent the base of the aquatic food chain that provides substantial food for human society.

Among the many thousands of species of microalgae are a few hundred that cause harm in various ways. Potentially harmful species are found in multiple phytoplankton groups. Many are eukaryotes, (i.e., organisms with a nucleus and other organelles enclosed within membranes) such as dinoflagellates, raphidophytes, diatoms, euglenophytes, cryptophytes, haptophytes, pelagophytes, and chlorophytes. Some are prokaryotes, (i.e., single-celled organisms such as cyanobacteria that lack a membrane-bound nucleus or other organelle). While dinoflagellates comprise the majority of toxic harmful algal bloom (HAB) species in the marine environment where seawater reverse osmosis (SWRO) plants are located, many of the toxic species that pose a threat to drinking water supply in fresh- or brackish-water systems are cyanobacteria.

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Historically, blooms of harmful species are sometimes called “red tides”, as in some cases, these microscopic cells increase in abundance until their pigments make the water appear

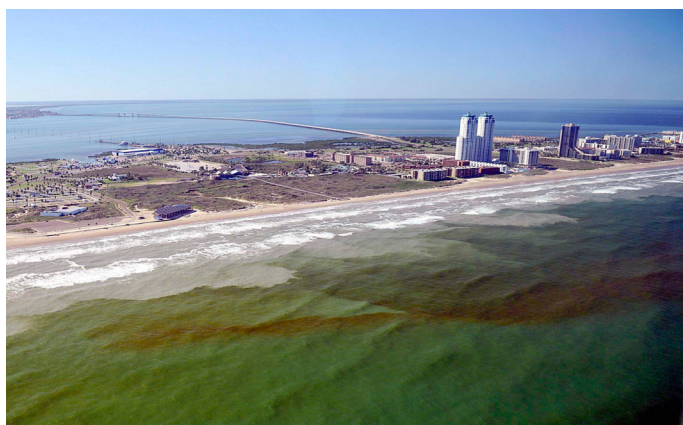


Figure 1.1. Water discoloration due to “red tide” in Texas.
Photo: Texas Department of Wildlife.

discolored and often red (Figure 1.1). There are, however, blooms of species that are orange or green or brown, and others which do not reach cell concentrations high enough to discolor the water, but which still cause harm. This harm is sometimes because of the potent toxins produced by those algae, but in other cases, the harm derives from the accumulated algal biomass that can shade aquatic vegetation, deplete oxygen as that biomass decays, and cause other societal or

ecosystem disruptions. The scientific community now uses the term ‘harmful algal bloom’ or HAB to describe these phenomena. The term HAB is very broad and covers blooms of many types, but HABs all have one unique feature in common - they cause harm. HABs are most common in coastal marine ecosystems, but they also occur in the open ocean, and in brackish or freshwater systems.

Toxic algal blooms are defined as those that produce potent toxins (poisonous substances produced within living cells or organisms), e.g., saxitoxin. These can cause illness or mortality in humans as well as marine life through either direct exposure to the toxin or ingestion of bioaccumulated toxin in higher trophic levels e.g. shellfish. Non-toxic HABs can cause damage to ecosystems and commercial facilities such as desalination plants, sometimes because of the biomass of the accumulated algae, and in other cases due to the release of compounds that are not toxins (e.g., reactive oxygen species, polyunsaturated fatty acids, mucilage) but that can still be lethal to marine animals or cause disruptions of other types. One prominent example of this latter mechanism relates to the high biomass that some blooms achieve. When this biomass begins to decay, oxygen is consumed, leading to widespread mortalities of all plants and animals in the affected area. These “high biomass” blooms are sometimes linked to excessive pollutant inputs, but can also occur in relatively pristine waters.

Six human poisoning syndromes are linked to the consumption of shellfish or fish contaminated by HAB toxins (Table 1.1): amnesic shellfish poisoning (ASP), diarrhetic shellfish poisoning (DSP), neurotoxic shellfish poisoning (NSP), paralytic shellfish poisoning (PSP), azaspiracid shellfish poisoning (AZP), and ciguatera fish poisoning (CFP). The latter is not a threat to desalination plants because the causative species, *Gambierdiscus toxicus*, lives attached to seaweeds, dead coral, and other surfaces on the ocean bottom, and thus will not be drawn into plant intake waters to any significant extent. Other threats to human health are posed by HAB-derived aerosols that cause respiratory problems and water-borne compounds that lead to skin irritation.

Macroalgae (seaweeds) are also considered HABs, as blooms of macroalgae have been increasing and causing impacts of various types along many of the world’s coastlines. Macroalgal blooms often occur in nutrient-enriched nearshore areas that are shallow enough for light to penetrate to the sea floor. Booms of buoyant seaweeds can accumulate at the water surface. Both types of blooms have a broad range of ecological and societal effects, and often last longer than “typical” phytoplankton HABs. Some, like the spectacular “green

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Table 1.1. Human illnesses associated with HABs.

Syndrome	Causative organisms	Toxins produced	Route of acquisition	Clinical manifestations
Ciguatera fish poisoning (CFP)	<i>Gambierdiscus toxicus</i> and multiple <i>Gambierdiscus</i> species	Ciguatoxins, maitotoxin	Toxin passed up marine food chain; illness results from eating large, carnivorous reef fish	Acute gastroenteritis, paresthesias and other neurological symptoms
Paralytic shellfish poisoning (PSP)	<i>Alexandrium</i> species, <i>Gymnodinium catenatum</i> , <i>Pyrodinium bahamense</i> var. <i>compressum</i> , and others	Saxitoxins	Eating shellfish harvested from affected areas	Acute paresthesias and other neurological manifestations; may progress rapidly to respiratory paralysis and death
Neurotoxic shellfish poisoning (NSP)	<i>Karenia brevis</i> and others	Brevetoxins	Eating shellfish harvested from affected areas; toxins may be aerosolized by wave action	Gastrointestinal and neurological symptoms; respiratory and eye irritation with aerosols
Diarrhetic shellfish poisoning (DSP)	<i>Dinophysis</i> species; <i>Prorocentrum lima</i>	Okadaic acid and others	Eating shellfish harvested from affected areas	Acute gastroenteritis
Azaspiracid shellfish poisoning (AZP)	<i>Azadinium spinosum</i> and others	Azaspiracids	Eating shellfish harvested from affected areas	Neurotoxic effects with severe damage to the intestine, spleen, and liver tissues in test animals
Amnesic shellfish poisoning (ASP)	<i>Pseudo-nitzschia australis</i> and others	Domoic acid	Eating shellfish (or, possibly, fish) harvested from affected areas	Gastroenteritis, neurological manifestations, leading in severe cases to amnesia, coma, and death

tides” of northeast China (Figure 1.2; Smetacek and Zingone 2013) are floating masses of seaweed that may pose significant problems to power plants, desalination plants, and recreational resources in some areas. Despite the long list of HAB impacts that are well known and recurrent throughout the world, (e.g., Hallegraeff 1993; Landsberg 2002; Anderson et al. 2012) new impacts are emerging. One current example is with desalination plants. The global expansion of HABs due to pollution, coastal development, and other factors (see section 1.4), is occurring at a time when there is also an increase in the construction of seawater desalination plants. In 2015, there were more than 18,600 contracted or commissioned desalination plants in more than 150 countries worldwide, and the desalination market is forecast to grow by 12% per year (Virgili 2015). Interactions between



Figure 1.2. Spectacular “green tide” in Qingdao China. These annually recurrent, massive outbreaks result from the growth and accumulation of the seaweed *Ulva prolifera* that originate far to the south of Qingdao, carried to the region by ocean currents. Photo: D. Liu.

some of these plants and nearshore HABs is inevitable. Concerns that arise include the possible retention of algal-produced toxins and taste and odor compounds in treated water, as well as the clogging of filters and fouling of membranes. Algal biomass (i.e., the solid or particulate component of an algal bloom) and algal-derived compounds (those dissolved in seawater) can be seriously disruptive, particularly to those plants that use SWRO to produce fresh water. A recent example is the bloom of *Cochlodinium polykrikoides* in the Gulf¹ and Sea of Oman in 2008/2009 that affected a large number of SWRO desalination plants, closing some for as long as four months (Richlen et al. 2010; Shahid and Al Sadi

2015). Since economic considerations are leading to a huge expansion in SWRO plants compared to those that use thermal processes, we can expect many more impacts of HABs on desalination plants than have been recorded thus far. It is also likely that species that are not considered harmful to other sectors of society will be harmful to the desalination industry simply because they produce disproportionately large amounts of dissolved organic materials and suspended solids. With proper documentation of bloom events and communication between HAB scientists and the desalination industry, a list of species that are prolific producers of algal organic matter (and that are non-toxic) can be generated and used by desalination plant operators to facilitate mitigation strategies.

1.2 HARMFUL OR TOXIC BLOOM SPECIES

Although many different phytoplankton and macroalgal species are now considered harmful, this group still represents a small fraction of the many thousands of species of algae in the ocean. Moestrup et al. (2017) list 144 toxic or harmful marine algal species. This list contains species known to produce toxins as well as those that cause harm due to excessive biomass, mucus production, or morphology, (spines etc.). Another 35 toxic cyanobacterial species are listed, but these are predominantly from fresh water. The list, which is continually updated, is available at: <http://www.marinespecies.org/hab/index.php>.

There is no list of species that have caused harm, or are likely to, at desalination plants. This is in part because plants that have been affected by HABs often do not have the taxonomic expertise to identify the organisms that are causing problems, and rarely do those plants send bloom samples to the appropriate experts. All too often, plants experience problems from algal blooms, but no identification of the causative algal species is made or publicized. In hopes that this will change going forward, Chapter 3 provides guidance on how to collect water samples for algal identification and counting, and Chapter 11 presents case studies of algal bloom events and the steps taken to try to mitigate their impacts. Table 1.2 lists some of

¹ Here the Gulf refers to the shallow body of water bounded in the southwest by the Arabian Peninsula and Iran to the northeast. The Gulf is linked with the Arabian Sea by the Strait of Hormuz and the Gulf of Oman to the east and extends to the Shatt al-Arab river delta at its western end.

the most common toxin-producing species, and Appendix 1 provides photographs and short descriptions of some of these species, as well as others that might represent a threat to desalination plants. With thousands of species of algae in the ocean, many of which form blooms at one time or another, it is not possible to list all those that represent possible threats to desalination plants. Thus, neither the list in Table 1.2 nor the species described in Appendix 1 are comprehensive. Readers are urged to refer to the Web links provided in Chapter 3 for other identifications. Readers are also urged to contact the Editor with information on species that cause desalination plant problems in the future, as Appendix 1 and other parts of this manual will be updated periodically and information made available online through MEDRC (<http://www.medrc.org/>) and IOC (<http://hab.ioc-unesco.org/>) websites.

Table 1.2. Some toxic marine planktonic species of potential concern for SWRO operations. (Adapted from Caron et al. 2010). This list is not comprehensive.

Microalgae	Toxin(s)	Poisoning Syndrome	References
Diatoms			
<i>Pseudo-nitzschia</i> spp.	Domoic acid (DA)	Amnesic Shellfish Poisoning (ASP) Human effects <ul style="list-style-type: none"> • Gastrointestinal symptoms • Neurological symptoms • Death Ecosystem effects <ul style="list-style-type: none"> • Marine mammal mortalities • Bird mortalities 	Subba Rao et al. (1988); Bates et al. (1989); Martin et al. (1990); Buck et al. (1992); Garrison et al. (1992); Rhodes et al. (1996); Horner et al. (1997); Lundholm et al. (1997); Rhodes et al. (1998); Trainer et al. (2000, 2001); Baugh et al. (2006)
<i>P. australis</i>			
<i>P. brasiliiana</i>			
<i>P. caciantha</i>			
<i>P. calliantha</i>			
<i>P. cuspidata</i>			
<i>P. delicatissima</i>			
<i>P. fraudulenta</i>			
<i>P. fukuyoi</i>			
<i>P. galaxiae</i>			
<i>P. granii</i>			
<i>P. kodamae</i>			
<i>P. multiseriis</i>			
<i>P. multistriata</i>			
<i>P. plurisecta</i>			
<i>P. pungens</i>			
<i>P. pseudodelicatissima</i>			
<i>P. seriata</i>			
<i>P. subpacifici</i>			
<i>P. turgidula</i>			
Dinoflagellates			
<i>Alexandrium</i> spp.	Saxitoxins (STXs)	Paralytic Shellfish Poisoning (PSP) Human effects <ul style="list-style-type: none"> • Gastrointestinal symptoms • Paralysis • Death Ecosystem effects <ul style="list-style-type: none"> • Marine mammal mortalities 	Sommer and Meyer (1937); Gaines and Taylor (1985); Steidinger (1993); Scholin et al. (1994); Taylor and Horner (1994); Jester (2008); John et al. (2014); Usup et al. (2012); Prud'homme van Reine WF. (2017)
<i>A. acatenella</i>			
<i>A. catenella</i> ¹			
<i>A. fundyense</i> ¹ (renamed)			
<i>A. catenella</i>			
<i>A. hiranoi</i>			
<i>A. ostenfeldii</i> ¹			
<i>A. pacificum</i> ¹			
<i>A. australiense</i> ¹			
<i>Pyrodinium bahamense</i>			
<i>Gymnodinium catenatum</i>			
<i>Lingulodinium polyedrum</i>	Yessotoxins (YTXs)	Human and ecosystem effects None reported, but animal bioassays show toxicity	Holmes et al. (1967); Draisci et al. (1999a); Armstrong and Kudela (2006); Rhodes et al. (2006); Howard et al. (2007)
<i>Gonyaulax spinifera</i>			
<i>Protoceratium reticulatum</i>			

Table 1.2. (Continued)

Microalgae	Toxin(s)	Poisoning Syndrome	References
Dinoflagellates (Cont.)			
<i>Azadinium</i> spp. <i>A. spinosum</i> <i>A. trinitatum</i> <i>A. cuneatum</i> <i>A. concinnum</i> <i>A. daliense</i> <i>A. poporum</i> <i>A. obesum</i>	Azaspiracids (AZAs)	Azaspiracid Shellfish Poisoning (AZP) Human effects • Gastrointestinal symptoms Ecosystem effects • None reported	Satake et al. (1998); James et al. (2003); Jauffrais et al. (2012); McCarron et al. (2009); Ofuji et al. (2014); Tillman et al. (2009, 2010, 2011, 2012)
Raphidophytes			
<i>Chattonella marina</i> <i>Fibrocapsa japonica</i> <i>Heterosigma akashiwo</i>	Brevetoxins (PbTxS); other fish-killing toxins, possibly related to fatty acids and oxygen radicals	Neurotoxic Shellfish Poisoning (NSP) Human effects • Gastroenteritis • Neurologic symptoms • Respiratory irritation and/or failure Ecosystem effects • Marine mammal mortalities • Fish mortality events	Loeblich and Fine (1977); Hershberger et al. (1997); Gregorio and Connell (2000); Tyrell et al. (2002); O'Halloran et al. (2006)

[†] All members of the “tamarensis” complex of *Alexandrium* were recently reclassified by John et al. (2014). See also Prud'homme van Reine WF. (2017).

As an alternative, Table 1.3 presents a list of algal species that have bloomed in the Gulf, Sea of Oman, and Arabian Sea region, the global center of desalination activity. Once again, this is not a comprehensive list, and only some of these species have been documented to cause problems in desalination plants, but the list does show the diversity of organisms that can achieve high biomass levels that probably would cause disruptions if those blooms occurred near plant intakes. Unfortunately, for some bloom-formers the species designation was not known or specified in the publications, so only genus names can be listed. In time, it would be of great value to add resolution at the species level to tables such as this, as well as more details about the cell size and cell wall characteristics of many of these species.

The best advice to plant operators seeking to mitigate the effects of a specific algal bloom is to collect samples and identify the causative organism, hopefully to the species level, but at least to genus. With some training and modest microscope facilities, this can be done on site (Chapter 3). There are also outside experts and services that will do this type of work on demand. The Intergovernmental Oceanographic Commission (IOC) Science and Communication Centre on Harmful Algae, University of Copenhagen, Denmark can offer assistance in identification of eukaryotic microalgae – see

http://hab.ioc-unesco.org/index.php?option=com_content&view=article&id=15&Itemid=0.

1.3 ALGAL CELL CHARACTERISTICS

1.3.1 Toxins

Among the thousands of species of microalgae in the ocean, only a hundred or so are toxic. This means that most algal blooms at desalination plant sites are likely to be of concern because of the algal biomass or associated organic products. Nevertheless, when toxic species

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do occur, it is important to be aware of the dangers. Here common aspects of cell physiology and toxin production are described. Details on the chemical structure and other properties of HAB toxins are given in Chapter 2, which also discusses the levels of these toxins that pose risks to human consumers. Chapter 10 discusses the removal of HAB toxins and taste and odor compounds during SWRO and thermal desalination.

Table 1.3. Common bloom-forming species in the Gulf, Sea of Oman, and Arabian Sea region. (Adapted from Al Shehhi et al. 2014; Al Azri et al. 2012).

Country	Region	Observed species	References
India	Arabian Sea	<i>Trichodesmium erythraeum</i> , <i>Noctiluca scintillans</i> , <i>Thalassiothrix longissima</i> , <i>Amphiprora</i> sp., <i>Thalassiosira</i> sp., <i>Fragilaria cylindrus</i>	D'Silva et al. (2012); Saeedi et al. (2011); Padmakumar et al. (2012); Joseph et al. (2008); Krishnan et al. (2007)
Bahrain KSA	the Gulf	<i>Gonyaulax</i> sp., <i>Noctiluca</i> sp.	
Pakistan	Arabian Sea	<i>Noctiluca scintillans</i> , <i>Prorocentrum minimum</i> , <i>Phaeocystis</i> sp.	Chaghtai and Saifullah (2006); Saifullah (1979); Rabbani et al. (1990); Chaghtai and Saifullah (2001)
Kuwait	the Gulf	<i>Noctiluca scintillans</i> , <i>Karenia</i> sp., <i>Gymnodinium</i> sp., <i>Gymnodinium impudicum</i> , <i>Pryodinium bahamense</i> , (<i>Karenia selliformis</i> , <i>Prorocentrum rathymum</i>)	Heil et al. (2001); Thangaraja et al. (2007); Glibert et al. (2002); Al-Yamani et al. (2000)
UAE	the Gulf Sea of Oman	<i>Noctiluca scintillans</i> , <i>Cochlodinium polykrikoides</i> , <i>Trichodesmium erythraeum</i> , <i>Dinophysis caudata</i> , <i>Prorocentrum minimum</i> , <i>P. triestinum</i> , <i>P. balticum</i> , <i>P. micans</i> , <i>Coscinodiscus radiatus</i> , <i>Chaetoceros peruvianus</i> , <i>C. compressus</i> , <i>C. curvisetus</i> , <i>C. socialis</i> , <i>Cylindrotheca closterium</i> , <i>Guinardia delicatula</i> , <i>Pseudo-nitzschia multiseriata</i> , <i>P. pungens</i> , <i>P. seriata</i> , <i>P. delicatissima</i> , <i>Skeletonema costatum</i> , <i>Alexandrium</i> sp., <i>Amphidinium klebsii</i> , <i>Akashiwo sanguinea</i> , <i>Ceratium furca</i> , <i>C. tripos</i> , <i>Dinophysis miles</i> , <i>D. acuminata</i> , <i>Gonyaulax polygramma</i> , <i>G. spinifera</i> , <i>Gonyaulax grindleyi</i> , <i>Gymnodinium sanguinum</i> , <i>Peridinium quinquecorne</i> , <i>Protoceratium reticulatum</i> , <i>Gyrodinium</i> sp., <i>Ostreopsis lenticularis</i> , <i>Dictyocha fibula</i> , <i>Pyrodinium bahamense</i> , <i>Scrippsiella trochoidea</i> , <i>Rhizosolenia setigera</i> , <i>Skeletonema costatum</i> , <i>Leptocylindrus danicus</i> , <i>Bacteriastrum delicatulum</i>	Thangaraja et al. (2007); Richlen et al. (2010); R. Alshihhi, pers. comm.; A. Rajan (pers. comm.)

Table 1.3. (Continued)

Country	Region	Observed species	References
Oman	Arabian Sea, Sea of Oman	<i>Phaeocystis globosa</i> , <i>Nitzschia longissima</i> , <i>Navicula directa</i> , <i>Rhizosolenia</i> spp., <i>Chaetoceros didymus</i> , <i>Noctiluca scintillans</i> , <i>Gymnodinium</i> sp., <i>Karenia</i> sp., <i>Dinophysis</i> sp., <i>Trichodesmium</i> sp., <i>Coscinodiscus</i> sp., <i>Ceratium furca</i> , <i>Prorocentrum arabianum</i> , <i>Prorocentrum minimum</i> , <i>Gymnodinium breve</i>	Madhupratap et al. (2000); Thangaraja et al (2007); Morton et al. (2002); Al Azri et al. (2012); Tang et al. (2002); Al-Busaidi et al. (2008); Al Gheilani et al. (2011); Saeedi et al. (2011)
Qatar	the Gulf	<i>Pseudo-nitzschia</i> spp., <i>Alexandrium</i> spp., <i>Pyrodinium bahamense</i> <i>Alexandrium</i> sp., <i>Dinophysis</i> sp., <i>Pseudo-nitzschia</i> sp., <i>Gymnodinium breve</i>	Al-Ansi et al. (2002)
Iran	the Gulf	<i>Karenia</i> spp, <i>Cochlodinium polykrikoides</i> , <i>Trichodesmium</i> sp., <i>Noctiluca scintillans</i> , <i>Navicula</i> sp.	Thangaraja et al. (2007); Fatemi et al. (2012)

For virtually all HAB species, toxin production is a constitutive property of the cell, meaning that if toxin is produced, it is present in all stages of growth; however, the amount of toxin in a cell can vary dramatically with growth conditions. Some cells, such as *Dinophysis* species that produce okadaic acid, for example, produce less toxin when they are actively dividing (exponential phase growth) than when they are limited by some nutrient(s) and are in what is termed “stationary phase” (Figure 1.3). The exact opposite occurs with other species, such as those in the genus *Alexandrium* that produce saxitoxin. In those species, some of the highest

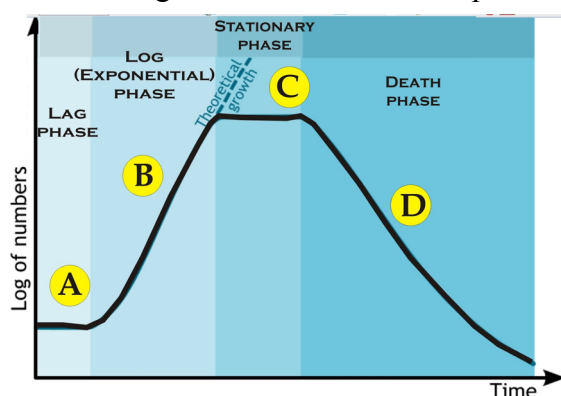


Figure 1.3. Phases of algal growth in laboratory batch culture. In lag phase (A), there is no growth after the initial inoculation; cells divide and increase exponentially in phase B, then enter stationary phase (C) when no growth occurs again because nutrients or other growth factors are depleted or sub optimal. Phase D represents death or mortality of the culture. Modified from M. Komorniczak.

toxin production during a growth cycle occurs when the cells are growing exponentially. Furthermore, in those species, the amount of toxin produced can vary with different types of nutrient limitation. Cells that run out of phosphorus, for example, produce much more saxitoxin than those that are nutrient replete. By reducing nitrogen supplies, the cells can be made much less toxic.

Thus, the nutritional characteristics of the water in which the HAB is occurring can influence levels of toxicity, sometimes as much as 10-fold. Further complicating efforts to estimate the amount of toxin in a given HAB is the genetic heterogeneity between strains of the same species. This means that strains of a given species isolated from different locations, or from the same location at different times, can vary dramatically in toxicity (sometimes 100 fold or more) even when those strains are grown under identical conditions. Identifying the species and counting the cells that are being drawn into a plant is a good start, but estimating the toxicity of those cells is simply not reliable without detailed knowledge of the toxicity range of that species within that region. In some cases, that information is published, but the range of values can often be quite large for the reasons given above, and thus introduce considerable uncertainty into these types of calculations. The best recommendation is to collect samples and either test them on

site using the simple toxin testing procedures described in Chapter 2 and Appendix 2, or to send those samples to an appropriate testing laboratory for direct toxin analyses.

Recognizing that desalination plant operators might wish to estimate the amount of toxin present in a specific bloom, Table 1.4 lists the maximum toxicity observed in laboratory cultures of the major toxic HAB species. The table also provides estimates of the amount of toxin that might be contained in a liter of water if blooms of 100,000, 500,000 and 5,000,000 cells/L of each species were present, if those cells contained the maximum level of toxicity measured in laboratory cultures of that species. These are arbitrary cell concentrations intended to represent small, moderate, and large blooms. This is a highly conservative way to estimate the level of toxicity in a HAB, as the list of toxin values in the table is not comprehensive, nor is the species list, and thus the data in Table 1.4 are presented here only as a general guide.

1.3.2 Cell size

There are major physiological and morphological differences between species within a genus, or species within different algal classes or phyla, and thus major differences in potential impacts to desalination plants, or in the pretreatment options that might be effective in cell removal. With respect to size, HAB cells can vary by a factor of more than 1000. Some, like the brown tide organism, *Aureococcus anophagefferens*, are tiny 2-3 μm spheres, the upper end of the range defining the picoplankton (0.2 – 2 μm), whereas at the other extreme there are cells such as the prolific red tide-former *Noctiluca scintillans* that are 200 – 2,000 μm (0.2 - 2 mm) in diameter. Many HAB cells, however, are in the 20 – 60 μm range. Some HAB species occur as individual cells, occasionally paired with another as they divide, whereas others form long chains or occur in colonies. Images and short descriptions of these and other species described in this manual are given in Appendix 1.

1.3.3 Cell wall coverings and surface charge

Microalgal cells display a variety of surface features that can influence their resistance to rupture (lysis), as well as their surface charge and thus their susceptibility for aggregation and removal through processes such as dissolved air flotation (see Chapter 9). For example, among the dinoflagellates, one of the major HAB classes, there are cells that have hard, cellulose “plates” that are joined together like tiles to form a rigid cell wall, but there are also many dinoflagellates that have soft, pliable, and easily ruptured cell walls. By definition, all diatoms have silicified cell walls, but some have large, thick, and rigid coverings while others have thin and fragile walls. More importantly, algal cells are often surrounded by various organic molecules, such as nucleic acids, lipids, glycoproteins and carbohydrates (Dodge 1973). The surface charge of microalgae is thought to be generated by the hydrolysis or ionization of these molecules (Maruyama et al. 1987). Ives (1956) was the first to determine the surface charge of several freshwater species using electrophoresis and found that they carried a negative charge; however, the author made no observations using flagellated species because the swimming ability of these organisms interfered with their motion in the electric field. Geissler (1958) also reported a negative charge on several freshwater diatoms and confirmed the finding by observing the strong attachment of positively-charged dye particles onto the cell surface. Tenney et al. (1969) demonstrated the binding of cationic polymers on the cell surface and postulated that the association was electrostatic instead of chemical in nature. Several authors have speculated that the surface charge of marine microalgae is also negative (e.g. Yu et al. 1994). Sengco (2001) measured the electrophoretic mobility of nine species of marine microalgae. All species displayed a slight electronegative charge ranging from -0.19 to $-0.57 \times 10^{-8} \text{ m}^2 \text{ s}^{-1} \text{ V}^{-1}$. Zeta potential ranged from -2.51 to -7.62 mV. These

Table 1.4. Maximum or representative toxicity for select HAB species. Also shown are water column toxin concentrations at three different cell concentrations representative of potential blooms, calculated using the maximum toxin content estimates in cultures (typically measured under nutrient-replete conditions). Toxin content varies with different types and degrees of nutrient limitation, and among strains of each of these species, so this Table does not represent all possible situations.

Species	Toxin	Maximum toxin content (pg/cell)	Maximum toxicity of dense bloom (µg/L)			Reference
			100,000 cells/L	500,000 cells/L	5,000,000 cells/L	
<i>Alexandrium fundyense</i> (now <i>A. catenella</i>)	Saxitoxin	58.7	5.87	29.35	293.5	Anderson et al. 1994
<i>Alexandrium catenella</i> (now <i>A. pacificum</i>),	Saxitoxin	18.3	1.83	9.15	91.5	Kim et al. 1993
<i>Alexandrium minutum</i>	Saxitoxin	11.6	1.16	5.8	58	Chang et al. 1997
<i>Alexandrium ostenfeldii</i>	Saxitoxin	217	21.7	108.5	1,085	Mackenzie et al. 1996
	Spirolides	78.2 ¹	7.82	39.1	391	Gribble et al. 2005
<i>Azadinium poporum</i>	Azaspiracid	0.02	0.0002	0.001	0.01	Krock et al. 2015
<i>Azadinium spinosum</i>	Azaspiracid	0.1	0.001	0.01	0.1	Jauffrais et al. 2012
<i>Dinophysis acuminata</i>	Okadaic acid,	58.8	5.88	29.4	294	Nagai et al. 2011
	Dinophysistoxins	9.6	0.96	4.8	48	
	Pectenotoxins	73.3	7.33	36.65	366.5	
<i>Dinophysis acuta</i> ⁷	Okadaic acid,	51.8	5.18	25.9	259	Nielsen et al. 2013
	Dinophysistoxins	115.4 ²	11.54	57.7	577	
	Pectenotoxins	182	18.2	91	910	
<i>Dinophysis caudata</i>	Okadaic acid, Dinophysistoxins Pectenotoxins	~600 ³	60	300	3,000	Basti et al. 2015
<i>Dinophysis fortii</i>	Okadaic acid,	49.4	4.94	24.7	247	Nagai et al. 2011
	Dinophysistoxins	1.6	0.16	0.8	8	
	Pectenotoxins	191.1	19.1	95.5	955	

Table 1.4. (Continued)

Species	Toxin	Maximum toxin content (pg/cell)	Maximum toxicity of dense bloom (µg/L)			Reference
			100,000 cells/L	500,000 cells/L	5,000,000 cells/L	
<i>Dinophysis norvegica</i>	Okadaic acid,	1.01 ⁴	0.1	0.5	5	Rodriguez et al. 2015
	Dinophysistoxins	2.19 ⁴	0.22	1.1	11	
	Pectenotoxins	24.02 ⁴	2.4	12	120	
<i>Dinophysis tripos</i>	Okadaic acid,	0.08	0.008	0.04	0.4	Nagai et al. 2013
	Dinophysistoxins	1236	123.6	618	6180	
	Pectenotoxins					
<i>Gymnodinium catenatum</i>	Saxitoxin	101	10.1	50.5	505	Band-Schmidt et al. 2006
<i>Karenia brevis</i>	Brevetoxin	49	4.9	24.5	245	Corcoran et al. 2014
<i>Karlodinium veneficum</i>	Karlotoxins	1.34	0.134	0.67	6.7	Fu et al. 2010
<i>Ostreopsis siamensis</i>	Palytoxins	16	1.6	8	80	Suzuki et al. 2012
<i>Pseudo-nitzschia australis</i>	Domoic acid	37	3.7	18.5	185	Garrison et al. 1992
<i>Pseudo-nitzschia brasiliiana</i>	Domoic acid	.0095	0.00095	0.0048	0.048	Sahraoui et al. 2011
<i>Pseudo-nitzschia calliantha</i>	Domoic acid	0.01	0.001	0.005	.05	Álvarez et al. 2009
<i>Pseudo-nitzschia cuspidata</i>	Domoic acid	0.019	0.002	0.01	0.1	Trainer et al. 2009
<i>Pseudo-nitzschia delicatissima</i>	Domoic acid	0.12	0.012	0.06	0.6	Rhodes et al. 1998
<i>Pseudo-nitzschia fraudulenta</i>	Domoic acid	0.03	0.003	0.015	0.15	Rhodes et al. 1998

Table 1.4. (Continued)

Species	Toxin	Maximum toxin content (pg/cell)	Maximum toxicity of dense bloom (µg/L)			Reference
			100,000 cells/L	500,000 cells/L	5,000,000 cells/L	
<i>Pseudo-nitzschia galaxiae</i>	Domoic acid	0.00036	0.000036	0.00018	0.0018	Cerino et al. 2005
<i>Pseudo-nitzschia granii</i>	Domoic acid	0.000004	0.0000004	0.000002	0.00002	Trick et al. 2010
<i>Pseudo-nitzschia multiseriata</i>	Domoic acid	67	6.7	33.5	335	Bates et al. 1999
<i>Pseudo-nitzschia multistriata</i>	Domoic acid	0.697	0.0697	0.349	3.49	Orsini et al. 2002
<i>Pseudo-nitzschia pseudodelicatissima</i>	Domoic acid	0.0078	0.00078	0.0039	0.039	Moschandreu et al. 2010
<i>Pseudo-nitzschia pungens</i>	Domoic acid	0.47	0.047	0.235	2.35	Rhodes et al. 1996
<i>Pseudo-nitzschia seriata</i>	Domoic acid	33.6	3.36	16.8	168	Lundholm et al. 1994
<i>Pseudo-nitzschia turgidula</i>	Domoic acid	0.09	0.009	0.045	0.45	Bill 2011
<i>Pyrodinium bahamense</i>	Saxitoxin	120	12	60	600	Ustup et. al. 1994

¹ (calculated from fmol/cell value - 692g/mole)

² (DTX-1b)

³ (Calculated from plot)

⁴ (calculated from bulk analysis of plankton sample)

⁵ (lab incubation of nutrient enriched field sample)

data confirm the prediction that marine algal species, including the dinoflagellates, possess negative surface charges like their freshwater counterparts (Maruyama et al. 1987; Shiota 1989; Yu et al. 1994). The magnitude of these charges was, however, small compared to freshwater algae, as Ives (1956) reported a range of zeta potential between -7.6 mV to -11.6 mV at pH values from 7.2 to 8.8 in freshwater, while the values reported by Sengco (2001) ranged from -2.5 to -7.7 mV. Zhu et al. (2014) measured the zeta potential of the dinoflagellate *Prorocentrum minimum* to be about -4 mV at a moderate cell concentration.

A few of the species listed in Table 1.3 are worth highlighting because of the scale of their impacts, or their prevalence in regions with significant desalination capacity, or simply because they are prolific bloom formers. One of the most significant is *Cochlodinium polykrikoides*, the organism that disrupted desalination operations at many plants in the Gulf and Sea of Oman in 2008 and 2009 (Richlen et al. 2010; Shahid and Al Sadi 2015). First described from Puerto Rico in the Caribbean by Margalef (1961), the geographic distribution of *C. polykrikoides* is widespread, and populations have been documented in tropical and warm-temperate waters around the world, including the Caribbean Sea, eastern and western Pacific Ocean, the eastern Atlantic Ocean, Indian Ocean, and Mediterranean Sea (see Kudela et al. 2008; Matsuoka et al. 2008). This species has been spreading globally in recent years and thus represents a significant threat to desalination operations worldwide. This species

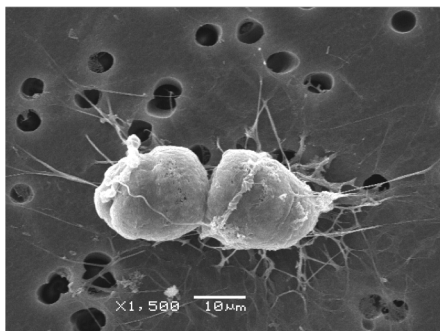


Figure 1.4. Scanning electron micrograph of two cells of *Cochlodinium polykrikoides* showing mucilage excretions. Scale bar = 10 μm . Photo: S. Morton.

does not produce a toxin that affects humans, but it does produce massive, dense blooms that cover large areas, frequently discolor the water, kill coral reefs (Foster et al. 2011), and also has been known to cause mass mortalities at fish farms and other aquaculture facilities (reviewed in Kudela and Gobler 2012). The mechanism(s) of fish or coral mortality are not known, but Tang and Gobler (2009) describe labile compounds similar to reactive oxygen species (ROS). A significant amount of mucus or mucilage is produced by *C. polykrikoides* (Figure 1.4), and this is undoubtedly one of the reasons it has been so problematic at SWRO plants.

Species within the genus *Phaeocystis* are well known for their production of mono-specific (i.e., dominated by a single algal species), high-biomass blooms worldwide (Schoemann et al. 2005). Among the 6 species in the genus, only 3 (*P. pouchetii*, *P. antarctica*, *P. globosa*) have been reported as blooming species. Of particular importance is the existence of a complex life cycle exhibiting alternation between small, free-living cells 3–9 μm in diameter and gelatinous colonies usually reaching several mm. These large colonies, consisting of thousands of small cells embedded in a polysaccharide matrix, are not toxic. They are, however, significant threats to SWRO plants due to their high particulate biomass and high organic content, and thus their potential to cause clogging of filters and fouling of membranes.

Other dinoflagellate species, such as *Gonyaulax hyaline* and *G. fragilis* (e.g., Mackenzie et al. 2002; Sampedro et al. 2007) are noted for their massive mucilage production during blooms in New Zealand and the Mediterranean Sea. The diatom *Cylindrotheca closterium* has been linked to major mucilage events in the northern Adriatic Sea, stimulated by nutrient loadings from the Po and other rivers (Ricci et al. 2014). Some of the mucilage events formed by phytoplankton populations have been linked to high N/P ratios and increased stratification in coastal waters, and thus are at least partially reflective of human influences on the nutrient balance of coastal waters (Danovaro et al. 2009; Ricci et al. 2014).

Another diatom noted for mucilage production is *Coscinodiscus wailesii*, a species that has been recorded worldwide and that causes blooms that harm shellfish and cultures of macroalgae (e.g., Nagai et al. 1995), while also causing problems with commercial fisheries operations due to net clogging. Its distribution, first restricted to the tropical Pacific and western Atlantic oceans, has extended to Europe, the USA, and Japan in recent years. Some of the damage from this species occurs when the mucilage aggregates, sinks, and covers the seabed, where it can decay and cause anoxic conditions.

The filamentous blue-green alga *Trichodesmium erythraeum* is a common 'red tide' organism in tropical and subtropical coastal waters. It can live as solitary cells or in floating colonies. The colonies are visible to the naked eye and sometimes form extensive blooms. It is said that the Red Sea derived its name from visible blooms of this organism – sometimes described as "sea sawdust" or "sea straw". At the start of a bloom, the filaments usually appear throughout the water column, but during late bloom stages, the development of strong gas vacuoles causes *Trichodesmium* to rise to the surface of the water column. The alga is perceived as a nuisance to swimmers on beaches and has significant impacts on recreation, but harmful effects on humans or marine life have seldom been reported. Some species of *Trichodesmium* have been reported to produce neurotoxins (e.g., Hawser et al. 1991; Kerbrat et al. 2010, 2011). Colonies of *Trichodesmium* are capable of fixing atmospheric nitrogen (i.e., obtaining nitrogen from N₂ gas in seawater), which allows the alga to thrive under low nutrient oceanic conditions. It is possible, however, that coastal nutrient pollution (especially phosphates) can stimulate or prolong the blooms once they are washed inshore.

The final bloom-forming species to be highlighted here is *Noctiluca scintillans*, well known for its production of vivid red or green tides (Figure 1.5) as well as intense blue-green bioluminescence that lights up the water at night. This species occurs in two forms. Red *Noctiluca* is heterotrophic (non-photosynthetic) and engulfs food from the water around it, including, diatoms, other dinoflagellates, fish eggs and bacteria. In contrast, green *Noctiluca* contains a photosynthetic symbiont (*Pedinomonas noctilucae*), but it also feeds on other plankton when the food supply is abundant. Widely distributed throughout the world, *Noctiluca scintillans* is often found along the coast in shallow areas of the continental shelf where algal blooms occur that make up a large portion of this species' diet (Harrison et al. 2011). Accordingly, *Noctiluca* blooms are often seen in areas where pollution and nutrient enrichment due to human activities occur. *Noctiluca* is a large cell - roughly spherical, ranging from 200 to 2,000 µm in diameter. *Noctiluca* does not appear to be toxic, but as it feeds voraciously on phytoplankton, it accumulates and excretes high levels of ammonia into the surrounding area, and some ecosystem impacts have been linked to that mechanism.



Figure 1.5. Green and red tides formed by *Noctiluca*. Photos: H. Gheilani and K.C. Ho.

Some report ammonia concentrations as high as 250 µg/L during *Noctiluca* blooms (G. Hallegraeff, pers. comm.). This characteristic should be of interest to the desalination industry because shock chlorination of water containing high levels of ammonia can lead to production of the highly potent carcinogen N-nitrosodimethylamine (NDMA) (e.g., Mitch and Sedlak 2002). Current NDMA guidelines for drinking waters are as low as 10 ng/L.

1.3.4 Life histories

A number of HAB species have dormant, cyst stages in their life histories (Dale 1983) that are a critical aspect of bloom initiation and decline. These include *Alexandrium* spp., *Pyrodinium bahamense*, *Cochlodinium polykrikoides*, *Gymnodinium catenatum*, *Chattonella* spp., *Pyrodinium bahamense*, and *Heterosigma akashiwo*. The highly resistant resting stages remain in bottom sediments (sometimes accumulating in high concentrations in areas termed ‘seedbeds’; Anderson et al. 2014) when conditions in the overlying waters are unsuitable for growth. When conditions improve, such as with seasonal warming, or simply after a certain period of dormancy or maturation, the cysts germinate, inoculating the water column with a population of cells that begins to divide asexually via binary fission to produce a bloom. As the bloom progresses, vegetative growth ultimately slows (typically due to the draw-down and

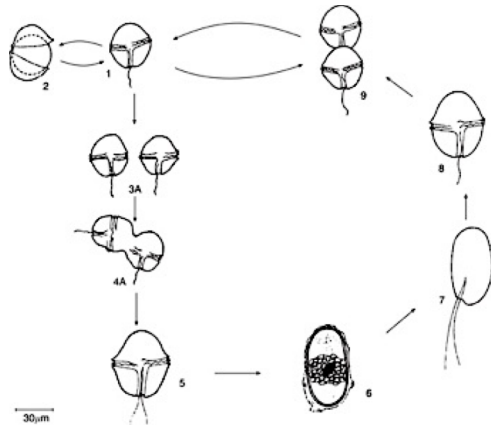


Figure 1.6. Life cycle diagram of *Alexandrium catenella*. Stages are identified as follows: (1) vegetative, motile cell; (2) temporary or pellicle cyst; (3) ‘female’ and ‘male’ gametes; (4) fusing gametes; (5) swimming zygote or planozygote; (6) resting cyst or hypnozygote; (7,8) motile, germinated cell or planomeiocyte; and (9) pair of vegetative cells following division. Redrawn from Anderson (1998).

limitation of nutrients) and the cells undergo sexual reproduction, whereby gametes are formed that fuse to form the swimming zygotes that ultimately become dormant cysts. Figure 1.6 shows the life history of *Alexandrium catenella* (formerly *A. fundyense*). Clearly, the location of cyst seedbeds can be an important determinant of the location of resulting blooms, and the size of the cyst accumulations can affect the magnitude of the blooms as well (Anderson et al. 2014). Some cyst seedbeds can be enormous – two that were documented in the Gulf of Maine, USA, are in excess of 22,000 km², with total cyst abundances as high as 40 x 10¹⁶ cysts in the top cm of sediment alone (Anderson et al. 2014). Another way to view these abundances is that many areas have in excess of 50 million cysts in one square meter of bottom sediment. In many areas, however, the environmental regulation of cell division is more important to eventual bloom magnitude than the size of the germination inoculum from cysts.

Cysts are also important in species dispersal. Natural (storms or currents) or human-assisted (e.g. via ballast water discharge or shellfish seeding) transport of cysts from one location to another can allow a species to colonize a region and extend its geographic range. In 1972, a tropical storm introduced *Alexandrium catenella* into southern New England waters from established populations further to the north and east. Since that time, toxic blooms of the species have become an annually recurrent phenomenon in the region. An example of human-assisted species introductions is the appearance of *Gymnodinium catenatum* in Tasmania in the 1970s, coincident with the development of a wood chip industry involving commercial vessels and frequent ballast water discharge (McMinn et al. 1997).

In the context of desalination plant design and operations, it is important to recognize that when a bloom of a cyst-forming species occurs in an area or region near a plant for the first time, the species is likely to bloom again in that area in future years due to the deposition and accumulation of cysts or resting stages. This is the manner in which some species disperse and colonize new areas. In this context, the recent appearance of *Cochlodinium polykrikoides* in the Gulf and Sea of Oman regions (Richlen et al. 2010) is indeed worrisome, as that species has a cyst (Tang and Gobler 2012) and thus is likely to recur for many years.

1.4 TRENDS AND SPECIES DISPERSAL

The nature of the global HAB problem has changed considerably over the last several decades. Virtually every coastal country is now threatened by harmful or toxic algal species, often in many locations and over broad areas. Over 40 years ago, the problem was much more scattered and sporadic.

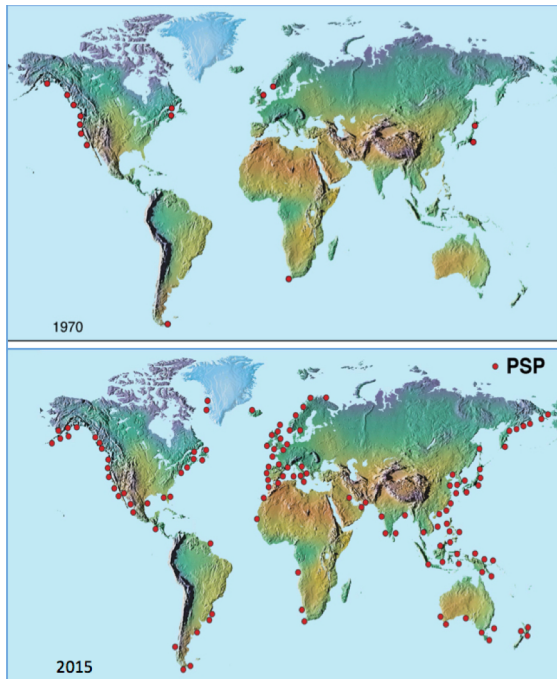


Figure 1.7. Expansion of the paralytic shellfish poisoning (PSP) problem over the past 35 years. Sites with proven records of PSP-causing organisms are noted in 1970, and again in 2015. Source: US National Office for Harmful Algal Blooms, Woods Hole Oceanographic Institution.

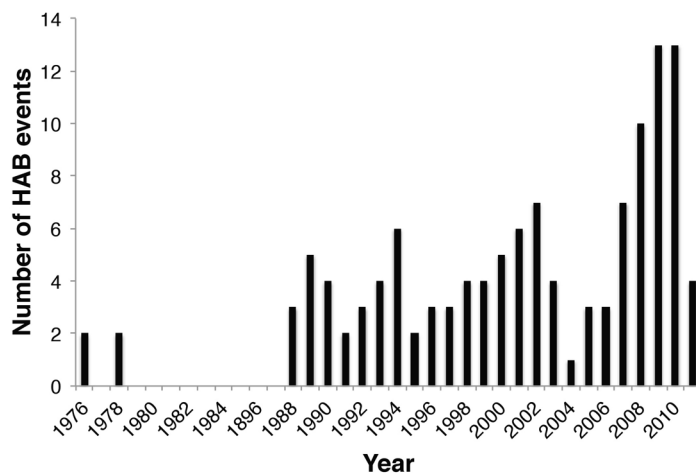


Figure 1.8. Time series of algal bloom events along the coast of Oman. Modified from Al Azri et al. 2012.

Figure 1.7 shows the global expansion of the PSP poisoning syndrome from 1970 to 2015 (caused by multiple *Alexandrium* species, as well as *Gymnodinium catenatum* and *Pyrodinium bahamense*). Figure 1.8 shows the increase in the number of algal bloom events along the coast of Oman from 1976 to 2011. Similar plots could be provided for many parts of the world. Clearly, the number of toxic or harmful blooms, the economic losses from them, the types of resources affected, and the number of HAB species have all increased dramatically in recent years. Disagreement only arises with respect to the reasons for this expansion, of which there are several possibilities (Anderson 1989; Hallegraeff 1993).

New bloom events may simply reflect indigenous populations that are discovered because of improved chemical detection methods, more observers, and better scientific communication. The discovery of ASP toxins along the west coast of the USA in 1991 (Work et al. 1993) is a good example of this, as toxic diatom species were identified and their toxin detected as a direct result of communication with Canadian scientists who had discovered the same toxin and toxic species four years earlier (Wright et al. 1989).

Other ‘spreading events’ are most easily attributed to natural dispersal via currents, rather than human activities. The first NSP event ever to occur in North Carolina was shown to be a Florida bloom transported over 1500 km by the Gulf Stream – a natural phenomenon with no linkage to human activities.

Many believe that humans have contributed to the global HAB expansion by transporting HAB species in ship ballast water (e.g. *Gymnodinium catenatum* in Tasmania; McMinn et al. 1998) or by shellfish relays and seeding. Some types of species are easily transported - especially those that produce resting stages, but long survival in the dark is also possible for species that do not form cysts (e.g., Popels and Hutchins 2002). Furthermore, species that bloom in high concentrations are more likely to be effectively transported since they can be taken in as large populations in the ballast tank, leading to more survivors on discharge. Human-mediated transport of HAB species is especially enhanced between sheltered areas, such as harbors and aquaculture sites, where many dinoflagellates thrive. All these reasons make many HAB species good candidates for transport, and the low number of invasions so far demonstrated is most probably a conservative estimate of the real number.

Another factor underlying the global increase in HABs is that we have dramatically increased aquaculture activities worldwide, and this inevitably leads to increased monitoring of product quality and safety, revealing indigenous toxic algae that were probably always there.

Climatic changes can also affect HAB species distributions, either directly through temperature variations or storms, or, indirectly, through periodic or long-term effects on oceanographic conditions, e.g., changes in stratification or in water circulation patterns.

Nutrient enrichment is another major cause for the increasing frequency of HAB events in some regions (GEOHAB 2006). Manipulation of coastal watersheds for agriculture, industry, housing, and recreation has drastically increased nutrient loadings to coastal waters. Just as the application of fertilizer to lawns can enhance grass growth, marine algae grow in response to nutrient inputs to coastal waters. Fertilizer finds its way into lakes and oceans through runoff from agricultural farms, golf courses, and suburban lawns. Other nutrients get added from the atmosphere, soil erosion, upwelling, aquaculture facilities, and sewage plants. Shallow and restricted nearshore waters that are poorly flushed appear to be most susceptible to nutrient-related algal problems. Nutrient enrichment of such systems often leads to excessive production of organic matter, a process known as eutrophication, and increased frequencies and magnitudes of phytoplankton blooms, including HABs. There is no doubt that this is occurring in certain areas of the world where pollution has increased dramatically. It is real, but less evident in areas where coastal pollution is more gradual and unobtrusive.

A frequently cited dataset from an area where pollution was a significant factor in HAB incidence is from the Inland Sea of Japan, where visible red tides increased steadily from 44 per year in 1965 to over 300 per year a decade later, matching the pattern of increased nutrient loading from pollution (Figure 1.9). Effluent controls were instituted in the mid-1970s, resulting in a 70% reduction in the number of red tides, a level that has persisted to this day. A related data set for the Black Sea documents a dramatic increase in red tides up to the mid-1990s, when the blooms began to decline. That reduction, which has also continued to this day, has been linked to reductions in fertilizer usage in upstream watersheds by former Soviet Union countries no longer able to afford large, state-subsidized fertilizer applications to agricultural land (Anderson et al. 2002).

The Gulf, bordered by many desalination plants, is also experiencing problems with nutrient pollution and eutrophication (Sheppard et al. 2010). It is thus no surprise that the frequency of HABs is increasing in the Gulf, with examples being reported from almost all areas (e.g.,

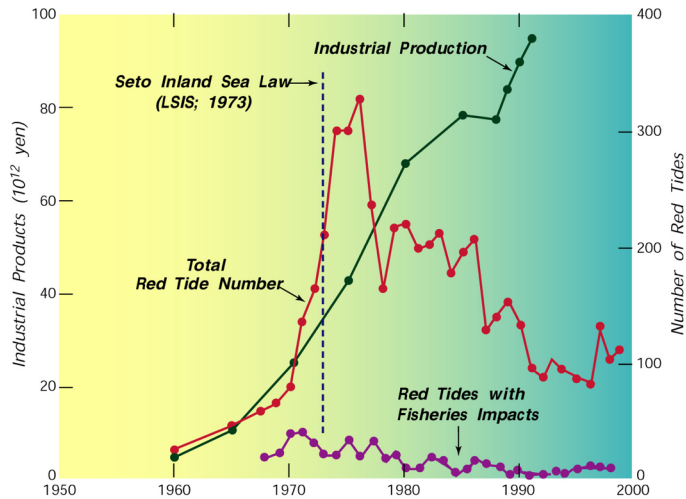


Figure 1.9. Time series of red tides and industrial production in the Seto Inland Sea, Japan. Decreases in pollution inputs were mandated by the Seto Inland Sea Law in 1973, which was followed by a significant decrease in red tides thereafter, including toxic blooms with fisheries impacts. Redrawn from Okaichi (2004).

Thangaraja et al. 2007; Al Azri et al. 2012; D’Silva et al. 2012; Saeedi et al. 2011). In addition to the input from human sewage and agriculture, a rise in nutrient levels around fish cages (mariculture) may be another contributing factor to this increase. In Kuwait Bay, for example, mariculture led to a HAB incident that killed caged and wild fish in 1999 (Al-Yamani et al. 2000).

The global increase in HAB phenomena is thus a reflection of two factors – an actual expansion of the problem due to a variety of factors, and an increased awareness of its size or scale. It is expanding due to natural processes as well as through human activities such as

pollution and ballast water-related species introductions, but improved methods and enhanced scientific inquiry have also led to a better appreciation of its true size. The fact that part of the expansion is a result of increased awareness or improved detection capabilities should not negate our concern – HABs are a serious and growing problem affecting many sectors of society and industry, including desalination.

1.5 GROWTH FEATURES, BLOOM MECHANISMS

1.5.1 Scale of blooms

HABs vary dramatically in their spatial and temporal scales. Some are small and localized, occurring within embayments, harbors, or other coastal features, and covering small areas (Figure 1.10, left). These types of blooms are often relatively short-lived, lasting a month or two at most, terminating due to simple transport processes that carry the population out of an area, or to environmental factors such as nutrient limitation or losses from the zooplankton and other grazers that consume the HAB cells as food. At the other extreme, some HABs are massive, extending hundreds of kilometers along coastlines, sometimes visible from space



Figure 1.10. A small, localized algal bloom in Norway, and a massive bloom in the Gulf of California, seen from space. Photos: E. Dahl and NASA respectively.

(Figure 1.10, right). These large coastal blooms can move with winds, tides, and currents such that the impacts not only extend spatially over large stretches of a coast, but also can be sustained for weeks, months, or even years.

One feature that characterizes many HABs is that they are "patchy" in their distribution, both horizontally and vertically. On a large scale, this is exemplified in Figure 1.10, an image from a satellite that shows patches with dense accumulations of cells, interspersed with other areas where the concentrations are much lower. Patchiness can also occur at much smaller scales where the high concentrations of cells can be a kilometer or less in size.

The relevance of patchiness to desalination plant operators is that because of it, algal biomass conditions can change dramatically from one day to another or one hour to another as patches of HAB cells encounter the intake with normal currents and wind-driven flow. Pretreatment processes that work one day may not work the next, or vice versa. In some cases, a continuous pretreatment effort may not be warranted, as some days will have far fewer cells than other times. In an ideal world, the operator would have bloom distribution data at sufficient resolution to allow a pretreatment program to be undertaken that is responsive to present conditions, but that also reflects knowledge of what will be coming into the plant in the near future. In this regard, there are autonomous instruments of various types that can provide information on algal species and their abundance on a real-time basis, (see Chapter 3) so that operators can adjust their pretreatment strategies accordingly. Another variant of the patchiness concept is presented in section 1.5.3.6 where the vertical distribution of HAB cells is discussed.

1.5.2 Cell growth

HABs are typically caused by single-celled algae that increase in abundance through a process called binary fission – one cell divides to form two cells, those two cells become four, four become eight, and so on. This is the “exponential growth” that is depicted in Figure 1.3. The rate of cell division varies dramatically among species, with most dinoflagellates taking 1-3 days to divide under good growth conditions, whereas diatoms and other species can divide several times in a single day. In some cases, HAB species are able to form nearly mono-specific populations, benefitting from mechanisms such as grazer avoidance (through swimming, migration patterns, or even cell morphology that discourages predators), or the inhibition of grazers or other competing algal species through the release of allelopathic substances – a type of inter-species chemical warfare likened to a “watery arms race” (Smetacek 2001). At other times, HAB species are simply a minor component of a complex community of co-occurring microscopic plants and animals, but they make themselves known through their toxins or other harmful traits.

There are no easy generalizations about the cell concentrations that might be encountered during blooms. At barely detectable concentrations (10^2 – 10^3 cells/L), some harmful species can have dramatic effects; this is the case of highly toxic species like the PSP-producers *Pyrodinium bahamense* var. *compressum* and *Alexandrium catenella*, which may also form much denser blooms (10^6 – 10^7 cells/L). Other species, including many that are less toxic or non-toxic, easily reach these same concentrations, while small forms such as *Aureococcus anophagefferens*, a brown tide organism, can exceed 10^9 cells/L. Vertically migrating cells like *Cochlodinium polykrikoides* can aggregate in dense patches at the water surface that exceed 10^{10} cells/L. In contrast, the DSP-producing species of the genus *Dinophysis* rarely reach concentrations higher than 10^4 – 10^5 cells/L.

A common misconception is that HABs are caused by the explosive growth of a single species that then rapidly dominates the water column. Given the above information, however,

it should be clear that it is only necessary to have conditions that favor the growth of a moderately large population of a given species and the proper hydrographic and meteorological conditions to permit the accumulation of those cells. In other words, coupled with normal or average growth rates, winds, tides, currents, fronts, and other hydrographic features can combine with organism behavior (e.g., vertical migration) to create discrete “patches” of cells (blooms) at all scales.

1.5.3 Bloom dynamics and coastal oceanography

Though the number of HAB species is only a small fraction of the many algal species in the ocean, their diversity in terms of shape (morphology), physiology, and ecology is very large. In effect, there are hundreds of common HAB species and they differ in their growth characteristics and in the types of blooms they cause and the waters they inhabit. Given this diversity of species and habitats in which they occur, there exist few unifying principles that explain bloom dynamics in all habitats. A few common processes and mechanisms for bloom development and accumulation are highlighted below.

1.5.4 Bloom initiation

HABs can be initiated from cells present at low concentrations, sometimes persisting in the background for months or years before a bloom develops (the “hidden flora” concept). Other

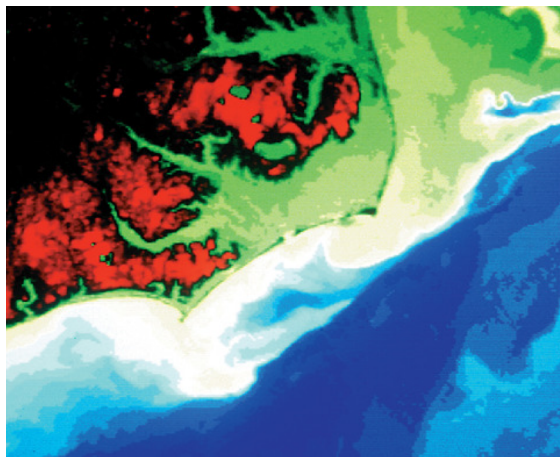


Figure 1.11. Satellite image of sea surface temperature, showing the warm Gulf Stream (blue) off the coast of North Carolina, USA. Several filaments of the Gulf Stream extend toward shore. These carried a toxic population of *Karenia brevis* that originated in the Gulf of Mexico, >1500 km away. Photo: NASA.

HABs are delivered to a location by tides and currents (see below). Still other HABs are initiated from resting cysts (Figure 1.11) that germinate from bottom sediments, significantly impacting many aspects of HAB phenomena. In those instances, cyst or spore germination provides the inoculum for blooms, and the transformation back to the resting state can remove substantial numbers of vegetative cells from the population and act as a major factor in bloom decline. Cysts are also important for population dispersal, including through ballast water transfer. They permit a species to survive through adverse conditions, and since sexuality is typically required for their formation, they facilitate genetic recombination. They can even be major sources of toxin to shellfish and other benthic animals.

1.5.5 Bloom transport

Once a population is established, its geographic extent and biomass are affected by physical controls such as the transport and accumulation of cells in response to water flows (e.g., Franks and Anderson 1992), by the swimming behavior of organisms (Kamykowski 1995) and by the maintenance of suitable environmental conditions (including temperature and salinity, stratification, irradiance, and nutrient supply). These factors all interact to determine the timing, location, and ultimate biomass achieved by the bloom, as well as its impacts.

Physical processes that are likely to influence the population dynamics of HAB species are operative over a broad range of spatial and temporal scales. Large-scale circulation patterns (Figure 1.10) affect the distribution of water masses and their associated HABs. Some HABs are delivered into a specific region via advection (transport) after developing elsewhere. In

such cases, the population increases can be significant and alarming, but should be attributed to transport and not to in situ growth. Eddies (spinning masses of water) or filaments from the open ocean (Figure 1.11) can, for example, impinge on shelf regions, transporting HABs and nutrients to nearshore waters. This type of transport has been invoked for the delivery of the Florida red tide organism *Karenia brevis* to nearshore waters from an offshore zone of initiation (Walsh et al. 2006). Another prominent example is the wind-driven delivery of offshore *Dinophysis acuminata* cells into Bantry Bay in southwest Ireland (Raine et al. 2010).

1.5.6 Fronts

Physical processes at intermediate scales can lead to the formation of convergence zones, fronts, and upwelling. Fronts in the ocean (Figures 1.12, 1.13) are directly analogous to the more familiar weather fronts where two air masses meet, but in the ocean, representing the boundary between two water masses.

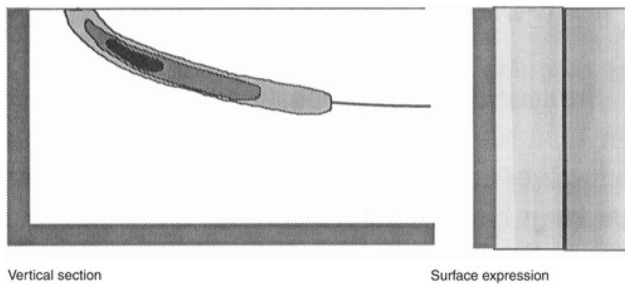


Figure 1.12. Accumulation of HAB cells near a front. This schematic demonstrates how cells can accumulate at a frontal convergence, with a surface manifestation of the bloom at the frontal convergence (right panel), and a subsurface extension of the bloom that extends below the surface along the sloping pycnocline (density discontinuity). Adapted from Franks 1992.



Figure 1.13. Algal bloom showing accumulation at a front (straight lines parallel to shoreline), and in windrows or streaks of cells aligned with the wind, and perpendicular to shore. Photo: M. Godfrey.

There are many types of fronts in the ocean. A tidal front forms when the water is well mixed in a shallow zone due to tidal energy near the bottom and winds at the surface, whereas the water overlying deeper areas further offshore remains stratified (layered), and therefore has a different density structure. The front is the interface between these two water masses. Another common front is found within or outside of estuaries where low salinity, upstream waters meet higher salinity coastal waters.

Just as storms and other dynamic features are commonly found at fronts in the atmosphere, oceanic fronts are frequently the site of enhanced algal biomass. This is the result of the interaction between physical processes such as upwelling, shear, and turbulence, and physiological processes such as swimming and enhanced nutrient uptake by the algal cells. One example is the

linkage between tidally generated fronts and the sites of massive blooms of the toxic dinoflagellate *Gyrodinium aureolum* (now called *Karenia mikimotoi*) in the North Sea (Holligan 1979). The pattern generally seen is a high concentration of cells at the surface of the frontal convergence, contiguous with a subsurface cell maximum which follows the sloping interface between the two water masses beneath the stratified side of the front (Figure 1.12). Foam and other debris also accumulate at the frontal interface, making it easy to see. The surface signature of the chlorophyll or algal cell maximum at the front (sometimes a visible red tide) may be 1–30 km wide. Cell concentrations are generally lower and more uniform on the well-mixed, typically offshore side of the front. If located offshore, the bloom at a front may be harmless, but when movement of the front and its associated cells brings

HAB populations into contact with fish and other susceptible resources, including desalination plants, negative impacts can result.

Frequently, wind will create patterns called “windrows”. Winds that blow steadily across the ocean, and the small waves that such winds generate, can create vortices, or rotating cells, in the surface waters. These vortices align in the direction of the wind, and are made visible by streaks of foam, seaweed, debris, and algal cells. Figure 1.13 shows an algal bloom at a frontal feature, with windrows extending offshore.

1.5.7 Upwelling systems

A common mechanism that leads to a widespread and sustained HAB is when there is a source population of cells living in offshore waters, with periodic delivery of those cells to the nearshore zone as a result of winds and currents (GEOHAB 2005). This is often related to processes called upwelling and upwelling relaxation or downwelling. Large upwelling systems tend to occur along the eastern boundaries of the world’s oceans, such as along the west coasts of the Americas, the continental shelves of northwest and southwest Africa, and the western edge of the Iberian Peninsula. Smaller-scale upwelling can occur in virtually all coastal waters if the wind blows in the proper direction to move surface waters away from the coast. In these upwelling systems, the winds force offshore transport of surface water due to a

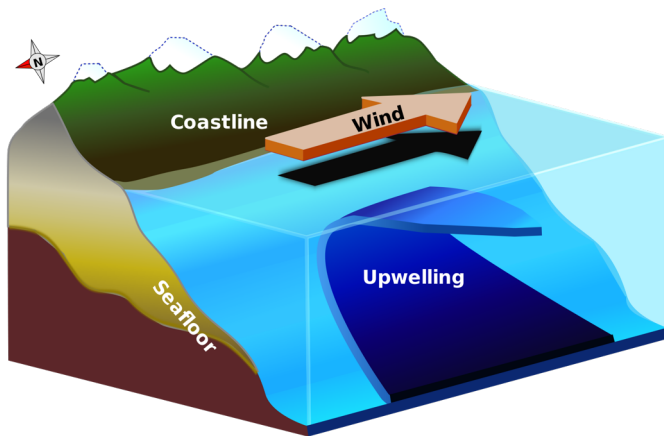


Fig. 1.14. Schematic of coastal downwelling, driven by alongshore winds that force surface waters offshore, and deeper waters onshore. Image: Lichtspiel.

process called Ekman transport that moves water 90 degrees to the right of the wind direction. This offshore flow is compensated for by the onshore flow and “upwelling” of deep, colder, nutrient-rich water into coastal zone (Figure 1.14). The boundary along the coast between the nearshore upwelled water and the warmer adjacent ocean surface water is usually a front (Figure 1.12) that has high biological productivity, including HABs, fueled by the upwelled nutrients. This feature can then be delivered to shore as a result of the

relaxation or reversal of the winds, allowing offshore waters and the associated high biomass populations to move to shore very quickly. The 2008/2009 *Cochlodinium* bloom in the Gulf and Sea is thought to be an example of the upwelling process. Satellite imagery shows large patches of cells throughout much of the eastern Gulf and Sea of Oman during upwelling intervals (see Chapter 4), with these populations transported to shore where they had devastating impacts (Zhao and Ghedira 2014).

1.5.8 Alongshore transport

The preceding sections describe mechanisms that concentrate cells at certain hydrographic features and deliver them to shore via cross-shore transport (i.e. perpendicular to shore). A related mechanism is alongshore transport whereby an established HAB is carried along a coastline by currents, sequentially causing impacts at different sites. Many HABs originate in one location and are delivered to other areas through this type of transport. These transport events can span hundreds of km, and can last months. Upwelling and downwelling winds will affect the location and timing of impacts on shore, acting on blooms as they move down the

coast. The appearance of HABs can be sudden and unexpected at times, and in some of these instances, alongshore transport is the explanation. Operators should learn the nature of the transport pathways in the vicinity of their plant intakes to better anticipate and respond to HABs of this type.

An example of this type of transport is found with blooms of the PSP-toxin producing *Alexandrium catenella* in the Gulf of Maine (USA). In that region, the bloom populations are found within a low-salinity coastal current that travels along the coast (Franks and Anderson 1992). This water mass provides a suitable growth habitat for the *Alexandrium* cells as its southerly transport is regulated by river runoff, Coriolis forces (due to the Earth's rotation), wind stress and other large-scale hydrographic forcings. Of these factors, wind appears to be particularly important in determining transport variability in surface waters. Downwelling-favorable winds (from the north or northeast) compress the plume against the coast and accelerate it alongshore, while an upwelling favorable wind (from the south) thins the low-salinity surface plume as it is moved offshore. Upwelling winds also retard the southward progression of the plume and its associated cells. In the downwelling case, the bloom would progress rapidly down the coast, whereas with upwelling, the bloom would move more slowly. The general velocity of alongshore transport of this bloom and *Alexandrium* cells during downwelling is roughly 0.2 m/s, or 17 km/d or 120 km in a week.

1.5.9 Vertical distributions

An important feature of some HAB events, particularly in the context of desalination, is that the algal cells are often not uniformly distributed in the vertical direction (GEOHAB 2008). Typically, the “water column” in nearshore waters has a stratified structure whereby there is a surface layer that is warmer or fresher, and thus more buoyant than deeper waters. That layer is often stirred by winds, and is thus termed the “mixed layer”. Algal cells and other constituents of the plankton that are non-motile are distributed uniformly through the mixed layer. Species that swim, however, such as many HAB species, can override that random mixing process and form aggregations at specific depths – sometimes at the surface, sometimes deeper. In some instances, these subsurface layers of cells do not move vertically because they are linked to some feature, such as the interface or density discontinuity between the mixed layer and the deeper waters (called the pycnocline) below which nutrients are typically higher than in the surface. Cells residing at that location would have ready access to high nutrients. For example, off the French coast, a thin layer of dinoflagellates, including the HAB species *Dinophysis acuminata*, is frequently observed in the proximity of the pycnocline (Gentien et al. 1995). Thin, subsurface layers have been observed at scales as small as 10 cm in the vertical and as large as 10 km in the horizontal.

Some subsurface cell aggregations do move up and down, typically on a daily basis, due to a process called diel vertical migration. These migrating populations often reside in surface waters during the day to harvest the sunlight for photosynthesis, and then swim to the pycnocline and below to take up nutrients at night. This strategy can explain how dense accumulations of cells can appear in surface waters that are devoid of nutrients and which would seem to be incapable of supporting such apparent, prolific growth. In truth, the growth is not rapid; the cells are aggregating, not growing fast. This behavior also explains the disappearance, and the reappearance of cells or surface bloom patches on a daily basis.

Typically, vertical movement down to 10, 15 or even 20 m have been observed, depending on the organism and depth of the mixed layer or water column. An example of the extent and timing of vertical movement is seen in Park et al. (2001) who observed the behaviour of *Cochlodinium polykrikoides*, the same species that caused desalination plant disruptions in 2008 and 2009 in the Gulf and Sea of Oman regions (Richlen et al. 2010; Shahid and Al Sadi

2015). In the daytime, between 1100 and 1600 hrs, the species concentrated near the surface at depths less than 2m (Figure 1.15). The highest surface cell concentrations were observed at approximately 1600 hrs, when > 60% of the cells in the population were found in the top meter, forming a visible red tide. Thereafter, the population began to migrate downwards, leading to a distinct subsurface maximum at 1700 hrs. The species arrived at the bottom (15 m in this study) by 2000 hrs, but cells were somewhat dispersed in the bottom layers. The upward migration of the species from the bottom began around 0600 hrs, before sunrise, and the population was concentrated back in the service layer by 1100 hrs once again. This pattern is depicted in Figure 1.15.

Swimming speeds of *C. polykrikoides* determined from this study were ~3 m/h, which is fast

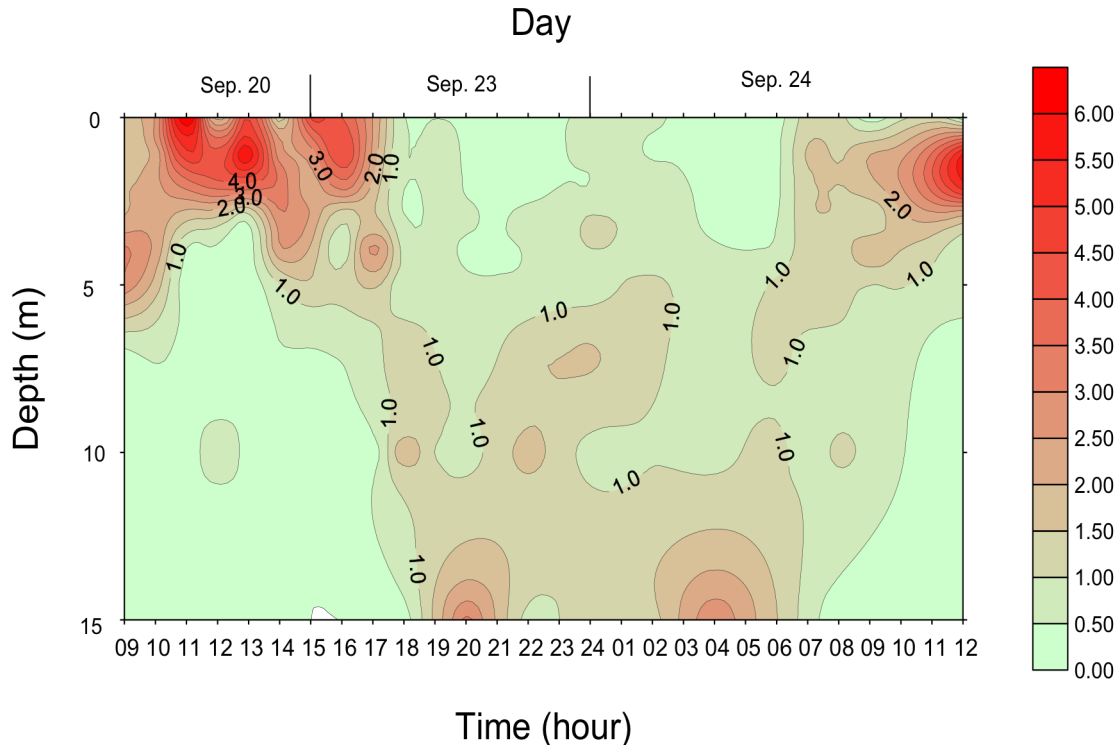


Figure 1.15. Temporal changes in the vertical distribution of *Cochlodinium polykrikoides* in Kwangyang Bay, Korea. Relative densities (colors) are the ratios of cell counts at each depth to the average number of cells in the water column. Modified from Park et al. 2001.

compared to many dinoflagellates, which typically swim ~ 1 m/h. Figure 1.16 shows the hypothetical depth that different species of algae can reach under the assumption that they swim downward for 10 hours. The fastest swimmer, and deepest migrator, is *Cochlodinium polykrikoides*, but a number of other prolific bloom formers (e.g., *Lingulodinium polyedrum*, *Prorocentrum micans*, *Heterosigma akashiwo*) or toxin producers (e.g., *Alexandrium catenella*, *A. minutum*, *Dinophysis acuta*) all can descend 15 - 20 m in a day.

Vertical migration is a behavioral feature of some HABs that should be of concern to desalination plants in the context of intake design, as well as routine operations. Near-surface intakes (i.e., those with intake channels or intake pipes at depths of 4-5 m or less) would see increased numbers of cells during daylight hours and low numbers at night. Deep intakes (i.e., those at 8-10 m or deeper) would see just the opposite – maximum numbers of cells of vertically migrating species at night. One practical application of this knowledge would be that in a major bloom of a migrating species (as in the 2008/2009 *Cochlodinium* HAB in the Gulf and Arabian Sea), there might well be times of the day (nighttime) when the plant could be operated without taking in too many cells. Likewise, this means that pretreatment filtration

rates that are effective at one time of day might not work well at other times, and therefore that actions might need to be varied to compensate for the large differences in the number of cells present in the intake waters at different times of the day.

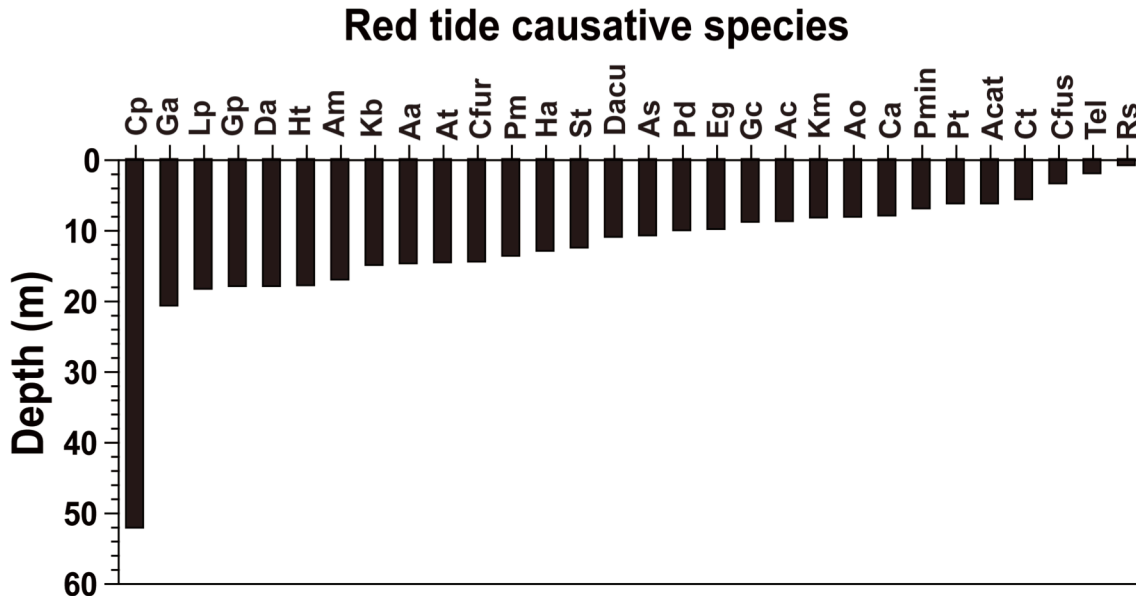


Figure 1.16. Depth (m) which a phototrophic, motile algal species can reach when it swims downward for 10 h. This depth was calculated by multiplying the maximum swimming speed (mm/sec.) of a given species by 36,000 sec. Cp: *Cochlodinium polykrikoides*, Ga: *Gymnodinium aureolum*, Lp: *Lingulodinium polyedrum*, Gp: *Gonyaulax polygramma*, Da: *Dinophysis acuta*, Ht: *Heterocapsa triquetra*, Am: *Alexandrium minutum*, Aa: *Alexandrium affine*, At: *Alexandrium tamarense*, Cfur: *Ceratium furca*, Pm: *Prorocentrum micans*, Kb: *Karenia brevis*, Ha: *Heterosigma akashiwo*, St: *Scrippsiella trochoidea*, Dacu: *Dinophysis acuminata*, As: *Akashiwo sanguinea*, Pd: *Prorocentrum donghaiense*, Gc: *Gymnodinium catenatum*, Ac: *Amphidinium carterae*, Eg: *Eutreptiella gymnastica*, Km: *Karenia mikimotoi*, Ao: *Alexandrium ostenfeldii*, Ca: *Chattonella antiqua*, Pmin: *Prorocentrum minimum*, Pt: *Prorocentrum triestinum*, Acat: *Alexandrium catenella*, Ct: *Ceratium tripos*, Cfus: *Ceratium fusus*, Tel: *Teleaulax* sp., Rs: *Rhodomonas salina*. H.J. Modified from Jeong et al. 2015.

1.6 SUMMARY

Harmful algal blooms are increasing in frequency and magnitude in many parts of the world, and one of the sectors of society that is being increasingly affected is the desalination industry. Given trends in the development of that industry, as well as the global expansion of the HAB problem, impacts will continue to occur, and are likely to increase. Desalination plant operators and managers are urged to take a more active role in determining the nature of the algal populations that are in the waters near their intakes, as this can directly help with identification of timely and appropriate mitigation strategies. One of the many challenges desalination plant managers face is that HABs are incredibly diverse in terms of toxicity, cell size, morphology, and bloom dynamics, and this diversity needs to be recognized when developing and implementing monitoring and mitigation strategies. Partnerships between regional HAB scientists and desalination operators and managers are encouraged as these will help the managers understand the nature of the problems they are facing.

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