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# *KARENIA*: The biology and ecology of a toxic genus

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## Abstract

*Karenia* is a genus containing at least 12 species of marine unarmored dinoflagellates. Species of the genus can be found throughout the world in both oceanic and coastal waters. They are usually sparse in abundance, but occasionally form large blooms in coastal waters. Most *Karenia* species produce a variety of toxins that can kill fish and other marine organisms when they bloom. In addition to toxicity, some *Karenia* blooms cause animal mortalities through the generation of anoxia. At least one species, *K. brevis*, produces brevetoxin that not only kills fish, marine mammals, and other animals, but also causes Neurotoxic Shellfish Poisoning and respiratory distress in humans. The lipid soluble brevetoxin can biomagnify up the food chain through fish to top carnivores like dolphins, killing them. *Karenia* dinoflagellates are slow growers, so physical concentrating mechanisms are probably important for the development of blooms. The blooms are highly sporadic in both time and space, although most tend to occur in summer or fall months in frontal regions. At the present time, our understanding of the causes of the blooms and ability to predict them is poor. Given the recent discovery of new species, it is likely that new *Karenia* species and toxins will be discovered in the future.

## 1. Introduction

The genus *Karenia* includes about 12 described species (Table 1) of marine unarmored dinoflagellates. They have become well known because most produce toxins that kill fish and other marine organisms. At least one species, *K. brevis*, can produce the neurotoxic brevetoxins, which cause Neurotoxic Shellfish Poisoning (NSP) in humans and generates an aerosol that causes respiratory distress in humans.

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*Karenia* species are found throughout the world. Most have been described as a result of investigations into extensive animal mortalities or human health problems. *K. mikimotoi* was the focus of the earliest studies on species now included in the *Karenia* genus. It was initially described as *Gymnodinium mikimotoi*, which caused fish kills and oyster mortalities in Japan (Oda, 1935). Once *Gymnodinium breve* (now *Karenia brevis*), was discovered to be the cause of the Florida red tide that causes widespread animal mortality and affects human health (Davis, 1948; Gunter et al., 1948; Woodcock, 1948), it became one of the most studied species of harmful algae with extensive investigations into its toxicity, physiology and bloom formation.

For half a century, animal mass mortality, NSP, and respiratory distress caused by frequent blooms of *K. brevis* in the Gulf of Mexico, and animal mass mortality by *K. mikimotoi* in many parts of the world were thought to be the primary problems caused by *Karenia*. In the past few decades however, new blooms of newly discovered species of *Karenia* have developed in many parts of the world, also causing animal mass mortalities, NSP, and respiratory distress. We also now know that blooms in the Gulf of Mexico, while still dominated by *K. brevis*, are often mixtures of several species of *Karenia*. Although brevetoxin is the most intensively studied toxin produced by some *Karenia* species, gymnodimine, gymnocins, and a variety of toxic sterols, polyunsaturated fatty acids (PUFAs), and other compounds are produced by various *Karenia* species. It is likely that more species and more toxins of *Karenia* will be discovered in the future.

## 2. Systematics

*Kareniaceae* is a taxonomic family of unarmored dinoflagellates that had most recently been classified as *Gymnodinium* (Daugbjerg et al., 2000). Within the family are 3 genera, *Karenia*, *Karlodinium*, and *Takayama*, which all apparently kill fish (Bergholtz et al., 2005). The genus *Karenia* G. Hansen & Moestrup 2000 was created as a result of a molecular and morphological study of athecate dinoflagellates previous contained within the *Gymnodinium* genus (Daugbjerg et al 2000). *Karenia* initially contained three species: *K. brevis* (Davis, 1948) G. Hansen & Moestrup, *K. mikimotoi* (*Gymnodinium mikimotoi* Miyake & Kominami ex Oda, 1935) and *K. brevisulcata* (F.H. Chang, 1999) G. Hansen & Moestrup, 2000. A major characteristic that differentiates the *Kareniaceae* from other dinoflagellates is that, instead of peridinin (which most dinoflagellates have), they have the accessory pigments fucoxanthin, 19'-butanoyloxyfucoxanthin, 19'-hexanoyloxyfucoxanthin, and 19-hexanoyloxyparacentrone 3-acetate (gyroxanthin-diester) (Hansen et al., 2000; Steidinger et al., 2008a).

*Karenia* are relatively small unarmored dinoflagellates with no distinct cell wall plates, so are quite pleiomorphic. As a result, cells can be relatively difficult to identify to species using standard light microscopy, particularly using standard fixatives such as Lugol's iodine. Even the early studies (Wilson, 1967) described the wide range of morphologies that can exist in a clonal culture of *Karenia brevis*. Tools from molecular genetics are now helping considerably to distinguish the different species. For example, Haywood et al. (2004) compared the morphology and molecular taxonomy of six species of *Karenia*, which resulted in the description of three new species.

The classification history of some species within the *Karenia* genus has been complex. For example, *K. brevis* was previously described as *Gymnodinium breve* (Davis, 1948), *Gymnodinium brevis* Davis, 1948 and *Ptychodiscus brevis* (Davis) Steidinger, 1979. *K. mikimotoi* was initially described from Japanese waters as *Gymnodinium mikimotoi* Miyake & Kominami ex Oda, 1935. Both *Gymnodinium nagasakiense* Takayama & Adachi, 1984 and *Gyrodinium nagasakiense* Takayama & Adachi, 1984 were later found to be the same as *G. mikimotoi,* based on DNA sequencing data (Hansen et al., 2000). To complicate matters, in European waters, what is now called *K. mikimotoi*, was initially identified as *Gyrodinium aureolum* after Hulburt (1957) in response to a bloom in 1966 (Braarud and Heimdal 1970). The fact that blooms of European *G. aureolum* were associated in mass mortalities of fish, while American strains where the type material was isolated, did not have any harmful effects led the European strains to be referred to as *Gyrodinium* cf. *aureolum*, *G.* cf. *nagasakiense* and *G.* cf. *mikimotoi* (Gentien, 1998). It was not until Hansen et al. (2000) performed an in depth morphological, molecular and pigment study of a variety of geographically distinct strains of *Gyrodinium aureolum* and *Gymnodinium mikimotoi* that the European strain of *G. aureolum* was confirmed as being conspecific with *G. mikimotoi* (Hansen et al., 2000). This study also suggested that *Gyrodinium aureolum* Hulburt 1957 should be placed in the genus *Gymnodinium* and renamed *Gymnodinium aureolum* (Hansen et al., 2000). This reclassification was further corroborated by Hansen (2001) and Tang et al. (2008), although Hansen (2001) suggested that the classification of *Gymnodinium aureolum* may be temporary and called for an in depth examination of the *Gyrodinium*/*Gymnodinium* genera.

There has been speculation as to whether *K. mikimotoi* has been introduced from Asia into European waters and should be considered an ‘exotic flagellate’ (Elbrachter, 1999, Gomez, 2008). Partensky et al. (1988) as well as Chang (1996) suggested that differences observed in DNA content and the formation of small cells in culture was a basis for separation of the Asian and European strains, although molecular studies using partial LSU rDNA sequences where a single base substitution was observed could not support this (Guillou et al., 2002; Hansen et al., 2000). A recent in depth molecular study using concatenated rDNA and ITS sequences as well as the *rbc*L genes suggest the separation of *K. mikimotoi* into two different subgroups with *K. mikimotoi* from Europe and New Zealand being more closely related than isolates from Japan (Al-Kandari et al., *in press*.).

Over the past two decades, blooms of other *Karenia* species have been discovered in many parts of the world. In 1999, *Karenia brevisulcata* (first named *Gymnodinium brevisulcatum*) was observed in New Zealand in a bloom that produced fish kills and human respiratory distress symptoms very similar to those produced by *K. brevis* blooms (Chang, 1999). *Karenia longicanalis* (Yang et al., 2001) was described from a bloom in Hong Kong. *Karenia digitata* was identified from blooms in Japan and Hong Kong that caused large fish kills (Yang et al. 2000).

In the Atlantic, Botes et al. (2003a) described the new species *K. cristata* and *K. bicuneiformis* from blooms in South Africa. *K. cristata* blooms caused animal deaths and respiratory problems in humans. Haywood et al. (2004) described three new species, from

New Zealand, including *K. bidigitata* (now considered a synonym for *K.bicuneiformis*), *K. selliformis*, and *K. papilionacea*.

Although initially isolated from New Zealand (Haywood et al., 2004), *K. selliformis* has also been found in association with fish kills in Kuwait (Glibert et al., 2002, Heil et al., 2001). Similar strains, based on very similar LSU rRNA gene sequences have also been reported from Chile and Tunisia as well (Guillou et al., 2002).

*K. papilionacea* was first described from New Zealand waters and the Gulf of Mexico (Haywood et al., 2004). In a re-examination of *K. brevis*-like cells from the South China Sea and Hong Kong region, Yeung et al. (2005) also identified *K. papilionacea*-like cells.

An additional new species from New Zealand, *Karenia concordia,* was described by Chang and Ryan (2004). This species co-occurred with *K. mikimotoi* and *K. brevisulcata* in a 2002 New Zealand bloom.

De Salas et al. (2004a) described the new species *K. umbella* from blooms in Tasmania that caused fish kills. *K. asterichroma* from blooms in Tasmania caused large fish kills in aquaculture (de Salas et al., 2004b). *K. asterichroma* occurred in blooms with 5 other species of *Karenia*, so its contribution to toxicity is not known.

Almost certainly there is a bias towards species that form large blooms and/or cause animal mortalities or human illnesses. It seems likely that more *Karenia* species exist that simply have not caught the attention of researchers yet. For example, Henrichs et al. (2011) have suggested that the oceanic *Brachidinium* probably belongs in the *Karenia* genus. This indicates that *Karenia* species may be more widespread than currently thought.

For detailed description of *Karenia* species, see Daugbjerg et al. (2000) in general, Steidinger et al. (2008b) for species in the Gulf of Mexico, Haywood et al. (2004) and de Salas et al. (2005) for species in New Zealand, and de Salas et al. (2004a, b) for species in Tasmania.

In this paper, we will refer to only the most recent species name, which in many cases is different from what it was named in the original reference paper.

## 3. Life cycle

While we are aware of at least 12 species of *Karenia*, most research on the basic biology has been conducted on *K. brevis*. Wilson (1967) described its basic morphology and the amount of morphological variation that occurs in a culture. He observed cells 20–40 microns in size in culture but noted that cells up to 90 microns could be observed in the field. He also observed nonmotile spherical cells that appeared to be resting stages.

*K. brevis* reproduces asexually most of the time, dividing by binary fission once every 2 to 10 days. Like most dinoflagellates, they divide primarily at night, the diel phased timing being under the control of a biological clock (Van Dolah et al., 2009). They occasionally produce planozygotes, indicating the capability for sexual reproduction. Wilson (1967) observed that up to 40% of the cells in culture existed as pairs at times and appeared to be in

the process of conjugation. Walker (1982) observed an increase in gamete production when different clones of *K. brevis* were mixed together, and when they were subjected to nitrogen limitation, blue or green light, and lower temperatures. She observed the aggregation and fusion of isogamous gametes and subsequent formation of planozygotes.

Hypnozygote resting cysts that could provide a benthic seed stock as part of the life cycle have been hypothesized (Wilson, 1967; Steidinger and Ingle, 1972; Steidinger, 1975). Wilson (1967) observed what appeared to be benthic resting cysts in cultures. Kang (2010) found many cells that appear similar to the resting cells observed in cultures of *K. brevis* at many locations in the sediments on the West Florida Shelf, but they have not yet been confirmed genetically as *K. brevis*. Because much of the area where *K. brevis* blooms is shallow enough that light reaches the bottom, it certainly seems plausible that part of its life cycle may be in the benthos. Sinclair and Kamykowski (2008) have shown that *K. brevis* will swim into sediment porewaters. The existence of such cysts or active benthic cells could alter our view of the possible initiation mechanisms of blooms of this species. Most research on *K. brevis* tends to focus on the water column. More research on the benthos as a habitat for part of the life cycle may prove fruitful.

The life cycle of *K. mikimotoi* has not been examined in such detail. A study on a *K. mikimotoi* culture from Japan revealed the presence of sexual reproduction with the formation of isogamous gametes, although with a low incidence (Ouchi et al., 1994). Observations *of K. mikimotoi* cultures grown for molecular and morphological analysis did not reveal the presence of any temporary cysts (Hansen et al., 2000). The formation of small cells through vegetative cell division has been observed in laboratory culture (Partensky and Vaulot, 1989). Small cells have also been observed in field samples towards the end of blooms (Partensky and Vaulot, 1989; Gentien, 1998).

## 4. Swimming behavior

*K. brevis* can swim approximately 1m/hr using 2 flagella over a rather wide range of environmental conditions (McKay et al., 2006). Studies by Heil (1986), Kamykowski et al. (1998) and Kerfoot et al. (2004) indicate that *K. brevis* exhibits both phototaxis and geotaxis. It tends to accumulate at the surface during the day and disperse downward throughout the water column at night. The studies by Heil (1986) showed that upward swimming began before the light period began and downward swimming began before the dark period began, suggesting that the diel swimming behavior is controlled by a biological clock. This was confirmed by her observation of continued diel vertical migration in continuous darkness for 4 days. Its swimming behavior is thought to interact with hydrographic features that cause it to become concentrated in certain hydrographic areas independent of growth, which could be a mechanism for the initiation of blooms. The physical accumulation at the surface can also help it become essentially monospecific in a parcel of water. This diel change in degree of aggregation at the surface can have a large impact on satellite imagery (Schofield et al., 2006). Mesocosm studies by Sinclair and Kamykowski (2008) showed that *K. brevis* can migrate to the sediment surface and into the sediments where higher nutrient concentrations occur.

Vertical migration of *K. mikimotoi* within the water column has been observed to be dependent on water column stability with vertical migration occurring while the water column is well mixed. When stratification is greater migration does not occur (Dahl and Brockman, 1989; Gentien, 1998), and in some instances it has been suggested it can take longer than a day (Holligan et al., 1984). Field studies of *K. mikimotoi* revealed that when migration does occur it can undergo diel vertical migration at speeds of around 2m/hr (Koizumi et al., 1996), about twice as fast as *K. brevis*.

## 5. Physiology

Culture studies have been conducted primarily on *K. brevis* and *K. mikimotoi*. Overall, Karenia species do not appear to have any unusual physiological characteristics that would distinguish them from other dinoflagellate species that would predict that they could outcompete other species to dominate blooms.

### 5.1 Temperature

*K. brevis* has been observed in the field between 7 and 33°C, but optimal growth in laboratory cultures is between 22 and 28 °C (Magaña and Villareal, 2006; Vargo, 2009). *K. mikimotoi* has been found over a wide range of temperatures, 4–31°C (Gentien, 1998); however, in some instances growth was observed within a strict window within that temperature range. For example *Gyrodinium aureolum* isolated in 1977 from the Oslofjord by Tangen (assumed to be *K. mikimotoi)* did not grow at temperatures <10°C or > 25°C (Nielsen and Tønseth, 1991).

### 5.2 Salinity

*K. brevis* generally grows between salinities of 18 and 45 PSU, but has a maximum growth rate between 30 and 34 PSU (Magaña and Villareal, 2006; Maier Brown et al., 2006; Vargo, 2009). Because *K. brevis* prefers full salinity seawater and is usually not found at salinities below about 24 PSU, blooms are generally found in coastal waters but not estuaries. The only time blooms occur in estuaries is during droughts when the salinity is high in the estuary (Steidinger and Ingle, 1972; Landsberg and Steidinger, 1998). They are also found in the high salinity lagoons of Texas (Tester et al., 2004).

Contrary to this generalization of high salinity that has been widely observed, Dortch et al. (1998) found *K. brevis* near the mouth of the Mississippi River in waters as low as 5 PSU and numerous locations below 24 PSU. This appears to be a one-time event in which *K. brevis* populations from the western panhandle of Florida were transported westward towards the Mississippi Delta into low salinity water.

*K. mikimotoi* has been found over a wide range of salinities, from 9 to 35 PSU (Gentien, 1998), however maximum growth in some culture studies was observed at salinities > 12 PSU (Nielsen and Tønseth, 1991).

### 5.3 Light

All *Karenia* species have chlorophylls a and c; and have fucoxanthin, 19'-butanoyloxyfucoxanthin, 19'-hexanoyloxyfucoxanthin, and 19-hexanoyloxyparacentrone 3-acetate (gyroxanthin-diester) as accessory pigments instead of peridinin, like most other dinoflagellates (Steidinger et al., 2008a). *K. brevis* and *K. mikimotoi* also have gyroxanthin (Richardson and Pinckney, 2004).

*K. brevis* has a compensation point around 6–8 μmol photo $m^{-2}$ $sec^{-1}$ and saturation around 35–120 μmol photon $m^{-2}$ $sec^{-1}$ (Magaña and Villareal, 2006; Vargo, 2009). Schaeffer et al. (2007) show significant differences among clones of *K. brevis* in their photosynthetic characteristics and that they can grow well in a wide range of light intensities. This indicates they are adapted for the high light intensities they experience when aggregated at the surface as well as the low light intensities found in the bottom waters and sediment surface. Studies on changes in the pigment and biochemical composition of *K. brevis* under a variety of environmental conditions indicate that they are not significantly different from other species of dinoflagellates (Shanley, 1985; Higham et al., 2004; Evens and Leblond, 2004). While *K. brevis* appears well adapted to low light levels, it appears to use the photoprotective xanthophyll cycle pigments diadinoxanthin and diatoxanthin to tolerate high light intensity when it accumulates at the surface during the day (Evens et al., 2001).

*K. mikimotoi* seems to also tolerate a wide range of light intensities, from the surface to the pycnocline (Gentien, 1998). Cells exhibit photoadaptation mechanisms with cells growing in low light conditions containing more chlorophyll *a*, improving photosynthetic efficiency at low light intensities. Photosynthetic efficiency was also improved when dark adapted cells were returned to high irradiances (Garcia and Purdie, 1994). Saturation was observed to be approx 200 μmol photon $m^{-2}$ $sec^{-1}$ (Richardson and Kullenberg,1987).

### 5.4 Nutrition

*Karenia* dinoflagellates are considered primarily autotrophic, but they do have some capability for using organic compounds and ingesting microbes. Studies with field populations of *K. brevis* show that it can use nitrate, ammonia, urea, glutamate, and dissolved organic matter from *Trichodesmium* (Bronk et al., 2004). Sinclair et al. (2009) have shown that *K. brevis* takes up ammonia and urea at night as well as day, which could be important in obtaining nutrients during diel vertical migration. Baden and Mende (1979) showed that *K. brevis* can use glycine, valine, and methionine. Shimizu et al. (1995) found that urea and glycine added to cultures of *K. brevis* stimulates a shift to a more heterotrophic mode, and increased biomass and brevetoxin amount 2 to 4 fold. Mulholland et al. (2004, 2006) have shown that *K. brevis* can utilize dissolved organic matter that has been excreted by *Trichodesmium*. Vargo and Shanley (1985) have shown that *K. brevis* uses organic phosphorus, using alkaline phosphatase. Jeong et al. (2005) and Glibert et al. (2009) have documented that cultures of *K. brevis* can ingest cells of the cyanobacteria *Synechococcus* and enhance its growth rate. It appears that *K. brevis* is nutritionally quite versatile, utilizing inorganic nutrients, organic nutrients, and phagotrophy on other microbes. The fact that *K. brevis* lives in the oligotrophic central Gulf of Mexico (Geesey and Tester, 1993) indicates that it can survive on very low levels of nutrients.

Other species of *Karenia* probably have similar capabilities. Mountfort et al. (2006) found that glycolate and alanine added to cultures of *K selliformis* doubled the biomass and gymnodimine production. Nitrogen has been identified as an important nutrient in *Karenia* blooms. *K. mikimotoi* has been observed to utilise nitrate, nitrite and ammonium as N sources however urea and uric acid were not so well utilized in laboratory studies(Yamaguchi and Itakura 1999). Urea was observed to be taken up in the East China Sea (Li et al., 2009). Glutamine and tryptophan were utilised as well as both organic and inorganic forms of P (Yamaguchi and Itakura, 1999). Gentien (1998) has suggested that *K. mikimotoi* is stimulated by the organics released from decaying diatom blooms. A field study on *K. mikimotoi* from the Ushant front in the western English Channel revealed ammonia to be the preferred nitrogen source. In addition, dark N uptake did not occur in nutrient replete cells, while it was observed in nutrient limited cells (Dixon and Holligan, 1989).

## 6. Biotic interactions

In addition to *K. brevis* ingesting other microbes, other microbes can also attack *K. brevis*. Paul et al. (2002) isolated an apparent virus that lyses *K. brevis*. Onji et al. (1999, 2000) have isolated a virus that lyses *K. mikimotoi*. What role such viruses may play in the population dynamics of *Karenia* species is unknown at this time. Certainly viruses can spread more easily in a dense bloom, causing their decline, but some blooms maintain their high densities for many months.

Doucette et al. (1999) isolated two strains of bacteria that were lethal to *K. brevis* and *K. mikimotoi*. Subsequent studies by Mayali and Doucette (2002) revealed a complex situation in which the bacteria were lethal only when *K. brevis* was present at high concentrations, but the toxic bacteria were rendered much less toxic in the presence of certain other bacteria. Roth et al. (2008) examined two strains of bacteria that can kill *K. brevis* and also found a complex interaction between bacteria and *Karenia* lethality.

Experiments conducted by Collumb and Buskey (2004) suggest that the copepod *Acartia tonsa* does not ingest *K. brevis*, a result of selective feeding. It was shown that this was not the result of brevetoxin or direct toxicity. Breier and Buskey (2007) argued that *K. brevis* is nutritionally deficient to *Acartia tonsa*, leading to reduced grazing rates and reproduction rates. The same observations were made on two species of rotifers given the opportunity to feed on *K. brevis* (Kubanek et al., 2007). Huntley et al. (1986) and Sykes and Huntley (1987) found that that two species of copepods would not eat *K. brevis* but were affected by toxins in the water that caused their heart rate to increase and the loss of control of their muscles. Turner and Tester (1989) found that three species of copepods that live in the same area as *K. brevis* ate the toxic dinoflagellate with no apparent problems. Two other species of copepods would not ingest *K. brevis*. The unknown mechanism (discussed below as possible allelochemicals) behind this may reduce grazing pressure by metazoan zooplankton on *K. brevis* relative to other competitive algal species. In field studies, Lester et al. (2008) have shown that the zooplankton communities inside blooms of *K. brevis* are quite different from those outside the blooms. This could be due to specific effects that *K. brevis* has on zooplankton, or to responses to overall algal biomass inside and outside the bloom, or to

other environmental differences in the water masses that led to the bloom occurring in some water masses and not others in the first place. *K. mikimotoi* has also been observed to be toxic to rotifers (Zou et al., 2010) and have a negative effect on some ciliates (Hansen, 1995), however in some mesocosm experiments, reduction of grazing pressure has resulted in an increase in *K. mikimotoi* numbers (Turner and Graneli, 2006). It should also be noted that some dinoflagellate species can have an adverse impact on *K. mikimotoi.* Uchida et al. (1999) observed the dinoflagellate *Heterocapsa circularisquama* to kill *K. mikimotoi* at certain cell densities. *K. mikimotoi* was also observed to have a negative impact on *H. circularisquama* at certain cell densities.

## 7. Allelochemistry and toxin production

Kubanek et al. (2005) and Prince et al. (2008a, b) found that *K. brevis* produces allelochemical compounds that suppress the growth of most other species of algae tested. Prince et al. (2010) concluded that these compounds are not brevetoxin, but a variety of unstable, polar organics. Poulson et al. (2010) found that *K. brevis* produces multiple compounds other than brevetoxin that are allelopathic to other phytoplankton species and showed that there can be complex interactions.

Similar compounds have been observed in other *Karenia* species. Yasomoto et al. (1990) isolated two toxins, a glucolipid (1-acyl-3-digalactosylglyercol) and a fatty acid (octadecapentaenoic acid (OPA)) from *K. mikimotoi*. Arzul et al. (1995) found that polyunsaturated fatty acids (PUFAs) from *K. mikimotoi* inhibit diatom growth and bacterial bioluminescence and are hemolytic. Multiple investigators have observed that *K. mikimotoi* produces lipophylic toxins and observed toxic effects from a variety of PUFAs in tissue culture studies (Bodennec et al., 1995; Fossat et al., 1999; Sola et al., 1999). Gentien et al. (2007) also observed allelopathic effects of *K. mikimotoi* PUFAs on diatoms and these compounds also show a degree of autotoxicity. Chang (2011) found that *K. concordia, K. brevisulcata,* and *K. mikimotoi* produce lipophilic allelochemicals that inhibit other species of algae. The allelochemicals were especially effective against cryptophytes, raphidophytes, prasinophytes, and diatoms, but less effective against other dinoflagellates. These cytotoxic compounds disrupted cell membranes, apparently by altering ion pumps and osmotic balance. Chang et al. (2008) showed that *K. concordia* in New Zealand had hemolytic and cytotoxic activity. Neely and Campbell (2006) showed that *K. brevis* and *K. mikimotoi* have hemolytic activity. Mooney et al. (2007) showed that *K. brevis, K. mikimotoi, K. papilionacea*, and *K. umbella* all produce unusual lipids, sterols, and PUFAs and suggested that most species in *Kareniaceae* produce PUFAs and sterols that are ichthyotoxic. The mode of toxicity of the sterols is unknown but it is thought that they could have allelochemical properties as well. The toxicity of the PUFAs can be enhanced by lipid peroxidation in the presence of reactive oxygen species (Mooney et al., 2007). Zou et al. (2010) showed that *K. mikimotoi* is hemolytic but needs direct cell contact to kill.

Most of these bioactive compounds have not been fully characterized, but one has been well described. Gymnodimine is a spirocyclic imine ring produced by *K. selliformis* (Miles et al., 2003; Mackensie et al., 2004; Munday et al., 2004; Mountfort et al., 2006; Molgó et al., 2007; Munday, 2008) that activates calcium receptors and alters nicotic actylocholine

receptors in muscles (Molgó et al., 2007) and acts as a neuromuscular blocking agent (Mountfort et al, 2006). As a result, it causes widespread death of both invertebrates and vertebrates. It is not known if it has any allelochemical properties. Munday et al. (2004) concluded that gymnodimine may be fairly widespread in marine food webs. Gymnodimine has been found in shellfish in New Zealand, Tunisia, and Canada, but no human health effects have been observed (Mackensie et al., 1996; Seki et al., 1996; Munday et al., 2004; Molgó et al., 2007; Munday, 2008). *K. mikimotoi* has been observed to produce Gymnocin A and B (Satake et al., 2002, 2005) however these have been observed to be only weakly toxic to fish (Silke et al., 2005).

In addition to organic compounds, Marshall et al. (2005a, b) have shown that many algae produce superoxide for allelopathic purposes against other algae and bacteria. *K. brevis* and *K. mikimotoi* were among the larger producers of superoxide. Interestingly, the raphidophytes *Chattonella antigua, C. marina, Heterosigma akashiwo,* and *Fibrocapsa japonica* that also produce brevetoxin produce large amounts of superoxide in even higher concentrations (Mooney et al., 2011).

It appears that all *Karenia* species that have been studied produce allelochemicals. Many species also produce compounds that kill various marine animals. As most of these compounds are not identified, we do not know the overlap between these two groups of compounds. It certainly seems plausible that most of these compounds that are allelochemicals against other microbes (algal competitors; viral, bacterial, and protozoan predators) could kill larger animals because of biochemical similarities, particularly at the high concentrations generated in blooms. Similarly, as many of the compounds are lipid soluble, it can be hypothesized that a small fraction of these allelochemicals can make their way through the food web to humans. While there is no evidence yet that brevetoxin serves as an allelochemical, such studies have investigated only a small fraction of the biotic interactions possible. That some of the cytotoxic allelochemicals produced from *Karenia* species appear to affect ion transport across membranes suggests that brevetoxin, which affects sodium channels, may serve as an allelochemical. Alternatively, Errera and Campbell (2011) suggest that brevetoxin may aid in osmoregulation through its effects on the sodium channel.

Allelochemistry can be advantageous against microbial predators because cell to cell contact can expose the predator to a toxin before the algae is killed. Inhibition of the microbial predator leaves the toxic algal cell alive to propagate its genotype. This will not work against large metazoan grazers that gather many algal cells at a time. The algal cell with the toxin is dead by the time the toxin affects the large predator and the toxic genotype is lost. Furthermore, the death of the large predator helps all competing algal species and genotypes, not just the one producing the toxin. Also the toxin from one cell is probably not enough to affect a large animal.

Even if not naturally selected for attacking or deterring metazoans, allelochemicals aimed at microbes can still affect metazoans because of similar biochemical sensitivities, especially at high algal concentrations. This may prolong dense blooms once high concentrations of toxin have reduced the predator population, but does not help low concentrations of algae

to develop into a bloom in the first place. Diel vertical migration and Langmuir circulation cells can lead to high concentrations locally, and this may help an initially sparse population to concentrate enough to generate high enough concentrations of allelochemicals to affect metazoans.

## 8. Animal deaths

Whether the compounds produced by *Karenia* are allelochemicals or serve some other purpose, their biochemical mechanisms can affect a variety of animals. In some cases where they occur at sublethal concentrations, instead of directly causing mortality, the compounds are incorporated into animal tissues, such that they can then biomagnify up the food chain to concentrations that are lethal. In other cases, certain animals appear to simply not be susceptible to the toxin. For example, brevetoxin appears to not be toxic to most filter feeding molluscs, but can be toxic to animals that eat the molluscs. Landsberg (2002) has reviewed the literature on the wide variety of animals that are killed by various algal toxins.

A complicating factor is that many *Karenia* species probably produce more than one toxin. Therefore animal mortalities associated with blooms of *Karenia* cannot always be blamed on any one particular toxin. For example, *K. brevis*, in addition to brevetoxin, produces O,O-dipropyl(E)-2-(1-methyl-2-oxopropylidene) phosphorohydrazidothioate-(E)oxime, which is toxic to fish (Mazumder et al., 1997). Furthermore, many blooms are composed of more than one species of *Karenia*, making it difficult it difficult to assign toxins and effects to particular species. For example, many species of *Karenia* tend to bloom together along the west coast of Florida (Steidinger, 2009). Blooms in New Zealand in 1992–1993 and 2002 included *K. concordia, K. mikimotoi*, and *K. brevisulcata* and both gymnodimine and brevetoxin were found in the tissues of animals (Chang et al., 1996; Satake et al, 1996; Ishida et al, 1996; MacKensie et al, 1996; Seki et al, 1996; and Chang and Ryan, 2004).

Another complicating factor is that toxicity is usually the result of high biomass. High biomass not only generates large amounts of toxins, but also mucilage and anoxia in certain situations. Therefore, it is not always easy to distinguish mortality from toxicity, mucilage interference with respiration, or anoxia or some combination of the three.

Blooms of *K. mikimotoi* have killed fish and invertebrates throughout the world (Gentien, 1998), including Japan (Oda, 1935; Honjo et al., 1990; Ono et al, 1996; Matsuyama et al., 1998; Okaichi, 2004), Korea (Park et al., 1989; Kim et al., 1995), and Europe (Braarud and Heimdal, 1970; Helm et al., 1974; Tangen, 1977; Lindahl, 1983; Gentien et al., 1998; Silke et al., 2005; Davidson et al., 2009). It can be found in many other places, but not necessarily associated with mass animal mortality. Other species of *Karenia* have much more restricted distributions.

*K. brevis* lives primarily in the Gulf of Mexico. Records of fish kills in the Gulf of Mexico go back to at least 1530 (Steidinger et al., 1998) and 1648 (Magaña et al., 2003). It was not until 1946–1947 that *K. brevis* was discovered to be the cause (Davis, 1948; Gunter et al., 1948; Woodcock, 1948). Since then, many mass mortalities of many species of fish have been documented, along with invertebrates, seabirds, turtles and mammals (Gunter et al.,

1947, 1948; Landsberg, 2002; Steidinger et al., 2008a; Landsberg et al., 2009). *K. brevis* blooms on the west coast of Florida kill enough fish to affect population size and the overall fish community (Gannon et al., 2009; Landsberg et al., 2009). Blooms along the Texas coast have occurred less frequently, but have also resulted in mass fish kills (Buskey et al., 1996; Magaña et al., 2003).

Toxicity to invertebrates is more sporadic. While some bivalves are harmed by *K. brevis* (Leverone et al., 2006; Summerson and Peterson, 1990), many filter feeding molluscs appear to not be affected by brevetoxin, leading to their accumulation of the toxin in their fatty tissues and thus leading to Neurotoxic Shellfish Poisoning (NSP) in humans (Landsberg et al., 2009). Other invertebrates are killed by blooms of *K. brevis*, although we cannot be sure at this time if it is due to brevetoxin or other toxins produced by *K. brevis*, or toxins produced by other species of *Karenia* that tend to coexist with *K. brevis* in these blooms. Landsberg (2002) provides a good review of the wide variation in effects on invertebrates.

In some cases, widespread mortality is due more to anoxia resulting from dense blooms. In 1971 and 2005, large blooms of *K. brevis* occurred on the West Florida Shelf during the summer when water temperatures were particularly high and vertical stratification of the water column was strong (Smith, 1975; Landsberg et al., 2009). This led to anoxia of the bottom waters and mass mortality of the benthic community over thousands of square kilometers of the West Florida Shelf.

Marine mammals can apparently die from brevetoxin by either breathing the aerosol or from their diet. Landsberg and Steidinger (1998) argue that widespread death of manatees occurs along the west coast of Florida in the spring when the manatees undergo migration in the area and only in years of low rainfall and runoff so that the salinity in the estuaries is not too low for the growth of *K. brevis*. Seagrass and/or filter feeding epiphytes can apparently accumulate high concentrations of brevetoxin and then kill manatees at a later date when no red tide is apparent.

Flewelling et al. (2005) argued that bottlenose dolphins can die from brevetoxin in the absence of a red tide due to biomagnification of brevetoxin up the food chain to fish that are eaten by dolphins. Naar et al. (2007) have documented that many species of fish accumulate brevetoxin in their tissues and it remains many months after their exposure to *K. brevis* blooms.

Flewelling et al. (2010) have documented brevetoxin in sharks and rays from mass deaths associated with blooms of *K. brevis*. Large numbers of seabirds are sometimes also killed during blooms of *K. brevis*. This appears to be due to them consuming contaminated fish or invertebrates (Forrester et al., 1977; Steidinger et al. 2008a; Landsberg et al., 2009).

Blooms of other *Karenia* species that have killed animals have appeared only in the last few decades. Blooms of *K. cristata* in South Africa in 1989–1990 killed abalone (Botes et al., 2003b). Blooms of *K. digitata* caused large fish kills in Japan and Hong Kong in 1995–1996 (Yang et al., 2000). Chang (1999) and Wear and Gardner (2001) found that a bloom of *K. brevisulcata* in Wellington Harbour, New Zealand caused widepread death of benthic animals and fish. An analysis of the lipid soluble toxins from cultures of *K. brevisulcata*

indicated that they affected sodium channels like brevetoxin and other characteristics were similar to brevetoxin. Chang et al. (2008) showed that *K. concordia* killed large numbers of fish and shellfish in New Zealand in 2002 and had hemolytic and cytotoxic activity. In Tasmania, blooms of *K. umbella* in 1989 and *K. asterichroma* in 2003 led to large fish kills (de Salas et al., 2004a, b).

## 9. Human health impacts

While a number of toxins produced by *Karenia* species can kill animals, only brevetoxin is known to affect human health. While the effects of brevetoxin can be severe, no human deaths have been directly attributed to the toxin (Plakas and Dickey, 2010).

### 9.1 Brevetoxin

Brevetoxin is the toxin from *Karenia* species that affects human health and has been studied the most. Brevetoxins are produced by *K. brevis*, and there is some evidence that *K. bicuneiformis, K. brevisulcata, K. concordia, K. cristata, K. papilionacea,* and *K. selliformis* may also produce brevetoxins or similar molecules. The raphidophytes *Chattonella antigua, C. marina, Fibrocapsa japonica*, and *Heterosigma akashiwo* also produce brevetoxins (Landsberg, 2002; Furey et al, 2007; Ramsdell, 2008).

The brevetoxins are lipid soluble cyclic polyether compounds with molecular weights of around 900 that are tasteless, odorless, and heat stable. *K. brevis* produces two parent compounds, PbTx-1 and PbTx-2, which have somewhat different structures (Furey et al., 2007; Ramsdell, 2008). PbTx-1 is somewhat flexible with 10 fused polyether rings. PbTx-2 is more rigid with 11 polyether rings (Furey et al., 2007). PbTx-1 is more toxic but PbTx-2 occurs in higher concentrations (Steidinger et al., 2008a; Plakas and Dickey, 2010). Brevetoxins are polyketides synthesized by the polyketide synthase (PKS) pathway (Wright and Cembella, 1998). While there were earlier speculations that perhaps bacteria associated with *K. brevis* actually produce brevetoxin because laboratory cultures sometimes lose their ability to produce brevetoxin, genetic studies have now confirmed that the PKS genes exist in the *K. brevis* genome (Snyder et al., 2003, 2005; Monroe and Van Dolah 2008; Monroe et al., 2010). It is possible that bacteria are involved by stimulating the production of brevetoxin, especially if it serves as an allelochemical. *K. brevis* also produces brevisamide and brevisin, which are 4-fused cyclic ether rings and brevenals, which are 5-fused cyclic ether rings (Bourdelais et al., 2004, 2005; Ramsdell, 2008; Van Wagoner et al., 2010). These are thought to be incomplete products of the PKS biosynthetic pathway. Brevenal acts as an antagonist to brevetoxin and may also be useful as a therapeutic agent against cystic fibrosis (Potera, 2007).

In addition to PbTx-1 and PbTx-2, another 10 congeners are the result of small modifications, primarily reductions, oxidations, and hydrolysis, of these two main compounds, primarily once they are released from the cells and are modified by physical/chemical processes or microbes in the water, and metabolism by animals in the food chain. Each genotype of *K. brevis* produces somewhat different amounts and ratios of these two toxins, and the array changes with environmental and physiological changes (Lekan and Tomas, 2010; Errera et al., 2010). Even more changes occur as the brevetoxins enter

the water, air, and food web, and are metabolized. Genetic variation was more important than environmental variation (temperature, salinity, nutrients) in determining amount of brevetoxins. Errera et al. (2010) found a 10-fold range in the amount of brevetoxin and brevenal produced by different genotypes of *K. brevis*. They also observed a shift to the more toxic PbTx-1 at lower salinity. Recently, Errera and Campbell (2011) have found that a rapid decrease in salinity can induce a 10-fold increase in brevetoxin production.

Brevetoxin is a long molecule that spans voltage gated sodium channels, causing them to remain open for an excessive amount of time, leading to uncontrolled sodium influx and depolarization of the membrane (Ramsdell, 2008). As a result of the persistent activation and repetitive firing of neurons, brevetoxin affects neuromuscular junctions, which can lead to respiratory distress; and affects cardiac muscle, leading to slow and arrhythmic heart beat (Ramsdell, 2008).

In several cases, *Karenia* species other than *K. brevis* have caused brevetoxin-like symptoms in humans. *K. concordia* in New Zealand caused respiratory distress and NSP in humans (Chang, 2011). Blooms of *K. brevisulcata* in New Zealand in 1998 caused mass mortality of animals and aerosols from the blooms affected the respiration of humans (Truman, 2007). The symptoms were similar to those produced by *K. brevis* in the Gulf of Mexico. An analysis of the lipid soluble toxins from cultures of *K. brevisulcata* indicated that they affected sodium channels like brevetoxin, and other characteristics were similar to brevetoxin, but not completely. *K. cristata* bloomed in South Africa in 1995–1996 and caused respiratory problems in humans (Botes et al., 2003a, b). It is not known if brevetoxin was involved in this case. Brevetoxin specific ELISA tests indicated the presence of brevetoxin in *K. bicuneiformis, K. papilionacea*, and *K. selliformis* (Haywood et al., 2004). To date, there has been no actual confirmation of brevetoxin in these 6 species by LC-MS however.

Brevetoxin can affect human health in three ways – by ingestion of contaminated food, by skin contact in water, and by inhalation of the aerosol.

### 9.2 Neurotoxic Shellfish Poisoning

Neurotoxic Shellfish Poisoning (NSP) results from humans eating filter feeding molluscs that have accumulated brevetoxin in their fatty tissues. We now know that brevetoxin can be found in the tissues of other seafood as well, such as non-filter feeding molluscs (Poli et al., 2000) and fish (Naar et al., 2007). The toxin tends to accumulate more in the fatty tissues of organs than in muscle tissue. Because humans usually eat only the muscle tissue of fish, but the entire body of shellfish, shellfish has been the primary source of NSP.

Because of a monitoring program and the banning of shellfish harvesting during red tides along the west coast of Florida, NSP cases are now extremely rare. There are no restrictions on the consumption of fish however, because it has been assumed that fish exposed to brevetoxin die and are not available for consumption. We now know that fish exposed to sublethal concentrations in fact do accumulate brevetoxin (Naar et al., 2007). While the concentrations in the muscle tissue is less than that found in the liver and other organs or in the whole bodies of shellfish, we do not know what effects these low concentrations of

brevetoxin could have on human health. Interestingly, Kirkpatrick et al. (2010a) have found increased incidences of hospital admittances for gastrointestinal disorders during periods of red tide along the west coast of Florida.

NSP has occurred primarily in the Gulf of Mexico, particularly the west coast of Florida, but more recently it has also occurred in North Carolina due to an unusual transport of a *K. brevis* bloom from the west Florida coast to North Carolina by the Gulf Stream (Tester et al., 1989; Tester and Stumpf, 1991) and New Zealand where a new bloom of *K. concordia* developed (Chang, 2011). While blooms of *Karenia* are largest and most frequent in the Gulf of Mexico, few cases of NSP occur there because of careful monitoring. Cases of NSP occurred in North Carolina and New Zealand because new blooms occurred where they had not occurred before and were unexpected and thus not monitored for seafood safety.

After the consumption of brevetoxin contaminated food, symptoms begin within minutes to hours but diminish within a few days (Watkins et al., 2008; Plakas and Dickey, 2010). The primary gastrointestinal and neurological symptoms are abdominal pain, nausea, vomiting, diarrhea, headache, vertigo, numbness of lips, mouth and face, dilated pupils, muscle pain, loss of coordination, partial paralysis, convulsions, disorientation, tingling sensations, temperature sensation reversals, and respiratory distress (Watkins et al., 2008; Kirkpatrick et al., 2004; Fleming et al., 2011).

### 9.3 Skin contact

Because some brevetoxin is released into the water, primarily because of cell lysis, swimmers can experience eye and nose irritation (Kusek et al, 1999; Ramsdell, 2008). This appears rare and is not considered to be a major health hazard.

### 9.4 Aerosol

Because *Karenia* is a delicate, unarmored dinoflagellate, the cells can be ruptured relatively easily by turbulence at the surface or along the shore, releasing the brevetoxin into the air as an aerosol. Humans that breathe brevetoxin contaminated aerosols immediately experience coughing, sneezing, runny nose, watery eyes, a burning sensation in the nose and throat, chest tightness, and shortness of breath (Fleming et al., 2005; Abraham and Baden, 2006). Large aerosol particles (6–10 microns) only make it into the upper respiratory tract, causing throat and nasal irritation, while small aerosol particles (0.1–0.2 microns) make it into the lower respiratory tract, making breathing difficult (Ramsdell, 2008).

Kirkpatrick et al. (2006) found pneumonia, bronchitis, asthma and respiratory distress to increase 31%, 56%, 44% and 64% respectively during a red tide up to 1.6 km inshore along the west coast of Florida. Humans with asthma are particularly sensitive to brevetoxin aerosols and often end up in the hospital with severe symptoms (Kirkpatrick et al., 2004, 2011a; Abraham and Baden, 2006; Fleming et al. 2007, 2011)

Humans have experienced respiratory distress from blooms of other species of *Karenia* in New Zealand (Truman, 2007; Chang, 2011), South Africa (Botes et al., 2003a, b), and New Jersey, USA (Mahoney et al., 1990).

### 9.5 Other effects

Some studies have indicated that brevetoxin may affect the immune system (Bossart et al., 1998; Benson et al., 2005; Fleming et al., 2011). Radwan and Ramsdell (2008) showed that brevetoxin forms covalent DNA adducts and is thus potentially mutagenic.

## 10. Ecosystem pathways for toxins

Brevetoxin is the only toxin that has been studied enough that we have some understanding of the pathway of the toxin from the *Karenia* cell to the animals and humans it affects.

*K. brevis* produces PbTx-1 and PbTx-2 as the primary endproducts of the PKS biosynthetic pathway and the other congeners are the result of modifications further down the ecosystem pathway. The changing suite of congeners down the ecosystem pathway is complex and we only understand parts of it. As organisms metabolize brevetoxin, primarily through the cytochrome P450 system (Fleming et al., 2011), the resulting congeners tend to be more polar.

If there is sufficient turbulence in the water, such as at the surface and at the shoreline, the delicate cells can be disrupted, releasing the brevetoxins into the water. These brevetoxins appear to be the most toxic to fish. Laboratory studies have shown that fish exposed to intact *K. brevis* cells are much less affected than fish exposed to disrupted cells (Ramsdell, 2008). The brevetoxin is thought to be taken up by fish and other animals at the gill surface. Brevetoxin in the water in the presence of other species of algae declines as a result of uptake and/or degradation (Myers et al., 2008). Other microbes undoubtedly also cause a decline in brevetoxin concentrations in water.

Some of the brevetoxin can end up at high concentrations in the surface microlayer (Rumbold and Snedaker, 1999). These can then end up in aerosol particles in the air and ultimately inhaled by humans and marine mammals. Photodegradation (Hardman et al., 2004) and other physical/chemical processes alter the suite of brevetoxin congeners such that a different mix is observed in the air (Pierce et al., 2003, 2005; Cheng et al., 2005, 2010). Brevetoxin aerosols can be found at least 1.6 kilometers inland (Kirkpatrick et al., 2010b).

Intact cells are harvested by various filter feeders. Tester et al. (2000) have shown that planktonic copepods can feed on *K. brevis* and accumulate brevetoxin in their tissues, which can then be transferred up the food chain to fish. Some species of copepods appear to not be affected by brevetoxin, thus accumulating it, while others avoid feeding on *K. brevis*, thus not accumulating brevetoxin. Higher up the food chain, many fish species have also been found to accumulate brevetoxin, primarily in the fatty tissues of their organs, but some is also found in the muscle tissues that humans eat (Naar et al., 2007). Long after a bloom, up to 1500 ppb of brevetoxin in muscle and 2700 ppb in internal organs were found. Animals such as dolphins that get a large part of their diet from fish can end up with large amounts of brevetoxin in their tissues as well, leading their death (Flewelling et al., 2005). Fire et al. (2007) found low levels of brevetoxin in dolphins in Sarasota Bay in the absence of any obvious recent blooms.

Dense blooms tend to kill animals quickly, so the brevetoxin ends up in the detrital food chain. Brevetoxin can be found in the sediments (Mendoza et al., 2008). Sublethal concentrations however, do not kill animals initially, allowing brevetoxin to accumulate in tissues and then propagate up the food chain, until high enough concentrations build up in the tissues of top carnivores that they become lethal. This propagation of brevetoxin up the food chain can lead to the death of animals in places and times when there are no blooms of *K. brevis* (Flewelling et al., 2005). As a result, dense blooms may tend to kill animals at the lower end of the food chain, while sublethal concentrations of *K. brevis* may eventually lead to the death of animals at the upper end of the food chain.

Benthic filter feeding molluscs such as mussels, clams, and oysters can also feed on *K. brevis*, accumulating high concentrations of brevetoxin, primarily in the fatty tissues of their organs (Landsberg et al., 2009). It is the consumption of the whole body of these molluscs that can lead to NSP. The suite of brevetoxins changes as they are metabolically processed by the animals (Pierce et al., 2004; Weidner et al., 2004). Depuration time in shellfish is typically 2–8 weeks (Watkins et al., 2008). Because filter feeding mollusks are so good at harvesting large amounts of sparse algal cells, a dense bloom is not needed to accumulate high amounts of brevetoxin in their tissues. For this reason, shellfish are considered potentially toxic in the presence of 5000 cells/l of *K. brevis*, concentrations far below that needed for visual or satellite detection or the amount needed to kill fish.

Manatees are herbivores that eat seagrasses and macroalgae, but they also die in blooms of *K. brevis* (Landsberg and Steidinger, 1998; Flewelling et al., 2005). It appears that filter feeders such as tunicates attached to the blades of seagrass accumulate brevetoxin and end up ingested by manatees (O'Shea et al., 1991; Landsberg et al., 2009).

A complicating factor for air breathing animals such as dolphins, manatees, turtles, and sea birds is that they have two major routes of exposure, diet and aerosol, and it is not always easy to determine the relative importance of each in contributing to the animal's death.

## 11. Global distributions

Our understanding of the global distribution of *Karenia* species is probably very incomplete because most studies are initiated only in response to obvious blooms and that is how most *Karenia* species have been discovered. Zingone et al. (2006) conducted a careful examination of potentially toxic phytoplankton species along the west coast of Italy and found *K. bicuneiformis, K. cristata, K. mikimotoi, K. papilionacea*, and *K. selliformis* present, even though they were not creating blooms. It is likely that more studies like this in other parts of the world will discover more species of *Karenia* and extend the spatial distribution of species already known.

*K. mikimotoi* and *K. selliformis* appear to be worldwide in distribution. *K. mikimotoi* has been documented in the Gulf of Mexico, Atlantic coast of North America, South Atlantic, North Atlantic coast of Europe including Spain, France (Gentien, 1998), Ireland (Raine et al., 2001; Silke, 2005; O'Boyle and Silke, 2010), Great Britain (Pingree et al., 1975, Holligan et al., 1984; Davidson et al., 2009) Norway, (Braarud and Heimdal, 1970, Tangen,

1977) Sweden, (Lindahl, 1983, Lindahl, 1986, Graneli et al., 1989) Denmark (Carstensen et al., 2004), Germany (Elbrachter, 1999), Japan (Honjo, 1994; Yamaguchi, 1994; Ono et al., 1996; Okachi, 2004), Korea (Park et al., 1989; Kim et al., 1995), Hong Kong (Gentien, 1998), China (Qi et al., 2003; Li et al., 2009) New Zealand (Wear and Garder, 1998; Chang ,1999; Chang and Ryan, 2004). Descriptions and impacts from *K. mikimotoi* blooms are discussed in these papers.

*K. selliformis* has been found in the Gulf of Mexico (Haywood et al., 2007), Canada, New Zealand, Australia, Mediterranean, Tunisia (Munday et al., 2004) and Kuwait (Heil et al., 2001).

Other species of *Karenia* appear to have much more restricted distributions. *K. brevis* lives primarily in the Gulf of Mexico, where it is found in low concentrations in the open waters (Geesey and Tester, 1993), but forms toxic blooms frequently along the west coast of Florida and occasionally along the Texas and Mexico coasts (Steidinger, 2009; Magaña et al., 2003). The Gulf Stream occasionally carries blooms originating in the Gulf of Mexico along the east coast of North America (Murphy et al., 1975; Tester et al., 1989; Tester and Stumpf, 1991; Tester and Steidinger, 1997). *K. brevis* was first discovered to be the cause of fish kills in 1946–1947 (Davis, 1948; Gunter et al, 1948; Woodcock, 1948), but records of fish kills going back to at least 1530 (Steidinger et al., 1998) and 1648 (Magaña et al., 2003) suggesting that *K. brevis* has been forming blooms for centuries at least and probably much longer in the Gulf of Mexico. Much of the research has been conducted along the west coast of Florida (Steidinger, 2009). These blooms have been studied for over 50 years now. We now know that *K. longicanalis, K. mikimotoi, K. papilionacea*, and *K. selliformis* also exist in the Gulf of Mexico (Steidinger et al, 2009; Steidinger, 2009). Cortez-Altamirano et al. (1996), Figueroa-Torres and Weiss-Martinez (1999), and Licea et al. (2004) have examined blooms of *K. brevis* in Mexico.

Other species of *Karenia* have begun forming HABs in other parts of the world such as New Zealand, Tasmania, Ireland, Japan, South Africa, Chile, and the Mediterrean Sea. These other species of *Karenia* kill fish and other marine life, but appear to not have the same impacts on human health as Karenia brevis has in the Gulf of Mexico. Recently, blooms of *K. concordia* producing brevetoxin have caused NSP in New Zealand (Chang, 2011). Blooms of *K. brevisulcata* have also occurred in New Zealand (Wear and Gardner, 2001; Chang, 1999; Chang and Ryan, 2004). Blooms of *K. asterichroma* have occurred in Tasmania (de Salas et al., 2004b).

## 12. Population dynamics

Most species of *Karenia* have only recently been discovered as a result of new sporadic blooms. Therefore, we do not have enough data to say much about their population dynamics or the processes leading to the blooms. Indeed, most research focuses on blooms that cause problems, so most data are collected during and after a bloom, not before as the bloom is developing. Recent developments in satellite imagery are beginning to overcome this for surface blooms to some extent (Davidson et al 2009, Shutler et al., 2011), but not for subsurface populations. The two species for which we have the most long term data are

*K. brevis* and *K. mikimotoi*. Steidinger (2009) provides an overview of *K. brevis* along the west coast of Florida. Gentien (1998) provides an overview of *K. mikimotoi*. Honjo (1994), Yamaguchi 1994, Ono et al. (1996) and Okaichi (2004) provide overviews of *K. mikimotoi* in the coastal waters of Japan.

While blooms get the most attention, they are actually rather rare over space and time. In some instances *Karenia* blooms can be located in a thin layer in the pycnocline and therefore may not be detected during routine sampling (Gentien et al., 2005). Most of the time, *Karenia* cells are sparse, and only become abundant occasionally at certain locations. As a result, we really do not know much about the main population dynamics of *Karenia* species. Furthermore, they are treated as planktonic species even though they live primarily in relatively shallow coastal waters. We do not know if part of their life cycle is in the benthos or perhaps epiphytic. Blooms attract the most attention because it is their high biomass that generates the most animal morality and human health problems.

## 12.1 Blooms

While blooms of *K. brevis* and *K. mikimotoi* have been known to occur for many hundreds of years and are part of their natural population dynamics, it is not clear if the other, newly discovered species of *Karenia* have always bloomed on occasion and are only now being discovered, or if these recent blooms are a new phenomenon, perhaps a result of a changing environment.

In terms of species composition, one can find a whole range of examples. Some blooms are essentially monospecific (Steidinger and Vargo, 1988). In other cases, other species of algae are mixed in with *Karenia*. It has been recently discovered that many of these *Karenia* blooms actually include several species of *Karenia*. That several species of *Karenia* would bloom at the same time and place suggests that their basic biology and ecological requirements are similar, but that also brings up the question of the competitive exclusion principle, and how these different *Karenia* species coexist if they occupy similar niches.

A fundamental question to be addressed is how *Karenia* species can develop such a large biomass in a bloom. This is a very complex question, and in most instances the involved in the development of high biomass blooms are not known but are probably a combination of biological and physical factors. *Karenia*, like most dinoflagellates, replicate very slowly, less than once a day. Dinoflagellates are basically the slowest of all the algal taxa. How can they outcompete fast growing competitors such as diatoms? How are dinoflagellates different from diatoms and other algae in a way that allows them to compete?

While dinoflagellates are among the slowest growing algae, they are the fastest swimmers. This allows them to undergo diel vertical migration. This allows them access to higher concentrations of nutrients below the pycnocline in stratified waters not available to most competing species of algae (Heil, 1986; Kamykowski et al., 1998). In the case of at least *K. brevis*, it can also swim into the sediment pore waters to obtain the even higher nutrient concentrations there (Sinclair and Kamykowski, 2008).

Dinoflagellates in general appear to have a greater ability to utilize organic nutrients in addition to inorganic nutrients (Smayda, 1997; Glibert and Legrand, 2006; Burkholder et al., 2008). Most coastal waters contain much more organic nutrients than inorganic nutrients, so this could allow *Karenia* to ultimately develop a much higher biomass than algae than can only use inorganic nutrients.

*Karenia* species appear to produce a number of allelochemicals that could help them outcompete faster growing algae and resist attacks from microbial predators. Allelochemicals are generally not effective against large grazers on a microscopic scale at low concentrations, but once a bloom has developed, the high concentration of allelochemicals may reduce large grazers as well and help maintain or prolong the bloom. There is some evidence to support this with *K. mikimotoi* and diatoms (Gentien et al., 2007).

Diel vertical migration, ability to use organic nutrients, and the production of allelochemicals may allow *Karenia* to outcompete other species, but these factors alone do not explain the sporadic distribution in time and space of blooms or predict any specific bloom.

Physical factors play an important role for two reasons. First, dilution rate as a result of turbulent mixing must be lower than the growth rate of the algae, which is slow in the case of *Karenia* and dinoflagellates in general. This is necessary for both the early growth and maintenance of a bloom. Some of the *Karenia* species bloom in embayments where advection out of the water body is low. Examples include Wellington Harbor, New Zealand for *K. concordia*, the high salinity lagoons of Texas (Tester et al., 2004) for *K. brevis*, and Tampa Bay, Florida under high salinity conditions during a drought (Steidinger and Ingle, 1972) for *K. brevis*.

In general however, *Karenia* species tend to bloom in open coastal waters where advection and turbulent mixing is stronger. Olascoaga et al. (2006) and Beron-Vera and Olascoaga (2009) have argued that persistent Lagrangian Coherent Structures may provide the low mixing parcels of water that can act as incubators that allow a bloom to get started without excessive mixing dilution. These Lagrangian Coherent Structures can persist for approximately two months on the West Florida Shelf, enough time for *K. brevis* to increase its biomass approximately 100,000-fold by cell division alone (assuming no grazing loss). Olascoaga (2010) found that the three areas in the Gulf of Mexico with the lowest mixing activity in her analysis to be off the coast of Florida, Texas, and Mexico, precisely where *K. brevis* forms the most blooms. In general, it appears that many *Karenia* blooms occur in stratified waters where turbulent mixing is low.

A second factor that is quite likely to be important is a physical concentrating mechanism. In many if not most cases, blooms appear to increase in size faster than the dinoflagellates can grow. This implies a physical concentrating mechanism. As a result of diel vertical migration, *K. brevis* tends to aggregate at the surface during the day. This can concentrate cells by only about one order of magnitude however (cells in a 10 m water column swimming to the surface and becoming concentrated in the upper 1 m, for example). Langmuir circulation cells can also aggregate cells in convergence zones on a small scale.

These mechanisms might concentrate *Karenia* enough for their allelochemicals to become more effective. Other mechanisms are needed for the much greater concentrations observed over larger scales. The most obvious case is downwelling, in which cells at the surface from a large area are transported to the downwelling site and accumulate there as they swim upward to counteract the downward movement of the water. Over time, this mechanism can generate very high concentrations of organisms (Hetland and Campbell, 2007).

### 12.2 Nutrients for blooms

While a large amount of nutrients are needed to generate a large bloom biomass, high concentrations of nutrients are not necessary, and nutrients may not necessarily play a major role in initiating a bloom. Low concentrations of nutrients can generate low concentrations of *Karenia* over a large area. A physical concentrating mechanism can then aggregate these cells into a bloom that contains far more nutrients than would be in the water parcel they occupy.

While nutrients are clearly a factor in generating many algae blooms in certain areas around the world, they may be less important in the initiation of a *Karenia* bloom. A sudden pulse of inorganic nutrients is more likely to give diatoms a competitive advantage over *Karenia*. Nutrient sources that could give *Karenia* an advantage over diatoms and other algae are those below the pycnocline or in the sediments that they can migrate to, or organic nutrients that they can more easily assimilate than other algae. In addition to the large pool of organic nutrients in seawater and freshwater runoff, dieoff of diatom blooms, benthic biota, fish, or excretion by organisms such as *Trichodesmium* could provide a source of nutrients.

It is important to distinguish new and old nutrients, as new nutrients will generate more plant biomass, while old nutrients will not. For an individual species, such as *Karenia*, this distinction needs to be modified. For example, if upwelled inorganic (new) nutrients generate a diatom bloom which subsequently dies and release nutrients to *Karenia*, those recycled nutrients are technically old nutrients, but act as new nutrients to generate new biomass of *Karenia*. The same would be true for new nutrients taken up by macroalgae or seagrasses that subsequently die and release their nutrients to *Karenia*.

It is also important to distinguish nutrient sources that help initiate a bloom and those that are important in increasing its biomass and sustaining it over time. Many nutrient sources are potentially available to increase the *Karenia* biomass. It is more difficult to identify a nutrient source that can explain when and where blooms have first developed. Most nutrient sources appear to be more widespread than the blooms.

### 12.3 K. brevis in the Gulf of Mexico

The species that has the largest impact on human health and has been investigated in more detail is *K. brevis*. It appears to live in the oligotrophic waters of the oceanic regions of the Gulf of Mexico in low concentrations, at somewhat higher concentrations on the continental shelves, and occasionally bloom to extremely high concentrations closer to the coast (Geesey and Tester, 1993). Further evidence that it is adapted to relatively oligotrophic conditions is the fact that it can survive being transported by the Gulf Stream out of the Gulf

of Mexico and up the east coast of North America (Murphy et al., 1975; Tester et al, 1989; Tester and Stumpf, 1991; Tester and Steidinger, 1997).

Blooms of *K. brevis* are most frequent along the west coast of Florida, between Tampa Bay and Sanibel Island (Brand and Compton, 2007). This is where tidal mixing is at a minimum (He and Weisberg, 2002) and a transport barrier reduces mixing between inshore and offshore waters (Yang et al, 1999; Olascoaga et al. 2006; Olascoaga, 2010). In Florida, Texas, and Mexico, *K. brevis* is most likely to form blooms in the fall months (Tester and Steidinger, 1997; Steidinger et al, 1998; Brand and Compton, 2007; Hetland and Campbell, 2007). Hetland and Campbell (2007) have shown that downwelling during the fall months along the Texas coast can lead to a 1000-fold concentration of *K. brevis* cells, making it a likely factor in the development of blooms there. On the west coast of Florida however, winds in the fall tend to favor upwelling (Stumpf et al., 1998, 2008; Yang and Weisberg, 1999; He and Weisberg, 2003; Walsh et al., 2006; Weisberg et al., 2009). This has led to many studies hypothesizing that *K. brevis* in bottom waters is carried inshore to frontal boundaries (He and Weisberg, 2003; Walsh et al., 2006; Stumpf et al., 2008; Milroy et al., 2008; Weisberg et al., 2009; Schaeffer et al., 2009). But upwelling alone will not concentrate the cells, only bring deep dwelling cells closer to the coastline. Once they upwell to the surface, surface currents will carry them back offshore. Some studies (Vargo et al., 2004; Stumpf et al., 2008; Weisberg et al., 2009) indicate that the upwelling occurs in frontal regions, where some unknown mechanism will concentrate the cells rather than let them be transported back offshore. This mechanism has not been identified. One scenario could be a low salinity plume overlaying the upwelling region, with the *Karenia* cells advecting under the plume then migrating up into it, generating a bloom along the salinity front. Such a mechanism has been described for dinoflagellate blooms in the Gulf of Maine (Hetland et al., 2002). Alternatively, Lanerolle, et al. (2006) suggest that a complex sequence of both upwelling and downwelling may be responsible for concentrating the cells.

Another problem with the upwelling hypothesis is that few data have shown significant amounts of *K. brevis* in bottom water on the West Florida Shelf. Most data show higher concentrations in surface waters than deep water. In this situation, the upwelling circulation will lead to a net flux of cells offshore. A mechanism is needed to trap and concentrate the cells inshore. The very broad West Florida Shelf could provide a large seed population even if sporadic and in low concentrations, but the source has not been identified (Walsh et al., 2002). It is not clear if the seed population is planktonic or benthic, from the inner or outer shelf, or throughout the shelf.

During the fall months when *K. brevis* blooms are most likely, other factors interact with this general upwelling circulation pattern (deep waters moving inshore and surface waters moving offshore). It is at this time that vertical stratification weakens and breaks down (Weisberg et al., 2001). Winds increase and upwelling increases in the fall (Stumpf et al., 1998). This is the time that alongshore currents shift from northward to southward (Yang and Weisberg, 1999; Carlson and Clarke, 2009). This is also the time that shallow waters in the north cool down and send plumes of cold water southward along the coast, generating thermal fronts (He and Weisberg, 2003). This is also the peak of the wet season and land runoff in South Florida (Brand and Compton, 2007), when salinity fronts are generated

along the coastline. It is suspected that the interaction of the shoreward movement of the bottom waters containing low concentrations of *K. brevis* with these thermal and salinity fronts at a time of weakening vertical stratification may provide a mechanism (still not understood) for concentrating *K. brevis*.

Almost certainly, physical factors are very important in the development of *Karenia* blooms, but so far we have no models that can predict exactly when or where a bloom will develop.

### 12.4 Nutrient sources on the west coast of Florida

To generate the large biomass in a *Karenia* bloom, large amount of nutrients are needed. There are many potential sources of nutrients available to the *Karenia* blooms along the west Florida coastline, but it is not clear if any of them can be the major source and/or explain the early development of the blooms and their eventual size.

Surface waters of the West Florida Shelf have low concentrations of nutrients, particularly nitrogen (Vargo, 2009). This may be why *K. brevis*, which appears to be adapted for surviving the oligotrophic waters of the central Gulf of Mexico, survives on the West Florida Shelf as well. These low nutrient concentrations do not necessarily indicate low nutrient inputs however. Because the wide West Florida Shelf is rather shallow, much of it is within the photic zone, so much of the nutrient inputs are probably rapidly taken up by the benthic plant community (macroalgae, seagrasses, sedimentary microalgae). Benthic chlorophyll on the West Florida Shelf is much higher than in the water column above (Walsh and Steidinger, 2001).

A number of researchers have noted a rough correlation between land runoff and *K. brevis* blooms (Gunter et al., 1947; Slobodkin, 1953; Odum et al., 1955; Finucane, 1964; Steidinger and Joyce, 1973; Dixon and Steidinger, 2004). Some have even suggested an iron index as an indicator of land runoff (Ingle and Martin, 1971). One also observes a general correlation on a seasonal basis, with *K. brevis* blooms most likely during the fall months when land runoff is at its peak (Brand and Compton, 2007). Rounsefell and Nelson (1966) summarized much of the earlier research on this topic. In all cases, these are only general correlations, and there are many exceptions, e.g., blooms during droughts and no blooms during large runoff events. Though rare, blooms have developed during the spring dry season, and some years have no obvious blooms during the wet season.

A perusal of the 50 year monitoring data collected by the State of Florida shows a number of cases in which blooms of *K. brevis* first appear near the mouth of rivers. Olascoaga et al. (2008) document a bloom in 2004 that appears to originate near the mouth of the Caloosahatchee River, and Yentsch et al. (2008) do the same for a bloom in 2005 near the mouth of the Caloosahatchee River. Vargo et al. (2004) observed elevated concentrations of silica in all four blooms he examined, indicating the blooms were in water masses with land runoff influences.

Brand and Compton (2007) argued that land runoff nutrients were significant in increasing *K. brevis* biomass because the biomass is larger inshore in lower salinity water than offshore in higher salinity water. They also argued that *K. brevis* biomass has increased significantly

over the past 50 years, during a time that land runoff nutrients have increased significantly but offshore nutrients have not.

It should be noted that even if there is a strong correlation between blooms and land runoff, it would not necessarily be the result of nutrients. The increased salinity fronts generated during land runoff might help set up concentrating mechanisms for generating high concentrations of the slow growing *Karenia*.

In addition to surface water runoff from land, groundwater inputs to coastal waters must also be considered. Miller et al. (1990) showed the importance of groundwater in Charlotte Harbor and Hu et al. (2006) argued that groundwater could be a major source of nutrients to the West Florida Shelf. As a result of various human activities on land, groundwater nutrient concentrations have increase dramatically in recent decades (Scott et al., 2006). Related to this is the possibility that *K. brevis* could migrate down into the sediments to take advantage of higher nutrient concentrations in the porewaters (Sinclair and Kamykowski, 2008). The higher nutrient concentrations there are reflected in the fact that chlorophyll concentrations are higher in the sediments than the water column above (Walsh and Steidinger, 2001).

Other early studies focused on upwelling of nutrient rich deep water onto the shelf and its transport across the shelf to the coastal region (Steidinger and Haddad, 1981; Tester and Steidinger, 1997; Lanerolle et al., 2006; Janowitz and Kamykowski, 2006; Weisberg et al., 2009). The overall estuarine circulation of the shelf with bottom water flowing inshore more than offshore (Weisberg et al., 2001), certainly will tend to generate a net flux of nutrients inshore, allowing the shelf to act as a nutrient trap to some degree. While this certainly supplies some nutrients to the blooms, Walsh et al. (2003) concluded that the amount of nutrients transported by this mechanism is insufficient to support the blooms observed.

A somewhat unique characteristic of the West Florida Shelf is the presence of large phosphate deposits along the west coast of Florida and presumably on out onto the shelf (Compton, 1997; Brand 2002; Walsh et al., 2006). This generates low N/P ratios and an ecosystem that is nitrogen limited (Brand, 2002; Walsh et al., 2006; Brand and Compton, 2007). As a result, inorganic nitrogen concentrations are usually very low on much of the West Florida Shelf, even inshore. Any input of nitrogen is quickly taken up by phytoplankton that have sufficient phosphorus and are starved for nitrogen. This situation provides a selective advantage to nitrogen-fixing cyanobacteria.

Some researchers have noted an apparent correlation between blooms of the nitrogen – fixing *Trichodesmium* and *K. brevis* (Gunter et al., 1948; Geesey and Tester, 1993). It has been shown that *Trichodesmium* excretes organic nitrogen that can then be taken up by *K. brevis* (Havens et al., 2004; Mulholland et al., 2004, 2006). Cyanobacteria , especially nitrogen-fixers, need more iron than eukaryotic algae (Rueter et al., 1990; Brand, 1991; Paerl et al., 1994). Lenes et al. (2001), Walsh and Steidinger (2001), and Walsh et al. (2006) have hypothesized that iron limits the growth of *Trichodesmium* on the West Florida Shelf, and iron-rich dust from Africa is a major source of iron and may serve as a stimulant for blooms of *Trichodesmium*, which could then lead to blooms of *K. brevis*. Biegalski and

Villareal (2005) observed higher input of atmospheric iron during a bloom of *K. brevis* along the Texas coast.

While inshore waters probably get more iron from land runoff, atmospheric dust is probably the major source of iron offshore. It seems quite plausible that this iron is enhancing the growth of *Trichodesmium* and augmenting the nitrogen pool of the West Florida Shelf that is available to *K. brevis*. Whether or not atmospheric dust input is the major factor stimulating blooms of *K. brevis* is less clear. An examination of the timing of atmospheric dust input, *Trichodesmium*, and *K. brevis* blooms shown in Walsh and Steidinger (2001) and Berg et al. (2004) shows only partial correlation, as also noted by Stumpf et al. (2008). Furthermore, atmospheric dust will tend to cover large areas of the West Florida Shelf, but the blooms generally start in relatively small areas. Atmospheric iron probably increases the biomass of *Trichodesmium* and *K. brevis*, but it is not clear if it can explain when or where *K. brevis* blooms will occur.

The dieoff of other organisms and the release of their nutrients is another potential source of nutrients. Some have considered decomposition of dead fish (Vargo et al., 2008; Walsh et al., 2009). Once a bloom is dense enough to kill fish, nutrients from decomposing fish could certainly help sustain a bloom of *K. brevis*, especially if it dominates the community. It is less clear if fish kills from some other cause could be an important factor in initiation of the sporadic blooms of *K. brevis*. Another possibility is the dieback of benthic plants on the shelf, particularly in the deeper water where the plants are near their compensation point. The fall months are when benthic plants are under the greatest energy balance stress – when temperatures are still high (keeping respiration rates high) but light intensity and daylength are declining. This is typically the time of year that dieoffs of seagrass and macroalgae are observed. Bottom temperature and water clarity above vary spatially and temporally due to hydrography and other factors. They would be factors in determining the extent to which benthic plants might die and release nutrients slowly to *K. brevis*. If a benthic population of *K. brevis* exists, it would also be under energy balance stress, perhaps stimulating it to migrate to the surface. For example, bottom temperatures could actually increase in the fall when the advection of cold bottom water from offshore stops and stratification breaks down. This increase in temperature at a time of reduced light could either stimulate a benthic population of *K. brevis* to migrate up into the surface waters and/or lead to the death of macroalgae and seagrasses and subsequent release of nutrients to *K. brevis*.

Dying diatom blooms are another potential source of nutrients. Many seasonal sequences throughout the world start with diatom blooms utilizing upwelled inorganic nutrients. As the diatom blooms die, they release nutrients and dinoflagellates become more dominant. It seems likely that *K. brevis* may get most of its nutrients only after recycling through diatoms and other parts of the food web; and inorganic nutrients from bottom water or land runoff simply enhances that food web.

Whatever the initial source of nutrients, the blooms are typically much larger inshore than offshore (Brand and Compton, 2007). This suggests that even if land runoff is not an important factor in initiating blooms, it is probably important for the eventual buildup of

larger biomass. Upwelling of offshore nutrients, atmospheric iron, and dead fish as nutrient sources cannot explain this inshore-offshore gradient.

### 12.5 K. concordia in New Zealand

Beyond the Gulf of Mexico, another location that has experienced significant human health problems (along with animal mortalities) from *Karenia* is New Zealand (Chang, 1995). The first significant blooms of *Karenia* were in January (summer) 1993 along the northeast coast (Bay of Plenty) of the North Island of New Zealand. The newly identified species was *K. concordia* and it apparently produces toxins similar to *K. brevis* (Chang et al., 1998). Hundreds of people ended up with NSP and respiratory distress (Chang, 1995; Trusewich et al., 1996; Chang et al., 1998), as there was no monitoring program in place because there had been no problems previously. Another bloom of *K. concordia* developed along the northeast coast (Hauraki Gulf) of the North Island in October (spring) 2002 (Chang and Ryan, 2004; Chang et al., 2008). In this case, no human effects were observed, but widespread mortality of fish and abalone occurred. Although one bloom occurred in the summer and the other in the spring, both were in years of El Nino, in which upwelling favorable winds were stronger than normal. The 2002 bloom occurred after the winds died down and a warm tongue of offshore water was transported inshore over the cold upwelled water (Chang and Ryan, 2004; Chang et al., 2008). It is known that low concentrations of *K. brevisulcata, K. concordia* , and *K. mikimotoi* occur in the warm offshore waters (Chang and Ryan, 2004). It is thought that the transport of the warm water over the upwelled water brought *K. concordia* into Hauraki Gulf and its diel vertical migration behavior allowed it to take advantage of the nutrient rich water below. There is less information on the 1993 bloom, but Chang et al. (1996) noted that the temperature was lower and the salinity was higher than normal when the bloom developed in the Bay of Plenty, suggesting a similar set of circumstances.

### 12.6 K. brevisulcata in New Zealand

A different species, *K. brevisulcata*, bloomed January to March (summer) 1998 along the south coast of the North Island of New Zealand and in Wellington Harbor on the north coast of the South Island (Chang, 1999; Wear and Gardner, 2001; Truman et al., 2005). Humans experienced respiratory distress and skin irritations. Animal mortality was extremely widespread, including zooplankton, benthic invertebrates, and both benthic and pelagic fish (Wear and Gardner, 2001). It was noted that the water was unusually warm and stratified at the time of the bloom.

### 12.7 K. cristata and K. bicuneiformis in South Africa

Along the southwest coast of South Africa, blooms of *Karenia* have developed in the fall months of numerous years (Botes et al., 2003a, b). *K. cristata* has bloomed in 1988, 1989, 1995, and 1996. Humans experienced respiratory effects and skin irritation during those blooms. Mortality of abalone has also been observed. Blooms of *K. bicuneiformis* have occurred in 1995 and 1997. No human effects or animal mortalities were observed associated with this species. It appeared that these blooms in the fall were associated with periods of calm weather followed by winds generating surface movements to the shoreline and downwelling (Botes et al., 2003a, b).

### 12.8 K. mikimotoi

Blooms of *K. mikimotoi* have occurred in many parts of the world, causing major fish kills, particularly since the 1960s. In Europe anecdotal evidence suggest that this species was blooming off the south west coast of Ireland as early as the late 1800s (http://ioc-unesco.org/hab/index.php?option=com_oe&task=viewDocumentRecord&docID=4605). In Europe, the first major bloom of *K. mikimotoi* occurred in the fall 1966 along the Norwegian coast (Braarud and Heimdal, 1970). Blooms usually occur during the summer or fall when the water is stratified. In Europe, blooms are observed in coastal waters, but are believed to develop in more offshore areas between fronts of different water masses (Pingree et al., 1975, Tangen 1977, Lindahl 1986, Gentian 1998, Gentian et al., 2005, Davidson et al., 2009). Pingree et al. (1978) has argued that surface blooms occur where pycnocline populations in stratified waters meet frontal boundaries where the water is mixed or at times when stratified waters become mixed. Gentien (1998) has suggested that *K. mikimotoi* tends to reside in the pycnocline if it is strong and undergo diel vertical migration if the pycnocline is relatively weak. Blooms may be enhanced by anoxia in the bottom waters. At the present time, there is no mechanistic model that can fully explain or predict when and where blooms of *K. mikimotoi* occur.

Pingree et al. (1975) documented a bloom at a front at the western entrance to the English Channel in 1975. He argues that *K. mikimotoi* resides in the pycnocline of the stratified waters of the Atlantic Ocean and form a surface bloom at the front where the stratified water meets the mixed waters of the English Channel (Pingree et al., 1978). Similar blooms occurred in July in 1977 and 1978, and in September in 1980 and 1981 at fronts between inshore mixed waters and offshore stratified waters along the coast of Scotland (Gowen, 1987). The blooms in 1980 and 1981 killed large numbers of fish (Jones et al, 1982; Davidson et al., 2009). Davidson et al. (2009) have also documented blooms of *K. mikimotoi* in the Orkney Islands in 1999 and 2003, the Shetland Islands in 2003 and a large bloom in northern Scotland that started on the west coast in July 2006 and moved along the coastline to the east coast. This bloom killed large numbers of benthic invertebrates and some fish. *K. mikimotoi* blooms have also been observed in Ireland, sometimes with devasting impacts on farmed fish (Raine et al., 2001, Silke et al., 2005). In this area, thermal jets are believed to play a role transporting the bloom along the Irish coast (Raine et al., 2010). Blooms have occurred in the summer at fronts along the Atlantic coast of France in 1984 and 1987 (Gentian et al., 1998). In July 1995, a similar bloom expanded to the entire coastline of western France.

In Scandinavian waters blooms of *K. mikimotoi* have been associated with offshore inflow into the Skaggerak (Lindahl, 1986). The relationship between land run off and *K. mikimotoi* blooms is complex. Blooms have been observed along the southern coast of Norway after heavy freshwater input (Dahl et al., 1987), however in some instances the amount of nitrogen needed to sustain a *K. mikimoti* in coastal areas is not associated with land run off but with nutrients from more offshore areas or physical processes (Lindahl, 1986). This was also observed in Scottish waters in 2006 where the number of *K. mikimotoi* cells in Scapa Bay in the Orkney islands could not be supported by the nitrogen entering the system from land based sources (Davidson et al., 2009). In September 1982, blooms developed along a

front between the higher salinity North Sea and lower salinity Skagerrak (Lindahl, 1983, 1993; Richardson and Kullenberg, 1987). A similar bloom developed in the late summer and fall 1987 as a pycnocline residing population of *K. mikimotoi* surfaced at a front in the Skagerrat (Richardson and Kullenberg, 1987).

The other major area that gets frequent blooms of *K. mikimotoi* is Japan (primarily the Seto Inland Sea), Hong Kong, and Korea. Although some blooms of *K. mikimotoi* occurred earlier in Japan (Oda, 1935; Honjo, 1994; Okaichi, 2004), major blooms leading to mortality of fish and pearl oysters began in 1965 and have continued with great frequency since then (Partensky et al., 1988; Okaichi, 1989; Honjo, 1994; Dahl and Tangen, 1993; Kimura et al., 1999). Most of these blooms occur in the Seto Inland Sea, but also occur elsewhere along the coasts of Japan (Matsuoka et al., 1989). They occur primarily in the summer when the water is stratified (Kimura et al., 1999). The increase in blooms after 1965 has been attributed to anthropogenic eutrophication, and a decline in these blooms in the 1980s and 1990s has been attributed to environmental regulation reducing that eutrophication (Prakesh, 1987; Kimura et al., 1999). The blooms appear to be associated with high rainfall and land runoff (Yanagi et al., 1992, 1995; Kimura et al., 1999). Imai et al. (2006) have argued that blooms of *K. mikimotoi* in the Seto Inland Sea occurred prior to the period of eutrophication in the 60s and 70s and thus it is considered an ‘inherent red tide species from ancient times’. Honjo et al. (1990) and Kimura et al. (1999) argued that the blooms are more prevalent where the bottom waters have gone anaerobic and it is shallow enough that the dinoflagellates can migrate to the bottom on a diel basis.

Lam and Ho (1989) document the large increase in HABs in Tolo Harbor, Hong Kong, some of which are *K. mikimotoi*. Blooms of *K. mikimotoi* typically occur around September to December (Wong, 1989). Interestingly, *K. mikimotoi* tends to bloom in the winter or spring in Port Shelter, Hong Kong (Wong, 1989), which suggests an effect of the interaction of seasonal changes in the wind direction and the orientation of the water bodies. The best documented bloom occurred in March and April 1998, killing large number of fish (Hodgkiss and Yang, 2001; Hodgkiss et al., 2001). The bloom included some *K. digitata* mixed in with the dominant *K. mikimotoi* (Lu and Hodgkiss, 2004). The bloom produced very thick mucus, which interfered with fish respiration (Dickman, 2001). It was associated with heavy rainfall (Yang and Hodgkiss, 2001). Wong (1989) suggested that the blooms were stimulated by organic compounds produced by fish cages in the area.

*K. mikimotoi* bloomed for the first time in Korea in the summer and fall of 1981 and killed a large amount of shellfish (Park et al., 1989; Kim et al., 1995). This bloom was composed of several algal species, of which *K. mikimotoi* was one. In 1984, another bloom of *K. mikimotoi* occurred in Korea (Partensky et al., 1988).

While the most blooms of *K. mikimotoi* appear to occur in Europe, Japan, and Hong Kong, sporadic blooms have occurred elsewhere. Mahoney et al. (1990) blooms that developed along the coast of New Jersey, USA in the late summer of both 1984 and 1985 when the weather was calm and water was stratified. Invertebrates were killed and humans experienced nausea, throat and eye irritation, and lung congestions. The blooms

were densest at the coastline but extended offshore two to eight kilometers at lower concentrations.

A *K. mikimotoi* bloom was observed in the pycnocline in October (spring) 1988 off the coast of Argentina south of the Plata River (Negri, 1992), but no animal mortalities were observed.

### 12.9 K. selliformis in New Zealand, Chile and Kuwait

In 1994, and bloom of *K. selliformis* developed along the south coast of the South Island of New Zealand, leading to the death of many fish and shellfish (de Salas et al., 2005). *K. selliformis* formed monospecific blooms in the coastal waters of southern Chile around the Chiloe Archipelago in March and April (fall) 1999, killing large numbers of fish and shellfish (Clement et al., 2001; Carreto et al., 2001; Uribe and Ruiz, 2001). It was thought that this bloom started with low concentrations offshore that then greatly increased in abundance as the population was carried inshore. It was noted that temperatures were unusually high and rainfall was greatly reduced from normal at the time of the bloom. Blooms of *K. selliformis* killed large numbers of fish in Kuwait Bay in August and September 2001 (Heil et al., 2001). This developed only a few weeks after similar blooms developed upstream in the coastal waters of Iran. A large increase in nutrients was observed right before the bloom developed.

### 12.10 K. umbella and K. asterichroma in Tasmania

Along the southeast coast of Tasmania, a bloom composed of a mixture of *K. umbella, K. asterichroma*, and three unidentified species of *Karenia* developed in May (late fall) 2003, killing large number of fish (de Salas et al., 2004a, b).

### 12.11 K. digitata and K. longicanalis in Hong Kong and Japan

Blooms of *K. digitata* developed in the coastal waters of Hong Kong and western Japan in the summers of 1995 and 1996, causing large fish kills (Yang et al., 2000). In May 1998, a bloom of *K. digitata* developed in Hong Kong and it was followed two weeks later by a bloom of *K. longicanalis* (Yang et al., 2001). Both species were associated with large fish kills.

*K. brevis* blooms frequently in the Gulf of Mexico and *K. mikimotoi* blooms frequently in Europe, Japan, and Hong Kong. Blooms of the other species of *Karenia* appear to be very infrequent. This suggests that these species normally exist at very low concentrations, and form blooms only under very unusual circumstances. Blooms of all the *Karenia* species except *K. brevis* and *K. mikimotoi* have first appeared only in the past few decades. Were all these *Karenia* species simply overlooked in the past or have environmental conditions changed to support their occasional blooming?

### 12.13 Increase of Karenia blooms?

On a global scale, there is widespread agreement that Harmful Algal Blooms in general are increasing (Smayda, 1990, 2008; Hallegraeff, 1993; Glibert et al., 2005a, b; Anderson et

al., 2002, 2008; Glibert and Burkholder, 2006; Heisler et al, 2008) and that anthropogenic nutrients are a major cause in many cases. Is this the case for *Karenia*?

Brand and Compton (2007) examined the monitoring data collected by the State of Florida (Florida Fish and Wildlife Research Institute, 2002) on *K. brevis* and concluded that its abundance had increased dramatically over the past 50 years. They argued that the only plausible source of the increased nutrients needed for this increased biomass was land runoff from anthropogenic sources. This increase parallels the increase in groundwater nutrients (Scott et al., 2006), coastal nutrients (Turner et al., 2006) and macroalgae (Lapointe and Bedford, 2007) observed along the west coast of Florida in recent decades. Kuhar et al. (2009) concluded that both scientists and the public believe that *K. brevis* blooms are increasing in frequency, geographic distribution, and persistence over time. Magaña et al. (2003) stated that there is a perception that *K. brevis* blooms along the Texas coast have increased as well.

Prakesh (1987) and Kimura et al. (1999) have argued that there has been a substantial increase in blooms of *K. mikimotoi* in the Seto Inland Sea of Japan that is related to eutrophication.

In the past two decades, a number of new species have been discovered, primarily as a result of mass mortality events and improved identification and molecular techniques. As a result, more species are likely to be described as a result of improving molecular techniques. Botes et al. (2003a) showed that *K. cristata* first bloomed in South Africa in 1988, killing large amounts of shellfish. De Salas et al. (2004a) describes new blooms of *K. umbella* in Tasmania, and other species of *Karenia* in Norway, Japan, New Zealand, Chile, and Hong Kong. Zingone et al. (2006) have documented the recent appearance of numerous toxic species of algae, including 5 species of *Karenia* that were not seen decades ago in the Mediterranean Sea. Heil et al. (2001) described a fish kill by a new *Karenia* species in Kuwait Bay. While many of these species may have lived in those ecosystems at low concentrations unnoticed, large blooms and fish kills are less likely to go unnoticed. In some cases, the spread of aquaculture and high concentrations of fish in cages might be a factor. In other cases, it seems plausible that anthropogenic eutrophication could be a factor leading to higher concentrations of these species that now cause problems and get noticed. As aquaculture expands and eutrophication increases, it is possible that *Karenia* blooms and associated fish kills could increase.

The development of *Karenia* blooms is obviously complex and poorly understood at this time. Because of their sporadic nature, it is difficult to determine if blooms have in fact increased over time, either in frequency or magnitude. Nutrients are only one of many factors that may be involved. Eutrophication may be involved in the increase of some *Karenia* blooms, but certainly not all.

## 13. Detection systems.

The primary goal of HAB detection and early warning is to prevent human illness. In the case of *K. brevis* blooms, to prevent NSP, the consumption of intoxicated shellfish, effective

monitoring measures require closure of shellfish harvesting if *K. brevis* abundance exceeds a threshold level. Re-opening shellfish harvesting is based on toxicity testing of contaminated shellfish. Consequently, sensitive and specific methods are needed for both cell abundance and brevetoxin detection.

### 13.1 Cell abundance and species-specific detection

The federal regulatory standard in the US for the closure of shellfish harvesting during *Karenia brevis* blooms is set at $5 \times 10^3$ cells $L^{-1}$. Direct counts of water samples by light microscopy has been the primary method for detection and enumeration of *K. brevis*. This standard approach, however, is now complicated by observations that blooms may consist of multiple species, along with the inherent highly variable morphology of an individual species, which makes positive identifications by light microscopy difficult (Heil & Steidinger, 2009)

New technologies for *Karenia* detection include pigment based, optical, molecular, and imaging methods. Monitoring using pigment analysis by high performance liquid chromatography (HPLC) has been proposed based on the biomarker pigment gyroxanthin-diester (Richardson & Pickney, 2004). This pigment is found in other closely related gymnodinoid species of *Karenia*, as well as *Karlodinium* and *Takayama* (de Salas et al., 2003; 2005), so does not provide species-specific detection.

The Optical Plankton Detector (OPD, BreveBuster), developed for *K. brevis*, also relies on the unique absorption of spectrum of *K. brevis* to detect its presence in a mixed phytoplankton community (Kirkpatrick et al., 2000). Using stepwise discriminant analysis based on $4^{th}$ – derivative normalized absorption spectra, the OPD has been deployed on an automated underwater vehicle to provide greater spatial resolution for early detection of blooms (Robbins et al., 2006).

To improve taxonomic specificity and limit of detection, molecular techniques have proven to be invaluable. For example, nucleic acid sequence-based amplification (NASBA) approaches have been developed for *K. brevis* (Casper et al., 2004; 2007) and *K. mikimotoi* (Ulrich et al., 2010). Cell-based fluorescent in situ hybridization (FISH) assays have been developed for *K. brevis* (e.g. Mikulski et al., 2005) and cell-free hybridization assays for *K. brevis, K. mikimotoi, K. selliformis*, and *K. papilionacea* (Goodwin et al., 2005; Haywood et al., 2007). A multiplexed flow cytometric approach was carried on using the Luminex 100 platform and XMap technology to detect simultaneously 14 different species of dinoflagellates. This bead array method is based on color coded microspheres, which are conjugated to probes designed for each single species (Scorzetti et al., 2009). Recently the same technology was used with locked-nuclei acid modified capture probes for the detection of *K. brevis* and *K. mikimotoi* (Diaz et al., 2010). This flow cytometry-based technology has the potential for detection and quantification of multiple (up to 100) RNA targets simultaneously (Scorzetti et al., 2009; Diaz et al., 2010).

In addition, microsatellite markers have been developed for *K. brevis* (Henrichs et al., 2008; Renshaw et al. 2006) and *K. mikimotoi* (Nishitani et al., 2009). These hypervariable

molecular markers are used to assess genetic diversity within and among bloom populations and to infer the relationship between populations.

One of the most promising new technologies for early warning of HABs is imaging-in-flow cytometry. This approach, using the Imaging Flow Cytobot (Olson & Sosik, 2007; Sosik & Olson, 2007) has provided valuable early warning capabilities for HABS, such as *Dinophysis ovum* (Campbell et al. 2010a) and *K. brevis* in the Gulf of Mexico (Campbell et al., 2010b). Although automated image classification is possible at the species-specific level in some cases, currently identification of *Karenia* is at the genus level. The variation in morphology, as discussed above, has limited the ability of the automated classifier (Sosik and Olson, 2007) to reliably distinguish among species of *Karenia*; however, the continuous and automated approach has permitted timely and successful early warning.

### 13.2 Satellite imagery of blooms

To assess the extent of *Karenia* blooms, data are needed at spatial and temporal scales not attainable by routine monitoring of cell counts. Satellite imagery was an obvious choice for HAB detection and has been used to detect blooms of *Karenia* worldwide for a number of years. Beginning in the 1970s, the Coastal Zone Color Scanner (CZCS) provided data for the Gulf of Mexico (Steidinger and Haddad, 1981). Subsequently the Sea-Viewing Wide Field-of-View Sensor/OrbView-2 (SeaWiFS), and most recently fluorescence data from Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite have been used (Hu et al., 2005; Vanhoutte-Brunier et al., 2008; Carvalho et al., 2010).

Satellite imagery for detection is limited, however, to surface (1 optical depth) and is obscured if clouds are present. More importantly, detection of chl a is not specific, as all phytoplankton contain chl a, and in coastal waters the signal can be influenced by resuspended sediments, colored dissolved organic material (CDOM) and bottom reflectance (Cannizzaro et al., 2008). Based on laboratory experiments, estimated detection for *Karenia* is limited to concentrations above $5 \times 10^4$ *Karenia* cells $l^{-1}$ (Tester et al., 1998), so is not capable of early detection of bloom initiation. With the availability of SeaWIFS ocean color measurements, Stumpf proposed the chlorophyll anomaly method, which detects increases between a single image and the mean for the previous two months, as an index of *K. brevis* blooms (Stumpf et al., 2003; Tomlinson et al. 2004). Corrections for false positive predictions due to resuspension of benthic algae were developed by Wynne et al. (2005). Based on field observations of bio-optical properties, Cannizzaro et al. (2008) found the backscatter ($b_b(\lambda)$): chl a ratio was significantly lower for *K. brevis*, so proposed a classification scheme based on high chlorophyll and low backscatter to detect *K. brevis*. They also introduced the use of fluorescence line height (FLH) parameter from MODIS data. The combination of these approaches together with ancillary data from field observations (time series of abundance, winds, current and sea surface temperature) have been shown to improve ocean color forecasting (Hu et al., 2008). NOAA's Harmful Algal Bloom Operational Forecast System (HAB-OFS) provides a weekly HAB Bulletin http://tidesandcurrents.noaa.gov/hab/bulletins.html) that uses daily ocean color satellite imagery together with field observations of cell counts and optical properties, buoy data, forecasted wind and current data to predict the location, development and extent of blooms. Evaluation

of remote sensing techniques (Tomlinson et al., 2009), use of several satellite ocean color algorithms (Carvalho et al., 2011) and the capabilities of the HAB operational forecast system (Stumpf et al., 2009) have been reviewed recently.

Earth observation data have been used with some success in a study of a *K. mikimotoi* bloom in Scottish waters during 2006 (Davidson et al., 2009, Shutler et al., 2011) and provided complimentary information to support field measurements and cell counts about the origins and progress of the bloom. The data showed some potential to classify the bloom as *K. mikimotoi* and more work is needed to refine this tool so it can be implemented as a monitoring tool (Davidson et al., 2009, Shutler et al., 2011).

### 13.3 Toxins

To re-open commercial shellfish harvesting affected by *K. brevis* blooms, toxicity testing is required to verify toxin levels have returned to acceptable levels. The traditional method, the mouse bioassay (MBA) was first used by McFarren et al. (1965) to estimate risk to humans from consuming oysters contaminated with brevetoxin. A number of limitations of the MBA, including lack of specificity and sensitivity, as well as on ethical grounds (Plakas and Dickey 2010) have led to the search for a replacement.

Alternative methods for quantification of brevetoxin include both pharmacological and structural approaches (Baden and Adams, 2000; Poli, 2008). In shellfish, brevetoxins are extensively metabolized, so identification and determination of the toxicity of metabolites is also essential (Abraham et al., 2008; Plakas and Dickey, 2010). Pharmacological based assays include cytotoxicity, based on the activity of voltage gated sodium channel (e.g. Plakas et al., 2002; David et al., 2003; Wang et al., 2004), and receptor binding assays, based on the affinity of brevetoxin for sodium channels (Trainer and Poli, 2000; Van Dolah et al., 1994). Toxin detection based on structure of the compounds includes both immunological, such as the competitive ELISA to detect brevetoxins in *K. brevis* (Naar et al., 2002), or electrochemiluminescence (Poli et al., 2007), and LCMS (Poli et al., 2000; Errera et al., 2010). The advantages and disadvantages of these methods are reviewed by Plakas and Dickey (2010, and references therein).

Over the last decade, structural methods using LCMS have become essential for confirmation and increasingly for quantification (e.g. Errera et al., 2010). Although instrumentation was too expensive and of limited sensitivity just a decade ago (Baden and Adams, 2000), current instruments have increased sensitivity by orders of magnitude. As additional toxins are discovered and identified in new *Karenia* species, the importance of standards will continue to be an important concern.

## 14. Conclusions

Many of the *Karenia* species are known to live in offshore waters. It is hypothesized that focused research may reveal a higher diversity of *Karenia* species offshore and a wider global distribution of many of these species. When blooms have been examined carefully using species specific molecular techniques, they have been found to be composed of more than one species of *Karenia*. It is hypothesized that the use of molecular techniques to test

for the presence of many *Karenia* species will reveal that most or all blooms are composed of more than one *Karenia* species. If so, our current attribution of animal and human health effects to particular toxins and species is probably overly simplistic. Many new toxins produced by *Karenia* species have been discovered in recent years and we can expect these new discoveries to continue.

Many descriptive studies show an association between *Karenia* blooms and frontal regions between inshore and offshore waters. It is hypothesized that source populations of *Karenia* may be offshore, and the highly sporadic inshore blooms occur only when rather unusual and unique sequences of events occur. While inshore transport, downwelling-upwelling, stratification-destratification, frontal regions, atmospheric iron, nitrogen fixation by *Trichodesmium,* and land runoff all appear to be associated with the development of blooms, it is clear that no one factor or simple combination or sequence of factors can explain the highly sporadic spatial and temporal distribution of *Karenia* blooms. *Karenia* blooms are most common during late summer and fall, but blooms occasionally occur in spring as well. Most attempts to explain the occurrence of particular blooms do not also explain why blooms do not also occur elsewhere along the coastline with similar situations or in other years under similar conditions. Furthermore, most explanations given for blooms of *Karenia* would work for most dinoflagellates, not just *Karenia*. We really do not know how *Karenia* might outcompete other dinoflagellate species.

*Karenia* species would appear to be adapted primarily for taking up recycled nutrients (from *Trichodesmium*, dying fish, dying diatoms, or other biota), rather than taking up new inorganic nutrients from upwelling or land runoff. New nutrients generate biomass of other species, which only later may release nutrients to *Karenia* and its competitors. Such biological complexity may account for it highly sporadic and unpredictable distribution. Many nutrient sources occur over large areas, but most blooms start in relatively small, localized areas. *Karenia* blooms appear to often be associated with frontal regions, but the detailed mechanism for how it helps generate *Karenia* blooms has yet to be described.

It is hypothesized that, as a broad generalization, physical factors are primarily responsible for moving and concentrating *Karenia* cells inshore, and inshore nutrients, including anthropogenic ones, determine how large the blooms become. If this generalization is correct, blooms of *Karenia* may remain highly sporadic and unpredictable, but larger and more devastating blooms may occur under certain physical conditions where anthropogenic eutrophication releases more nutrients into coastal waters. These blooms can have major impacts on marine ecosystems, including fisheries and aquaculture. Animal mass mortalities and toxic aerosols can also impact aesthetics and tourism along coastlines. At least some *Karenia* species are a serious hazard to human health.

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**Table 1.**

Species within the genus *Karenia*[1]

| Species (synonyms) | First Described (location/citation) | Toxins | Human Impacts | Animal Impacts |
|---|---|---|---|---|
| *Karenia asterichroma* | Tasmania, Australia<br>de Salas et al. 2004a | not characterized | none known | mortality of fish (aquaculture) |
| *Karenia bicuneiformis* (*K. bidigitata*) | South Africa<br>Botes et al. 2003a;<br>New Zealand<br>Haywood et al. 2004 | brevetoxin by ELISA[2] (unconfirmed) | none known | none known |
| *Karenia brevis (Davis 1948) G. Hansen & Moestrup* (*Gymnodinium breve*, *Gymnodinium brevis*, *Ptychodiscus brevis)* | Florida, USA<br>Davis 1948 | brevetoxins[3]<br>brevisamide[4]<br>brevisin[4]<br>brevenal[5]<br>hemolysins[6]<br>O,O-dipropyl(E)-2-(1-methyl-2-oxopropylidene) phosphoro-hydrazidothioate-(E)oxime[L1][7] | NSP, respiratory distress | mortality of fish, invertebrates, birds, turtles, and mammals |
| *Karenia brevisulcata (F.H. Chang, 1999) G. Hansen & Moestrup, 2000)* (*Gymnodinium brevisulcatum)* | New Zealand<br>Chang 1999 | allelochemicals, compounds that affect sodium channels[8] | respiratory distress | mortality of fish and invertebrates |
| *Karenia concordia* (*K.* cf. *brevis)* | New Zealand<br>Chang & Ryan 2004 | allelochemicals, hemolysins, cytotoxic compounds[8] | NSP-like symptoms | mortality of fish and abalone |
| *Karenia cristata* | South Africa<br>Botes et al. 2003a | not characterized | respiratory distress | mortality of abalone |
| *Karenia digitata* | Japan, Hong Kong<br>Yang et al. 2000 | not characterized | none known | mortality of fish |
| *Karenia longicanalis* | Hong Kong<br>Yang et al. 2001 | not characterized | none known | mortality of fish |
| *Karenia mikimotoi* (*Gymnodinium mikimotoi* Miyake & Kominami ex Oda, 1935) *(Gymnodinium mikimotoi*, *Gymnodinium nagasakiense*, *Gymnodinium aureloum*, *Gyrodinium aureolum)* | Japan Oda 1935 | gymnocin-A[9]<br>gymnocin-B[10]<br>hemolysin[6]<br>PUFA[7, 11] | none known | mortality of fish and invertebrates |
| *Karenia papilionacea* | New Zealand<br>Haywood et al. 2004 | brevetoxin by ELISA (unconfirmed)[2]<br>PUFA[7] | none known | none known |
| *Karenia selliformis* | New Zealand<br>Haywood et al. 2004 | gymnodimine[12,13]<br>brevetoxin by ELISA (unconfirmed)[2] | none known | mortality of fish and shellfish |
| *Karenia umbrella* | Tasmania<br>de Salas et al. 2004a | PUFA[7] | none known | salmon farm mortality |

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