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Fish Kill Incidents and Harmful Algal Blooms in Omani Waters

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حوادث نفوق الأسماك وازدهار الطحالب الضارة في المياه العمانية

حمد محمد الغيلاني، كازومي ماتسوكا، عبد العزيز يحيى الكندي، شهلة عامر وكولين ويرنغ

الخلاصة: المد الأحمر أو ظاهرة ازدهار الطحالب الضارة يعتبر تغيرا طبيعيا يؤدي إلى عدة تأثيرات على الثروة السمكية الساحلية والاقتصاد المحلي والصحة العامة. المد الأحمر اخذ في الازدياد في السنوات الأخيرة. بعض أدى إلى نفوق الأسماك واثر على الثروة السمكية والاستزراع كم اثر على البيئة بشكل عام بالإضافة إلى تأثيره على محطات تحليه المياه. على كل حال، معظم أنواع العوالق البحرية المسببة للمد الأحمر في سلطنة عمان غير سامة مثل نكتلوكا سنتلينس. بينما أنواع أخرى سامة مثل بروروسنترم ارابين وترايكوزميم، والتي تم رصدها مؤخرا. المد الأحمر في عمان مرتبط بظاهرتي التقليب ونقص الأكسجين. لكن مشكلات مرتبطة بصحة الإنسان أثناء المد الأحمر لم تسجل في عمان.

ABSTRACT*:* Red tide, one of the harmful algal blooms (HABs) is a natural ecological phenomenon and often this event is accompanied by severe impacts on coastal resources, local economies, and public health. The occurrence of red tides has become more frequent in Omani waters in recent years. Some of them caused fish kill, damaged fishery resources and mariculture, threatened the marine environment and the osmosis membranes of desalination plants. However, a number of them have been harmless. The most common dinoflagellate *Noctiluca scintillans* is associated with the red tide events in Omani waters. Toxic species like *Karenia selliformis*, *Prorocentrum arabianum,* and *Trichodesmium erythraeum* have also been reported recently. Although red tides in Oman have been considered a consequence of upwelling in the summer season (May to September), recent phytoplankton outbreaks in Oman are not restricted to summer. Frequent algal blooms have been reported during winter (December to March). HABs may have contributed to hypoxia and/or other negative ecological impacts.

Keywords: Red tide, HABs, fish kill, *Noctiluca scintillans*, phytoplankton, upwelling, hypoxia.

Introduction

Throughout the world's coastal waters, harmful algal bloom are being reported with increasing frequency and causing severe impacts on coastal resources, local economies and public health. Harmful algal blooms (HABs) are caused by microalgae, usually single-celled prokaryotic and eukaryotic photosynthetic organisms that live in freshwater, estuarine and marine realms. Harmful and toxic incidents caused by dinoflagellates are intensifying and spreading all over the world accompanied with extensive ecological damage during the last four decades (Cho, 1981; Olsen *et al.,* 1988; Smayda and Fofonoff, 1989; Chen and Gu, 1993; Hallegraeff, 1993; Nuzzi*et al.,* 1996; Anderson, 1997; Wong, 1989; Kim *et al.,*1990, 1993; Steidinger, 1993) including the coastal waters of Oman (Thangaraja *et al.,* 1990, 1991, 1998, 2000, 2007; Al Gheilani *et al.,* 2005, 2007; Al Kindi *et al.,* 2007, unpublished; Al Busaidi *et al.,* 2008; Richlen *et al.,* 2010; Matsouka *et al.,* in preparation). The reasons for the increasing red tides may be related to the global climate change, increase of human impact in coastal zones, awareness resulting from scientific research and reports of HABs events.

The negative effects caused by such micro-algae include the biotoxins, physical damage and the anoxia or hypoxia (Al Gheilani *et al.,* 2005). However, cell densities of causative micro-algae cannot increase forever and as soon as the first critical nutrient runs out, the bloom will collapse

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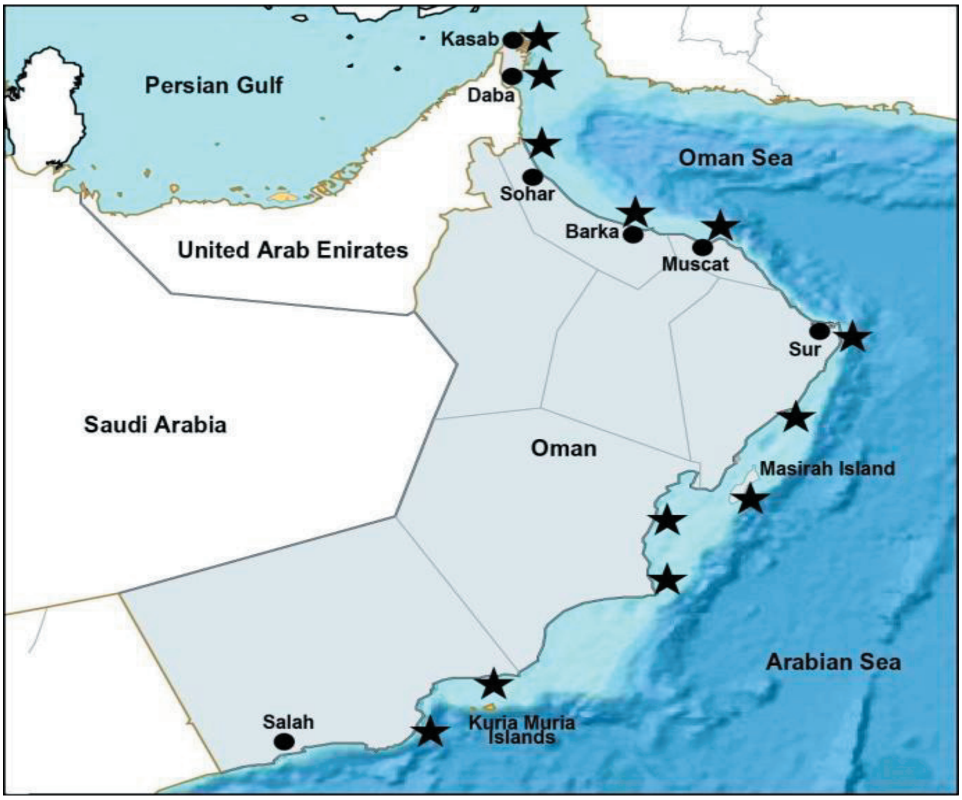

Figure 1. Distribution of red tide in Omani coast.

(Van den Bergh *et al.,* 2002). Thus, for understanding HAB phenomena the behavior of nutrients is one of the important subjects for research.

Since HABs are globally distributed and integral parts of marine and brackish-water ecosystems, the main research problems can be addressed comprehensively and effectively only through international, interdisciplinary and comparative research on important questions about the dynamics of HABs within their oceanographic and ecological systems (GEOHAB, 1998). Recurring algal blooms and red tides in the coastal waters of Oman have been documented for nearly three decades, and some of them cause damage to the marine environment and economic losses to the fisheries industry. The other negative effects of red tides-causing dinoflagellates in Omani waters include the production of biotoxins, physiological damages to fish and the anoxia or hypoxia in the environment (Al Gheilani *et al.,* 2005). Hence, in order to diminish fisheries damages, especially for aquaculture, adequate monitoring systems of the outbreaks are required. As HABs are of national concern to Oman, there is need to foster national cooperative research on HABs in order to find better solutions regarding this issue.

This paper intends to provide an overview of HABs history, causative species and previous research activities for establishing counter measures to HABs damages in the Sultanate of Oman.

History of HAB Occurrences and Investigations in Oman

Early scientific records of red tide events in Oman prior to 1976 were rare. The first HAB / red tide incident was reported during the 4th week of August 1976 along the Salalah coast between Taqah and Raysut, and caused a loss of about 7,000-10,000 tons of fish (Barwani, 1976, unpublished report). Subsequently, there were two more incidents of mass mortality of fish in Muscat; one in October 1976 and the other in February 1978, and causative organisms were *N. scintillans* and *Gonyaulax* sp. (Zahran, 1978), respectively. Since 1988, there has been regular documentation and monitoring of red tides and their impacts on the coastal waters of Oman (Thangaraja, 1990, 1991; Thangaraja *et al.,* 1998, 2000, 2007; Al Gheilani *et al.,* 2010, unpublished). Different coastal regions of Oman show variation in susceptibility to algal blooms and red tides, however most of the incidents have been recorded from the Muscat region (Fig. 1). The red tides appear to have become more widespread and persistent since late 1980s (Fig. 2).

A review of different HABs occurrences from 1976 to 2009 showed that about 81 red tide events have been recorded along the coastal waters of Oman; of which 10 incidents have resulted in mass mortality of fish and other marine organisms (Figs. 2 and 3; Table 1).

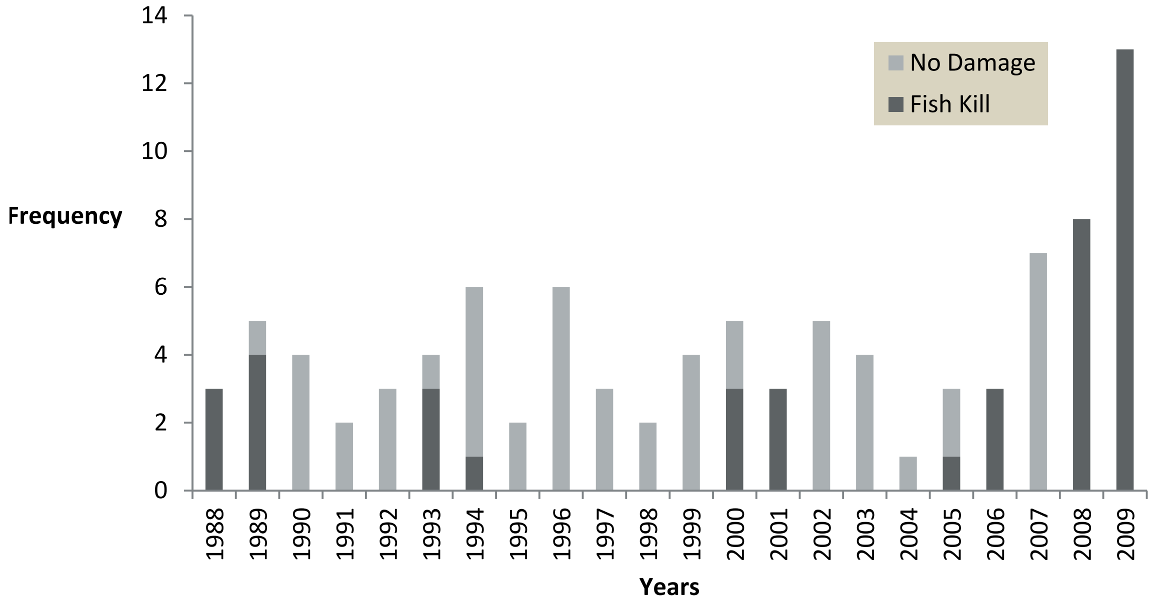

Figure 2. Major HABs event occurring in Oman (70) and HABs outbreaks causing fisheries damage and marine organism mortalities (22) (Data: Ministry of Fisheries Wealth).

Of the 22 identified HABs causative species, 16 were dinoflagellates and most of the fish kills were caused by these dinoflagellates (Thangaraja *et al.,* 2000, unpublished report of The Ministry of Agriculture and Fisheries Wealth). Red tide data (Thangaraja *et al*., 2000, data from Ministry of Agriculture and Fisheries; Al Gheilani *et al.,* unpublished) showed that 80% of all identified algal blooms were caused by dinoflagellates singly or in combination with diatoms. *Noctiluca scintillans* is the most important species causing more than 50% of HABs in Omani waters, but most *Noctiluca* blooms (31 from 37 blooms) did not affect marine organisms.

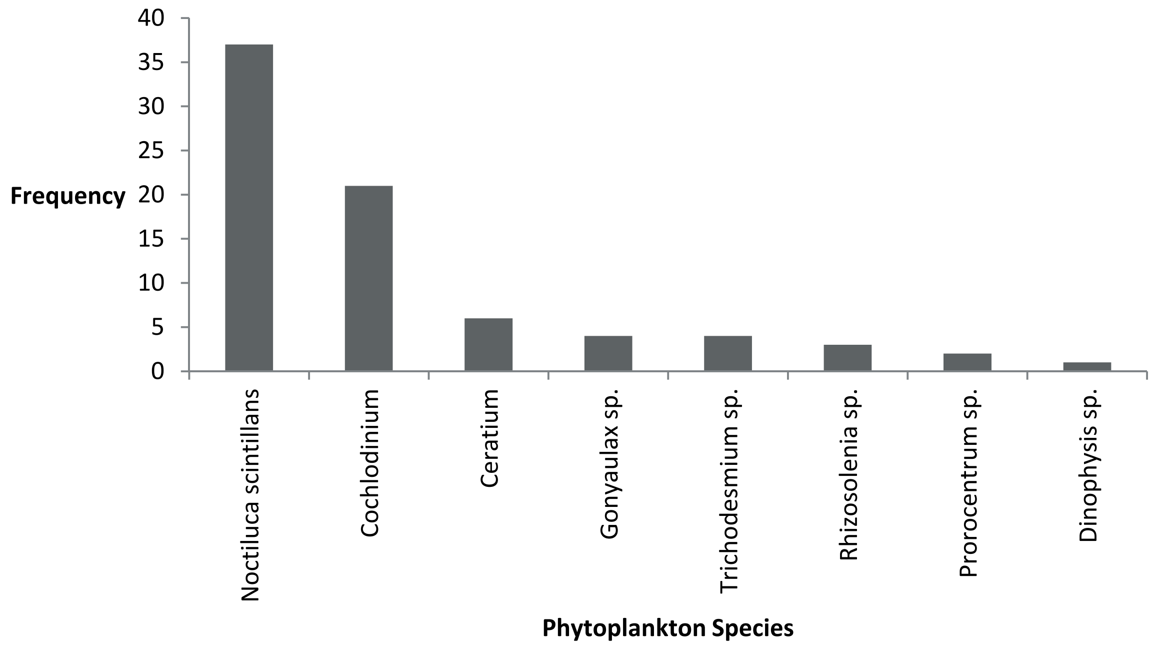

Figure 3. Main HABs causing species in Omani waters.

Table 1. Massive fish kills recorded in Omani waters (1976-2009).

Period	Major Species	Area	Mortality
August 1976	-	Salalah	7000-1000 tons of fish
September 1988	*Ceratium fucus* *C. macroceros* Diatom	Seeb to Qurum	Mass mortality of marine organisms
August to September 2000	*Coscinodiscus* spp	Barka	15-30 tons of fish
March 2001	-	Sur	250 tons of fish
April 2001	-	Al Sharqiya	34 tons
November to December 2001	-	Al Sharqiya and Al Wasta	40 tons of fish 250 turtles
January 2004	-	Bander Kharan	3000 tuna fish
October 2005	*Noctiluca scintillans; Prorocentrum micans and Trichodesmium erythraeum*	Masirah	Massive fish Kill
September 2006	-	Sohar	Massive fish kill
October 2008 to April 2009	*Cochlodinium polykrikoides*	Oman and Arabian Sea	200 tons of fish and shellfish

Mechanism of Algal Blooms in Oman

For intensive fish mass mortality in Oman, the following two scenarios are possible; 1) depletion of dissolved oxygen, and/or 2) blooms of toxic phytoplankton species.

Oxygen depletion

The phenomenon of oxygen depletion is increasing in coastal waters of the world (Kamykowski and Zentara, 1990) with occurrence as permanent, seasonal and episodic features. Oxygen depletion in the waters can result in hypoxic or anoxic conditions in the coastal areas. Two principal factors that lead to the development of hypoxia and anoxia; 1) water column stratification that isolates the bottom water from exchange with oxygen-rich surface water and followed by 2) decomposition of organic matter in the isolated bottom water that reduces oxygen levels (Sarmiento *et al.,* 1988; Diaz, 2002).

Persistent low oxygen is evident in oxygen minimum zones (OMZ) defined as regions where oxygen concentrations are <0.5ml*l^{-1} (22µM; Levin, 2003). The OMZ in the Northern Arabian Sea impinges on the continental margin creating permanently hypoxic conditions in the deep coastal to baythal benthic environment (Reichart, *et al.,* 2002). On the Oman continental margin, the OMZ extends down from about 60 m to about 1000 m deep, with gradual increasing dissolved oxygen (DO) below this depth to "normal" near saturated oxygen levels by 2000-2500m (Lamont and Gage, 2000). Bacterial oxidation in sinking organic matter typically found just below the thermocline at the depth from 50 to 100 m (Morrison *et al.,* 1999) brings highly fertile conditions for growth of phytoplankton and other photosynthetic organisms in the northern Arabian Sea and the Oman Sea. Consequently, the Arabian Sea has one of the thickest oxygen depleted layers of ocean water found anywhere in the world (Gooday *et al.,* 2000; Herring, 2002). Sometimes, due to shifts in the overlying wind field, these deep oxygen-poor waters upwell to the surface indirectly leading to periodic mass fish kills.

In the Arabian Sea the differences in oxygen concentrations between the mixed layer, thermocline and deep waters become most apparent during periods of strong thermal stratification (at the end of the summer) when mixing across the thermocline is nearly impossible. The mixed layer has temperatures ranging from 25 to 32ºC and high DO content (DO= 4ml$l^{-1}$to 6ml l^{-1}or higher). The temperature of the thermocline is between 24ºC and 26ºC and the DO concentrations are between 2ml $l^{-1}$and 4ml l^{-1}, while the deeper water has temperature below 24ºC and DO concentrations below 2mll^{-1}(Morrison *et al.,* 1999).

The breakdown of stratification of water column occurs in periods of upwelling (cold water brought to the surface) and either relaxation or downwellings (surface water pushed down along the coast). During the upwelling, water masses transported from 60 or 70 m depth result in the lowering of the temperature to 23-25 ºC at the sea surface. These cool waters are also poor in oxygen but rich in nutrients. This nutrient rich water is then susceptible to

Table 2. Species causing HABs in Omani waters and their effects.

	Number. of Occurrences	Impact
Single Species		
Noctiluca scintillans	37	Fish mortality (6) No damage (31)
Cochlodinium polykrikoides	21	Fish and shellfish mortality (21)
Ceratium sp.	06	Fish mortality (3) No damage (3)
Rhizosolenia sp.	03	No damage
Trichodesmium sp.	04	Fish mortality (1) No damage (3)
Gonyaulax polygramma	04	Fish mortality (4)
Prorocentrum sp.	02	No damage
Coscinodiscus	01	Fish mortality
Karenia mikimotoi	01	No damage
Mixed Species		
Gonyaulax, Noctiluca	02	Fish mortality (2)
C. fusus, C. macroceros, diatoms	01	Fish mortality
N. scintillans, C.furca, C. macroceros, P. micans, Pyrophacus holorogicum, Peridinium	01	No damage
Rhizosolenia, Pleurosigma sp., *Nitzschia pungens, Coscinodiscus spp., Fragilaria* sp., *Triceratium* sp., *Chaetoceros* sp., *Ceratium sp.*	01	No mortality
Coscinodiscus marginalis, Asteromptelus spp., *Chaetoceros* sp., *Rhizosolenia* sp., *Ceratium* sp.	01	No mortality
Dinophysis, Ceratium spp.	01	Fish mortality
N. pungens, Rhizisolenia alata, Thalassisora, Cyclotela, Pyrocystis, Gymnodium splendens, P. minimum, P. arabianum	01	Fish, green turtle and bird mortality

trigger the development of phytoplankton bloom (mostly harmless diatoms), at least for the few days that follow the onset of upwelling. Savidge and Gilpin (1999) estimated chlorophyll *a* concentrations and primary production to be maximal in the coastal upwelling zone in N W Indian Ocean during the late monsoon season. After a rapid growth, the phytoplankton produce oxygen at least in the upper layers of the water column, but during night they consume oxygen. Later in the cycle, the nutrient cannot sustain any further growth of the phytoplankton and dead or dying cells start to sink or decay. In bacterial denitrification, nitrate ions are used for oxidation of organic matter, in this process they are reduced to molecular nitrogen with nitrite as an intermediate (Codispoti and Christansen, 1989). Nitrification, the oxidation of nitrite and ammonium also occurs in these waters (Ward *et al*., 1989).

The low oxygen condition physiologically stressful for fish usually varies among taxa. The point at which various animals suffocate varies, but generally effects start to appear when oxygen drops below 2 ml l^{-1} or 2.8 mg l^{-1}, for seawater, this is about 18% saturation (Diaz and Rosenberg, 1995).

In several parts of the world, fish kills have been attributed to low dissolved oxygen levels generated by high biomass blooms and not necessarily due to toxicity. For example, from 1980–1989, at least 50% of fish kill in the Gulf of Mexico and 69% in the South Atlantic, USA, were attributed to low dissolved oxygen (Lowe, *et al*., 1991). Similarly, the low DO levels have caused fish mortality in Oman.

In most cases the dominant red tide causative species in the Oman Sea is *N. scintillans* (Table 2).

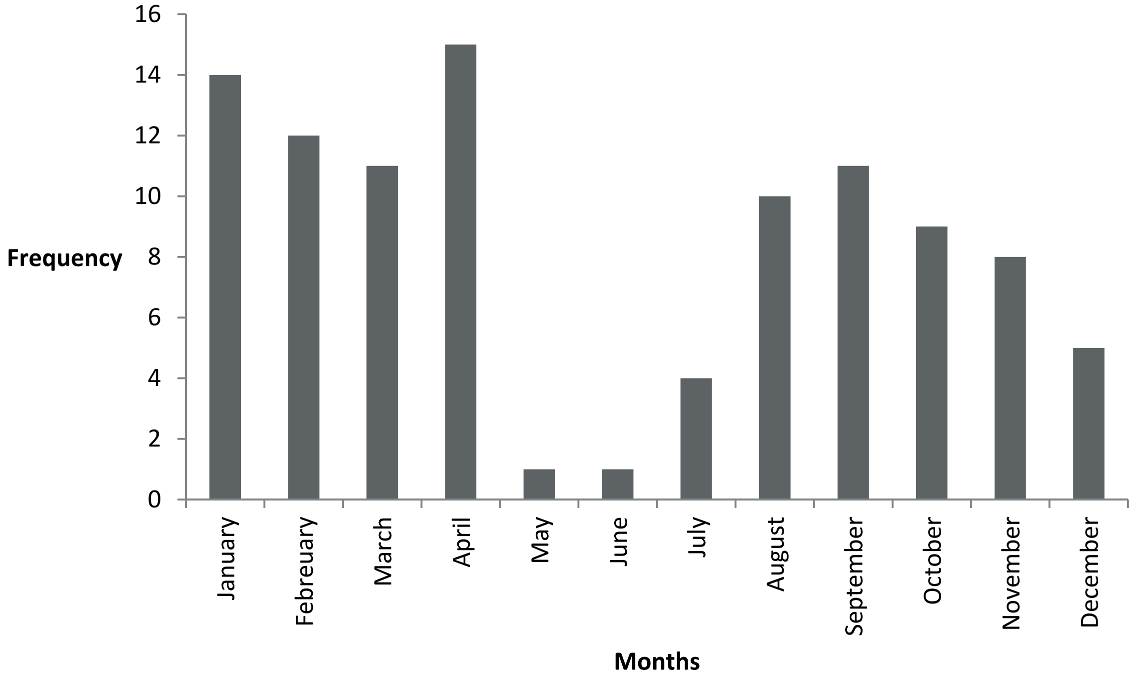

Figure 4. Seasonal variation of HABs in Omani waters.

The appearance of *N. scintillans* was noted in plankton samples collected within the waters of Muscat from 1st February till the end of March 1988 (Thangaraja, 1990). At that time red tide of this species was recorded along the coast of the Oman Sea from Khasab to Sur. *N. scintillans* produced many patches of orange red coloration in the waters from Al-Bustan to Qurum on 1st, 8th, and 10th February with a peak on the 19th March, 1988. This species formed red tide blooms almost every year in the Oman Sea between January and May since 1988 (Thangaraja, 1990). The bloom intensity of *N. scintillans* is increasing year by year. In 1999 a new strain of this species formed green tide in the eastern coasts in the Oman Sea (MSFC, 1976-2010).

Phytoplankton blooms were also observed three times between February 1988 and April 1989 along the coast of Muscat (Latitude 23º37'N; Longitude 58º36'E) (Thangaraja *et al.,*1990). Blooms occurring from 5th to 20th of September 1988 (with a peak on the 14th) caused discoloration of waters from Seeb to Qurum, and mass mortality of marine organisms happened in a 30 km coastal stretch. The dinoflagellates identified were *Ceratium fusus*, *C. macroceros*, *C. furca, Prorocentrum micans, Pyrophacus horologicum* and *Protoperidinium* species. However, excepting *C. fusus*, the other dinoflagellates were few in number. Large blooms of these organisms caused first discoloration of the water and then mass mortality of marine life. Low oxygen levels were recorded (2.64 ml/l and 1.87 ml/l) at water depths of 2-3 meters and 8-10 meters respectively, on 14th September 1988 at Al-Ghubrah coast. Seawater temperature was 27.5°C, salinity 35.9% and pH 8.31-9.0 (Thangaraja, 1990). Although, *Ceratium* spp. are not toxic, they are known to cause deterioration of the water quality (Onoue, 1990).

N. scintillans blooms repeatedly appeared in the Muscat coasts in the plankton samples from 25th February to 5th April 1989. Dense patches of discoloration were noticed about 5 km off shore on 5th April during the regular plankton survey. On 11th April the bloom developed denser than that of the previous year, the intensity of red tide started declining on 12th April. Between 11th and 13th April, eight species of dead fish were found at Al-Bustan coast during this bloom. This was a significant record of fish kills by *N. scintillans* bloom (Thangaraja, 1990). Previous data suggest that in Oman no red tide was noticed in the summer season but these events are common in winter months including January and February (Fig. 4).

It was observed that *N. scintillans* bloom affected marine ecosystems in two different ways; first depletion of oxygen and then bacterial infection. According to Thangaraja (1990), in the first incident of fish kill during February to March 1988 both above-mentioned effects were recognized, but in 1989 only the depletion of oxygen was observed. The dead fish collected during 1989 bloom showed no morphological abnormalities of gills or gill clogging. The guts were in advanced stages of putrefaction and therefore their contents were not examined. Thousands of the pelagic fish, *Atherinomorus lacunosus* were killed with "fin and tail rot" disease caused by bacterial infection following the *Noctiluca* bloom

(Thangaraja, 1990). There are several examples which show that either acute/chronic exposure to microalgal toxins or harmful mechanisms associated with HABs was sufficient to increase the susceptibility of aquatic organisms to disease. During 1989-1990, a *N. scintillans* bloom in the Pie Hai Sea (Northern China Sea) resulted in losses of about $100 millions in shrimp *Penaeusorientalis* mariculture. Poor water quality caused an increase in the susceptibility of prawns to parasitic infections, which led to disease mortalities and additional losses valued at $I million (Chen and Gu, 1993).

Most of the HABs-related fish mortality events in Oman have been attributed to *Noctiluca* blooms (Table 2). Accumulated ammonia is produced after death, and dissolution of *Noctiluca* cells caused fish mortalities (Schaumann, *et al*., 1988, Okaichi and Nishio, 1976, Suvapepun, 1989). When the bloom of *Noctiluca* at maximum cell densities of $5.3x10^6m^3$ occurred accompanied with a mass mortality of demersal fish and benthic organisms along the east coast of Jakarta Bay of Indonesia in July 1986, ammonia, nitrogen and phosphate levels in the seawater just after the mortality were significantly increased (Adnan, 1989). In some cases, such conditions may not result in mortality but in avoidance by fish, leading to localized reductions in fisheries. *Noctiluca* can also create a large quantity of mucus, which mechanically damages fish gills or interferes with fish respiration (Subramanian, 1985). Thus large blooms of heterotrophic *Noctiluca* can consume significant amounts of oxygen and after their subsequent decay bacterial production can result in severe oxygen depletion. Therefore, although not considered toxic, large *Noctiluca* blooms can significantly contribute to deterioration of water quality, accompanied with depleted dissolved oxygen (Elbrachter and Qi, 1998; Subramanian, 1985; Suvapepun, 1989; Ho and Hodgkiss,1992).

Another major incident of phytoplankton blooms was reported in Oman along Seeb Al-Hail shores approximately 10 km from Muscat during the second week of August 2000. In the last week of August 2000, another incident of fish kill was reported in Barka, some 80 km from Muscat. It was the consequence of a series of local upwelling of oxygen poor waters with DO levels measuring less than 1-2ppm (Mathews *et al.,* 2001). Analysis of water samples taken from the area revealed that large centric diatoms of the genus *Coscinodiscus* were responsible for the bloom (Claereboudt *et al.,* 2001). However, this genus is known not to contain toxic species for the moment. Non-toxic *Coscinodiscus* caused depletion of oxygen in already oxygen poor waters (Claereboudt *et al.,* 2001). DO concentrations were found to be 2.6 mg/l at 5 m depth and 0.40 mg/l at 10 m depth (Thangaraja *et al.*, 2000). Analyses of nutrients off coastal waters along Dhofar coasts showed that the waters had become eutrophic with nutrient levels in excess of 20μM nitrate–nitrogen and 2 μM phosphate-phosphorous found between July and mid October 2000 (Savidge *et al.,* 1990). High levels of nutrients and low temperature (<20°C) accounted for dense blooms of phytoplankton (maximum>20μg chlorophyll a l^{-1}) and the annual development of dense beds of macroalgae along the Arabian Sea coasts (Savidge *et al.,* 1990). As Malcolm *et al.* (1999) also suggested that during the monsoon season, upwelling is the major influence on the nutrient supply in the surface waters of the Arabian Sea off the coast of Oman, high nutrient such as levels of NO_3 (= 18 μmol l^{-1}) and PO_4 (1.48 μmoll^{-1}) in the close inshore coastal zone and also higher concentrations (NO_3=12.5 μmoll^{-1}; PO_4= 1.2 μmoll^{-1}) at the region of offshore upwelling off the shelf during September/October 1994.

Toxic Algal Blooms in Oman and Their Impact

The abnormal production of phytoplankton (diatoms, dinoflagellates and blue green algae) such as *Trichodesmium* sp., *Dinophysis* spp., *Gonyaulax* spp., and *Ceratium*s pp. led to discolouration of water and caused either environmental impacts or mass mortality of marine organisms in Omani waters in 2000 (Thangaraja *et al.,* 2000). A total 109 fish species were recorded as causative organisms for massive fish kills. These species consists of the coral reef associated fish species (59%), demersal fish species inhabiting shallow coastal waters (28%), and pelagic species (13%) (Claereboudt *et al.,* 2001).

The upwelling of nutrients in SW monsoon triggered blooms in March-April and November-December 2001. As a result of these HABs, widespread fish and green turtle (*Cheloniamydas*) mortalities appeared in the Southern region of Oman. About 284 tons of fish during March and April and 40 tons of fish along with 250 turtles, some dolphins and birds were killed during November and December, 2001 (MAF and MRMEWR, 2002). The taxonomic composition of the bloom showed that the bloom was dominated by diatom *Nitzschia pungens* Grunow ex Cleve*(=Pseudo-nitzschia pungens* (Grunow ex Cleve) Hasle), *N.* cf. *subcurvata* Hasle *(Pseudo-nitzschiasubcurvata* (Hasle) Fryxell*)*, *Rhizosolenia alata* Brightwell (=*Proboscia alata* (Brightwell) Suderstom, *Thalassiosira* spp., and *Cyclotella*spp. (Stirn *et al.,* 1993). The secondary succession phase appeared to be dominated by dinoflagellate such as *Pyrocystis* sp., and potentially toxic dinoflagellates *Gymnodium splendens* Lebour*(=Akasahio sanguinea* (Hirasaka) G. Hansen et Moestrup*)* and *Prorocentrum minimum* (Pavillard) (Garrison *et al.,* 1998). An unarmored ichtyo-toxic dinoflagellates *Karenia selliformis* Haywood, Steidinger et MacKenzie originally described from New Zealand in 2004 first occurred in water samples collected from the north and south of Khaluf in concentrations of 2,492,000 cells/liter [Drs. J. Landberg, K. Steidinger and A. Haywood at the Florida Marine Research Institute, St. Petersburg, Florida, U.S.A. (preliminary unpublished report, 2005)]. *K. selliformis* is phylogenetically related to *K. mikimotoi* (Miyake and Kominami) G. Hansen et Moestrup and *K. brevis (*Davis) G. Hansen et Moestrup (Haywood *et al.,* 2004). Other species such as *K. mikimotoi* and *Karenia* *digitata* Yang, Takayama, occurring in Hong Kong during March and April 1998 killed fish worth US $40,000,000 (Lu and Hodgkiss, 2004). Although *Karenia* spp. including *K. mikimotoi* has reportedly caused mass fish mortality in Kuwait Bay (Heil *et al.,* 2001; Gilbert *et al.,* 2002), it is not unknown in the Arabian Sea. The toxins produced and released by these microorganisms might be responsible for the mortality of green turtles, dolphins and birds in Oman (Jupp, 2001).

Moreover, a new species of planktonic dinoflagellate, *Prorocentrum arabianum* was recorded during this incident in 2001 and was added to the list of hazardous species, because *P. arabianum* was capable of producing a cytotoxic as well as an ichthyotoxic compound (Morton *et al.,* 2002).

After the major fish and marine organism mortality event in 2001, nine other red tide incidents were recorded in 2002 and six incidents were recorded in 2003. *N. scintillans* was identified as red tide causative species in all cases except for one. *K. mikimotoi* was found in the plankton samples from bloom in March 2003. However, none of these blooms caused any damage to fisheries or other marine organisms (unpublished data, Ministry of Agriculture and Fisheries). In 2004, five algal blooms were recorded and *N. scintillans* was probably responsible for all blooms. Fish mortality was observed in three of these incidents occurring in January, April and September 2004 (unpublished report of Ministry of Agriculture and Fisheries Wealth).

Recently, at the end of October 2005, extensive blooms occurred in the east of Masirah Island accompanied with massive fish mortality. This HABs event lasted for eight days accompanied by a red-orange discolouration of the water. Hydrographical surveys using satellite images revealed low temperatures due to upwelling of waters with oxygen deficient. Plankton analysis revealed *N. scintillans*, *Prorocentrum micans* and toxic blooms of cyanobacteria *Trichodesmium erythraeum (Ehrenberg)* (Al Busaidi *et al.,* 2008). More recently, in August 2006, massive fish kills occurred in Muscat. Depletion of oxygen was suspected to be the reason of the demersal fish kill. Also, in September 2006, a massive fish kill occurred in Sohar. The levels of oxygen were within the normal range. No harmful species were reported, but the water temperature was lower than the usual condition (Ministry of Agriculture and Fisheries, 2006). No fish kill were recorded in 2007. However, extremely large fish kills were recorded in 2008-2009 caused by blooms of *Cochlodinium polykrikoides*. The blooms were started in the Oman Sea in September 2008 in Musandam and Al Batinah Coasts and ended in April 2009 in the Arabian Sea and the Oman Sea. More than 200 tons of fish and shellfish were killed. During these blooms, seventy tons of Goldlined seabream were killed at an aquaculture farm in Quraiat, Muscat. The levels of oxygen were very low (less than 1mg/l) during *Cochlodinium* blooms. As well as the low oxygen levels during *Cochlodinium* blooms, damage to fish gills were also recorded (Richlen *et al.,* 2010; Matsouka*et al.,* unpublished; Al Gheilani *et al.,* unpublished).

These HABs events occur on a regular basis in Oman and require a long-term solution.

Conclusion

A programme for the establishment of a HABs monitoring system was launched in the Sultanate of Oman in 1978. The system deals with monitoring of environmental conditions, including studies on red tides, and collection of data on the taxonomy of marine biota, hydrology and water quality. Meteorological and oceanographic data including current, temperature, oxygen, algae and nutrients are obtained on a regular basis from different sites and positions along the coastal waters of Oman. However, the quality of technology for detecting, modeling and predicting harmful algal blooms needs improvement. Modeling of bloom-forming mechanisms of various causative organisms are tried in order to create a prediction system. Unfortunately, this has not been very effective mostly because of incomplete data acquisition and accumulation. Water quality data collection and reporting are not consistent among different agencies, reducing the effectiveness of the data for modeling of bloom-forming mechanisms. Spatial and temporal monitoring of harmful algal blooms continue in Oman and research is being conducted that will assist in management of the blooms. Scientists and managers are making efforts to create less cumbersome, cheaper, faster and automated detection techniques, which would greatly benefit them in responding to these events more efficiently and effectively. However, vigorous efforts need to be devoted to the elucidation of the biology and ecology of red tide organisms and their blooming mechanisms, modeling and mitigation methods in the Sultanate. Since Oman has a large mariculture operation, future research efforts need to be focused on the influence of mariculture activity in triggering HAB occurrences in coastal areas to help retain a healthy marine ecosystem along the coast of Oman. Hence, there is also an urgent need for bloom mitigation strategies in aquaculture areas in the Sultanate.

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