Microalgal Blooms in the Coastal Waters of New South Wales, Australia

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We investigated the frequency and causative taxa of observed microalgal blooms in New South Wales (NSW) coastal waters from 2000 to 2009 and compared these to an earlier bloom inventory from 1990 to 1999. The majority of recurrent blooms are harmless water discolourations caused by *Noctiluca scintillans* and *Trichodesmium erythraeum*. The recent reporting period witnessed the first blooms of *Astrionellopsis glacialis*, *Guinardia* sp., *Skeletonema* sp., cf. *Heterocapsa* sp., *Dinophysis caudata*, *Prorocentrum dentatum*, *Prorocentrum rhathymum*, *Fibrocapsa japonica*, *Gymnodinium catenatum*, *Oscillaroria* sp., and *Anabaena circinalis*.

The frequency of blooms appears to have increased over time with a shift in maximum bloom activity from January (1990 to 1999) to October (2000 to 2009). Peak bloom years correspond with El Niño episodes, the most significant being 1997 to 1998 and 2002 to 2003. No significant difference was found between the causative species or spatial distribution of dominant taxa over two decades. Differences were observed in bloom type in estuaries with more 'potentially harmful to marine organisms' blooms during 1990 to 1999 and more 'harmless' blooms during 2000 to 2009. More 'unidentified' blooms were reported during 2000 to 2009 compared to 1990 to 1999, for both marine and estuarine waters. We emphasize that although algal bloom reports are ad hoc in their nature, they can contribute valuable baseline information, which may suggest causative relationships for evaluating trends in phytoplankton ecology.

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KEYWORDS: biotoxins, harmful algal blooms, human health, microalgal blooms, phytoplankton.

INTRODUCTION

When microalgae (phytoplankton) significantly increase in number, deviating from their species–specific cycle of biomass, they are said to "bloom" (Smayda 1997). Three major types of algal blooms have been distinguished – those that are harmless water discolorations, those that are harmful to marine organisms (e.g. fish kills due to clogging of gills and/or anoxic conditions) and those that produce toxins that bioaccumulate in seafood products (Hallegraeff et al. 2003). The most important public health problems caused by algal toxins are Amnesic Shellfish Poisoning (ASP), Ciguatera Fish Poisoning (CFP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP) and Paralytic Shellfish Poisoning (PSP).

Algal blooms are driven by a combination of hydroclimatic conditions, nutrient influx and/or species specific triggers (e.g. micronutrient availability) and while the rapid growth of microalgae can be a natural phenomenon, it is considered that the prevalence of algal blooms worldwide is increasing (Hallegraeff 2010). Progressive oceanic warming is projected to further alter the biogeography, composition, phenology and physiology of microalgae, and will occur on timescales of decades to centuries (IPCC 2007). Rising sea-surface temperatures (SSTs) may decrease or increase microalgal abundance depending on global location. Tropical and midlatitude nutrient-limited environments are predicted to experience a reduction in microalgal abundance, while higher latitude environments (light-limited) are expected to experience the inverse (e.g. Reid et al. 1998, Edwards et al. 2006, Doney 2006, Moore et al. 2008, Hallegraeff 2010, Gladan et al. 2010). Changing water chemistry, as exemplified by an increase in dissolved CO_2 and a concomitant decrease in pH i.e. "Ocean Acidification" (Cubillos et al. 2007, Hare et al. 2007, Rost et al. 2008), and the supplementation of micronutrients via precipitation and dust deposition (Shaw et al. 2008, Hallegraeff 2010), are also predicted to alter phytoplankton abundance and composition, favouring some taxa over others. Geographical range extensions in microalgae are already being documented, with some species increasing their habitat range from tropical and temperate waters to colder environments, while certain coldwater assemblages are retracting (reviewed in Hallegraeff 2010). An earlier onset of the spring productivity period has already been observed in terrestrial environments (Inouye et al. 2000), but is now being reported for phytoplankton in the marine environment (Kahru et al. 2011). This shift, however, may not always be clear in the aquatic environment, with variations among trophic units, functional groups, phytoplankton physiology, cell size and elementary stoichiometry all expected to alter with progressive warming (Peperzak 2003, Edwards and Richardson 2004, Hays et al. 2005, Ducklow et al. 2008, Wasmund 2008, Finkel et al. 2010).

Microalgal blooms in Australia have been predominantly a freshwater problem to date. In 1991, 1000 km of New South Wales (NSW) Barwon-Darling River experienced the world's largest cyanobacterial (blue green algal) bloom. Warm temperatures and an influx of sulphate-rich saline groundwater were implicated as the bloom drivers for this massive toxic event (Donnelly et al. 1997). Algal blooms in NSW coastal marine waters, on the other hand, have been significantly smaller in scale and generally non-toxic. In 1993, however, Hallegraeff suggested that there had been an apparent increase in the frequency, strength and extent of visible algal blooms between the years 1984 and 1993 with few bloom reports prior to 1984. Further investigation demonstrated that for the period up until 1999, blooms in NSW coastal waters were indeed becoming more frequent and occurring most commonly during the late summer, early autumn period, when cold, nutrient-rich water was transported (upwelled) into the warm surface layers (Ajani et al. 2001a, 2001b). Microalgal blooms during this time were dominated by the harmless dinoflagellate, *Noctiluca scintillans* and the filamentous cyanobacterium *Trichodesmium erythraeum*.

With over half a century of physical and chemical data from NSW coastal waters now under review, trends in water chemistry (declining silicate, increasing salinity and nitrate), temperature (increasing) and physical circulation (stronger flowing East Australian Current, EAC) are emerging, with consequences predicted for phytoplankton in south-eastern Australian waters – increasing biomass in autumn and early winter coupled with an increasing component of flagellates in the autumn bloom period (Thompson et al. 2009). In the absence of any continuous phytoplankton composition data from these waters, our study investigates the frequency and causative taxa of observed algal blooms from 2000 to 2009 and, in combination with previous bloom reports (1990 to 1999), we explore changes in seasonal and annual occurrence of blooms, causative taxa, bloom types and the spatial occurrence of two dominant species over the past two decades. Whilst it is recognised that blooms are spatially patchy, and reporting is intrinsically subjective (often lacking details such as bloom magnitude and duration), the collation of this historical information provides valuable baseline data, which may suggest causative relationships for future hypothesis testing. The case for more systematic reporting and unambiguous identification of algal blooms in Australian coastal waters to further strengthen this valuable, long-term dataset is discussed.

MATERIALS AND METHODS

Algal blooms collated for this study were those which occurred in the marine and estuarine coastal waters of New South Wales, Australia (28°S to 37°S) from the period 2000 to 2009 (Fig. 1). The majority of blooms were visual water discolorations reported to government agencies, local councils, water authorities and universities from members of the public, local council officers or beach life guards. Other potentially harmful bloom reports, not evident as visible water discolorations, were captured as a result of limited phytoplankton monitoring programs carried out by local councils, NSW Industry and Investment (NSW Food Authority) and the NSW shellfish industry. The NSW Office of Water also provided bloom reports from Regional Algal Coordinating Committees (RACCs) which manage the response to algal bloom events in NSW. Where possible, algal bloom 'observers' were asked to complete an Algal Bloom Data Sheet (Office of Environment and Heritage, OEH) that included: date and time of bloom; location, extent and duration of bloom; colour/appearance/odour of bloom, weather conditions and sample details. If a

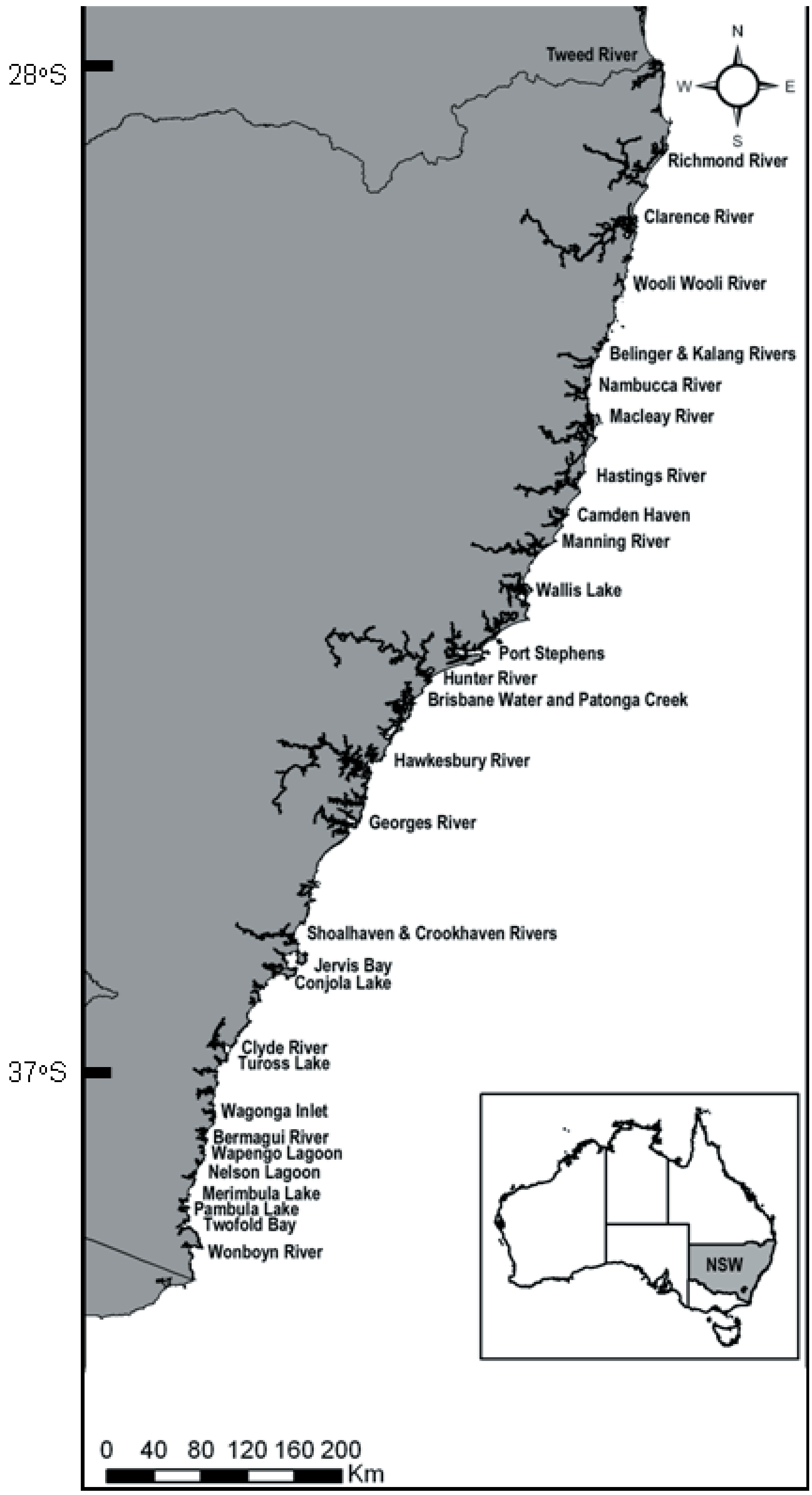

Fig. 1. Map of New South Wales, Australia, showing major rivers and estuaries.

water sample was collected, it was submitted to an appropriate laboratory (as advised by the RACCs or OEH), and the causative organism(s) identified by suitably qualified microalgal taxonomists.

For the purposes of data assessment, blooms were collated by date, location and causative taxa (these were the only data variables common to all reports across the sampling period) and classified into three recognised bloom types–'harmless', 'potentially harmful to marine organisms' and 'potentially harmful to humans' (Hallegraeff et al. 2003). Where a causative organism belonged to a genus that contained both toxic and non-toxic species e.g. *Pseudo-nitzschia*, and it was not possible to identify down to the species level, the bloom was classified conservatively into 'potentially harmful to humans'. Blooms that were not microscopically examined, that is, no sample was taken from the bloom or the sample deteriorated prior to examination, were classified as 'unidentified'. We included these 'unidentified' bloom reports in the final dataset for two reasons – to provide a more accurate measure of bloom frequency and to provide a historical record of bloom occurrences and their locations in NSW coastal waters.

In order to gain a longer-term perspective of reported bloom occurrences, algal blooms for the 2000 to 2009 reporting period were then pooled with bloom data from the period 1990 to 1999, as documented in the antecedent summary by Ajani et al. (2001a). To explore any potential relationship between the frequency of bloom events and regional oceanographic variability, the number of reported blooms was compared to a six-month running average of the Southern Oscillation Index (SOI). SOI values were obtained from the Australian Governments' Bureau of Meteorology website at http://www.bom.gov.au/climate/current/soi2.shtml. Decadal differences were examined for annual and seasonal bloom frequency, causative taxa, bloom type and any potential latitudinal trend in the major taxa (arbitrarily partitioned as being north or south of Sydney). A paired t-test was applied for causative taxa comparisons and Pearson's Chi-square tests for all other comparisons.

RESULTS

Current Reporting Period: 2000 to 2009

A total of 157 algal blooms were recorded for the 2000 to 2009 reporting period (Tables 1-4). Reported blooms ranged from four in 2007 to 34 in 2003 (Fig. 2). Blooms were most frequent in October and least frequent in July (Fig. 3). The majority of blooms were 'harmless' water discolorations (n=85), followed by those that were 'unidentified' (n=49), those 'potentially harmful to humans' (n=19) and those 'potentially harmful to marine organisms' (n=4).

Noctiluca scintillans and *Trichodesmium erythraeum* were the two most commonly occurring bloom species during this reporting period. In addition to these taxa, novel blooms of the following taxa were identified: the 'harmless' *Asterionellopsis glacialis* (marine), cf. *Heterocapsa* sp. (estuarine), *Guinardia* sp. (marine), *Skeletonema* sp. (estuarine) and *Prorocentrum dentatum* (estuarine); the 'potentially harmful to marine organisms' taxa *Dinophysis caudata* and *Fibrocapsa japonica*; and those that are 'potentially harmful to humans' being *Oscillaroria* sp. *Anabaena circinalis, Prorocentrum rhathymum* and *Gymnodinium catenatum* (Table 5).

Decadal comparison: 1990-1999 to 2000-2009

To examine longer-term trends in bloom frequency and causative taxa, we pooled data from the current reporting period with data from the previous decade. Over the twenty year reporting period a total of 280 blooms (n=123, 1990 to 1999; n=157, 2000 to 2009) were reported. The frequency of blooms ranged from zero in 1990 to 34 in 2003 with peak bloom years occurring between 1997 to 1998 and 2002 to 2003 (Fig. 2). These peak bloom events corresponded to years of sustained negative SOI values (Fig. 4).

Blooms occurred most frequently from January to March during 1990 to 1999, and from October to November during 2000 to 2009 (Fig. 3). A Pearson's Chi-square test was conducted to investigate this shift in maximum bloom occurrence, revealing a significant difference between the two decades ($X^2 = 99.3$, $p < 0.05$).

Dominant bloom-forming taxa over the twenty year period were *Noctiluca scintillans*, *Trichodesmium erythraeum* and those belonging to the 'unidentified' group. Five other recurrent taxa were noteworthy - *Mesodinium rubrum*, *Gymnodinium* spp., *Heterosigma akashiwo*, *Alexandrium* spp., *Pseudo-nitzschia* spp. and *Gonyaulax polygramma* (Fig. 5). 'Other' blooms were those that only occurred once across the sampling period. To examine if there had been any significant change in the dominant bloom-forming taxa overtime, a paired t-test was conducted and found to be not significant ($t = 0.49$, $p>0.05$).

When blooms were examined by type, both marine and estuarine waters were dominated by 'harmless' blooms (Fig. 6a). To examine if bloom type had changed between the two sampling periods, a Pearson's Chi-square test was performed on pooled marine and estuarine data, revealing a significant

Table 1. 'Harmless' algal blooms reported from New South Wales marine (M) and estuarine (E) waters 2000-2009*

Date	*Location*	*Bloom Taxa*
29-Feb-2000	Bondi Beach to Clovelly Beach (Sydney) (M)	*Noctiluca scintillans*
14-Mar-2000	Sailors Bay, Long Bay, Willoughby Bay (Sydney Harbour) (E)	*Skeletonema* sp.
12-Apr-2000	Lake Macquarie (E)	*Noctiluca scintillans*
03-May-2000	Evans Head (M)	*Trichodesmium erythraeum*
26-Sep-2000	Ballina Beach to Coffs Harbour (M)	*Asterionellopsis glacialis*
3-Oct-2000	Shelley Beach, Ballina (M)	Mixed diatoms
29-Oct-2000	Lake Illawarra (E)	*Noctiluca scintillans*
01-Nov-2000	Port Hacking River (Sydney) (E)	*Noctiluca scintillans*
20-Nov-2000	Tweed Coast (M)	*Trichodesmium erythraeum*
23-Nov-2000	Brunswick River to Richmond River (M)	*Trichodesmium erythraeum*
28-Nov-2000	Boambee Beach Coffs Harbour (M)	*Trichodesmium erythraeum*
10-Dec-2000	Hastings River, Port Macquarie (E)	*Trichodesmium erythraeum*
15-Dec-2000	Lake Illawarra (E)	*Noctiluca scintillans*
17-Dec-2000	Shelley Beach, Manly (M)	*Noctiluca scintillans*
02-Jan-2001	Cudgen Creek, Kingscliff (M)	*Trichodesmium erythraeum*
14-Jan-2001	Coogee (Sydney) (M)	*Noctiluca scintillans*
27-Feb-2001	Byron Bay (M)	*Trichodesmium erythraeum*
29-Aug-2001	Georges River (Sydney) (E)	*Heterocapsa* sp.
21-Sep-2001	North Head, Sydney Harbour (M)	*Mesodinium rubrum*[#]
29-Sep-2001	Richmond River, Ballina (E)	*Trichodesmium erythraeum*
15-Oct-2001	Byron Bay (M)	*Trichodesmium erythraeum*
26-Oct-2001	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
22-Jan-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
09-Aug-2002	Colloroy Beach (M)	*Noctiluca scintillans*
30-Aug-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
02-Sep-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
09-Sep-2002	Farm Cove, Sydney Harbour (E)	*Noctiluca scintillans*
12-Sep-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
07-Oct-2002	Blacksmiths Beach (near Lake Macquarie) (M)	*Guinardia* sp.
12-Oct-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
14-Oct-2002	Middle Harbour, Sydney (E)	*Noctiluca scintillans*
30-Oct-2002	Byron Bay (M)	*Trichodesmium erythraeum*
01-Nov-2002	Ballina (M)	*Trichodesmium erythraeum*
01-Nov-2002	Whale Beach to Kiama (M), Sydney Harbour (E)	*Mesodinium rubrum*[#]
07-Nov-2002	Richmond River, Ballina (E)	*Trichodesmium erythraeum*
12-Feb-2003	Austinmer Beach (M)	*Noctiluca scintillans*
18-Feb-2003	Merimbula Lake (E)	*Noctiluca scintillans*
20-Feb-2003	Northern Beaches to Botany Bay (M)	*Noctiluca scintillans*
12-Mar-2003	North Harbour (Sydney Harbour) (E)	*Noctiluca scintillans*
14-Mar-2003	Kurnell (M)	*Noctiluca scintillans*
26-Mar-2003	Mereweather Beach (Newcastle) (M)	*Noctiluca scintillans*

Table 1 continued

27-Mar-2003	Kurnell (M)	*Noctiluca scintillans*
07-Apr-2003	Bermagui Harbour (E)	*Noctiluca scintillans*
08-Apr-2003	Shelley Beach, Manly (M)	*Noctiluca scintillans*
23-Apr-2003	Port Hacking (M)	*Trichodesmium erythraeum*
24-Apr-2003	Port Hacking (M)	*Trichodesmium erythraeum*
07-May-2003	Berowra Creek (E)	*Prorocentrum dentatum*
23-Jul-2003	Parsley Bay (Sydney Harbour) (E)	*Mesodinium rubrum*
21-Oct-2003	Rose Bay (Sydney Harbour) (E)	*Noctiluca scintillans*
18-Nov-2003	Lake Illawarra (E)	*Noctiluca scintillans*
28-Nov-2003	Botany Bay (M)	*Noctiluca scintillans*
4-Dec-2003	Middle Harbour (E) and Manly (M)	*Noctiluca scintillans*
29-Dec-2003	Belmore Basin (E)	*Noctiluca scintillans*
2-Jan-2004	Manly Cove (M)	Mixed diatoms
2-Feb-2004	North Head, Sydney Harbour (M)	*Noctiluca scintillans*
5-Feb-2004	Bundeena (M)	*Noctiluca scintillans*
4-Mar-2004	Cabbage Tree Bay (M)	*Noctiluca scintillans*
12-Aug-2004	Castlecrag, North Sydney and Cockle Bay, Syd Harbour (E)	*Noctiluca scintillans*
25-Aug-2004	Clontarf Beach (Sydney Harbour) (E)	*Noctiluca scintillans*
04-Feb-2005	La Perouse (M)	*Trichodesmium erythraeum*
22-Apr-2005	Como/Oately, Port Hacking (E)	*Noctiluca scintillans*
29-Apr-2005	Wyong (E)	*Noctiluca scintillans*
18-Aug-2005	Newcastle Beaches (M)	*Noctiluca scintillans*
18-Aug-2005	Plantation Point, Jervis Bay (M)	*Noctiluca scintillans*
9-Sep-2005	Rose Bay, Balmoral Beach (M)	*Noctiluca scintillans*
22-Nov-2005	Bate Bay (M)	*Noctiluca scintillans*
23-Nov-2005	Sydney Northern Beaches and Newcastle (M)	*Noctiluca scintillans*
24-Oct-2006	Commonwealth Reserve, Solitary Islands (M)	*Trichodesmium erythraeum*
11-Nov-2006	Fairy Bower, Manly (M)	*Noctiluca scintillans*
20-Nov-2006	Solitary Islands (M)	*Trichodesmium erythraeum*
1-Dec-2006	Sydney South Coast Beaches (M)	*Noctiluca scintillans*
6-Dec-2006	Solitary Islands (M)	*Trichodesmium erythraeum*
12-Nov-2007	Mermaid Reef, Diamond Head (M)	*Trichodesmium erythraeum*
24-Dec-2007	Richmond River (E)	*Trichodesmium erythraeum*
6-Mar-2008	Lake Illawarra (E)	*Noctiluca scintillans*
24-Sep-2008	Paramatta River, Birkenhead Point (Sydney Harbour) (E)	*Noctiluca scintillans*
1-Oct-2008	Iron Cove, Clontarf Beach (Syd Harbour) (E)	*Noctiluca scintillans*
2-Oct-2008	Manly (M)	*Noctiluca scintillans*
3-Oct-2008	Woolloomooloo Bay (E), Seaforth (M)	*Noctiluca scintillans*
1-Jan-2009	Lake Macquarie (E)	*Noctiluca scintillans*
20-Feb-2009	Shelley Beach; Toowoon to Bateau Bay (M)	*Noctiluca scintillans*
25-Apr-2009	Solitary Islands (M)	*Anaulus australis*
21-May-2009	Stockton Beach, Newcastle (M)	*Anaulus australis*
21-Aug-2009	Manly Cove (M)	*Noctiluca scintillans*
20-Oct-2009	Park Beach, Coffs Harbour (M)	*Trichodesmium erythraeum*

#*Mesodinium rubrum* = ciliate with microalgal symbionts
***Office of Environment and Heritage unpublished data.**

Table 2. 'Potentially harmful to marine organisms' algal blooms reported from New South Wales marine (M) and estuarine (E) waters 2000-2009*

Date	*Location*	*Bloom Taxa*
24-Nov-2000	Port Hacking (M)	*Scrippsiella* sp.
21-Oct-2002	Redhead Beach, Newcastle (M)	*Thalassiosira* spp.
29-Oct-2003	Sydney Harbour (E)	*Dictyocha octonaria*
18-Jan-2006	Calabash Bay, Hawkesbury River (E)	*Dinophysis caudata*

***Office of Environment and Heritage unpublished data.**

Table 3. 'Potentially harmful to humans' algal blooms reported in New South Wales marine (M) and estuarine (E) waters 2000-2009*

Date	*Location*	*Bloom Taxa*
Dec -Mar 2001	Bombah Broadwater, Myall Lakes (E)	*Microcystis aeruginosa/Anabaena circinalis*
16-Mar-2000	Drummoyne, Sydney Harbour (E)	*Prorocentrum cordatum*
22-Dec-2000	Lake Illawarra (E)	*Gymnodinium* sp.
18-Apr-2001	Parramatta River, Sydney Harbour (E)	*Pseudo-nitzschia* sp.
14-May-2001	Balmain & Five Dock, Sydney Harbour (E)	*Heterosigma akashiwo*
27-Sep-2001	Narrabeen Creek (Sydney) (E)	*Oscillatoria* sp.
05-Oct-2001	Calabash Bay (Berowra Creek) (E)	*Heterosigma akashiwo*
05-Apr-2002	Iron Cove, Sydney Harbour (E)	*Karlodinium micrum*
02-Apr-2003	Twofold Bay (M)	*Dinophysis acuminata*
02-Apr-2003	Wopengo Lake (E)	*Dinophysis acuminata*
09-May-2003	Wallaga Lake (E)	*Fibrocapsa japonica*
22-Oct-2003	Rose Bay, Sydney Harbour (E)	*Alexandrium catenella*
18-Nov-2004	Botany Bay (M)	*Alexandrium* sp.
26-Nov-2005	Botany Bay (M)	*Alexandrium* sp.
23-Mar-2007	Lake Illawarra (E)	*Prorocentrum rhathymum*
27-Aug-2007	Richmond River (E)	*Anabaena/Anabaenopsis* sp.
18-Jan-2008	Calabash Bay, Hawkesbury (E)	*Pseudo-nitzschia delicatissima* gp*; Dinophysis caudata; Lingulodinium polyedrum*
2-Oct-2009	Central coast beaches (M); entrance to Hawkesbury River; Brisbane Waters; Botany Bay (E)	*Alexandrium catenella*
15-Dec-2009	Berowra Creek (E)	*Gymnodinium catenatum*

***Office of Environment and Heritage unpublished data.**

Table 4. 'Unidentified' algal blooms reported from New South Wales marine (M) and estuarine (E) waters 2000-2009*

Date	*Location*	*Bloom Taxa*
26-Jun-2000	Lake Macquarie (E)	Unidentified species
14-Sep-2000	North Head, Sydney Harbour (M)	Unidentified species
29-Sep-2000	Crescent Head to Port Macquarie (M)	Unidentified species
30-Sep-2000	Tuncurry Beach (M)	Unidentified species
05-Oct-2000	Beach from Nelson lagoon to Wapengo lagoon (M)	Unidentified species
30-Nov-2000	Lake Illawarra (E)	Unidentified species
07-Dec-2000	Maroubra Beach to Coogee Beach (M)	Unidentified species
13-May-2001	Jones Beach, Mollymook (M)	Unidentified species
04-Oct-2001	Lennox Head (M)	Unidentified species
05-Oct-2001	Elizabeth Beach, Pacific Palms (M)	Unidentified species
10-Oct-2001	Port Hacking (M)	Unidentified species
28-Oct-2001	Little Boulder Beach, Ballina (M)	Unidentified species
29-Oct-2001	Quakers Hat Bay, Sydney Harbour (E)	Unidentified species
25-Jan-2002	Tallows Beach, Byron Bay (M)	Unidentified species
02-May-2002	Bennetts Beach, Hawks Nest (M)	Unidentified species
21-Aug-2002	Yamba (M)	Unidentified species
23-Aug-2002	Dee Why (M)	Unidentified species
27-Aug-2002	Newport and Avalon Beaches (M)	Unidentified species
17-Sep-2002	Rushcutters Bay, Sydney Harbour (E)	Unidentified species
25-Sep-2002	Sydney Fish Markets, Sydney Harbour (E)	Unidentified species
11-Oct-2002	Sharpes Beach, Ballina (M)	Unidentified species
30-Oct-2002	One Mile Beach, Forster (M)	Unidentified species
31-Oct-2002	North Harbour, Manly (E)	Unidentified species
17-Nov-2002	Yamba Beach (M)	Unidentified species
19-Nov-2002	Collaroy/Narrabeen (M)	Unidentified species
22-Nov-2002	Drummoyne, Sydney Harbour (E)	Unidentified species
16-Dec-2002	Manly (M)	Unidentified species
01-Jan-2003	Huskisson to Vincentia, Jervis Bay (M)	Unidentified species
02-Jan-2003	North Creek, Ballina (E)	Unidentified species
02-Jan-2003	Light House Beach, Ballina (M)	Unidentified species
17-Mar-2003	East Corrimal Beach (M)	Unidentified species
25-Mar-2003	Little Manly Cove, South Steyne Beach (M)	Unidentified species
27-Mar-2003	Terrigal Haven (M)	Unidentified species
28-Mar-2003	Dover Heights (M)	Unidentified species
01-Apr-2003	Manly Beach, Whale Beach, Bungan Beach (M)	Unidentified species
07-Aug-2003	Watsons Bay (E)	Unidentified species
02-Sep-2003	Shelley Beach, Ballina (M)	Unidentified species
10-Oct-2003	Bronte to Bondi Beaches (M)	Unidentified species
17-Jun-2004	Manly Lagoon (E)	Unidentified species
26-Oct-2004	Seven Mile Beach, Lennox Head (M)	Unidentified species
18-Nov-2004	Silver Beach, Kurnell (M)	Unidentified species
21-Sep-2005	Bungan Beach (M)	Unidentified species
22-Nov-2005	Pittwater (E) and Northern Beaches (M)	Unidentified species
4-Sep-2006	Jervis Bay (M)	Unidentified species
5-Nov-2006	Yamba (M)	Unidentified species
4-Mar-2009	Cabbage Tree Bay, Norah Head (M)	Unidentified species
18-Sep-2009	Frazer Park, Budgewoi (M)	Unidentified species
1-Oct-2009	Bawley Point (M)	Unidentified species
1-Oct-2009	Terrigal, North Avoca (M)	Unidentified species

*Office of Environment and Heritage unpublished data

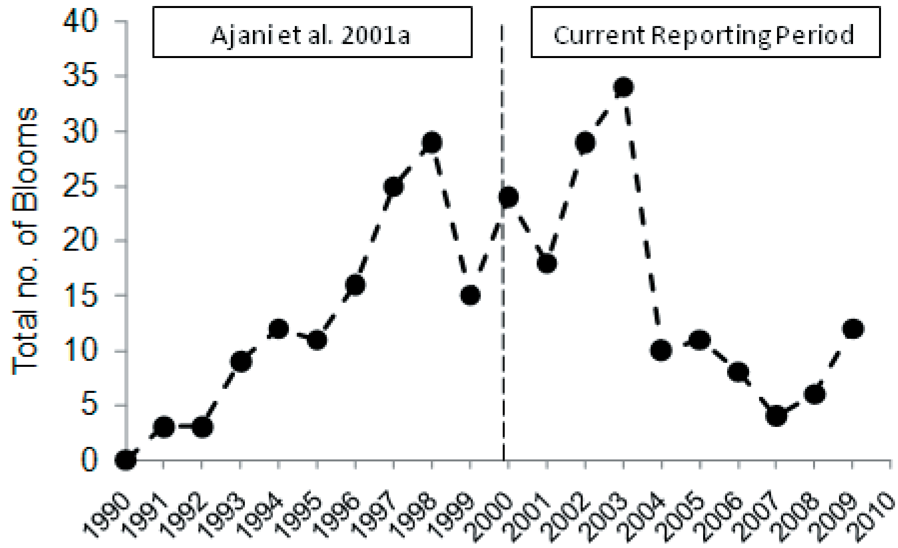

Figure 2. Total number of reported blooms per year for the previous reporting period 1990-1999 (Ajani et al. 2001a) and the current reporting period (2000-2009).

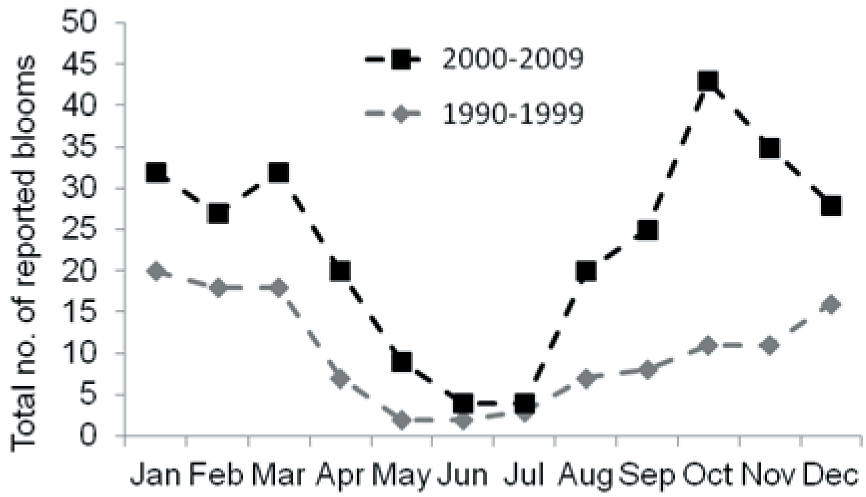

Figure 3. Monthly distribution of total number of reported blooms for the previous reporting period 1990-1999 (grey line) and the current reporting period (2000-2009, black line).

Table 5. Phytoplankton taxa responsible for observed blooms in New South Wales marine and estuarine waters (1990-2009) inclusive of first recorded bloom events for both reporting periods.

Bloom Type	Functional Group	Taxa	Bloom Occurrence in Marine and/ or estuarine waters	First Report during 1990-1999#	First Reportduring 2000-2009
Harmless	Cyanobacteria	*Trichodesmium erythraeum* Ehrenberg	M,E	*	
	Diatoms	*Anaulus australis* Drebes & Schulz	M	*	
		Asterionellopsis glacialis (Castracane) Round	M		*
		Guinardia sp. Peragallo	M		*
		Pseudo-nitzschia cf. *pungens* (Cleve) Hasle	E	*	
		Pseudo-nitzschia cf. *calliantha* Lundholm, Moestrup & Hasle	E	*	
		Skeletonema sp. (Greville) Cleve	E		*
	Dinoflagellates	*Gymnodinium sanguineum* Hirasaka	E	*	
		cf. *Heterocapsa* sp. Stein	E		*
		Noctiluca scintillans (Macartney) Kofoid & Swezy	M,E	*	
		Prorocentrum dentatum Stein	E		*
	Coccolithophorids	*Gephyrocapsa oceanica* Kamptner	M	*	
	Protozoans	*Mesodinium rubrum* Lohmann	M,E	*	
Potentially harmful to marine organisms	Diatoms	*Chaetoceros* sp. Ehrenberg	E	*	
		Thalassiosira spp. Cleve	M,E	*	
		Thalassiosira partheneia Schrader	M	*	
		Thalassiosira weissflogii (Grunow) Fryxell & Hasle	E	*	
	Dinoflagellates	*Dinophysis caudata* Saville-Kent	E		*
		Gonyaulax sp. Diesing	E	*	
		Gonyaulax polygramma Stein	M	*	
		Gymnodinium cf. *mikimotoi* Miyake & Kominami ex Oda	E	*	
		Scrippsiella sp. Balech ex Loeblich III	M,E	*	
	Silicoflagellates	*Dictyocha octonaria* Ehrenberg	M,E	*	
	Raphidophytes	*Fibrocapsa japonica* Toriumi & Takano	E		*
		Heterosigma akashiwo (Hada) Hada ex Hara & Chihara	E	*	

Table 5 continued

Bloom Type	Functional Group	Taxa	Bloom Occurrence in Marine and/ or estuarine waters	First Report during 1990-1999#	First Reportduring 2000-2009
Potentially harmful to humans	Cyanobacteria	*Anabaena circinalis* Rabenhorst ex Bornet & Flahault	E		*
		Microcystis aeruginosa (Kützing) Kützing	E	*	
		Oscillatoria sp. Vaucher ex Gomont	E		*
	Diatoms	*Pseudo-nitzschia* spp. Peragallo	E	*	
		Pseudo-nitzschia delicatissima gp (Cleve) Heiden	E	*	
		Pseudo-nitzschia cf. *multiseries* (Hasle) Hasle	E	*	
	Dinoflagellates	*Alexandrium* sp. Halim	E	*	
		Alexandrium catenella (Whedon & Kofoid) Balech	M	*	
		Dinophysis acuminata Claparède & Lachmann	M,E	*	
		Gymnodinium catenatum Graham	E		*
		Gymnodinium sp. Stein, emend. Hansen & Moestrup	E		*
		Karlodinium micrum[@] (Leadbeater & Dodge) Larsen	E	*	
		*Prorocentrum cordatum** (Ostenfeld) Dodge	E	*	
		Prorocentrum rhathymum Loeblich III, Sherley & Schmidt	E		*
	Raphidophytes	*Chattonella globosa* Hara & Chihara	E	*	
		Haramonas sp. nov. Horiguchi	E	*	

Ajani et al. (2001a)
[@]Previously *Gymnodinium galatheanum* Braarud sensu Kite & Dodge
*Previously *Prorocentrum minimum* (Pavillard) Schiller

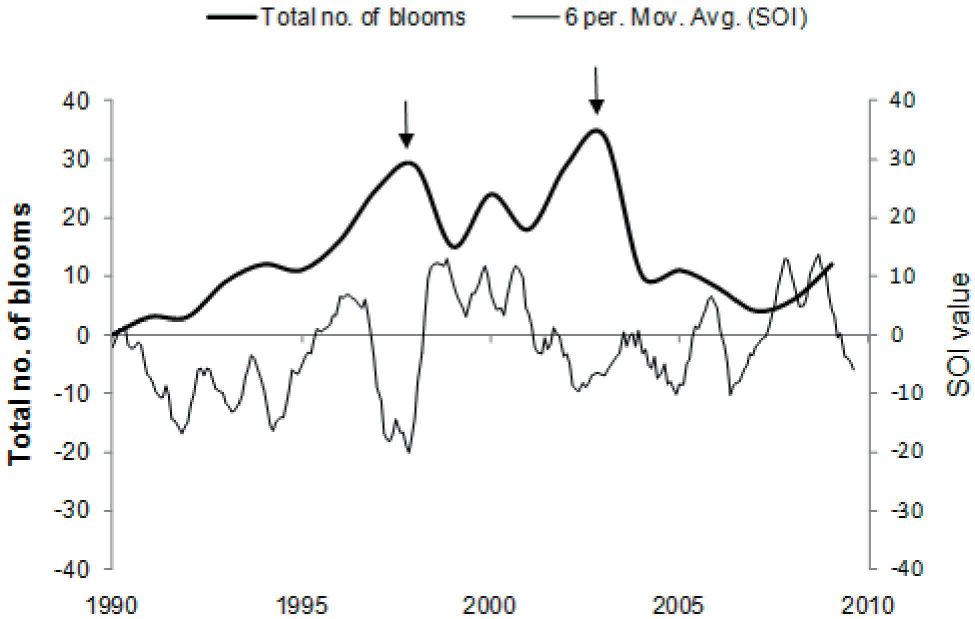

Figure 4. Total number of reported blooms per year (left axis) and six month running average of the Southern Oscillation Index value (right axis). Arrows show peak bloom years corresponding to sustained negative SOI values (El Niño episodes).

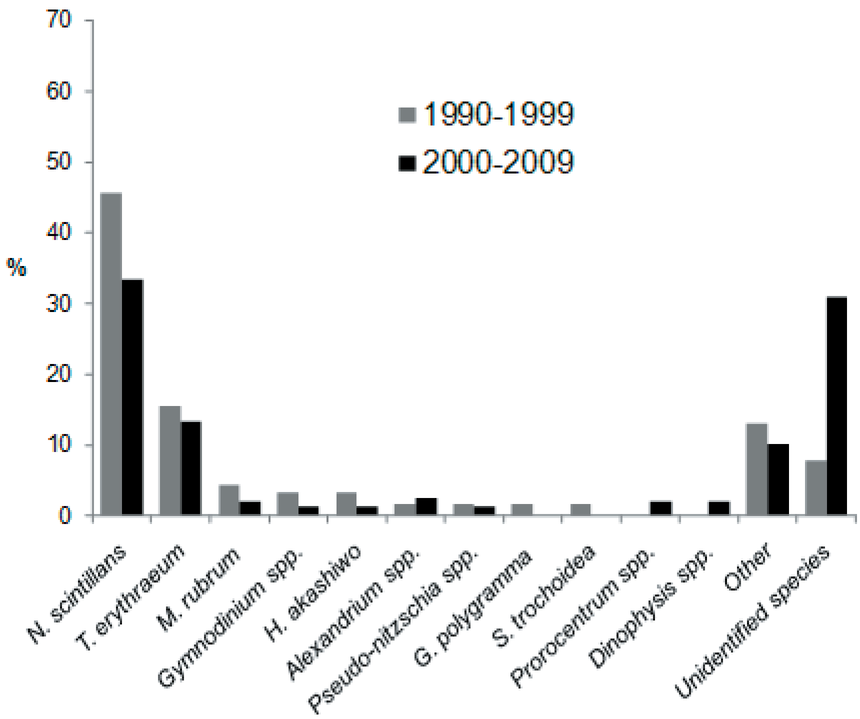

Figure 5. Percentage frequency of bloom reports for major microalgal taxa across the two reporting periods; grey bar=1990-1999; black bar=2000-2009; abbreviations *N. scintillans* = *Noctiluca scintillans*; *T. erythraeum* = *Trichodesmium erythraeum*; *M. rubrum* = *Mesodinium rubrum*; *H. akashiwo* = *Heterosigma akashiwo*; *G. polygramma* = *Gonyaulax polygramma*; *S. trochoidea* = *Scrippsiella trochoidea*.

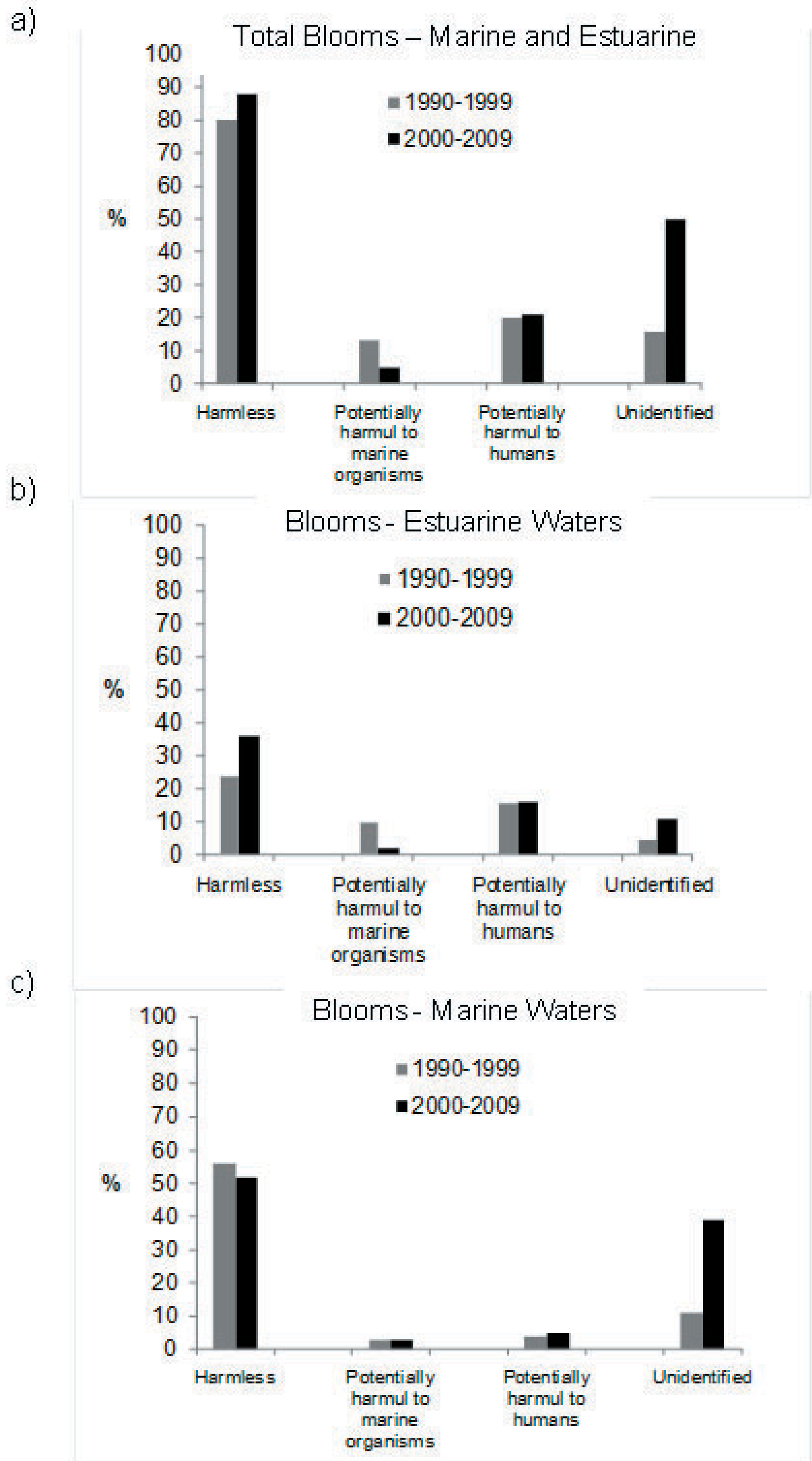

Figure 6. Percentage contribution of reported blooms to bloom type categories in a) total contribution of marine and estuarine blooms; b) estuarine waters only; and c) marine waters only; grey bar=1990-1999; black bar=2000-2009.

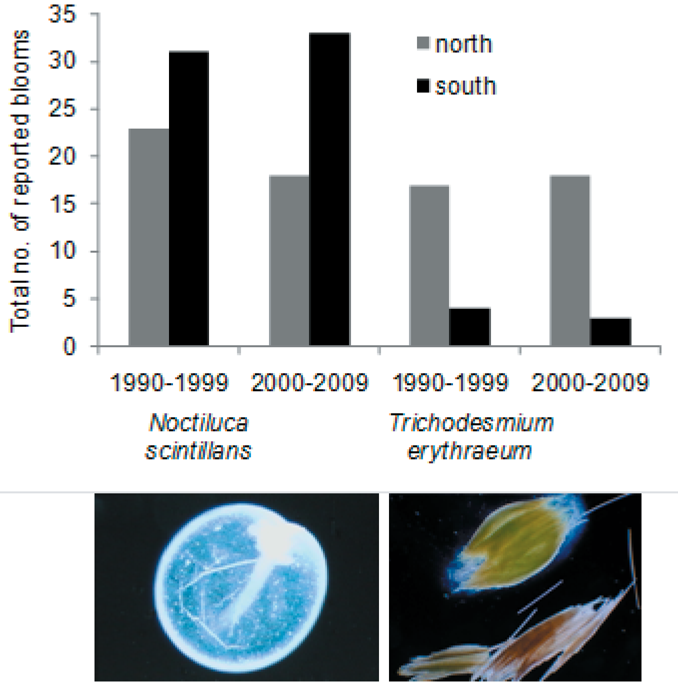

Figure 7. North (grey bar) and south (black bar) distributions of total number of reported blooms for the two dominant bloom forming taxa, *Noctiluca scintillans* and *Trichodesmium erythraeum* for the earlier reporting period 1990-1999 (grey bar) and the current reporting period (2000-2009). Images x100 magnification.

difference between decades (X^2 = 78.0, $p < 0.05$). To further elucidate where these differences lie, marine and estuarine bloom types were examined separately. Chi-square tests were applied to each dataset to examine if there had been any change overtime in either of these environments. For those blooms principally occurring in waterways identified as estuaries, significant differences were revealed between decades (X^2 = 19.6, $p < 0.05$), with significantly more 'potentially harmful to marine organisms' blooms reported during 1990-1999, a higher frequency of 'harmless' blooms during 2000 to 2009, and a greater number of 'unidentified' blooms during 2000 to 2009 (Fig 6b). For those occurring in the marine environment, a significant difference was also seen between 'unidentified' blooms, with a greater number being reported in the current reporting period (X^2 = 71.8, $p < 0.05$) (Fig. 6c).

As shown in Fig. 5, two species remained dominant throughout both reporting periods - *Noctiluca scintillans* and *Trichodesmium erythraeum*. Given the emphasis on increasing SST as a potential driver for species range extensions and retractions, we sought to test for a latitudinal trend in their reported bloom frequency. The number of blooms for each taxon was partitioned as occurring north or south of Sydney. A Chi-square test was performed on this latitudinal frequency distribution, revealing no significant difference for either *Noctiluca scintillans* (X^2 = 1.22, p >0.05) or *Trichodesmium erythraeum* (X^2 = 0.31, p >0.05) overtime (Fig 7).

DISCUSSION

Microalgal blooms in NSW coastal waters are frequently reported to government agencies, water authorities and local councils. We have shown that these reported blooms are dominated by harmless water discolourations, the majority of these being caused by the large dinoflagellate *Noctiluca scintillans* and the cyanobacterium *Trichodesmium erythraeum* and this remains unchanged over the past twenty years. Whilst historically *Noctiluca scintillans* has always been a relatively minor component of the phytoplankton community (Dakin and Colefax 1940, Jeffrey and Carpenter 1974, Hallegraeff and Reid 1986), its presence in NSW coastal waters has significantly increased in more recent years (Murray and Suthers 1999, Ajani et al. 2001a) and its range expanded into the waters of Tasmania, South Australia, Western Australia and Queensland (Hallegraeff 2010). Reported bloom data presented covering the past twenty years suggests that *Noctiluca scintillans* remains a consistent red tide organism in NSW coastal waters.

Although our data also suggests little change in the frequency of *Trichodesmium erythraeum* blooms over the past twenty years (Fig 4e), this taxon is predicted to be a major beneficiary of long term warming (Hallegraeff 2010). During a severe dust storm in Queensland coastal waters in 2002, Shaw et al. (2008) concluded that tropical cyanobacteria, such as *Trichodesmium erythraeum*, were the phytoplankton group that most likely accounted for the stimulation in satellite-derived chlorophyll a concentrations. The authors hypothesized that these dust storms delivered a critical source of dissolved iron into the water column and increased the standing stock by natural fertilisation. It is anticipated that with further drought predictions set to increase the number of severe dust storms in Australia (Shao et al. 2007), and an increase in the poleward extension of the EAC (bringing subtropical water further south) (Ridgway 2007), *Trichodesmium erythraeum* blooms will increase in frequency, and/or shift their interannual timing, in NSW coastal waters.

While *Noctiluca scintillans* and *Trichodesmium erythraeum* are both 'harmless' bloom taxa, microalgal bloom type requires more focused investigation in relation to ocean warming (Moore 2008, Hallegraeff 2010). Our limited understanding of marine ecosystem function and how it will respond to climate warming, coupled with a limited knowledge of phytoplankton physiology and ecology in NSW coastal waters, make it difficult to predict how the frequency of these bloom types we detail in this work will change over time. Estuarine data from our study show more 'potentially harmful to marine organisms' blooms during 1990 to 1999 compared to 2000 to 2009, and more 'harmless' blooms during 2000-2009 compared to previous years. Whilst it is difficult to explain these results in light of potential bloom drivers, the greatest increase in bloom frequency in these waters occurred in the 'unidentified' bloom type. The increasing number of 'unidentified' blooms in our dataset highlights the need for more systematic reporting and unambiguous identification of the causative species of blooms in NSW coastal waters. Accordingly, data such as bloom magnitude, bloom duration and spatial extent of each bloom would provide a more robust dataset for predicting interannual and long term trends in bloom types, and may provide a clearer understanding of species range extensions or retractions.

Within the annual cycle of reported blooms, the frequency of blooms appears to have altered over the past two decades. Maximum bloom activity occurred in January during the 1990 to 1999 reporting period, and shifted to October during the more recent period. In the absence of a continuous phytoplankton community dataset with which to test the certainty of this observed shift, the seasonal bloom data allows us to hypothesise that the spring diatom bloom observed regularly in these waters is experiencing an earlier onset. This in turn may trigger an earlier, secondary trophic effect resulting in an increase in abundance of the heterotrophic, *Noctiluca scintillans*. Further detailed studies would be required to test this hypothesis.

Our data indicates that the frequency of reported blooms in NSW coastal waters has increased over time. However, on decadal timescales, the El-Niño-La Niña climatic cycle could be a major factor in bloom frequency and may confound the overall increase seen in reported blooms. Peak bloom periods in our study were found to occur between 1997 to 1998 and 2002 to 2003 (Fig. 4). These correspond to periods of sustained negative SOI values, indicating El Niño episodes. While three El Niño episodes occurred during our sampling period, the two most significant of these warming phases were during 1997 to 1998 and 2002 to 2003, when warmer than average sea surface temperatures, a reduction in rainfall and a decrease in the strength of the Pacific Trade Winds in eastern Australia were documented. Thompson et al. (2009) found that SeaWIF (Sea-viewing Wide Field-of-View Sensor) chlorophyll a anomalies for southeastern Australian waters were associated with the transition from negative to positive SOI and were also recorded during these years, 1997 to 1998 and 2002 to 2003. Maclean (1989) suggested a similar relationship between bloom events and the El Niño-Southern Oscillation when reviewing red-tides in the Indo-Pacific region during the 1970s to 1980s. Elsewhere in the Pacific region, the relationship between bloom events and El Nino has also been raised. A bloom of the toxic dinoflagellate *Karenia concordia* along the north-eastern coast of New Zealand in 2002 occurred with El Niño conditions prevailing, providing wind and upwelling conditions favorable for phytoplankton growth (Chang and Ryan 2004). Yin et al. (1999) also reported that a series of red tides in Hong Kong, causing millions of dollars loss due to fish kills, occurred during the El Niño event of 1997 to 1998. These blooms were linked to the dramatic change in oceanographic conditions observed during this phase.

Given the uncertainties associated with bloom data, the relationship between bloom events and SOI cannot be considered causative. Nevertheless, it allows us to hypothesize that future peak bloom activity in south-eastern Australian coastal waters is likely to be coupled to shifts in the El Niño-Southern Oscillation cycle. To test such a hypothesis, a phytoplankton dataset would be required that consistently recorded bloom information such as species abundance and composition, bloom magnitude and bloom duration. Such basic information is necessary to quantify the spatio-temporal variability of these events. The collection of such accurate and systematic bloom data in NSW coastal waters requires localised, up-to-date and accessible bloom manuals. These manuals must be adequately resourced by the NSW government, by way of the Regional Algal Coordinating Committees (RACCs).

The case for historical/observational science, such as presented here, is strongly re-emerging as an important supplement to experimental science (Francis and Hare, 1994; Sagarin, 2001, 2008). With considerable knowledge gaps, and a critical need to hastily understand the changes that a warmer world is bringing, Sagarin (2008) argues that non-traditional data, such as presented here, can provide meaningful temporal and spatial associations about our shifting environment. Despite the limited nature of this anthropogenically derived bloom data, such as a rise in bloom reports due to an increase in public awareness, population growth, urbanisation of the coastal zone, increased reliance on fisheries resources, and/or weather patterns etc. (see review Ajani et al. 2001a), microalgal bloom reports can contribute valuable historical information, suggest causative relationships for testing and highlight key data requirements for evaluating future trends in phytoplankton phenology. The value of this type of data has recently been recognized with the formation of a global Harmful Algae Event Database (HAEDAT). When fully established, this information system will consist of data on harmful algal events, harmful algae monitoring and algal bloom management systems used throughout the world (http://iodeweb6.vliz.be/haedat/index.php). It is anticipated that an algal bloom dataset such as presented in this study will be one of the first contributions from Australian waters towards this global endeavour.

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REFERENCES

Ajani, P.A., Hallegraeff, G.M. and Pritchard, T. (2001a). Historic overview of algal blooms in marine and estuarine waters of New South Wales, Australia. *Proceedings of the Linnean Society of New South Wales* **123**, 1-22.

Ajani, P.A., Lee, R., Pritchard, T. and Krogh, M. (2001b). Phytoplankton dynamics at a long-term coastal station off Sydney, Australia. *Journal of Coastal Research* **34,** 60-73.

Chang, F.H. and Ryan, K.G. (2004). *Karenia concordia* sp. nov. (Gymnodiniales, Dinophyceae), a new non-thecate dinoflagellate isolated from the New Zealand northeast coast during the 2002 harmful algal bloom events. *Phycologia* **43**, 552-562

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K.L., Hauengue, M., Kovats, R.S., Revich B. and Woodward, A. (2007). Human health. 'Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change'. (Eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson) pp. 391-431. (Cambridge University Press, Cambridge, UK).

Cubillos, J.C., Wright, S.W., Nash, G., de Salas, M.F., Griffiths, B., Tilbrook, B., Poisson, A. and Hallegraeff, G.M. (2007). Calcification morphotypes of the coccolithophorid *Emiliania huxleyi* in the Southern Ocean: changes in 2001 to 2006 compared to historical data. *Marine Ecology-Progress Series* **348**, 47-54.

Dakin, W.J. and Colefax, A. (1940). The plankton of the Australian coastal waters of New South Wales. Part 1. *University of Sydney, Department of Zoology Monograph* **1**, 303-314.

Doney, S.C. (2006). Oceanography - Plankton in a warmer world. *Nature* **444**(7120), 695-696.

Donnelly, T.H., Grace, M.R. and Hart, B.T. (1997). Algal blooms in the Darling-Barwon River, Australia. *Water Air and Soil Pollution* **99**(1-4), 487-496.

Ducklow, H.W., Erickson, M., Kelly, J., Montes-Hugo, M., Ribic, C.A., Smith, R.C., Stammerjohn, S.E. and Karl, D.M. (2008). Particle export from the upper ocean over the continental shelf of the west Antarctic Peninsula: A long-term record, 1992-2007. *Deep Sea Research Part II: Topical Studies in Oceanography* **55**(18-19), 2118-2131.

Edwards, M., Johns, D.G., Leterme, S.C., Svendsen, E. and Richardson, A.J. (2006). Regional climate change and harmful algal blooms in the northeast Atlantic. *Limnology and Oceanography* **51**(2), 820-829.

Edwards, M. and Richardson, A.J. (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. *Nature* **430**(7002), 881-884.

Finkel, Z.V., Beardall, J., Flynn, K.J., Quigg, A., Rees, T.A.V. and Raven, J.A. (2010). Phytoplankton in a changing world: cell size and elemental stoichiometry. *Journal of Plankton Research* **32**(1), 119-137.

Francis, R.C. and Hare, S.R. (1994). Decadal-scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. *Fisheries Oceanography* **3**(4), 279-291.

Gladan, Z.N., Marasovic, I., Grbec, B., Skejic, S., Buzancic, M., Kuspilic, G., Matijevic, S. and Matic, F. (2010). Inter-decadal Variability in Phytoplankton Community in the Middle Adriatic (Katela Bay) in Relation to the North Atlantic Oscillation. *Estuaries and Coasts* **33**(2), 376-383.

Hallegraeff, G.M. (1992). Harmful algal blooms in the Australian region. *Marine Pollution Bulletin* **25**(5-8), 186-190.

Hallegraeff, G.M. (2010). Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology* **46**(2), 220-235.

Hallegraeff, G.M. and Reid, D.D. (1986). Phytoplankton species successions and their hydrological environment at a coastal station off Sydney. *Australian Journal of Marine and Freshwater Research* **37**, 361-377.

Hallegraeff, G.M., Anderson, D.M. and Cembella, A.D. (2003). 'Manual on Harmful Marine Microgalgae.' (UNESCO Publishing) pp. 1-793.

Hare, C.E., Leblanc, K., DiTullio, G.R., Kudela, R.M., Zhang, Y., Lee, P.A., Riseman, S. and Hutchins, D.A. (2007), Consequences of increased temperature and CO_2 for phytoplankton community structure in the Bering Sea. *Marine Ecology-Progress Series* **352**, 9-16.

Hays, G.C., Richardson, A.K. and Robinson, C. (2005). Climate change and marine plankton. *Trends in Ecology and Evolution.* **20**(5), 337-344.

Inouye, D.W., Barr, B., Armitage, K.B. and Inouye, B.D. (2000). Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Science.* **97**(4), 1630-1633.

Jeffrey, S.W. and Carpenter, S.M. (1974). Seasonal succession of phytoplankton at a coastal station off Sydney. *Australian Journal of Marine and Freshwater Research* **25**, 361-369.

Kahru, M., Brotas, V., Manzano-Sarabia, M. and Mitchell, B.G. (2011). Are phytoplankton blooms occurring earlier in the Arctic? *Global Change Biology* **17**(4), 1733-1739.

Maclean, J.L. (1989). Indo-Pacific red tides, 1985-1988. *Marine Pollution Bulletin* **20**(7), 304-310.

Moore, S.K., Trainer, V.L., Mantua, N.J., Parker, M.S., Laws, E.A., Backer, L.C. and Fleming, L.E. (2008). Impacts of climate variability and future climate change on harmful algal blooms and human health. *Environmental Health* **7**(Suppl2):S4 doi:10.1186/1476-069X-7-S2-S4.

Murray, S. and Suthers, I. M. (1999). Population ecology of *Noctiluca scintillans* Macartney, a red-tide forming dinoflagellate. *Australian Journal of Marine and Freshwater Research* **50**(3), 243-252.

Peperzak, L. (2003). Climate change and harmful algal blooms in the North Sea. *Acta Oecologica* **24,** S139-S144.

Reid, P.C., Edwards, M., Hunt, H.G. and Warner, A.J. (1998). Phytoplankton change in the North Atlantic. *Nature* **391**(6667), 546-546.

Ridgway, K.R. (2007). Long-term trend and decadal variability of the southward penetration of the East Australian Current. *Geophysical Research Letters* **34**(13), L13613.

Rost, B., Zondervan, I. and Wolf-Gladrow, D. (2008). Sensitivity of phytoplankton to future changes in ocean carbonate chemistry: current knowledge, contradictions and research directions. *Marine Ecology-Progress Series* **373**, 227-237.

Sagarin, R. and Micheli, F. (2001). Climate change - Climate change in non-traditional data sets. *Science* **294**(5543), 811-811.

Sagarin, R.D. (2008). Return to Warden's grove - Science, desire, and the lives of sparrows. *Science* **320**(5873), 180-180.

Shao, Y.P., Leys, J.F., McTainsh, G.H. and Tews, K. (2007). Numerical simulation of the October 2002 dust event in Australia. *Journal of Geophysical Research-Atmospheres* **112** D08207 doi:10.1029/2006JD007767 pp. 391-431.

Shaw, E.C., Gabric, A.J. and McTainsh, G.H. (2008). Impacts of aeolian dust deposition on phytoplankton dynamics in Queensland coastal waters. *Australian Journal of Marine and Freshwater Research* **59**(11), 951-962.

Smayda, T.J. (1997). What is a bloom? A commentary. *Limnology and Oceanography* **42**(5), 1132-1136.

Taylor, F.J.R. (Ed.) (1990). Red tides, brown tides and other harmful algal blooms: the view into the 1990's. In 'Toxic Marine Phytoplankton' (Eds. E. Graneli, B. Sundstrom, L. Elder and D. M. Anderson) pp. 527-533 (Elsevier: New York.)

Thompson, P.A., Baird, M.E., Ingleton, T. and Doblin, M.A. (2009). Long-term changes in temperate Australian coastal waters: implications for phytoplankton. *Marine Ecology-Progress Series* **394**, 1-19.

Wasmund, N., Nausch, G. and Matthaus, W. (1998). Phytoplankton spring blooms in the southern Baltic Sea - spatio-temporal development and long-term trends. *Journal of Plankton Research* **20**(6), 1099-1117.

Yin, K.D., Harrison, P.J., Chen, J., Huang, W. and Qian, P.Y. (1999). Red tides during spring 1998 in Hong Kong: is El Nino responsible? *Marine Ecology-Progress Series* **187**, 289-294.