Domoic Acid Poisoning as a Possible Cause of Seasonal Cetacean Mass Stranding Events in Tasmania, Australia

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Abstract

The periodic trend to cetacean mass stranding events in the Australian island state of Tasmania remains unexplained. This article introduces the hypothesis that domoic acid poisoning may be a causative agent in these events. The hypothesis arises from the previously evidenced role of aeolian dust as a vector of iron input to the Southern Ocean; the role of iron enrichment in *Pseudo-nitzschia* bloom proliferation and domoic acid production; and importantly, the characteristic toxicosis of domoic acid poisoning in mammalian subjects leading to spatial navigation deficits. As a pre-requisite for quantitative evaluation, the plausibility of this hypothesis was considered through correlation analyses between historical monthly stranding event numbers, mean monthly chlorophyll concentration and average monthly atmospheric dust loading. Correlation of these variables, which under the domoic acid stranding scenario would be linked, revealed strong agreement (r=0.80-0.87). We therefore advocate implementation of strategic quantitative investigation of the role of domoic acid in Tasmanian cetacean mass stranding events.

Keywords**:** cetacean mass stranding, domoic acid, iron fertilisation, aeolian dust, Southern Ocean

Introduction

Cetacean mass stranding events are a frequent occurrence along coastlines surrounding the Tasmanian state of Australia (Gales et al. 2012). The Tasmanian stranding record details 680 stranding events over the past 200 years, with 67 of 380 stranding events over the past two decades being considered mass strandings based on the classification of two or more individuals (other than mother-calf pairs) (Evans et al. 2002). The majority of stranding events comprise species of the cetacean sub-order Odontocetii or “toothed whales”, especially long-finned pilot whale (*Globicephala macrocephalus*).

The causes of mass stranding events in odontocetes are currently unknown but numerous environmental factors have been implicated, including coastal topography and oceanography (Brabyn and McLean 1992), meteorological and geomagnetic conditions (Mazzariol et al. 2011), seismic activity and sonar noise (Fernandez et al. 2005). Most recently, the periodicity of Tasmanian mass stranding events were shown to correlate closely with both zonal and meridional winds (Evans et al. 2005). The authors posed that such persistent wind patterns may be associated with nutrient-rich waters, and thereby cetacean foraging being forced closer to shore. In turn, an increase in the concentration of cetaceans in continental shelf waters would raise the probability of a random stranding event. This finding, whilst it did not identify the proximal cause of stranding, represents a significant advance towards understanding the potentially climate-related phenomenon in this geographic region.

Domoic acid (DA; $C_{15}H_{21}NO_{6;}$ CAS 14277-97-5) is a neurotoxin produced by the pennate diatom *Pseudo-nitzschia* spp., which has a cosmopolitan distribution (Kim et al. 2015). DA can cause amnesic shellfish poisoning in humans, with symptoms including vomiting, seizures, memory loss and disorientation (Perl et al. 1990). DA has also been shown to be the causative agent in sea lion (*Zalophus californianus*) and northern fur seal (*Callorhinus ursinus*) mass mortality events in central California (Lefebvre et al. 2010; Scholin et al. 2000). Sea lions and fur seals affected by DA poisoning exhibited neurological dysfunction but were otherwise in good body condition. Clinical investigation of subjects revealed brain lesions, particularly of the hippocampus (Lefebre et al. 2010; Montie et al. 2012). The hippocampus is a part of the cerebral cortex, which is associated with episodic memory and spatial navigation (Eichenbaum et al. 1999; Burgess et al. 2002). In humans, it is commonly subject to atrophy and degeneration in cognitive disorders such as Alzheimer's disease (Kold and Wishaw, 1996). Recently, Cook et al., (2015) advanced this research through application of functional Magnetic Resonance Imaging (MRI) of Californian Sea Lions undergoing rehabilitation. Animals with hippocampal lesions showed significantly altered hippocampal networks, which may lead to maladaptive navigational behaviour and subsequent mortality in the wild.

DA is a water soluble, tricarboxylic acid with a very short half-life in most tissue compartments (Fuquay et al. 2012). Further, it has a very poor ability to penetrate the blood-brain barrier (Edebo et al. 1998; Pulido 2008). Toxicosis therefore appears to occur through acute exposure, enhanced by rapid biomagnification during DA-producing *Pseudo-nitzschia* bloom events, rendering higher trophic predators, such as pinnipeds and odontocetes, at the greatest risk. The transfer of DA through the food web to cetaceans has previously been evidenced with the detection of DA in fecal samples from humpback whales (*Megaptera novaeangliae*) and blue whales (*Balaenoptera musculus*) feeding in Monterey Bay, California (Lefebvre et al. 2002). Whilst less is known about the long term effects of chronic exposure (Pulido 2008), it is clear that the characteristic toxicologic pathology of DA in mammalian subjects could contribute substantially to cetacean disorientation leading to stranding.

Until recently, oceanic forms of *Pseudo-nitzschia* were thought to be non-toxic. However, iron fertilization experiments in the Southern Ocean revealed that not only does iron enrichment stimulate growth of *Pseudo-nitzschia* spp., one of the dominant diatom species in the region (Gervais and Riebesell 2002; Kopczynska et al. 2007), but the species also responds to iron addition by producing DA (Trick et al. 2010). The sub-Antarctic Southern Ocean is characterized as a high-nutrient, low-chlorophyll region and it has been postulated that the system is iron-limited (Sedwick et al. 1999). A major natural source of iron input to the ocean surface is deposition of land-derived aeolian dust (Jickells et al. 2005). Research within the author team has previously evidenced the role that episodic input of iron-rich Australian dust plays in increasing primary productivity in the sub-Antarctic Southern Ocean (Gabric et al. 2002). This raises the possibility of a link between Australian dust events and Tasmanian cetacean strandings through the production of DA by *Pseudo-nitzschia.*

Establishing an unambiguous connection between DA production and odontocete mass stranding events is not a simple endeavour and requires a multidisciplinary approach including histopathological investigation of subjects; knowledge of foraging prior to stranding; chemical or biochemical verification of DA in the tissues of subjects and taxonomic and DA analysis of phytoplankton in the region. In the absence of such multi-dimensional data-sets, retrospective investigations have previously performed time-series cross-correlation between *Pseudo-nitzschia* bloom activity and stranding events (Torres de la Riva et al. 2009), finding correlative relationships for several stranding species and lending support for DA as an active agent in these events.

Here we introduce the potential role of domoic acid as a causative agent in Tasmanian cetacean mass stranding events. We consider the plausibility of the hypothesis as a first step towards the facilitation of resource-intensive quantitative analysis. To do so, we performed multi-annual, correlation analyses of mass-stranding events along the Tasmanian coastline with monthly satellite derived chlorophyll data and dust activity as a natural source of iron enrichment. The potential role of DA as a causative agent in mass-stranding events is discussed and a framework for strategic investigations to test the hypothesis is proposed.

Methods and Materials

We performed correlation analyses of variables that, under the DA related stranding scenario would be related and contributing factors. The frequency of stranding events by month was cross correlated with both proximate ocean chlorophyll-*a* (CHL-*a*) and dust activity.

Details of cetacean stranding events around Tasmania were obtained from the Tasmanian stranding database (Department of Primary Industries, Parks, Water and Environment (DPIPWE) Marine Mammal Conservation Program). The earliest recorded event in this database occurred in 1911, however, due to uncertainty concerning the completeness of the earlier parts of the record, only mass stranding events from 1965 onwards were examined. The minimum number of animals affected in any single stranding event was 10, hence for the purpose of this investigation, a mass-stranding event was defined as an event that involved ≥10 animals, as opposed to the commonly accepted ≥2 individuals (Gales et al., 2012). If stranding events occurred within one week of each other on the same coastline, they were classed as a single event. This yielded a total of 64 events with up to 216 animals reported in a single event. Stranding frequencies summed by month over the 48-year period provided a monthly chronology of stranding events for correlative evaluation.

Quantitative taxonomic data on diatom distribution (both spatial and temporal) is highly scarce for this remote global region. As such, we used ocean CHL-*a* concentration, obtained by remote sensing, as a proxy for the investigation of ocean phytoplankton productivity, assumed to reflect diatom bloom occurrence, as previously applied in the literature (Wilson et al, 2015). The mean monthly CHL-*a* concentration product based on the combined record of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data was obtained for a 14 year period, January 1998 - December 2011 from the NASA hosted Oceancolor website. The monthly variation in CHL-*a* was determined for an area of interest bounded by 140-160°E and 40-50°S (Figure 1). Authors have previously identified this area of the Tasman Sea/Southern Ocean as having a high likelihood of phytoplankton response to iron-rich dust inputs from the Australian continent (Cropp et al. 2013).

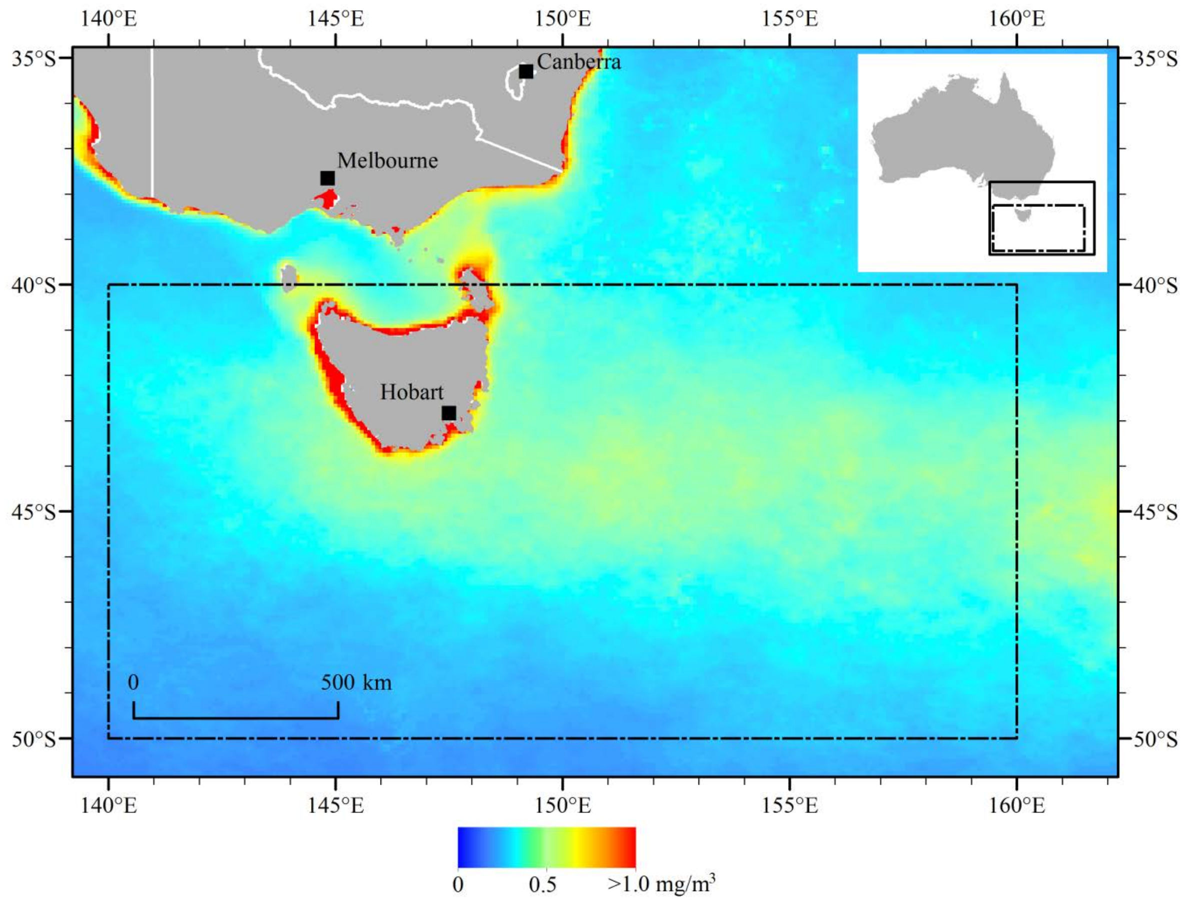

Fig 1 Long term (1998-2011) distribution of mean chlorophyll-*a* concentration from satellite sources in the regional area of interest.

To characterise the variability in Australian dust activity for the period that stranding events were studied, a metric known as the Dust Storm Index (DSI) was examined. The DSI is based on the archive of Australian Bureau of Meteorology (ABM) observation records, and has been developed to analyse dust activity over the continent for historic timeframes (O'Loingsigh et al. 2014). The DSI value for a given period (e.g. month or year) for any observation location is derived from the daily weather codes reported at that meteorological station over the period. Beyond the scope of this paper, a full explanation of the DSI is provided by O'Loingsigh et al. (2014).

The dust observation records from 180 long-term ABM stations are available nationwide for Australia. This study used a geographical subset of all stations in New South Wales, South Australia, Victoria and Tasmania (88 stations), to cover the south-eastern (SE) portion of the continent nearest to the ocean area of interest (DSI_{SE}). The selected stations for DSI_{SE}, whilst not representing major source regions themselves, are instead best placed to detect dust leaving the continent in transport over the Tasman Sea, Southern Ocean and the bounded area of interest.

Results and Discussion

Stranding occurrences were strongly biased to the austral summer (Figure 2), with a peak of 10 events in each of the months of November and December recorded over the 48 year period. These two months alone involved 1289 of a total of 4215 animals. When monthly stranding frequencies were overlaid with multi-year CHL-*a* and DSI_{SE} climatologies, a clear co-varying trend is evident (Figure 2). The highest CHL-*a* concentrations in the area of interest also occurred in the austral summer from November to February and were coincident with elevated dust activity and atmospheric loading at this time, with elevated relative values of DSI_{SE} evident (McTainsh et al. 1998). A rapid decline in stranding occurrence is noticeable for April, and remains low throughout the subsequent austral winter. All three variables showed good agreement with these lower values.

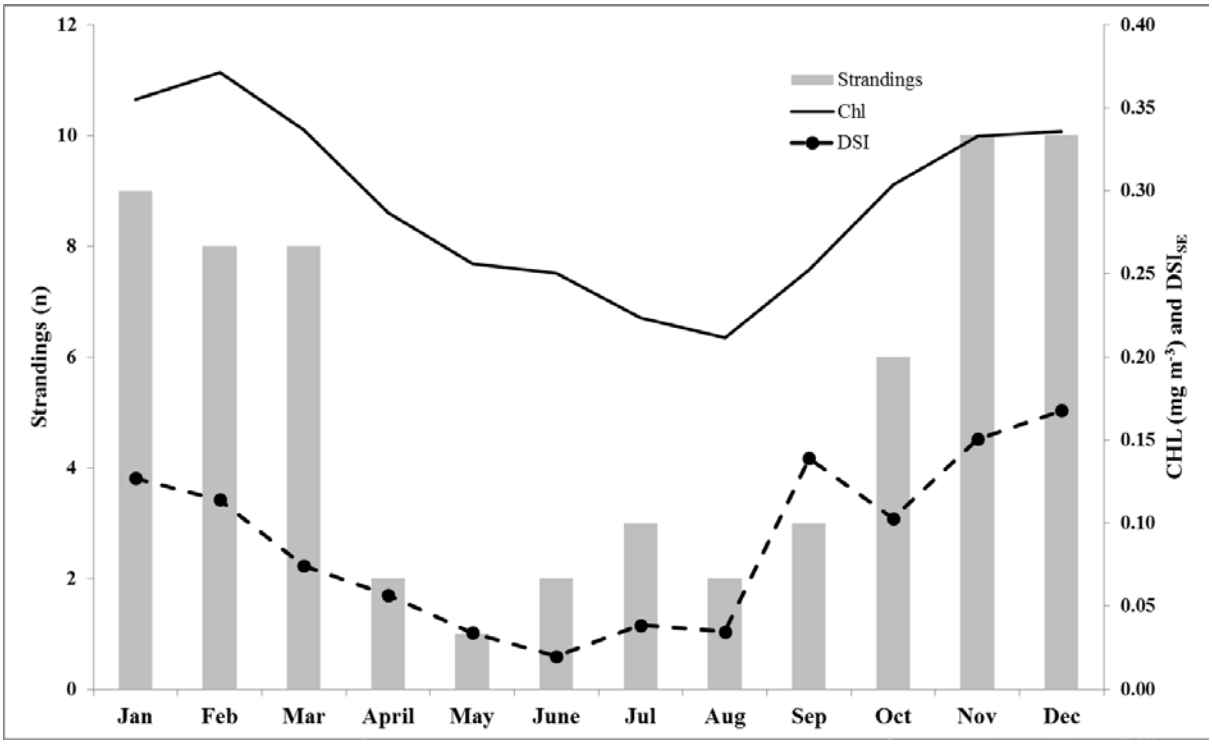

Fig 2 Monthly stranding frequency (1965-2013) presented alongside mean monthly chlorophyll-*a* and mean dust storm index (1998-2011)

The calculated correlation coefficient (Pearson r) for the relationship between CHL-*a* and stranding frequency was 0.87 and 0.80 between DSI_{SE} and stranding frequency respectively (Figure 3). This very strong correlative relationship between related and contributing factors under the DA stranding scenario provides support for the validity of the hypothesis and suggests that further quantitative investigation is merited.

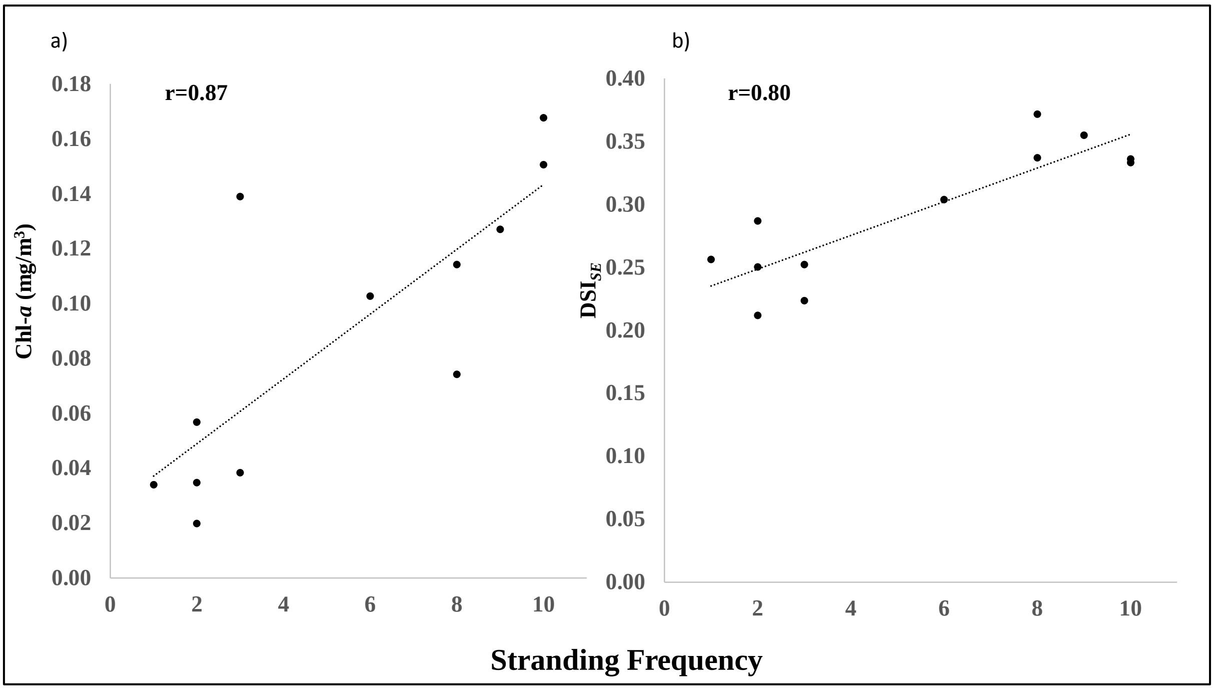

Fig 3 Scatterplots showing the correlative relationship between stranding frequency and CHL-*a* and DSI respectively

The periodicity of southeast Australian cetacean stranding events has previously been demonstrated by Evans et al. (2005). The current work progresses the previous climate-related pathway of investigation, posing that a cause of stranding may be associated with DA poisoning, known to result in spatial disorientation in other mammalian subjects.

The unequivocal verification of DA as a causative agent in seasonal stranding events requires long-term, multi-faceted monitoring programs. Reliable detection of DA in the biological fluids of subjects, either by High Performance Liquid Chromatography (HPLC) or Enzyme-Linked Immunosorbent Assay (ELISA) techniques, is an integral component of diagnosing a DA-related mortality (Lefebrve et al, 2010). When acceptable timeframes of sample acquisition are possible (immediately post-mortem), blood, urine, faeces, breast milk and aqueous humour represent readily accessible matrices for DA detection. The short half-life of domoic acid, however, often results in non-detection, even when there is strong evidence of a DA related mortality (Wilson et al. 2015). DA detection can be further complicated in strong socially bonded cetacean pods, such as those of pilot whales, where not all stranded individuals may display acute symptoms of the toxin. As such, histopathological examination of brain and heart and post-mortem brain imaging plays a critical role in the verification of acute effects of DA toxicosis. Such examination requires the removal and fixation of intact organs soon after death. Extensive post-mortem sampling efforts such as these simultaneously lend themselves to stomach content collection and analysis for the purpose of exposure pathway investigation. A comprehensive bio-monitoring program would similarly aim to confirm the presence of DA acid producing *Pseudo-nitzschia* in the proximate ocean sector in response to any stranding event.

In practice, such comprehensive sampling campaigns are unrealistic without considerable resource allocation. The frequent remoteness of Tasmanian stranding locations, combined with the large number of animals affected during these events, and importantly, the priority allocated to animal rescue at such times, presents the reality that attending stranding officers are stretched in their capacity. The additional task of logistically-demanding post-mortem tissue harvesting, sample fixation and transport of skulls and organs of large cetaceans is therefore not a trivial consideration. Presentation of this correlative evidence in support of the potential role of DA in cetacean mass stranding events in this region therefore represents a vital first step towards facilitation of robust quantitative investigation. Quantitative investigation remains imperative for advancing our understanding of the role of DA in these cyclical mass stranding events and in turn our understanding of how climate change stands to impact the periodicity and severity of these events (Havens et al. 2015; Cook et al, 2015).

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References

Brabyn M, McLean I (1992) Oceanography and coastal topography of herd-stranding sites for whales in New Zealand. J Mammal 73:469-476

Burgess N, Maguire E, O'Keefe J (2002) The human hippocampus and spatial and episodic memory. Neuron 35:625-641

Cook P, Reichmuth C, Rouse A, Libby L, Dennison S, Carmichael O, Kruse-Elliott K, Bloom J, Van Bonn W, Gulland F, Ranganath C (2015) Algal toxin impairs sea lion memory and hippocampal connectivity, with implications for strandings. Science 350:1545-1546

Cropp R A, Gabric A, Levasseur M, McTainsh G, Bowie A, Hassler C, Law C, McGowan H, Tindale N, and Viscarra Rosse R (2013) The likelihood of observing dust-stimulated phytoplankton growth in waters proximal to the Australian continent. J Marine Syst 117-118:43-52

Edebo L, Edebo A, Haamer J, Lange S (1998) Toxicity and metabolism of phycotoxins. In Miraglia M, van Egmond H, Brera C, Gilbert J (ed) Mycotoxins and Phycotoxins - developments in chemistry, toxicology and food safety. Alaken Inc, USA, pp 529-545

Eichenbaum H, Dudchenko P, Wood E, Shapiro M, Tanila H (1999) The hippocampus, memory and place cells: Is it spatial memeory or a memory space? Neuron 23:209-226

Evans K, Morrice M, Hindell M (2002) Three mass strandings of sperm whales (*Physester macrocephalus*) in southern Australian waters. Marine Mammal Science 18(3):622-643.

Evans K, Thresher R, Warneke RM, Bradshaw CJA, Pook M, Thiele D, Hindell M (2005) Periodic variability in cetacean strandings: Links to large scale climate events. Biol. Lett. 1:147-150

Fernandez A, Edwards JF, Rodriguez F, De Los Monteros E, Herraez P, Castro P, Jaber J, Martin V, Arbelo M (2005) “Gas and fat embolic syndrome" involving mass stranding of beaked whales (Family *Ziphiidae*) exposed to anthropogenic sonar signals. Veterinary Pathology 42:446-457

Fuquay J, Muha N, Wang Z, Ramsdell J (2012) Toxicokinetics of domoic acid in the fetal rat. Toxicology 294:36-41

Gabric AJ, Cropp R, Ayers GP, McTainsh G, Braddock R (2002) Coupling between cycles of phytoplankton biomass and aerosol optical depth as derived from SeaWiFS time series in the Subantarctic Southern Ocean. Geophysical Research Letters 29:16-11-16-14 doi:10.1029/2001gl013545

Gales R, Alderman R, Thalmann S, Carlyon K (2012) Satellite tracking of long-finned pilot whales (*Globicephala melas*) following stranding and release in Tasmania, Australia. Wildlife Research 39:520-531

Gervais F, Riebesell U (2002) Changes in primary productivity and chlorophyll *a* in response to iron fertilization in the Southern Polar Frontal Zone. Limnology and Oceanography 47:1324-1335

Havens K, Paerl H (2015) Climate change at a crossroads for control of harmful algal blooms. Environmental Science and Technology 49:12605-12606.

Jickells TD et al. (2005) Global iron connections between desert dust, ocean biogeochemistry, and climate. Science 308:67-71

Kolb B, Wishaw I Q (1996) Fundamentals of human neuro-psychology. W H Freeman and Company, New York

Kopczynska E, Savoye N, Dehairs F, Cardinal D, Elskens M (2007) Spring phytoplankton assemblages in the Southern Ocean between Australia and Antarctica. Polar Biology 31:77-88.

Kim J H, Park B S, Kim J H, Wang P, Han M S (2015) Intraspecific diversity and distribution of the cosmopolitan species Pseudo-nitzschia pungens (Bacillariophyceae): morphology, genetics, and ecophysiology of the three clades. Journal of Phycology 51(1):159-172.

Lefebvre K, Bargu S, Kieckhefer T, Silver M (2002) From sanddabs to blue whales: the pervasiveness of domoic acid. Toxicon 40:971-977

Lefebvre K, Robertson A, Frame ER, Colegrave KM, Nance S, Baugh KA, Wiedenhoft H, Gulland F (2010) Clinical signs and histopathology associated with domoic acid poisening in northern fur seals (*Callorhinus ursinus*) and comparison of toxin detection methods. Harmful Algae 9:374-383

Mazzariol S et al. (2011) Sometimes sperm whales (*Physester macrocephalus*) cannot find their way back to high seas: A multidisciplinary study on mass stranding. PLoS ONE 6:1-17

McTainsh GH, Lynch AW, Tews EK (1998) Climatic controls upon dust storm occurrences in eastern Australia. Journal of Arid Environments 39:457-466

Montie E, Wheeler E, Pussini N, Battey T, Van Bonn W, Gulland F (2012) Magnetic resonance imaging reveals that brain atrophy is more severe in older Californian sea lions with domoic acid toxicosis. Harmful Algae 20:19-29.

O'Loingsigh T, McTainsh GH, Tews EK, Strong CL, Leys JF, Shinkfield P, Tapper NJ (2014) The Dust Storm Index (DSI): A method for monitoring broadscale wind erosion using meteorological records. Aeolian Research 12:29-40

Perl TM, Bedard L, Kosatsky T, Hockin JC, Todd ECD, Remis RS (1990) An outbreak of toxic encephalopathy caused by eating mussels contaminated with domoic acid. New England Journal of Medicine 322:1775-1780

Pulido O (2008) Domoic acid toxicology pathology: A review. Marine Drugs 6:180-219

Scholin C et al. (2000) Mortality of sea lions along the central California coast linked to a toxic diatom bloom. Nature 403:80-84

Sedwick PN, DiTullio GR, Hutchins DA, Boyd PW, Griffiths FB, Crossley AC, Trull T, Queguiner B (1999) Limitation of algal growth by iron deficiency in the Australian Subantarctic Region. Geophysical Research Letters 26:2865-2868 doi:10.1029/1998gl002284

Torres de la Riva G, Johnson CK, Gulland F, Langlois GW, Heyning JE, Rowles TK, Mazet JAK (2009) Association of an unusual marine mammal mortality event with *Pseudonitzschia* spp. blooms along the southern California coastline. Journal of Wildlife Disease 45:109-121

Trick C, Bill B, Cochlan W, Wells M, Trainer V, Pickell L (2010) Iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas. PNAS 107:5887-589

Wilson C et al (2015) Southern right whale (Eubalaena australis) calf mortality at Península Valdés, Argentina: Are harmful algal blooms to blame? Marine Mammal Science 32(2):423-451