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The likelihood of observing dust-stimulated phytoplankton growth in waters proximal to the Australian continent

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ABSTRACT

We develop a tool to assist in identifying a link between naturally occurring aeolian dust deposition and phytoplankton response in the ocean. Rather than examining a single, or small number of dust deposition events, we take a climatological approach to estimate the likelihood of observing a definitive link between dust deposition and a phytoplankton bloom for the oceans proximal to the Australian continent. We use a dust storm index (DSI) to determine dust entrainment in the Lake Eyre Basin (LEB) and an ensemble of modelled atmospheric trajectories of dust transport from the basin, the major dust source in Australia. Deposition into the ocean is computed as a function of distance from the LEB source and the local over-ocean precipitation. The upper ocean's receptivity to nutrients, including dust-borne iron, is defined in terms of time-dependent, monthly climatological fields for light, mixed layer depth and chlorophyll concentration relative to the climatological monthly maximum. The resultant likelihood of a dust-phytoplankton link being observed is then mapped as a function of space and time. Our results suggest that the Southern Ocean (north of 45°S), the North West Shelf, and Great Barrier Reef are ocean regions where a rapid biological response to dust inputs is most likely to be observed. Conversely, due to asynchrony between deposition and ocean receptivity, direct causal links appear unlikely to be observed in the Tasman Sea and Southern Ocean south of 45°S.

1. Introduction

The supply of dust-derived nutrients to the global ocean is postulated to be a key control on marine primary production, none more so than in southern hemisphere oceanic regions downwind of arid continental regions, such as South America (Gasso and Stein, 2007; Wolff et al., 2006) and Australia (Cropp et al., 2005; Jickells et al., 2005). Indeed, in high nutrient low chlorophyll (HNLC) regions such as the Southern Ocean (SO), dust-borne iron (Fe) limits primary production, controls phytoplankton species composition, and potentially control the transfer of carbon to the deep ocean, thus affecting atmospheric CO_2 concentrations (Boyd et al., 2000; Cassar et al., 2007; Ridgwell, 2002). Conversely, in low nutrient low chlorophyll (LNLC) regions, such as the Mediterranean, tropical North Atlantic (Brust et al., 2011) and tropical waters of northern Australian, dust can stimulate cyanobacterial blooms, which are strongly iron or phosphorus limited or co-limited by both nutrients (Mills et al., 2004; Pulido-Villena et al., 2010).

A direct link between a particular dust deposition event and a subsequent phytoplankton bloom has been frustratingly difficult to demonstrate, with some authors suggesting that dust-driven phytoplankton bloom events are rare (Boyd et al., 2009). Notwithstanding the compelling results of several artificial iron-fertilization field experiments in the equatorial Pacific and Southern Oceans (Boyd and Law, 2001; Coale et al., 2004; Martin et al., 1994), there is only limited and often indirect evidence for an impact of natural dust deposition on phytoplankton growth in Australian regional waters (Gabric et al., 2010; Shaw et al., 2008). In some cases no phytoplankton response has been detected, even after a major dust storm event (Mackie et al., 2008a).

The difficulty in establishing an unequivocal dust-phytoplankton linkage is partly due to the unpredictable and transitory nature of dust events and the operational difficulties of monitoring deposition into the remote oceans. Australia is a spasmodic continental dust source when compared

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with some northern hemisphere (NH) regions (Shao et al., 2011). Although this creates measurement challenges, the adjacency of the continent to both HNLC and LNLC ocean regions makes Australia an ideal laboratory to detect a linkage. Furthermore, Australian mineral dust is Fe-rich by comparison with NH soils (Radhi et al., 2011). The main pathways of dust leaving the Australian continent, are to the north-west over the Indian Ocean, south over the Southern Ocean (SO), and to the southeast over the Tasman Sea in association with the west-to-east passage of cold fronts (McTainsh, 1989). Dust can occasionally be advected north-east over the Great Barrier Reef (GBR) and Pacific Ocean (Shaw et al., 2008). Dust is entrained by warm pre-frontal northerly winds, frontal westerlies and post-frontal southerlies (Strong et al., 2010). During austral spring and summer, the northerly migration of the band of cold fronts contributes to increased dust storm activity over south-eastern Australia (McTainsh et al., 1998). Indeed, there is a strong seasonality in monthly average dust storm frequency related to wind conditions, rainfall, and vegetation patterns, with peak dust storm activity in northern Australia occurring during spring and early summer, while activity in southern Australia peaks later during summer (McTainsh and Leys, 1993).

Variability in ocean biological response to dust-borne Fe inputs has several possible explanations. First, the timing of dust inputs must coincide with the upper ocean conditions, predominantly ambient light and mixed layer depth (MLD), that are conducive to a phytoplankton bloom occurring. Second, for a response to Fe addition to occur, the ocean region must be one where Fe limits phytoplankton growth, e.g. High Nutrient Low Chlorophyll (HNLC) areas such as the Southern Ocean (Boyd and Law, 2001), or LNLC regions where diazotroph nitrogen fixation is iron limited (Karl et al., 2002; Law et al., 2011). However, the response to iron addition may be complicated by subtle interactions. These include co-limitation of algal growth by both light and Fe (Feng et al., 2010; Petrou et al., 2011; Sunda and Huntsman, 1997), Fe and silicic acid (Hutchins et al., 2001) or Fe and other micronutrients.

Data on ocean dissolved Fe (dFe) concentrations in the Australian region is sparse and largely limited to N–S transects (e.g. WOCE SR3) in the Southern Ocean (Lai et al., 2008; Lannuzel et al., 2011), the Subantarctic region (Bowie et al., 2009) and the SW Pacific and Tasman Sea (Boyd and Ellwood, 2010; Obata et al., 2008). Generally, the mean mixed layer dFe concentrations in the surface SO are low (<0.2 nM) due to phytoplankton uptake. However, Fe is continuously cycled through the food web in surface waters, and interacts with deeper waters through sedimentation, remineralisation and upwelling, the assessment of its availability is complex and cannot be estimated from dFe values alone (Bowie et al., 2009). Additionally, complex interactions between iron chemistry and phytoplankton biology prevent an easy prediction of iron bioavailability to phytoplankton in marine systems (Hassler et al., 2011b). The available data suggests that similar to the bioavailability of inorganic Fe oxyhydroxide colloids, the bioavailable iron associated with dust is generally not available to diatoms, but can be significant for cyanobacteria (Visser et al., 2003).

The Fe in mineral dust is typically insoluble (Baker and Croot, 2010), and a range of solubilities covering four orders of magnitude has been quoted in the literature (Mackie et al., 2006). In the Southern Ocean south of Australia in a study conducted during January–February 2007, dust Fe dissolution values ranged from 0.2 to 2.5%, but they were significantly higher (17.7%) for samples that may have included particles emitted from forest fires that were occurring in southern Australia at the time (Bowie et al., 2009).

Acidification of dust aerosols during atmospheric transport by oxidation with SO_2 has been proposed as the primary mechanism for the production of water-soluble forms of Fe (Waeles et al., 2007; Zhuang et al., 1992). However, in sharp contrast to the Northern Hemisphere (NH) where anthropogenic SO_2 is plentiful year round (Meskhidze et al., 2003, 2005), the Southern Hemisphere (SH) is relatively unpolluted, and the atmospheric burden of SO_2 is closely related to seasonal marine emissions of biogenic compounds such as dimethylsulphide (DMS), which in the Southern Ocean regularly peak during the austral summer (Gabric et al., 1995, 2010).

It is also pertinent to note that the solubility and bioavailability of dust derived Fe may be influenced by whether it has been wet or dry deposited. Law et al. (2011) report a strong in situ response by diazotrophs to a wet deposition event in the northern Tasman Sea (a LNLC region), which exceeded the response in dust amendment experiments, with direct evidence of increased supply of dissolved Fe during the wet deposition, and indirect evidence of enhanced bioavailability.

Here we address the problem of detecting dust-induced phytoplankton blooms by developing an estimate of the relative likelihood of observing such a link in each month for the oceans surrounding Australia that include both HNLC and LNLC waters. We compute the relative frequency of iron-rich dust deposition and ocean receptivity to dust-borne Fe, both pre-conditions for a phytoplankton bloom. Dust transport is simulated by a climatology of modelled air-parcel trajectories from a central location in the Lake Eyre Basin (LEB), the main Australian dust source region (Prospero et al., 2002) which is located in southern central Australia. Ocean receptivity to aeolian nutrients is characterised using local data on surface irradiance and ocean mixed layer depth, overlaid on recognized biogeographic provinces (Longhurst, 2007). The resulting maps are combined to produce a composite map of the likelihood of bloom events, as a function of space and time of year. Results are then discussed considering the regional phytoplankton seasonal dynamic and iron nutritive status, although data on the latter is limited in much of the ocean around Australia. This is the first attempt to provide a comprehensive picture of where and when dust deposition may elicit an observable phytoplankton response in ocean waters near Australia. Our approach contrasts with previous attempts at analysis of event-based dust-phytoplankton responses.

2. Methodology

Our approach is based on a climatological spatio-temporal perspective that acts as a ‘filter’ of Australian dust storm events and generates monthly maps which we use to indicate the likelihood that a dust-induced phytoplankton bloom may be observed in a particular region of the proximal ocean during each month of the year. The approach is based on a simple conceptual model of dust mineralogy, entrainment and deposition, and phytoplankton growth that is used to provide a quantitative estimate of the potential to observe a dust-Fe-phytoplankton response.

Several datasets (Table 1) are used to characterise the various relevant atmospheric and oceanic processes. These include soil mineralogy in the LEB (from which we estimate Fe content), atmospheric transport from a source located in the LEB based on modelled air parcel trajectories, the likelihood that an air parcel will contain dust, satellite-derived rain events to simulate wet deposition, satellite-derived solar irradiance at the ocean surface, and climatological nutrient and mixed layer depth in surrounding oceans. These data are synthesised and presented as monthly maps that can be used to categorise regions of ocean according to their potential to demonstrate a dust-phytoplankton connection for each month.

The relative likelihood of iron-rich dust being available for entrainment is calculated from maps of soil mineralogy of the LEB, giving the percentage abundance of Kaolinite, Illite and Smectite, assuming an average Fe content of 0.2% for Kaolinite, 2.0% for Illite, 3.2% for Smectite and 0% for any other minerals present (Viscarra Rossel, 2011).

The mineralogy of the soil is assumed constant in time. However, the likelihood of Fe-rich dust being available for entrainment is modified spatially and intra-annually by vegetation cover, which may also be considered a surrogate for soil moisture (Burgess et al., 1989). We used a Normalised Difference Vegetation Index (NDVI) seasonal climatology from SeaWiFS (Steven et al., 2003) as a proxy for vegetation cover (Shao et al., 2007), so that the likelihood of dust entrainment is