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# The influence of the Indian Ocean Dipole on interannual variations in phytoplankton size structure as revealed by Earth Observation

Robert J.W. Brewin[a,b,c,*], Takafumi Hirata[d], Nick J. Hardman-Mountford[a,b,1], Samantha J. Lavender[c,e], Shubha Sathyendranath[a], Ray Barlow[f,g]

[a] Plymouth Marine Laboratory (PML), Prospect Place, The Hoe, Plymouth PL1 3DH, UK
[b] National Centre for Earth Observation, PML, Plymouth PL1 3DH, UK
[c] School of Marine Science and Engineering, University of Plymouth, Drake Circus, Plymouth PL4 8AA, UK
[d] Faculty of Environmental Earth Science, Hokkaido University, North 10 West 5, Kita-ku, Sapparo, Hokkaido 060-0810, Japan
[e] ARGANS Ltd, Unit 3, Drake Building, Tamar Science Park, Derriford, Plymouth PL6 8BY, UK
[f] Bayworld Centre for Research & Education, P.O. Box 7296, Roggebaai 8012, South Africa
[g] Marine Research Institute, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

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ABSTRACT

Using a decade of satellite ocean-colour observations and a model that links chlorophyll-a to the size of the phytoplankton cells, parameterised using pigment data from the Indian Ocean, we examine the implications of the Indian Ocean Dipole (IOD) for phytoplankton size structure. The inferred interannual anomalies in phytoplankton size structure are related to those in sea-surface temperature (SST) and sea-surface height (SSH), derived using satellite radiometry and altimetry, and stratification, derived using the Simple Ocean Data Assimilation (SODA) database. In regions influenced by the Indian Ocean Dipole, we observe a tight correlation between phytoplankton size structure and the physical variables, such that interannual variations in the physical variables accounts for up to 70% of the total variance in phytoplankton size structure. For much of the Indian Ocean, low temperature, low SSH and low stratification (indicative of a turbulent environment) are correlated with larger size classes, consistent with theories on coupling between physical–chemical processes and ecosystem structure. To the extent that phytoplankton function is related to its size structure, changes in physical forcing are likely to influence biogeochemical cycles in the region and the pelagic food web. The limitations of our approach are discussed and we highlight future challenges in satellite ocean-colour monitoring, should climate change lead to any modification in our marine ecosystem.



## 1. Introduction

The SeaWiFS sensor has provided high quality satellite ocean colour observations for over a decade (McClain, 2009). By estimating the total chlorophyll-a concentration (an ubiquitous pigment in all phytoplankton) from the normalised water-leaving radiance spectrum, researchers have assessed both interannual and decadal changes in phytoplankton distributions and biological production (Antoine et al., 2005; Behrenfeld et al., 2006; Gregg and Conkright, 2002; Martinez et al., 2009; Polovina et al., 2008). In recent years, demand for additional biological information beyond that of chlorophyll-a has led to attempts to use satellite ocean colour observations to map different communities of phytoplankton on synoptic scales (e.g. Alvain et al., 2005, 2008; Aiken et al., 2007; Bracher et al., 2009; Brewin et al., 2010b; Ciotti and Bricaud, 2006; Devred et al., 2011; Hirata et al., 2008, 2011; Kostadinov et al., 2009, 2010; Mouw and Yoder, 2010; Raitsos et al., 2008; Sathyendranath et al., 2004; Uitz et al., 2006).

The size structure of phytoplankton is intimately linked with a variety of processes that influence the ocean carbon cycle, including the marine food web (Caddy et al., 1995; Parsons and Lalli, 2002); nutrient uptake (Probyn, 1985; Sunda and Huntsman, 1997); and sinking rate and export (Boyd and Newton, 1999; Guidi et al., 2009; Laws et al., 2000; Michaels and Silver, 1988). The size of the phytoplankton community has a direct influence on the water-leaving radiance spectrum that are observed from satellites, through changes in absorption and backscattering of light (Ciotti and Bricaud, 2006; Devred et al., 2011; Hirata et al., 2008; Kostadinov et al., 2009; Mouw and Yoder, 2010; Sathyendranath et al., 2004). Furthermore, it has been well documented that small cells dominate

* Corresponding author at: Plymouth Marine Laboratory (PML), Prospect Place, The Hoe, Plymouth PL1 3DH, UK. Tel.: +44 1752 633429; fax: +44 1752 633101.
*E-mail address:* robr@pml.ac.uk (R.J.W. Brewin).

[1] Present address: CSIRO Marine and Atmospheric Research, Floreat, WA 6014, Australia.

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in marine waters which exhibit lower chlorophyll-a concentrations and large cells dominate at higher chlorophyll-a concentrations (Aiken et al., 2008; Chisholm, 1992).

Brewin et al. (2011b) conducted an intercomparison of a variety of models adapted to detect dominant phytoplankton size class in a satellite pixel. It was found that abundance-based approaches (that rely on observed patterns of change in the size–structure of the phytoplankton with the chlorophyll-a concentration) performed with similar accuracy to approaches that use the spectral shape of the absorption coefficient of phytoplankton, or approaches that use the second order variability in the remotely-sensed spectral radiance. Mounting evidence indicates that the fraction of microphytoplankton (cells $>20\,\mu m$) in the total chlorophyll-a concentration increases monotonically as a function of the total chlorophyll-a concentration, and that of the picophytoplankton fraction (cells $<2\,\mu m$) decreases monotonically (Brewin et al., 2010b; Chisholm, 1992; Devred et al., 2006, 2011; Hirata et al., 2011; Mouw and Yoder, 2010; Uitz et al., 2006). Furthermore, Brewin et al. (2010b), Devred et al. (2011) and Hirata et al. (2011) have expressed the fraction of nanophytoplankton (cells 2–20 $\mu m$) in the total chlorophyll-a concentration as a unimodal function of the total chlorophyll-a concentration.

With the advent of satellite-based phytoplankton community algorithms and armed with a decadal time-series of ocean-colour observations, recent studies have begun to describe interannual variability in phytoplankton community structure (Alvain et al., 2008; Devred et al., 2009; Uitz et al., 2010). Such information is of paramount importance if we are to improve our understanding of the functional role of phytoplankton in the carbon cycle which is needed to help predict future changes in our climate. Considering the El Niño (La Niña) Southern Oscillation (ENSO) cycle as the largest single source of interannual climatic variability on Earth (Diaz and Markgraf, 1992), many of these studies have focused on its impact on phytoplankton community structure.

Using contrasting satellite models, both Brewin et al. (2010a) and Kostadinov et al. (2010) observed significant correlations between the size structure of the phytoplankton in the global ocean and the multivariate ENSO index (MEI), which is used to evaluate the strength of the ENSO cycle (Wolter, 1987). Using a satellite algorithm, Alvain et al. (2008) observed blooms of diatoms in the equatorial Pacific during the onset of the 1998 La Niña and Masotti et al. (2011) observed changes in the composition of nanoeucaryotes and Synechococcus during the ENSO cycle. Making use of 10-years of satellite observations, Uitz et al. (2010) revealed large interannual variations in size-specific primary production in the equatorial Pacific, related to ENSO, with microphytoplankton showing the largest range of variability. Whereas many of these studies have focused on the interaction between ENSO and phytoplankton community structure, there is currently limited knowledge regarding the influence of other sources of interannual variability.

The Indian Ocean Dipole (IOD) is recognised as a major atmosphere–ocean phenomenon in the Indian Ocean that can arise in the presence or absence of ENSO (Behera et al., 1999; Saji et al., 1999; Vinayachandran et al., 2009; Webster et al., 1999). Saji et al. (1999) developed an index to quantify the strength of the IOD, which is calculated as the gradient in sea-surface temperature (SST) anomaly between the tropical western Indian Ocean and the tropical south-eastern Indian Ocean, referred to as the Dipole Mode Index (DMI). During neutral DMI conditions (e.g. October 2001, see Fig. 1), westerly winds blow over the tropical Indian Ocean and SST is relatively homogeneous across the equator, but with slightly cooler waters in the western tropical Indian Ocean causing a west-to-east gradient in the thermocline and active cumulus convection in the eastern Indian Ocean.

During a positive DMI event (e.g. October 1997, see Fig. 1), reversed winds lead to upwelling in the tropical south-eastern Indian Ocean and warmer SST in the western tropical Indian Ocean, causing an east-to-west gradient in the thermocline at the equator. Lower SST in the eastern Indian Ocean causes a westward migration of the cumulus convection, which can cause droughts in eastern areas such as Indonesia and Australia and heavy rainfall and flooding over East Africa (Ashok et al., 2001).

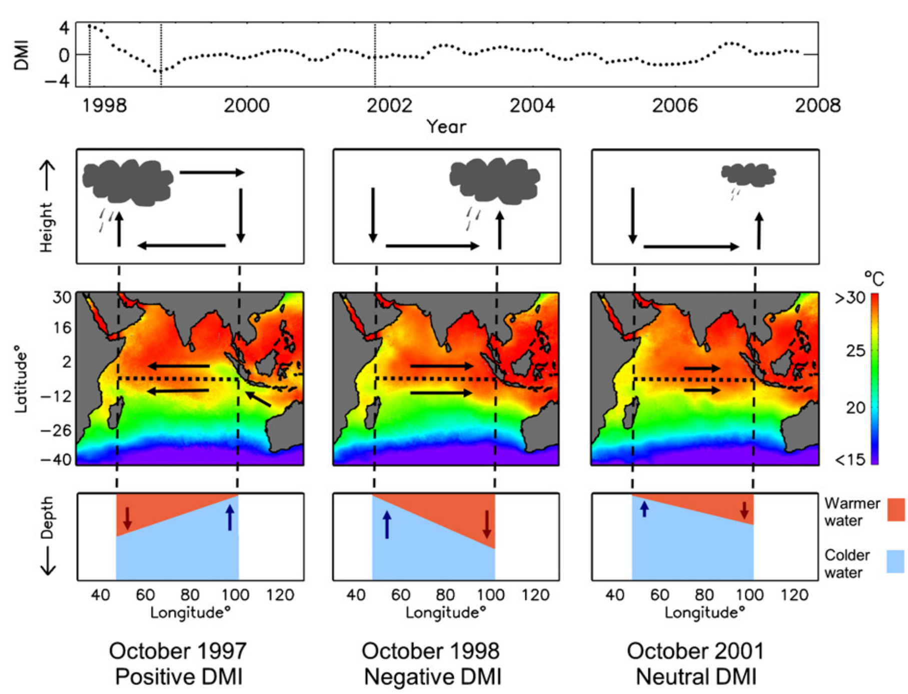


**Fig. 1.** A schematic of the effect of three phases of the Indian Ocean Dipole Mode Index (DMI) on ocean–atmosphere interactions. Left shows the DMI in positive phase, centre in negative phase and right in neutral phase. A time-series of the DMI index is provided at the top of the figure which shows the timing of the three phases during a 10-year time-series (1997–2007). SST data provided from AVHRR.