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Modeling the enhancement of sea surface chlorophyll concentration during the cyclonic events in the Arabian Sea

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ABSTRACT

The response of a marine system to a tropical cyclone is often less studied due to lack of direct observations of such events. In this paper, we demonstrate the multifold benefits of using a fully coupled physical-biogeochemical model, configured using Regional Ocean Modeling System (ROMS), in investigating the biogeochemical response of the upper ocean to a tropical cyclone in the semi-landlocked basin of Arabian Sea in the north Indian Ocean. We show that the model manages to capture the spatio-temporal variability of the biological state variables during and after the passage of cyclones. We also investigate the processes that lead to chlorophyll enhancement during cyclone passage - a benefit that model provides against satellite observations. We show that Ekman pumping leads to the shoaling of thermocline depth – which in turn, triggers productivity in the upper ocean by means of nutrient entrainment. The sea surface chlorophyll concentration reaches its peak approximately with the time-lag of a week after the increase in the nitrate concentration of the surface waters. We also show, using results from our model, that the chlorophyll enhancement followed by phytoplankton bloom is dependent on the intensity of the cyclone and is inversely dependent on the translational speed of the cyclone. Our study provides the first-ever comprehensive insights into the continuous and progressive physical-biogeochemical coupled processes across water column during cyclonic events in the Arabian Sea.

1. Introduction

Tropical cyclones (Vinayachandran and Mathew, 2003; Reddy et al., 2008; Maneesha et al., 2011) are known to modulate the upper layer stratification of the ocean waters and facilitate enhanced vertical mixing. This leads to the entrainment of nutrients in the euphotic zone from relatively deeper layers and fuels primary productivity (Shiah et al., 2000; Chen et al., 2003; Walker et al., 2005; Li et al., 2007; Eliot and Pattiaratchi, 2010; Rao et al., 2010; Piontkovski and Al-Hashmi, 2014). The degree of cooling and consequently the surface chlorophyll concentration depends, to a large extent, on the strength and translational speed of the winds associated with cyclones. While strength and cooling are directly proportional, translational speed is inversely related to cooling – both before and after cyclone passage – in the upper ocean waters (Mei et al., 2012; Piontkovski and Al-Hashmi, 2014). This is particularly important for slow moving cyclones having a translational speed between 1 and 10 knots and up to 10-fold increase in chlorophyll is observed in some cases. It is inferred that the slow translational speed allows more time for the cyclone to perturb the ocean beneath transporting nutrients from the deeper layers to the surface thereby triggering higher productivity.

Such cyclone induced phytoplankton blooms have been reported in many parts of the oceans, e.g., East China Sea (Li et al., 2013), Mediterranean Sea (Piontkovski and Al-Hashmi, 2014), Arctic Ocean (Zhang et al., 2014), the Pacific Ocean and date back to more than half a century (Franceschini and El-Sayed, 1968; Walsh et al., 1978). Tropical cyclones with varying intensity are also fairly common over the northern Indian Ocean, which consists of the Bay of Bengal and the Arabian Sea on either side of the Indian peninsula. Occurrences of such cyclone-induced blooms in these seas have also been widely reported (Subrahmanyam et al., 2002; Vinayachandran and Mathew, 2003; Smitha et al., 2006; Naik et al., 2008; Lotliker et al., 2014).

While the cyclone genesis is of prime research interest due to the associated societal impacts, our understanding of the subsurface dynamics of the oceans and its impact on marine ecology is limited due to a lack of observations during cyclone events. Most of these studies are

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based on remotely sensed data (Subrahmanyam et al., 2002; Sarangi et al., 2014; Preethi Latha et al., 2015) available for the surface or upper ocean and are limited to over a span of few days before and after the cyclonic event. Modeling based study of cyclonic events will complement for the data-gaps in satellite observations (due to cloud cover) and in-situ observations (due to rough weather). In addition, model can help resolve the time-series of the subsurface ocean properties such as nutrients and chlorophyll, which can not be resolved through observations.

In this paper, we study four cyclonic events in the Arabian Sea using a Regional Ocean Modeling System (ROMS) coupled to the biological model proposed by Fennel et al. (2006). We attempt to understand the dynamics of nutrient entrainment to the upper ocean followed by a resultant bloom and subsurface chlorophyll maxima in the wake of these cyclone passages. An attempt has also been made to derive the time-lag from the nutrient entrainment to the peak productivity and subsequently explain the observed time-lag. Lastly, we assess the role of the translational speed of cyclones in determining the magnitude of along-track productivity.

2. Data and methods

2.1. Study area

The Bay of Bengal (BoB) witnesses more tropical cyclones every year compared to the Arabian Sea (Singh et al., 2000). However, inherent characteristics of the BoB, such as strong upper layer stratification and presence of prominent barrier layers, do not allow a storm to generate enough perturbation in surface waters to effectively translate into enhanced surface productivity (Prasanna Kumar et al., 2002). On the other hand, the absence of barrier layer and relatively inferior stratification in the Arabian Sea (smaller Brunt-Vaisala frequency) makes this basin susceptible to enhanced vertical mixing followed by pronounced biological productivity. We have restricted our analysis of cyclonic events in this paper to already published events in order to generate verifiable outcomes (Fig. 1, Table 1).

2.2. ROMS model

The INCOIS coupled bio-physical model is comprised of a three-dimensional ocean circulation model, ROMS (Regional Ocean Modeling System) version 3.6 (Haidvogel et al., 2008), and a biological model consisting of the nitrogen cycle model containing parameterized sediment denitrification as described in Fennel et al. (2006), and a carbonate chemistry component following Zeebe and Wolf-Gladrow (2001). The ROMS model (Chakraborty et al., 2016, 2017) is set-up for the entire Indian Ocean basin from 30° E to 120° E in the east-west direction and 30° S to 30° N in the north-south direction. The model has a horizontal resolution of 0.25° and has 40 sigma levels in the vertical. The vertical profile has a resolution of 0.7 m nearshore. Off the shelf to a bottom depth of 5000 m, the vertical resolution ranges from 15 m at the surface to 500 m at the bottom. The bathymetry is taken from Sindhu et al. (2007). The vertical constraint parameters are selected so as to reproduce fine scale vertical resolution for the upper ocean. There are approximately 26 levels in the top 200 m of the water column in the deep ocean (with a depth $>$ 3500 m). The K-Profile Parameterization (Large et al., 1994) vertical mixing scheme was used. Biharmonic viscosity and diffusion schemes are chosen for horizontal mixing. The lateral boundaries in the east and south are open whereas the western and northern boundaries are solid walls. It is challenging to configure high resolution global models due to computational limitations. On the contrary, a global model with coarse resolution fails to capture fine scale variabilities in the regional oceans. In order to overcome these difficulties, we adopted one-way nested modeling approach in which a global ocean general circulation model provides boundary information to a regional model that is further coupled to an ecosystem model (Shulman et al., 2004). This approach utilizes strong relaxation at the open boundaries but weaker relaxation in shallow waters and productive zones to allow the model to respond more freely to surface atmospheric forcing.

The model is spun up for a period of 10 years from an initial state derived from the monthly climatological values of January of all the prognostic variables of the physical state of the ocean estimated from Estimating the Circulation and Climate of the Ocean (ECCO) data. The model is forced using climatological winds and fluxes derived respectively from QuikSCAT and objectively analyzed flux (OAux) data (Jin and Weller, 2008) during the spin-up time. Then the biological module is switched on. Nitrogen and oxygen, however, were initialized using the World Ocean Atlas (WOA) 2009 data. Due to a lack of information on the spatial distribution of other biological state variables in the Indian Ocean, the initial states of these biological variables were set uniformly throughout the ocean at 0.01 mg m^{-3} in the hope that given sufficient time the transient processes will decay and coupled dynamics in the model will be able to capture the salient spatio-temporal features of these variables. The three dimensional momentum and tracer fields are clamped at the eastern and southern boundary to the monthly climatological values derived from ECCO. However, the model uses a Flather (1976) boundary condition for the free surface and Chapman (1985) boundary conditions on the 2-D momentum fields. Closed boundary conditions are used for the biological variables knowing that the observations of biogeochemical variables are limited in and around the Indian Ocean. Clamped boundary conditions are used for nitrogen and oxygen. The climatological run is carried out for the coupled set-up for 30 years after which the model is forced with realistic atmospheric data in order to simulate the true state of the ocean. QuikSCAT wind is used to force the model during the period from January 01, 2000 to November 18, 2009 and the OAflux data is used to compute the air-sea fluxes (surface air temperature, surface specific humidity, net longwave radiation and net shortwave radiation) that are necessary to force the model. Daily-averaged model data are extracted from 01-Jan-2000 to 18-Nov-2009 for the analysis presented in this paper.

2.3. Depth-integrated primary productivity

In Vertically Generalized Productivity Model (VGPM; Behrenfeld and Falkowski, 1997) model, the optimal rate of productivity (optimal water column carbon fixation (g C (mg chlorophyll a)$^{-1}$ h^{-1}) is modeled as a seventh order polynomial function of SST. In our ROMS application, the relationship between optimal rate of productivity and SST follows the exponential relationship by Eppley (1972), as modified by Antoine et al. (1996). Availability of sunlight, in general, plays a major role in defining the vertical distribution of chlorophyll in the upper water column and is a major factor that limits column productivity immediately after the cyclone passage. To normalize this, model simulated depth-integrated primary productivity up to Mixed Layer Depth (MLD) has been derived for all the four cases in order to cover maximum extent of SCM in this region (Martin et al., 2013; Ravichandran et al., 2012; Furuya, 1990). MLD has been defined as the depth where the density is equal to the sea surface density plus the increment in density equivalent to 0.5 °C (Girishkumar et al., 2017).

3. Results and discussion

We have selected only those prominent cyclonic events for which studies with well-documented observations were available so that results could be tallied, confidence on the model can be built and acquired understanding may be translated to poorly-studied cyclonic events.

3.1. Case Study-1: cyclone 01A

An unnamed cyclone 01A (hereafter C01A) occurred in the eastern