Optimization of Biological Production for Indian Ocean upwelling zones: Part – I: Improving Biological Parameterization via a variable Compensation Depth

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Abstract

Biological modeling approach adopted by the Ocean Carbon Cycle Model Inter-comparison Project (OCMIP-II) provided amazingly simple but surprisingly accurate rendition of the annual mean carbon cycle for the global ocean. Nonetheless, OCMIP models are known to have seasonal biases which are typically attributed to their bulk parameterization of ‘compensation depth’. Utilizing the principle of minimum solar radiation for the production and its attenuation by the surface Chl-a, we have proposed a new parameterization for a spatially and temporally varying ‘compensation depth’ which captures the seasonality in the production zone reasonably well. This new parameterization is shown to improve the seasonality of CO$_2$ fluxes, surface ocean pCO$_2$, biological export and new production in the major upwelling zones of the Indian Ocean. The seasonally varying compensation depth enriches the nutrient concentration in the upper ocean yielding more faithful biological exports which in turn leads to an accurate seasonality in carbon cycle. The export production strengthens by $\sim$70% over western Arabian sea during monsoon period and achieved a good balance between export and new production in the model. This underscores the importance of having a seasonal balance in model export and new production for a better representation of the seasonality of carbon cycle over upwelling regions. The study also implies that both the biological and solubility pumps play an important role in the Indian Ocean upwelling zones.

Keywords: Indian Ocean upwelling zones, Carbon cycle, Seasonal cycle - CO$_2$ flux and Oceanic pCO$_2$, Biogeochemical model parameterization, Export production - New production balance.
1. Introduction

Among the world’s oceans, Indian Ocean is characterized by a unique seasonally reversing wind systems called monsoon winds. The monsoon winds are the major physical drivers for the coastal and open ocean upwelling in the Indian Ocean. The major upwelling systems in the Indian Ocean are (1) the western Arabian Sea (WAS; Ryther et al., 1965, Smith et al., 2001, Sarma., 2004, Wiggert et al., 2006, Murtugudde et al., 2007, McCreary et al., 2009, Prasanna Kumar et al., 2010, Naqvi et al., 2010, Roxy et al., 2015) (2) the Sri Lanka Dome (SLD; Vinayachandran et al., 1998, 2004), (3) Java and Sumatra coasts (SC; Murtugudde et al., 1999, Susanto et al., 2001, Osawa et al., 2010, Xing et al., 2012) and (4) the Seychelles-Chagos thermocline ridge (SCTR; Dilmahamod., 2016, Figure 1). The physical and biological processes and their variability over these key regions are inseparably tied to the strength of the monsoon winds and associated nutrient dynamics. The production and variability in the coastal upwelling systems are a key concern to the fishing community, since they affect the day-to-day livelihood of the coastal populations (Harvell et al., 1999, Roxy et al., 2015, Praveen et al., 2016). Coastal upwelling systems account for about 11% of the world oceanic biological production (Prasanna Kumar et al., 2001, Wiggert et al., 2005, Levy et al., 2007, McCreary et al., 2009, Liao et al., 2016) and are especially important for the Indian Ocean rim countries due to their developing countries status.

Arabian Sea is a highly productive coastal upwelling system characterized by phytoplankton blooms both in summer (Prasanna Kumar et al., 2001, Naqvi et al., 2003, Wiggert et al., 2005) and winter (Banse K. et al., 1986, Schubert et al., 1998, Wiggert et al., 2000, Barber et al., 2001, Prasannakumar et al., 2001, Sarma., 2004). Arabian Sea is known for the second largest Tuna fishing region among all oceans (Lee et al., 2005). The Somali and Omani upwelling
regions experience phytoplankton blooms that are prominent with Net Primary Production (NPP) exceeding 438.29 g C m\(^{-2}\) yr\(^{-1}\) (Liao et. al., 2016). On the other hand productivity over the SLD (Vinayachandran and Yamagata, 1998), in the sea of Sri Lanka is triggered by an open ocean Ekman suction. SLD shows strong Chl-a blooms during the summer monsoon (Murtugudde et al., 1999, Vinayachandran et al., 2004). Compared to the Arabian Sea this bloom lasts for more than four months due to the impact of biogeochemistry of the region (Vinayachandran et. al., 2004). During the winter monsoon, the southwest Bay of Bengal is also characterized by Chl-a blooms associated with the intense cyclonic activities (Vinayachandran and Mathew, 2003).

The SC upwelling is basically due to the stronger alongshore winds and its variation is associated with impact of equatorial and coastal Kelvin waves (Murtugudde et. al., 2000). The interannual variability associated with Java-Sumatra coastal upwelling is strongly coupled with ENSO (El-Nino Southern Oscillation) through Indonesian throughflow (Susanto. et. al., 2001, Valsala et al., 2011) and peaks in July through August with a potential new production of 1.02 \(10^{14}\) g C yr\(^{-1}\) (Xing et. al., 2012).

The SCTR region productivity has large spatial and interannual variability. The warmer upper ocean condition associated with El Nino reduce the amplitude of the subseasonal SST variability over the SCTR (Jung and Kirtman., 2016). The Chl-a concentration peaks in summer when the southeast trade winds induce mixing and initiate the upwelling of nutrient-rich water (Murtugudde et. al., 1999, Wiggert et al., 2006, Vialard. J. et. al., 2009, Dilmahamod et al., 2016).

Understanding the biological production and variability in the upwelling systems are important because it gives us crucial information regarding marine species variability (Colwell,
The observations also provide vital insights into physical and biological interactions of the ecosystem (Naqvi et al., 2010) although limitations of sparse observations often force us to depend on models to examine the large spatio-temporal variability of the ecosystem (Valsala et al., 2013). Simple to intermediate complex marine ecosystem models have been employed by several of the previous studies (Sarmiento et. al., 2000, Orr. et. al., 2001, Matsumoto et. al., 2008). However the representation of marine ecosystem variability by proper parameterizations in models has always been a daunting task. This is impediment to the accurate representation of biological primary and export productions in models (Friedrichs et al., 2006, 2007) and the parameterization issues also impact the modeling of upper trophic levels (Lehodey et al., 2010).

Biological production can be quantified with a better understanding of primary production by phytoplankton. Primary production depends on water temperature, light and nutrient availability (Brock. et. al., 1993, Moisan et. al., 2002) and this became the key reason for parameterizing the production in models as one or more combinations of these terms (Yamanaka et. al., 2004). Any of these parameters can be tweaked to alter production in models. For example the availability of nutrients and light determines the phytoplankton growth (Eppely et al., 1972) or growth rate (Boyd et. al., 2013). Stoichiometry and carbon-to-Chl-a ratios are other important factors to be considered in modeling (Christian et al., 2001, Wang et al., 2009) but we will not consider them in this study.

In 1995, an initiative by the IGBP/GAIM (International Geosphere-Biosphere program/Global Analysis, Integration and Modeling) and IGBP/JGOFS (Joint Global Ocean Flux Study) to study carbon cycle referred to as the Ocean Carbon cycle Model Intercomparison Project (OCMIP) greatly improved our understanding of global carbon cycle (Raymond Najjar...

Although OCMIP – II is a very simplified model, it is surprisingly accurate in simulating the annual mean state and the response to anthropogenic climate change (Orr et al., 2001, Doney et. al., 2004). However, the OCMIP – II model simulations comes with a penalty of higher seasonal biases when compared with observations (Orr et al., 2003). In this protocol the light limitation is formulated as a bulk quantity with the notion that the minimum light irradiance at which phytoplankton photosynthesis is sufficient to balance the community respiration, Ic, is the compensation irradiance (Sarmiento et al., 2006) and the depth at which the photosynthesis equals respiration is the compensation depth Zc (Smetacek and Passow, 1990), which is clearly different from the conventional euphotic zone depth (Morel., 1988). If the irradiance is below Ic, phytoplankton growth will be suppressed. If the irradiance is above this, the planktonic photosynthesis will exceed the community respiration and production will increase (Parsons et. al., 1984, Sarmiento et. al., 2006). Therefore the compensation depth represents the oceanic production zone in this approach.

However, Zc was held constant in time and space in OCMIP-II models (Raymond Najjar and James Orr, 1998, Matsumoto et. al., 2008) though in reality Zc varies in space and time (Najjar and Keeling, 1997) just as the euphotic zone depth does as documented in ship measurements (Qasim, 1977, 1982). The variation in compensation depth indicates the seasonality of the production zone itself. Availability of light and nutrients at an optimum level is clearly essential for primary production.

Most of the biophysical models prescribe a constant value for compensation depth (e.g., Zc = 75m in OCMIP –II protocol (Raymond Najjar and James Orr, 1998), Zc = 100m for Minnestoa
Earth System Model (Matsumoto et al., 2008) although in reality it is not a constant. Depending on the latitude, compensation depth varies between 50m and 100m in the real world (Najjar and Keeling, 1997). In our study we have attempted a novel biological parameterization scheme for spatially and temporally varying compensation depth in the OCMIP – II framework by representing it as a function of optimum solar radiation (Parsons et al., 1984) and Chl-a availability. In this hypothesis, the minimum solar radiation required for photosynthesis is taken as 10 W m$^{-2}$ below which the production reduces to 20% (Parsons et al., 1984) and the Chl-a concentration which determines the attenuation of solar radiation with depth in the production zone is also assumed to vary to yield the spatio-temporal variability of $Z_c$. The basic currency of phosphate will act as limiting factor for biological production within this varying compensation depth. This spatially and temporally varying compensation depth represents the seasonality in the production zone.

Regions of sustained upwelling like the eastern equatorial Pacific are well understood in terms of the role of upwelling in increasing the surface water pCO$_2$ to drive an outgassing of CO$_2$ into the atmosphere (Feely et al., 1999, Valsala et al., 2014). The Indian Ocean on the other hand only experiences seasonal upwelling which is relatively weak in the deep tropics but stronger off the coasts of Somalia and Oman and in the SLD region (Valsala et al., 2013). The relative importance of the solubility vs. biological pump is not well understood. Our focus here on implementing seasonality in the compensation depth of OCMIP models nonetheless leads to new insights on the impact of improved biological production on surface water pCO$_2$ and air-sea CO$_2$ fluxes. The largely positive effects of the variable compensation depth over the Indian Ocean and the sensitivity experiments where upwelling is muted strongly imply that the biological pump may play as much of a role as the solubility pump in determining surface pCO$_2$ and CO$_2$ fluxes.
The paper is organized as follows. Model, Data and Methodology are detailed in Section 2. The spatially inhomogeneous $Z_c$ derived out of the new parameterization and its impact in simulated seasonality of biology and carbon cycle are detailed in Section 3. Further results and discussion are followed in Section 4 and a conclusion is given in Section 5.

2. Model, Data and Methods

2.1. Model

The study utilizes the Offline Ocean Tracer Transport Model (OTTM) (Valsala et al., 2008) coupled with OCMIP biogeochemistry model (Raymond Najjar and James Orr, 1998). OTTM does not compute currents and stratifications (i.e., temperature and salinity) on its own. It is capable of accepting any ocean model or data-assimilated product as physical drivers. The physical drivers prescribed include 4-dimensional currents ($u,v$), temperature, salinity, and 3-dimensional mixed layer depth, surface freshwater and heat fluxes, surface wind stress and sea surface height. The resolution of the model setup is similar to the parent model from which it borrows the physical drivers. With the given input of Geophysical Fluid Dynamics Laboratory (GFDL) reanalysis data, the zonal and meridional resolutions are $1^\circ$ with 360 grid points longitudinally and $1^\circ$ at higher latitudes but having a finer resolution of $0.8^\circ$ in the tropics, with 200 grid points, respectively. The model has 50 vertical levels with 10m increment in the upper 225m and stretched vertical levels below 225m. The horizontal grids are formulated in spherical co-ordinates and vertical grids are in $z$ levels. The model employs a B-grid structure in which the velocities are resolved at corners of the tracer grids. The model uses a centered-in-space and centered-in- time (CSCT) numerical scheme along with an Asselin-Robert filter (Asselin., 1972) to control the ripples in CSCT.
The tracer concentration (C) evolves with time as

$$\frac{\partial C}{\partial t} + U \nabla_H C + W \frac{\partial C}{\partial z} = \frac{\partial}{\partial z} K_z \frac{\partial}{\partial z} C + \nabla_H \cdot (K_h \nabla_H C) + \Phi$$

(1)

where $\nabla_H$ is the horizontal gradient operator, $U$ and $W$ are the horizontal and vertical velocities respectively. $K_z$ is the vertical mixing coefficient, and $K_h$ is the two-dimensional diffusion tensor. $\Phi$ represents any sink or source due to the internal consumption or production of the tracer as well as the emission or absorption of fluxes at the ocean surface. Here, the source and sink term are provided through the biogeochemical model. Vertical mixing is resolved in the model using K-profile parameterization (KPP) (Large et al., 1994).

In addition to KPP, the model uses a background vertical diffusion reported by Bryan and Lewis (Bryan and Lewis, 1979) in order to represent the convention and mixing that happens in a time scale of a few days. For horizontal mixing model incorporates Redi fluxes (Redi, 1982) and GM fluxes (Gent and Mcwilliams, 1990) which accommodate the eddy induced variance from the mean in the tracer transport. A weak Laplacian diffusion is also included in the model for computational stability where sharp gradient of concentration occurs.

The biogeochemical model used in the study is based on the OCMIP – II protocol as stated above. The main motivation of OCMIP–II model design is to simulate the ocean carbon cycle with reductionist approach to ocean biology using appropriate biogeochemical parameterizations. The major advantage of the OCMIP – II protocol is (i) it reproduces the first order carbon cycle and the associated elemental cycles in the ocean reasonably well and (ii) it is much easier to implement and computationally efficient than the explicit ecosystem models. The present version of the model has five prognostic variables coupled with the circulation field, viz., inorganic phosphate (PO$_4^{3-}$), dissolved organic phosphorous (DOP), oxygen (O$_2$), dissolved
inorganic carbon (DIC) and alkalinity (ALK). In order to retrieve the accurate spatial and
temporal distribution of CO$_2$ flux and pCO$_2$, the model uses a “nutrient restoring” approach
(Najjar et. al., 1992, Anderson and Sarmiento., 1995) for biological production. The basic
currency for biological production in the model is phosphate because of the availability of a
more extensive database and to eliminate the complexities associated with nitrogen fixation and
denitrification. The biogeochemical dynamics implemented in the model are given Appendix-A

The air – sea CO$_2$ flux in the model is estimated by,

$$F = K_w \Delta pCO_2 \quad (2)$$

where $K_w$ is gas transfer velocity and $\Delta pCO_2$ is the difference in partial pressure of carbon
dioxide between the ocean and atmosphere. The design and validation of the physical model is
reported by Valsala et. al.,(2008, 2010) and biogeochemical design by Najjar and Orr (1998).

2.2. Data

The present setup of the model uses ocean reanalysis products based on MOM–4
(Modular Ocean Model) developed by GFDL (Chang et. al., 2012). Monthly data from 1961 to
2010 were utilized in the present study. For validating the results observational datasets of CO$_2$
flux and pCO$_2$ were taken from Takahashi et al., (2009). Satellite derived Net Primary
Production data were taken from Sea-viewing Wide Field of view sensor (SeaWiFS) Chl-a
product, calculated using Vertically Generalized Production Model (VGPM) (Behrenfeld and
Falkowski, 1997). The initial conditions for PO$_4$ and O$_2$ were taken from World Ocean Atlas
(Conkright et al., 1994). Initial conditions for DIC and ALK were taken from the Global Ocean
Data Analysis Project (GLODAP) dataset. The data sources and citations are given in the
Acknowledgement.
A spin-up for 50 years from the given initial conditions are performed with the climatological physical drivers. Because the initial conditions were provided from a mean state observed climatology this duration of spin-up is sufficient to reach statistical equilibrium in the upper 1000 m (Le Quere et al., 2000). Atmospheric pCO$_2$ has been set to a value from the 1950s in the spin-up run for calculating the air-sea CO$_2$ exchange. A seasonal cycle of atmospheric pCO$_2$ has been prescribed.

After the spin-up, an interannual simulation for 50 years from 1961 to 2010 has been carried out with the corresponding observed atmospheric pCO$_2$ described in Keeling et al, (1995). The first five years of the interannual run were looped five times through the physical fields of 1961 repeatedly for a smooth merging of the spin-up restart to the interannual physical variables. Since the study is focused only on bias corrections to seasonal cycle with a variable $Z_c$, a model climatology has been constructed from 1990 to 2010. This includes the anthropogenic increase of oceanic DIC in the climatological calculation and is comparable with the Takahashi et al. (2009) observations.

Additional two sensitivity experiments have been performed separately by providing annual mean currents or temperatures as drivers over selected regions of the basin for segregating the role of varying compensation depth ($\text{var}Z_c$) in improving the seasonality of carbon cycle and biological production. The model driven with annual mean currents suppress the effect of upwelling by muting the ekman divergence over the region of interest. On the other hand, the model forced with annual mean temperatures suppresses the cooling effect of upwelling. This will highlight the effect of new parameterization in simulating seasonality of carbon cycle and biological production. A smoothing technique with linear interpolation ($u = u(1 - x) + \bar{u}x$) is applied to the offline-data in order blend the annual mean fields ($\bar{u}$)
given to the selected region with the rest of the domain (u) in order to reduce a sudden transition at the boundaries.

2.3. Compensation depth ($Z_c$) parameterization

The OCMIP – II simulation protocol separates the production and consumption zones by a depth termed as compensation depth ($Z_c$); the depth at which photosynthesis is equal to respiration of the photosynthetic community (Smetacek and Passow., 1990). The light intensity at compensation depth is compensation irradiance ($I_c$) with larger values at higher temperatures since respiration is temperature dependent (Parsons et. al., 1984, Ryther, 2003). We define a spatially and temporally varying compensation depth (hereinafter varZc) as a depth where solar radiation (attenuated by surface Chl-a, Jerlov et al., 1976) reaches a minimum value of 10 W m$^{-2}$. In this way the varZc has both spatio-temporal variability of light as well as Chl-a data. The Chl-a is given as monthly climatology as constructed from the satellite data. Observations show that the primary production reduces rapidly to 20% or less of the surface value below a threshold of 10 W m$^{-2}$ (Parsons et. al., 1984, Ryther, 2003). Figure 2 compares the scatter of average relative photosynthesis within varZc as a function of solar radiation for the Indian Ocean. This encapsulate the corresponding curve from the observations for the major phytoplankton species in the ocean such as diatoms, green algae and dinoflagellates (Ryther et al., 1956, 2003, Parsons et al., 1984). The model permits 100% relative photosynthesis for radiation above 50 W m$^{-2}$. However the availability of phosphate concentration in the model act as an additional limiter for production which indirectly represents the photoinhibition at higher irradiance, for example oligotrophic gyres.
3. Results and Discussions

The inclusion of seasonality in Zc by way of parameterizing varZc leads to a remarkable spatio-temporal variability in compensation depth (Figure 3). The compensation depth over the Arabian Sea varies from 10m to 25m during DJF and deepens up to 45m during MAM in parallel with incoming solar radiation. During the monsoon season (JJAS), the compensation depth again shoals to 10m-35m due to the attenuation of solar radiation by the increased biological production (Chl-a). During Oct–Nov the Zc slightly deepens as compared to JJAS.

The Bay of Bengal compensation depth deepens from 35m to 40m during DJF and further deepens to 50m during MAM when the solar radiation is maximum and biological production is minimum (Prasannakumar et al., 2002). Further reduction of compensation depth can be seen through JJAS as a result of reduction in solar radiation during monsoon cloud cover. The Zc during Oct–Nov is on an average of 35m. However, caution is needed since the Bay of Bengal is dominated by freshwater forcing from rivers and precipitation and temperature inversions occur routinely (Howden and Murtugudde, 2001, Vinayachandran et. al., 2013). The impact of these factors on compensation depth variability is not clear and is not addressed here.

The equatorial Indian Ocean can be seen as a belt of 40m-45m deep compensation depth throughout the season except for JJAS. During JJAS, a shallow compensation depth is seen near the coastal Arabian Sea (around 10m to 35m) presumably due to the coastal Chl-a blooms. Deep compensation depth off the coast of Sumatra (~ 40m to 50m) is found during JJAS. Java-Sumatra coastal upwelling is centered on September-Nov (Susanto et al., 2001) and upwelling originates at around 100m deep (Xing et al., 2012).
Southward of 10°S in the oligotrophic gyre region, the compensation depth varies from 40m to more than 60m throughout the year. A conspicuous feature observed while parameterizing the solar radiation and Chl-a dependent Zc is that its maximum value never crosses 75 m especially in the Indian Ocean which is the value specified in OCMIP-II models. The cutoff depth of 75 m in OCMIP-II is obtained from observing the seasonal variance in the oxygen data (Najjar and Keeling, 1997) as an indicator of production zone. However, parameterizing a production zone based on optimum solar radiation and Chl-a (Parsons et al., 1984) predicts a production zone and its variability that is largely less than 75 m. The consequence of this in the seasonality of the modeled carbon cycle is illustrated as follows.

3.1. Simulated seasonal cycle of pCO$_2$ and CO$_2$ fluxes

The annual mean biases in simulated CO$_2$ fluxes and pCO$_2$ were evaluated by comparing with Takahashi et al., (2009) observations (Figure 4). The model biases are significantly reduced with the implementation of varying Zc compared to that of the constant Zc. A notable reduction in pCO$_2$ bias (by ~ 10µatm) is observed along the WAS region [Figure (4d)].

In order to address the role of the new biological parameterization of a variable compensation depth, we extended our study by choosing four key regions where the biological production and CO$_2$ fluxes are prominent in the Indian Ocean with additional sensitivity experiments (see Introduction and references therein). The boxes we considered are, (1) Western Arabian Sea (WAS) [40°E:65°E, 5°S:25°N] (2) Sri Lanka Dome (SLD) [81°E:90°E, 0°:10°N] (3) Seychelles-Chagos Thermocline Ridge (SCTR) [50°E:80°E, 5°S:10°S] (4) Sumatra Coast (SC) [90°E:110°E, 0°:10°S; Figure 1]. The seasonal variations of Zc over these selected key regions
are shown in Figure 5. A detailed analysis of CO$_2$ fluxes, pCO$_2$, biological export and new production for these key regions are presented below.

### 3.2. Western Arabian Sea (WAS) region

The WAS Zc has a double peak pattern over the annual cycle. Over the February-March period Zc deepens up to a maximum of 43.85 ± 2.3 m into March and then shoals to 25.75 ± 1.5 m (Fig 5) during the monsoon period (uncertainty represents the interannual standard deviations of monthly data from 1990-2010). This shoaling of compensation depth during the monsoon indicates the potential ability of the present biological parameterization to capture the wind driven upwelling related production in the WAS. During the post monsoon period, the second deepening of compensation depth occurs during November with a maximum depth of 34.91 ± 2.2 m. The ability to represent the seasonality of biological production zone renders a unique improvement in CO$_2$ flux variability especially in the WAS region in comparison to the OCMIP-II experiments (Orr et al, 2003, Figure (6a)).

OCMIP –II simulations with a constant Zc of 75 m underestimate the CO$_2$ flux when compared to the observations of Takahashi et al. (2009). This underestimation is clearly visible during monsoon period. Our simulations with the present biological parameterization having a spatially and temporally varying compensation depth results in a better seasonality of CO$_2$ flux when compared with Takahashi et al. (2009) observations (Figure 6a). The improvement brought about the varying Zc scheme is able to represent the seasonality of CO$_2$ flux especially during the monsoon period, when wind driven upwelling is dominant. Obviously the role of the biological and solubility pumps have to be deciphered in this context.
The CO₂ flux during July from observations, constZc simulations and varZc simulations are 3.09 mol m⁻² yr⁻¹, 1.82 ± 0.4 mol m⁻² yr⁻¹ and 3.10 ± 0.5 mol m⁻² yr⁻¹, respectively. Southwesterly wind-driven upwelling over the WAS especially off Somali coast (Smith & Codispoti, 1980, Schott, 1983, Smith, 1984) and Oman (Bruce, 1974, Smith & Bottero, 1977, Swallow, 1984, Bauer et al, 1991), pulls nutrient-rich subsurface waters closer to the surface while the available turbulent energy due to the strong winds leads to mixed layer entrainment of the nutrients resulting in a strong surface phytoplankton bloom (Krey & Babenerd, 1976, Banse, 1987, Bauer, 1991, Brock et al, 1991). This regional bloom extends over 700 km offshore from the Omani coast due to upward Ekman pumping driven by strong, positive wind-stress curl to the northwest of the low level jet axis and the offshore advection (Bauer et. al., 1991, Brock et al., 1991, Brock & McClain, 1992a, b, Murtugudde and Busalacchi., 1999) resulting in strong outgassing of CO₂ flux and an enhanced pCO₂ in the western Arabian Sea region (Valsala and Maksyutov, 2013, Sarma et al., 2002). The seasonal mean CO₂ flux during the southwest monsoon period (JJAS) for constZc simulations and varZc simulations are 1.44 ± 0.2 mol m⁻² yr⁻¹ and 2.31 ± 0.4 mol m⁻² yr⁻¹, respectively. The biological parameterization of varying compensation depth considerably improves the average CO₂ flux during the monsoon period by 0.86 ± 0.1 mol m⁻² yr⁻¹. The annual mean CO₂ flux from observations, constZc simulations and varZc simulations are 0.94 mol m⁻² yr⁻¹, 0.80 ± 0.17 mol m⁻² yr⁻¹ and 1.07 ± 0.2 mol m⁻² yr⁻¹, respectively. The annual mean CO₂ flux improved by 0.27 ± 0.05 mol m⁻² yr⁻¹.

Seasonality in pCO₂ also shows a remarkable improvement during the southwest monsoon period [Figure (6b)]. The pCO₂ with ConstZc is considerably lower at a value of 385.22 ± 3.5 µatm during June compared to observational values of 392.83 µatm. However, varZc simulations perform better in terms of pCO₂ variability. The peak value of pCO₂ reaches up to 405.42 ± 5.8
µatm. The seasonal mean pCO$_2$ during the southwest monsoon period from observations, constZc simulations and varZc simulations are 397.58 µatm, 389.18 ± 3.6 µatm and 399.95 ± 5.0 µatm, respectively. The improvement in pCO$_2$ brought about by varZc simulations is 10.76 ± 1.3 µatm compared to the constZc simulations. This inherently says that constZc simulations fail to capture the pCO$_2$ driven by upwelling during southwest monsoon, meanwhile varZc simulations are demonstrably better in representing this seasonal increase. The annual mean pCO$_2$ from observations, constZc and varZc simulations are 394.69 µatm, 389.62 ± 3.9 µatm and 391.19 ± 4.7 µatm, respectively. However it is worth mentioning that there are parts of the year where the constant Zc performs better compared to varying Zc. For instance during MAM as well as in November, the constZc simulations yielded a better comparison with the observed pCO$_2$ whereas varZc simulations yield a reduced magnitude of pCO$_2$. This may well indicate the biological vs solubility pump controls on pCO$_2$ during the intermonsoons. The role of mesoscale variability in the ocean dynamics may also play a role (Valsala and Murtugudde, 2015) Nevertheless during the most important season (JJAS) when the pCO$_2$, CO$_2$ fluxes and biological production are found to be dominant in the Arabian Sea, the varying Zc produces a better simulation.

The improvement shown by the implementation of new biological parameterization in the simulations of CO$_2$ flux and pCO$_2$ can be answered by further analysis of the model biological production. Figure 7 shows the comparison of model export production and new production with observational export production from satellite-derived NPP for constZc and varZc simulations. The model export production in the constZc simulations is much weaker when compared to varZc simulations. The varZc simulations have improved the model export production. Theoretically, the new and export productions in the model should be in balance with each other.
(Eppley and Peterson, 1979). ConstZc export production is much weaker than new production and it is not in balance. In contrast the varZc simulation yields a nice balance among them.

Comparing with the observational export production which peaks in August at a value of 154.78 g C m\(^{-2}\) yr\(^{-1}\), the varZc simulated export and new productions peak at a value of 160.44 ± 20.4 g C m\(^{-2}\) yr\(^{-1}\) and 167.18 ± 24.0 g C m\(^{-2}\) yr\(^{-1}\), respectively but in July. A similar peak can be observed in constZc simulated new production as well at a value of 178.19 ± 28.0 g C m\(^{-2}\) yr\(^{-1}\). This apparent shift of one month during JJAS in the model export production as well as in the new production is noted as a caveat in the present set up which will need further investigation.

Arabian Sea production is not just limited by nutrients but also the dust inputs (Wiggert and Murtugudde, 2006). The dust induced primary production in the WAS especially over the Oman coast is noted during August (Liao et. al., 2016). The mesoscale variability in the circulation and its impact on production and carbon cycle are also a limiting factor in this model as noted above.

The seasonal mean export production during the southwest monsoon period from satellite-derived estimate is 123.57 g C m\(^{-2}\) yr\(^{-1}\), whereas for constZc and varZc simulations it is 84.81 ± 16.0 g C m\(^{-2}\) yr\(^{-1}\) and 147.19 ± 23.8 g C m\(^{-2}\) yr\(^{-1}\), respectively. The new biological parameterization strengthened the model export production by 62.38 ± 7.8 g C m\(^{-2}\) yr\(^{-1}\) for the southwest monsoon period, which is over a 70% increase. This indicates a considerable impact of the biological pump in the model simulated CO\(_2\) flux and pCO\(_2\) over the WAS. For constZc simulations, the computed new production is slightly higher (150.84 ± 27.9 g C m\(^{-2}\) yr\(^{-1}\)) than that of varZc (133.03 ± 19.5 g C m\(^{-2}\) yr\(^{-1}\)). The annual mean export production from observations, constZc and varZc simulations are 94.31 g C m\(^{-2}\) yr\(^{-1}\), 77.41 ± 15.1 g C m\(^{-2}\) yr\(^{-1}\) and 122.54 ± 25.2 g C m\(^{-2}\) yr\(^{-1}\), respectively.
To understand how the varying compensation depth parameterization strengthened the export production in the model, we analyzed the phosphate profiles. It appears that the varZc parameterization allows more phosphate concentration (Figure 8a,b) in the production zone and thereby increases the corresponding biological production (Figure 8c, d). The net export production in the model during JJAS is consistent with the satellite data (Figure 8d, see also Figure 7a). However, in the constZc case the exports are rather ‘flat’ throughout the season with imperfect representation of seasonal biological export. The Table 1-4 summarizes all the values discussed here.

3.3 SriLanka Dome (SLD) Region

The seasonal variation in the compensation depth for the SLD has a similar pattern as that of the WAS. The compensation depth deepens to its maximum during March up to 45.23 ± 0.3 m and reaches its minimum during the following monsoon period at 30.79 ± 1.5 m [Figure (5)]. The similarities of varZc between WAS and SLD indicate that they both are under similar cycles of solar influx and biological production. The SLD chl-a dominates only up to July (Vinayachandran et al., 2004) which explains why production with varZc increase earlier compared to the WAS which occurs during August-October.

The seasonality in CO₂ flux and pCO₂ were compared with Takahashi et al., (2009) observations [Figure (9)]. The varZc results in a slight improvement in CO₂ flux when compared with constZc [Figure (9a)]. However both constZc and varZc simulations underestimate the magnitude of CO₂ flux when compared with observations. The seasonal mean CO₂ flux during
the monsoon period is 1.79 mol m\(^{-2}\) yr\(^{-1}\) from observations, which means SLD region is a source of CO\(_2\). But the mean values of constZc and varZc simulations yield flux values of -0.008 ± 0.2 mol m\(^{-2}\) yr\(^{-1}\) and 0.24 ± 0.2 mol m\(^{-2}\) yr\(^{-1}\), respectively. The constZc simulations misrepresent the SLD region as a sink of CO\(_2\) during monsoon period which is opposite to that of observations. The varZc simulations correct this misrepresentation to a source albeit at a smaller magnitude by 0.24 ± 0.09 mol m\(^{-2}\) yr\(^{-1}\) for the monsoon period. Compared to observations, the varZc case underestimates the magnitude of JJAS mean by 1.55 mol m\(^{-2}\) yr\(^{-1}\).

The annual mean CO\(_2\) fluxes for constZc and varZc simulations are -0.02 ± 0.1 mol m\(^{-2}\) yr\(^{-1}\) and 0.10 ± 0.2 mol m\(^{-2}\) yr\(^{-1}\), respectively. The varZc parameterization leads to an improvement of 0.13 ± 0.1 mol m\(^{-2}\) yr\(^{-1}\) in the annual mean CO\(_2\) flux when compared with constZc simulations. The observational annual mean of CO\(_2\) flux is 0.80 mol m\(^{-2}\) yr\(^{-1}\) which is highly underestimated by both simulations. This indicates a regulation of biological production of the region by varZc which makes this region a source of CO\(_2\) during monsoon. The role of the solubility pump may also be underestimated due to the biases in the physical drivers and the lack of mesoscale eddy activities in these simulations (Prasanna Kumar et. al., 2002, Valsala and Murtugudde., 2015).

The seasonality of pCO\(_2\) [Figure 9(b)] especially in the monsoon period has significantly improved. The mean pCO\(_2\) during the monsoon season from observation over the SLD region is 382.44 µatm. The seasonal mean pCO\(_2\) during monsoon period for constZc and varZc simulations are 371.67 ± 6.04 µatm and 379.24 ± 8.9 µatm, respectively. The annual mean pCO\(_2\) from observations, constZc and varZc simulations are 380.21 µatm, 370.76 ± 6.1 µatm and 374.94 ± 9.6 µatm, respectively. varZc simulations improve the JJAS mean pCO\(_2\) by 7.56 ± 2.8 µatm and the annual mean pCO\(_2\) by 4.18 ± 3.5 µatm, which is reflected in CO\(_2\) flux as well. This
is likely due to the impact of new biological parameterization in capturing the episodic upwelling in the SLD region which is further investigated by looking at its biological production.

The SLD biological production is highly exaggerated by the model for both constZc and varZc simulations (Figure 10a,b). The seasonal mean biological export for the monsoon period is 51.54 g C m\(^{-2}\) yr\(^{-1}\) as per satellite-derived estimates. However, the constZc and varZc simulations overestimate it by 167.71 ± 59.04 g C m\(^{-2}\) yr\(^{-1}\) and 151.51 ± 46.4 g C m\(^{-2}\) yr\(^{-1}\), respectively. This exaggerated export is visible in climatological annual means where for constZc and varZc simulations they are 144.43 ± 49.8 g C m\(^{-2}\) yr\(^{-1}\) and 156.08 ± 43.8 g C m\(^{-2}\) yr\(^{-1}\), respectively.

For constZc simulations, new production is overestimated from March to Oct when compared to the observations and second peak is observed in November (Figure 10a). But the overestimate in new production with varZc is observed only during JJAS period by a value of 26.23 g C m\(^{-2}\) yr\(^{-1}\). For the SLD region the varZc parameterization overestimates the export production but minimizes the excess new production, especially in the monsoon period by 64.15 ± 36.4 g C m\(^{-2}\) yr\(^{-1}\). This indicates that the varZc parameterization is somewhat successful in capturing the upwelling episode during monsoon over SLD. All values are summarized in Table 1-4.

### 3.4 Sumatra Coast (SC) region

The seasonal variation in the compensation depth over the SC region lies between 40 m and 46 m [Figure (5)]. The seasonal maximum occurs during JFM, especially in March with a depth of 45.5 m. During the monsoon period the compensation depth shoals slightly, with a minimum of 41.1 m in July. The variation in \(Z_c\) is relatively small as compared to the other regions which is consistent with its relatively low production throughout the year.
The seasonality of CO$_2$ flux and pCO$_2$ captured by constZc and varZc simulations are shown in Figure 11(a, b). The varZc simulations overestimate both CO$_2$ flux and pCO$_2$ especially during the monsoon. It is found that the constZc simulations are better compared to varZc simulations. The varZc simulations overestimate the seasonal mean CO$_2$ flux and pCO$_2$ by 1.19 mol m$^{-2}$ yr$^{-1}$ and 29.61 µatm, respectively, compared to observations (Table 1). However, constZc produces a better estimate compared with observations for CO$_2$ flux and pCO$_2$. The constZc simulations deliver a better annual mean than varZc (Table 1,2). The annual mean bias in constZc and varZc simulations for CO$_2$ flux is -0.0033 mol m$^{-2}$ yr$^{-1}$ and 0.31 mol m$^{-2}$ yr$^{-1}$, respectively. Similarly pCO$_2$ bias is 1.95 µatm and 9.07 µatm for constZc and varZc simulations.

Biological production simulated by the model in the SC explains the overestimation of CO$_2$ flux and pCO$_2$ (Figure 12). Both constZc and varZc simulations greatly overestimates export production in the model. But a small enhancement in the new production during JJAS in constZc case is an indicator of upwelling episodes. The seasonal mean new production during the monsoon from constZc and varZc are 63.64 ± 30.9 g C m$^{-2}$ yr$^{-1}$ and 78.11 ± 29.1 g C m$^{-2}$ yr$^{-1}$, respectively (Table 4). The seasonal mean export production during the monsoon from observation is 58.87 g C m$^{-2}$ yr$^{-1}$ (Table 3). ConstZc simulations represent a better new production, which is seen as a relatively small exaggeration of CO$_2$ flux and pCO$_2$. The biological response off SC is found to be better with constZc which is in contradiction to a general improvement found with varZc in the other regions examined here. Such discrepancies over the SC could be due to the effect of Indonesian Throughflow (Bates et al., 2006) which is not completely resolved in the model due to coarse spatial resolution.
3.5 Seychelles-Chagos Thermocline Ridge (SCTR) region

The SCTR is a unique upwelling region with a prominent variability in air-sea interactions (Xie et al., 2002). Wind-driven mixing and upwelling of subsurface nutrient rich water play a major role in biological production of this region (Dilmahamod et al., 2016). The seasonal cycle in the compensation depth is shown in figure 5. The maximum compensation depth occurs in November at about 44.94 m and the minimum at 33.2 m in July. The shoaling of compensation depth during the monsoon period shows that the biological parameterization captures the upwelling response over this region.

The seasonality of CO$_2$ flux and pCO$_2$ are shown in Figure 13. The Takahashi observations of CO$_2$ flux shows a peak in June with outgassing of CO$_2$ during the upwelling episodes. However, both constZc and varZc simulations underestimate this variability. The seasonality of CO$_2$ flux in varZc shows a significant improvement when compared to constZc simulations, but underestimated when compared to observations. The seasonal mean CO$_2$ flux during the monsoon for constZc and varZc simulations are 0.82 mol m$^{-2}$ yr$^{-1}$, -0.32 ± 0.3 mol m$^{-2}$ yr$^{-1}$ and -0.05 ± 0.4 mol m$^{-2}$ yr$^{-1}$, respectively. This represents a reduction in seasonal mean sink of CO$_2$ flux in the SCTR region during the monsoon by 0.27 ± 0.1 mol m$^{-2}$ yr$^{-1}$ bringing it closer to a source region (see Table 1 for details).

The improvement brought about in CO$_2$ flux is supported by the seasonal cycle in pCO$_2$. Based on observations, seasonal mean of pCO$_2$ with constZc during JJAS is underestimated by 11.47 µatm, varZc simulations underestimate it by 6.45 µatm. So it is evident that varZc simulations capture the upwelling episodes better, marked by a greater pCO$_2$ during JJAS period. However, the magnitude of pCO$_2$ is still underestimated compared to observations (Table 2).
Figure 14 shows the biological production of constZc and varZc simulations for SCTR. It is clear that both simulations overestimate the export production and underestimate the new production. The JJAS mean export production from observations, constZc and varZc are 51.08 g C m\(^{-2}\) yr\(^{-1}\), 57.39 ± 14.2 g C m\(^{-2}\) yr\(^{-1}\) and 99.23 ± 29.8 g C m\(^{-2}\) yr\(^{-1}\), respectively. The varZc simulations exaggerate the model export production by 48.14 g C m\(^{-2}\) yr\(^{-1}\). The varZc simulations improve the JJAS mean new production by 1.14 ± 2.2 g C m\(^{-2}\) yr\(^{-1}\) (Table 4). This slight improvement in the model new production especially during the monsoon period signals that the spatially and temporally varying compensation depth better captures the upwelling over SCTR.

Considering the annual mean values of model export and new production, constZc simulations are reasonably faithful to observations.

The underestimation of CO\(_2\) and pCO\(_2\) as well as the exaggeration of model export production and a slight overestimate in model new production may be due to two reasons. (1) SCTR is a strongly coupled region with remote forcing of the mixed layer – thermocline interactions (Zhou et al., 2008) which can affect the seasonality in biological production that the model may not be resolving reasonably (2) The bias associated with physical drivers, especially wind stress may underestimate the CO\(_2\) flux as well biological production. A similar overestimation of biological production was also reported in a coupled biophysical model (Dilmahamod et. al., 2016).

Table 1 – 4 shows the entire summary of seasonal and annual mean CO\(_2\) flux, pCO\(_2\) and biological production reported in Section 3.
4. Sensitivity Simulations

From the analysis of four major upwelling regions over Indian Ocean, it is evident that the biological parameterization of spatio-temporally varying compensation depth better captures upwelling episodes and thus it enhances the model export production. This is clearly visible over the WAS. In order to quantify how much the varZc parameterization contributed to seasonality of carbon cycle, two additional sensitivity simulations were carried out; (1) with annual mean offline currents and (2) annual mean offline temperatures with the notion of suppressing the dynamical and thermodynamical effects of seasonal upwelling over the WAS (see Section 2 for details). The focus on this region is motivated by its prominence as the most productive zone of the Indian Ocean. Moreover, the improvement in the biological processes in the model by the varZc parameterization is best captured in this region. The results are discussed in detail in the following subsections.

4.1 Impact of varZc parameterization in seasonality of carbon cycle with annual mean currents.

To quantify the impact of varZc parameterization, the model is forced with annual mean currents only over the WAS with unaltered currents in the rest of the ocean. The hypothesis is that the muting of the seasonal variability of Ekman divergence removes the upwelling and the biological pump contribution to production and carbon cycle. The comparison of constZc and varZc then allows us to decipher the impact of varZc on capturing the impacts of upwelling on biological production and the carbon cycle. The smooth blending of currents at the boundary of the WAS domain is achieved by a linear smoothing function as given in Section 2.
The model biological responses (inferred by comparing with the control run) in terms of the CO₂ flux shows a flat pattern over the monsoon period for constZc simulations [Figure 15(a)]. While the varZc simulations forced with the annual mean currents shows an enhanced CO₂ flux indicating the outgassing of CO₂ flux in the WAS due to wind-driven upwelling (Figure 15(b)). This qualitatively shows that the spatially and temporally varying compensation depth itself has improved the seasonality in the biological processes (export and new production) and captured the upwelling episodes during the monsoon. The varZc parameterization is responsible for improvement of $0.48 \pm 0.04$ mol m$^{-2}$ yr$^{-1}$ and $0.13 \pm 0.02$ mol m$^{-2}$ yr$^{-1}$ during JJAS seasonal and annual mean CO₂ flux, respectively. This improves the overall model CO₂ flux in the control run especially in July (Figure 15(b)).

Similar improvements were also noticed in pCO₂ (Figure 16). In the constZc simulations with annual mean currents, the pCO₂ dips down during JJAS monsoon period which indicates the inadequacy of constZc in capturing the upwelling enriched pCO₂ difference (Figure 16a, b). The varZc simulation slightly modifies the pCO₂ in the ‘right’ direction during JJAS despite the annual mean currents.

The export production and the new production in the model explain the modification of CO₂ flux and pCO₂ by varZc parameterization. The biological export production is highly underestimated in the constZc simulations forced with annual mean currents while the varZc simulations captures the seasonal upswing in production (Figure 17). The improved JJAS mean and annual mean export production by $43.51 \pm 8.6$ g C m$^{-2}$ yr$^{-1}$ and $30.28 \pm 13.7$ g C m$^{-2}$ yr$^{-1}$, respectively is a clear indication of the positive impacts of a variable Zc. Similarly the improvement in JJAS mean and annual mean new production (Figure 18) from varZc simulated with annual mean currents were $17.39 \pm 0.8$ g C m$^{-2}$ yr$^{-1}$ and $14.81 \pm 0.1$ g C m$^{-2}$ yr$^{-1}$,
respectively. In short the varZc biological parameterization improves the export and new productions in the model. This helps the model to capture the upwelling episodes over the study regions. Table 5 summarizes all the results of biological sensitivity runs.

4.2 Impact of varZc parameterization in seasonality of carbon cycle with annual mean temperatures.

Using the annual mean temperature over the WAS, we are suppressing the cooling effect of temperature due to upwelling and quantifying how much the model seasonality is improved by means of varZc parameterization. (see Section 2 for details). The varZc simulations forced with annual mean SST has greater JJAS mean and annual mean CO$_2$ flux by 0.88 ± 0.1 mol m$^{-2}$ yr$^{-1}$ and 0.28 ± 0.07 mol m$^{-2}$ yr$^{-1}$, respectively (Figure 19 and Table 6). For a given annual mean SST the solubility pump largely controls the CO$_2$ emission during JJAS if a variable Zc is prescribed, likely by the enrichment in the DIC (inferred from Figure 8b). Similarly the improvement in pCO$_2$ (Figure 20) with varZc simulation is also remarkable. The JJAS mean and annual mean improvements from the implementation of varZc are 11.05 ± 1.9 µatm and 1.91 ± 1.4 µatm, respectively. The detailed quantification of CO$_2$ and pCO$_2$ responses for this experimental setup is given in Table 6. The above analysis adds supporting evidence that the varZc simulations strengthen the seasonality of the model compared to the constZc case. This is presumably accomplished by the more accurate compensation depth and production zone implied with a variable Zc.
5. Summary and Conclusions

A spatially and temporally varying compensation depth parameterization as a function of solar radiation and Chl-a is implemented in the biological pump model of OCMIP-II for a detailed analysis of biological fluxes in the upwelling zones of the Indian Ocean. The varZc parameterization improves the seasonality of model CO₂ flux and pCO₂ variability, especially during the monsoon period. Significant improvement is observed in the WAS where monsoon wind-driven upwelling dominates biological production. The magnitude of CO₂ flux matches with observations, especially in July when monsoon winds are at their peak. Monsoon triggers upwelling in SLD as well which acts as a source of CO₂ to the atmosphere. The seasonal and annual mean are underestimated with constZc and the SLD is reduced to a sink of CO₂ flux. The varZc simulations modify the seasonal and annual means of CO₂ flux of SLD and depict it as a source of CO₂ especially during the monsoon, but the magnitude is still underestimated compared to Takahashi et al., (2009) observations. The SCTR variability is underestimated by both constZc and varZc simulations, portraying it as a CO₂ sink region whereas observations over the monsoon period indicate that the thermocline ridge driven by the open ocean wind-stress curl is in fact an oceanic source of CO₂. However, the varZc simulation reduced the magnitude of the sink in this region bringing it relatively closer to observations.

VarZc biological parameterization strengthens the export and new productions in the model, which allows it to a represent better seasonal cycle of CO₂ and pCO₂ over the study regions. The WAS export production is remarkably improved by 62.37 ± 7.8 g C m⁻² yr⁻¹ compared to constZc. This supports our conclusion that the varZc parameterization increases the strength of biological export in the model. Over the SLD, the JJAS seasonal mean export and new productions are underestimated in varZc compared to constZc simulations, but the annual mean
export production is improved. Export production at the SC and SCTR are highly exaggerated and there is hardly any improvement in new production with a variable Zc especially over the monsoon period. The inability of varZc parameterization to improve the seasonality of SC and SCTR may be due to the interannual variability of biological production associated with the Indonesian throughflow and remote forcing of the mixed layer-thermocline interactions and the effect of biases in the windstress data used as a physical driver in the model.

Further sensitivity experiments carried out with providing annual mean currents or temperatures in selected subdomains reveal that the varZc retains the seasonality of carbon fluxes, pCO₂, export and new productions in the right direction as in the observations. This strongly supports our contention that varZc parameterization improves the export and new productions and it is also efficient in capturing upwelling episodes of the study regions. This points out the significant role of having a proper balance in seasonal biological export and new production in models to capture the seasonality in carbon cycle. This also confirms the role of biological and solubility pumps in producing the seasonality of carbon cycle in the upwelling zones.

However the underestimation of seasonality of CO₂ flux over the SLD and overestimation over the SC as well as the SCTR is a cautionary flag for the study. This uncertainty poses an important scientific question as to whether the model biology over the SC and SCTR region is not resolving the seasonality in CO₂ flux and pCO₂ properly or whether the seasonality in the compensation depth is not able to fully capture the biological processes.

To address these questions we have used inverse modeling methods (Bayesian inversion) in order to optimize the spatially and temporally varying compensation depth using surface pCO₂ as
the observational constraints and computed the optimized biological production. The results will be reported elsewhere.
Appendix - A

For $Z < Z_c$,

\[ J_{prod} = \frac{1}{\tau} ([PO_4] - [PO_4^*]), \quad [PO_4] > [PO_4^*] \]  
(A1)

\[ J_{DOP} = \sigma J_{prod} - \kappa [DOP] \]  
(A2)

\[ J_{PO4} = -J_{prod} + \kappa [DOP] \]  
(A3)

\[ J_{ca} = R r_{C:P} (1 - \sigma) J_{prod} \]  
(A4)

\[ J_{DIC} = r_{C:P} J_{PO4} + J_{ca} \]  
(A5)

\[ J_{ALK} = -r_{N:P} J_{PO4} + 2 J_{ca} \]  
(A6)

For $Z > Z_c$,

\[ J_{prod} = 0, \quad [PO_4] \leq [PO_4^*] \]  
(A7)

\[ J_{DOP} = -\kappa [DOP] \]  
(A8)

\[ J_{PO4} = -\frac{\partial F}{\partial Z} + \kappa [DOP] \]  
(A9)

\[ F(Z) = F_c \left( \frac{Z}{Z_c} \right)^{\alpha} \]  
(A10)

\[ F_c = (1 - \sigma) \int_0^{Z_c} J_{prod} dZ \]  
(A11)

\[ J_{ca} = -\frac{\partial F_{Ca}}{\partial Z} \]  
(A12)

\[ F_{Ca} = R r_{C:P} F_c e^{-(z - Z_c)/d} \]  
(A13)
Where \( Z \) is the depth and \( Z_c \) is the compensation depth in the model. \( J_{\text{prod}}, J_{\text{DOP}}, J_{\text{PO4}}, J_{\text{Ca}} \) are the biogeochemical sources and sinks. Within the compensation depth (\( Z_c \)), the biological production in the model \( J_{\text{prod}} \) is calculated using equation A1. \([PO_4]\) is the model phosphate concentration and \([PO_4^\ast]\) is observational phosphate. \( \tau \) is the restoration timescale taken as 30 days. Whenever the model phosphate exceeds the observational phosphate, it allows production. The observational phosphate data were taken from the World Ocean Atlas (WOA) 1994 [Conkright et al., 1994]. During the biological production a fixed fraction (\( \sigma_{J_{\text{prod}}} \)) of phosphate is converted into Dissolved Organic Phosphate (DOP) which is a source for \( J_{\text{DOP}} \) [equation A2] and remaining – \( \kappa [DOP] \) is exported downward below the compensation depth, which is further remineralized into inorganic phosphate and made available for further biological production [equation A3]. The downward flux of phosphate which is not converted into DOP within the compensation depth is given by equation A11. The decrease of flux with depth due to remineralization is shown by equation A10. The values of the constants \( a, \kappa, \sigma \) are 0.9, (0.2 year)\(^{-1}\), 0.67, respectively. The rate of production is used to explain the formation of calcium carbonate cycle in the surface waters [equation A4] and its export is given by equation A12. Where \( R \) is the rain ratio, a constant molar ratio of exported particulate organic carbon to the exported calcium carbonate flux at compensation depth. The exponential decrease of calcium carbonate flux with scale depth \( d \) is given by equation A13. The biological source or biological sink of dissolved inorganic carbon (DIC) and alkalinity (ALK) is explained through equations A5 and A6, respectively. Where the values of rain ratio (\( R \)) is taken as 0.07 and the Redfield ratio, \( r_{C:P} = 106, r_{N:P} = 16 \) and scale depth \( d \) is chosen as 3500m.
Acknowledgement

The OCMIP-II routines were taken from (http://ocmip5.ipsl.jussieu.fr/OCMIP/). GFDL data for OTTM is taken from (http://data1.gfdl.noaa.gov/nomads/forms/assimilation.html). Takahashi data is taken from (http://www.ldeo.columbia.edu/res/pi/CO2/). The computations were carried out in High Performance Computing (HPC) of Ministry of Earth Sciences (MoES), IITM. Ms. Shikha Singh, Ms. Anju M (IITM) and Mr. Saran Rajendran (CUSAT) are thanked for initial helps and discussions.
721 **References**

726 Banse, K.: Seasonality of phytoplankton chlorophyll in the central and northern Arabian Sea,
728 Banse, K., McClain, C. R.: Winter blooms of phytoplankton in the Arabian Sea as observed by
730 Barber, R. T., Marra, J., Bidigare, R. C., Codispoti, L. A., Halpern, D., Johnson, Z., Latasa, M.,
731 Goericke, R., and Smith, S. L.: Primary productivity and its regulation in the Arabian Sea during
734 Estimates of net community production, Global Biogeochem. Cycles., 20, GB3021,
737 upon surface-layer depth and plankton biomass distribution in the Arabian Sea, Deep Sea Res.,
739 Behrenfeld, M. J., Falkowski, P. G.: Photosynthetic rates derived from satellite-based


Krey, J., Bahenerd, B.: Phytoplankton production atlas of the international Indian Ocean expedition, Institut fur Meereskundeander Universitat Kiel, Kiel, German.


Table: 1 WAS = Western Arabian Sea, SLD = Sri Lanka Dome, SC = Sumatra Coast, SCTR = Seychelles-Chagos Thermocline Ridge. JJAS mean and Climatological annual mean of CO₂ flux from Takahashi observations, constZc and varZc simulations. Units are in mol m⁻² yr⁻¹.

<table>
<thead>
<tr>
<th>Regions</th>
<th>CO₂ flux (mol m⁻² yr⁻¹)</th>
<th>JJAS Mean</th>
<th>Annual Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OBS constZc varZc</td>
<td>OBS constZc varZc</td>
<td></td>
</tr>
<tr>
<td>WAS</td>
<td>1.99 1.44 ± 0.2 2.31 ± 0.4</td>
<td>0.94 0.80 ± 0.1 1.07 ± 0.2</td>
<td></td>
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<tr>
<td>SLD</td>
<td>1.79 -0.008 ± 0.2 0.24 ± 0.09</td>
<td>0.80 -0.02 ± 0.1 0.10 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>0.31 0.60 ± 0.5 1.51 ± 1.01</td>
<td>0.21 0.21 ± 0.3 0.53 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>SCTR</td>
<td>0.82 -0.32 ± 0.3 -0.05 ± 0.4</td>
<td>0.55 -0.02 ± 0.1 -0.07 ± 0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table: 2 Same as Table 1, but for pCO₂. Units are in µatm.

<table>
<thead>
<tr>
<th>Regions</th>
<th>pCO₂ (µatm)</th>
<th>JJAS Mean</th>
<th>Annual Mean</th>
</tr>
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<tr>
<td></td>
<td>OBS constZc varZc</td>
<td>OBS constZc varZc</td>
<td></td>
</tr>
<tr>
<td>WAS</td>
<td>397.58 389.18 ± 3.7 399.95 ± 5.01</td>
<td>394.69 389.62 ± 3.9 391.19 ± 4.7</td>
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</tr>
<tr>
<td>SLD</td>
<td>382.44 371.67 ± 6.04 379.24 ± 8.9</td>
<td>380.21 370.76 ± 6.1 374.94 ± 9.6</td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>372.52 382.36 ± 12.7 402.14 ± 21.8</td>
<td>372.69 374.65 ± 9.3 381.76 ± 13.6</td>
<td></td>
</tr>
<tr>
<td>SCTR</td>
<td>377.18 365.71 ± 5.08 370.72 ± 7.4</td>
<td>379.89 372.69 ± 4.7 369.00 ± 5.4</td>
<td></td>
</tr>
</tbody>
</table>
Table: 3 JJAS mean and Climatological annual mean of Export production from satellite derived Net Primary Production data, constZc and varZc simulations. Units are in g C m$^{-2}$ yr$^{-1}$.

| Regions | Export Production (g C m$^{-2}$ yr$^{-1}$) | | Annual Mean | | | |
|---------|------------------------------------------| --- | --- | --- | --- |
|         | JJAS Mean | Annual Mean | | | |
|         | OBS | constZc | varZc | OBS | constZc | varZc |
| WAS     | 123.57 | 84.81 ± 16.04 | 147.19 ± 23.8 | 94.31 | 77.41 ± 15.1 | 122.54 ± 25.2 |
| SLD     | 51.54  | 167.71 ± 59.04 | 151.51 ± 46.4 | 43.25  | 144.43 ± 49.8 | 156.08 ± 43.8 |
| SC      | 58.87  | 260.11 ± 104.7 | 310.03 ± 99.5 | 54.53  | 172.52 ± 72.4 | 215.52 ± 70.8 |
| SCTR    | 51.08  | 57.39 ± 14.2 | 99.23 ± 21.8 | 40.45  | 55.15 ± 17.9 | 80.35 ± 26.04 |

Table: 4 Same as Table 3, but for New production.

| Regions | New Production (g C m$^{-2}$ yr$^{-1}$) | | Annual Mean | | | |
|---------|-----------------------------------------| --- | --- | --- | --- |
|         | JJAS Mean | | Annual Mean | | | |
|         | OBS | constZc | varZc | OBS | constZc | varZc |
| WAS     | --  | 150.84 ± 27.9 | 133.03 ± 19.5 | --  | 108.43 ± 23.4 | 81.47 ± 15.7 |
| SLD     | --  | 141.93 ± 64.1 | 77.78 ± 27.6 | --  | 111.05 ± 71.1 | 50.37 ± 26.3 |
| SC      | --  | 63.64 ± 30.9 | 78.11 ± 29.1 | --  | 56.69 ± 43.3 | 54.58 ± 23.3 |
| SCTR    | --  | 12.17 ± 16.3 | 13.32 ± 18.6 | --  | 13.74 ± 15.5 | 12.94 ± 13 |
Table 5: Table shows JJAS mean and climatological annual mean response from the model forced with annual mean currents.

<table>
<thead>
<tr>
<th>WAS region forced with Annual mean currents</th>
<th>JJAS mean</th>
<th>Climatological Annual mean</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>constZc</td>
<td>varZc</td>
<td>Improvement</td>
</tr>
<tr>
<td>CO₂ flux (mol m⁻² yr⁻¹)</td>
<td>0.80 ± 0.2</td>
<td>1.29 ± 0.2</td>
<td>0.48 ± 0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.65 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.79 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td>pCO₂ (µatm)</td>
<td>381.81 ± 3.4</td>
<td>387.24 ± 3.9</td>
<td>5.43 ± 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>388.68 ± 3.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>388.40 ± 3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.28 ± 0.1</td>
</tr>
<tr>
<td>Export production (g C m⁻² yr⁻¹)</td>
<td>60.71 ± 4.7</td>
<td>104.22 ± 13.4</td>
<td>43.51 ± 8.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>74.30 ± 4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>104.58 ± 18.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30.28 ± 13.7</td>
</tr>
<tr>
<td>New production (g C m⁻² yr⁻¹)</td>
<td>34.76 ± 2.3</td>
<td>52.16 ± 1.51</td>
<td>17.39 ± 0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>29.91 ± 1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>44.72 ± 1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.81 ± 0.1</td>
</tr>
</tbody>
</table>

Table 6: Same as Table 5 but from annual mean temperature simulations.

<table>
<thead>
<tr>
<th>WAS region forced with Annual mean temperature</th>
<th>JJAS mean</th>
<th>Climatological Annual mean</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>constZc</td>
<td>varZc</td>
<td>Improvement</td>
</tr>
<tr>
<td>CO₂ flux (mol m⁻² yr⁻¹)</td>
<td>1.85 ± 0.2</td>
<td>2.74 ± 0.4</td>
<td>0.88 ± 0.1</td>
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<td>0.81 ± 0.1</td>
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<td></td>
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<td></td>
<td>1.10 ± 0.2</td>
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<tr>
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<td>0.28 ± 0.07</td>
</tr>
<tr>
<td>pCO₂ (µatm)</td>
<td>393.20 ± 3.01</td>
<td>404.26 ± 4.9</td>
<td>11.05 ± 1.9</td>
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<td></td>
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<td>384.61 ± 3.3</td>
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<td>386.52 ± 4.8</td>
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<tr>
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<td></td>
<td>1.91 ± 1.4</td>
</tr>
</tbody>
</table>
Fig (1) Red boxes shows the study regions (1) WAS (Western Arabian Sea, [40°E:65°E, 5°S:25°N]) (2) SLD (Srilankan Dome, [81°E:90°E, 0°:10°N]) (3) SCTR (Seychelles-Chagos Thermocline Ridge, [50°E:80°E, 5°S:10°S]) (4) SC (Sumatra Coast, [90°E:110°E, 0°:10°S]).
Fig (2) P – I curve, Scatter for average relative photosynthesis against different light intensities in the model. Red curve shows the theoretical P – I curve from Parsons et al., (1984). Green curve shows average of the scatter in the model.
Fig (3): Seasonal mean map of Compensation Depth (Zc) as a function of Chl-a and light (a) DJF, (b) MAM, (c) JJAS, (d) OCT-NOV. Units are in meters.
Fig (4): Annual mean biases in model evaluated against Takahashi observations for CO$_2$ flux (a, b) and pCO$_2$ (c, d) with constant Zc (constZc) and Varying Zc (varZc). Units of CO$_2$ flux and pCO$_2$ are mol m$^{-2}$ yr$^{-1}$ and μatm respectively.
Fig (5): Seasonal variations in compensation depth (Zc) over the study regions as climatological state computed over 1990-2010. Error bar shows standard deviations of individual months over these years. Units are in meters.
Fig (6): Comparison of model (a) CO$_2$ flux and (b) pCO$_2$ simulated with constant $Z_c$ (const $Z_c$) and varying $Z_c$ (var $Z_c$) with Takahashi Observations (OBS) over Western Arabian Sea (WAS) region as climatological state computed over 1990-2010. Error bar shows standard deviations of individual months over these years. Units of CO$_2$ flux and pCO$_2$ are mol m$^{-2}$ yr$^{-1}$ and μatm respectively. Legend is common for both graphs.
Fig (7): Comparison of model export production (Mod. Exp. Prod) and New production (Mod. New Prod) with satellite derived export production (Obs. Exp. Prod) for (a) Const Zc and (b) var Zc simulations for Western Arabian Sea (WAS) region. Units are in g C m$^{-2}$ yr$^{-1}$. Legends are common for both graphs.
Fig (8): Bias estimation of Phosphate in the model with climatological observational data (a) \text{const Zc} and (b) \text{Var Zc} simulations and corresponding Biological production (c, d) in the model for Western Arabian Sea (WAS) region. Units of Phosphate (x 100 mol m\(^{-3}\)) and Biological Production (g C m\(^{-3}\) yr\(^{-1}\)).
Fig (9): Same as fig (6), but for Srilankan Dome (SLD) region.
Fig (10): Same as fig (7), but for Srilankan Dome (SLD) region.
Fig 11: Same as fig 6), but for Sumatra Coast (SC) region.
Fig (12): Same as fig (7), but for Sumatra Coast (SC) region.
Fig (13): Same as fig (6), but for Seychelles-Chagos Thermocline Ridge (SCTR) region.
Fig (14): Same as fig (7), but for Seychelles-Chagos Thermocline Ridge (SCTR) region.
Fig (15) Response of CO$_2$ flux from the model forced with annual mean currents over the Western Arabian Sea region (WAS) as climatological state computed over 1990-2010. Error bar shows standard deviations of individual months over these years. (a) const $Z_c$ and (b) var $Z_c$. Units are in mol m$^{-2}$ yr$^{-1}$. Legends are same for both graphs.
Fig (16) Same as Fig (15), but for $pCO_2$. Units are in μatm.
Fig (17) Response in Export Production of the model forced with annual mean currents in the Western Arabian Sea (WAS) region as climatological state computed over 1990-2010. Error bar shows standard deviations of individual months over these years. (a) Const Zc (b) var Zc. Units are in g C m⁻² yr⁻¹. Legends are same for both graphs.
Fig (18) Same as fig (17), but for New Production. Units are in g C m$^{-2}$ yr$^{-1}$. 
Fig (19) Response of CO$_2$ flux from the model forced with annual mean SST over the Western Arabian Sea region (WAS) as climatological state computed over 1990-2010. Error bar shows standard deviations of individual months over these years. (a) const Zc and (b) var Zc. Units are in mol m$^{-2}$ yr$^{-1}$. Legends are same for both graphs.
Fig (20). Same as Fig (19), But for pCO₂. Units are in μatm.