Biological Production in the Indian Ocean Upwelling Zones, Part – I: Refined Estimation via the Use of a Variable Compensation Depth in Ocean Carbon Models

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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 criteria of surface Chl-a based attenuation of solar radiation and the minimum solar radiation required for production, 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 the carbon cycle. The export production strengthens by ~70% over the western Arabian Sea during monsoon period and achieves 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 productions 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, Solubility and Biological pump.

1. Introduction

The Indian Ocean is characterized by the unique seasonally reversing monsoon wind systems which act as the major physical drivers for the coastal and open ocean upwelling processes. The major upwelling systems in the Indian Ocean are (1) the western Arabian Sea (WAS; Ryther and Menzel, 1965; Smith et al., 2001; Sarma, 2004; Wiggert et al., 2005, 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., 1999a; Susanto et al., 2001; Osawa et al., 2010; Xing et al., 2012) and (4) the Seychelles-Chagos thermocline ridge (SCTR; Murtugudde et al., 1999b; Dilmahamod et al., 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 its variability over these coastal upwelling systems are a key concern for 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) and are important for the Indian Ocean rim countries due to their developing country 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 and McClain, 1986; Wiggert et al., 2000; Barber et al., 2001; Prasannakumar et al., 2001; Sarma, 2004). The Arabian Sea is known for the second largest Tuna fishing region in the Indian Ocean (Lee et al., 2005). The Somali and Omani upwelling regions experience phytoplankton blooms that are prominent with Net Primary Production (NPP) exceeding 435 g C m^{-2} yr^{-1} (Liao et al., 2016). On the other hand productivity over the SLD (Vinayachandran and Yamagata, 1998) is triggered by open ocean Ekman suction with strong Chl-a blooms during the

summer monsoon (Murtugudde et al., 1999a; Vinayachandran et al., 2004). Similarly, the SC upwelling is basically due to the strong alongshore winds and its variation is associated with the impact of equatorial and coastal Kelvin waves (Murtugudde et al., 2000, Valsala and Rao, 2016). The interannual variability associated with the Java-Sumatra coastal upwelling is strongly coupled with ENSO (ElNiño Southern Oscillation) through the Walker cell and Indonesian throughflow (Susanto et al., 2001; Valsala et al., 2011) and peaks in July through August with a potential new production of 0.1 Pg C yr^{-1} (Xing et al., 2012). The SCTR productivity has a large spatial and interannual variability. The warmer upper ocean condition associated with El Niño reduces the amplitude of 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., 1999a; Wiggert et al., 2006; Vialard et al., 2009; Dilmahamod et al., 2016).

Understanding the biological production and variability in the upwelling systems is important because it gives us crucial information regarding marine ecosystem variability (Colwell, 1996; Harvell et al., 1999). The observations also provide vital insights into physical and biological interactions of the ecosystem (Naqvi et al., 2010) as well as the biophysical feedbacks (Murtugudde et al., 1999a), 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 complexity 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 with proper parameterizations in models has always been a daunting task. This is an impediment to the accurate representation of biological

primary and export productions in models (Friedrichs et al., 2006, 2007) and these 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 which 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 basic 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.

The Ocean Carbon-cycle Model Intercomparison Project (OCMIP) greatly improved our understanding of global carbon cycle (Najjar and Orr, 1998). OCMIP-II further introduced a simple phosphate-dependent production term in biological models for long-term simulations of the carbon cycle in response to anthropogenic climate change with an accurate annual mean state (Najjar and Orr, 1998; Orr et al., 2001; Doney et al., 2004). However, the OCMIP – II model simulations come with a penalty of strong seasonal biases when compared with observations (Orr et al., 2003). In this protocol, the community compensation depth (hereafter Zc) is defined as the depth at which photosynthesis equals entire community respiration and the irradiance at which this balance achieved is the compensation irradiance (E_{com}). Note that Zc is clearly different from the conventional euphotic zone depth (Morel, 1988). Within Zc, the production of organic phosphorous representing the biological production (in the present context the Net Community Production; NCP) is given as $J_{prod} = \frac{1}{\tau}([PO_4] - [PO_4^*])$, where $[PO_4]$ is the model phosphate concentration and $[PO_4^*]$ is observational phosphate concentration. τ is the restoration

timescale assumed to be 30 days. Whenever the model phosphate exceeds the observational phosphate, it allows production. At Zc, the NCP is zero and above Zc the Net Primary Production (NPP) exceeds the community respiration and the ecosystem will grow (Smetacek and Passow, 1990; Gattuso et al., 2006; Sarmiento and Gruber, 2006; Regaudix-de-Gioux and Duarte, 2010; Marra et al., 2014). However, Zc was held constant in time and space in OCMIP-II models (Najjar and Orr, 1998; Matsumoto et al., 2008) because the OCMIP-II protocol takes a minimalistic approach to biology and simplifies the model calculations with a very limited set of state variables suitable for long term simulations when implemented in coarse resolution models (Orr et al., 2005). However, 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 Zc indicates the seasonality of the production zone itself.

Most of the biophysical models prescribe a constant value for Zc, e.g., a default value of Zc = 75 m in OCMIP –II protocol (Najjar and Orr, 1998) and Zc = 100 m in Minnesota Earth System Model (Matsumoto et al., 2008). Depending on the latitude, Zc 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 Zc in the OCMIP–II framework by representing the production as a function of solar radiation (Parsons et al., 1984) and prescribed Chl-a. In this hypothesis, a spatially and temporally varying Zc is estimated from the vertical attenuation of insolation by the surface Chl-a. The depth at which the insolation reaches the compensation irradiance (chosen as 10 Wm^{-2}) is taken as Zc. Phosphorous is the basic currency which limits the production within this varying Zc. This spatially and temporally varying Zc represents the seasonality in the production zone which is lacking in the original OCMIP-II protocol.

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., 2001; Valsala et al., 2014). The Indian Ocean on the other hand experiences only seasonal upwelling which is relatively weak in the deep tropics but stronger off the coasts of Somalia and Oman and in the SLD (Valsala et al., 2013). The relative importance of the solubility vs. biological pump is not well understood. Our focus here on implementing seasonality in Zc 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 improvements due to the effect of a variable Zc 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 over the Indian Ocean.

The paper is organized as follows. Model, Data, and Methods are detailed in Section 2. The spatially inhomogeneous Zc derived with the new parameterization and its impact on simulated seasonality of biology and carbon cycle are detailed in Section 3. Further a conclusion is provided in Section 4.

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 (Najjar and 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 (Chang et. al., 2012), the zonal and meridional resolutions are 1^o with 360 grid points longitudinally and 1^o at higher latitudes but having a finer resolution of 0.8^o in the tropics, with 200 latitudinal grid points. 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 coordinates 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

$$\frac{\partial C}{\partial t} + U.\nabla_H C + W\frac{\partial C}{\partial z} = \frac{\partial}{\partial z}K_z\frac{\partial}{\partial z}C + \nabla_H.(K_h\nabla_H C) + J + F \qquad (1)$$

where ∇_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. J represents any sink or source due to the internal consumption or production of the tracer. F represents the emission or absorption of fluxes at the ocean surface. Here, the source and sink terms 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). For horizontal mixing, model incorporates Redi fluxes (Redi, 1982)

and GM fluxes (Gent and Mcwilliams, 1990) which represent the eddy-induced variance in the mean tracer transport. A weak Laplacian diffusion is also included in the model for computational stability where the sharp gradient in concentration occurs.

2.2. Biogeochemical model

The biogeochemical model used in the study is based on the OCMIP – II protocol as stated above. The main motivation of OCMIP–II protocol is to employ a minimalistic approach to simulate the ocean carbon cycle with a nutrient restoration approach to calculate the oceanic biological production (Najjar et al., 1992; Anderson and Sarmiento, 1995). The present version of the model has four prognostic variables coupled with the circulation field, viz., inorganic phosphate (PO_4^{3-}), dissolved organic phosphorus (DOP), dissolved inorganic carbon (DIC) and alkalinity (ALK). The basic currency for the biological model is phosphorous because of the availability of a more extensive phosphate database and to eliminate the complexities associated with nitrogen fixation and denitrification. Detailed model equations and variables are provided in Appendix-A with only a brief description given below.

The production of organic phosphorus in the model using the nutrient restoring approach is given by

$$J_{prod} = \frac{1}{\tau}([PO_4] - [PO_4]^*) \quad (2)$$

$$[PO_4] > [PO_4]^* \; ; Z < Zc$$

$$J_{prod} = 0 \quad (3)$$

$$[PO_4] \leq [PO_4]^*$$

Where J_{prod} represents the biogeochemical flows with respect to production of organic phosphorous. $[PO_4]^*$ is the observed phosphate concentration and τ=30 days is the restoration time scale (Najjar et. al., 1992).

The vertically integrated new production (g C m^{-2} yr^{-1}) in the model is defined as

$$New\ production = \int_{zc}^{0} -J_{prod}\ dz \qquad (4)$$

The export production (g C m^{-2} yr^{-1}) in the model is calculated as

$$Export\ production = (1-\sigma)\int_{0}^{zc} J_{prod}\ dz \qquad (5)$$

Air-sea CO_2 flux in the model is estimated by,

$$F = K_w\ \Delta\ pCO_2 \qquad (6)$$

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.

pCO_2 is calculated in the model by using DIC and ALK and is given by,

$$pCO_2 = \frac{[DIC]}{K_0}\frac{[H^+]^2}{[H^+]^2 + K_1[H^+] + K_1K_2} \qquad (7)$$

Where $[H^+]$ is calculated using Newton-Raphson iterative method (Press et. al., 1996, Najjar and Orr, 1998). K_0 is the solubility constant of CO_2 and K_1, K_2 are the dissociation constant for carbonic acid, respectively (Sarmiento and Gruber, 2006, Weiss, 1974, Mehrbach et al., 1973, Dickson and Millero, 1987, Najjar and Orr, 1998).

214 Details of all parameters in the biogeochemical model and calculations of solubility and
215 biological pump are listed in Appendix-A. The design and validation of the physical model is
216 reported by Valsala et al., (2008, 2010b) and biogeochemical model by Najjar and Orr (1998).

217

218 **2.3. Data**

219 For validating the model results, observational datasets of CO_2 flux and pCO_2 are taken
220 from Takahashi et al., (2009). Satellite-derived NPP data were taken from Sea-viewing Wide
221 Field of view Sensor (SeaWiFS) Chl-a product, calculated using Vertically Generalized
222 Production Model (VGPM) (Behrenfeld and Falkowski, 1997). The NPP data is scaled to export
223 production (EP) by multiplying with an e-ratio (e = 0.37) representative of Indian Ocean
224 upwelling zones (Sarmiento and Gruber, 2006, Laws et al., 2000; Falkowski et al., 2003). The
225 initial conditions for PO_4 are taken from the World Ocean Atlas (Garcia et al., 2014). Initial
226 conditions for DIC and ALK are taken from the Global Ocean Data Analysis Project (GLODAP;
227 Key et al., 2004) dataset. The dissolved Organic Phosphorous (DOP) is initialized with a
228 constant value of 0.02 μmol kg^{-1} (Najjar and Orr, 1998). The data sources and citations are
229 provided in the Acknowledgement.

230

231 **2.4. Methods**

232 A spin-up for 50 years from the given initial conditions is performed with the
233 climatological physical drivers. As the initial conditions are provided from a mean state of
234 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 as in Keeling et al. (1995).

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 on bias corrections to the seasonal cycle of pCO_2 and DIC with a variable Zc, a model climatology for carbon cycle has been constructed from 1990 to 2010, which 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 in order to segregate the role of varying Zc in improving the seasonality of carbon cycle. The aim of these sensitivity experiments is to understand how successful the new parameterization for Zc is in capturing the carbon cycle variability related to the upwelling episodes even though the seasonal cycle in physics is suppressed. The model driven with annual mean currents suppresses 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. A smoothing technique with linear interpolation ($u = u(1 - x) + \bar{u}x$) is applied to the offline-data in order to blend the annual mean fields ($\bar{u}$) provided to the selected region with the rest of the domain (u) in order to reduce a sudden transition at the boundaries. Here x represents an index which varies between 0 and 1 within a distance of 10^0 from the boundaries of

258 the region of interest to the rest of the model domain. Results of sensitivity experiments are
259 provided in supplementary material.

260

261 **2.5. Community compensation depth (Zc) parameterization**

262 The OCMIP – II protocol separates the production and consumption zones by a depth termed
263 as compensation depth (Zc); the depth at which photosynthesis is large enough to balance the
264 community respiration (i.e., both the autotrophic and heterotrophic respiration). At the
265 community compensation depth, the NCP is zero i.e., NCP = NPP - R_h = 0, (i.e., NPP = GPP –
266 R_a), GPP is gross primary production, and R_h and Ra are the heterotrophic and autotrophic
267 respirations, respectively (Smetacek and Passow, 1990; Najjar and Orr, 1998; Gattuso et al.,
268 2006; Regaudix-de-Gioux and Duarte, 2010; Marra et al., 2014). The light intensity at Zc is
269 compensation irradiance (E_{com}), the irradiance at which the gross community primary production
270 balances respiratory carbon losses for the entire community (Gattuso et al., 2006; Regaudix-de-
271 Gioux and Duarte, 2010). We define a spatially and temporally varying compensation depth
272 (hereafter varZc) as a depth where compensation irradiance (attenuated by surface Chl-a, Jerlov
273 et al., 1976) reaches a minimum value of 10 W m^{-2}. In this way, the varZc has both spatio-
274 temporal variability of light as well as Chl-a. The Chl-a is given as monthly climatology as
275 constructed from satellite data. Observations show that the primary production reduces rapidly to
276 20% or less of the surface value below a threshold of 10 W m^{-2} (Parsons et al., 1984; Ryther,
277 1956; Sarmiento and Gruber, 2006). Moreover higher ocean temperatures (those in the tropics)
278 enhance the respiration rates resulting in high compensation irradiance (Parsons et al., 1984;
279 Ryther, 1956; Lopez-Urrutia et al., 2006; Regaudix-de-Gioux and Duarte, 2010). A study by

Regaudix-de-Gioux and Duarte (2010) reported the mean value of compensation irradiance over the Arabian Sea as 0.4 ± 0.2 mol photon m^{-2} day^{-1} which is close to 10 W m^{-2} day^{-1}.

Figure 2 compares the scatter of average relative photosynthesis within varZc as a function of solar radiation for the Indian Ocean (see Appendix-B). This encapsulates 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; Parsons et al., 1984; Sarmiento and Gruber, 2006). The model permits 100% production of organic phosphorus for radiation above 10 W m^{-2}. However the availability of phosphate concentration in the model acts as an additional limit for production which indirectly represents the photoinhibition at higher irradiance; for example, in the 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 Zc (Figure 3). Zc over the Arabian Sea varies from 10 m to 25 m during December to February (DJF) and deepens down to 45 m during March to May (MAM) due to the increase in the surface solar radiation. During the monsoon season i.e., June to September (JJAS), Zc again shoals to 10 m - 35 m due to the attenuation of solar radiation by the increased biological production (Chl-a). During October to November (ON), Zc slightly deepens as compared to JJAS.

The Bay of Bengal Zc deepens from 35 m to 40 m during DJF and further deepens to 50 m during MAM when the solar radiation is maximum and biological production is minimum

301 (Prasannakumar et al., 2002). Further reduction of Zc can be seen through JJAS as a result of a
302 reduction in solar radiation during monsoon cloud cover. Zc during ON is 35 m on average.

303 The equatorial Indian Ocean can be seen as a belt of 40 m - 45 m Zc throughout the season
304 except for JJAS. During JJAS, a shallow Zc is seen near the coastal Arabian Sea (around 10 m to
305 35 m) presumably due to the coastal Chl-a blooms. Deep Zc off the coast of Sumatra (~ 40 m to
306 50 m) is found during JJAS. Java-Sumatra coastal upwelling is centered on SON (Susanto et al.,
307 2001) and upwelling originates at around 100 m depth (Valsala and Maksyutov, 2010a; Xing et
308 al., 2012).

309 Southward of 10^{o}S in the oligotrophic gyre region, Zc varies from 40 m to more than 60 m
310 throughout the year. A conspicuous feature observed while parameterizing the solar radiation
311 and Chl-a dependent Zc is that its maximum value never crosses 75 m especially in the Indian
312 Ocean which is the value specified in OCMIP-II models. The cutoff depth of 75 m in OCMIP-II
313 is obtained from observing the seasonal variance in oxygen data (Najjar and Keeling, 1997) as an
314 indicator of the production zone. However, our results show that parameterizing a production
315 zone based on solar radiation and Chl-a predicts a production zone and its variability that is
316 largely less than 75 m. The relevance of varZc in the seasonality of the modeled carbon cycle is
317 illustrated as follows.

318

319 **3.1. Simulated seasonal cycle of pCO_2 and CO_2 fluxes**

320 The annual mean biases in simulated CO_2 fluxes and pCO_2 were evaluated by comparing
321 with Takahashi et al., (2009) observations (Figure 4). The model biases are significantly reduced

322 with the implementation of varZc compared to that of the constant Zc (hereinafter constZc). A
323 notable reduction in pCO_2 bias (by ~ 10μatm) is observed along the WAS (Figure 4d).

324 In order to address the role of the new biological parameterization of a variable Zc, we
325 zoom in on four key regions where the biological production and CO_2 fluxes are prominent in the
326 Indian Ocean with additional sensitivity experiments (see Introduction and references therein).
327 The regions (boxes shown in Figure 1) we considered are, (1) Western Arabian Sea (WAS;
328 40^oE:65^oE, 5^oS:25^oN) (2) Sri Lanka Dome (SLD; 81^oE:90^oE, 0^o:10^oN) (3) Seychelles-Chagos
329 Thermocline Ridge (SCTR; 50^oE:80^oE, 5^oS:10^oS) and (4) Sumatra Coast (SC; 90^oE:110^oE,
330 0^o:10^oS; Figure 1). The seasonal variations of Zc over these selected key regions are shown in
331 Figure 5. A detailed analysis of CO_2 fluxes, pCO_2, biological export and new productions and the
332 impact of varZc simulations in improving the strength of biological pump and solubility pump
333 for these key regions are presented below.

334

335 **3.2. Western Arabian Sea (WAS)**

336 The WAS Zc has a double peak pattern over the annual cycle. During the February-March
337 period, Zc deepens down to a maximum of 43.85 ± 2.3 m into March and then shoals to 25.75 ±
338 1.5 m (Figure 5) during the monsoon period (uncertainty represents the interannual standard
339 deviations of monthly data from 1990-2010). This shoaling of Zc depth during the monsoon
340 indicates the potential ability of the present biological parameterization to capture the wind-
341 driven upwelling related production in the WAS. During the post-monsoon period, the second
342 deepening of Zc occurs during November with a maximum depth of 34.91 ± 2.2 m. The ability to
343 represent the seasonality of the production zone renders a unique improvement in CO_2 flux

344 variability especially in the WAS in comparison to the OCMIP-II experiments (Orr et al, 2003;
345 Figure 6a).

346 OCMIP –II simulations with a constZc of 75 m underestimate the CO_2 flux when compared
347 to the observations of Takahashi et al. (2009). This underestimation is clearly visible during the
348 monsoon period. Our simulations with the varZc result in a better seasonality of CO_2 flux when
349 compared with Takahashi et al. (2009) observations (Figure 6a). The improvement due to the
350 varZc scheme is able to represent the seasonality of CO_2 flux better especially during the
351 monsoon period when wind-driven upwelling is dominant. Obviously, the relative role of the
352 biological and solubility pumps have to be deciphered in this context.

353 The CO_2 flux during July from observations, constZc, and varZc simulations are 3.09 mol m^{-2}
354 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
355 upwelling over the WAS especially off the Somali coast (Smith and Codispoti, 1980; Schott,
356 1983; Smith, 1984) and Oman (Bruce, 1974; Smith and Bottero, 1977; Swallow, 1984; Bauer et
357 al., 1991), pulls nutrient-rich subsurface waters closer to the surface while the available turbulent
358 energy due to the strong winds lead to mixed layer entrainment of the nutrients resulting in a
359 strong surface phytoplankton bloom (Krey and Babenerd, 1976; Banse, 1987; Bauer, 1991;
360 Brock et al, 1991). This regional bloom extends over 700 km offshore from the Omani coast due
361 to upward Ekman pumping driven by strong, positive wind-stress curl to the northwest of the low
362 level jet axis and the offshore advection (Bauer et al., 1991; Brock et al., 1991; Brock and
363 McClain, 1992a, b; Murtugudde and Busalacchi, 1999, Valsala, 2009) resulting in strong
364 outgassing of CO_2 flux and an enhanced pCO_2 in the WAS (Valsala and Maksyutov, 2013;
365 Sarma et al., 2002). The seasonal mean CO_2 flux during the southwest monsoon period (JJAS)
366 for constZc and varZc simulations are 1.44 ± 0.2 mol m^{-2} yr^{-1} and 2.31 ± 0.4 mol m^{-2} yr^{-1},

367 respectively. The biological parameterization of varZc considerably improves the average CO_2
368 flux during the monsoon period by 0.86 ± 0.1 mol m^{-2} yr^{-1}. The annual mean CO_2 flux from
369 observations, constZc and varZc simulations are 0.94 mol m^{-2} yr^{-1}, 0.80 ± 0.17 mol m^{-2} yr^{-1} and
370 1.07 ± 0.2 mol m^{-2} yr^{-1}, respectively. The annual mean CO_2 flux is improved by 0.27 ± 0.05 mol
371 m^{-2} yr^{-1}.

372 Seasonality in pCO_2 also shows a remarkable improvement during the southwest monsoon
373 period (Figure 6b). The pCO_2 with constZc is considerably lower at a value of 385.22 ± 3.5 µatm
374 during June compared to observational values of 392.83 µatm. However, varZc simulation
375 performs better in terms of pCO_2 variability. The peak value of pCO_2 reaches up to 405.42 ± 5.8
376 µatm. The seasonal mean pCO_2 during the Southwest monsoon period from observations,
377 constZc, and varZc simulations are 397.58 µatm, 389.18 ± 3.6 µatm and 399.95 ± 5.0 µatm,
378 respectively. The improvement in pCO_2 by varZc simulation is 10.76 ± 1.3 µatm when compared
379 with the constZc simulation. This clearly shows that constZc simulation fails to capture the pCO_2
380 driven by upwelling during the Southwest monsoon while the varZc simulation is demonstrably
381 better in representing this seasonal increase. The annual mean pCO_2 from observations, constZc,
382 and varZc simulations are 394.69 µatm, 389.62 ± 3.9 µatm and 391.19 ± 4.7 µatm, respectively.
383 However, it is worth mentioning that there are parts of the year where the constZc performs
384 better compared to varZc. For instance, during MAM as well as in November, the constZc
385 simulation yields a better comparison with the observed pCO_2 whereas varZc simulation yields a
386 reduced magnitude of pCO_2. This may well indicate the biological vs. solubility pump controls
387 on pCO_2 during the intermonsoons. The role of mesoscale variability in the ocean dynamics may
388 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 varZc produces a better simulation.

The improvements shown by the use of varZc in the simulation of CO_2 flux and pCO_2 can be elicited 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 simulation is much weaker when compared to varZc simulation. The varZc simulation has 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). The constZc export production is much weaker than new production and it is not in balance. In contrast, the varZc simulation yields a close balance among them.

Compared 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, with 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 et al., 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.

410 The seasonal mean export production during the southwest monsoon period from satellite-
411 derived estimate is 123.57 g C m^{-2} yr^{-1}, whereas for constZc and varZc simulations it is 84.81 ±
412 16.0 g C m^{-2} yr^{-1} and 147.19 ± 23.8 g C m^{-2} yr^{-1}, respectively. The new biological
413 parameterization strengthens the model export production by 62.38 ± 7.8 g C m^{-2} yr^{-1} for the
414 southwest monsoon period, which is over a 70% increase. This indicates a considerable impact
415 of the biological pump in the model simulated CO_2 flux and pCO_2 over the WAS. For constZc
416 simulation, the computed new production is slightly higher (150.84 ± 27.9 g C m^{-2} yr^{-1}) than that
417 of varZc (133.03 ± 19.5 g C m^{-2} yr^{-1}). The annual mean export production from observations,
418 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
419 g C m^{-2} yr^{-1}, respectively.

420 To understand how the varZc parameterization strengthens the export production in the
421 model, we have analyzed the phosphate profiles. It appears that the varZc parameterization
422 allows more phosphate concentration (Figure 8a, b) in the production zone and thereby increases
423 the corresponding biological production (Figure 8c, d). The net export production in the model
424 during JJAS is consistent with the satellite data (Figure 7b). However, in the constZc case, the
425 exports are rather 'flat' throughout the season with a poor representation of seasonal biological
426 export. The Table 1-4 summarize all the values discussed here.

427 The impact of varZc in the biological and solubility pumps is computed as per Louanchi et
428 al., (1996, see Appendix A). The varZc parameterization strengthens the biological as well as the
429 solubility pump in the model thereby modifying the phosphate profiles and achieves a seasonal
430 balance in export versus new production (Figure 9a). During the monsoon period, the varZc
431 simulation increases the strength of the solubility and biological pumps by 10.43 ± 1.3 g C m^{-2}
432 yr^{-1} and 106.52 ± 9 g C m^{-2} yr^{-1}, respectively (see Table 5 and 6). Similarly, the annual mean

strength of solubility pump and the biological pump are increased by 3.29 ± 0.6 g C m^{-2} yr^{-1} and 81.18 ± 9.92 g C m^{-2} yr^{-1}, respectively. This supports the fact that the varZc parameterization basically modifies the biological and solubility pumps in the model simulation and thereby improves the seasonal cycle of CO_2 flux and pCO_2.

3.3 Sri Lanka Dome (SLD)

The seasonal variation in Zc for SLD has a similar pattern as that of WAS. Zc 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 indicates 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 increases earlier compared to WAS which occurs during ASO.

The seasonality in CO_2 flux and pCO_2 were compared with Takahashi et al., (2009) observations (Figure 10). varZc results in a slight improvement in CO_2 flux when compared with constZc (Figure 10a). However, both constZc and varZc simulations underestimate the magnitude of CO_2 flux when compared with observations. The seasonal mean CO_2 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 simulation misrepresents the SLD region as a sink of CO_2 during monsoon period which is opposite to that of observations. The varZc simulation corrects this misrepresentation to a source albeit at a smaller magnitude by

454 0.24 ± 0.09 mol m^{-2} yr^{-1} for the monsoon period. Compared to observations, the varZc case
455 underestimates the magnitude of JJAS mean by 1.55 mol m^{-2} yr^{-1}.

456 The annual mean CO_2 fluxes for constZc and varZc simulations are -0.02 ± 0.1 mol m^{-2} yr^{-1}
457 and 0.10 ± 0.2 mol m^{-2} yr^{-1}, respectively. The varZc parameterization leads to an improvement of
458 0.13 ± 0.1 mol m^{-2} yr^{-1} in the annual mean CO_2 flux when compared with constZc simulation.
459 The observational annual mean of CO_2 flux is 0.80 mol m^{-2} yr^{-1} which is highly underestimated
460 by both simulations. This indicates a regulation of biological production of the region by varZc
461 which makes this region a source of CO_2 during monsoon. The role of the solubility pump may
462 also be underestimated due to the biases in the physical drivers and the lack of mesoscale eddy
463 activities in these simulations (Prasanna Kumar et al., 2002; Valsala and Murtugudde, 2015).

464 The seasonality of pCO_2 (Figure 10b) especially in the monsoon period is significantly
465 improved. The mean pCO_2 during the monsoon season from observation over the SLD region is
466 382.44 µatm. The seasonal mean pCO_2 during monsoon period for constZc and varZc
467 simulations are 371.67 ± 6.04 µatm and 379.24 ± 8.9 µatm, respectively. The annual mean pCO_2
468 from observations, constZc, and varZc simulations are 380.21 µatm, 370.76 ± 6.1 µatm and
469 374.94 ± 9.6 µatm, respectively. varZc simulations improve the JJAS mean pCO_2 by 7.56 ± 2.8
470 µatm and the annual mean pCO_2 by 4.18 ± 3.5 µatm, which is reflected in CO_2 flux as well. This
471 is likely due to the impact of new biological parameterization in capturing the episodic upwelling
472 in the SLD region which is further investigated by looking at its biological production.

473 The SLD biological production is highly exaggerated by the model for both constZc and
474 varZc simulations (Figure 11a, b). The seasonal mean biological export for the monsoon period
475 is 51.54 g C m^{-2} yr^{-1} as per satellite-derived estimates. However, the constZc and varZc

simulations overestimate it at 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 simulation, new production is overestimated from March to October when compared to observations and the second peak is observed in November (Figure 11a). But the overestimate in new production with varZc is observed only during JJAS period by an amount 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 the monsoon over SLD. All values are summarized in Tables 1 to 4.

The solubility and biological pumps are modified by the varZc parameterization significantly when compared with the constZc simulation (Figure 9b). Over the monsoon period, the strength of the solubility and biological pumps are improved by 2.81 ± 1.1 g C m^{-2} yr^{-1} and 66.68 ± 9.7 g C m^{-2} yr^{-1}, respectively. Similarly, the annual mean strength of solubility and biological pump are increased by 0.99 ± 1.2 g C m^{-2} yr^{-1} and 52.5 ± 5.1 g C m^{-2} yr^{-1} respectively. All values are provided in Table 5 and 6.

3.4 Sumatra Coast (SC)

The seasonal variation in Zc 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

498 monsoon period, Zc shoals slightly with a minimum of 41.1 m in July. The variation in Zc is
499 relatively small as compared to the other regions which is consistent with its relatively low
500 production throughout the year.

501 The seasonality of CO_2 flux and pCO_2 captured by constZc and varZc simulations are shown
502 in Figure 12a, b. The varZc simulations overestimate both CO_2 flux and pCO_2, especially during
503 the monsoon. It is found that the constZc simulation is better compared to varZc simulation. The
504 varZc simulation overestimates the seasonal mean CO_2 flux and pCO_2 by 1.19 mol m^{-2} yr^{-1} and
505 29.61 μatm, respectively, compared to observations (Table 1). However, constZc produces a
506 better estimate compared with observations for CO_2 flux and pCO_2. The constZc simulation also
507 delivers a better annual mean than varZc (Table 1, 2). The annual mean bias in constZc and
508 varZc simulations for CO_2 flux is -0.0033 mol m^{-2} yr^{-1} and 0.31 mol m^{-2} yr^{-1}, respectively.
509 Similarly, pCO_2 bias is 1.95 μatm and 9.07 μatm for constZc and varZc simulations.

510 Biological production simulated by the model along SC explains the overestimation of CO_2
511 flux and pCO_2 (Figure 13). Both constZc and varZc simulations greatly overestimate export
512 production in the model. However, a small enhancement in the new production during JJAS in
513 constZc case is an indicator of upwelling episodes. The seasonal mean new production during
514 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},
515 respectively (Table 4). The seasonal mean export production during the monsoon from
516 observations is 58.87 g C m^{-2} yr^{-1} (Table 3). The constZc simulation represents a better new
517 production, which is seen as a relatively small exaggeration of CO_2 flux and pCO_2. The
518 biological response of SC is found to be better with constZc which is in contradiction to a
519 general improvement found with varZc in the other regions examined here. Such discrepancies
520 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 (also see Valsala and Maksyutov, 2010a).

The overestimation of export production by varZc simulation is also evident by the increase in strength of the biological and solubility pumps, respectively (Figure 9c). The annual mean and JJAS mean DIC increases in the production zone due to the biological pump are 67.21 ± 1.3 g C m^{-2} yr^{-1} and 83.62 ± 0.5 g C m^{-2} yr^{-1}, respectively. Similarly the increase in DIC due to the effect of solubility pump during the JJAS period and annual mean are 10.95 ± 5.2 g C m^{-2} yr^{-1} and 3.87 ± 2.2 g C m^{-2} yr^{-1} respectively (see table 5 and 6).

3.5 Seychelles-Chagos Thermocline Ridge (SCTR)

The SCTR is a unique open-ocean 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 the biological production of this region (Dilmahamod et al., 2016). The seasonal cycle in Zc is shown in Figure 5. The maximum Zc occurs in November at about 44.94 m and the minimum at 33.2 m in July. The shoaling of Zc during the monsoon period shows that the biological parameterization captures the response to upwelling over this region.

The seasonality of CO_2 flux and pCO_2 are shown in Figure 14. The Takahashi observations of CO_2 flux show 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 simulation, but underestimated when compared to observations. The seasonal mean CO_2 flux during the monsoon from observations, constZc and varZc simulations are 0.82 mol m^{-2} yr^{-1}, -0.32 ± 0.3

543 mol m^{-2} yr^{-1} and -0.05 ± 0.4 mol m^{-2} yr^{-1}, respectively. This represents a reduction in the seasonal
544 mean sink of CO_2 flux in the SCTR region during the monsoon by 0.27 ± 0.1 mol m^{-2} yr^{-1}
545 bringing it closer to a source region (see Table 1 for details).

546 The improved CO_2 flux is also supported by the seasonal cycle in pCO_2. Based on
547 observations, the seasonal mean of pCO_2 with constZc during JJAS is underestimated by 11.47
548 μatm, varZc simulation underestimates it by 6.45 μatm. So it is evident that varZc simulation
549 capture the upwelling episodes better, marked by a larger pCO_2 during JJAS period. However,
550 the magnitude of pCO_2 is still underestimated compared to observations (Table 2).

551 Figure 15 shows the biological production of constZc and varZc simulations for SCTR. It is
552 clear that both simulations overestimate the export production and underestimate the new
553 production. The JJAS mean export production from observations, constZc and varZc are 51.08 g
554 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
555 simulations exaggerate the model export production by 48.14 g C m^{-2} yr^{-1}. The varZc simulation
556 improves the JJAS mean new production by 1.14 ± 2.2 g C m^{-2} yr^{-1} (Table 4). The DIC variations
557 due to the biological pump over the monsoon period and the annual mean also correspond to the
558 exaggerated export production. During the monsoon period, the varZc simulation strengthens the
559 biological and solubility pumps by 72.64 ± 6.2 g C m^{-2} yr^{-1} and -4.56 ± 1.6 g C m^{-2} yr^{-1},
560 respectively, when compared to the constZc simulation (Figure 9d). This is also reflected in the
561 annual mean DIC variations due to the biological and solubility pump effects (see table 5 and 6).
562 This slight improvement in the model new production, especially during the monsoon period
563 signals that the varZc better captures the upwelling over SCTR. Considering the annual mean
564 values of model export and new production, constZc simulation is reasonably faithful to
565 observations.

566 The underestimation of CO_2 and pCO_2, as well as the exaggeration of model export
567 production and a slight, overestimate in model new production may be due to two reasons; (1)
568 SCTR is a strongly coupled region with remote forcing of the mixed layer – thermocline
569 interactions (Zhou et al., 2008) which can affect the seasonality in biological production that the
570 model may not be resolving reasonably, (2) the bias associated with physical drivers, especially
571 wind stress may underestimate the CO_2 flux as well biological production. A similar
572 overestimation of biological production was also reported in a coupled biophysical model
573 (Dilmahamod et al., 2016).

574 Table 1 – 4 shows the entire summary of seasonal and annual mean CO_2 flux, pCO_2 and
575 biological production reported in Section 3.

576

577 **4. Summary and Conclusions**

578 A spatially and temporally varying Zc parameterization as a function of solar radiation and
579 Chl-a is implemented in the biological pump model of OCMIP-II for a detailed analysis of
580 biological fluxes in the upwelling zones of the Indian Ocean. The varZc parameterization
581 improves the seasonality of model CO_2 flux and pCO_2 variability, especially during the monsoon
582 period. A significant improvement is observed in WAS where the monsoon wind-driven
583 upwelling dominates biological production. The magnitude of CO_2 flux matches with
584 observations, especially in July when monsoon winds are at their peak. Monsoon triggers
585 upwelling in SLD as well which acts as a source of CO_2 to the atmosphere. The seasonal and
586 annual mean are underestimated with constZc and the SLD is reduced to a sink of CO_2 flux. The
587 varZc simulation modifies the seasonal and annual means of the CO_2 flux of SLD and depict it as

588 a source of CO_2 especially during the monsoon, but the magnitude is still underestimated
589 compared to Takahashi et al. (2009) observations. The SCTR variability is underestimated by
590 both constZc and varZc simulations, portraying it as a CO_2 sink region whereas observations
591 over the monsoon period indicate that the thermocline ridge driven by the open ocean wind-
592 stress curl is, in fact, an oceanic source of CO_2. However, the varZc simulation reduces the
593 magnitude of the sink in this region bringing it relatively close to observations.

594 VarZc biological parameterization strengthens the export and new productions in the model,
595 which allows it to represent a better seasonal cycle of CO_2 flux and pCO_2 over the study regions.
596 The WAS export production is remarkably improved by 62.37 ± 7.8 g C m^{-2} yr^{-1} compared to
597 constZc. This supports our conclusion that the varZc parameterization increases the strength of
598 biological export in the model. Over the SLD, the JJAS seasonal mean export and new
599 production are underestimated in varZc compared to constZc simulations, but the annual mean
600 export production is improved. Export production at SC and SCTR are highly exaggerated and
601 there is hardly any improvement in new production with a variable Zc especially over the
602 monsoon period. The inability of varZc parameterization to improve the seasonality of SC and
603 SCTR may be due to the interannual variability of biological production associated with the
604 Indonesian throughflow and remote forcing of the mixed layer-thermocline interactions and the
605 effect of biases in the wind stress data used as a physical driver in the model.

606 Sensitivity experiments carried out by prescribing annual mean currents or temperatures over
607 selected subdomains reveal that the varZc retains the seasonality of carbon fluxes, pCO_2, and
608 export and new productions closer to observations. This strongly supports our contention that
609 varZc parameterization improves export and new productions and it is also efficient in capturing
610 upwelling episodes of the study regions. This points out the significant role of having a close

611 balance in seasonal biological export and new production in models to capture the seasonality in
612 the carbon cycle. This also confirms the role of biological and solubility pumps in producing the
613 seasonality of carbon cycle in the upwelling zones.

614 However, the underestimation of the seasonality of CO_2 flux over the SLD and
615 overestimation over the SC as well as the SCTR are a cautionary flag for the study. This
616 uncertainty poses an important scientific question as to whether the model biology over the SC
617 and SCTR region is not resolving the seasonality in CO_2 flux and pCO_2 properly or whether the
618 seasonality in the Zc is not able to fully capture the biological processes.

619 To address these questions we have used an inverse modeling approach (Bayesian inversion)
620 in order to optimize the spatially and temporally varying Zc using surface pCO_2 as the
621 observational constraint and computed the optimized biological production. The results will be
622 reported elsewhere.

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Appendix – A

The time evolution equations of the model variables are given by

$$\frac{d[PO_4]}{dt} = L([PO_4]) + J_{PO_4} \qquad (A1)$$

$$\frac{d[DOP]}{dt} = L([DOP]) + J_{DOP} \qquad (A2)$$

$$\frac{dDIC}{dt} = L([DIC]) + J_{DIC} + J_g DIC + J_v DIC \qquad (A3)$$

$$\frac{d[ALK]}{dt} = L([ALK]) + J_{ALK} + J_v ALK \qquad (A4)$$

Where L is the 3D transport operator, which represents the effects of advection, diffusion, and convection. [ ] or square brackets indicate the concentrations in mol m^{-3}. $J_{PO_4}, J_{DOP}, J_{DIC}, J_{ALK}$ are the biological source/sink terms and $J_v DIC$, $J_v ALK$ are the virtual source-sink terms representing the changes in surface DIC and ALK, respectively, due to evaporation and precipitation. $J_g DIC$ is the source-sink term due to air-sea exchange of CO_2.

The following equations represent for the biological processes in the model

For Z < Zc,

$$J_{prod} = \frac{1}{\tau}([PO_4] - [PO_4^*]), \qquad [PO_4] > [PO_4^*] \qquad (A5)$$

$$J_{DOP} = \sigma J_{prod} - \kappa[DOP] \qquad (A6)$$

$$J_{PO4} = -J_{prod} + \kappa[DOP] \qquad (A7)$$

$$J_{ca} = Rr_{C:P}(1-\sigma)J_{prod} \quad \text{(A8)}$$

$$J_{DIC} = r_{C:P}J_{PO4} + J_{ca} \quad \text{(A9)}$$

$$J_{ALK} = -r_{N:P}J_{PO4} + 2J_{ca} \quad \text{(A10)}$$

For Z >Zc,

$$J_{prod} = 0, \qquad [PO_4] \leq [PO_4^*] \quad \text{(A11)}$$

$$J_{DOP} = -\kappa[DOP] \quad \text{(A12)}$$

$$J_{PO4} = -\frac{\partial F}{\partial Z} + \kappa[DOP] \quad \text{(A13)}$$

$$F_c = (1-\sigma)\int_0^{Zc} J_{prod}\, dZ \quad \text{(A14)}$$

$$F(Z) = F_c\left(\frac{Z}{Zc}\right)^{-a} \quad \text{(A15)}$$

$$J_{ca} = -\frac{\partial F_{Ca}}{\partial Z} \quad \text{(A16)}$$

$$F_{Ca} = Rr_{C:P}F_C e^{-(Z-Zc)/d} \quad \text{(A17)}$$

Where Z is the depth and Zc is the compensation depth in the model. J_{prod} , J_{Ca} represents the biogeochemical flows with respect to production and calcification. Within Zc, the production of organic phosphorous in the model J_{prod} is calculated using equation A5. $[PO_4]$ is the model phosphate concentration and $[PO_4^*]$ is observational phosphate. τ is the restoration timescale assumed to be 30 days. Whenever the model phosphate exceeds the observational phosphate, it allows production, below which the production is zero. The observational phosphate data were taken from the World Ocean Atlas (WOA; Garcia et al., 2014). It is assumed that a fixed fraction

(σJ_{prod}) of phosphate uptake is converted into Dissolved Organic Phosphorus (DOP) which is a source for J_{DOP} (equation A6). The phosphate not converted to DOP results in an instantaneous downward flux of particulate organic phosphorus at Zc (equation A14). The decrease of flux with depth due to remineralization is shown by a power law relationship as in equation A15. The values of the constants a, κ, σ are 0.9, 0.2/year to 0.7/year, 0.67, respectively. The rate of production is used to explain the formation of calcium carbonate cycle in surface waters (equation A8) and its export is given by equation A16, where R is the rain ratio, a constant molar ratio of exported particulate organic carbon to the exported calcium carbonate flux at Zc. The exponential decrease of calcium carbonate flux with scale depth d is given by equation A17. The biological source or sink of dissolved inorganic carbon (DIC) and alkalinity (ALK) is explained through equations A9 and A10, respectively. Where the values of rain ratio (R) is taken as 0.07 and the Redfield ratio, $r_{C:P} = 117$, and $r_{N:P} = 16$ and scale depth d is chosen as 3500m.

Biological and Solubility Pump calculations

The biological effect on DIC is calculated from Louanchi et al., (1996). The tendency of DIC due to biomass production and calcite formation in the production zone is expressed as below.

$$\left(\frac{\partial DIC}{\partial t}\right)_b = \left(\frac{\partial PO_4}{\partial t}\right)_b \times R_{C:P} - J_{Ca} \qquad \text{(A18)}$$

The total tendency of DIC in the production zone is:

$$\left(\frac{\partial DIC}{\partial t}\right)_{total} = \left(\frac{\partial DIC}{\partial t}\right)_b + \int_x \int_y \mathrm{F} dx\, dy \qquad \text{(A19)}$$

where $\left(\frac{\partial DIC}{\partial t}\right)_b$ is the evolution of DIC due to the impact of biology (i.e., biological pump). The first term in the R.H.S of Equation A18 is the rate of change of phosphate resulting from photosynthesis and respiration in the model (i.e., J_{po4} in this case) multiplied by the carbon to phosphorous Redfield ratio ($R_{C:P}$ = 117:1) and J_{Ca} represents the calcite formation in the model (see Equation A8 & A16). The solubility pump is calculated as the surface integral of the flux F (Louanchi et al., 1996).

Appendix B

In order to compare our model production of organic phosphorous to the curve of Ryther et al., (1956) we have merely scaled our total production to "relative photosynthesis", which is, according to Ryther et al., (1956) an index between 0 and 1 indicating the strength of production estimated as $P_l/P_{max.}$ Here P_l is the photosynthesis at each intensity (of light) of different species and P_{max} is the maximum photosynthesis observed in the same control experiment. The curve between relative photosynthesis and light intensity shows the relation between photosynthetic activity and light in marine phytoplankton. Since our method relates biological production to a function of light (limitation) by Chl-a attenuation, it is the best curve to cross-compare our results. In this case we scaled our total biological production within Zc into relative values between 0-1 by P_l/P_{max}. in which P_l is taken as the individual grid cell biological component of organic phosphorus production and P_{max} is the maximum production available in the domain at any given instant. All the grid points are quite similar to the curve of Ryther et al., (1956) as shown in Figure 2.

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Table: 1 WAS = Western Arabian Sea, SLD = Sri Lanka Dome, SC = Sumatra Coast, SCTR = Seychelles-Chagos Thermocline Ridge. JJAS mean and the climatological annual mean of CO_2 flux from Takahashi observations, constZc, and varZc simulations. Units are mol m^{-2} yr^{-1}.

Regions	CO_2 flux (mol m^{-2} yr^{-1})					
	JJAS Mean			Annual Mean		
	OBS	constZc	varZc	OBS	constZc	varZc
WAS	1.99	1.44 ± 0.2	2.31 ± 0.4	0.94	0.80 ± 0.1	1.07 ± 0.2
SLD	1.79	-0.008 ± 0.2	0.24 ± 0.09	0.8	-0.02 ± 0.1	0.10 ± 0.2
SC	0.31	0.60 ± 0.5	1.51 ± 1.01	0.21	0.21 ± 0.3	0.53 ± 0.5
SCTR	0.82	-0.32 ± 0.3	-0.05 ± 0.4	0.55	-0.02 ± 0.1	-0.07 ± 0.2

Table: 2 Same as Table 1, but for pCO_2. Units are µatm.

Regions	pCO_2 (µatm)					
	JJAS Mean			Annual Mean		
	OBS	constZc	varZc	OBS	constZc	varZc
WAS	397.58	389.18 ± 3.7	399.95 ± 5.01	394.69	389.62 ± 3.9	391.19 ± 4.7
SLD	382.44	371.67 ± 6.04	379.24 ± 8.9	380.21	370.76 ± 6.1	374.94 ± 9.6
SC	372.52	382.36 ± 12.7	402.14 ± 21.8	372.69	374.65 ± 9.3	381.76 ± 13.6
SCTR	377.18	365.71 ± 5.08	370.72 ± 7.4	379.89	372.69 ± 4.7	369.00 ± 5.4

Table: 3 JJAS mean and the climatological annual mean of export production from satellite-derived Net Primary Production data, constZc, and varZc simulations. Units are g C m^{-2} yr^{-1}.

Regions	Export Production (g C m^{-2} yr^{-1})					
	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 Model derived values for New production. Units are g C m^{-2} yr^{-1}.

Regions	New Production (g C m^{-2} yr^{-1})					
	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: Biological pump impact over DIC in the model due to constZc and varZc simulations for JJAS and annual mean.

Regions	Biological Pump (g C m^{-2} yr^{-1})			
	constZc		varZc	
	JJAS Mean	Annual Mean	JJAS Mean	Annual Mean
WAS	45.18 ± 14.8	45.49 ± 14.38	151.7 ± 23.8	126.67 ± 24.3
SLD	89.39 ± 58.1	108.65 ± 48.6	156.07 ± 48.4	161.15 ± 43.5
SC	235.54 ± 95.4	155.21 ± 67.4	319.16 ± 94.9	222.92 ± 68.7
SCTR	30.49 ± 13.4	26.81 ± 16.8	103.13 ± 19.6	83.98 ± 23.6

Table 6: Same as Table 5, But for Solubility pump.

Regions	Solubility Pump (g C m^{-2} yr^{-1})			
	constZc		varZc	
	JJAS Mean	Annual Mean	JJAS Mean	Annual Mean
WAS	17.29 ± 3.5	9.63 ± 2.1	27.72 ± 4.8	12.92 ± 2.7
SLD	-0.09 ± 2.4	-0.32 ± 2.3	2.9 ± 3.5	1.31 ± 3.5
SC	7.22 ± 6.9	2.56 ± 3.8	18.17 ± 12.1	6.43 ± 6.0
SCTR	-3.95 ± 3.7	-0.35 ± 2.3	-0.61 ± 5.3	-0.86 ± 2.8

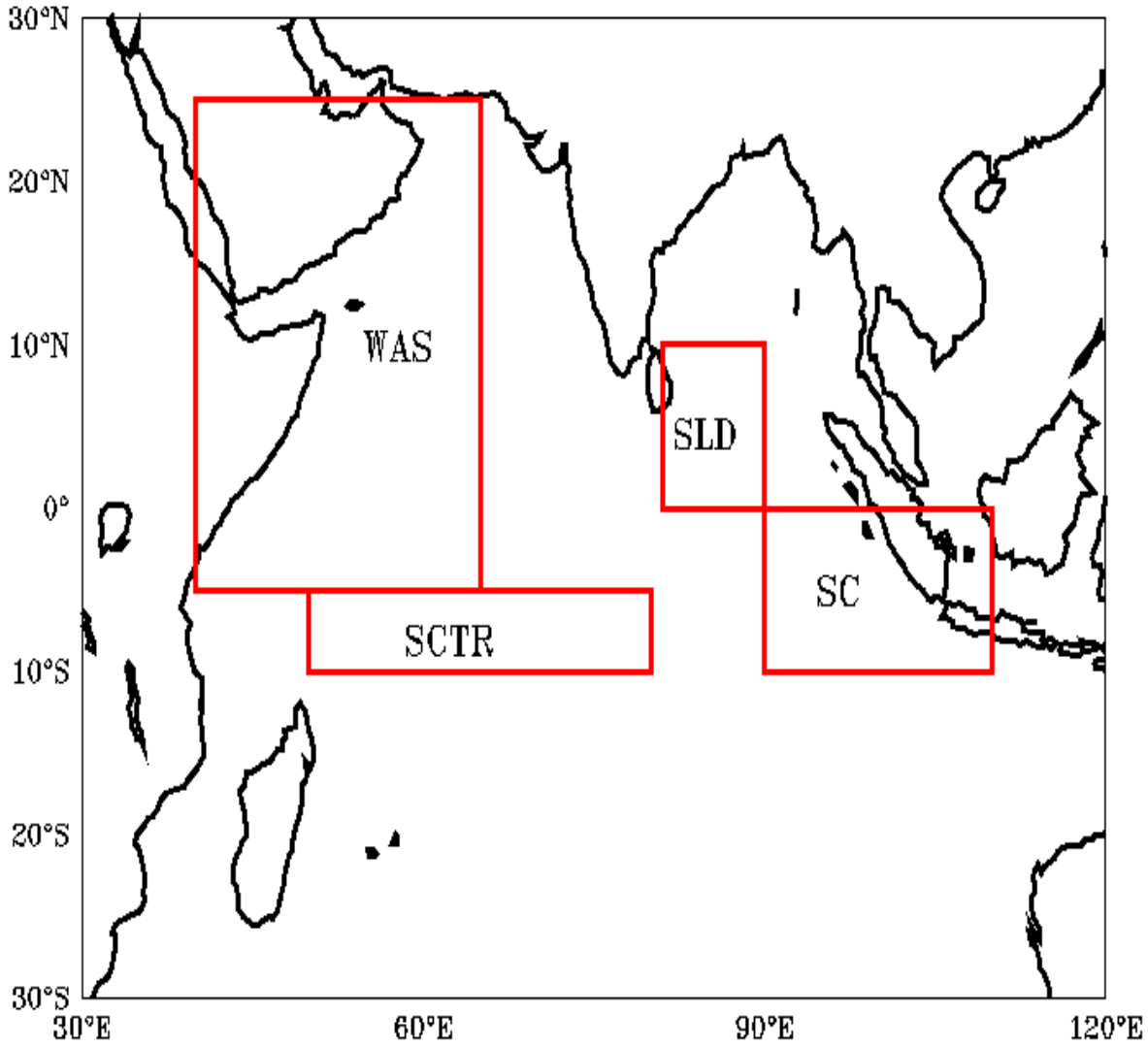

Figure 1: Red boxes shows the study regions (1) WAS (Western Arabian Sea, 40°E:65°E, 5°S:25°N) (2) SLD (Sri Lanka Dome, 81°E:90°E, 0°:10°N) (3) SCTR (Seychelles-Chagos Thermocline Ridge, 50°E:80°E, 5°S:10°S) and (4) SC (Sumatra Coast, 90°E:110°E, 0°:10°S).

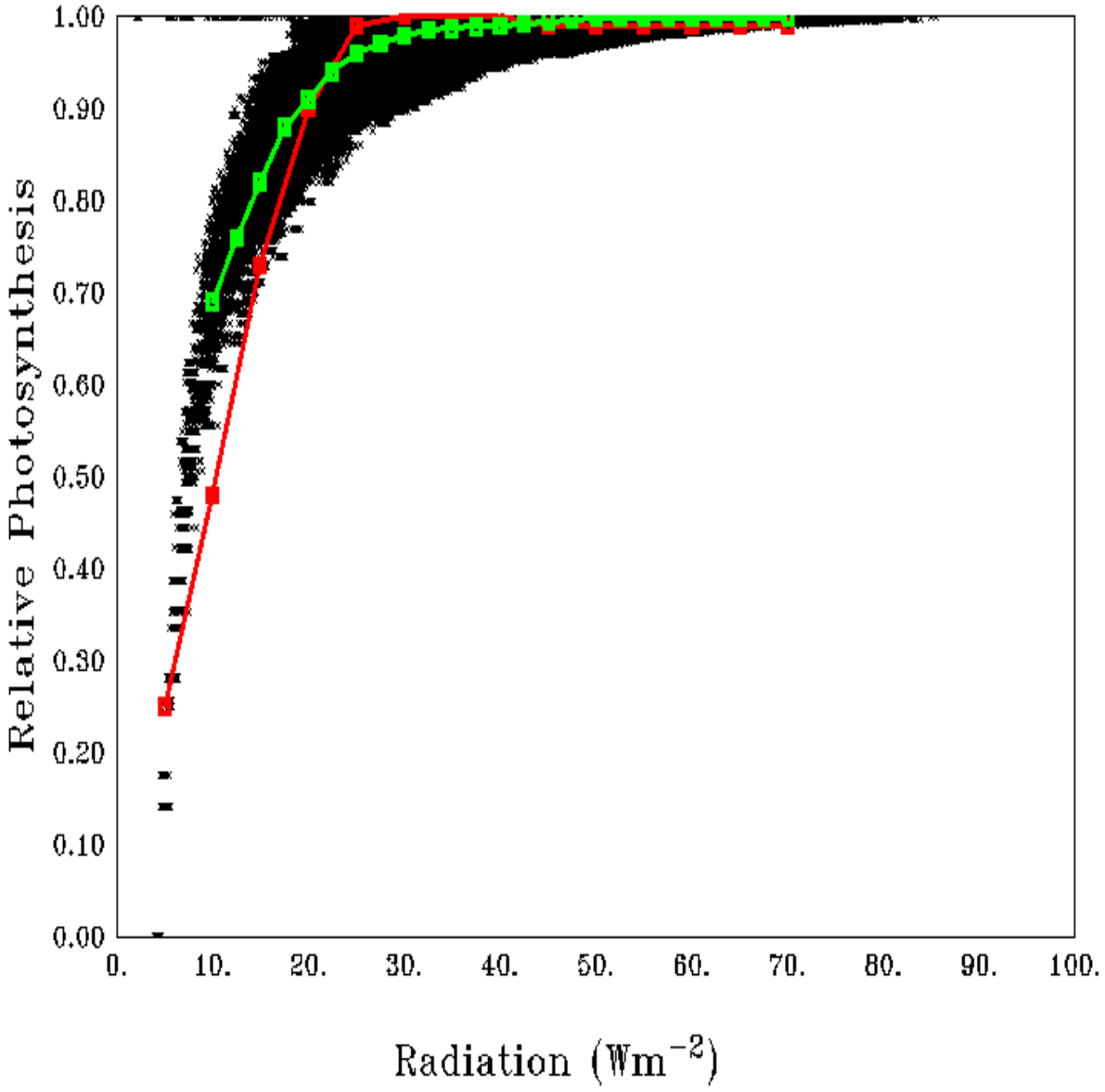

Figure 2: Scatter of average relative photosynthesis versus different light intensities in the model (black dots) and its mean (green curve). The red curve shows the theoretical P – I curve from Parsons et al., (1984).

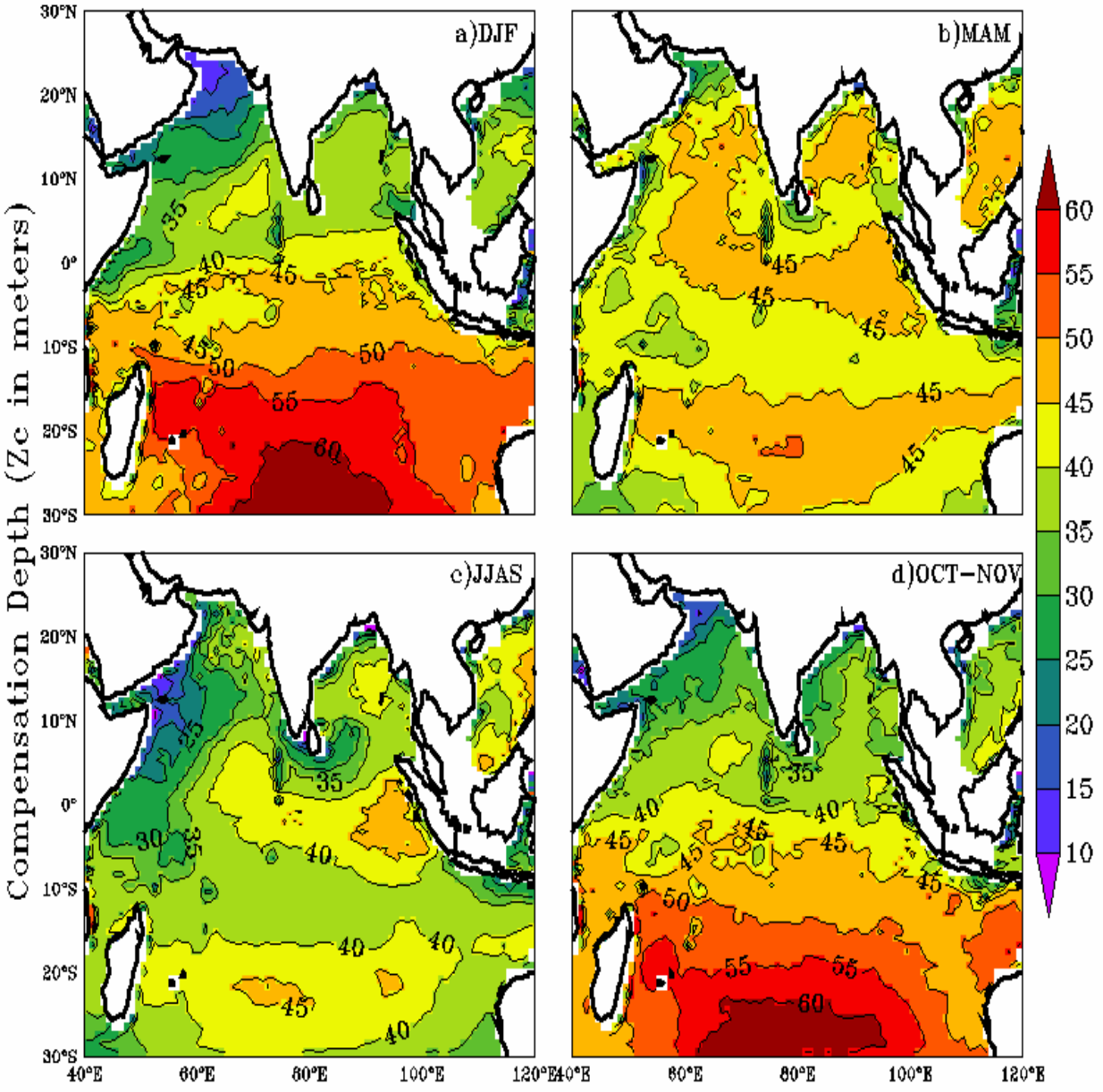

Figure 3: Seasonal-mean maps of varying compensation depth (varZc), (a) December to February (DJF), (b) March to May (MAM), (c) June to September (JJAS), (d) October to November (ON). Units are meters.

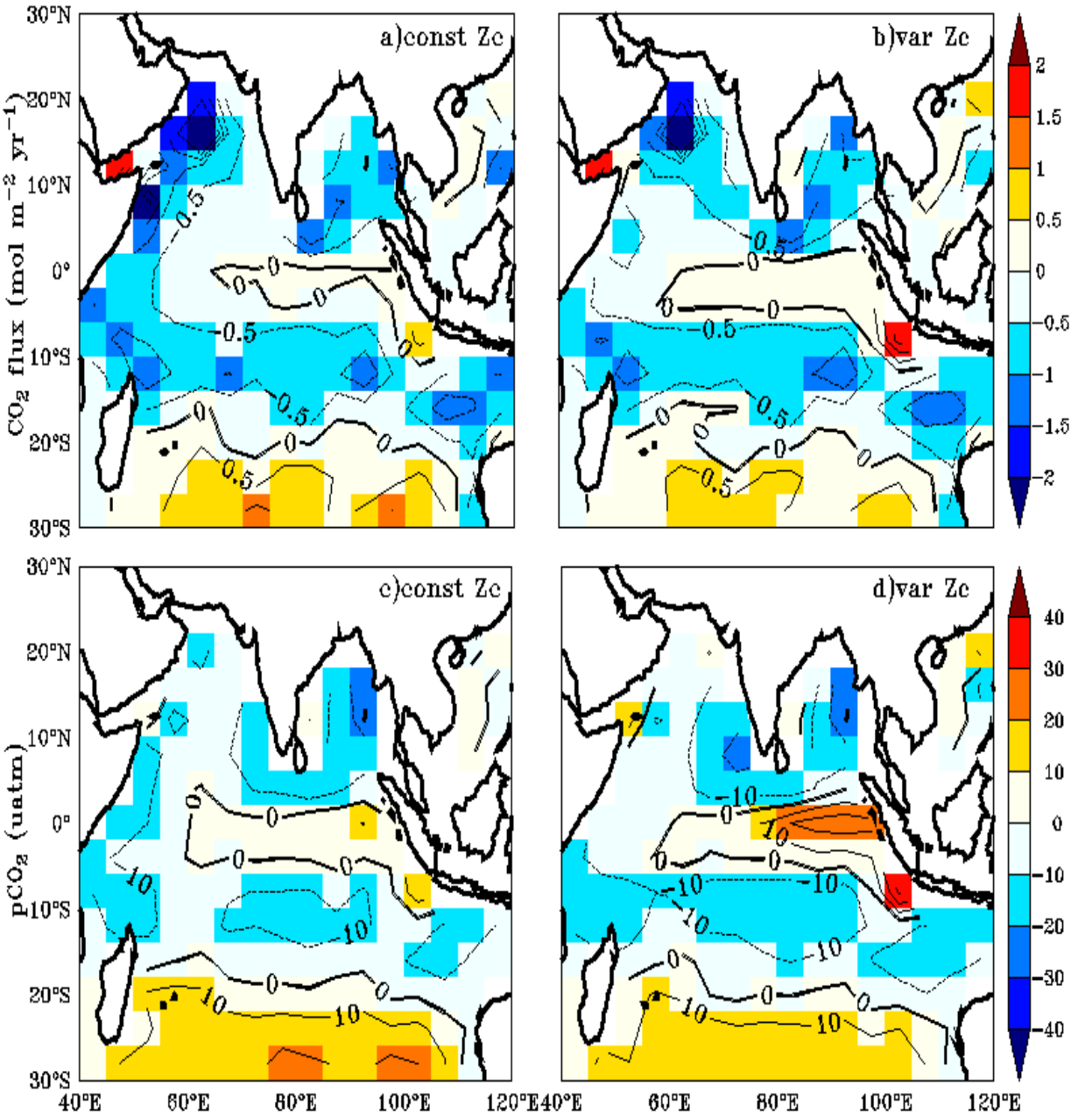

Figure 4: Annual mean biases in the model evaluated against Takahashi et al. (2009) observations for CO_2 flux (a, b) and pCO_2 (c, d) with constant Zc (constZc) and varying Zc (varZc). Units of CO_2 flux and pCO_2 are mol m^{-2} yr^{-1} and µatm, respectively.

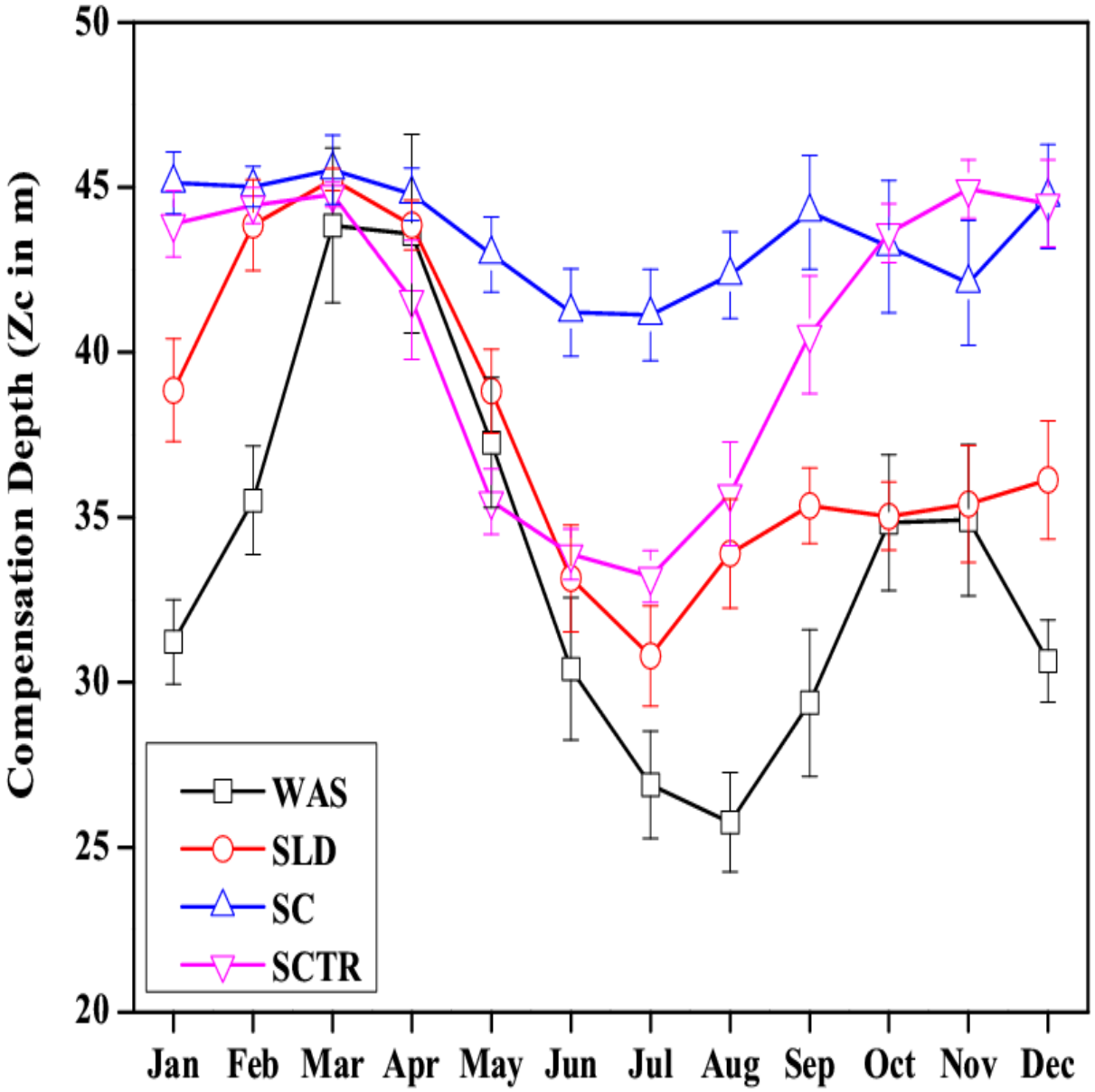

Figure 5: Seasonal variations in varZc over the study regions shown as climatology computed over 1990-2010. Error bar shows standard deviations of individual months over these years. Units are meters.

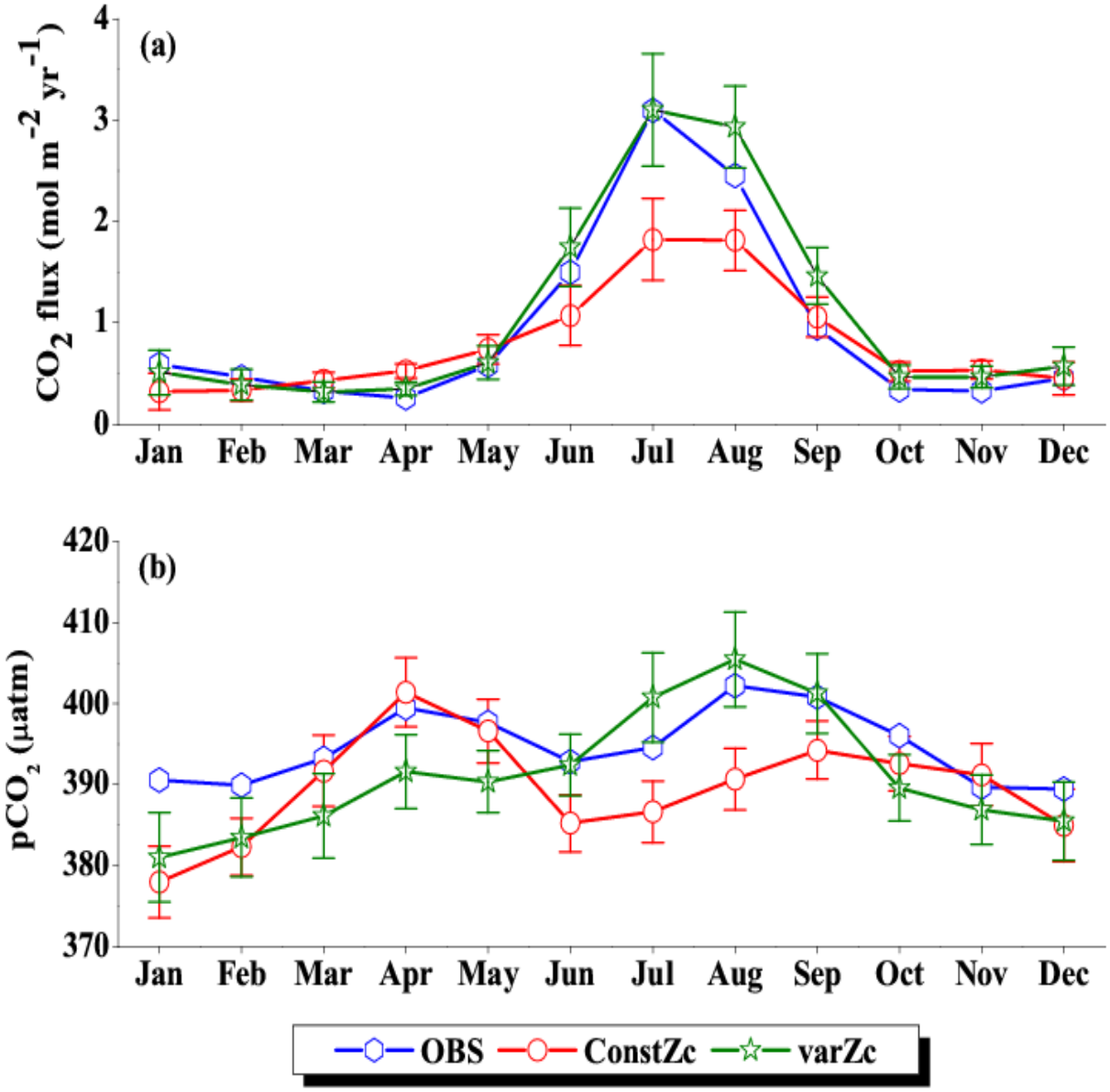

Figure 6: Comparison of model (a) CO_2 flux and (b) pCO_2 simulated with constZc and varZc with that of Takahashi et al. (2009) observations (OBS) over WAS as climatology computed over 1990-2010. Error bar shows standard deviations of individual months over these years. Units of CO_2 flux and pCO_2 are mol m^{-2} yr^{-1} and µatm, respectively. Legend is common for both graphs.

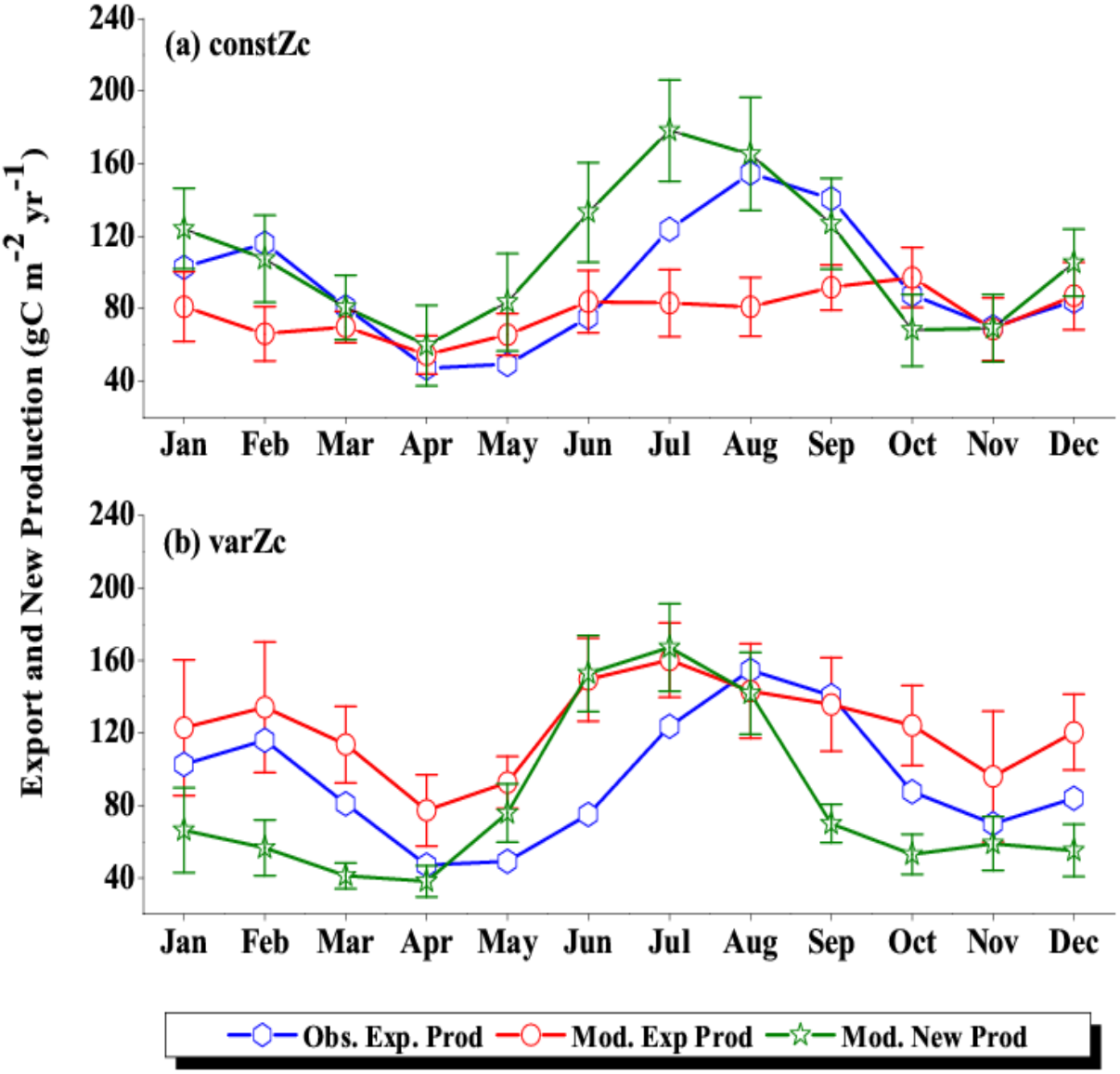

Figure 7: Comparison of model export production (Mod. Exp. Prod) and new production (Mod. New Prod) with satellite-derived export production (Obs. Exp. Prod) for (a) ConstZc and (b) varZc simulations for WAS. Units are g C m^{-2} yr^{-1}. Legends are common for both graphs.

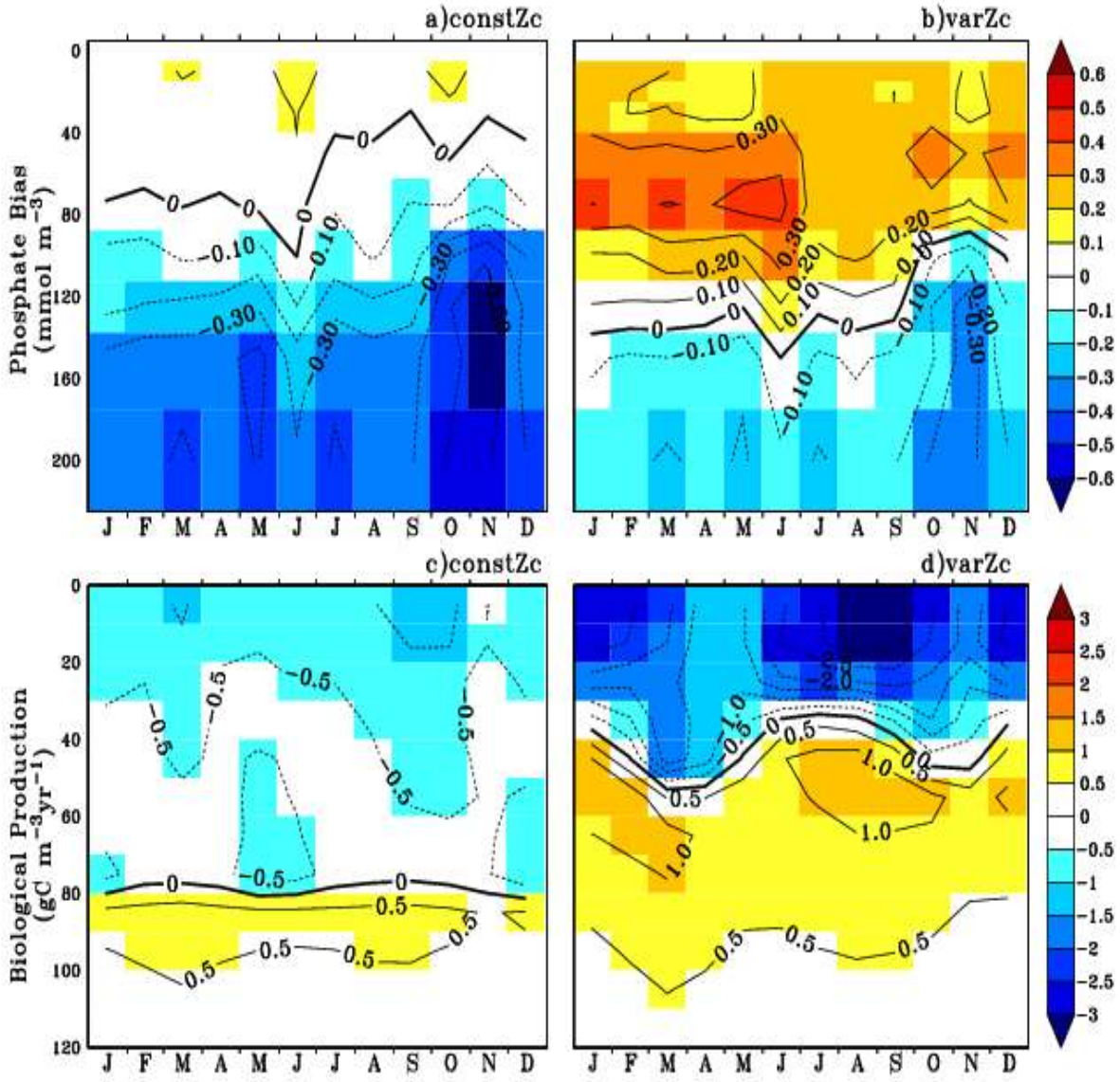

Figure 8: Annual mean bias of model phosphate when compared with climatological observational data (a) for constZc and (b) for varZc simulations. Corresponding annual mean biological source/sink profiles (c, d) in the model for WAS. Unit of phosphate is mmol m^{-3} and biological source/sink is g C m^{-3} yr^{-1}.

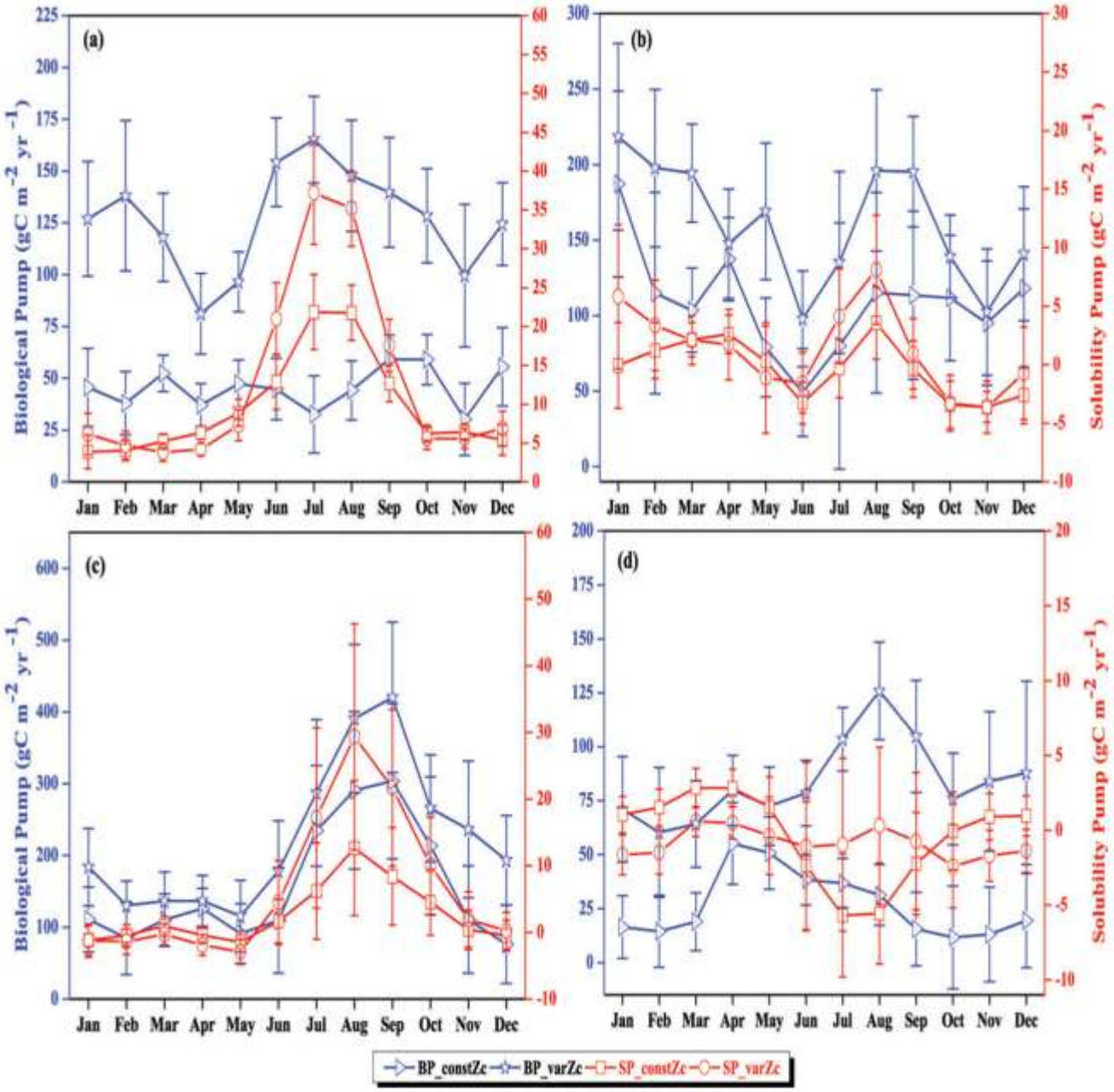

Figure 9: The strength of the biological pump (BP, black lines) and solubility pump (SP, red lines) from constZc and varZc simulations for (a) WAS (b) SLD (c) SC and (d) SCTR. The left axis shows the biological pump and the right axis shows the solubility pump. Error bar shows standard deviations of individual months over the years 1990 - 2010. Units are g C m^{-2} yr^{-1}.

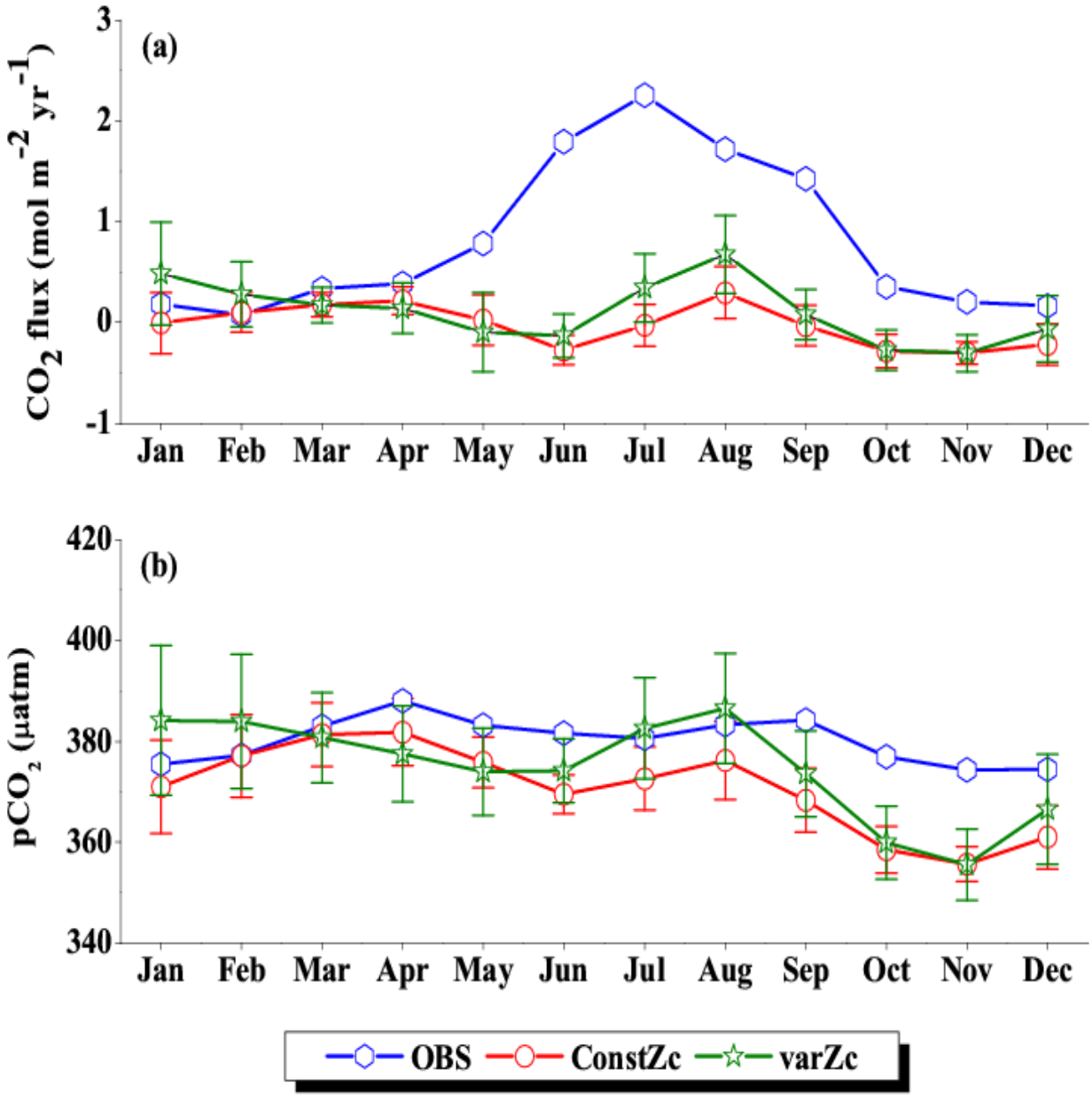

Figure 10: Same as Figure (6), but for SLD.

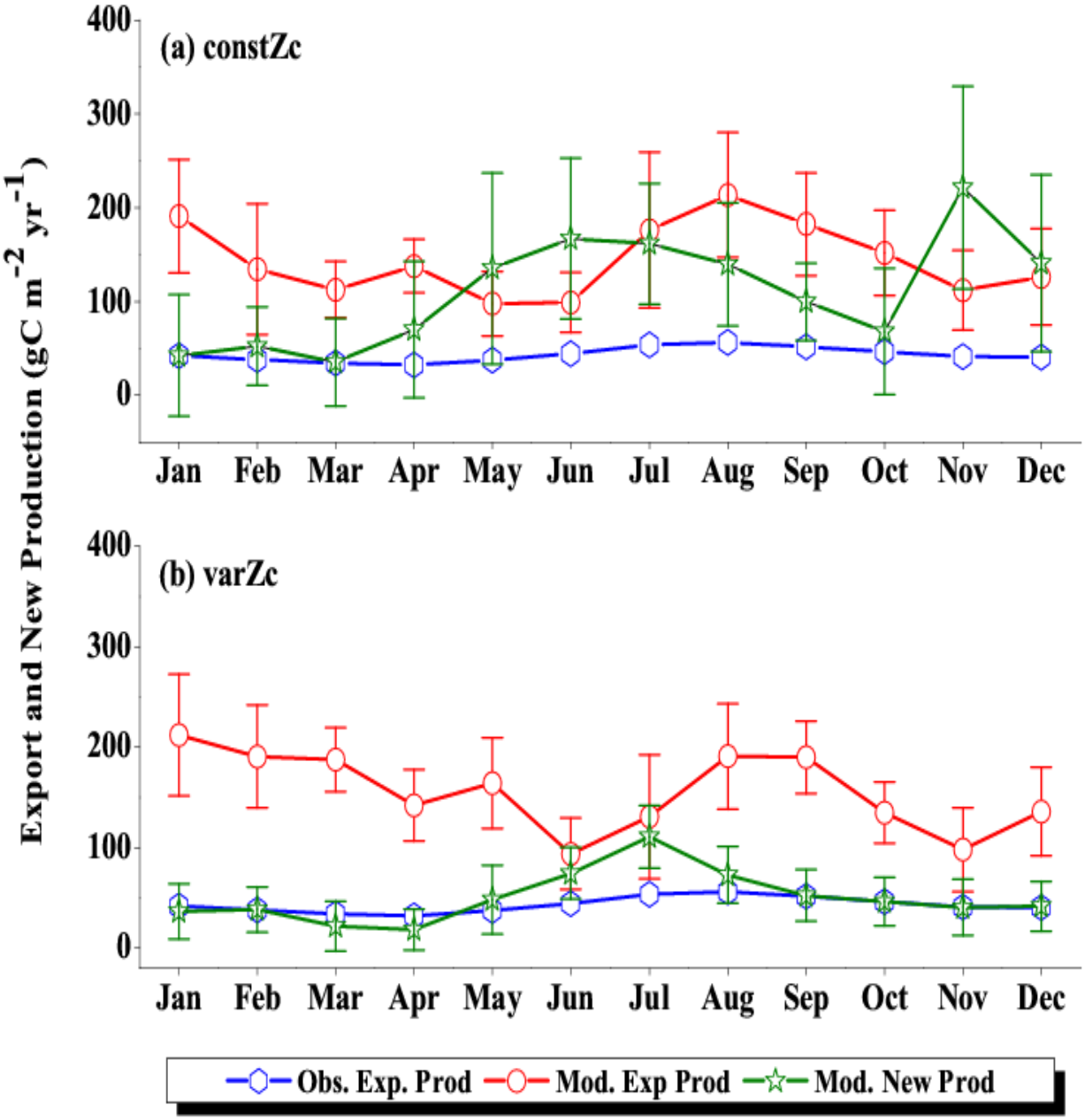

Figure 11: Same as Figure (7), but for SLD.

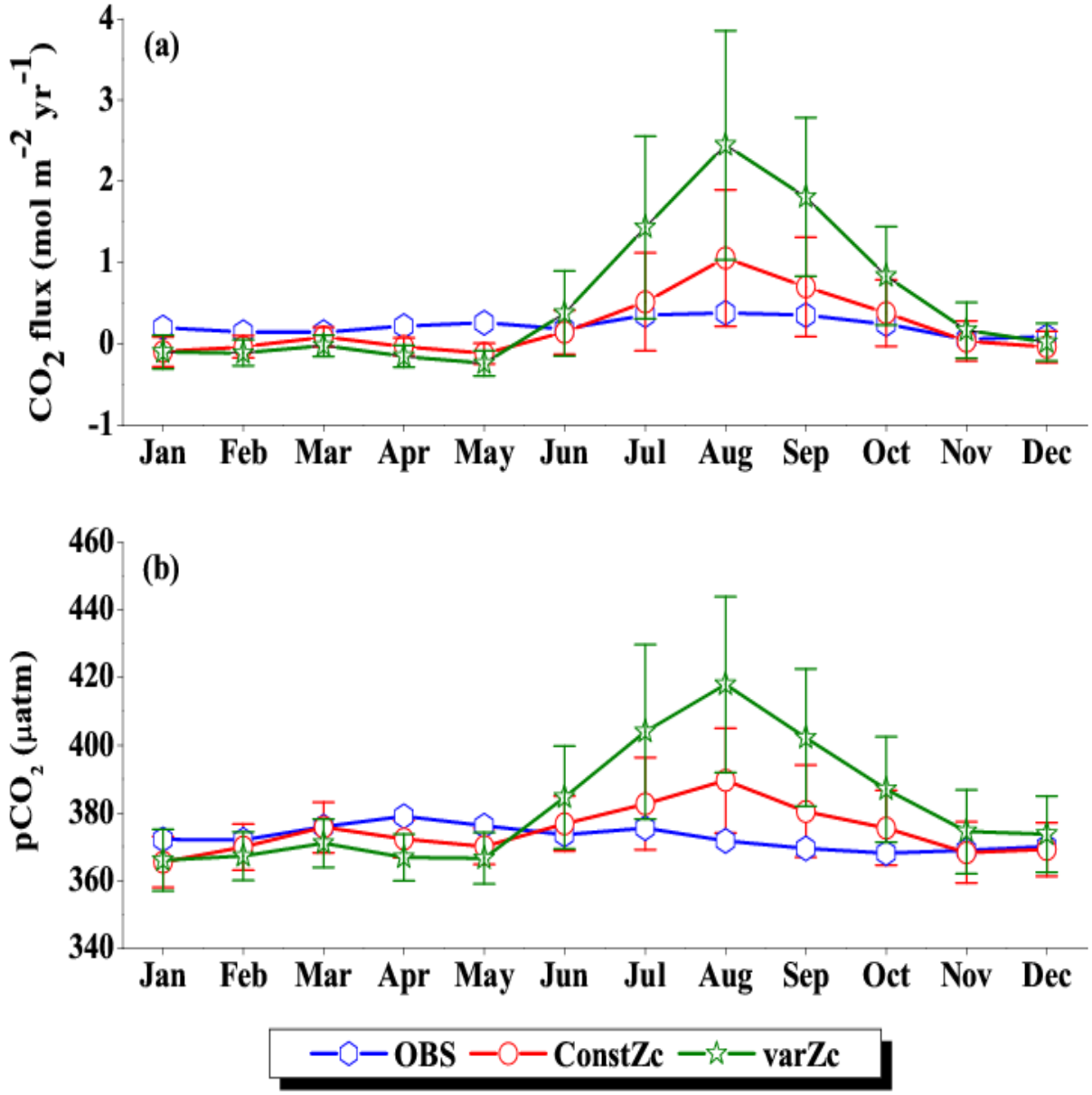

Figure 12: Same as Figure (6), but for SC.

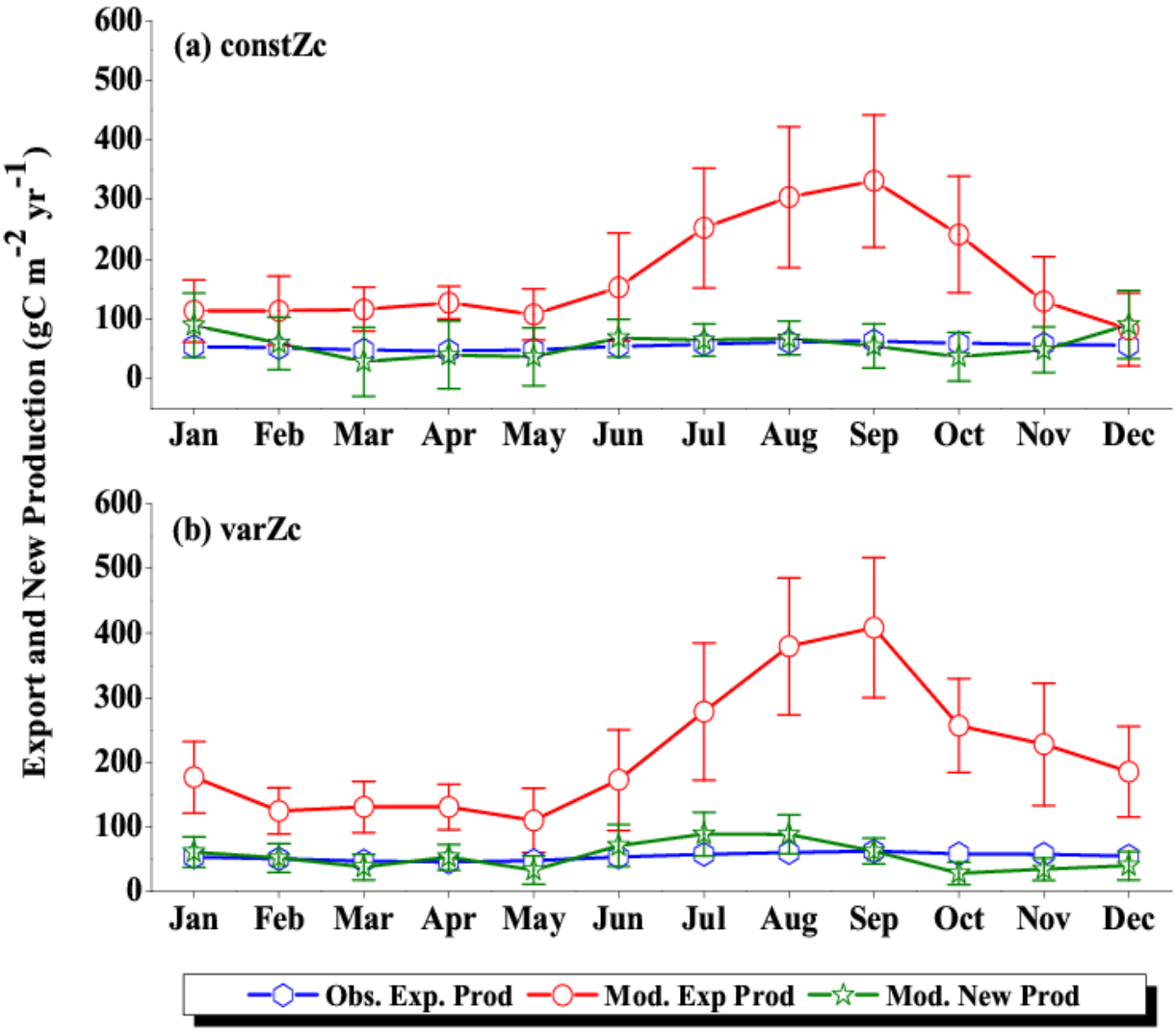

Figure 13: Same as Figure (7), but for SC.

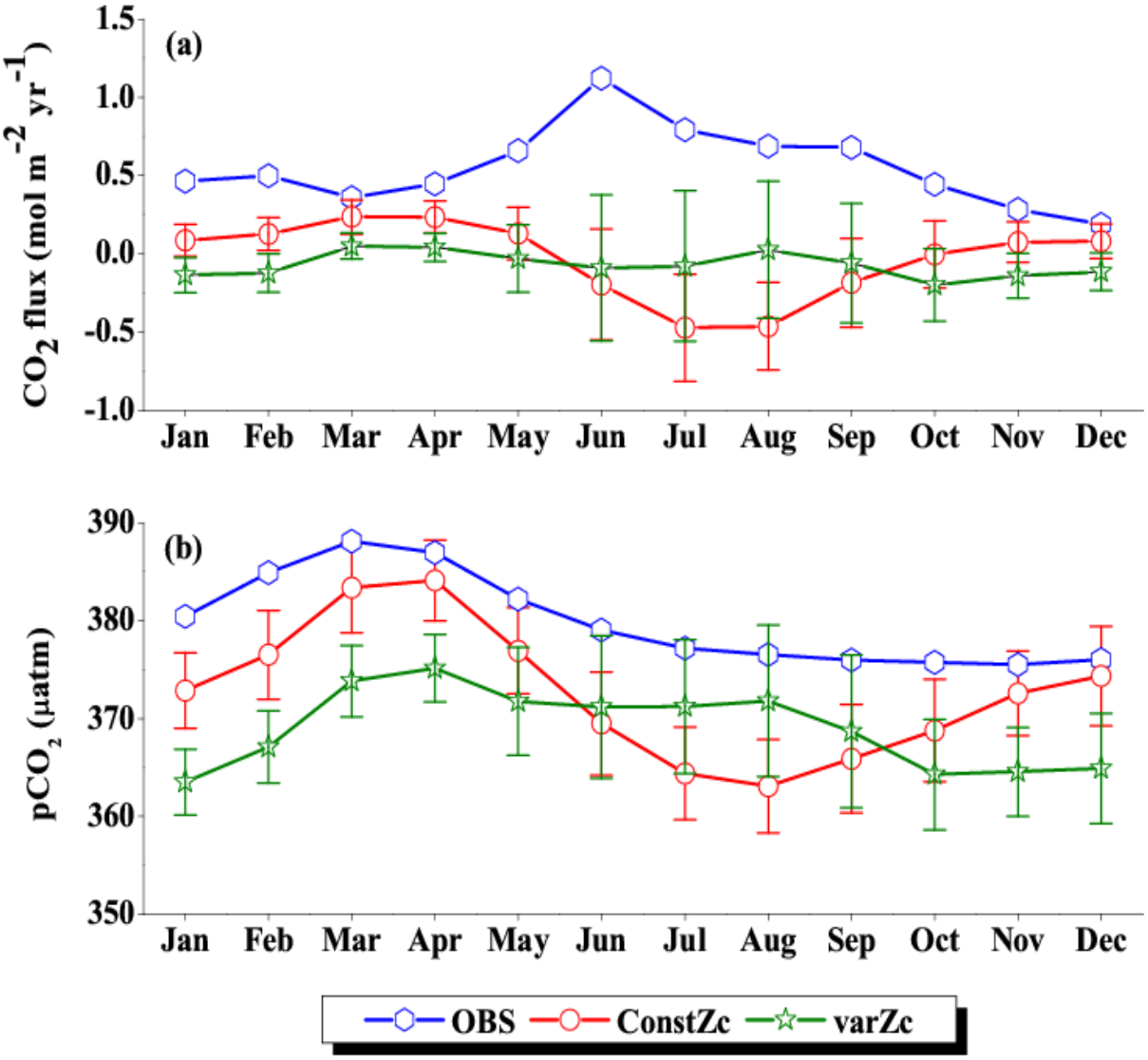

Figure 14: Same as Figure (6), but for SCTR.

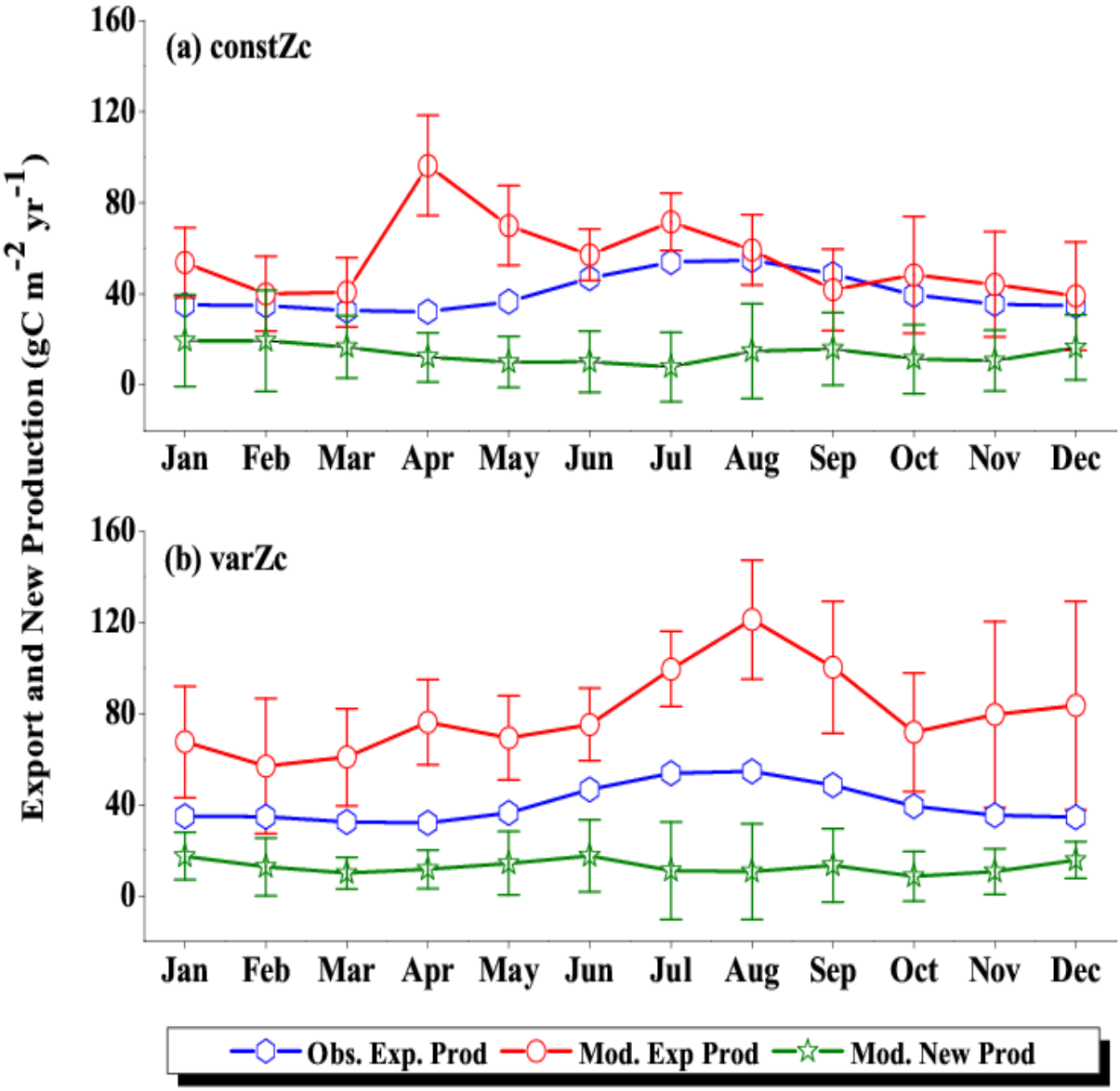

Figure 15: Same as Figure (7), but for SCTR.