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Process-based and Data-based estimates of variable community compensation depth for ocean BGC model with special reference to Indian Ocean

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Abstract

Ocean Carbon-Cycle Model Inter-comparison Project (OCMIP-II) provides accurate rendition of the annual mean carbon cycle for the global ocean. However it comes with a penalty of seasonal biases. Through this study we tried to capture the seasonality of carbon cycle in the model through process-based parameterization of community compensation depth (depth at which photosynthesis equals respiration of the whole biological community) and its retrieval via data-based inversion method. The biological parameterization is based on Chl-a dependent spatially and temporally varying Zc and the other is a statistical optimization by a cyclo-stationary Bayesian inversion method using surface ocean pCO_2 and phosphate data.

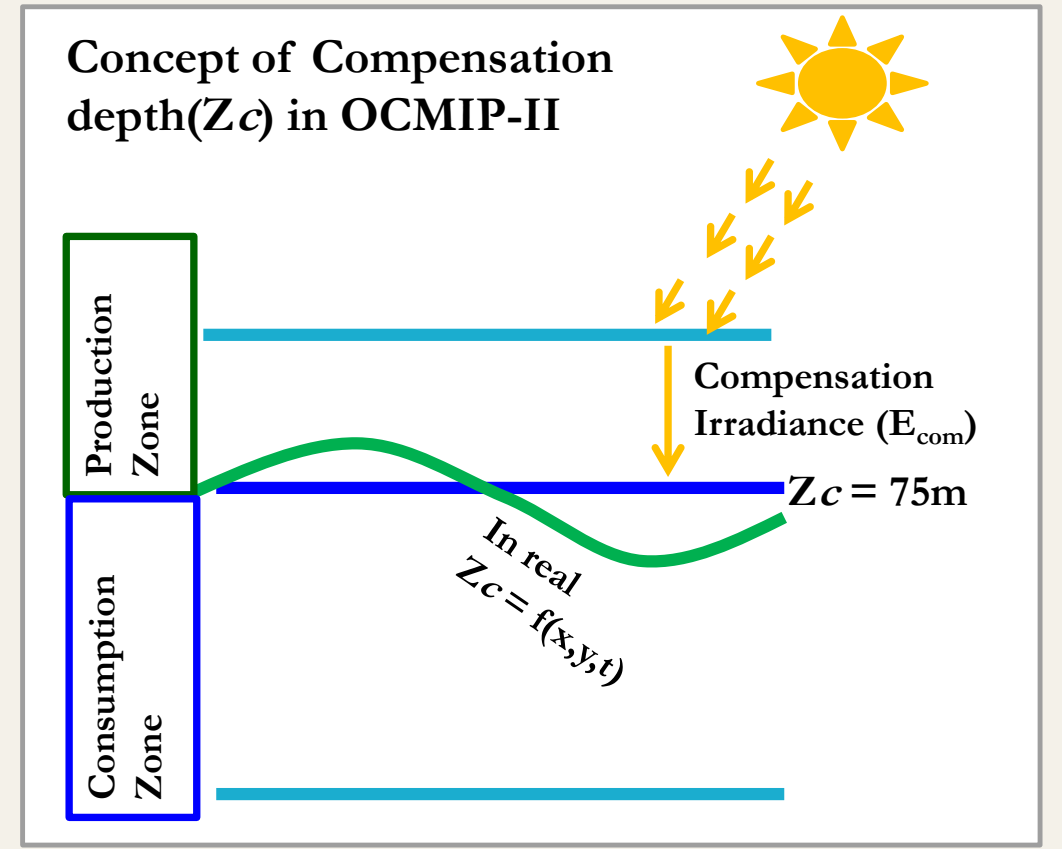
In the first method, by utilizing the Chl-a attenuated incoming solar radiation, a depth where solar radiation reaches 10 w m^{-2} has been proposed as a method to obtain spatially and temporally varying Zc. The spatio-temporal varying Zc has improved the seasonality of the simulated CO_2 fluxes, surface ocean pCO_2, export and new production in the major upwelling zones of Indian Ocean. Analysis proved that better representation of biological exports and the modified nutrient profiles in the model supported the seasonal correction in the OCMIP –II protocol. This scheme captured the carbon cycle response to episodic upwelling with the related biological processes in the Indian Ocean.

In the second attempt the surface pCO_2 and phosphate observations has been utilized to infer the spatially and temporally varying Zc via a cyclo-stationary Bayesian inversion method. Indian Ocean has been divided into 8 bioprovinces with 12 months of seasonality for which a prior Zc of 75m is assumed. A cost function based on model and observation mismatch has been minimized by taking Zc as a control variable. The data-based and process-based estimates of variable Zc are consistent and retrieved a similar seasonal cycle for all bioprovinces with slight differences in amplitudes.

Major conclusions are:
(a) Seasonality in carbon cycle of OCMIP –II could be improved by varying Zc,
(b) A balance in model export and new production is required for a better seasonality of carbon cycle.
(c) Surface ocean pCO_2 observations can be used as better observational constraint for upwelling zones.
(d) Using surface observations we are able to retrieve interior ocean biological model parameters.

Community Compensation Depth

The depth at which photosynthesis is large enough to balance the community respiration (i.e., both the autotrophic and heterotrophic respiration).
At the community compensation depth, the NCP is zero
i.e., NCP = NPP - R_h = 0,
i.e., NPP = GPP – R_a,
NCP – Net community production, NPP – Net primary production and GPP represents gross primary production
R_h and R_a are the heterotrophic and autotrophic respirations.



Ocean Biogeochemical Model Details

Ocean Tracer Transport Model (OTTM: Valsala et. al., 2008, 2010) coupled with OCMIP – II biogeochemical model (Najjar & Orr, 1998, Najjar et. al., 2007).

1. Physical Model

- The tracer concentration (C) evolves with time as

Vertical mixing & Horizontal diffusion

Emission/Absorption Fluxes

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

Horizontal & Vertical advection

Biological Source/Sink

- Vertical Mixing based on KPP (Large et. al., 1994)
- Eddy induced transport parameterization (Gent and McWilliams, 1990)
- Isopycnal tracer diffusion parameterization (Redi, 1982)

2. Biogeochemical Model

- The biogeochemical model is based on OCMIP-II protocol with a Nutrient restoration approach, having Phosphate as the basic currency.
- The production of biomass in the model using the nutrient restoring approach is given by

$$J_{prod} = \frac{1}{\tau}([PO_4] - [PO_4]^* ; \quad [PO_4] > [PO_4]* ; Z < Zc$$

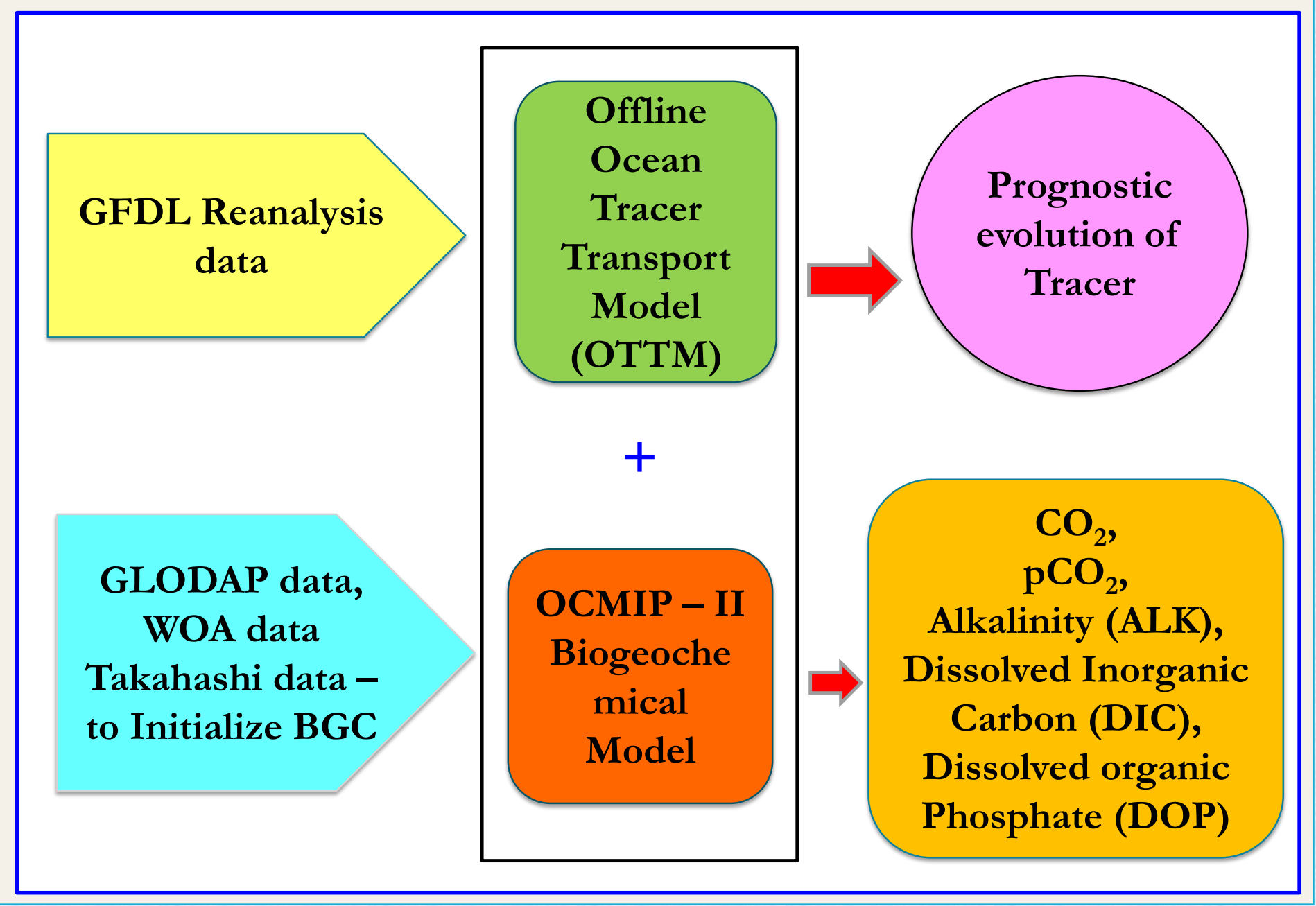
$$J_{prod} = 0; \quad [PO_4] \leq [PO_4]* ; Z > Zc$$

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

$$F = K_w \, \Delta \, pCO_2$$

- pCO_2 is calculated in the model by:

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


GFDL Reanalysis data
Offline Ocean Tracer Transport Model (OTTM)
+
OCMIP – II Biogeochemical Model
Prognostic evolution of Tracer
GLODAP data, WOA data Takahashi data – to Initialize BGC
CO_2, pCO_2, Alkalinity (ALK), Dissolved Inorganic Carbon (DIC), Dissolved organic Phosphate (DOP)

Schematic representation of the Ocean BGC model

Methodology 1: Process-based estimates of Zc via Biological Parameterization

A spatially and temporally varying compensation depth (varZc) is obtained by Surface Chl-a based attenuation of solar radiation with a minimum solar radiation required for production is taken as 10 Wm^{-2}

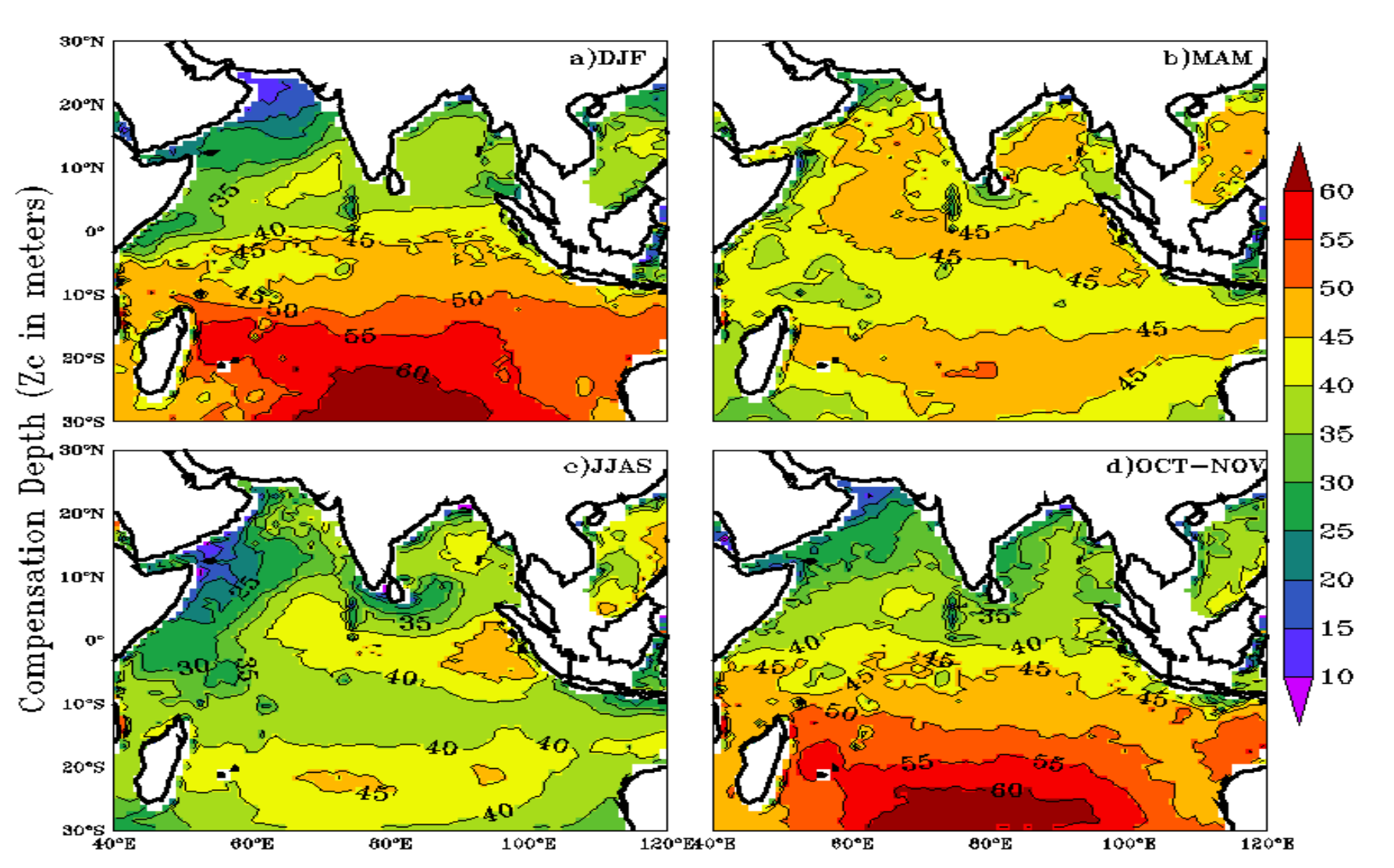


Figure 1: Seasonal-mean maps of varying compensation depth (varZc),. Units are meters.

Results

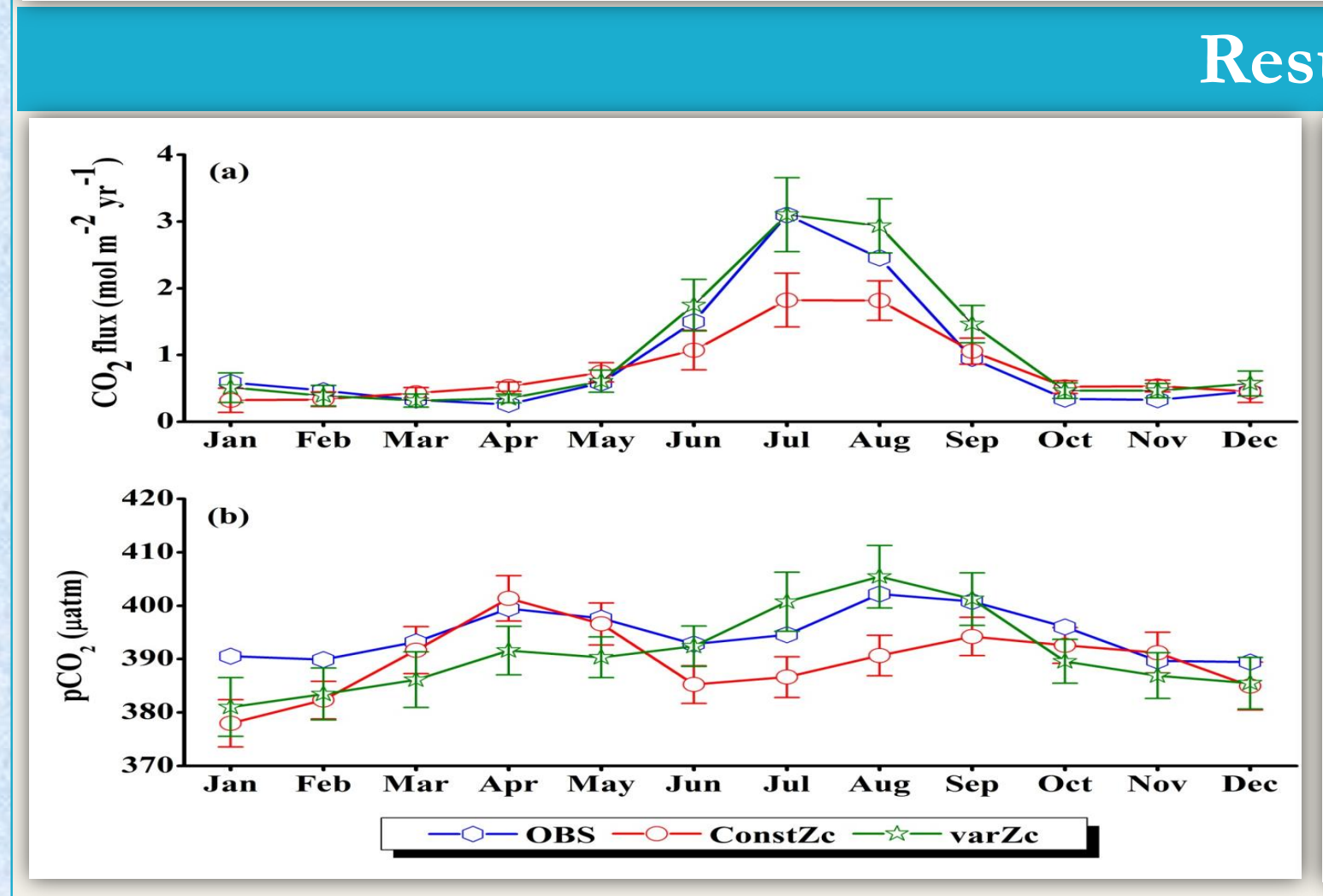


Figure 2: Comparison of model (a) CO_2 flux and (b) pCO_2 simulated with constZc and varZc with that of Takahashi et al. (2009) observations (OBS) over western Arabian Sea. Units of CO_2 flux and pCO_2 are mol m^{-2} yr^{-1} and µatm, respectively. Legend is common for both graphs.

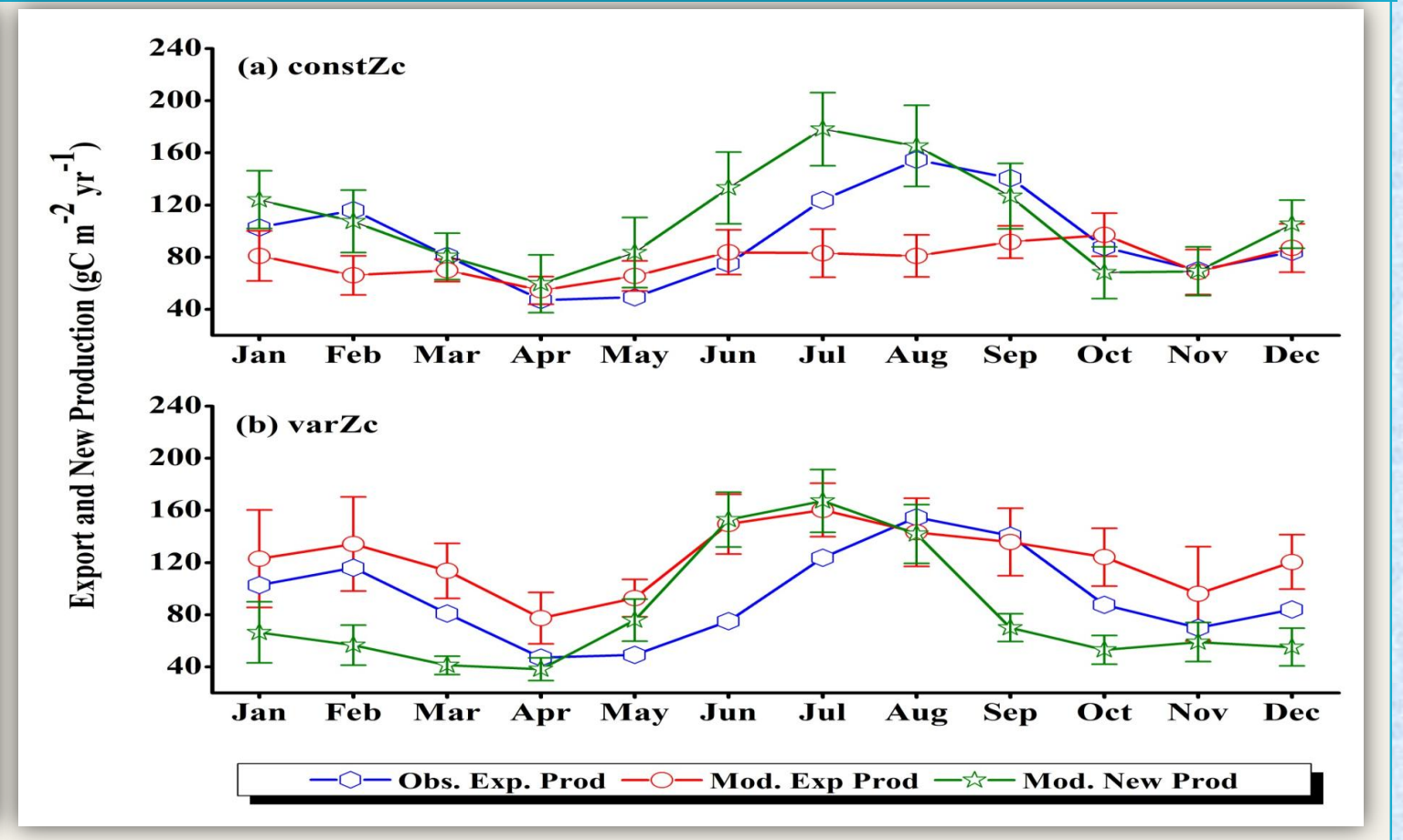


Figure 3: Comparison of model export production (Mod. Exp. Prod) and new production (Mod. New Prod) with satellite-derived export production (Obs. Exp. Prod) for (a) ConstZc and (b) varZc simulations for WAS. Units are g C m^{-2} yr^{-1}. Legends are common for both graphs.

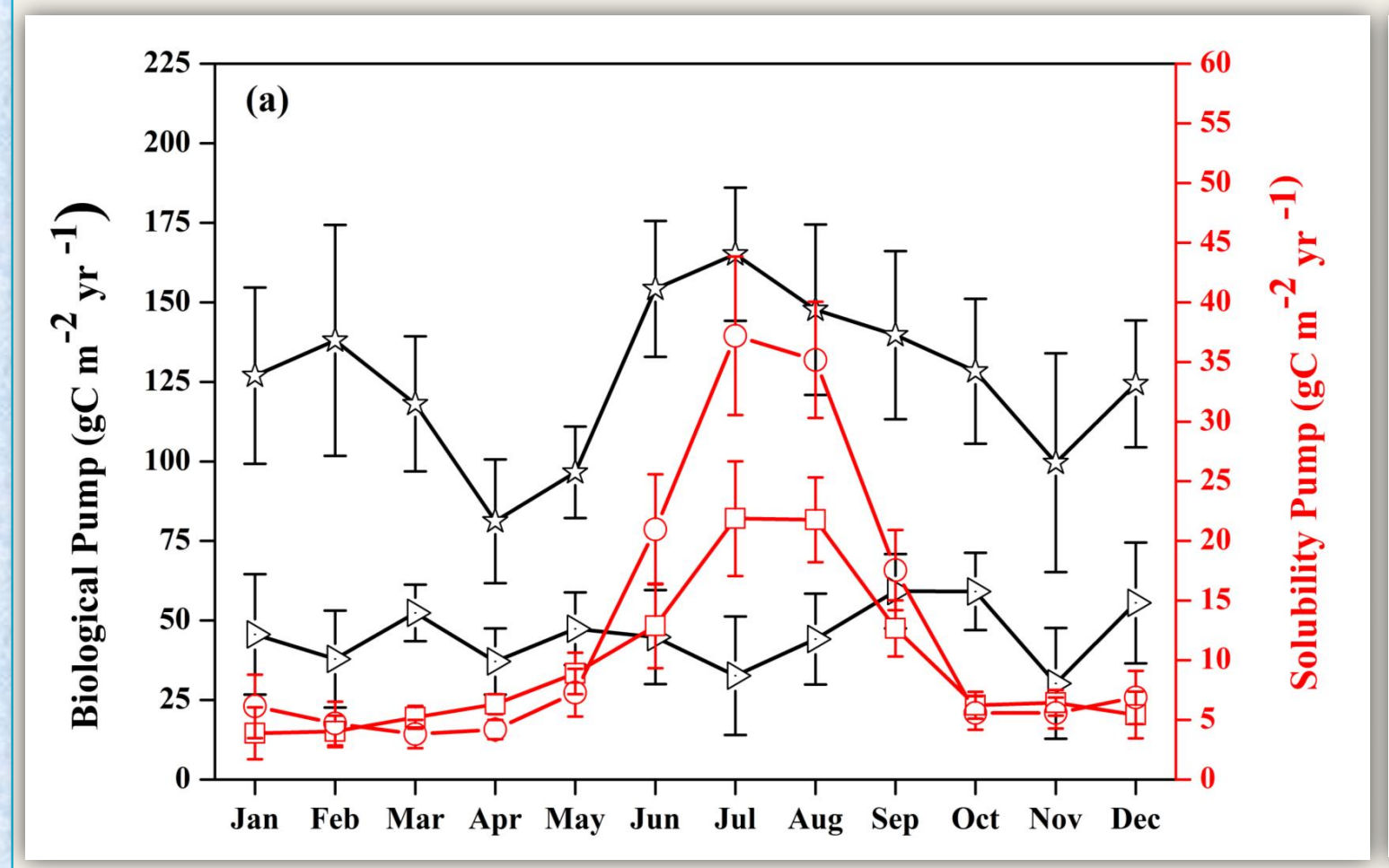


Figure 4:The strength of the biological pump (BP, black lines) and solubility pump (SP, red lines) from constZc and varZc simulations for Western Arabian Sea.

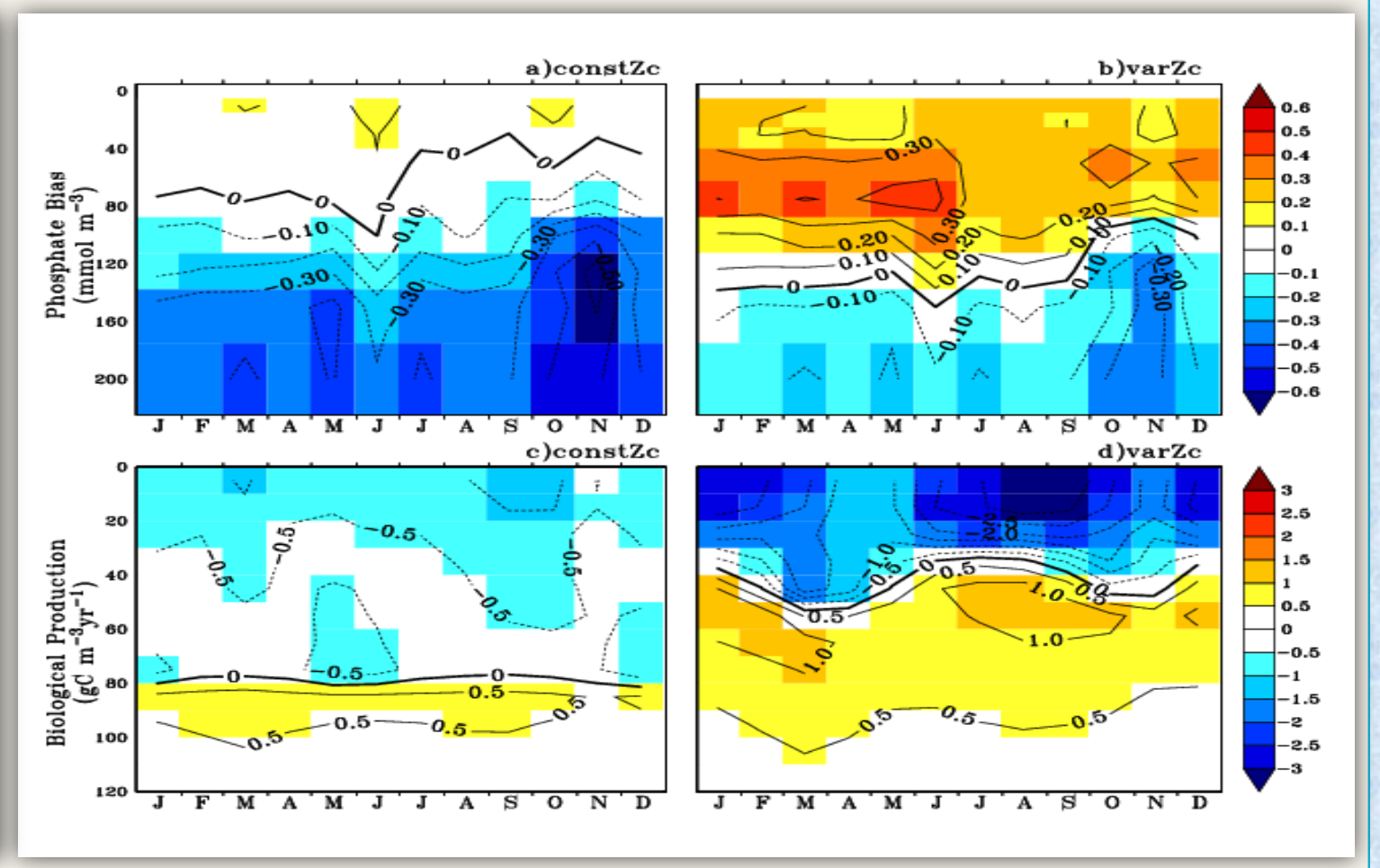


Figure 5: Annual mean bias of model phosphate when compared with climatological observational data (a) for constZc and (b) for varZc simulations. Corresponding annual mean biological source/sink profiles (c, d) in the model for WAS. Unit of phosphate is mmol m^{-3} and biological source/sink is g C m^{-3} yr^{-1}.

Methodology 2: Data-based estimates of Zc via Bayesian inversion

A spatially and temporally varying compensation depth is retrieved using surface pCO_2 and phosphate observations via Bayesian Inversion method without any prior information.

Linear Bayesian Inversion Framework:

A gradient of the cost function (J) is attempted to minimize by optimally estimating the varZc using the surface ocean pCO_2 and phosphate as observational constraints. (Tarantola, 1987, Enting, et. al., 1995, Kalnay, 2006, Lewis. et. al., 2006).

$$J(Z_c) = (D - GZ_c)^T C_D^{-1} (D - GZ_c)^T + (Z_c - Z_o)^T C_z^{-1} (Z_c - Z_o)^T$$

The linear Bayesian theory suggests that there exist an optimal values of Zc wherein the observations and model has minimum mismatch when

$$Z_{opt} = Z_o + [G^T C_D^{-1} G + C_z^{-1}]^{-1}.G^T C_D^{-1}(D - GZ_o)$$

D is the data vector obtained from the area averaged difference from observational datasets and control run climatology for each month over each region (96 x 1).

G represents a two dimensional sensitivity matrix obtained by the weighted area averaged difference of target variable (case1: pCO_2 and case 2: PO_4) between the sensitivity and the control run over each region for each month (96 x 96).

C_D is model-data mismatch error variance-covariance matrix (Figure 8) and C_z is prior error variance-covariance matrix (Figure 7).

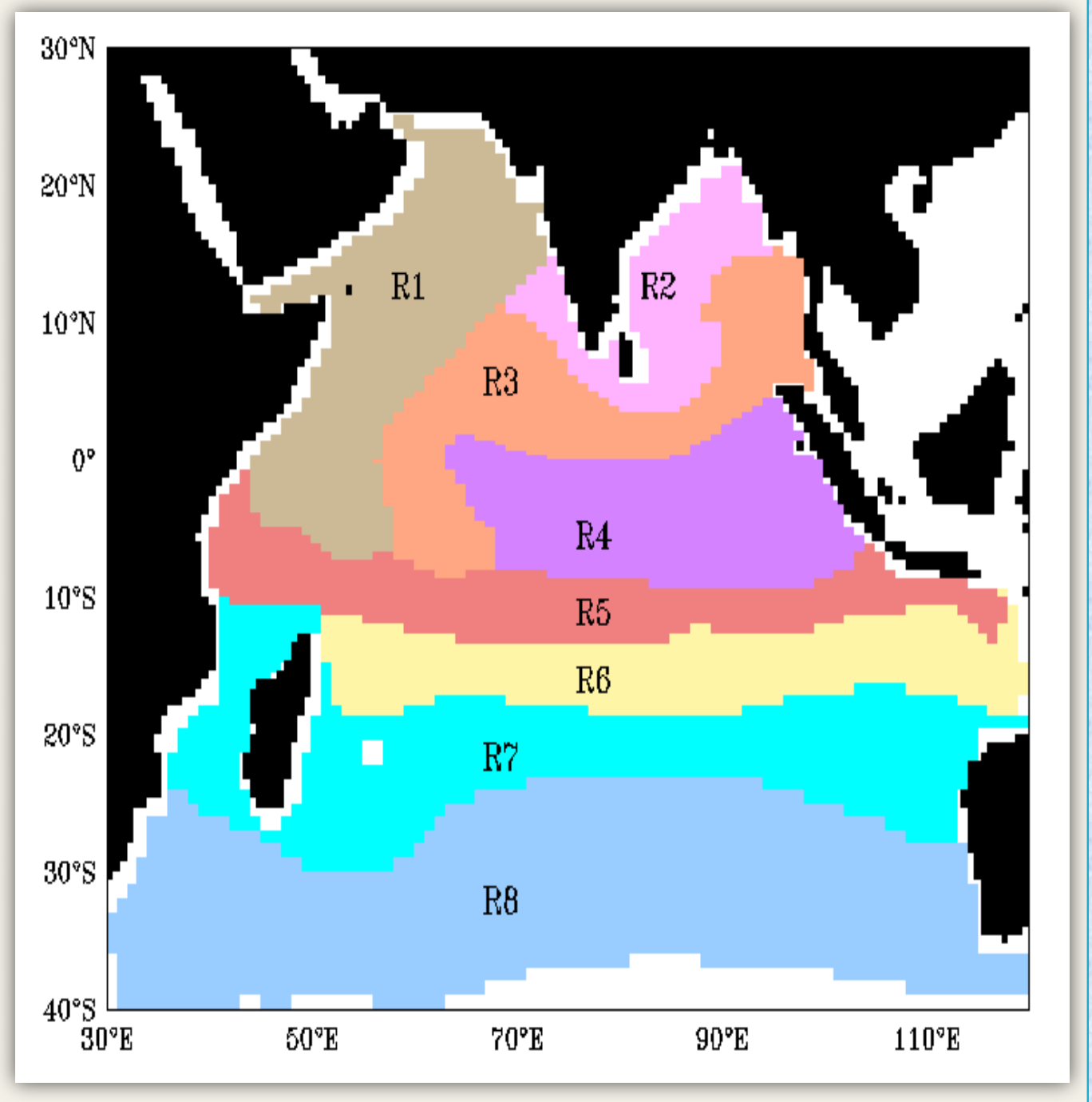
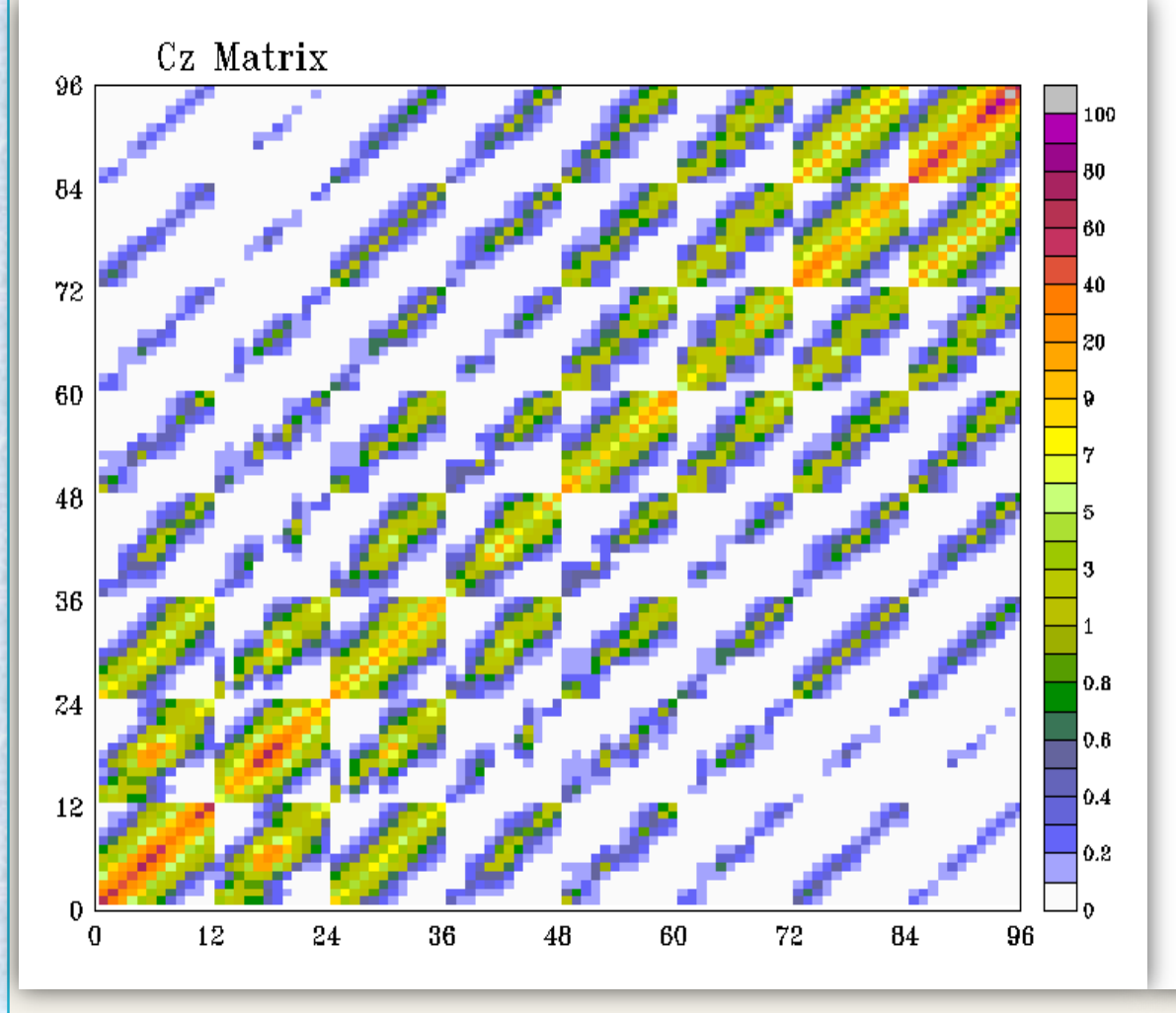


Figure 6. Indian Ocean bioprovinces selected based on the seasonal variation in varying compensation depth, namely – Region-1 (R1: Western Arabian Sea, WAS), Region-2 (R2: North Bay of Bengal and Around India, NBoB & AI), Region-3 (R3: East Bay of Bengal and Central Indian Ocean, EBoB & CIO), Region-4 (R4: East Equatorial Indian Ocean, EEIO), Region-5 (R5: South Equatorial Indian Ocean, SEIO), Region-6 (R6: South Tropical Indian Ocean, STIO), Region-7 (R7: South Subtropical Indian Ocean, SSIO) and Region-8 (R8: Subtropical Oligotrophic Gyre, SOG).

Methodology 2: Data-based estimates of Zc via Bayesian inversion



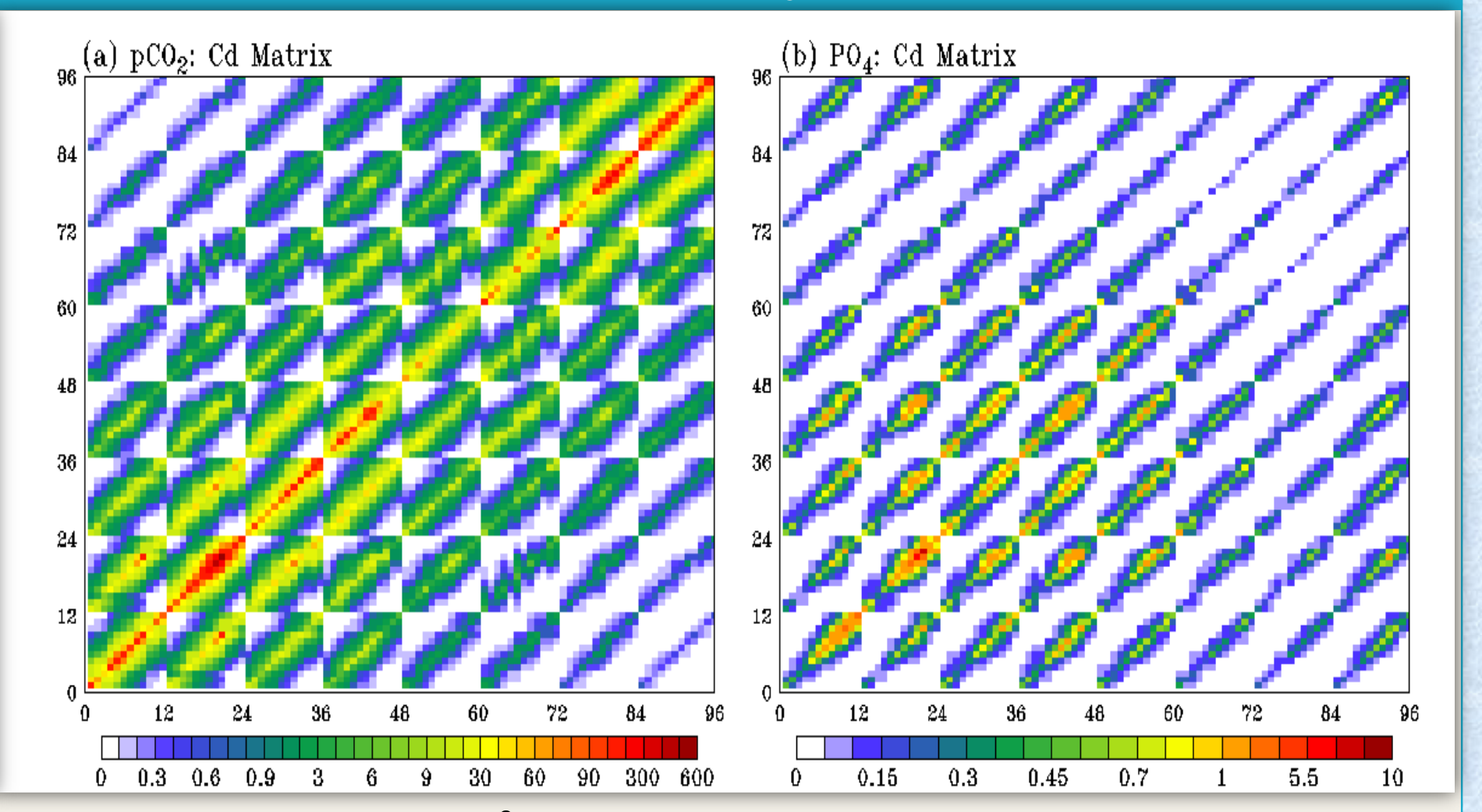


Figure 7: prior error variance-covariance of Zc (i.e. Cz). Units are in m^2. Figure 8: (a) pCO_2 observation error variance-covariance matrix. The principle diagonal elements represent the variances of pCO_2 observations of each oceanic region for each month and the off diagonal elements represents their cross co-variances. The mosaic of size 12 x 12 represents the variance – co-variances of pCO_2 within each oceanic region but with different climatological months. Units are in $(\mu atm)^2$. (b) PO_4 observation error variance-covariance matrix. Units are in $(mmolm^{-3})^2$.

Results

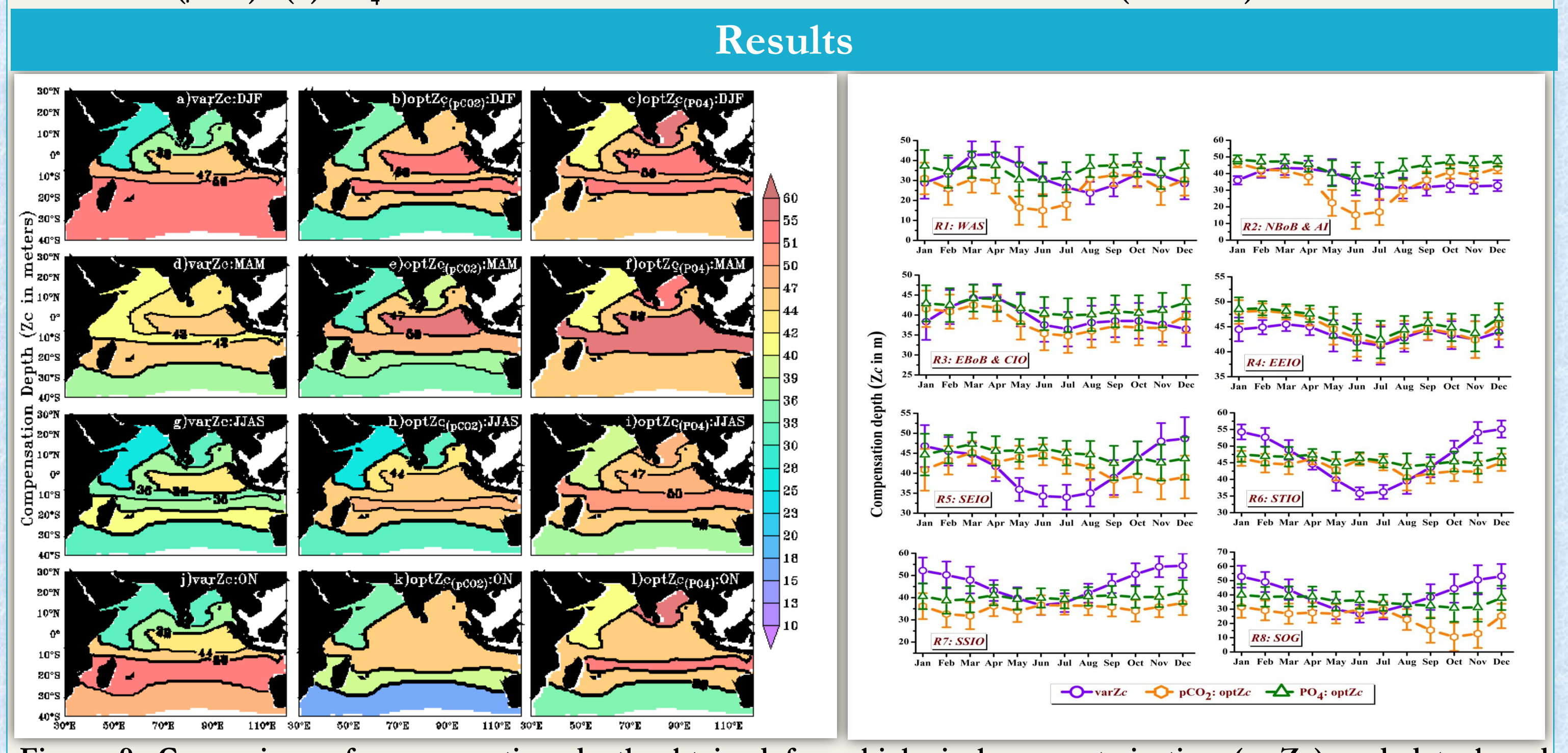


Figure 9. Comparison of compensation depth obtained from biological parameterization (varZc) and data based estimates via Bayesian inversion (OptZc (pCO_2 and PO_4)) computed over a climatological state from 1990 – 2010 for various Indian Ocean regions. Error bars shows standard deviations of individual months over these years. Units are in meters. Figure 6. Comparison of seasonal mean variable compensation depth from biological parameterization (varZc, panels a,d,g,j) and data based estimates via Bayesian Inversion using pCO_2 (optZc$_{(pCO2)}$, panels b,e,h,k) and PO_4 (optZc$_{(PO4)}$, panels c,f,i,l) .Units are in meters

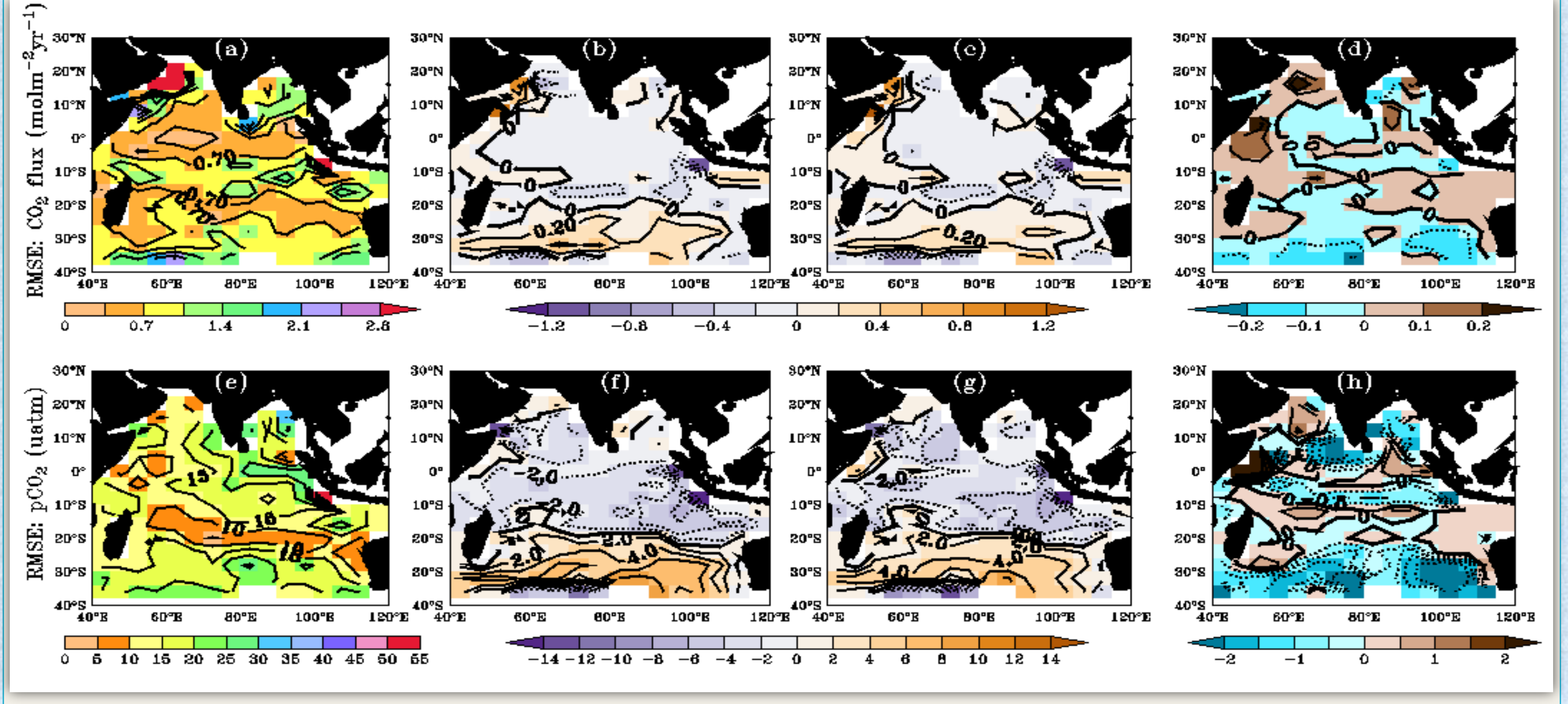


Figure 10. (a) RMSE of CO_2 flux from VarZc (Sreeush et al., 2018); (b) RMSE difference between CO_2 flux $_{(OptZc(pCO2))}$ and CO_2 flux$_{(varZc)}$ (c) same as (b) but for CO_2 flux$_{(OptZc(PO4))}$; (d) RMSE difference between CO_2 flux$_{(OptZc(PO4))}$ and CO_2 flux$_{(OptZc(pCO2))}$; (e) same as (a), but for pCO_2; (f) same as (b), but for $pCO_{2(OptZc(pCO2))}$; (g) same as (c), but for $pCO_{2(OptZc(PO4))}$; (h) same as (d) but for pCO_2. Units are in molm^{-2}yr^{-1} for CO_2 flux and µatm for pCO_2.

Conclusions

- A spatially and temporally varying community compensation depth (varZc) in ocean carbon models improves the seasonality in the carbon cycle.
- Both process based and data based estimates retrieves a consistent varZc with slight variation in magnitude.
- The importance of having a seasonal balance in model export and new production is highlighted
- varZc enhances the model export production by approx 70% as compared to constant Zc.
- The biological and solubility pump strengthened by the new varZc parameterization.
- Surface ocean pCO_2 data is a strong observational constraint for upwelling regions as compared to phosphate data.
- The study also highlights the importance of resolving interior ocean biogeochemical dynamics using surface observations.

References

1. Sreeush, M. G., Valsala, V., Pentakota, S., Prasad, K. V. S. R., and Murtugudde, R.: Biological Production in the Indian Ocean upwelling zones: Part – I: refined estimation via the use of a variable Compensation Depth in ocean carbon models, *Biogeosciences, 15,* 1895-1918, https://doi.10.5194/bg-15-1895-2018, 2018.
2. Sreeush, M. G., Valsala, V., Halder, S., Pentakota, S., Prasad, K. V. S. R., Naidu, C. V., and Murtugudde, R.: Biological production in the Indian Ocean upwelling zones: Part – II: Data based estimates of variable compensation depth for ocean carbon models via cyclo-stationary Bayesian inversion, *Deep Sea Research, Part II,* https://doi.org/10.1016/j.dsr2.2019.07.007, 2019.