Modelling for Ocean Forecasting and Process Studies

6-10 December 2021

Indian Ocean Global Ocean Observing System (IOGOOS) &

International Training Centre for Operational Oceanography (ITCOocean), INCOIS

Lecture-2: Nutrient Limitations of Arabian Sea Primary and Secondary production and evolutions of subsurface chlorophyll maxima

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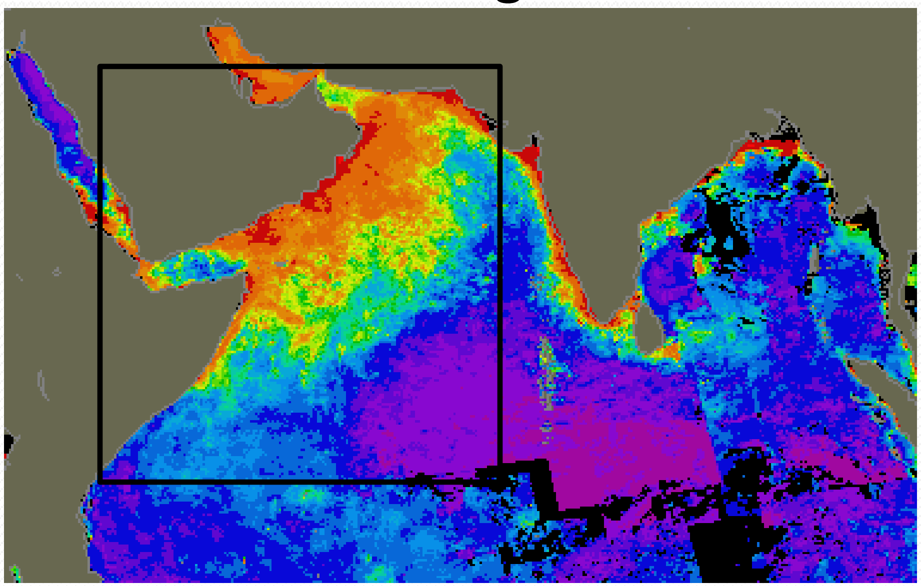
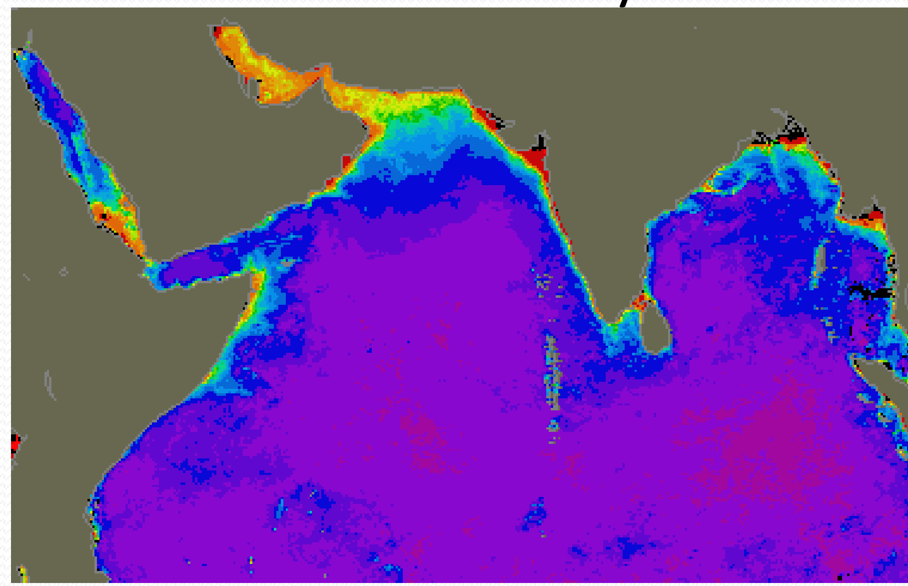
Arabian Sea Primary Production

August



January



Surface Ocean Chl-a variability from satellite observations (mgm^{-3})

Export Production

Regions	OBS
WAS	123.57

Biological Pump (model)

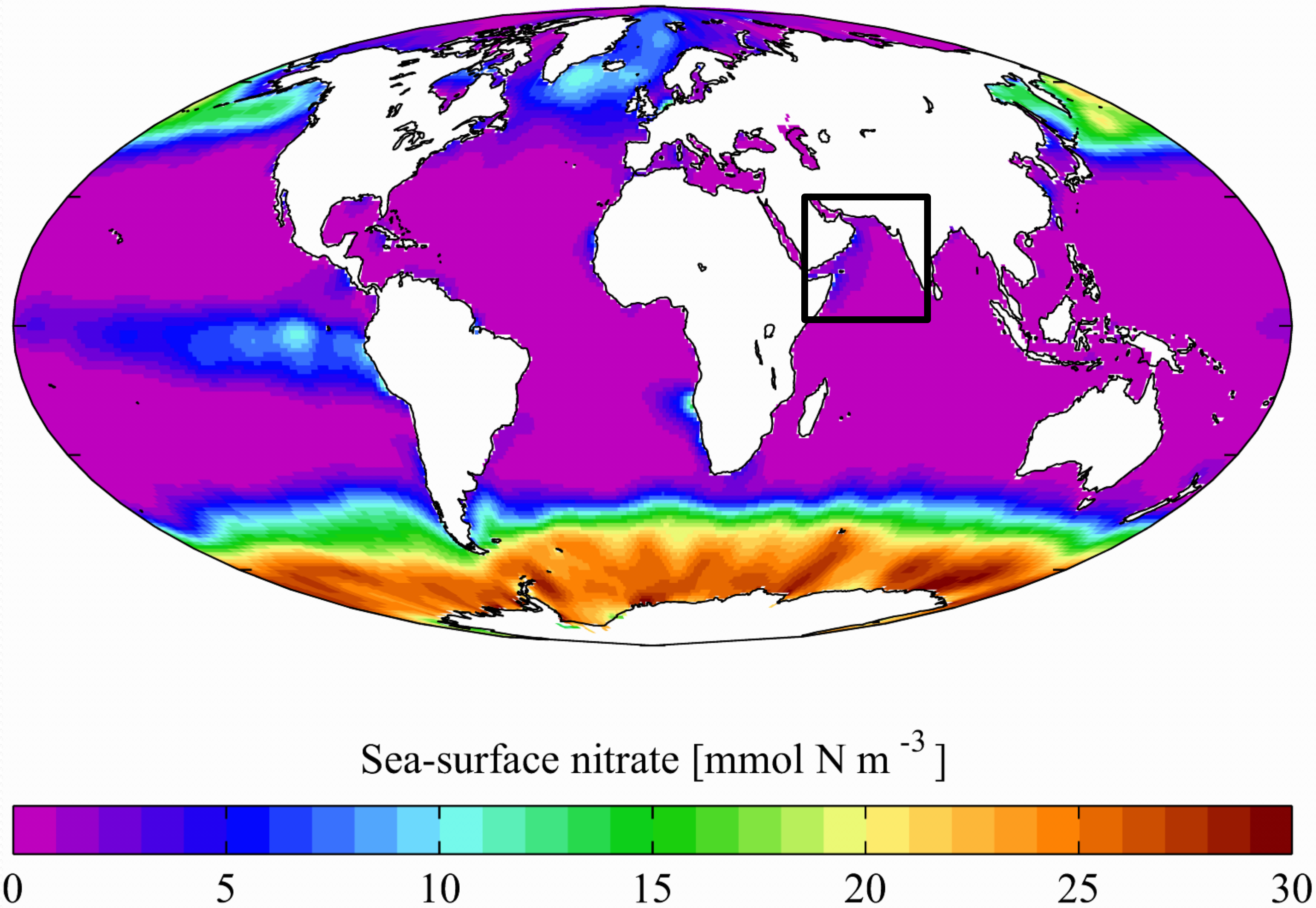
JJAS mean
151.7 ± 23.8

New Production (model)

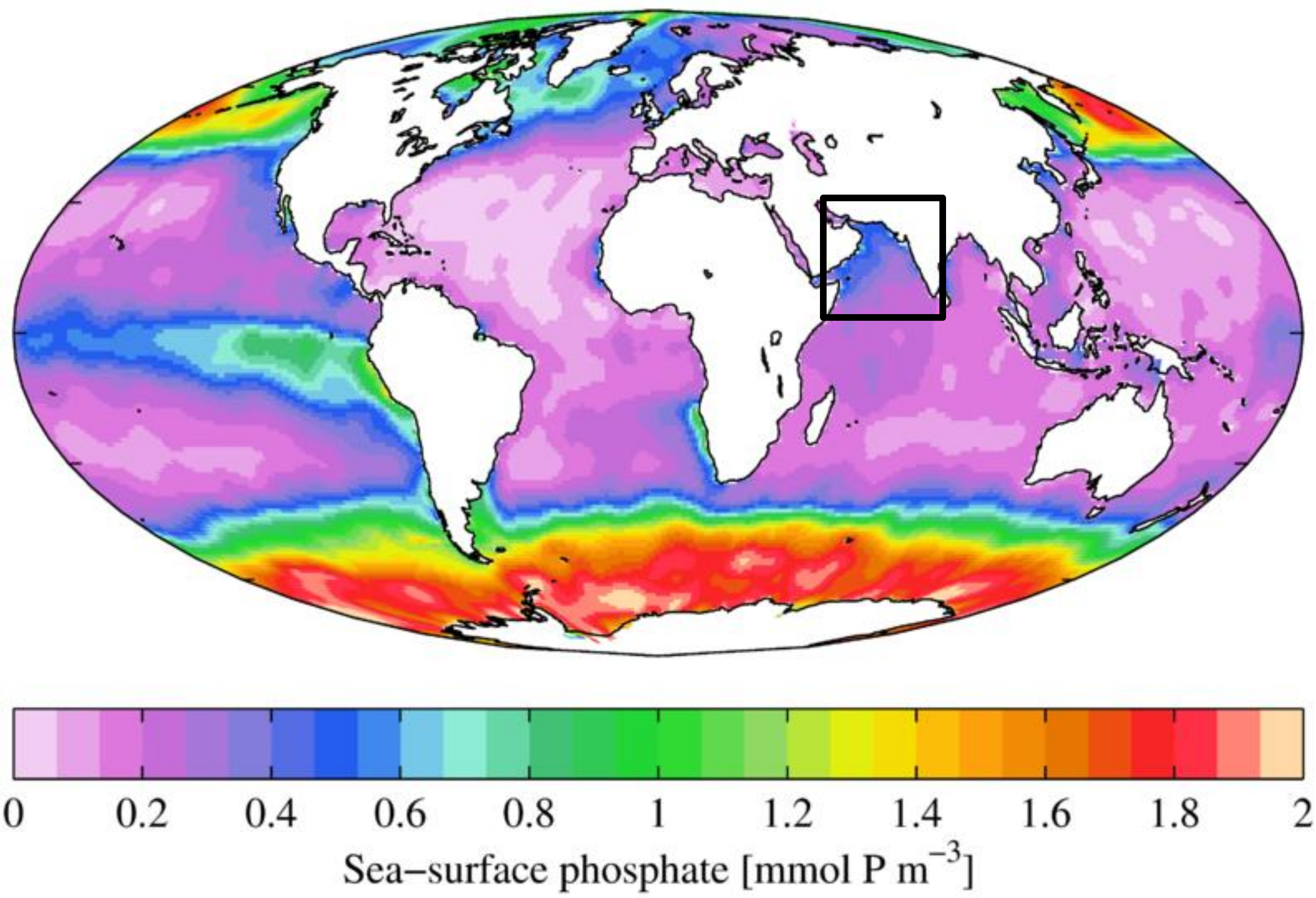
Regions	OBS	const*Zc*	var*Zc*
WAS	–	150.84 ± 27.9	133.03 ± 19.5

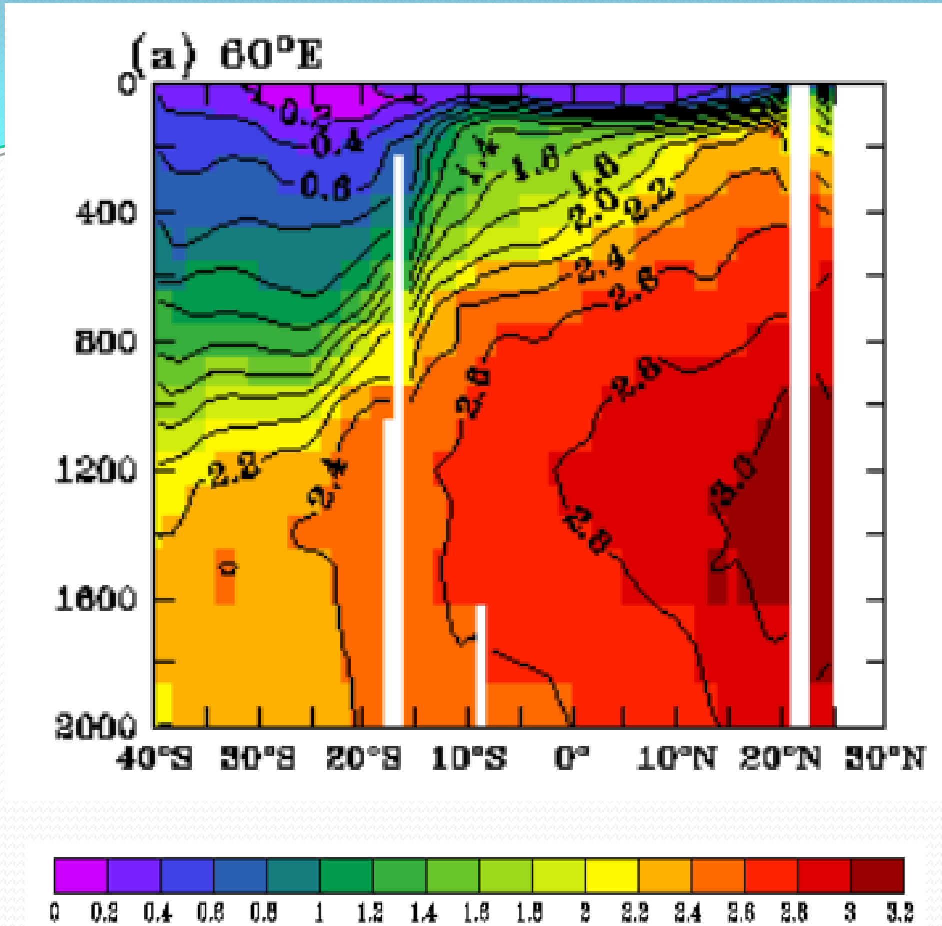
($gCm^2\ year^{-1}$)

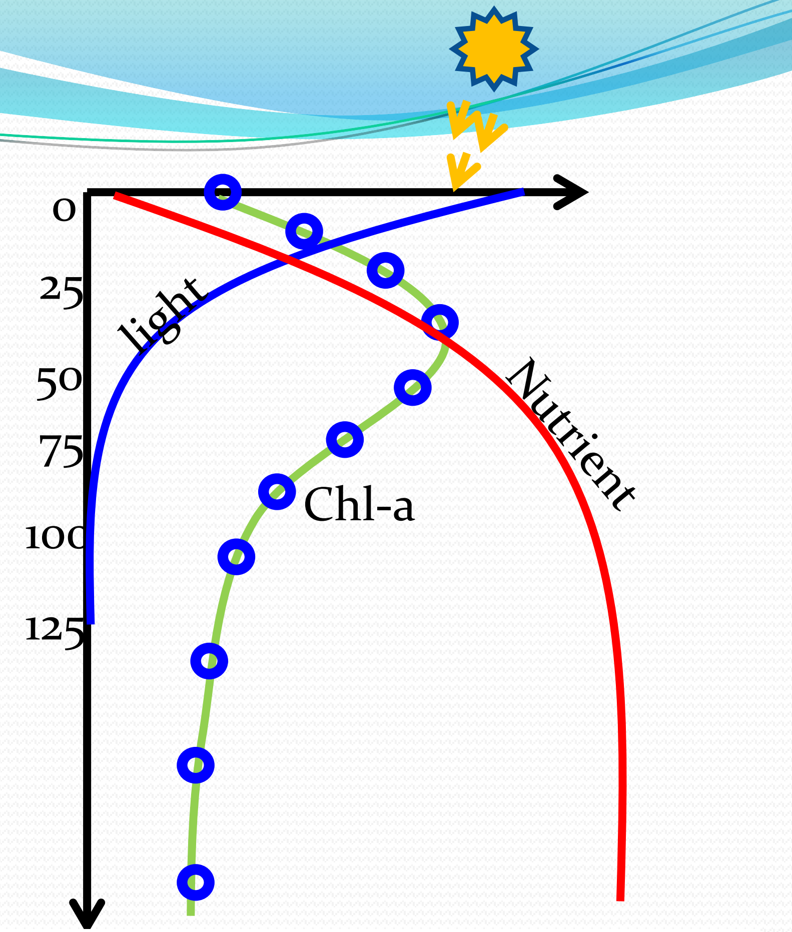
Surface Ocean Nitrate concentrations

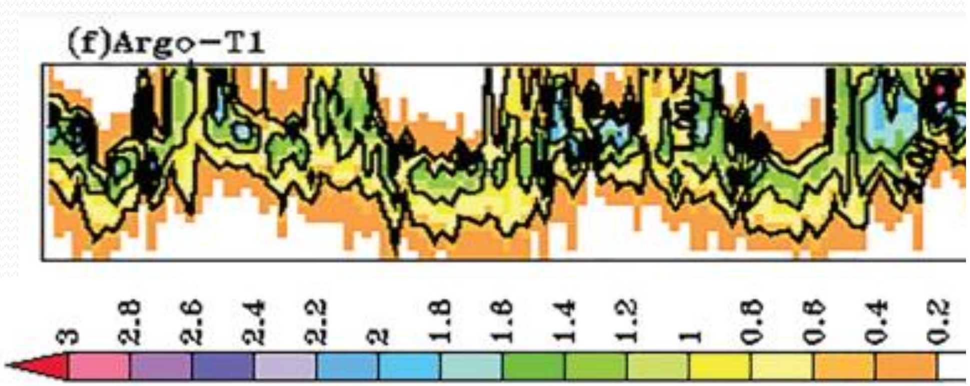


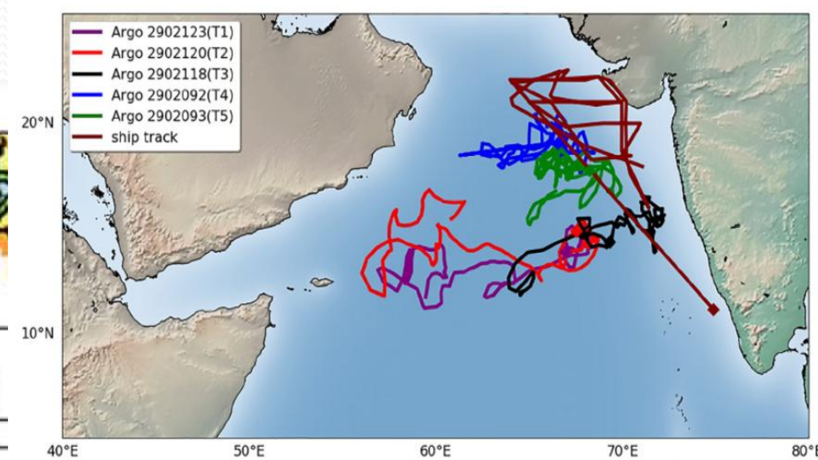
Surface Ocean Phosphate concentrations



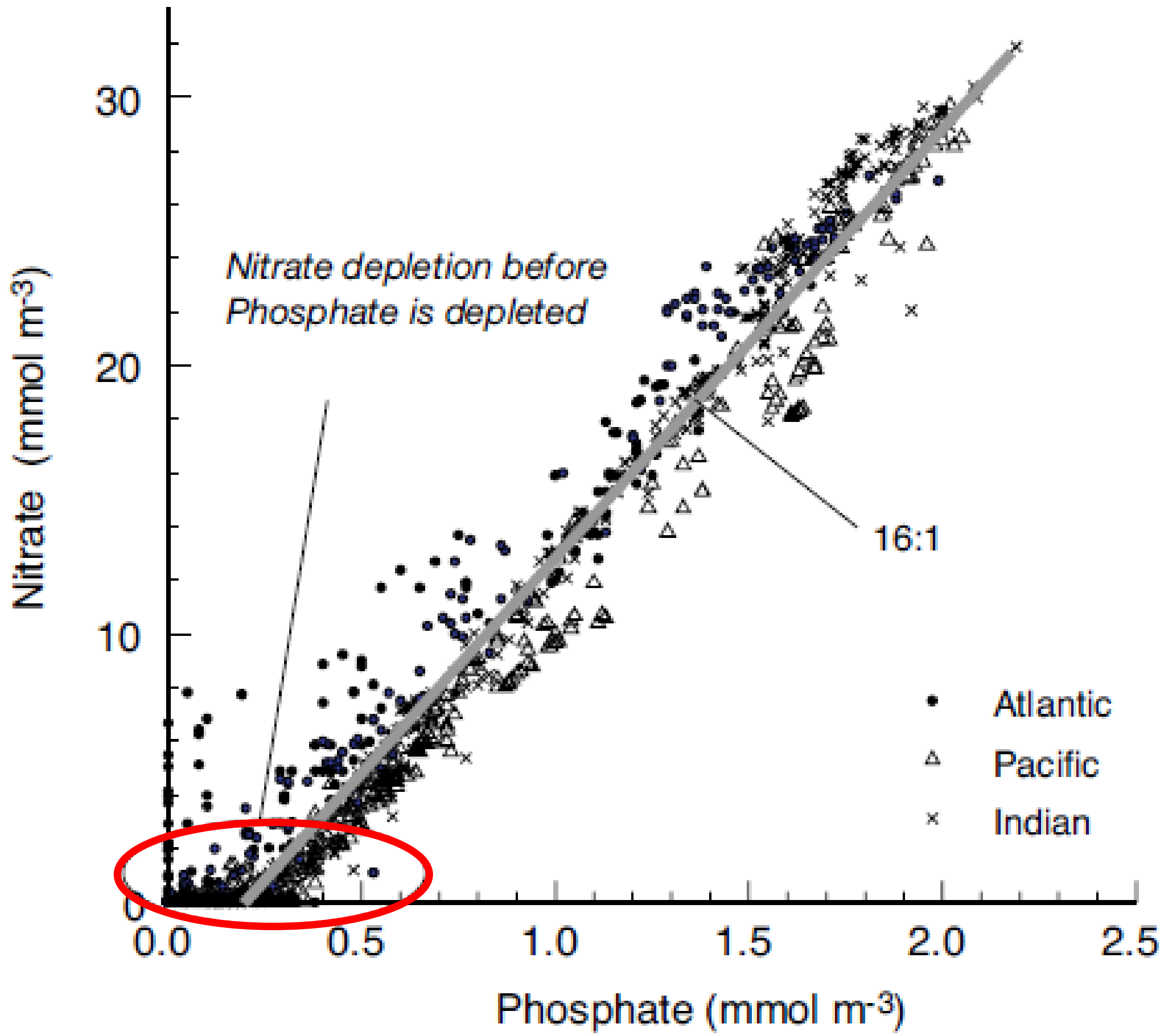

(a) 60°E
0
400
800
1200
1600
2000
40°S 30°S 20°S 10°S 0° 10°N 20°N 30°N
0.2
0.4
0.6
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2


0
25
50
75
100
125
light
Nutrient
Chl-a


(f)Argo-T1
3 2.8 2.6 2.4 2.2 2 1.8 1.6 1.4 1.2 1 0.8 0.6 0.4 0.2


Argo 2902123(T1)
Argo 2902120(T2)
Argo 2902118(T3)
Argo 2902092(T4)
Argo 2902093(T5)
ship track
20°N
10°N
40°E
50°E
60°E
70°E
80°E

Limiting Nutrients of Oceanic Primary Production



Nutrient Limitation.

Leibig Concept

The Stock of Phytoplankton will eventually be limited by the supply of a single cellular nutrient and growth will stop (Leibig, 1840)

Plankton concentration = min (C1, C2, C3, …)

Monod Concept

Influence of nutrient concentration on the rate of photosynthesis rather than on the extend of growth

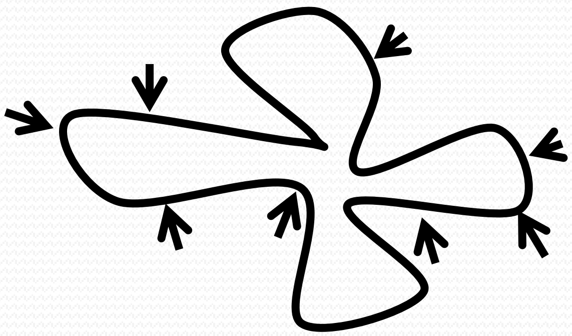
$$\text{Growth of plankton} \propto [C / (C + C_0)]$$

Phosphate as a limiter

- Because Nitrogen can be "fixed" by nitrogen fixation
- Because Phosphate supply is only through external sources
- On "large" space & time scale nitrate is maintained as a constant mean concentration and that is determined by how much phosphate is available.
- Therefore;
    - On small space & time scale, Nitrate is a limiting nutrient (0-100 years)
    - On longer scale Phosphate can be a limiter (100s of years)

Iron (Fe) as a limiter

- Iron is an important component of electron transport proteins involved in photosynthesis & respiration
- Iron is a component of enzymes required to utilize nitrate & nitrite, as well as for nitrogen fixation
- Reduced supplies of iron leads to reduced growth rate and reduced abundance of larger phytoplankton



Larger plankton with larger cell area increases the absorption of iron

Silicate as a limiter

- Large Phytoplankton (represents diatoms which can make siliceous shells, so their growth can be limited by both nitrogen components and silicate)
- Several other studies have argued that silicate limitation plays a significant role in phytoplankton (for e.g., diatom) productivity in Arabian Sea (Burckle, 1989; Koné et al., 2009; Paasche, 1973; Piketh et al., 2000 ; Wiggert et al., 2006).
- The absence of diatom frustules in the surface sediments of the eastern Arabian Sea points to the non-availability of silicate in the surface waters there (Burckle, 1989; Young & Kindle, 1994).
- Further, silicate may be a key limiting nutrient in the northern Arabian Sea, especially during the winter monsoon season which is inferred from the insignificant contribution of silicate by freshwater runoff (Balachandran et al., 2008; Naqvi et al., 2002)

Macro and Micro nutrients

- Nitrogen and phosphorus are essential macronutrients for the growth of aquatic plants and animals. Some phytoplankton (such as diatoms) also requires silicon for building their cell walls.
  - Eg: Nitrate (NO3), Phosphate (PO4), Inorganic Carbon (DIC), Silicic Acid/Silicate (SiOH4)
  - They are present in milli mole m^{-3} in the ocean

- Metals, such as iron and molybdenum, are needed in much smaller amounts and are considered micronutrients.
  - Eg: Fe
  - They present in micro mole m^{-3} in the ocean

Photosynthesis and Remineralization (aerobic and anaerobic)

Photosynthesis

$$106CO_2 + 16NO_3^- + HPO_4^{2-} + 78H_2O + 18H^+ \rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 150O_2$$

Redfield Ratio

$$C_{organic}:N:P:O_2 = (117 \pm 14):(16 \pm 1):(1):(-170 \pm 10)$$

Remineralization (aerobic)

$$C_{106}H_{175}O_{42}N_{16}P + 150\ O_2 \rightleftharpoons 106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 78\ H_2O$$

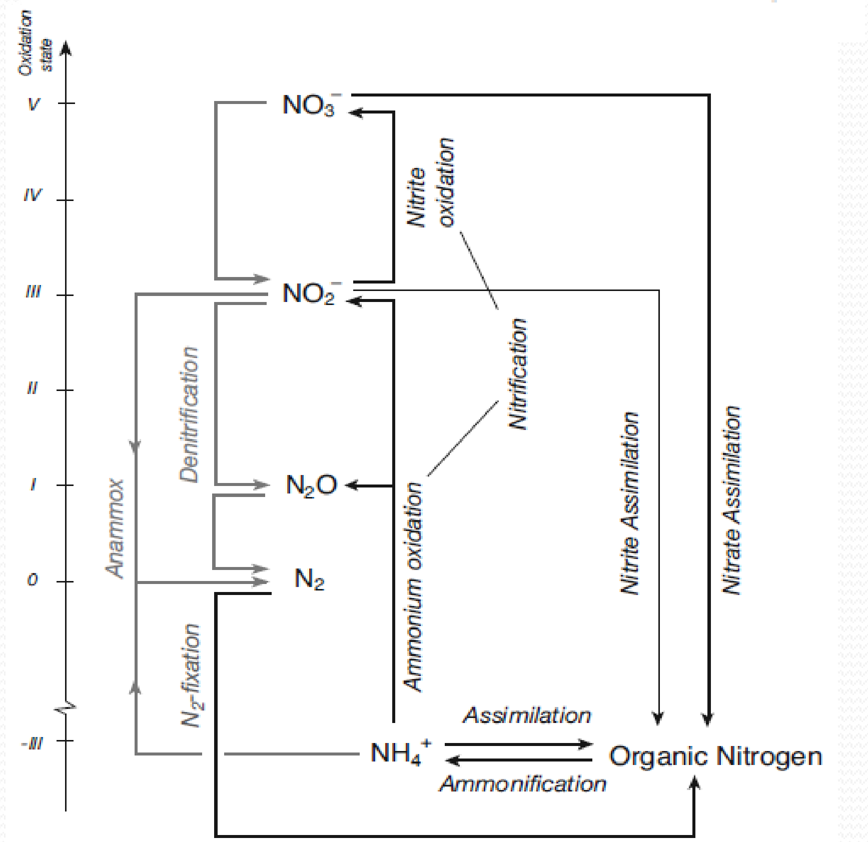
Remineralization (anaerobic)

$$C_{106}H_{175}O_{42}N_{16}P + 104\ HNO_3 \rightarrow 106\ CO_2 + 60\ N_2 + H_3PO_4 + 138\ H_2O$$

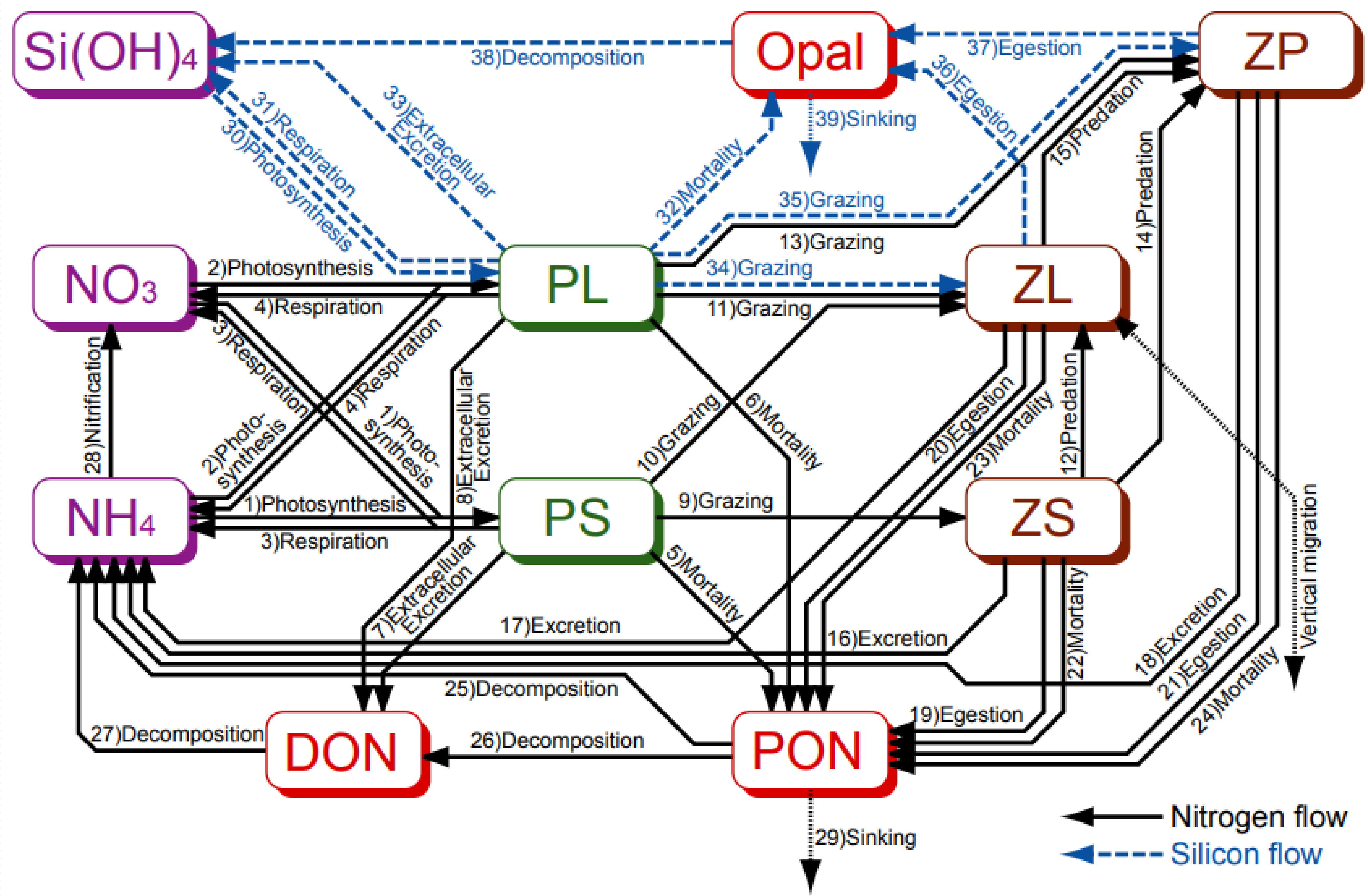
Ammonification : $org.N \rightleftharpoons NH_4^+$

Ammonium oxidation : $2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$

Nitrite oxidation : $2NO_2^- + O_2 \rightarrow 2NO_3^-$

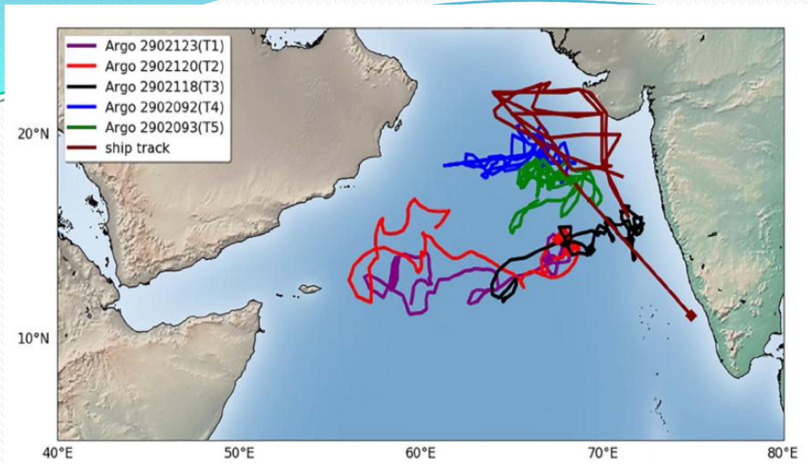


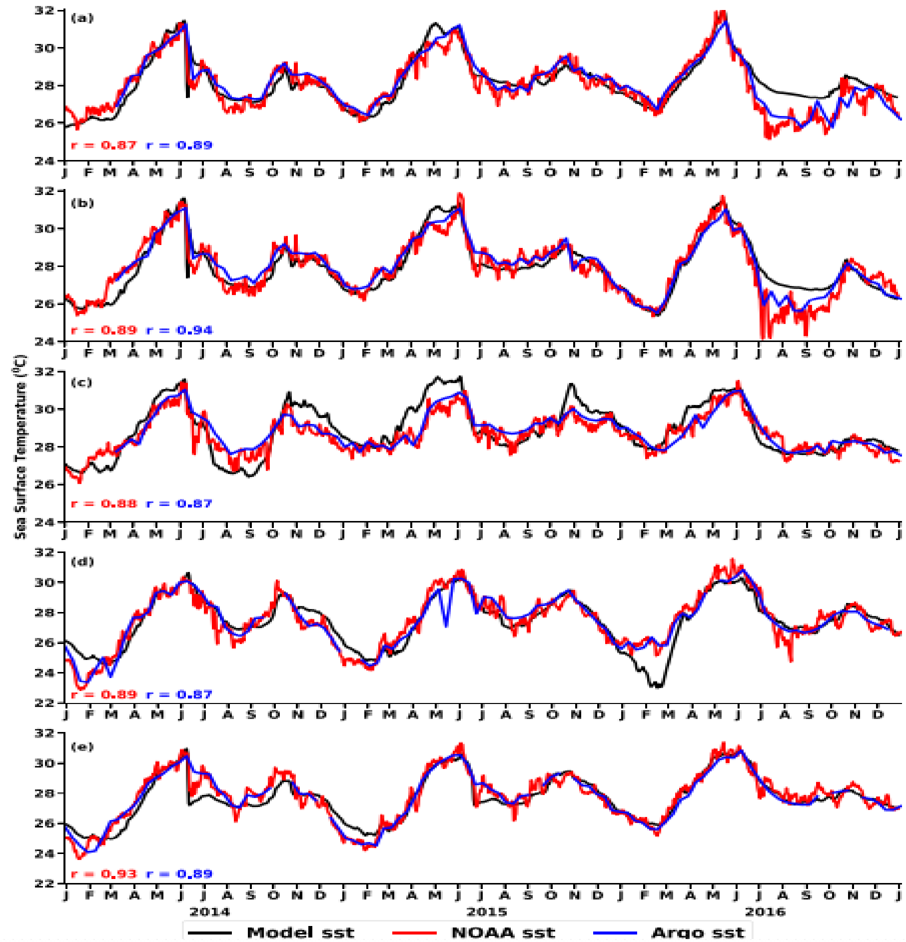
The role of nitrogen (Nitrate + Ammonium) and Silicate as limiting nutrients for the growth of plankton biomass in the Arabian Sea



13-component NEMURO model of Yamanaka et al., (2004)

Sea Surface Temperature





$$\frac{\partial U}{\partial t} - fV = \frac{\partial}{\partial z}\left(lqs_m \frac{\partial u}{\partial z}\right)$$

$$\frac{\partial V}{\partial t} + fU = \frac{\partial}{\partial z}\left(lqs_m \frac{\partial V}{\partial z}\right)$$

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(l\, q\, s_h \frac{\partial T}{\partial z}\right)$$

$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial z}\left(l\, q\, s_h \frac{\partial S}{\partial z}\right)$$

$$\mathrm{PS}_{\mathrm{Photosynthesis}} = V_{\mathrm{maxS}}\, e^{(k_S T)}\, \frac{\mathbf{I}}{\mathbf{I}_{\mathbf{optS}}} \mathbf{e}^{\left(1-\frac{I}{I_{optS}}\right)} \left\{ \frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + \mathrm{K_{NO_3S}}} \mathbf{e}^{(-\psi_S [\mathrm{NH_4}])} + \frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + \mathrm{K_{NH_4S}}} \right\} [\mathrm{PS}] \qquad (2a)$$

$$\mathrm{PL}_{\mathrm{Photosynthesis}} = V_{\mathrm{maxL}}\, e^{(k_L T)}\, \frac{\mathbf{I}}{\mathbf{I}_{\mathbf{optL}}} e^{\left(1-\frac{I}{I_{optL}}\right)} \min\left\{ \frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + \mathrm{K_{NO_3L}}} \mathbf{e}^{(-\psi_L [\mathrm{NH_4}])} + \frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + \mathrm{K_{NH_4L}}}, \frac{[\mathrm{Si(OH)_4}]}{[\mathrm{Si(OH)_4}] + \mathrm{K_{SiL}}} \right\} [\mathrm{PL}]$$

(2b)

Nutrient Limitation (NO3, NH4 and Silicate): Arabian Sea

$$(\text{PS Photosynthesis}) = V_{\max S} \cdot \left\{ \boxed{\frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + K_{\mathrm{NO_3S}}} \exp(-\Psi_{\mathrm{S}}[\mathrm{NH_4}])} + \boxed{\frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + K_{\mathrm{NH_4S}}}} \right\} \exp(k_{\mathrm{S}} T) \frac{I}{I_{\mathrm{optS}}} \exp\left(1 - \frac{I}{I_{\mathrm{optS}}}\right) [\mathrm{PS}], \qquad (\mathrm{A19})$$

$$(\text{PL Photosynthesis}) = V_{\max L} \min\left\{ \boxed{\frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + K_{\mathrm{NO_3L}}} \exp(-\Psi_{\mathrm{L}}[\mathrm{NH_4}])} + \boxed{\frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + K_{\mathrm{NH_4L}}}}, \boxed{\frac{[\mathrm{Si(OH)_4}]}{[\mathrm{Si(OH)_4}] + K_{\mathrm{SiL}}}} \right\} \exp(k_{\mathrm{L}} T) \frac{I}{I_{\mathrm{optL}}} \exp\left(1 - \frac{I}{I_{\mathrm{optL}}}\right) [\mathrm{PL}] \qquad (\mathrm{A21})$$

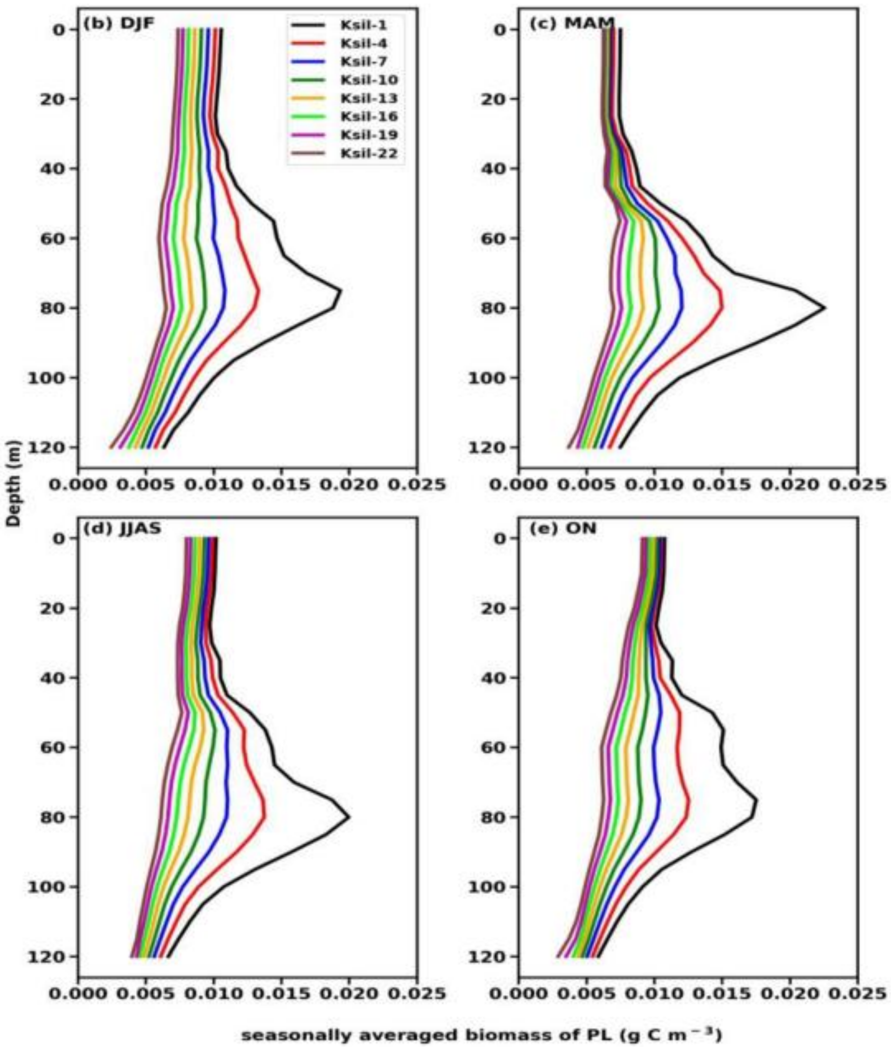
CASE 1 (No_Nitrate):
No New Production for PS & PL (flagellates and Diatom)

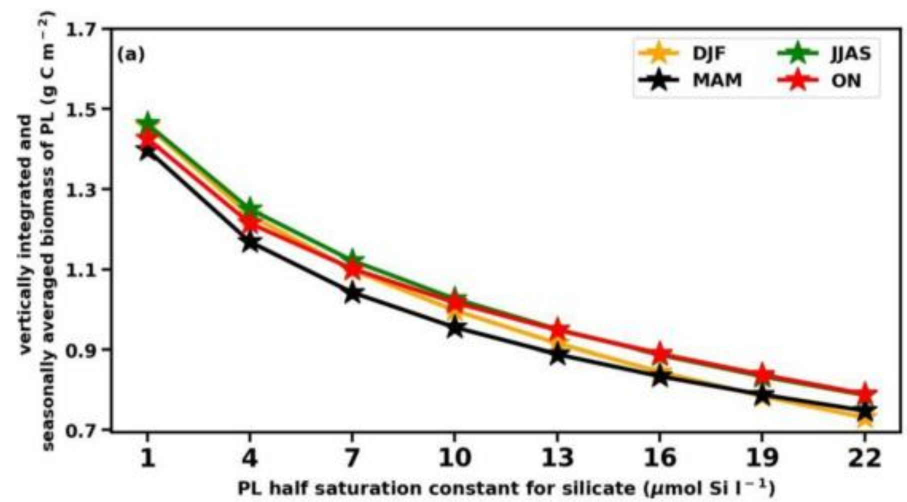
CASE 2 (No_Ammonium):
No Regenerated Production for PS & PL (flagellates and Diatom)

CASE 3 (No_Silicate):
No Silicate limitation on PL (i.e. Diatom)

$$\mathrm{PS_{Photosynthesis}} = V_{\mathrm{max}S}\, e^{(k_S T)}\, \frac{\mathbf{I}}{\mathbf{I_{optS}}} \mathbf{e}^{\left(1-\frac{I}{I_{optS}}\right)} \left\{ \frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + \mathrm{K_{NO_3S}}} \mathbf{e}^{(-\psi_S [\mathrm{NH_4}])} + \frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + \mathrm{K_{NH_4S}}} \right\} [\mathrm{PS}] \qquad (2a)$$

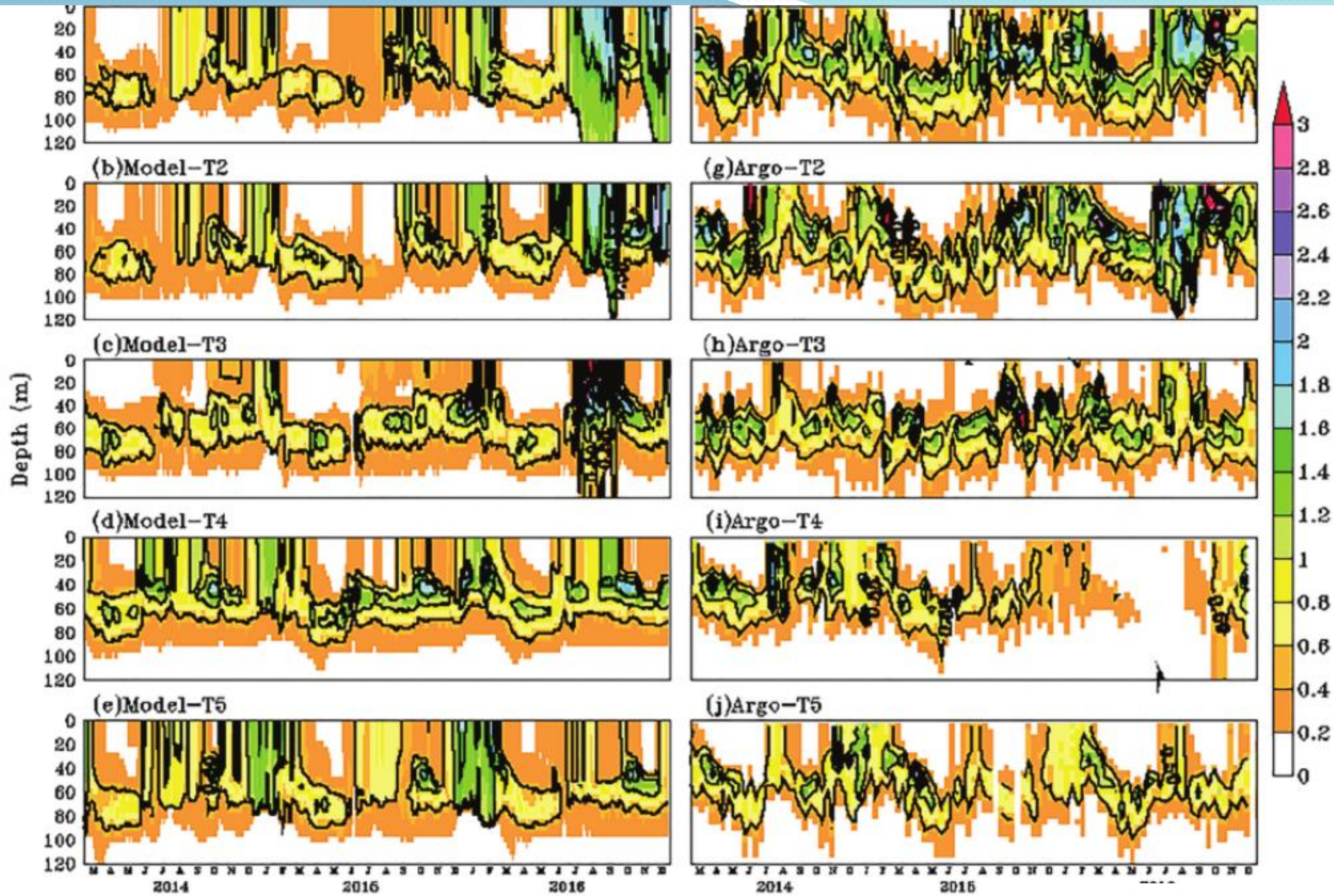
$$\mathrm{PL_{Photosynthesis}} = V_{\mathrm{max}L}\, e^{(k_L T)}\, \frac{\mathbf{I}}{\mathbf{I_{optL}}} e^{\left(1-\frac{I}{I_{optL}}\right)} \min\left\{ \frac{[\mathrm{NO_3}]}{[\mathrm{NO_3}] + \mathrm{K_{NO_3L}}} \mathbf{e}^{(-\psi_L [\mathrm{NH_4}])} + \frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + \mathrm{K_{NH_4L}}},\ \frac{[\mathrm{Si(OH)_4}]}{[\mathrm{Si(OH)_4}] + \boxed{\mathrm{K_{SiL}}}} \right\} [\mathrm{PL}] \qquad (2b)$$





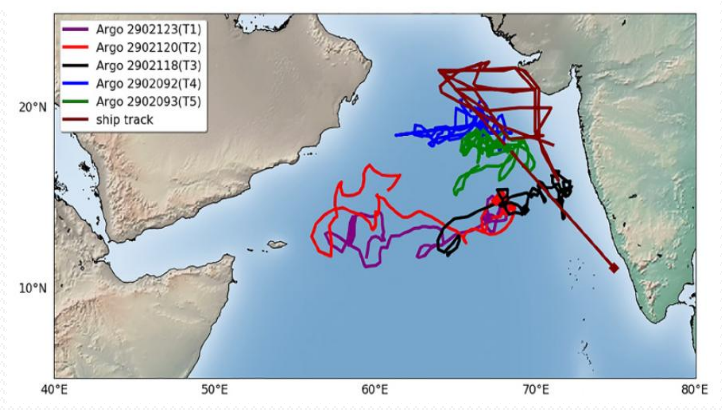
This indicates that the silicate concentration at SCM depths is less than Ksil and results in no SCM formation.

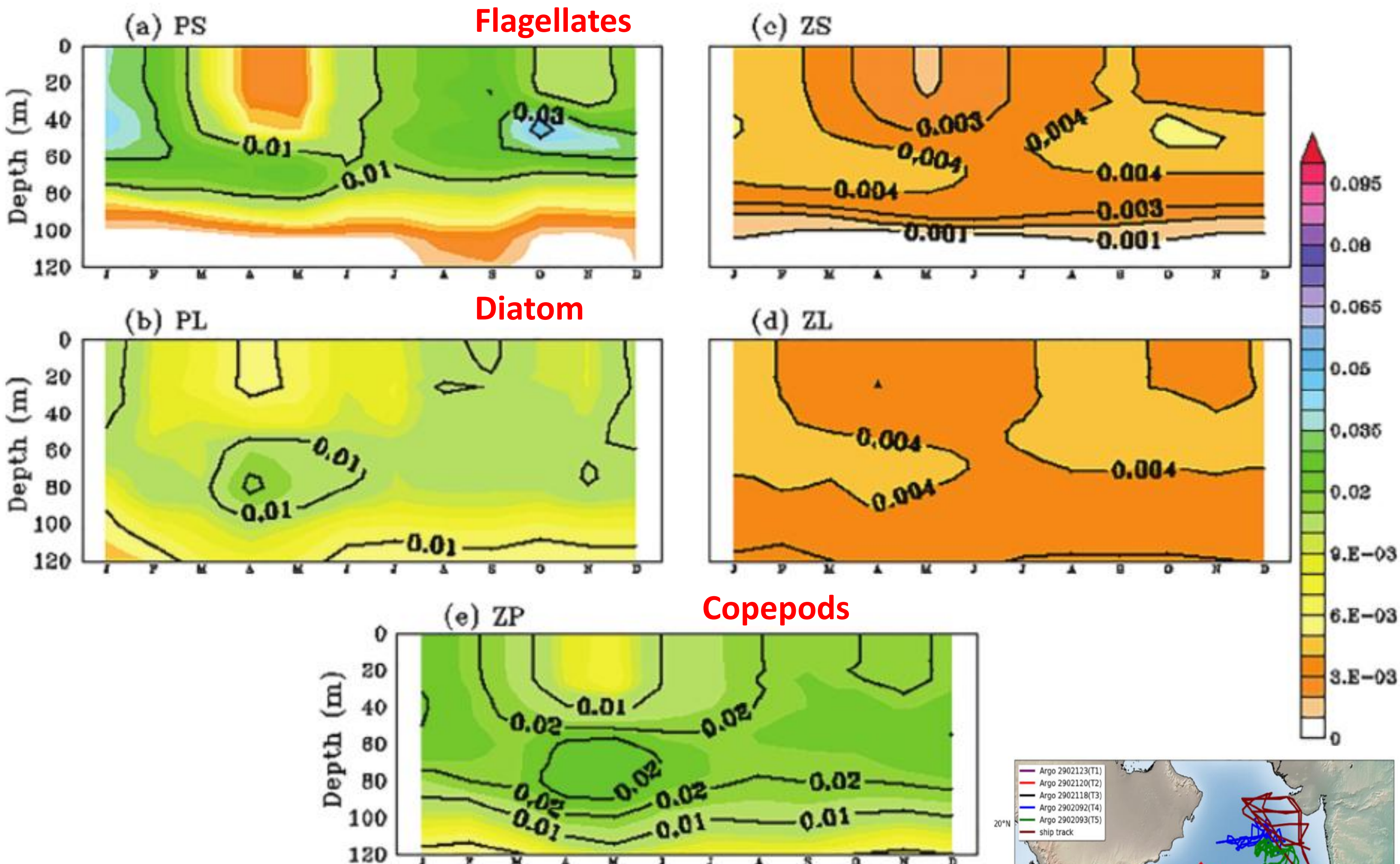
In our study, we adopt Ksil as 6 µmol Si l^{-1}

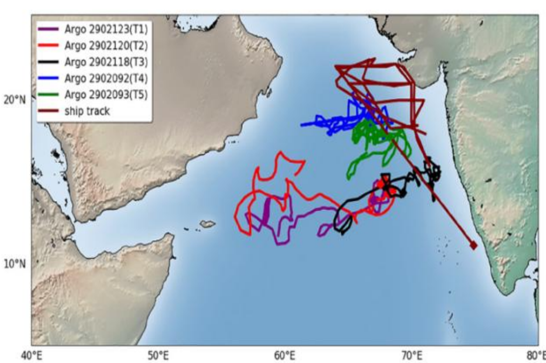


NEMURO-1D Chl-a

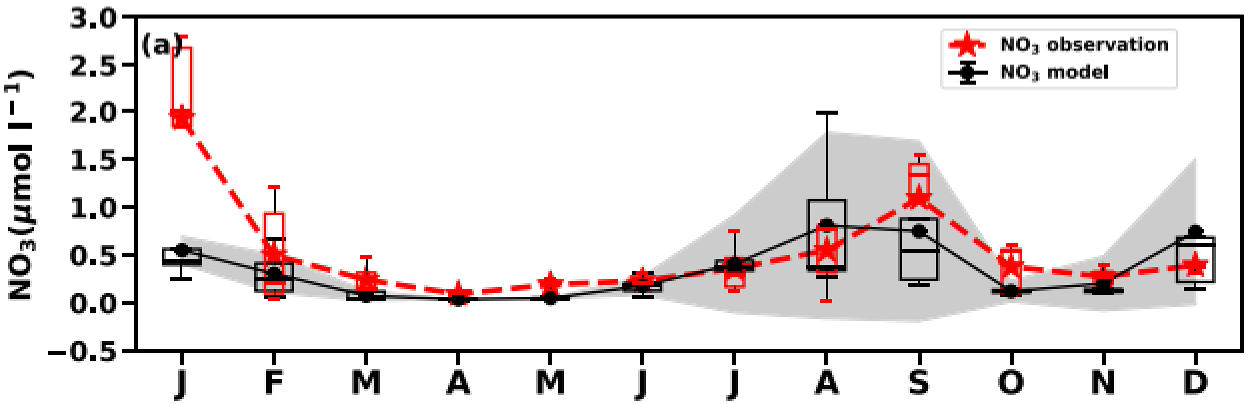
Argo Chl-a



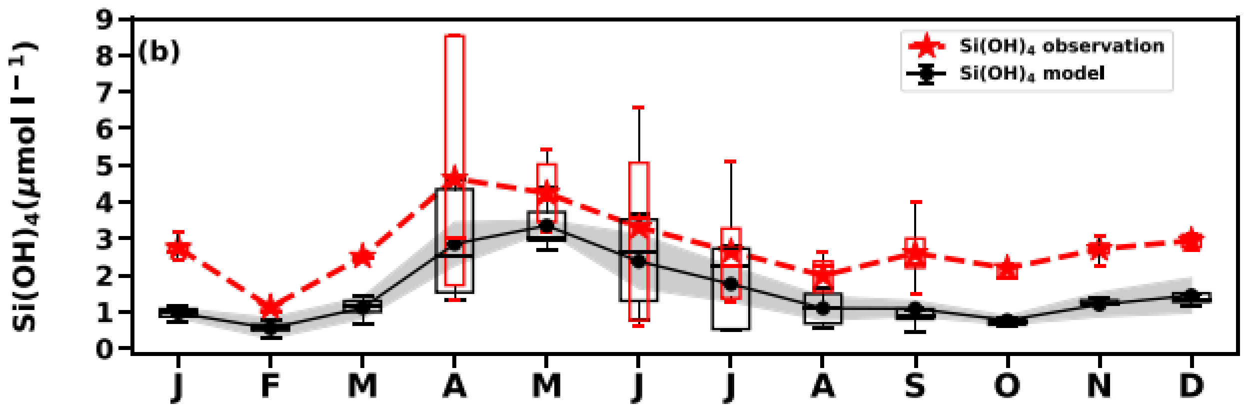

Flagellates
(a) PS
Diatom
(b) PL
(c) ZS
(d) ZL
Copepods
(e) ZP
Depth (m)
0.095
0.08
0.065
0.05
0.035
0.02
9.E-03
6.E-03
3.E-03
0


Argo 2902123(T1)
Argo 2902120(T2)
Argo 2902118(T3)
Argo 2902092(T4)
Argo 2902093(T5)
ship track
20°N
10°N
40°E
50°E
60°E
70°E
80°E

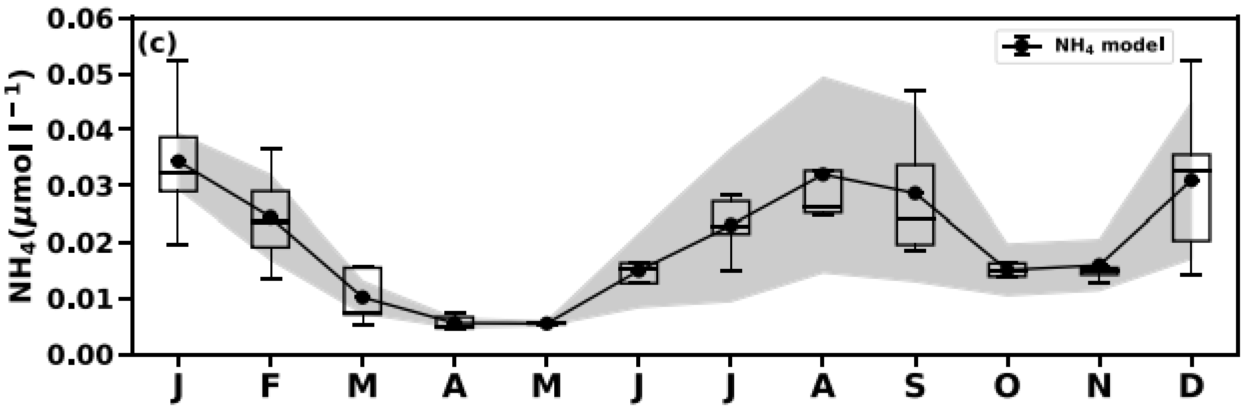
Surface Nitrate

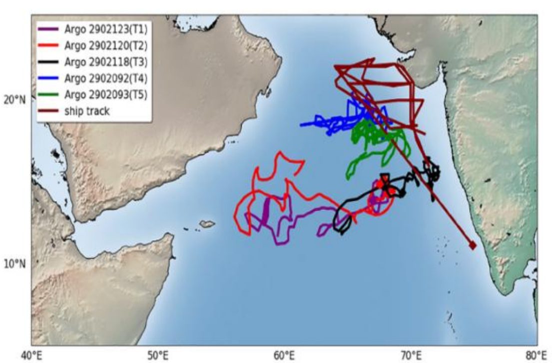


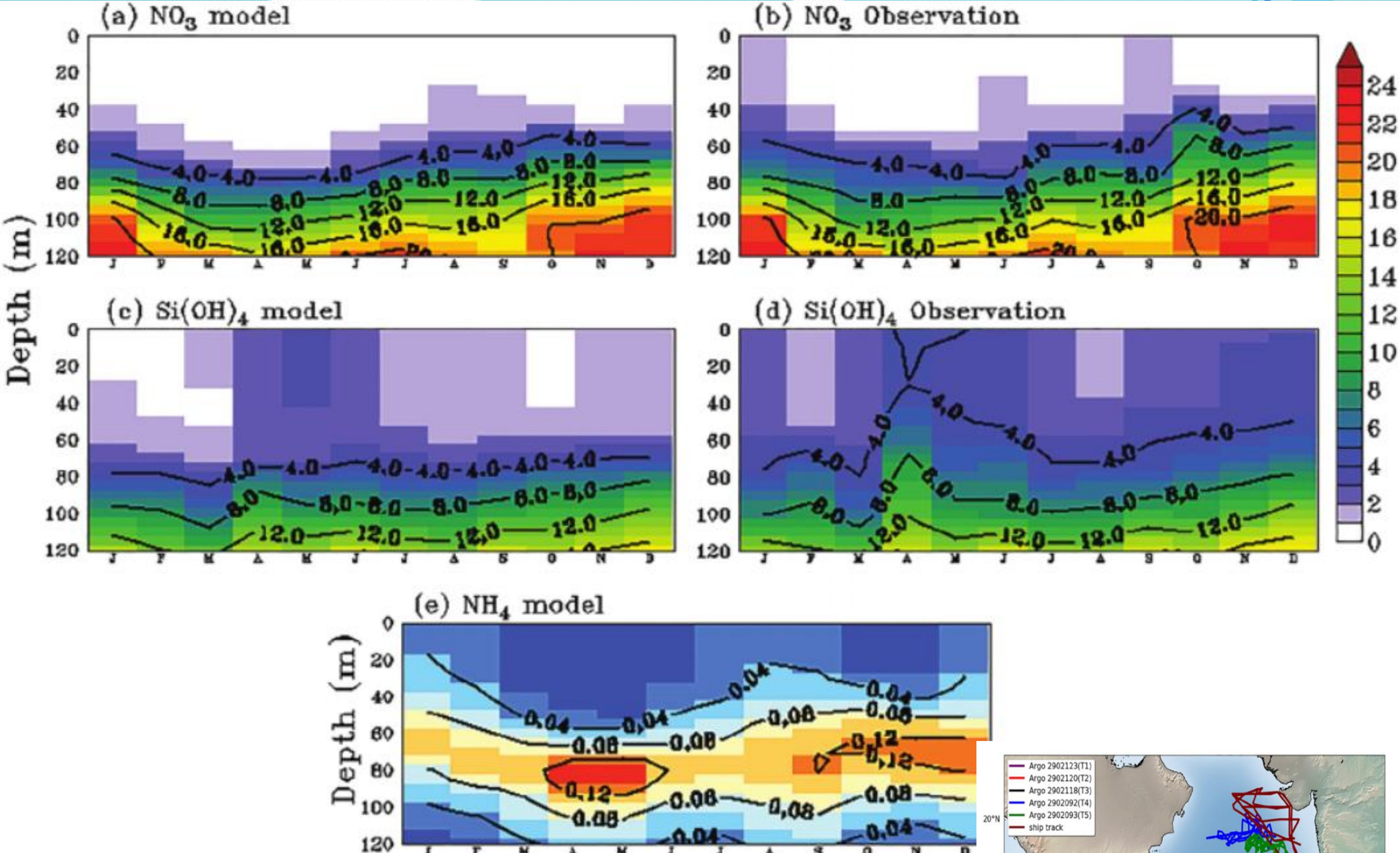
Surface Silicate



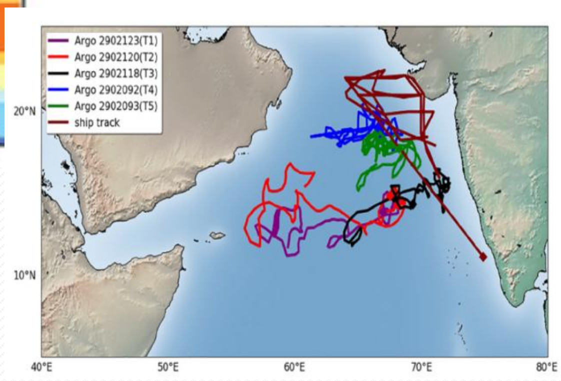
Surface NH4







(a) NO_3 model
(b) NO_3 Observation
(c) $Si(OH)_4$ model
(d) $Si(OH)_4$ Observation
(e) NH_4 model
Depth (m)
J F M A M J J A S O N D
0 20 40 60 80 100 120
0 2 4 6 8 10 12 14 16 18 20 22 24



Argo 2902123(T1)
Argo 2902120(T2)
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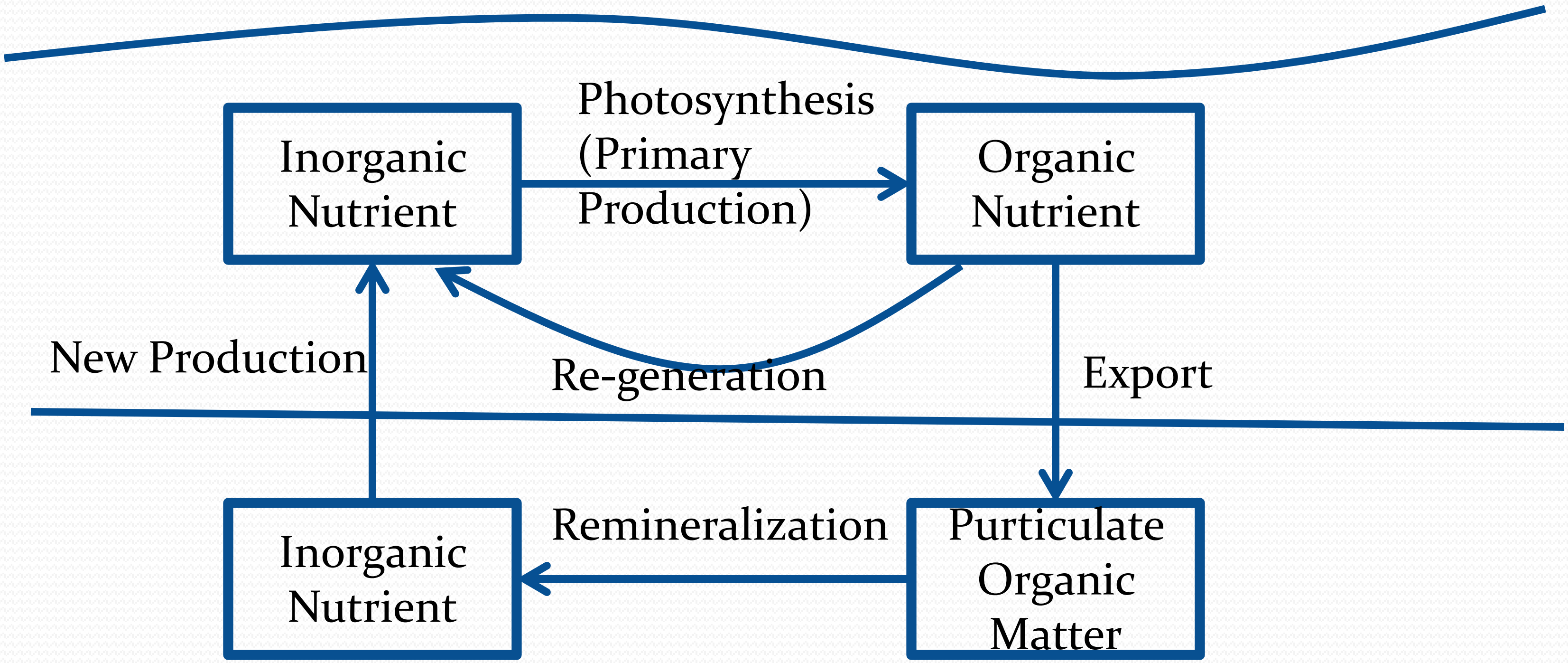
Argo 2902092(T4)
Argo 2902093(T5)
ship track
20°N
10°N
40°E
50°E
60°E
70°E
80°E

Primary, Re-generated and New Productions



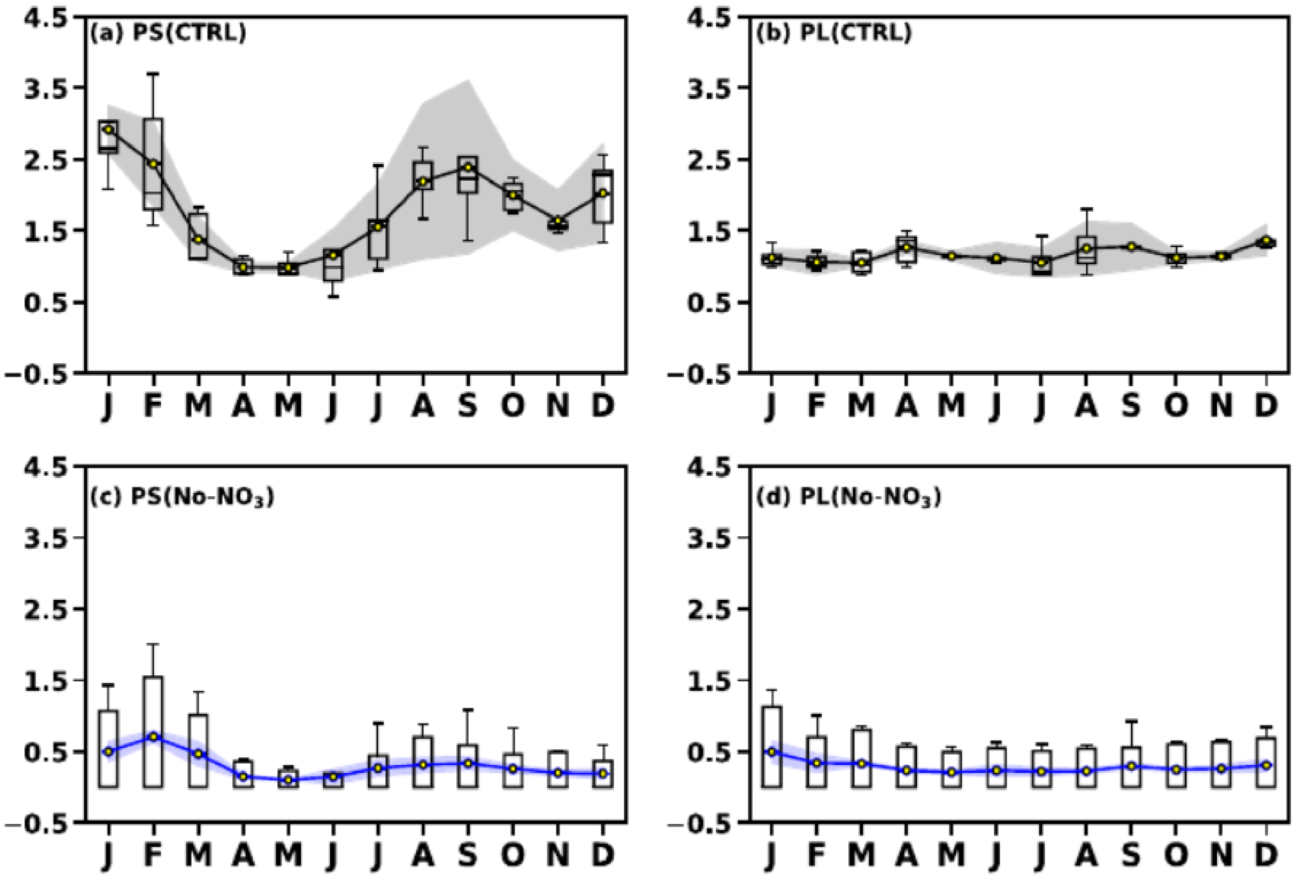
$$f = \frac{\text{New production}}{\text{Primary production}} \qquad e = \frac{\text{Export production}}{\text{Primary production}}$$

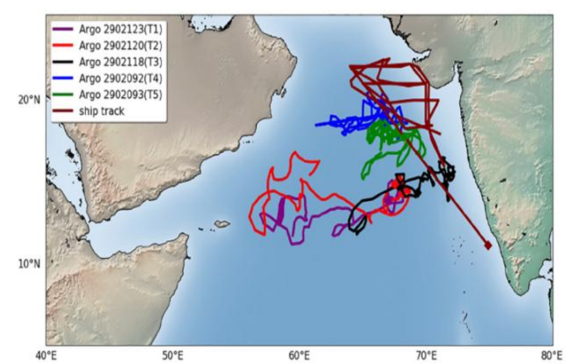
$$
\begin{aligned}
(\mathrm{PS\ Photosynthesis}) &= V_{\max S} \\
&\cdot \left\{ \cancel{\frac{[NO_3]}{[NO_3]+K_{NO_3S}}} \exp\left(-\Psi_S [NH_4]\right) + \frac{[NH_4]}{[NH_4]+K_{NH_4S}} \right\} \\
&\exp(k_S T) \frac{I}{I_{optS}} \exp\left(1 - \frac{I}{I_{optS}}\right) [PS], \qquad (A19)
\end{aligned}
$$

The photosynthesis has affinity to consume NH4 first and then NO3

The primary production reduces with limitation of NO3 in the Arabian Sea in the euphotic zone

Seasonality is also lost due to NO3 limitation



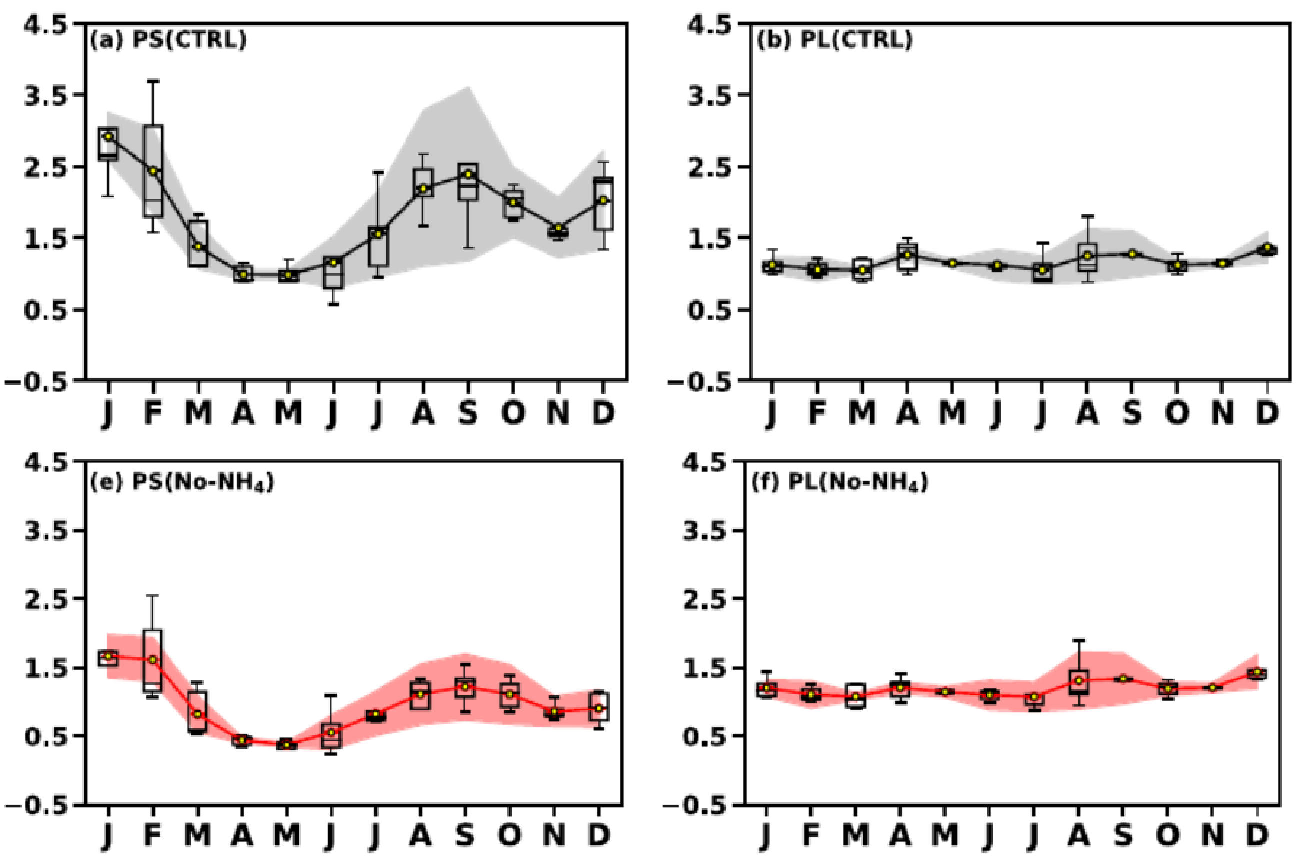


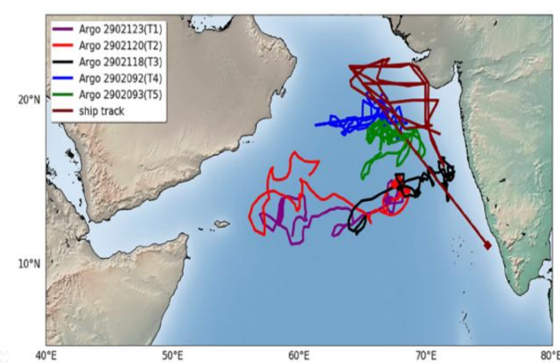
$$
\begin{aligned}
&(\text{PS Photosynthesis}) \\
&= V_{\max S} \\
&\cdot \left\{ \frac{[NO_3]}{[NO_3] + K_{NO_3S}} \exp\left(-\Psi_S [NH_4]\right) + \cancel{\frac{[NH_4]}{[NH_4] + K_{NH_4S}}} \right\} \\
&\exp\left(k_S T\right) \frac{I}{I_{\text{optS}}} \exp\left(1 - \frac{I}{I_{\text{optS}}}\right)[PS], \qquad (A19)
\end{aligned}
$$

The primary production reduces slightly with limitation of NH4 in the Arabian Sea in the euphotic zone

Seasonality is maintained with NH4 limitation

Indicates the limited role of re-generated production in the Arabian Sea

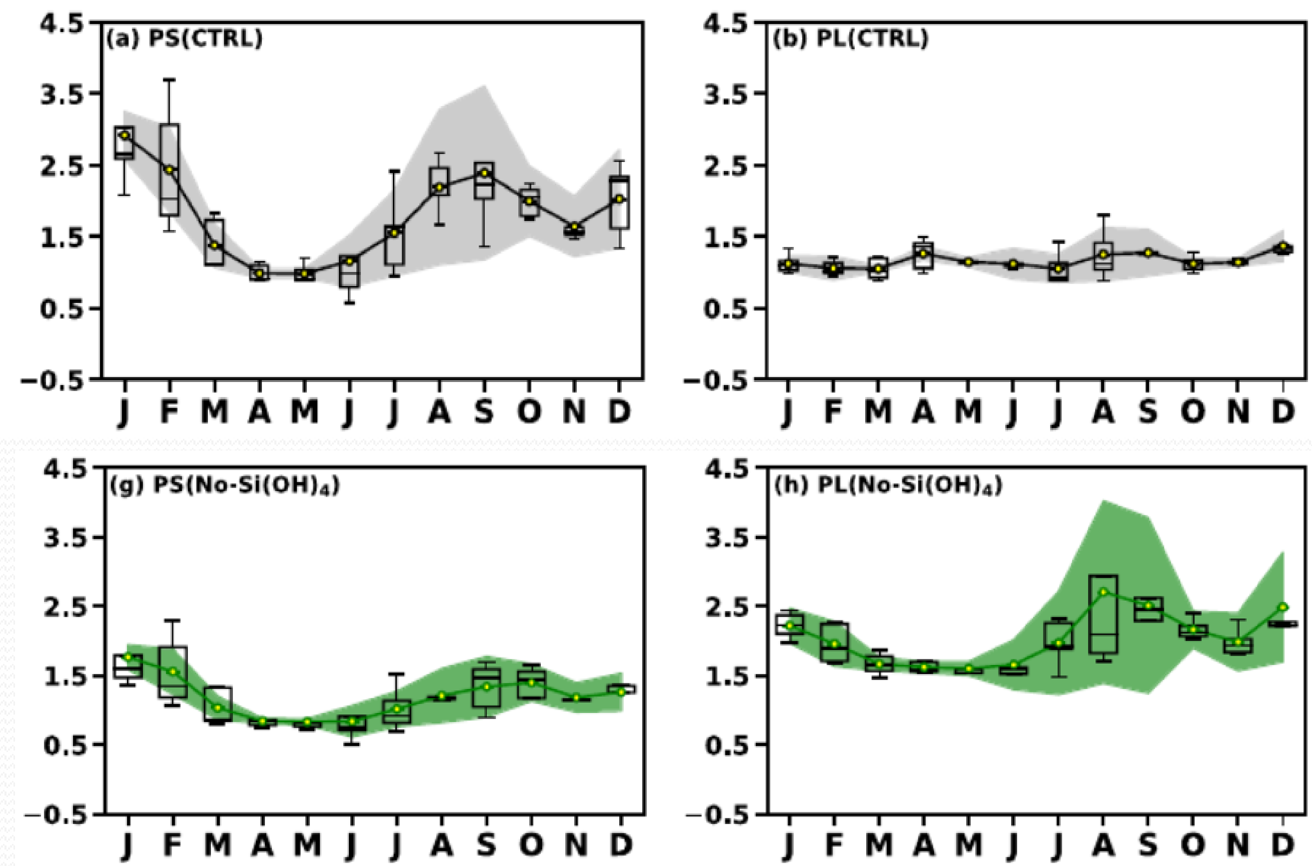


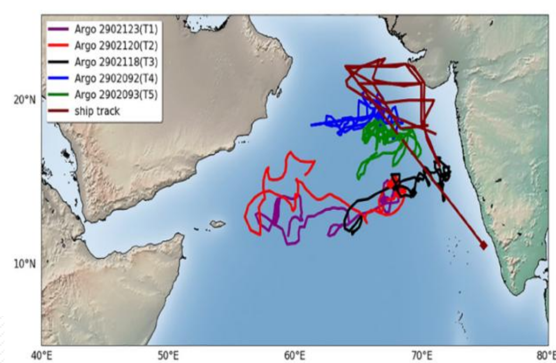


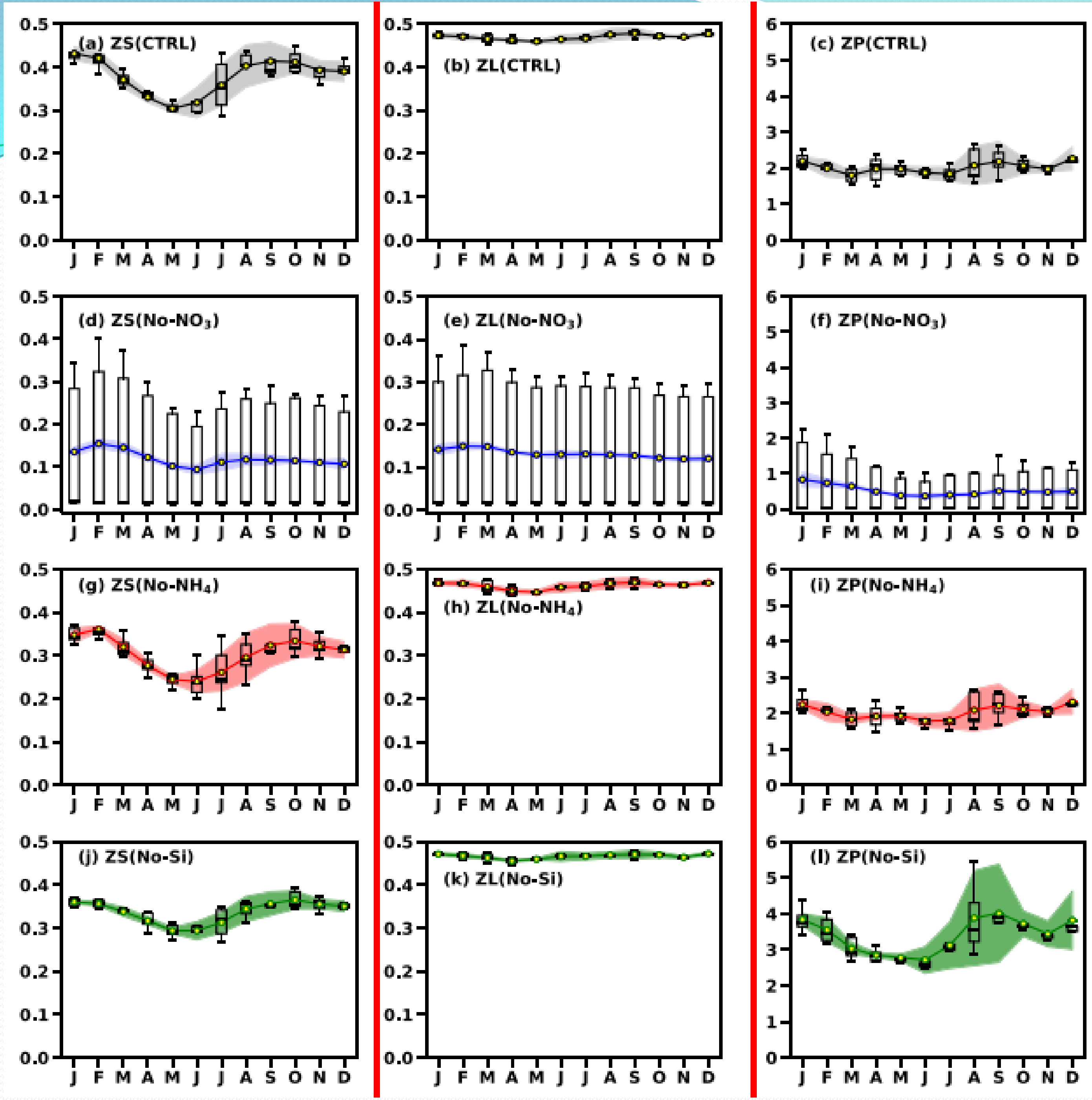
$$
\begin{aligned}
&(\text{PL Photosynthesis}) \\
&= V_{\max L} \min\left\{ \frac{[NO_3]}{[NO_3]+K_{NO_3 L}} \exp\left(-\Psi_L [NH_4]\right) \right. \\
&\qquad \left. + \frac{[NH_4]}{[NH_4]+K_{NH_4 L}},\ \cancel{\frac{[Si(OH)_4]}{[Si(OH)_4]+K_{SiL}}} \right\} \\
&\quad \exp(k_L T) \frac{I}{I_{optL}} \exp\left(1-\frac{I}{I_{optL}}\right)[PL] \qquad (A21)
\end{aligned}
$$

If no Silicate limitation imposed the Diatoms grows much more than the observed values in the Arabian Sea.

The flagellates growth is reduced in this case, indicating larger consumption of NO3 by Diatoms.



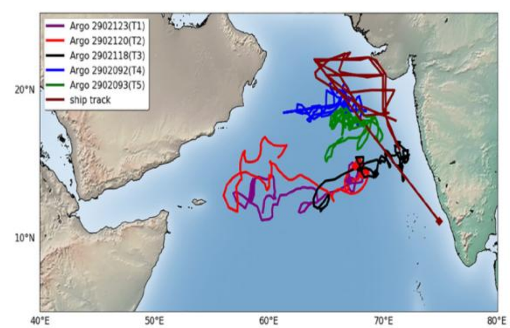




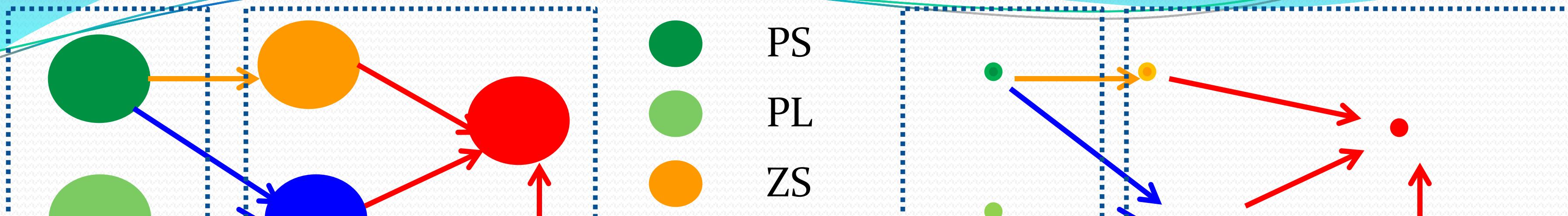
Responses of secondary producers on various nutrient limiting conditions in the Arabian Sea

Nitrate controls the variability of secondary producers in the Arabian Sea

Re-generated production of plankton and silicate limitation affects a little on the secondary producers



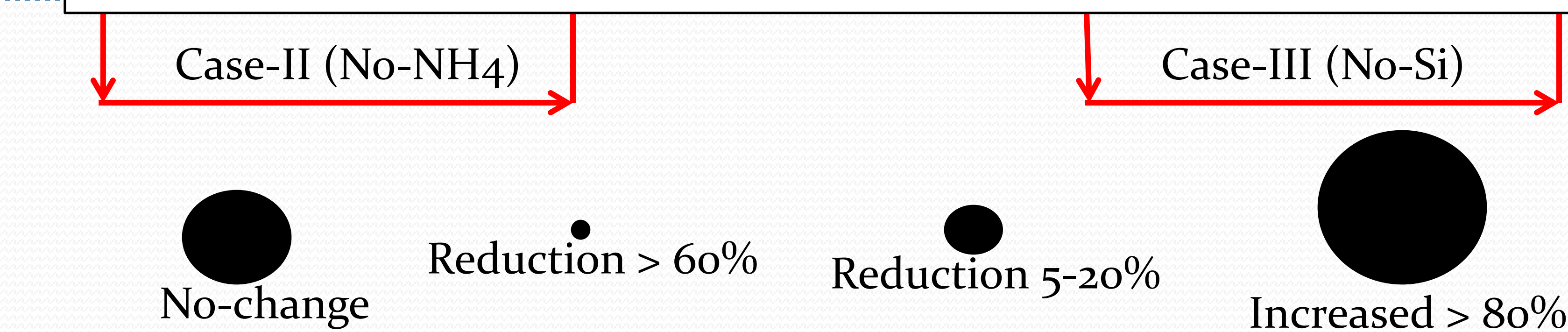
Role of Nutrient limitation in Pray-Predatory Relation in Arabian Sea



Nitrate (NO3) offers a fundamental limitation in Arabian Sea ecosystem.

Multi-species dependent higher trophic organisms (eg. Copepods, Euphausiids) withstand nutrient limitation as compared to single species depend organisms (ciliates).

(Anju et al., 2020, JGR)



Nitrate Limitation

$$N=\frac{[NO_3]}{NO_3]+K_{NO_3S}}e^{(-\psi_S[NH_4])})$$

Ammonia Limitation

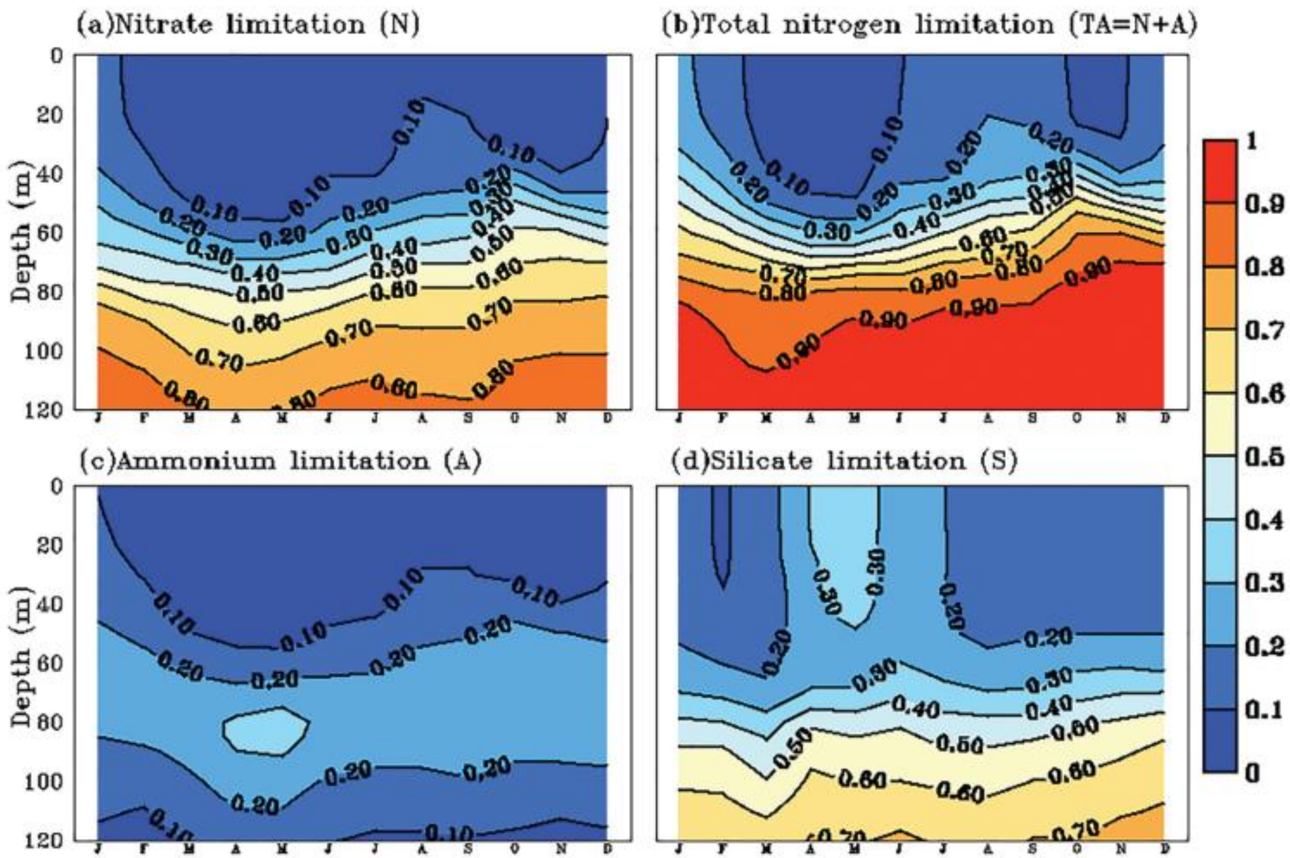
$$A=\frac{[NH_4]}{[NH_4]+K_{NH_4S}})$$

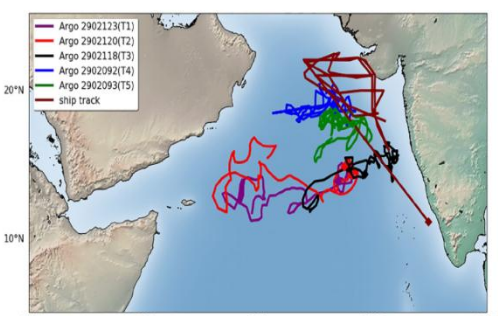
Silicate Limitation

$$S=\frac{[Si(OH)_4]}{[Si(OH)_4]+K_{SiL}}$$

Total Nitrogen Limitation

$$TA=\frac{[NO_3]}{NO_3]+K_{NO_3S}}e^{(-\psi_S[NH_4])})+\frac{[NH_4]}{[NH_4]+K_{NH_4S}})$$





Zero represents complete limitation, and one represents no limitation

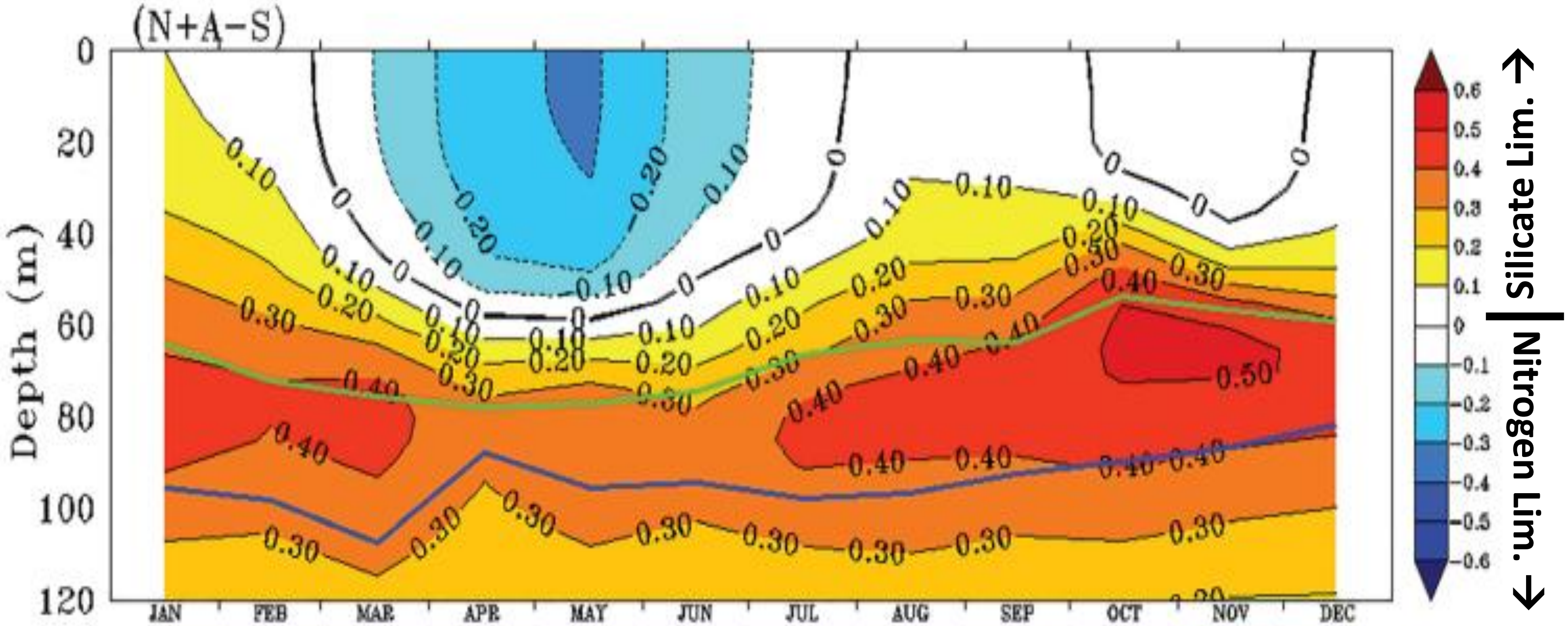


Figure 16. Seasonality of differences between nitrogen and silicate limitation factors for PL shown as climatology calculated from 2013 to 2016 (plus regions represent silicate limitation, and the negative regions represent nitrogen limitation). The thick black line represents 0 (i.e, $N + A = S$). The green and blue lines represent nitricline and silicicline, respectively.

Diatom production in the surface ocean dominated by nitrate limitation than silicate in most of the period, especially in March-May

Whereas in the subsurface ,Silicate limitation is dominant through out the year