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-3:
Oxygen limitations and denitrification of the Arabian Sea

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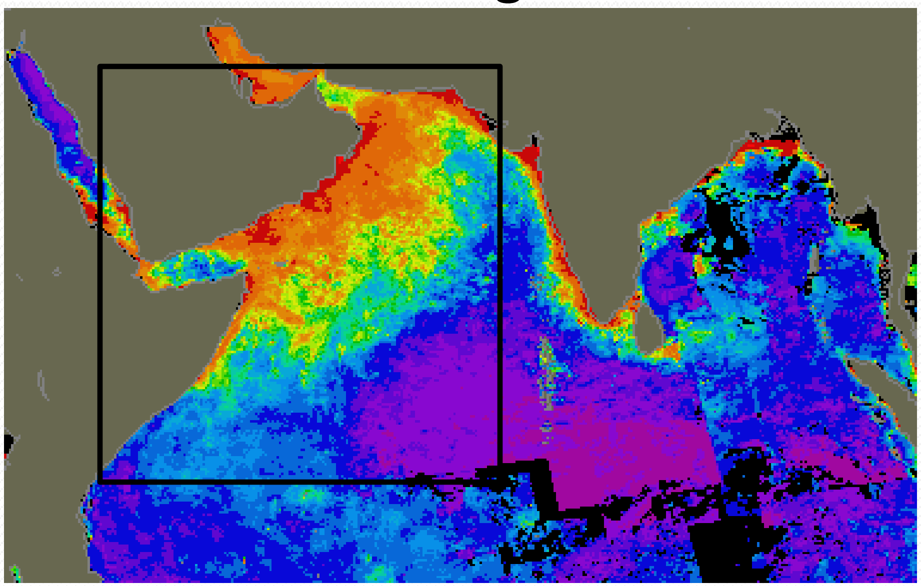
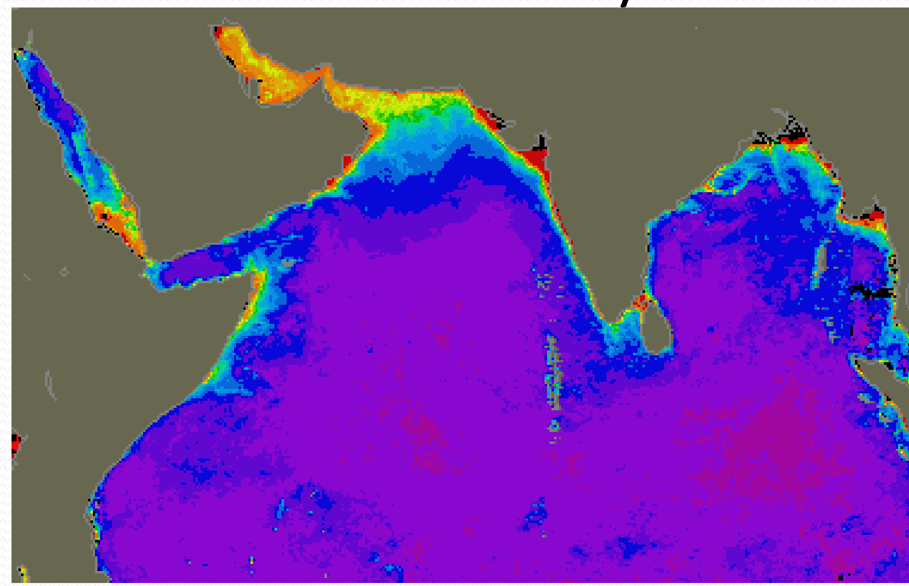
Arabian Sea Primary Production

August



January



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

Export Production

Regions	OBS
WAS	123.57

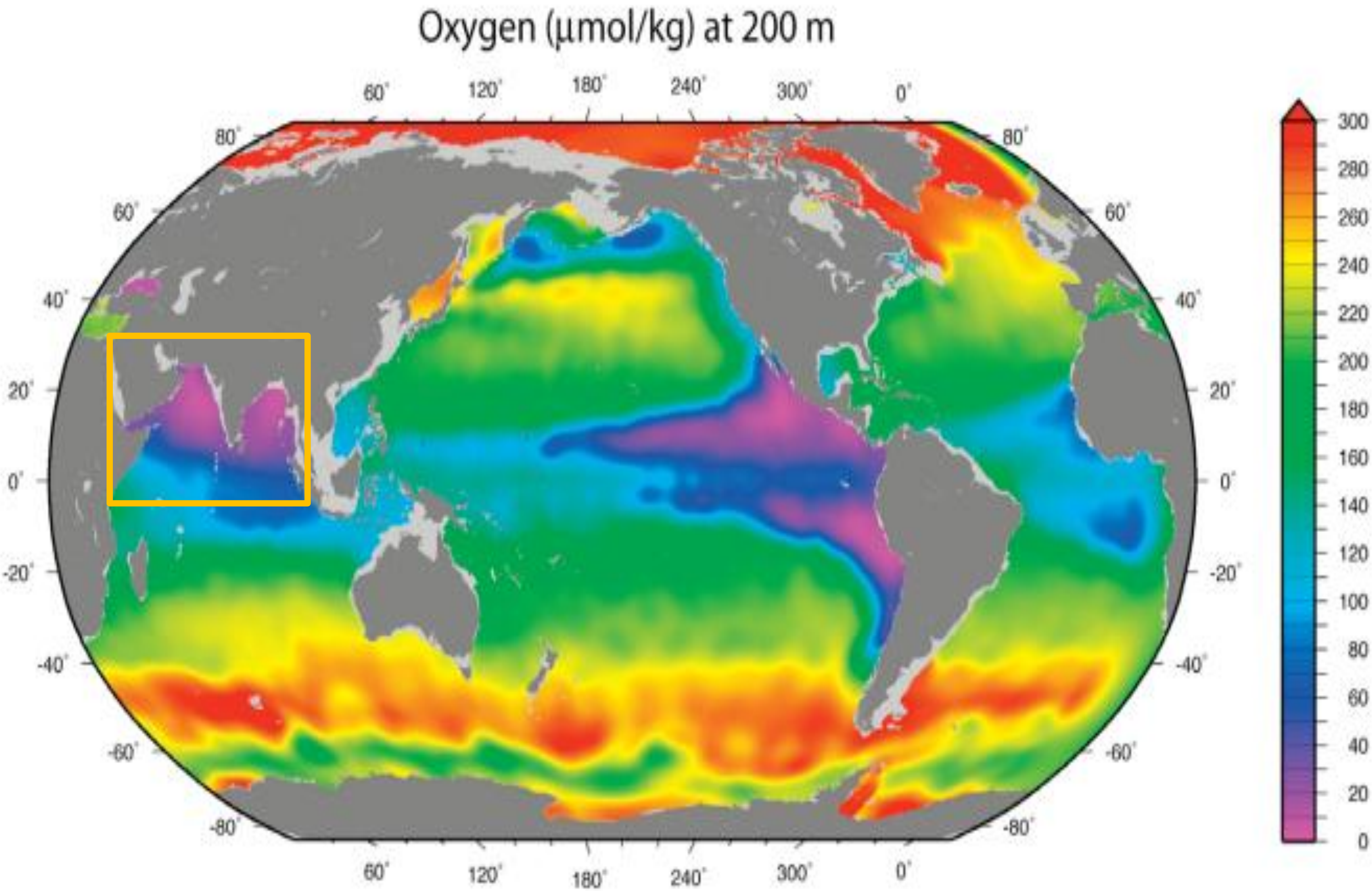
Biological Pump (model)

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 $year^{-1}$)



World Ocean Atlas-2013

Preformed and Remineralized Components of Oxygen cycle in the ocean

- In the most general form, we can think of the nutrient or oxygen concentration of a water parcel in the interior of the ocean as consisting of two components.
- The first is the preformed concentration, $C_{preformed}$, that this water parcel had when it left the surface
- The second one is the change in concentration, DC_{remin}, *that* occurred since that time as a result of remineralization.

Separation of Preformed and Remineralized Components

- In order to study the impact of aerobic remineralization on the ocean interior distribution of oxygen, we would like to estimate its remineralized component i.e., the change in O2 that occurred since a water parcel was last in contact with the atmosphere;

$$\Delta[O_2]_{remin} = [O_2]_{observed} - [O_2]_{preformed}$$

- Apparent oxygen utilization (AOU)

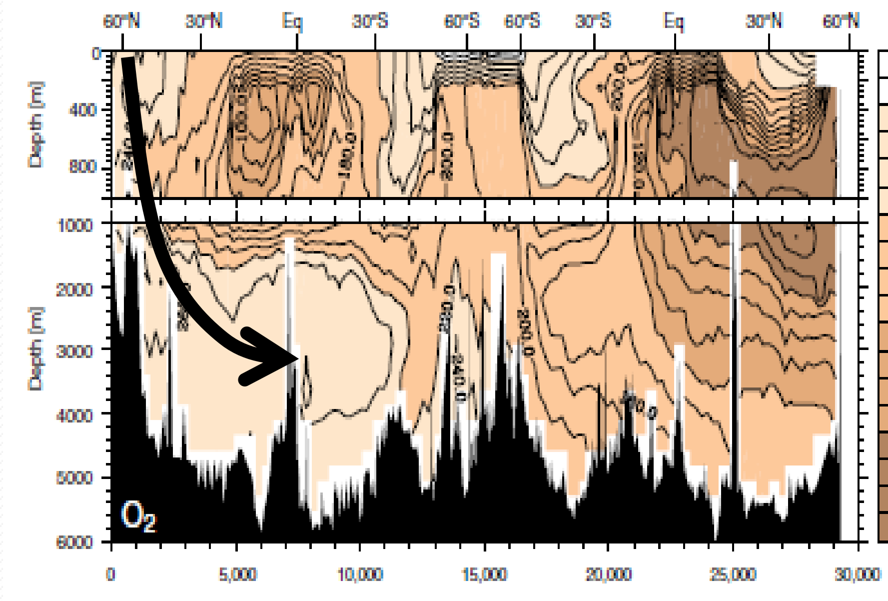
$$AOU = [O_2]_{sat} - [O_2]_{observed}$$

- [O2]sat can be a function of (θ, S).
- Note that AOU does not include the effect of remineralization that is due to denitrification

Separation of Preformed and Remineralized Components

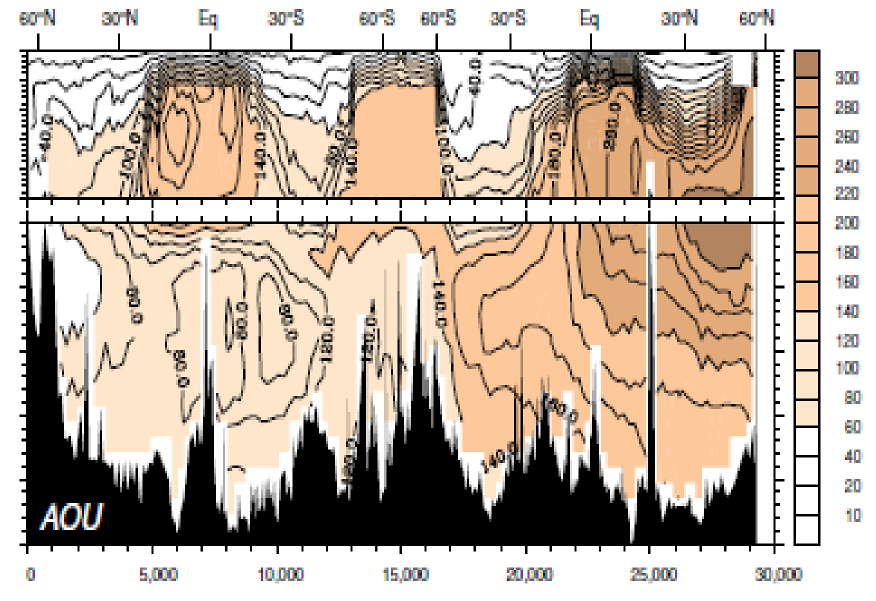
$$AOU = [O_2]_{sat} - [O_2]_{observed}$$

Atlantic Southern Ocean Pacific



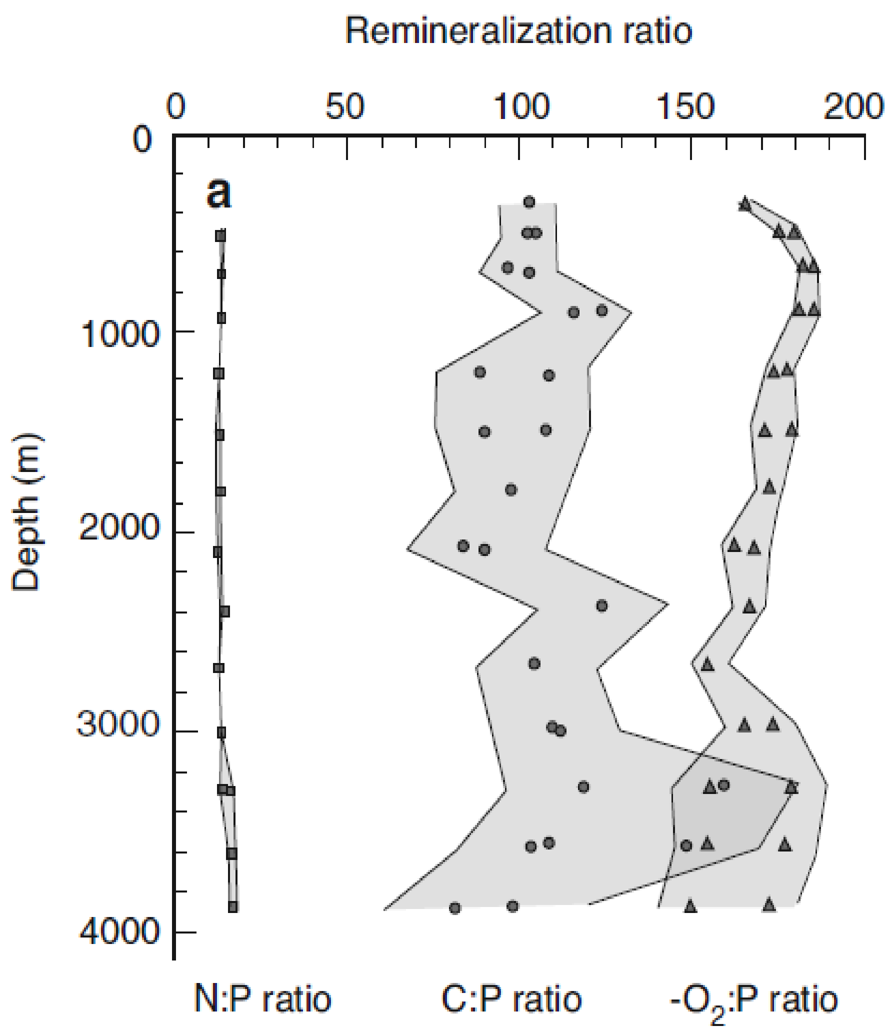
Oxygen distribution

Atlantic Southern Ocean Pacific



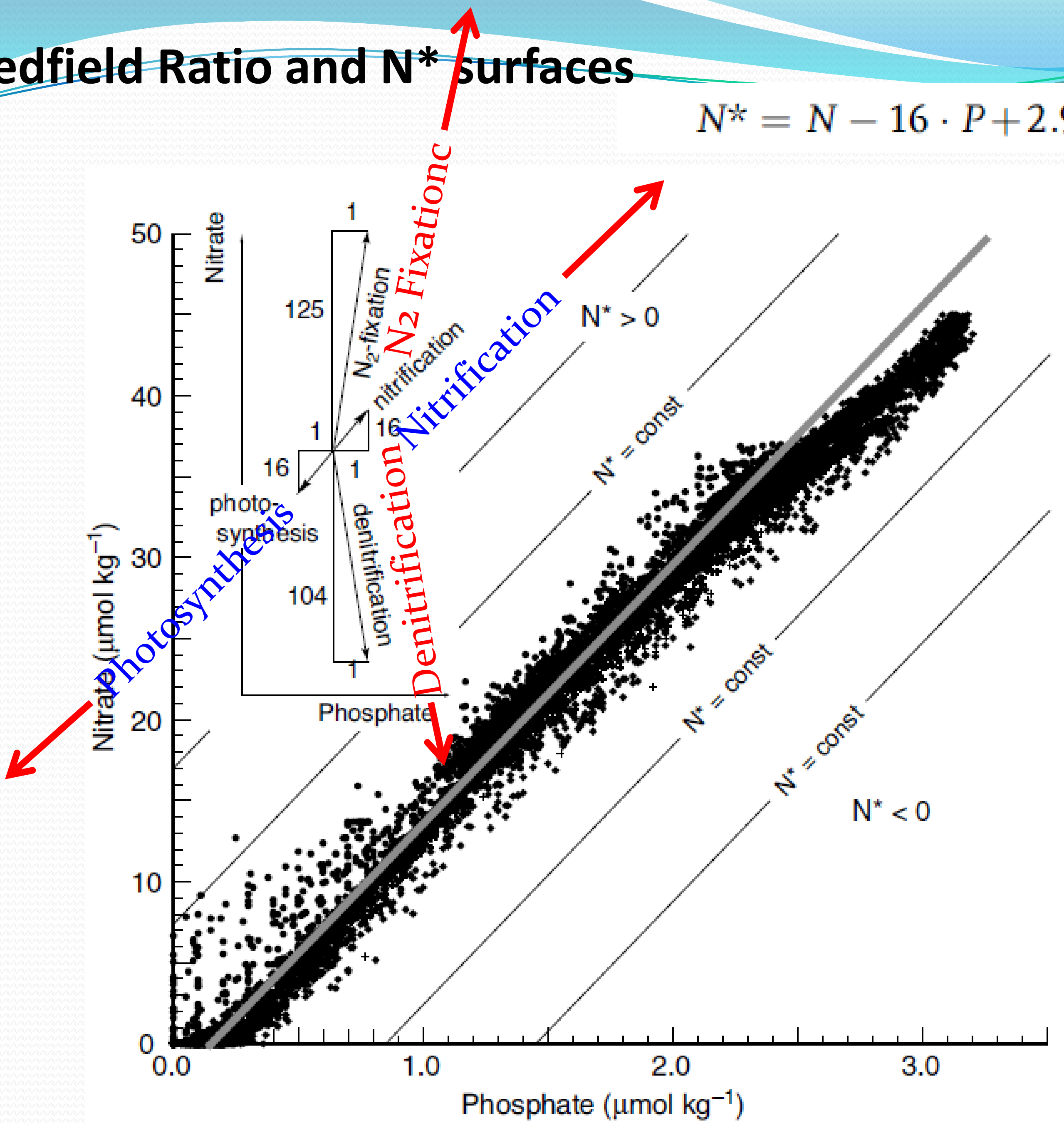
Apparent Oxygen Utilization (AOU)

Deep ocean remineralization ratio



The Redfield Ratio and N* surfaces

$$N^* = N - 16 \cdot P + 2.9 \text{ mmol m}^{-3}$$



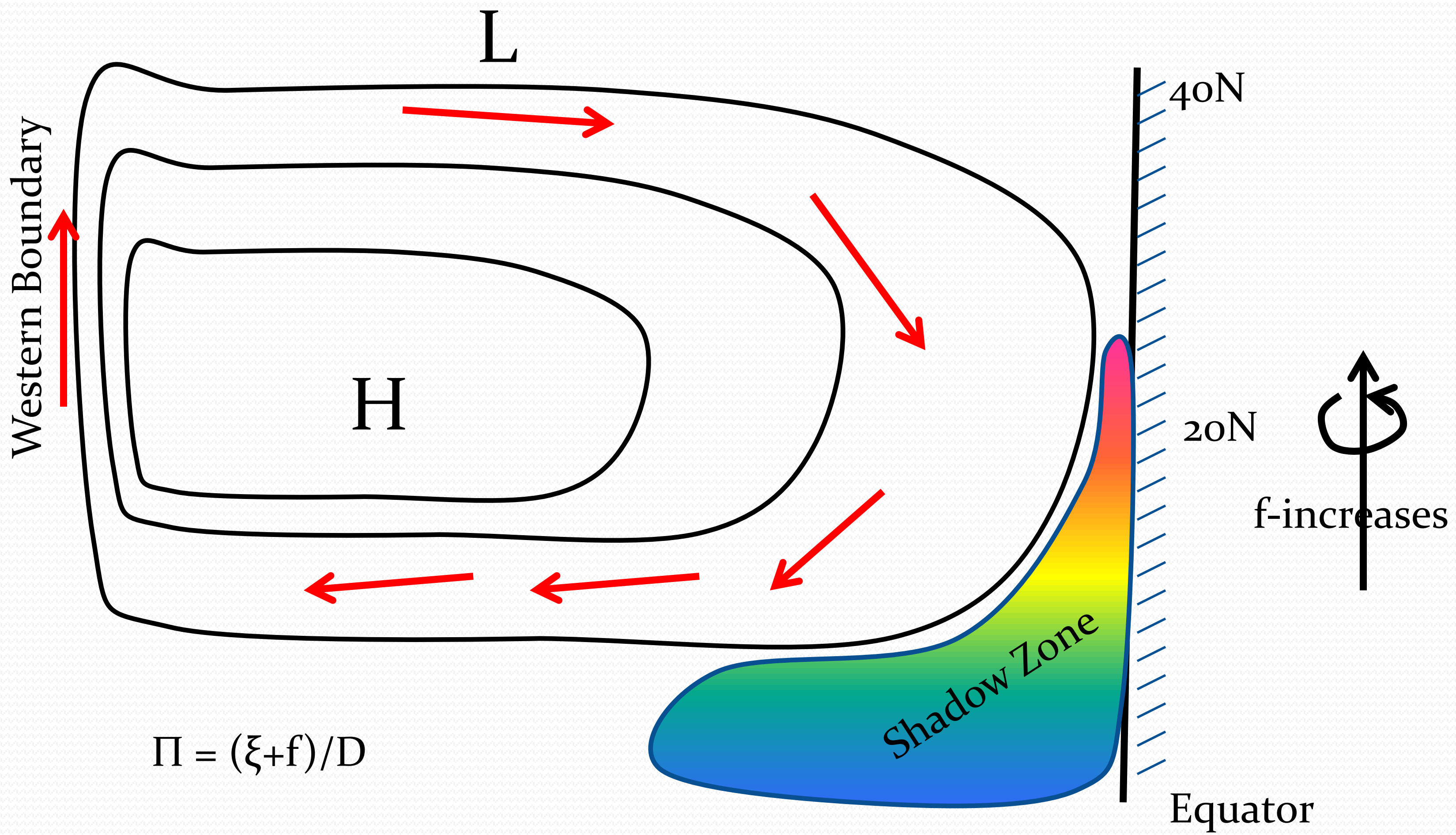
The Conservative Tracer N*

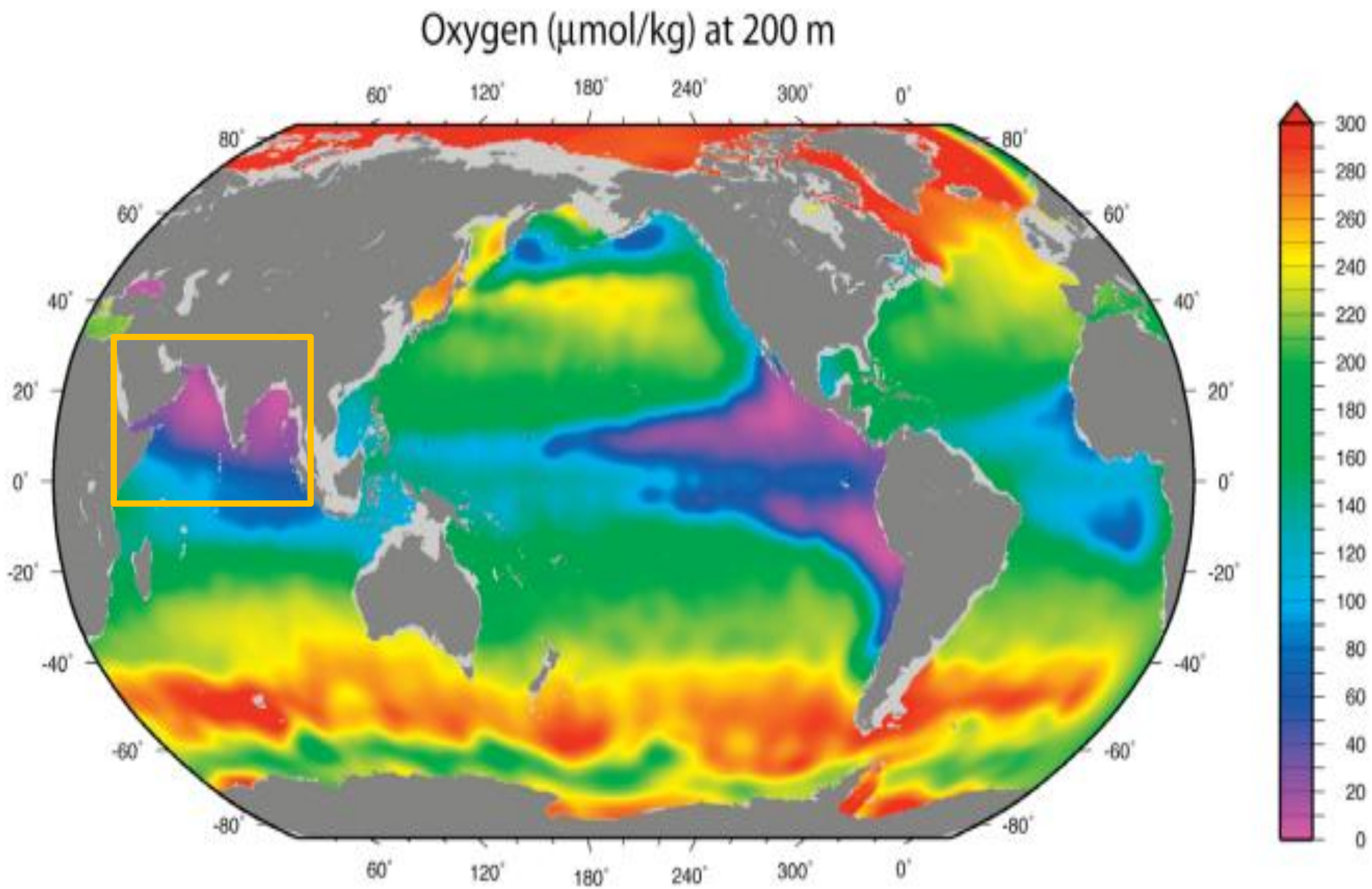
- This permits us to define a new tracer N* whose interior distribution is affected only by transport and denitrification:

$$N^* = N - 16 \cdot P + 2.9 \text{ mmol m}^{-3}$$

- The major areas of anoxia where water column denitrification is known to occur are in the thermocline of the Arabian Sea and eastern equatorial Pacific (figure 5.3.7) [cf. Broecker and Peng, 1982].
- Both areas belong to what are known as the shadow zones of the thermocline.
- The waters in these shadow zones are not directly ventilated from the outcrop of these density surfaces, because there exists no direct pathway to them that permits conservation of potential vorticity.
- As a result, these shadow zones are ventilated only in a diffusive manner, leading to relatively long residence times and a strong drawdown of the dissolved oxygen concentrations.

The shadow zones, annoxia and denitrification in deep ocean

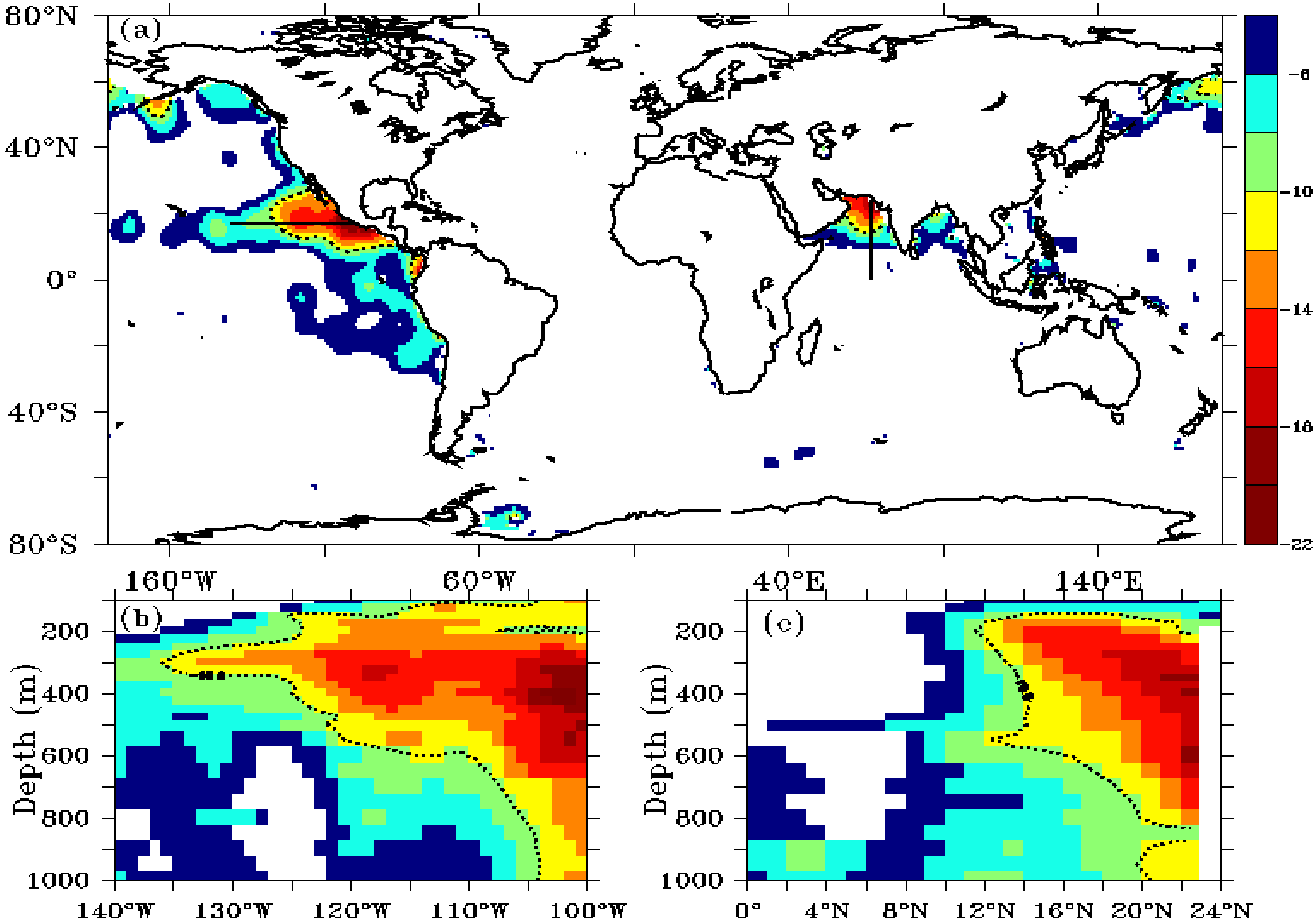


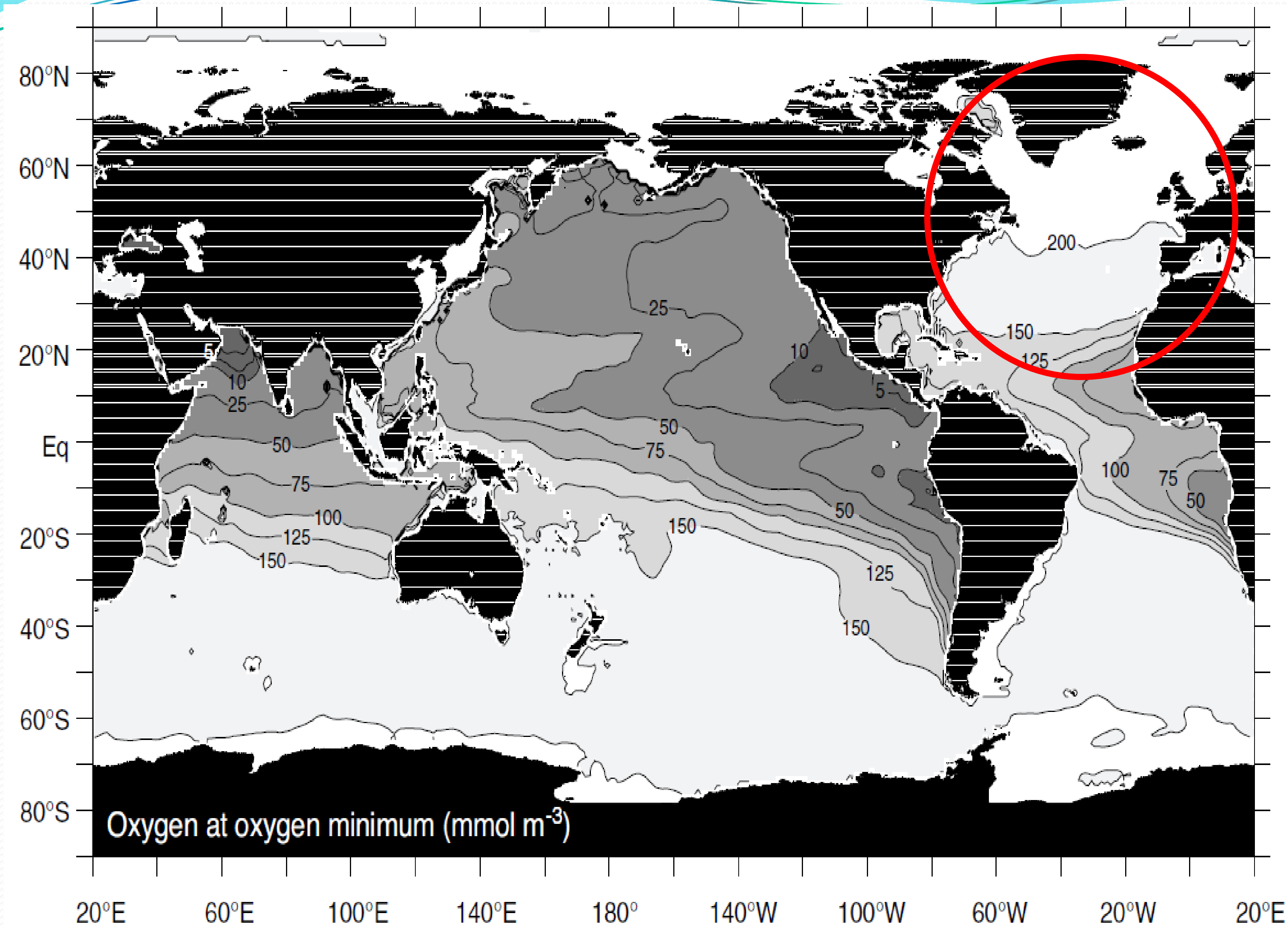


World Ocean Atlas-2013

N* profiles

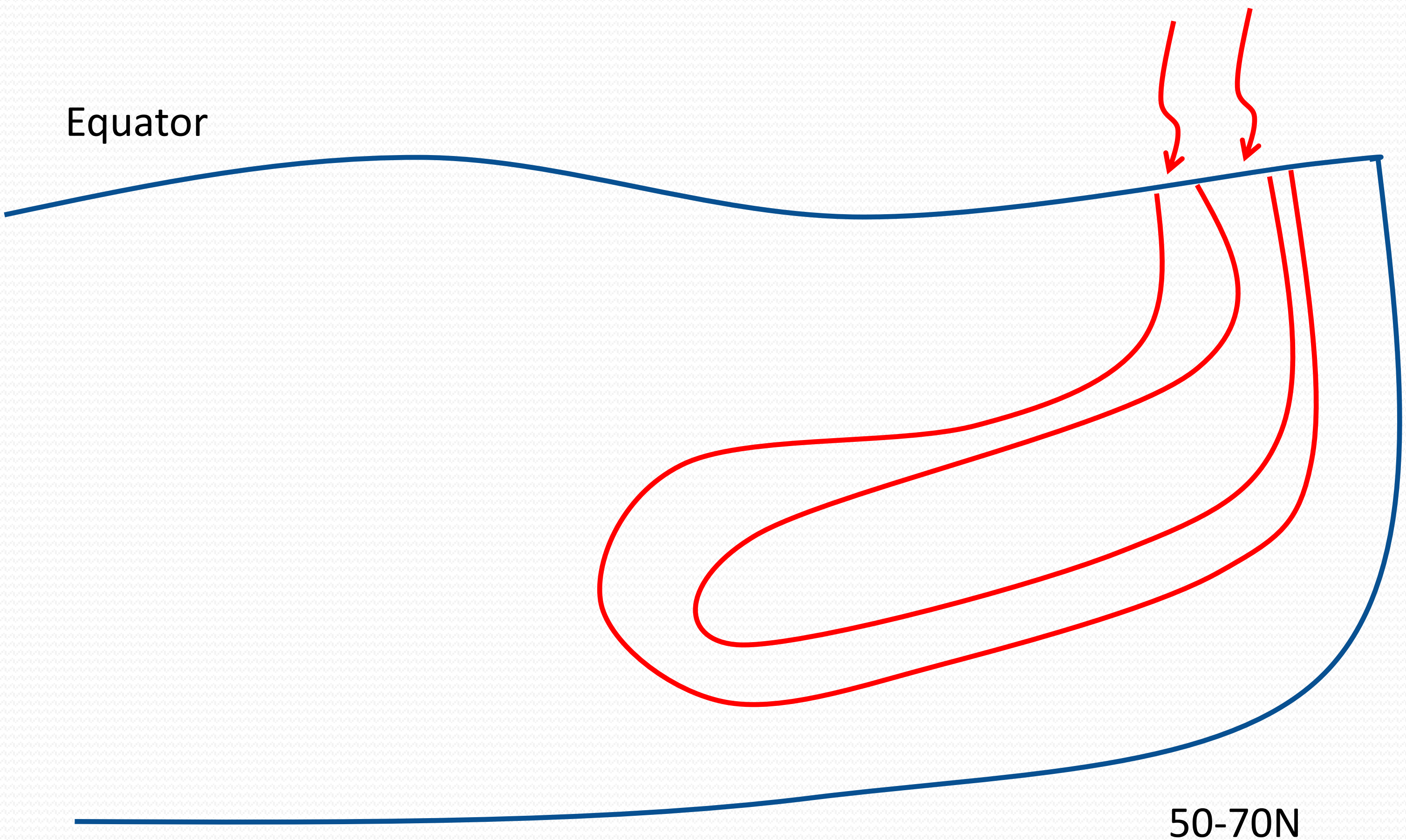
$$N^* = N - 16 \cdot P + 2.9 \text{ mmol m}^{-3}$$

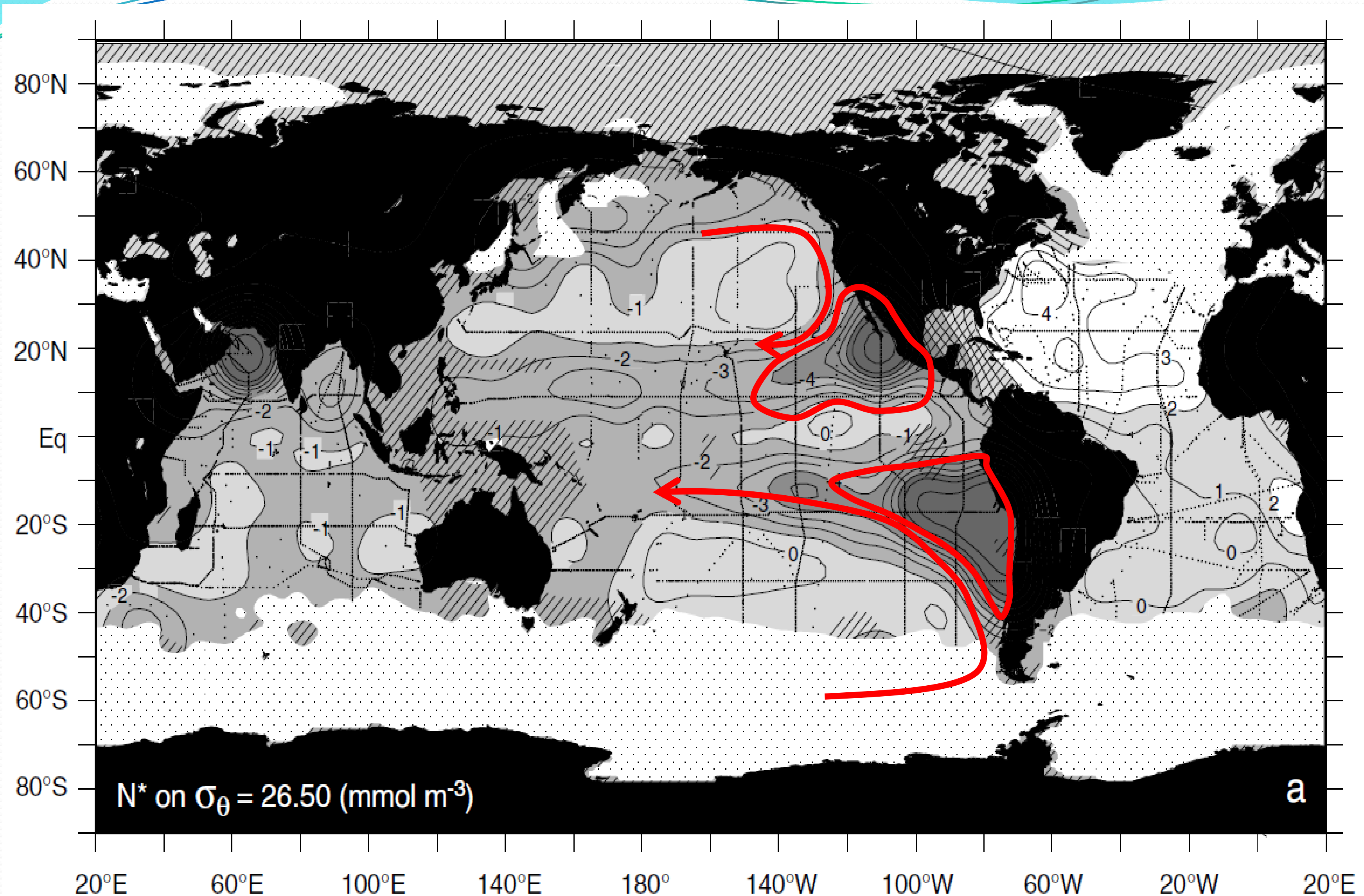




80°N
60°N
40°N
20°N
Eq
20°S
40°S
60°S
80°S
20°E
60°E
100°E
140°E
180°
140°W
100°W
60°W
20°W
20°E
200
150
125
100
75
50
25
10
5
Oxygen at oxygen minimum (mmol m-3)

Ocean ventilation, subduction and Oxygen replenishments

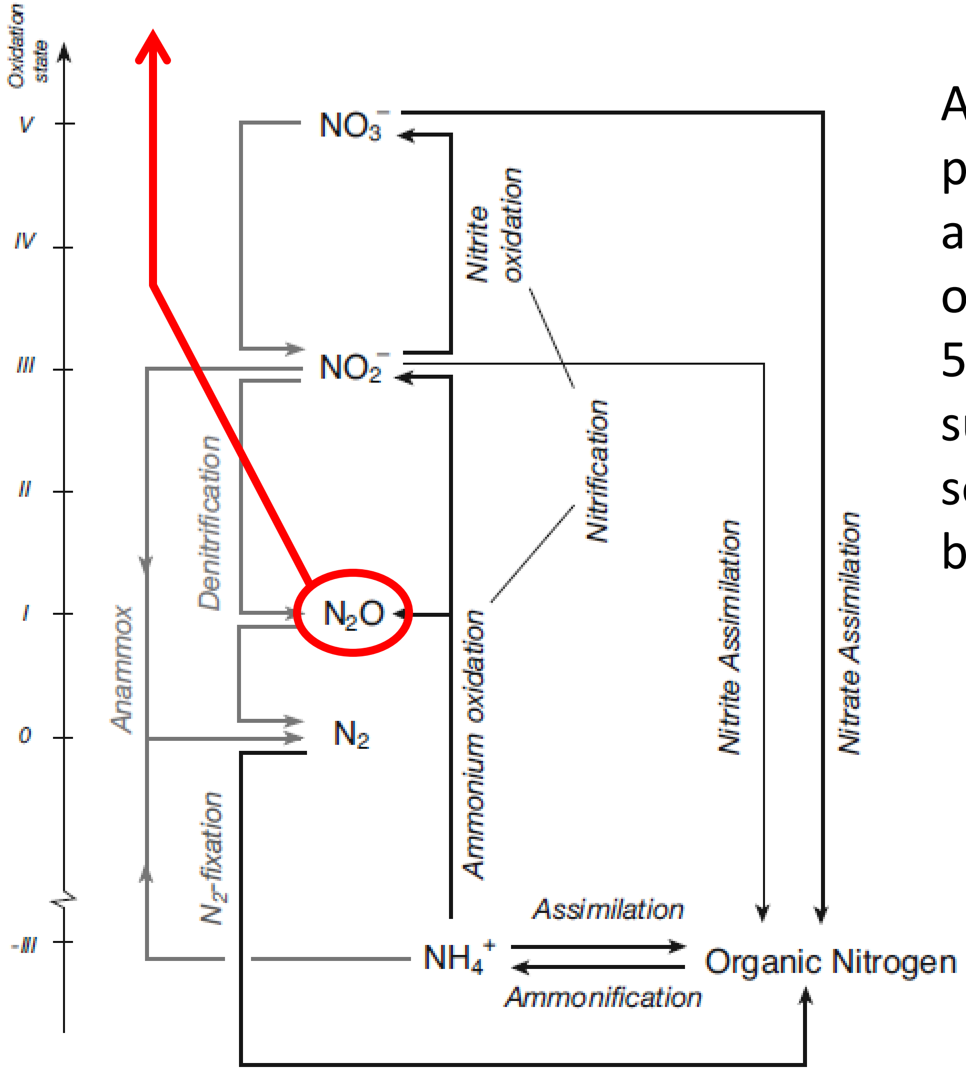



80°N
60°N
40°N
20°N
Eq
20°S
40°S
60°S
80°S
20°E
60°E
100°E
140°E
180°
140°W
100°W
60°W
20°W
20°E
N* on σ_θ = 26.50 (mmol m^{-3})
a

The Oceanic Nitrogen Budget

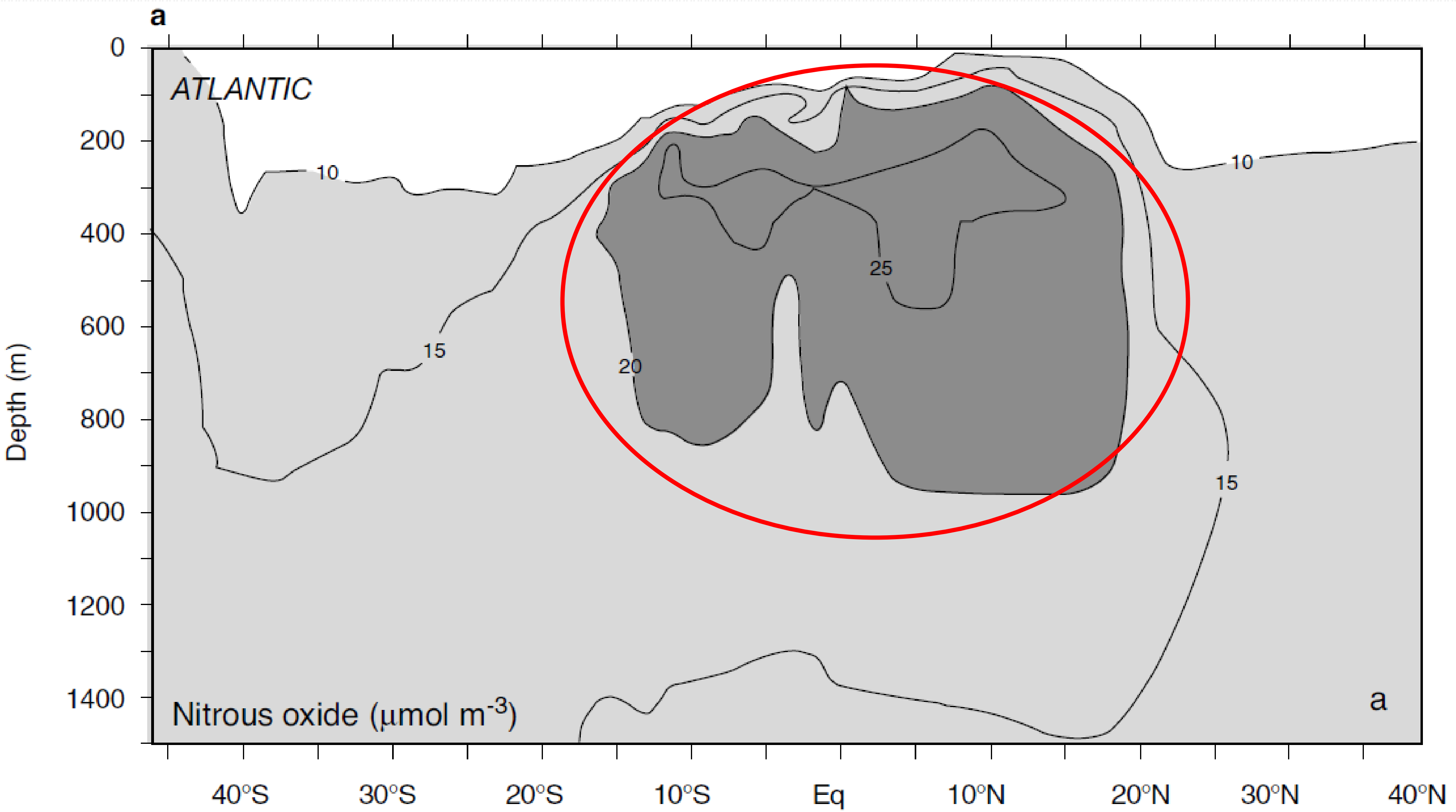
- In order to put in perspective the input of fixed nitrogen into the ocean by pelagic N2 fixation, the other source terms of the oceanic nitrogen budget need to be considered.
- Input of organic nitrogen from rivers (both DON and PON, for a total of about 80 Tg N yr^{-1}) and the atmospheric deposition of organic forms of nitrogen (another *50 Tg N yr^{-1}).*
- *Together with pelagic* and benthic N2 fixation, this brings the total input of fixed nitrogen to 265 ± 55 Tg N yr^{-1}.
- If we adopt the total fixed N losses tabulated by Gruber [2004], we arrive at a nearly balanced oceanic N cycle for the present-day ocean, albeit with large uncertainties.

Nitrous Oxide (N_2O)

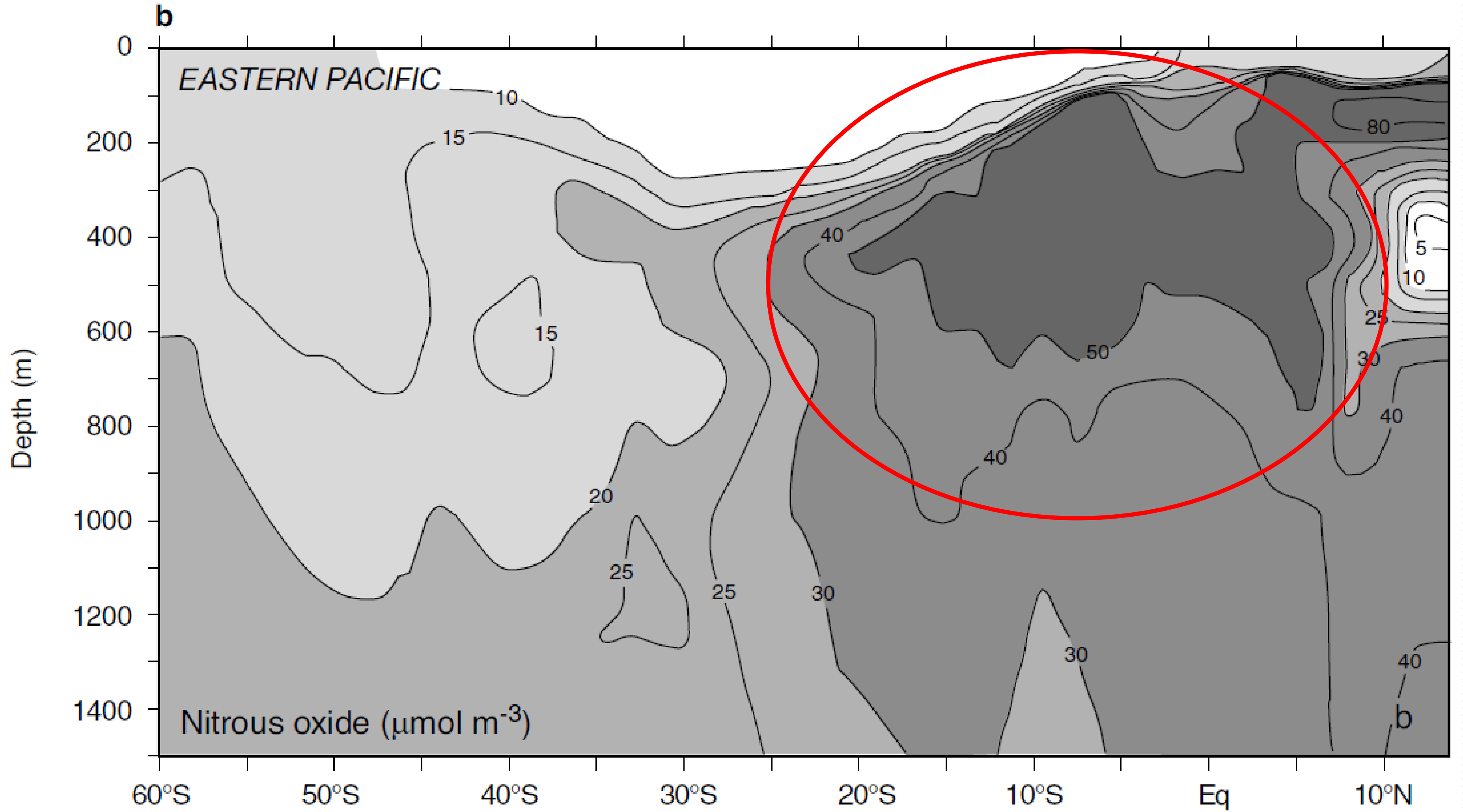


Although the loss of about 4 Tg N2O per year from the ocean into the atmosphere is a relatively small part of the fixed nitrogen budget (table 5.3.1), this flux represents a substantial fraction of the total N2O sources for the atmospheric N2O budget.

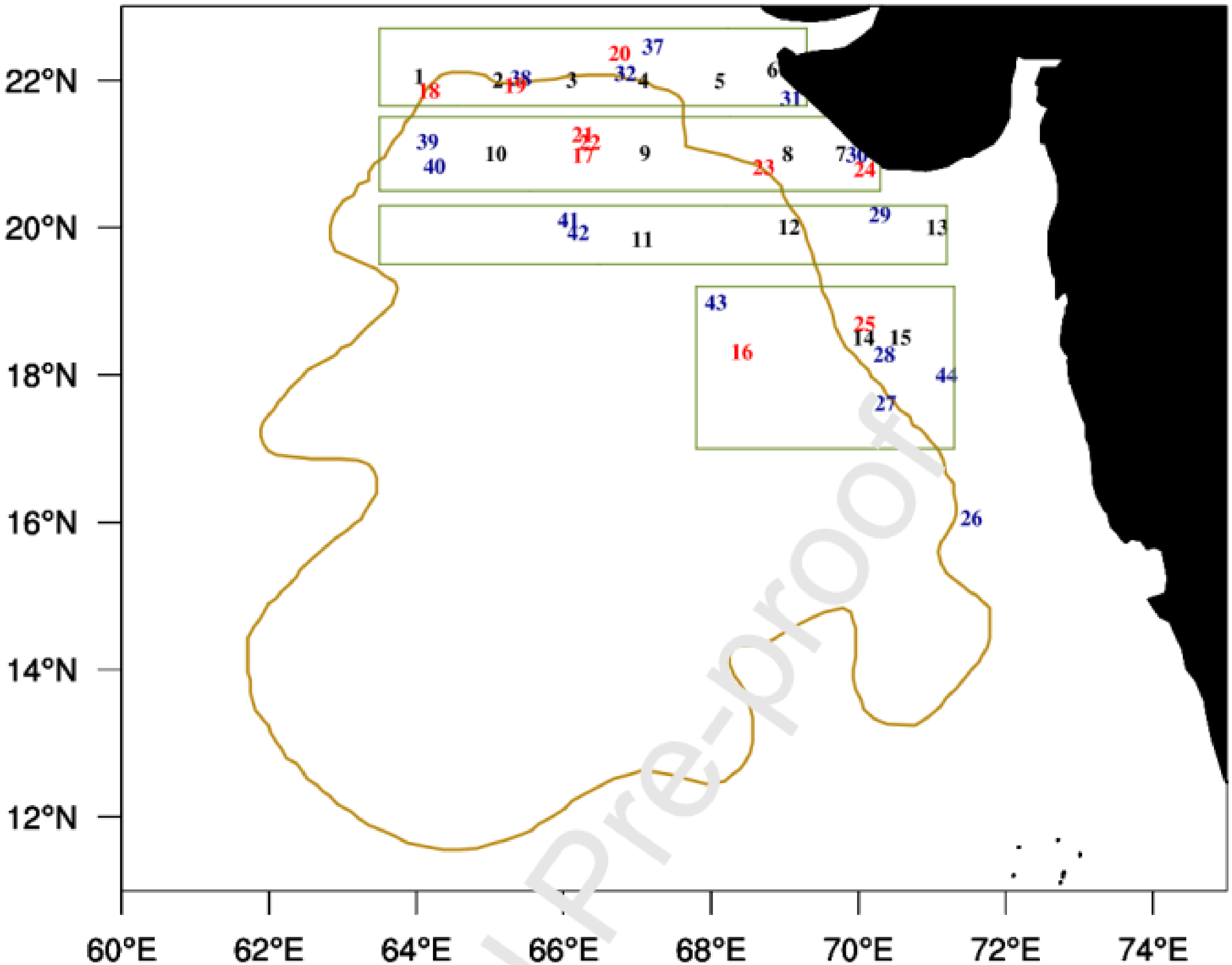
Nitrous Oxide (N_2O)



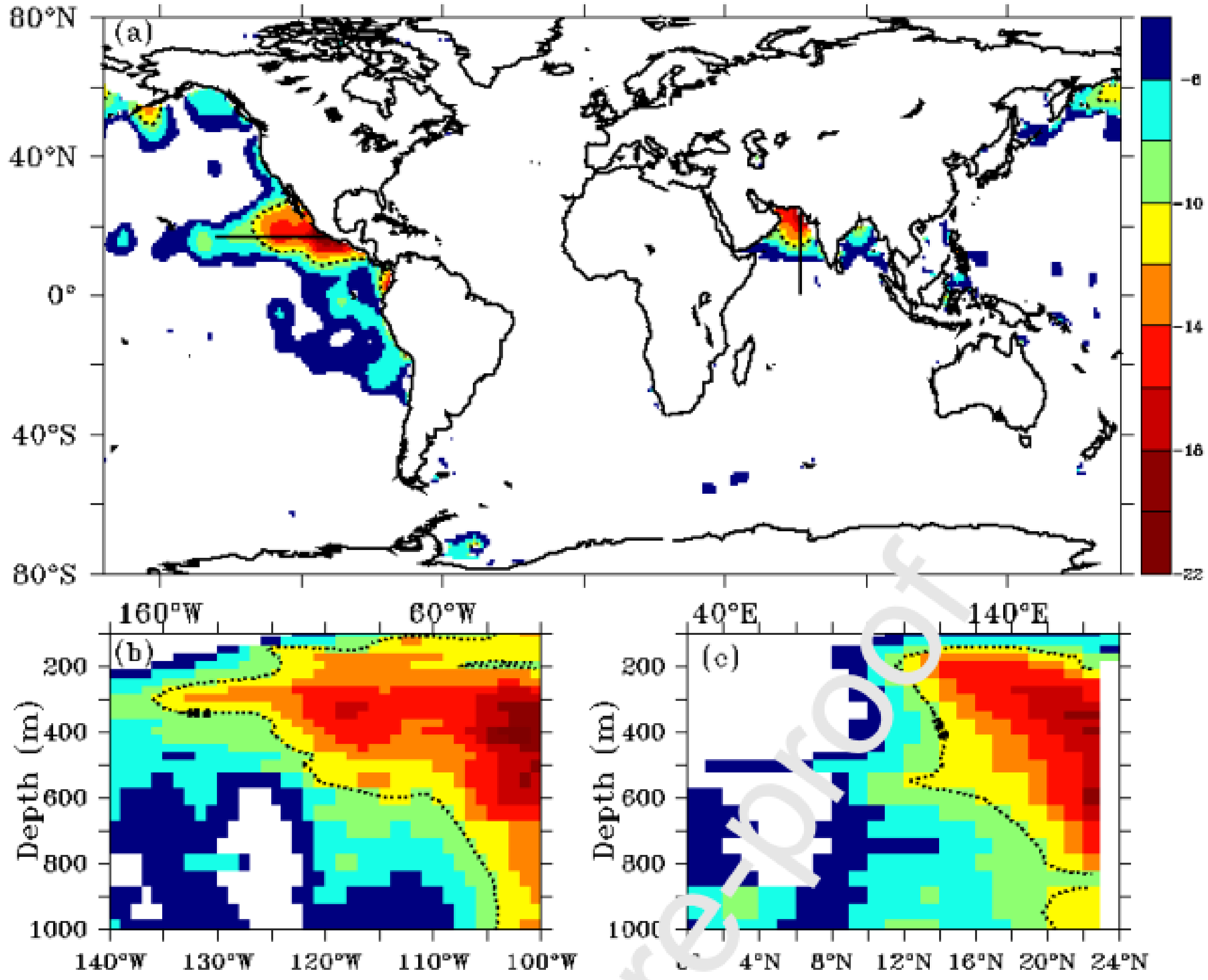
Nitrous Oxide (N_2O)



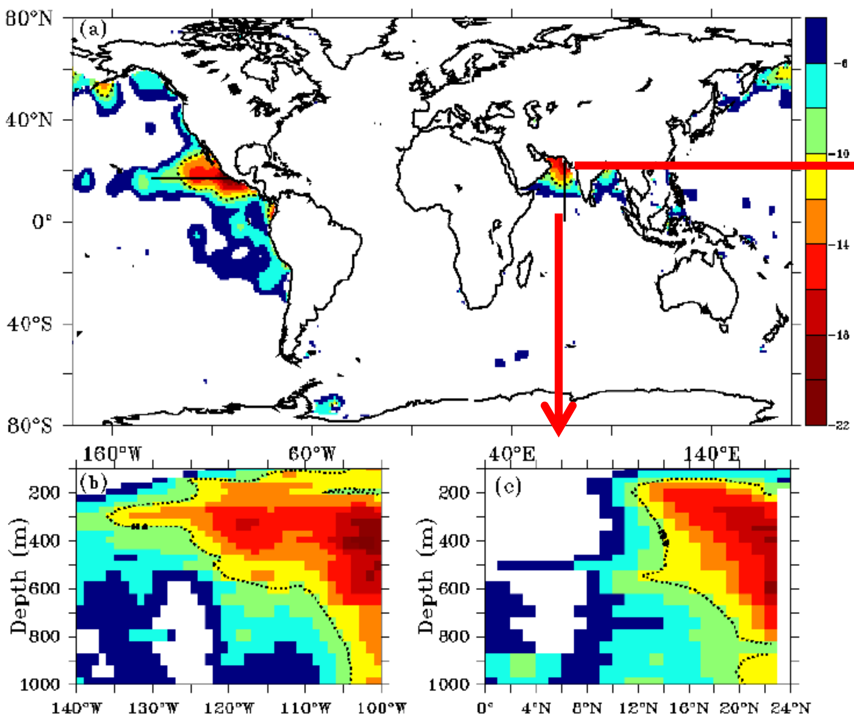
Arabian Sea Denitrification for ship observations (2009)

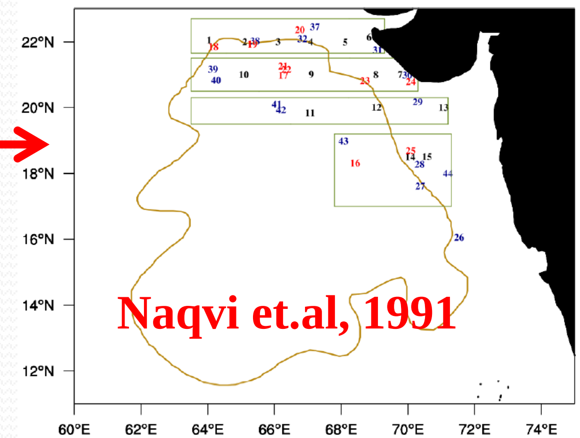


N* comparison of Arabian Sea and global oceans



How critical is Arabian Sea denitrification?

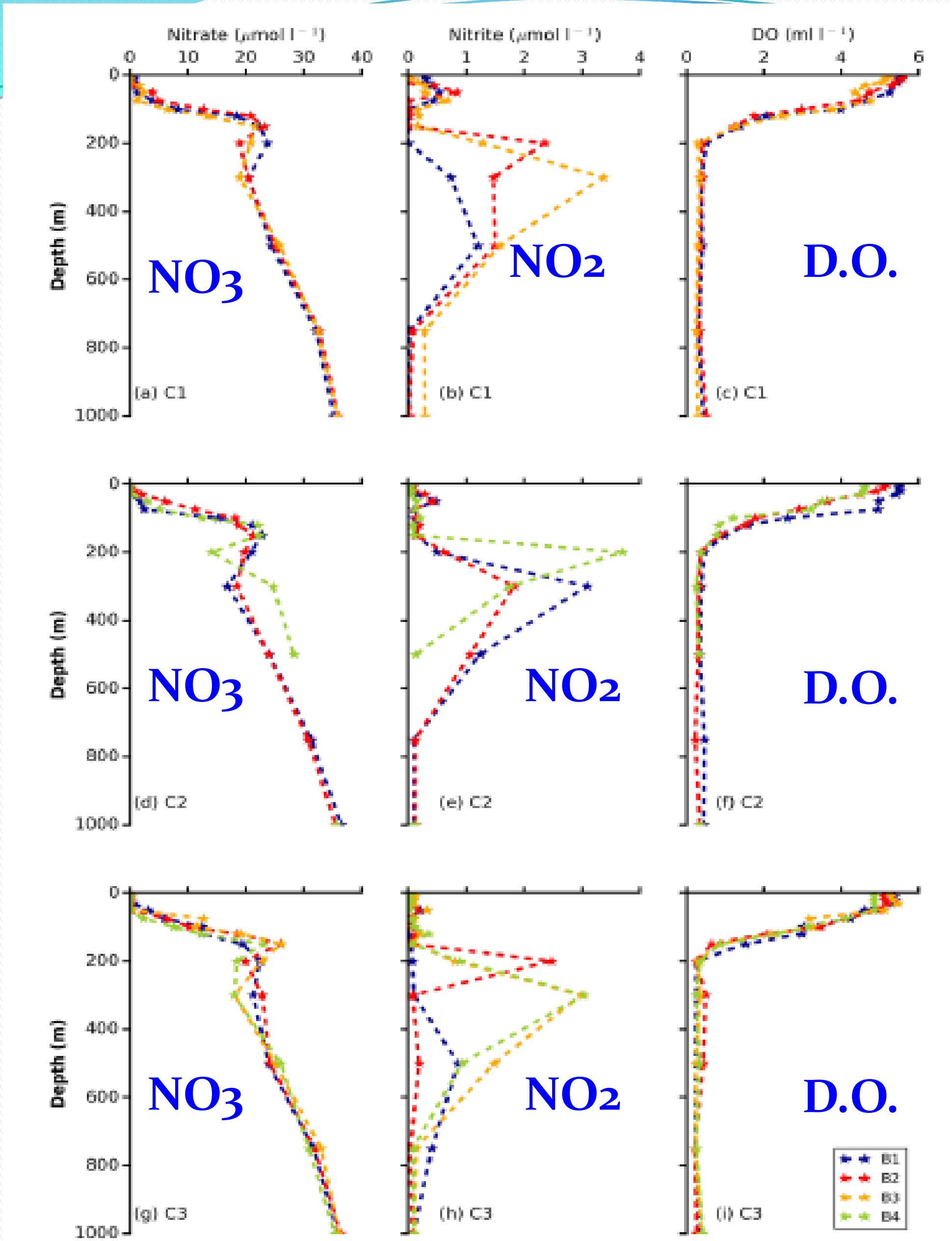




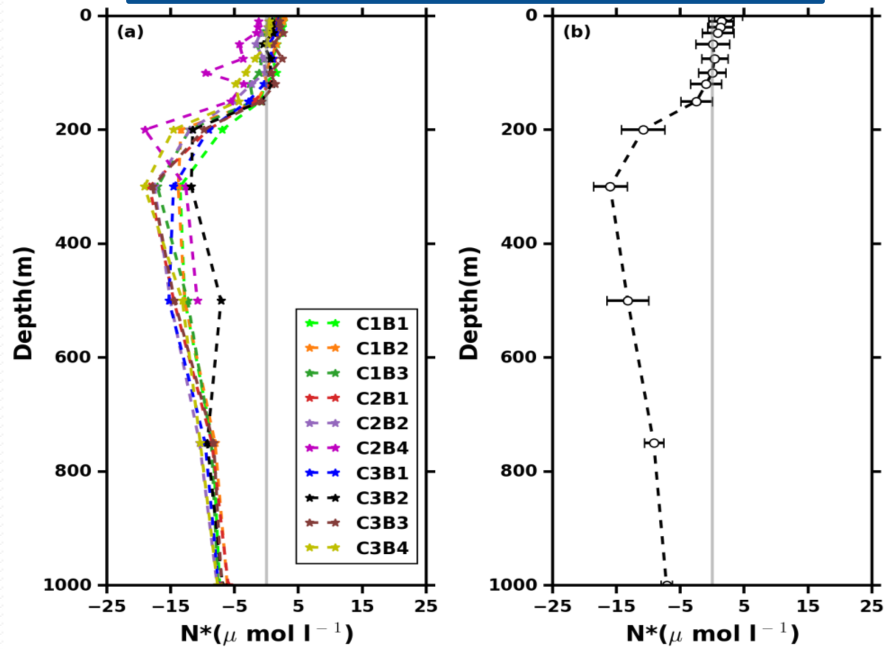
There are mainly two pockets of low values of N* observed in the world ocean and they are the north-eastern Pacific Ocean and eastern AS (Paulmier and Ruiz-Pino, 2009).

S. No	(Tg N/yr)	Study
1	29.5	Naqvi 1987
2	41.0 ± 18.0	Devol et.al., 2006
3	34.0	Yakushev & Neretin 1997
4	11.9 ± 5.0	Mantoura et. al., 1993
5	24.00 – 33.0	Naqvi & Shailaja 1993
6	21.0 ± 7.0	Howell et. al., 1997
7	6.0 – 60.0	Bange et. al., 2000
8	11.0 – 12.0	Kawamiya & Oschlies, 2003
9	25.3 ± 7.0	In our study (using CMLRE data) (Anju et al., 2021)

Recent CMLRE ship observations.



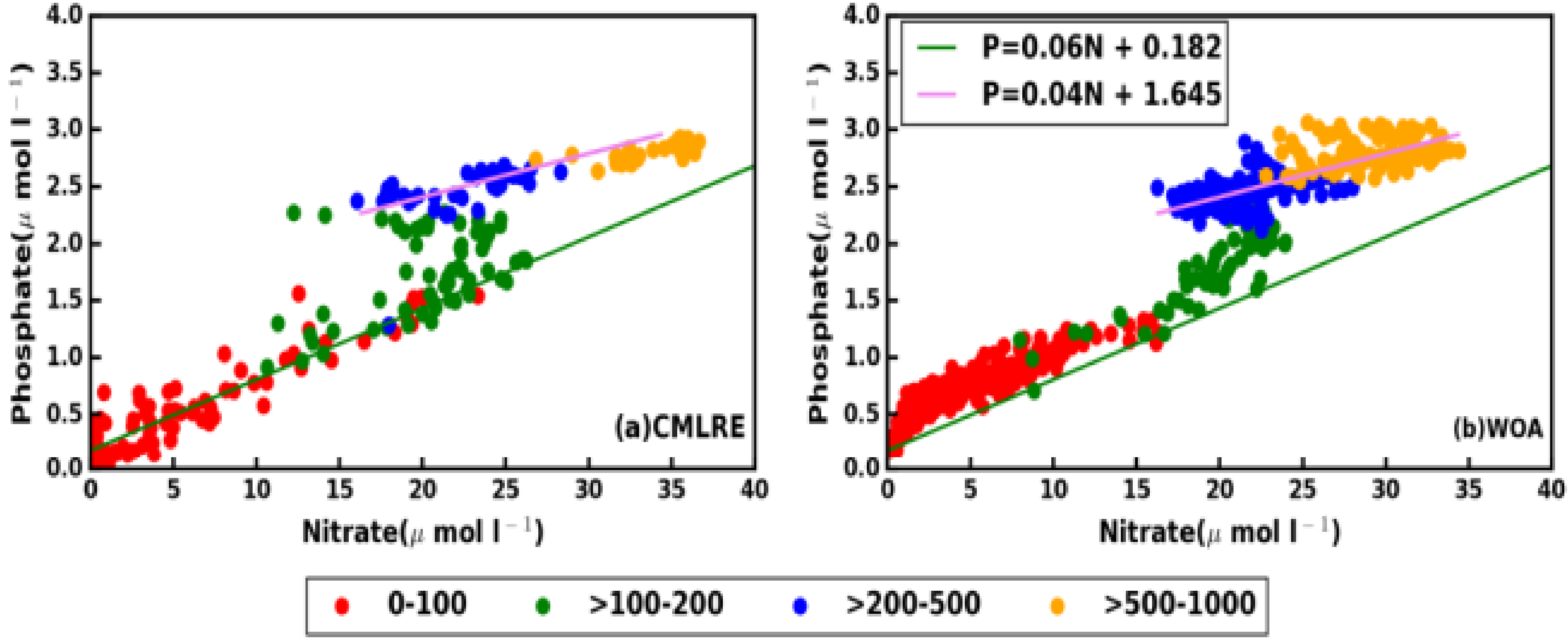
$$N^* = ([NO_3^-] - 16 \times [PO_4^{3-}] + 2.9\ \mu mol\ l^{-1})$$

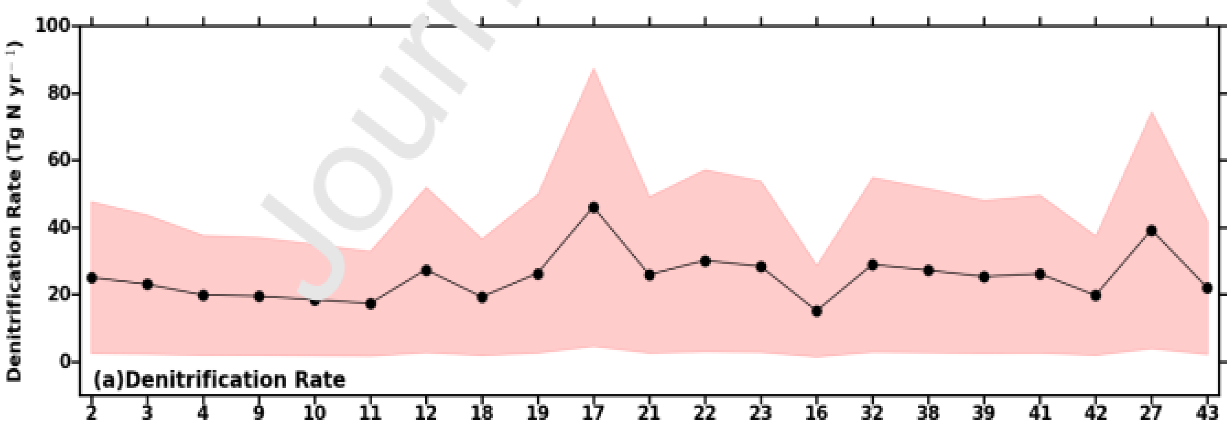


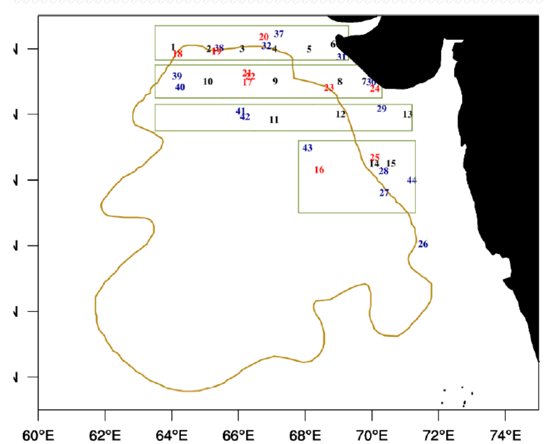
Decrease in nitrate (NO3) and increase in nitrite (NO2) indicates de-nitrification (Naqvi, 1994).

Low N* quantifies the strength of denitrification

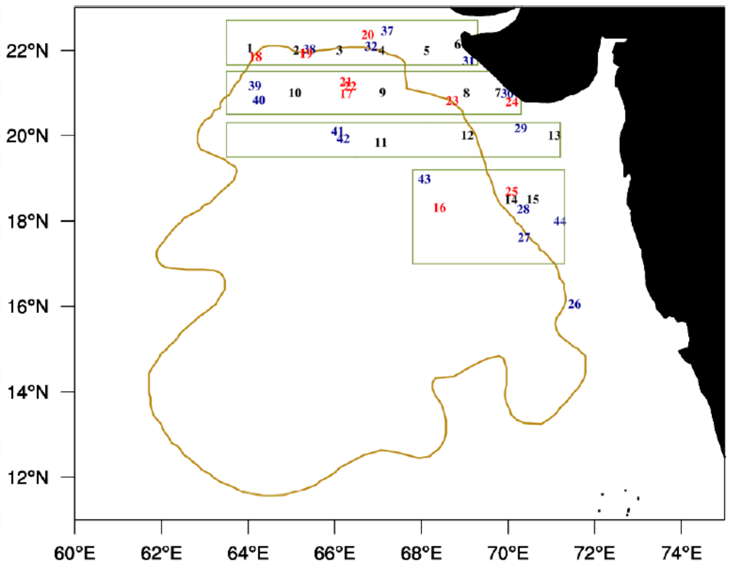
Modified Redfield ratios of Arabian Sea







Conclusion



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