Eddy driven ventilation in the Arabian Sea

Zouhair Lachkar (NYUAD)
Shafer Smith (Courant/NYU)

SYNBIOS
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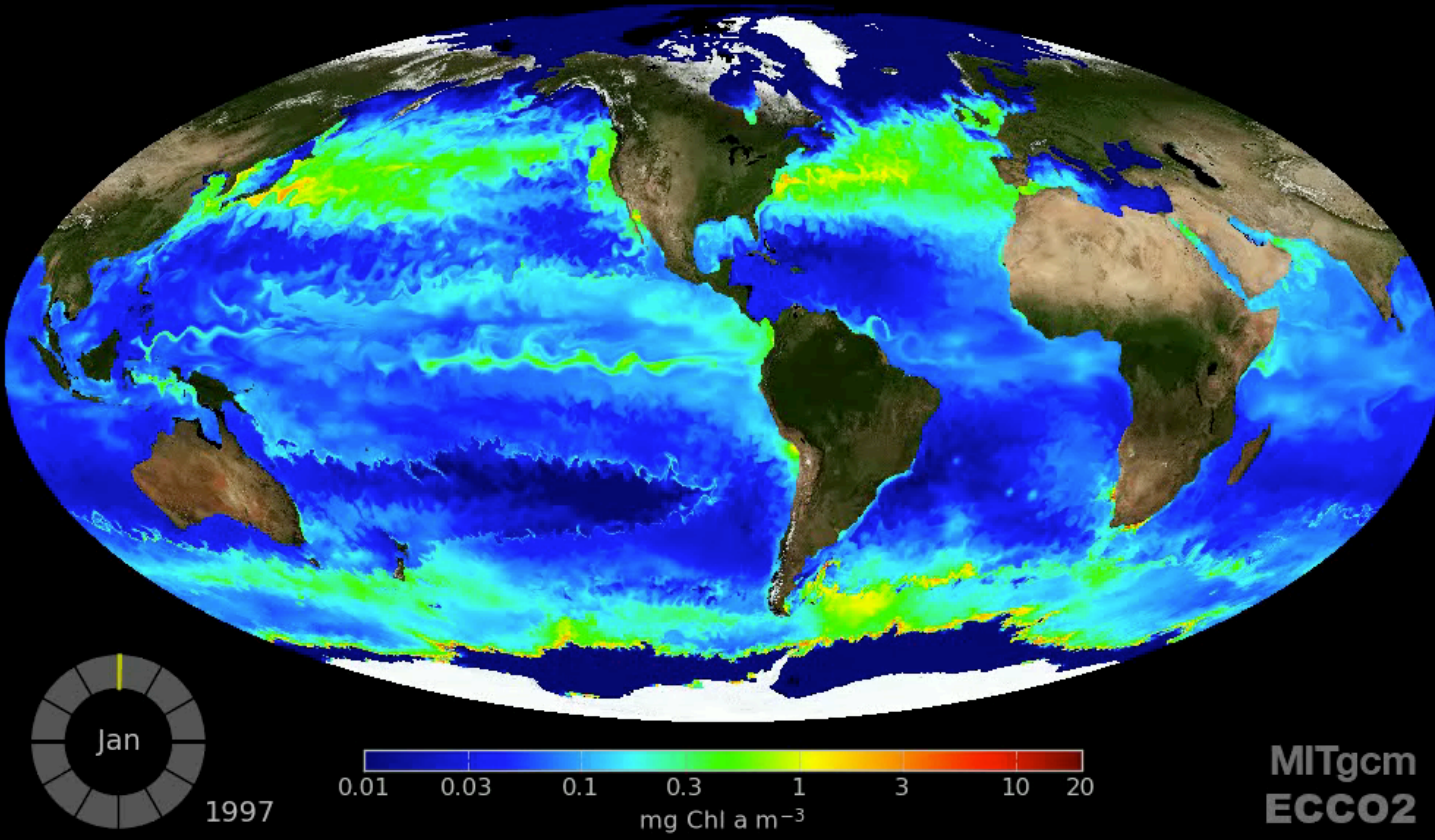
Outline

- Why the Arabian Sea?
- Project: Effects of changing monsoonal winds on Arabian Sea biogeochemistry, focus on oxygen
- Dynamics of oxygen in the oceans and the AS
- ROMS simulations of the AS
- Speculation

What makes the Arabian Sea unique?

- Extreme seasonality & complex dynamics (monsoon reversal, coastal upwelling, offshore advection, winter convection, eddies,…)
- Among the most productive (> 300 gC m^{-2} yr^{-1})
- 2/3 of dust deposited in ocean → Indian Ocean
- Thickest Oxygen Minimum Zone (150-1200m)
- Largest suboxic zone
- 1/2 of global N loss due to denitrification and anammox
- A globally significant source of N_2O (nitrous oxide)
- Potential to modulate climate on geological timescales

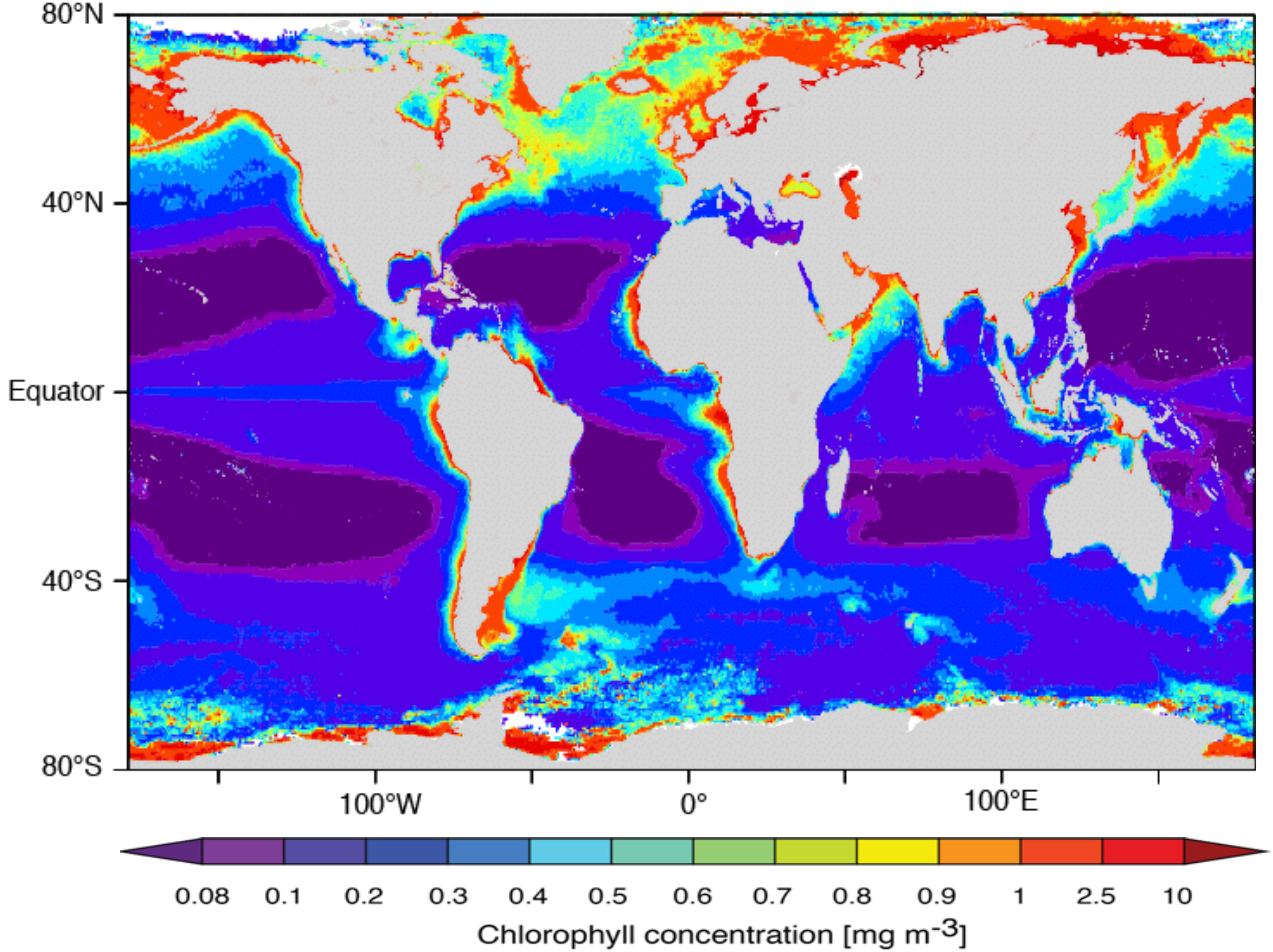
Chlorophyll from ECCO2



Williams & Follows 2007

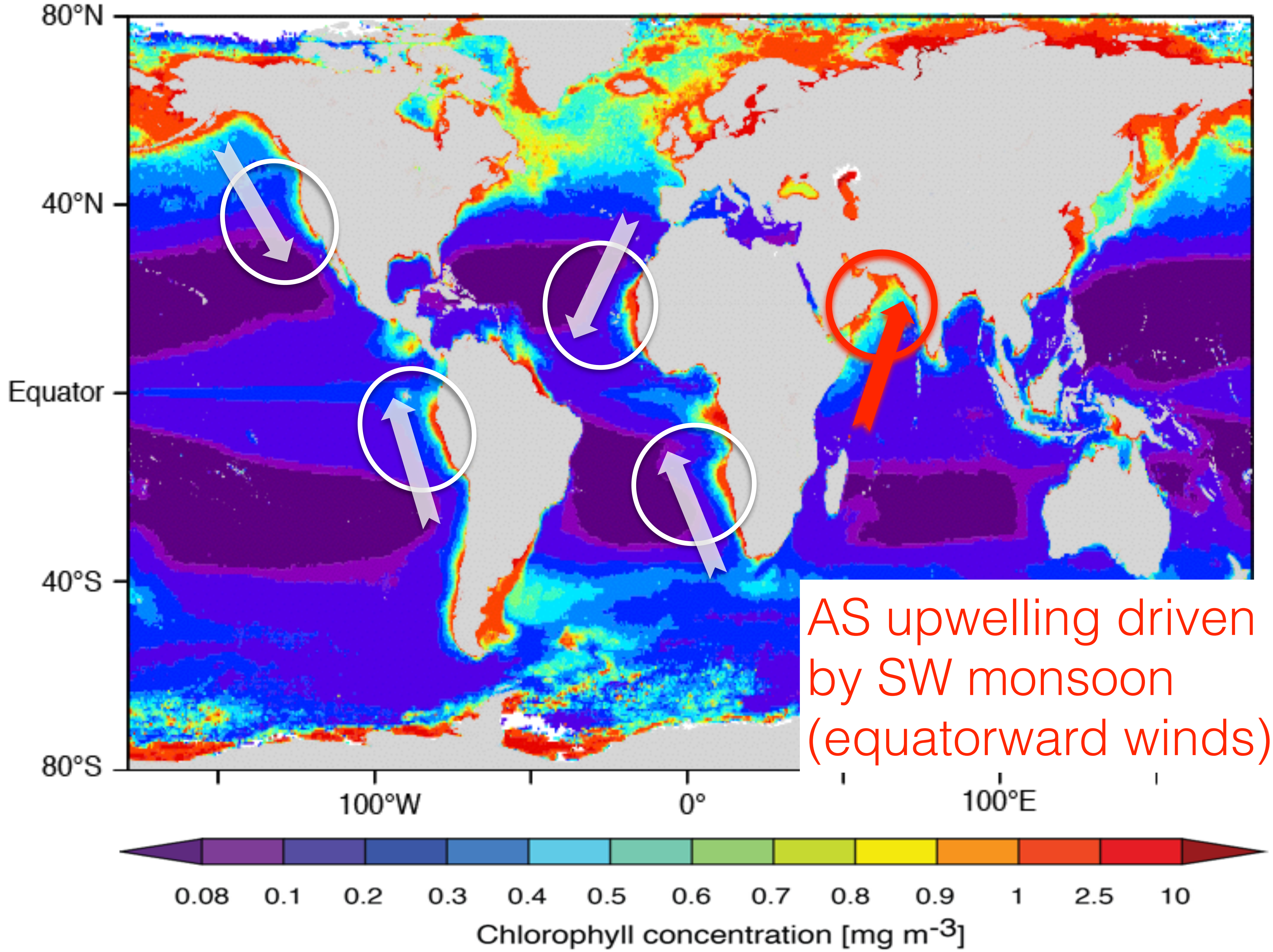
Coastal upwelling systems

Annual mean surface chlorophyll from SeaWiFS



Coastal upwelling systems

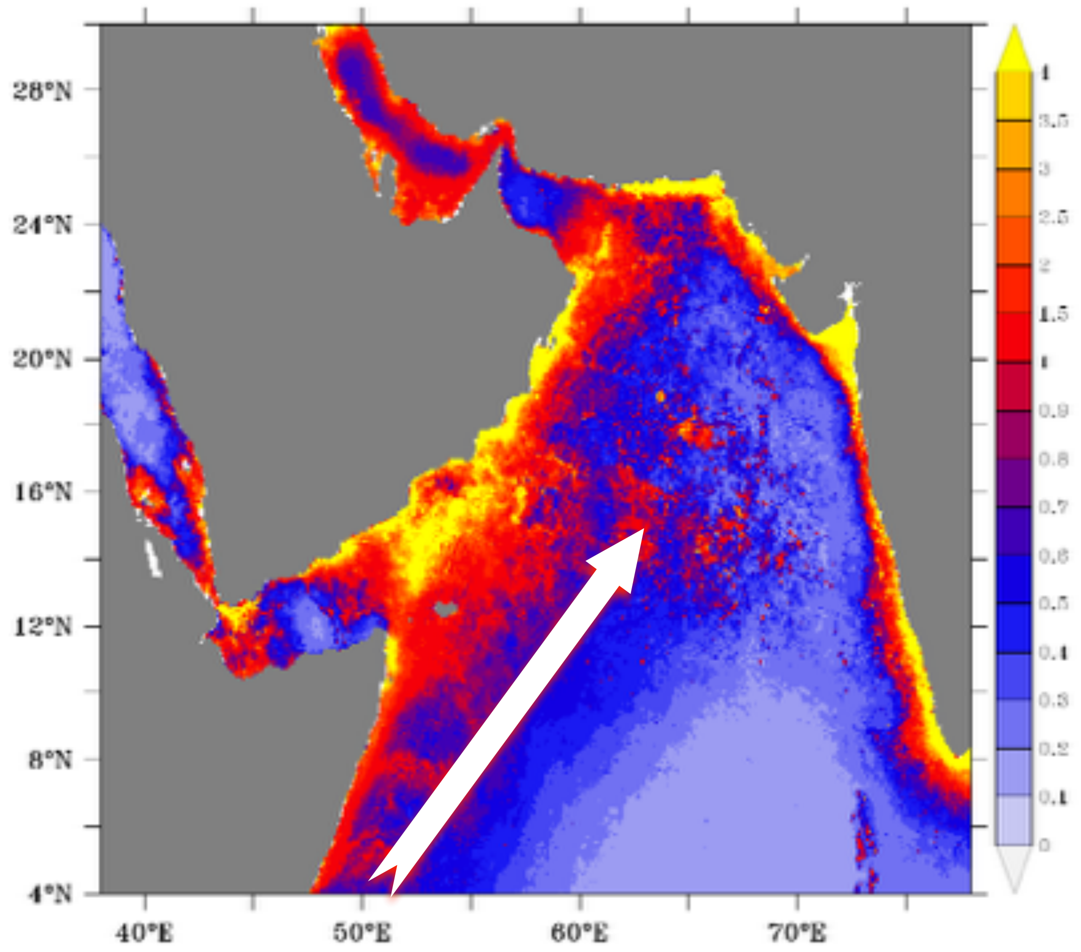
Arabian Sea: the only western boundary upwelling system



AS upwelling driven by SW monsoon (equatorward winds)

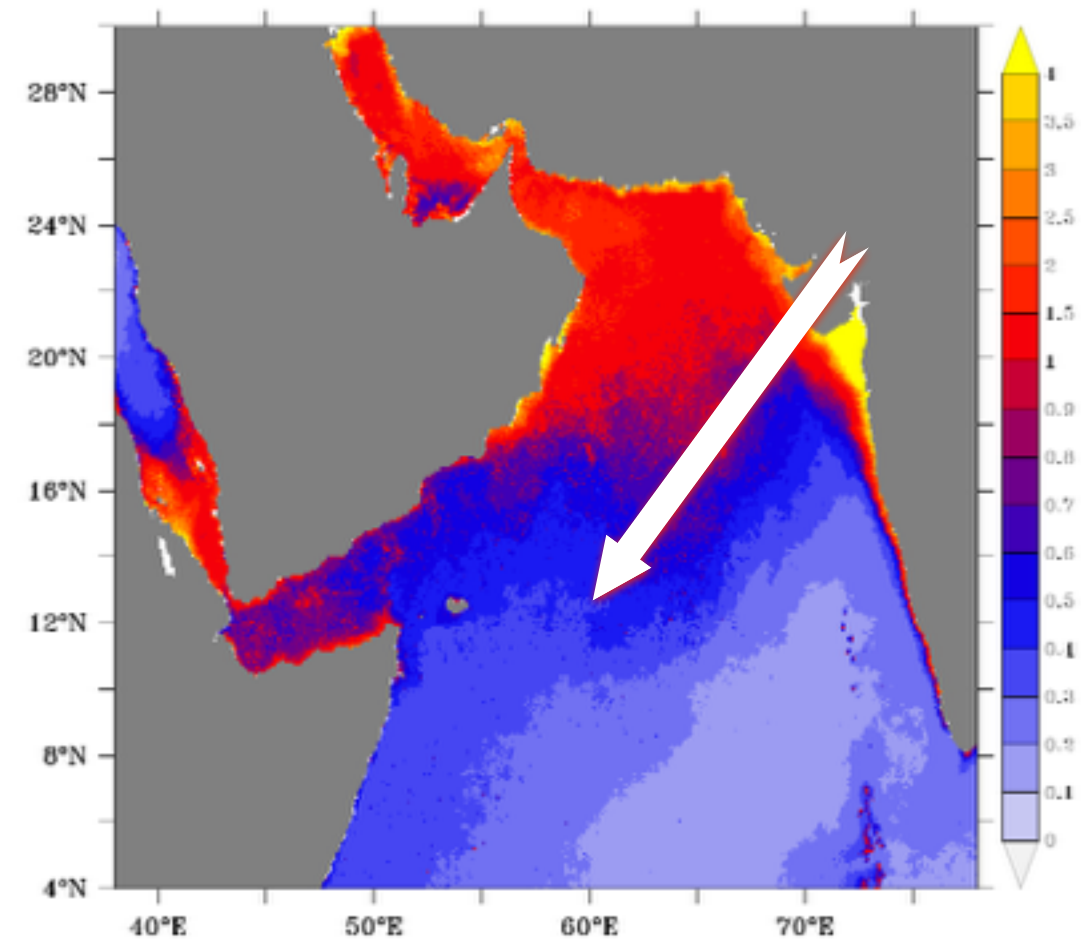
Arabian Sea: Two blooms per year!

Summer



Summer monsoon winds drives upwelling along Somali coast

Winter

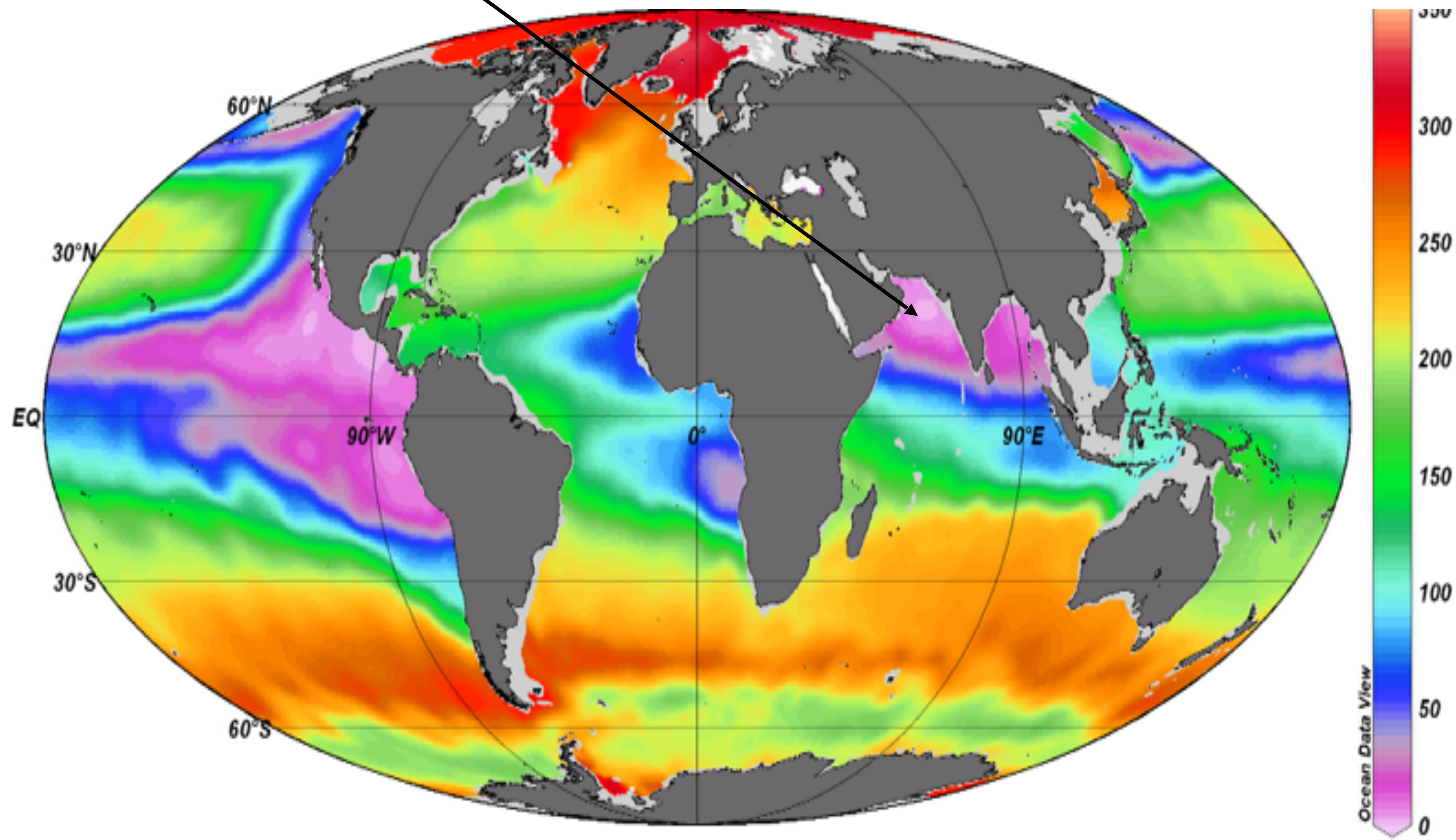


Winter monsoon winds drives convection at north of basin

Ocean color from SeaWifs

Oxygen minimum zones (OMZs)

Generally in eastern boundaries, with one exception:
Indian Ocean OMZ - northeast of basin



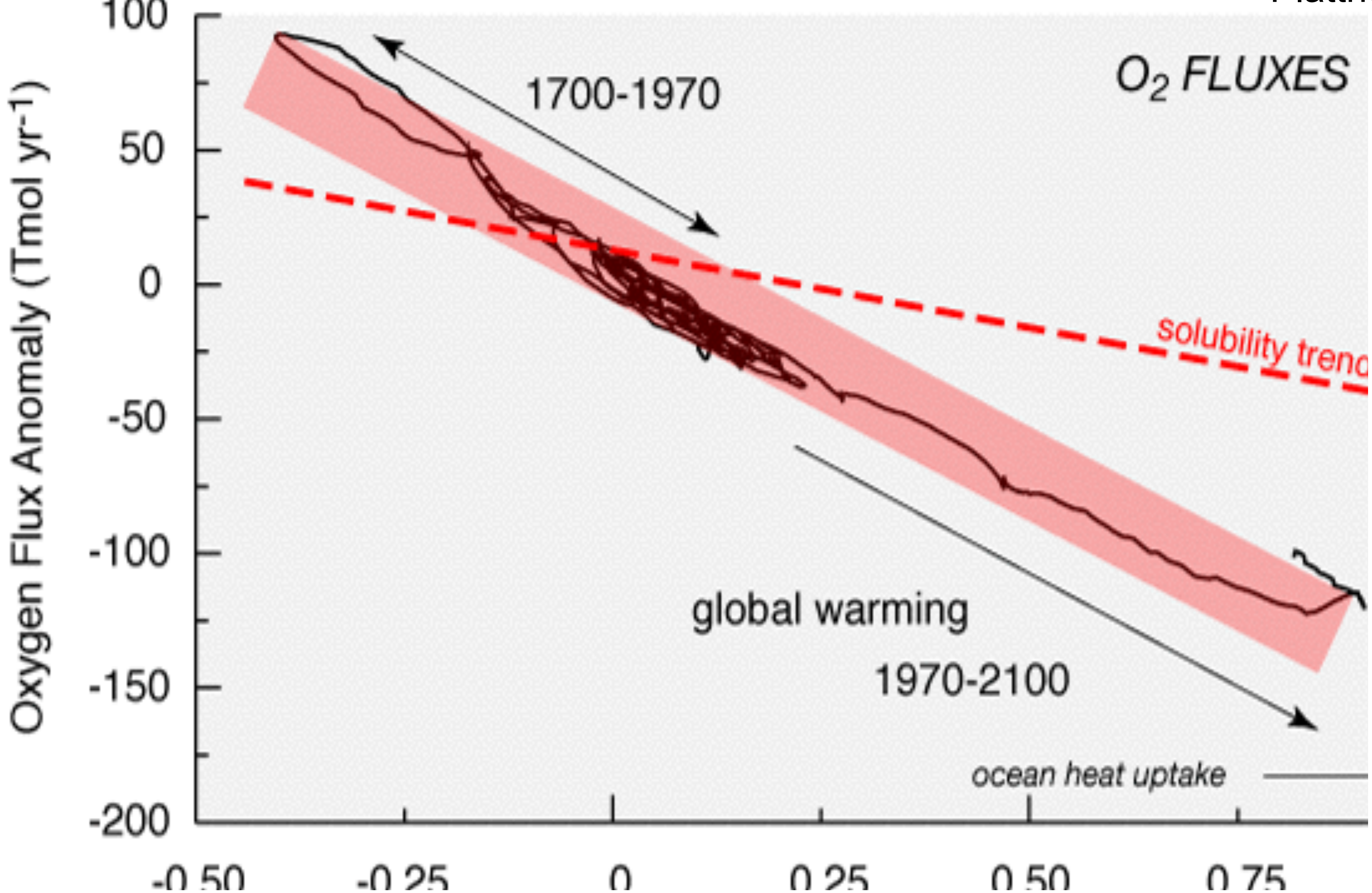
Oxygen at 400 m (µmol/L)

World Ocean Atlas

Ocean deoxygenation: the global perspective

Warming is causing the ocean to lose oxygen

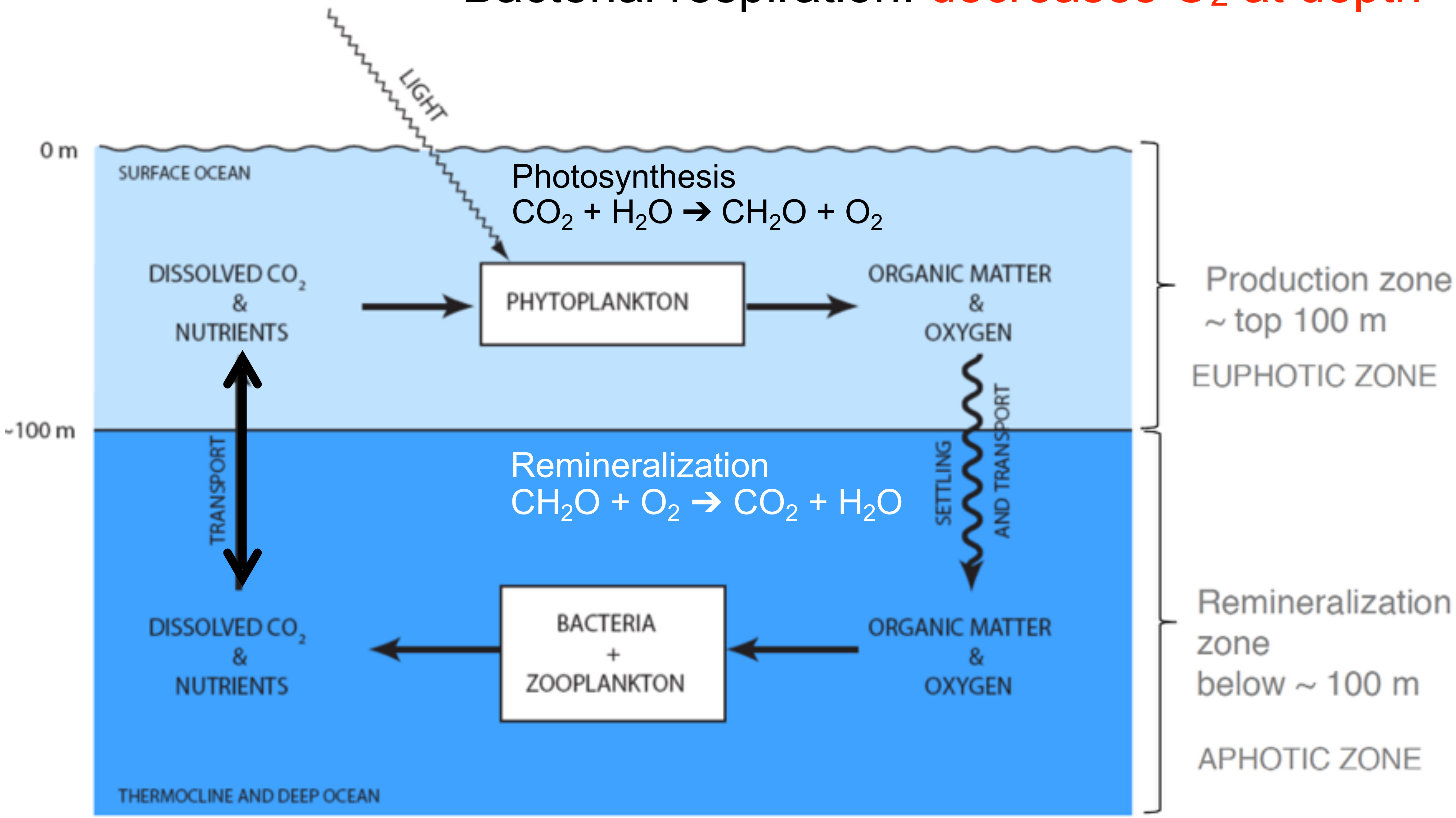
Plattner et al. (2002)



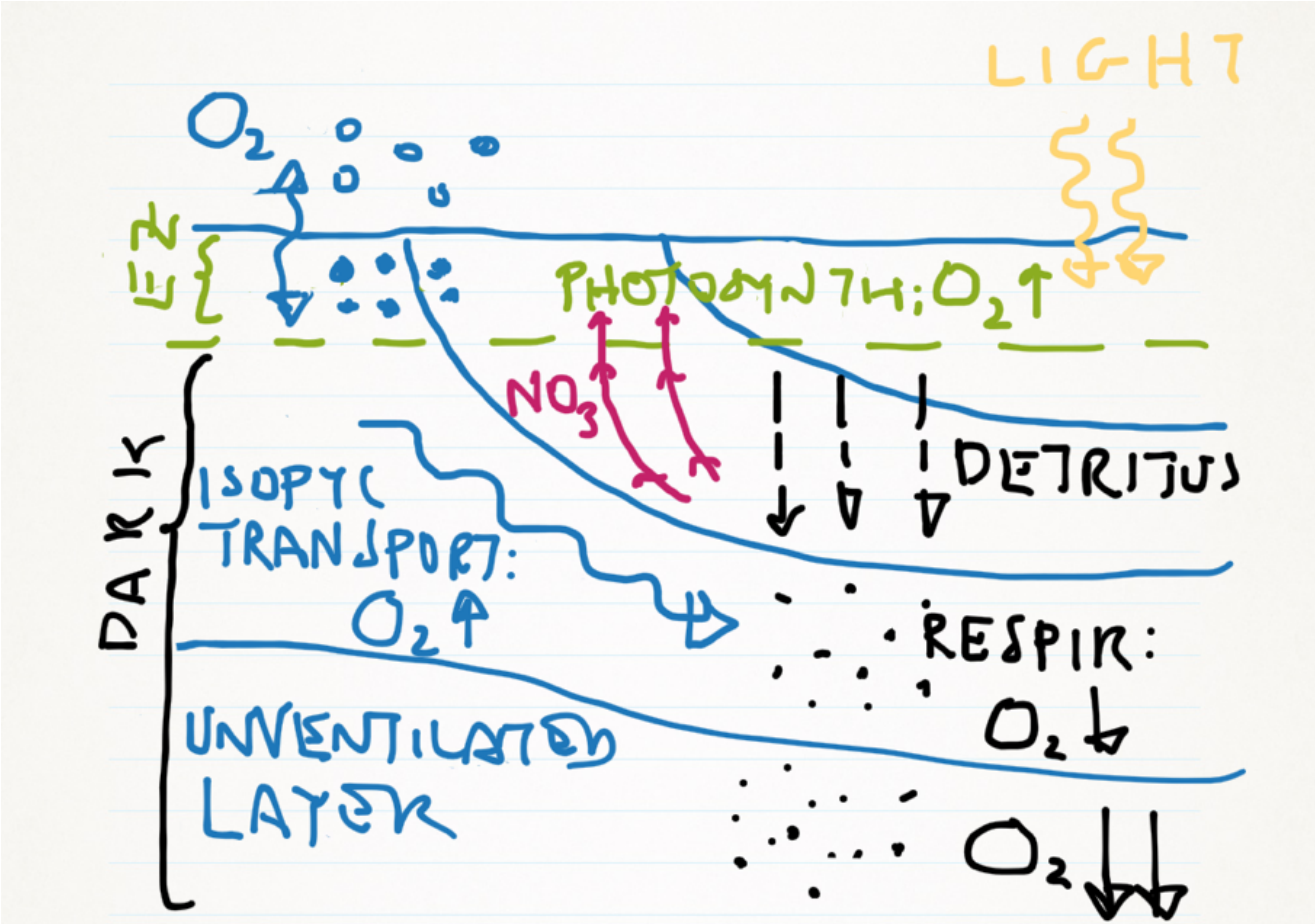
The ocean outgassing trend is larger than expected based on the solubility only

Oxygen: biological effects

Photosynthesis/air-sea flux: increases O_2 at surface
Bacterial respiration: decreases O_2 at depth



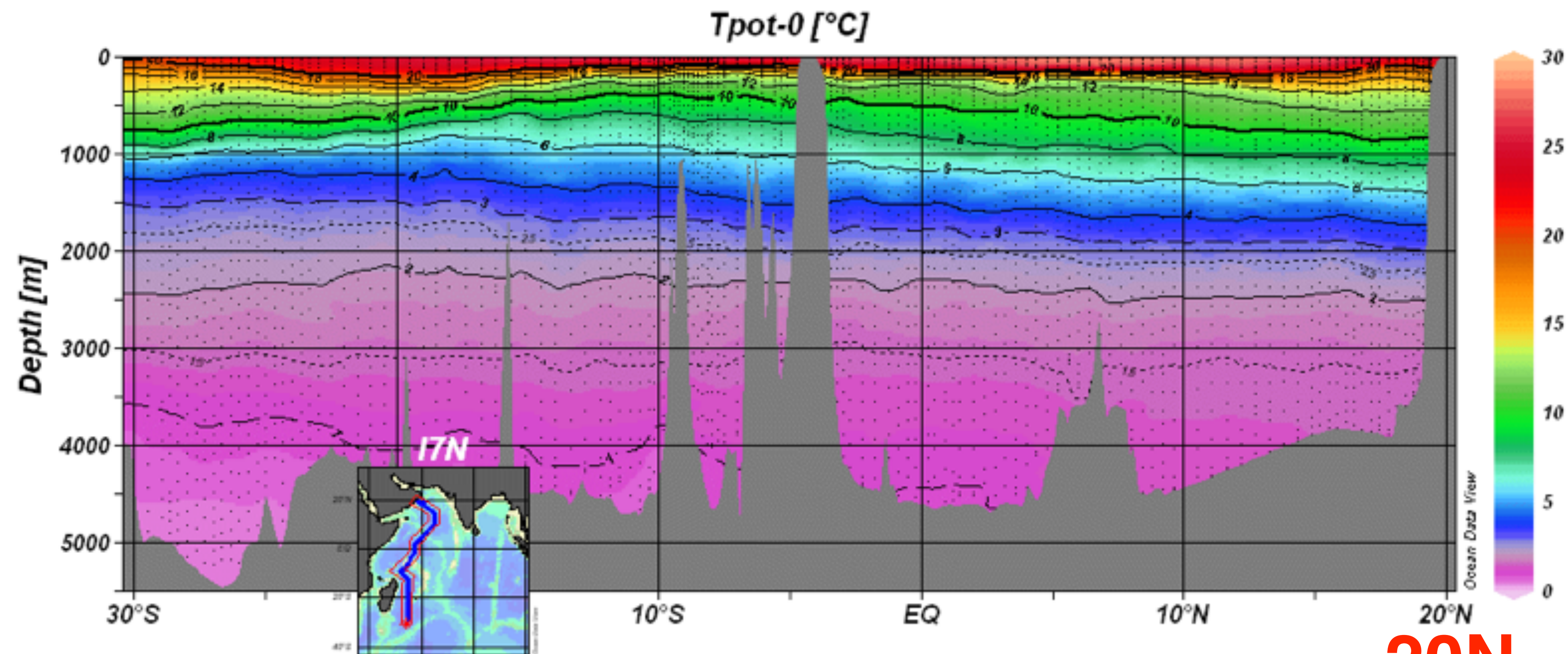
Oxygen: production & respiration & ventilation



made with Adobe Illustrator™

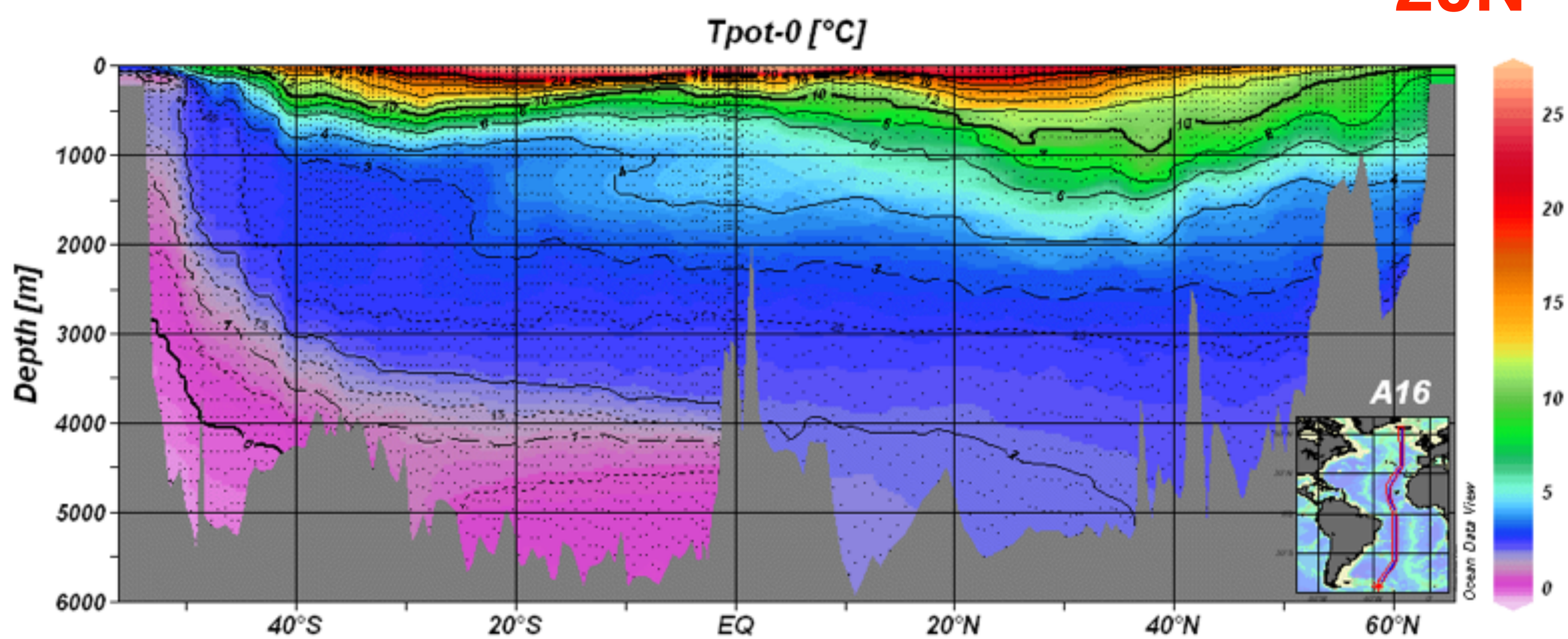
Indian Ocean: most isopycnals unventilated

Indian Ocean



20N

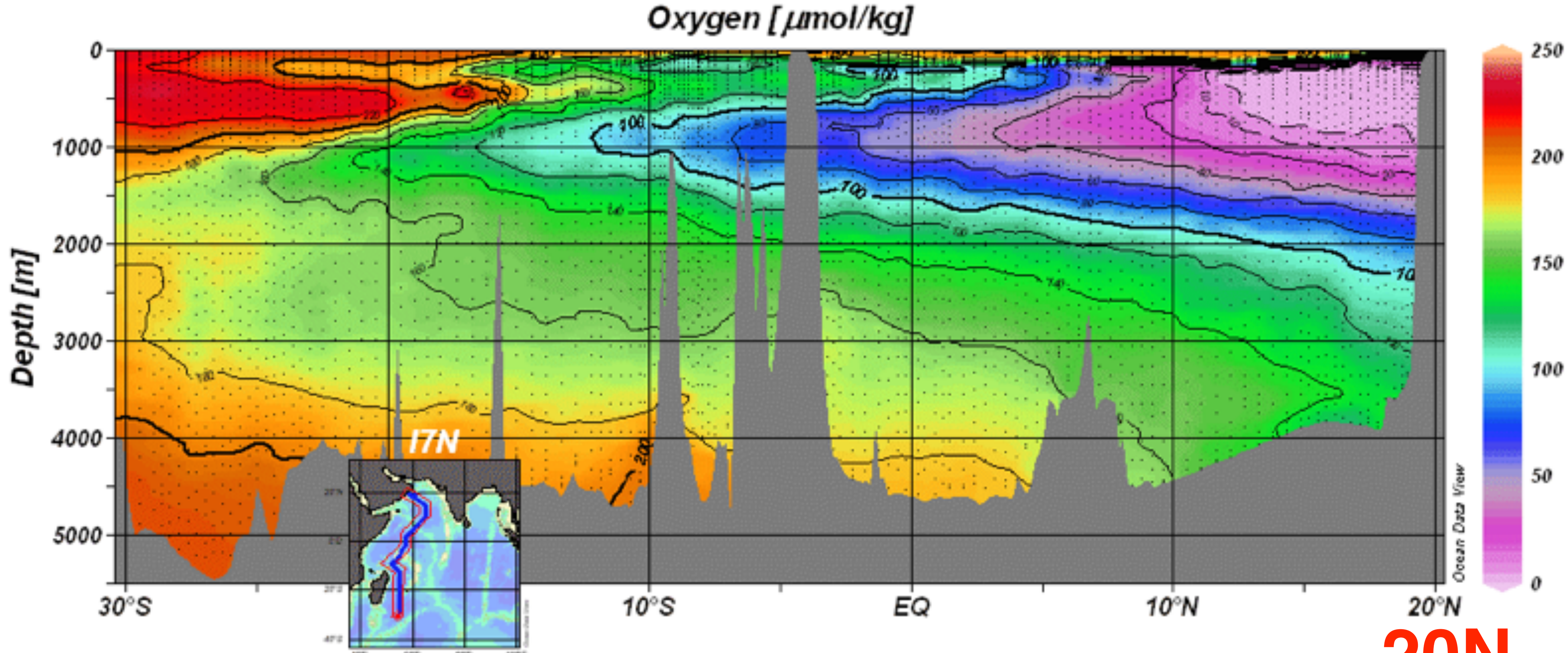
Atlantic Ocean



WOCE transects

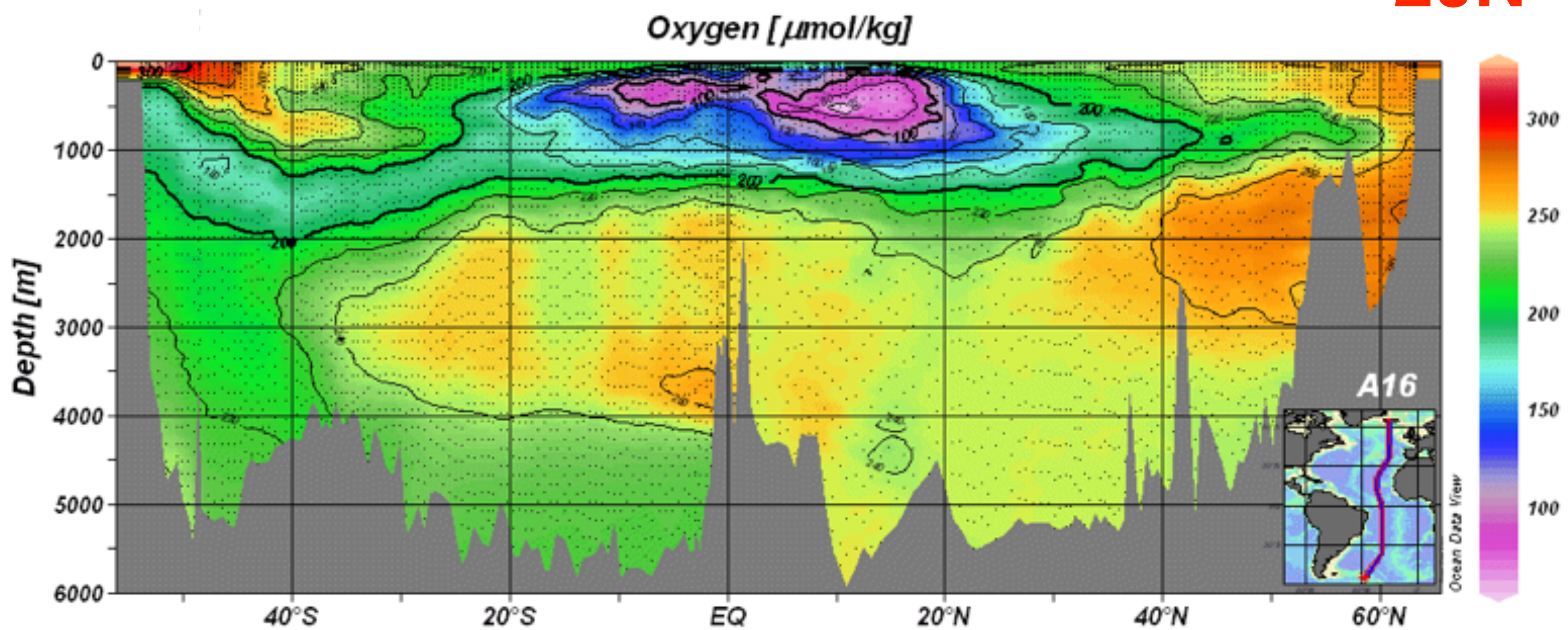
Indian Ocean: … less ventilated

Indian Ocean



20N

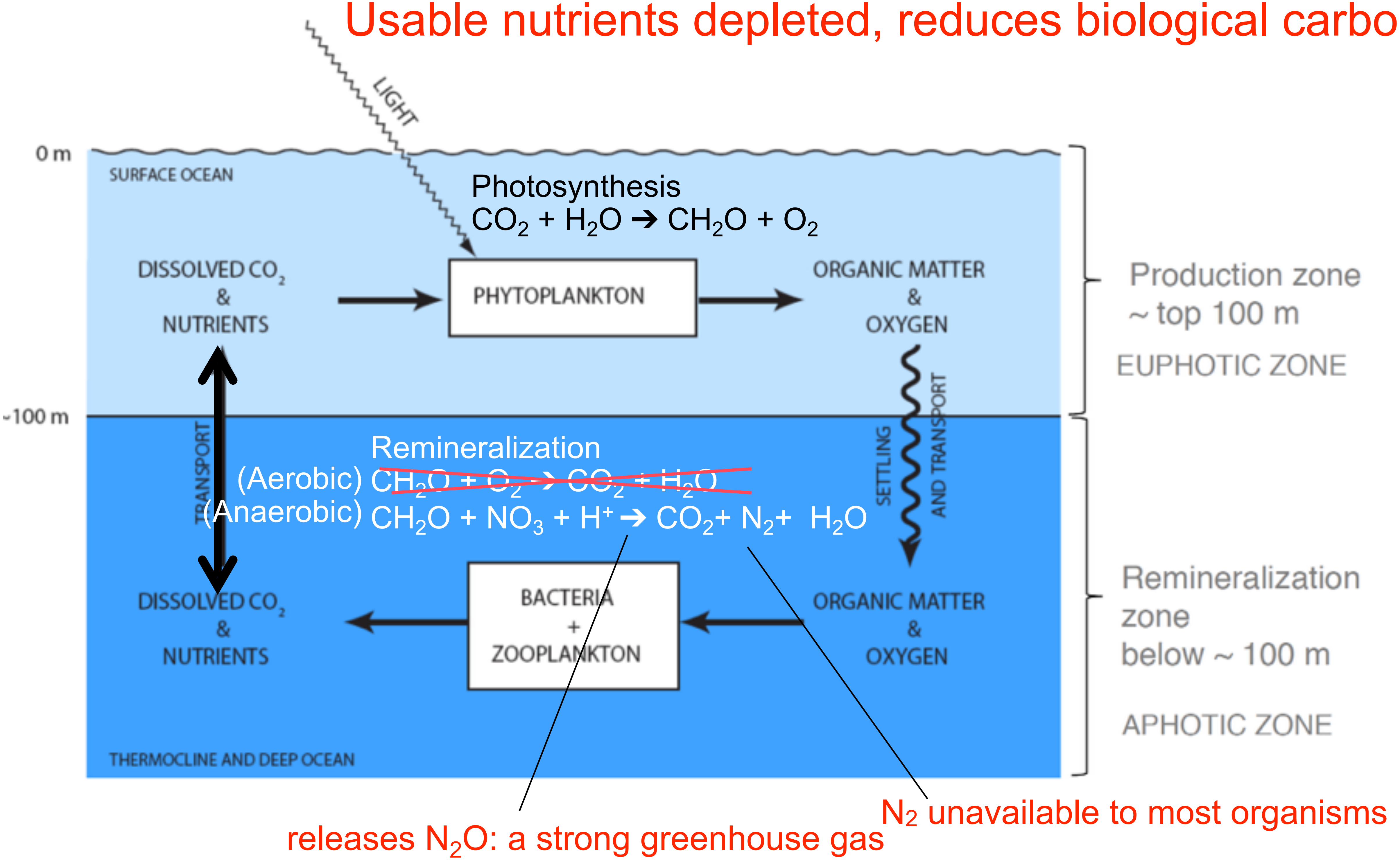
Atlantic Ocean



WOCE transects

In O_2-depleted water: denitrification

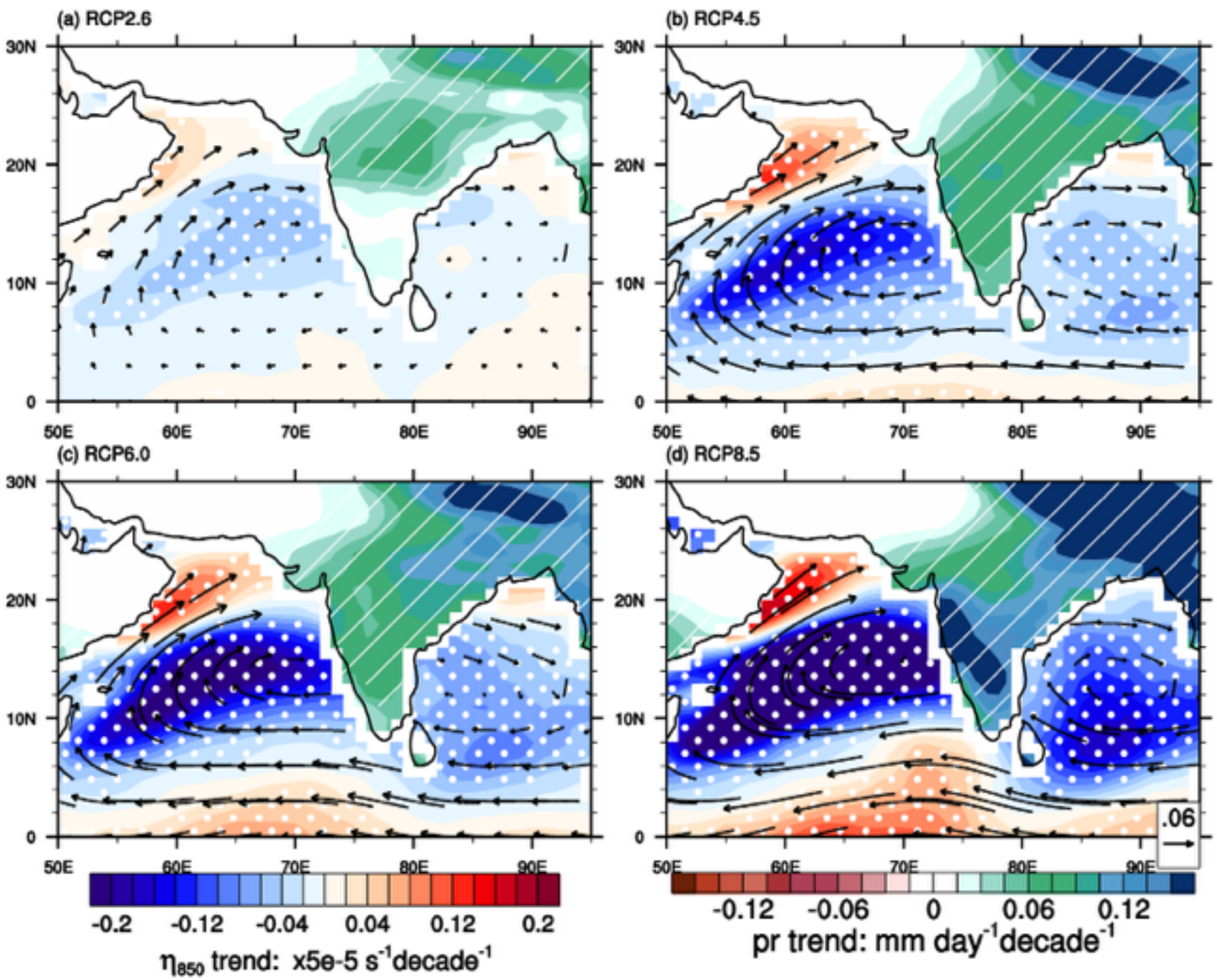
When O_2 depleted, bacteria consume NO_3, release N_2
Usable nutrients depleted, reduces biological carbon pump

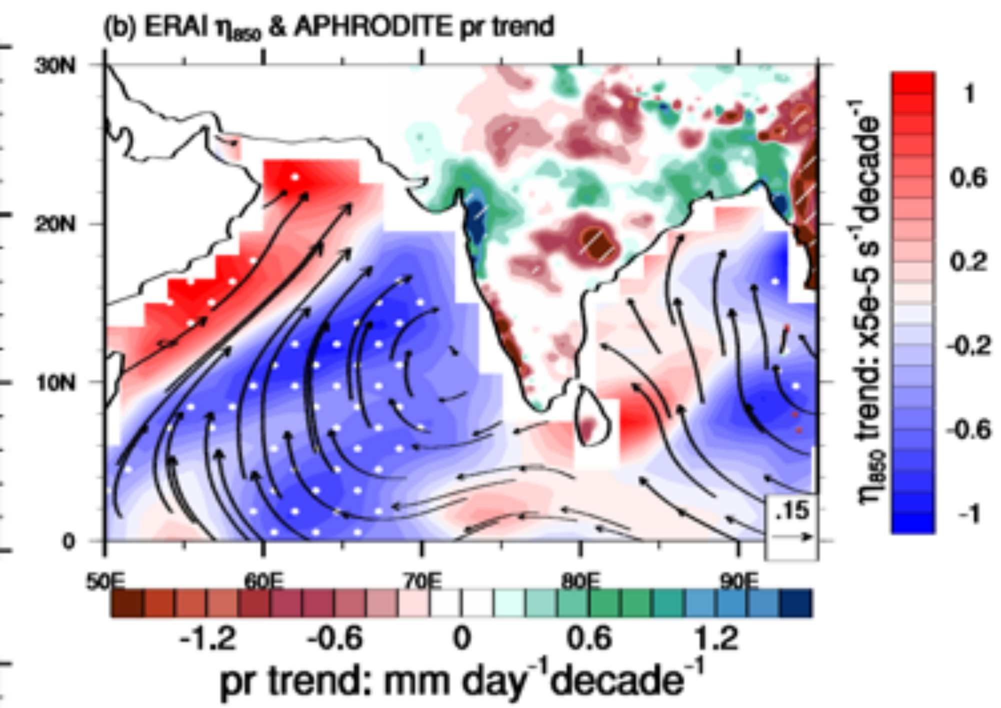


Denitrification in Arabian Sea ➔ 30-50% global loss of fixed N

The Monsoon — Arabian Sea climate feedback

Observations & models ➔ recent and future monsoon strengthening?





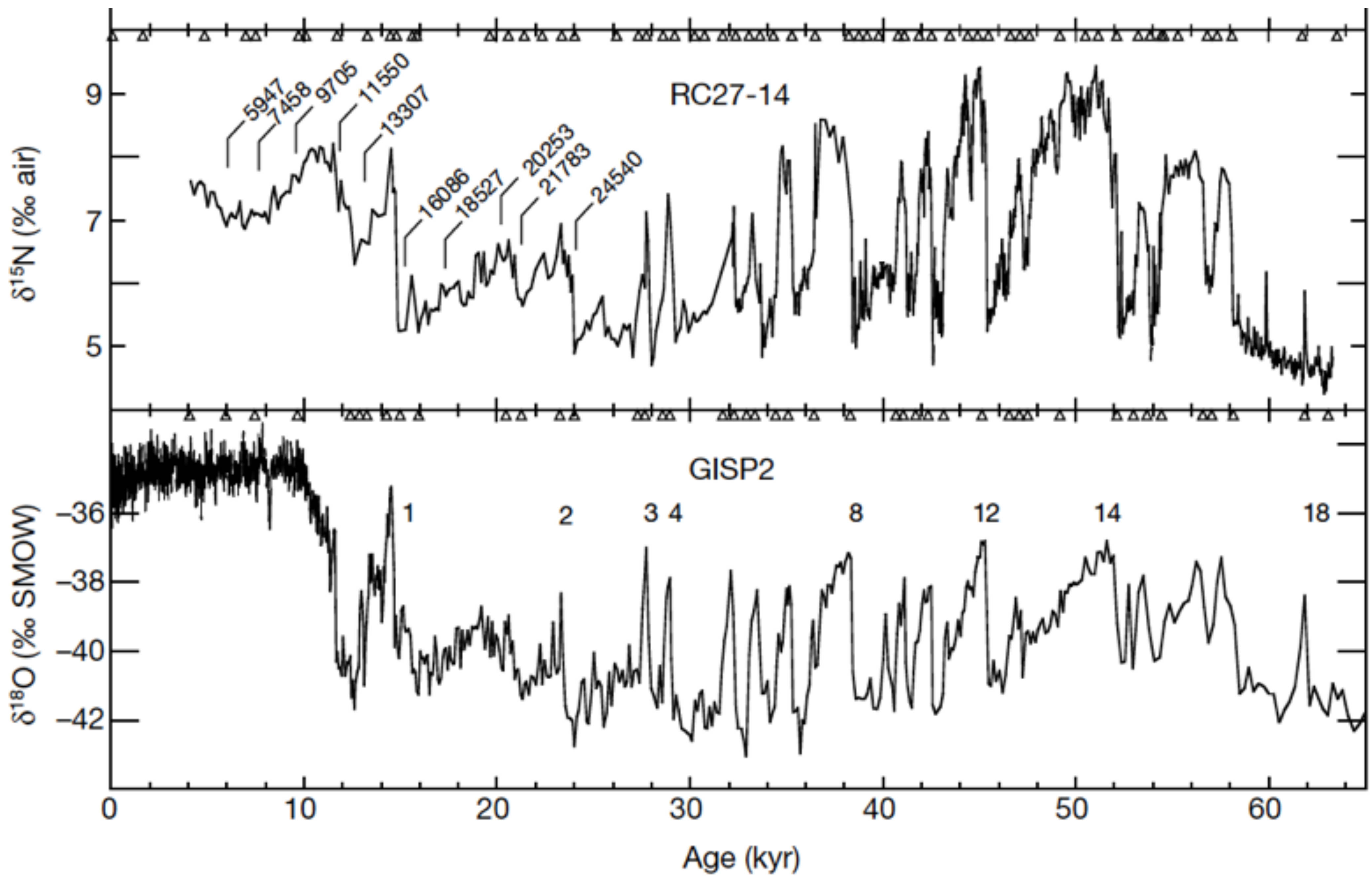
Trend: Monsoon winds have increased 1979-2007

Climate change simulations (2006-2099) show Monsoon increases with GH gas

Sandeep and Ajayamohan, submitted

The Monsoon – Arabian Sea climate feedback

Paleo data ➔ high sensitivity of Arabian Sea OMZ to NH climate variations



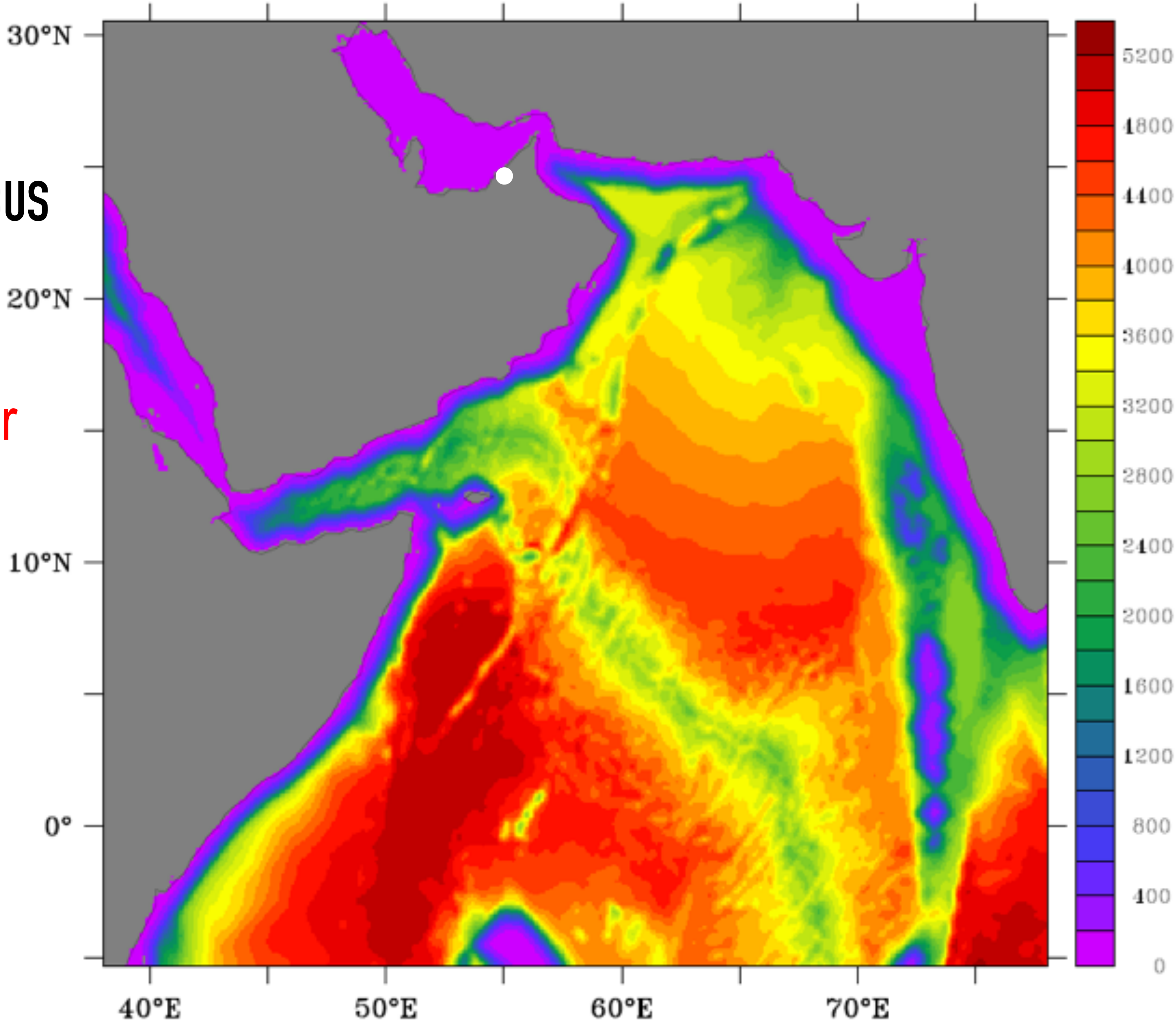
Altabet et al., 2002

Model setup

Regional Oceanic Modeling System (ROMS)
Resolution: 1/3, 1/6, 1/12, 1/24 deg, 32 levels
Atmospheric forcing: COADS, QuikSCAT
Varied winds: 0.5x, 1x, 1.5x
Boundary conditions: SODA reanalysis
W/ & W/O Marginal Seas
Climatological runs (12 year)
Biological model: NPZD, $N^3P^2Z^2D^2$, BioEBUS

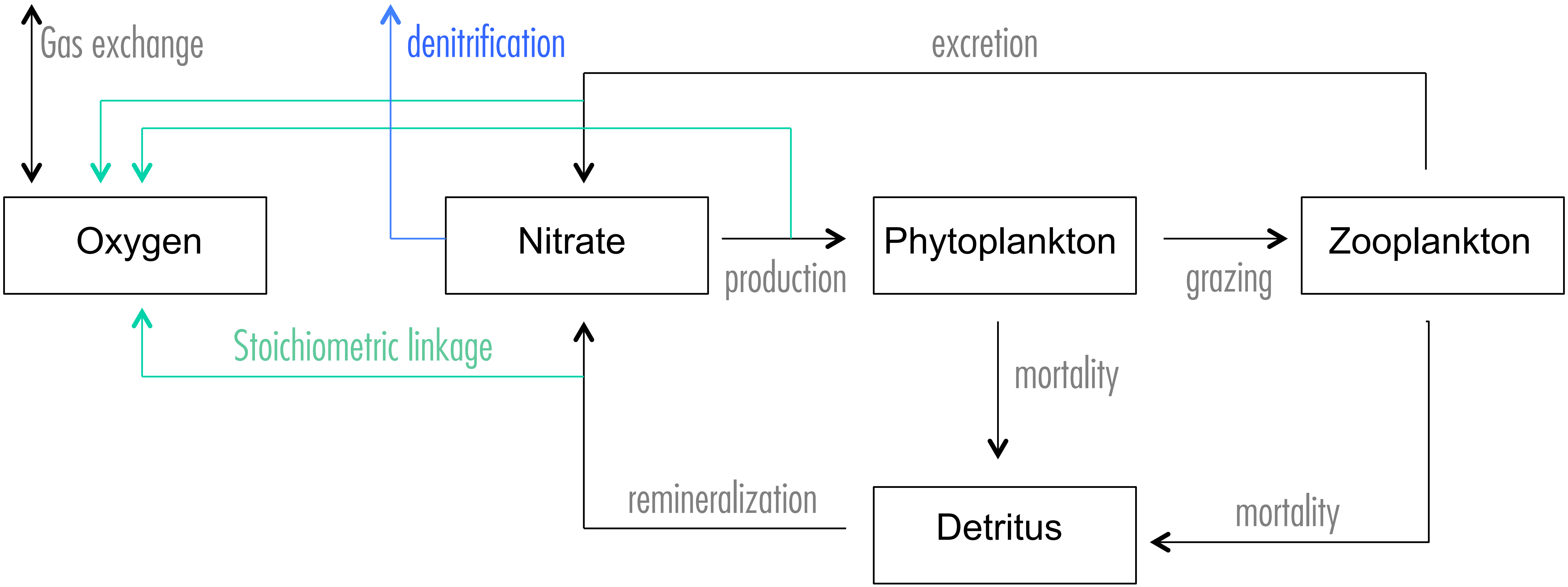
Run on NYUAD Butinah cluster

Arabian Sea Bathymetry

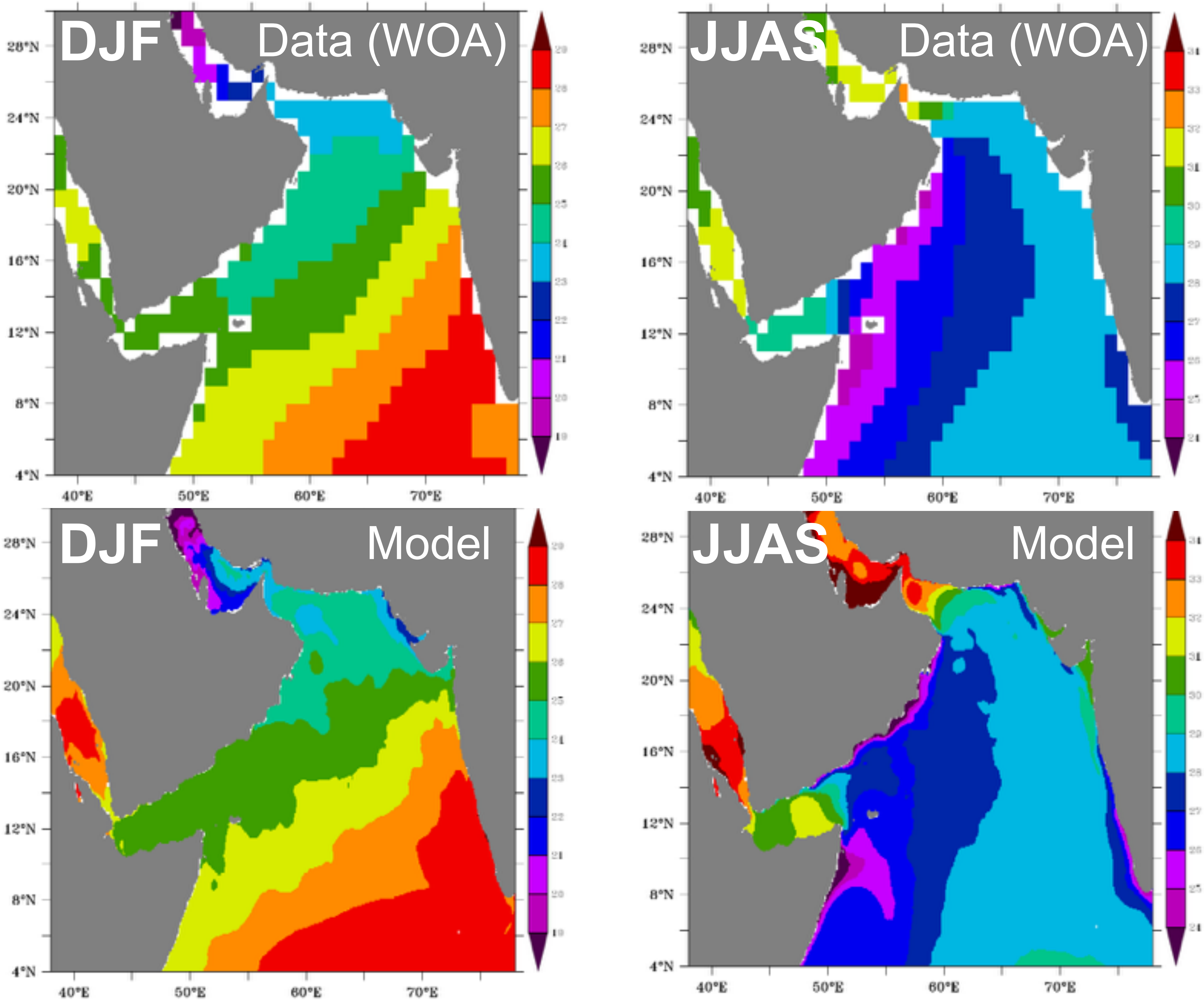


(Simple) biogeochemistry model

NPZD + O_2 + Denitrification

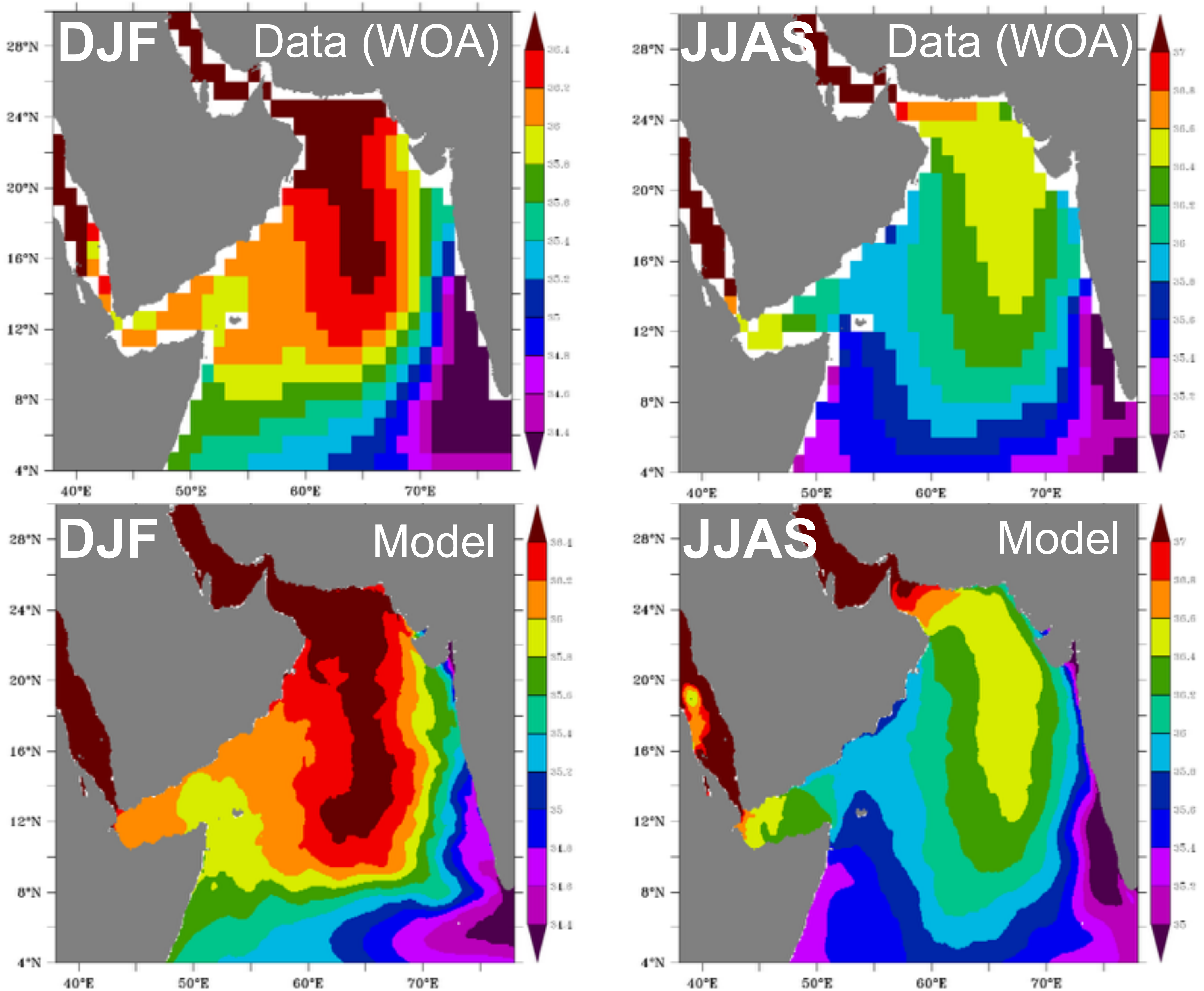


Model vs. observations: surface temperature



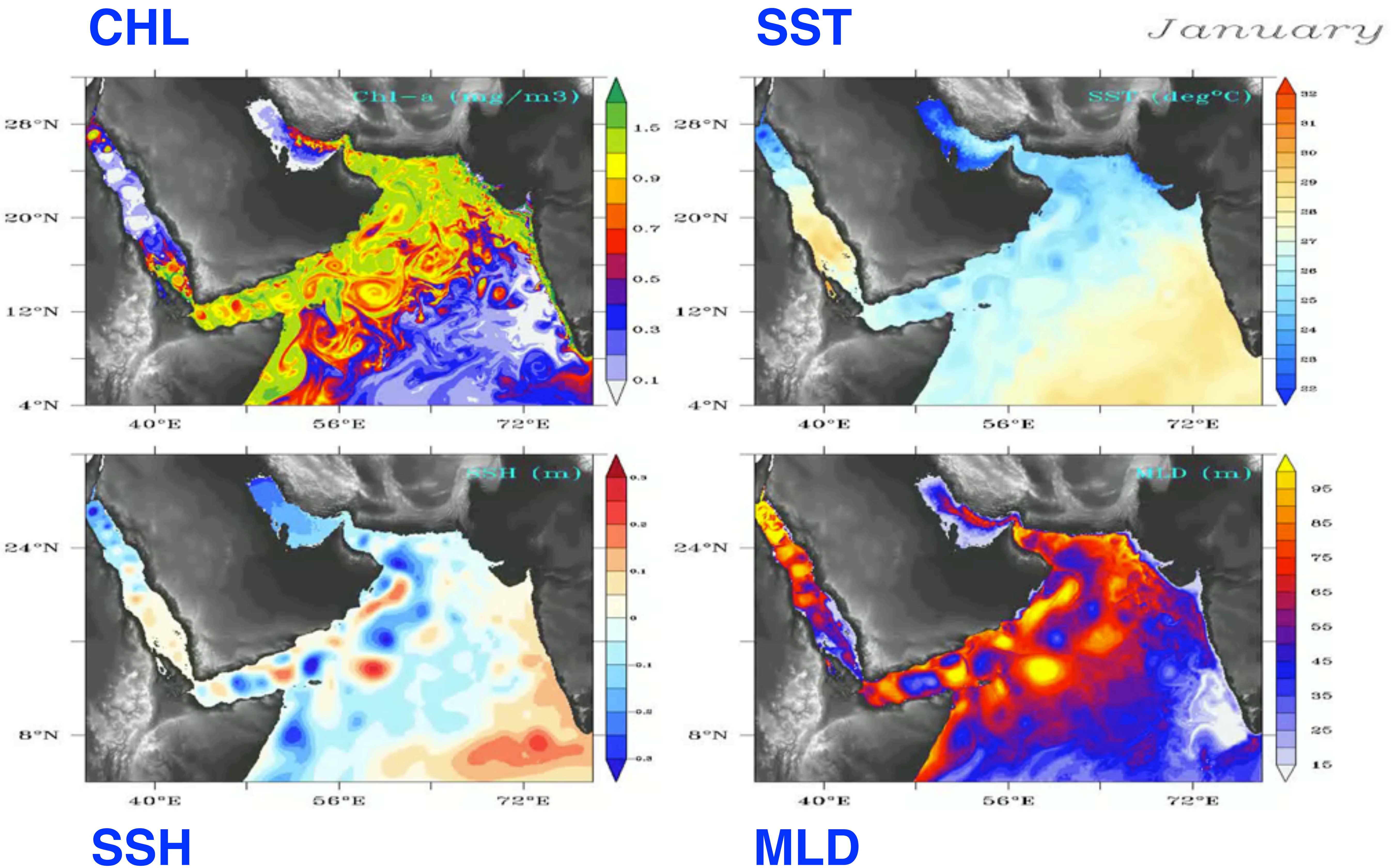
1/12º

Model vs. observations: surface salinity

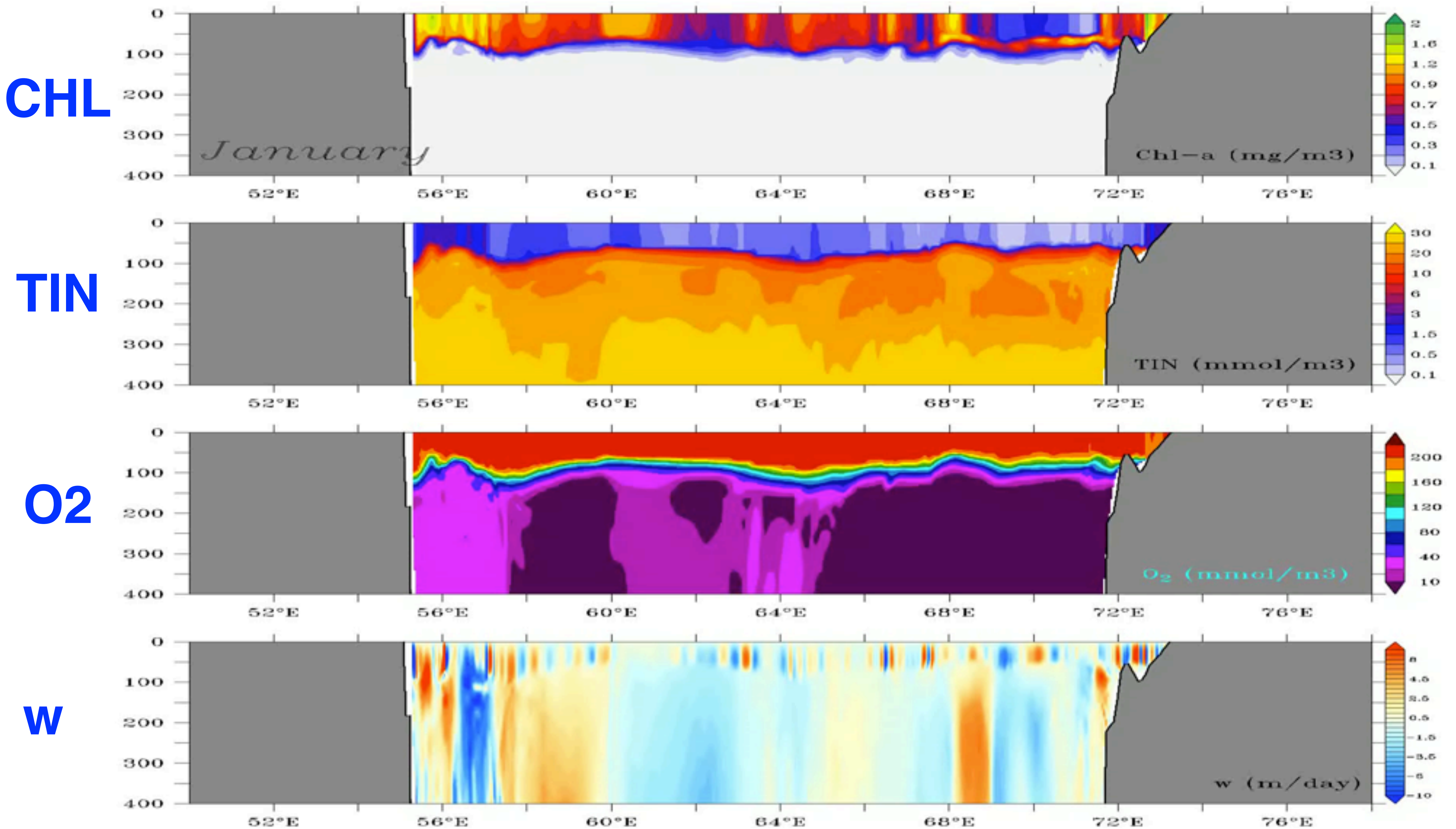


1/12º

Model fields (1/24°) — surface



Model fields (1/24°) — sections at 17N

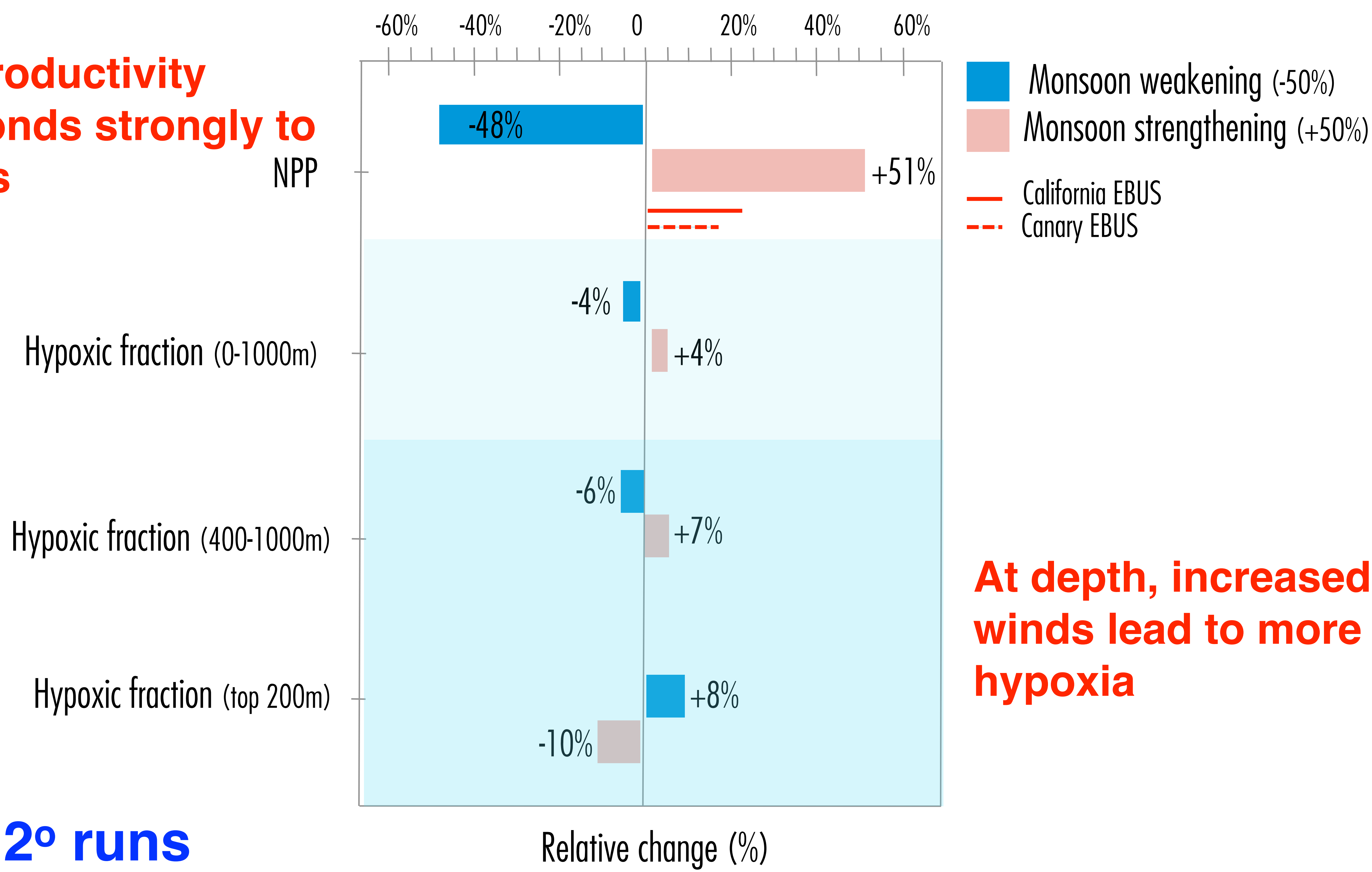


What happens when winds are reduced or increased?

Biogeochemical response to changes in monsoon intensity

Production: scales linearly with perturbation
Hypoxic volume: smaller response

AS productivity responds strongly to winds

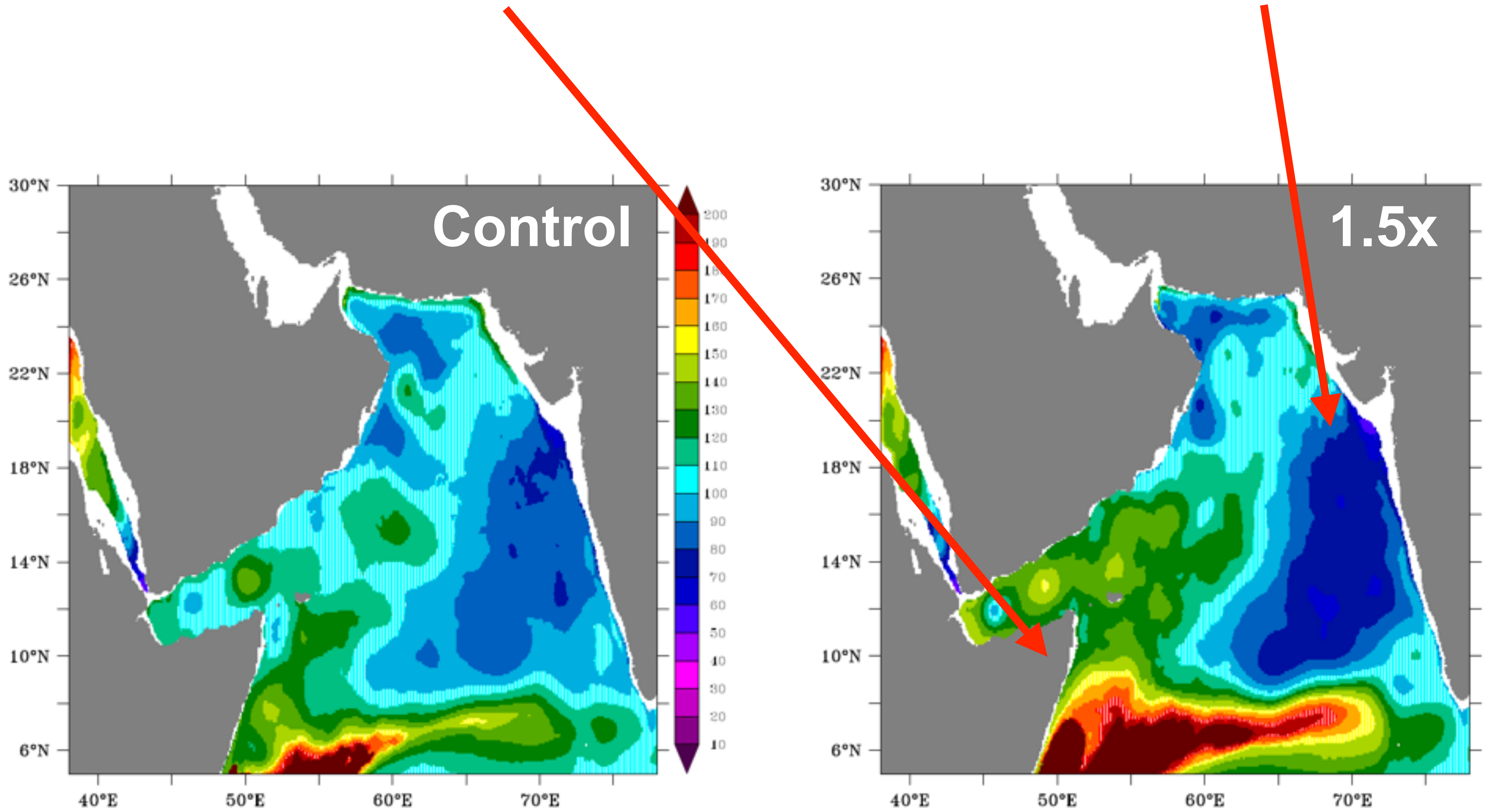


At depth, increased winds lead to more hypoxia

1/12º runs

Depth of hypoxic boundary with increased winds

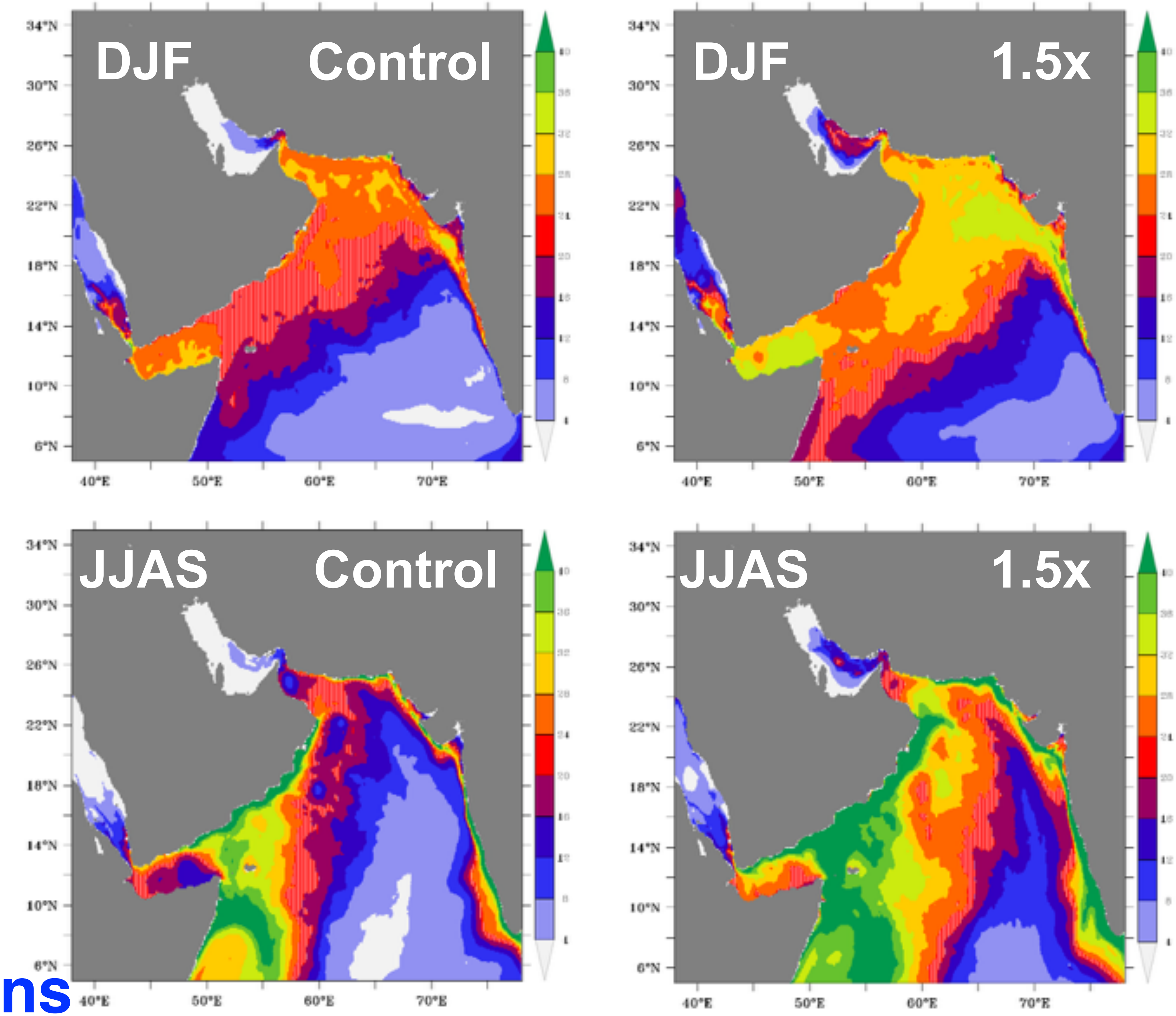
Deepening in western AS and shoaling of hypoxia in eastern AS



1/12º runs

New primary production with increased winds

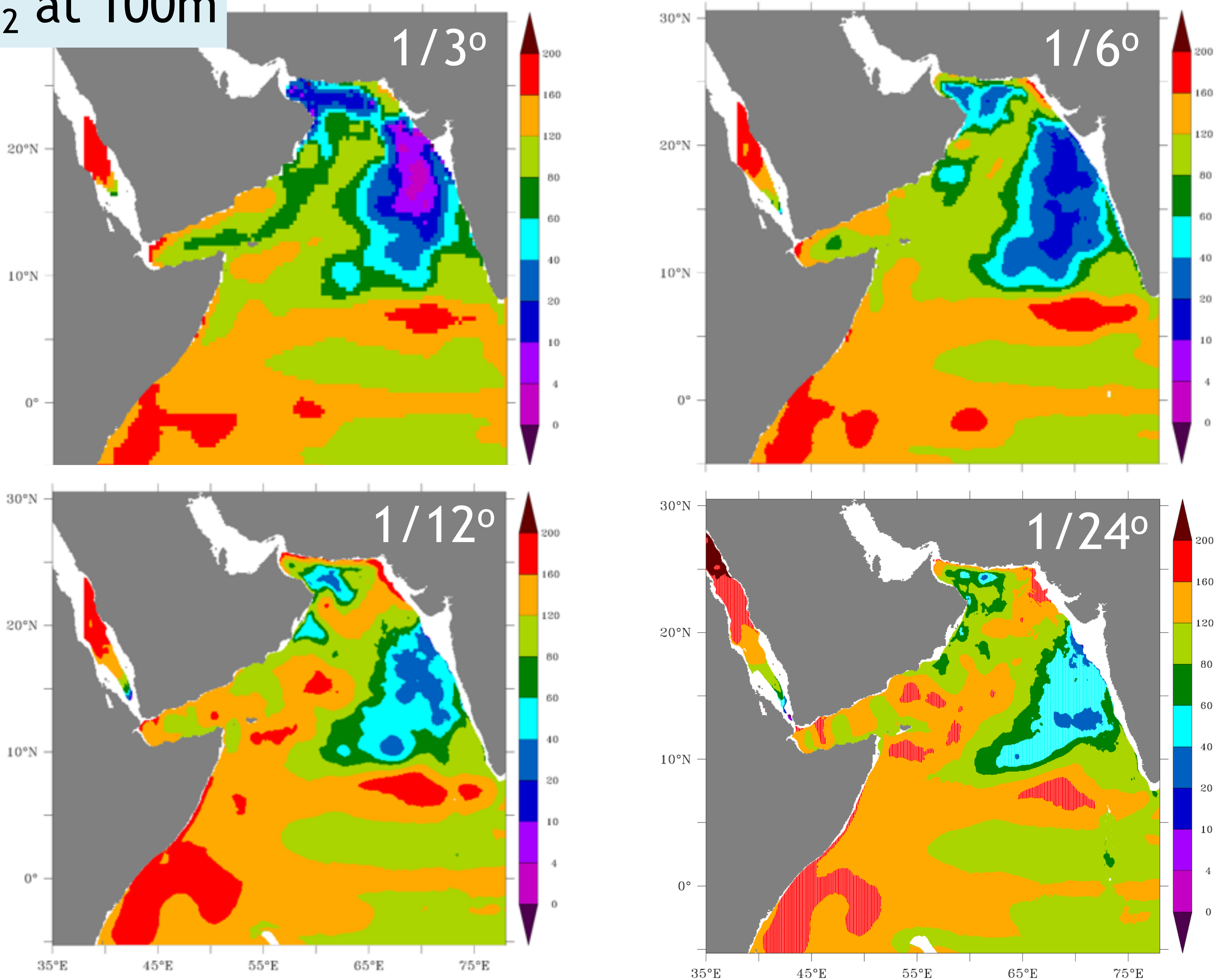
Scales linearly with wind perturbation (intensification of upwelling)



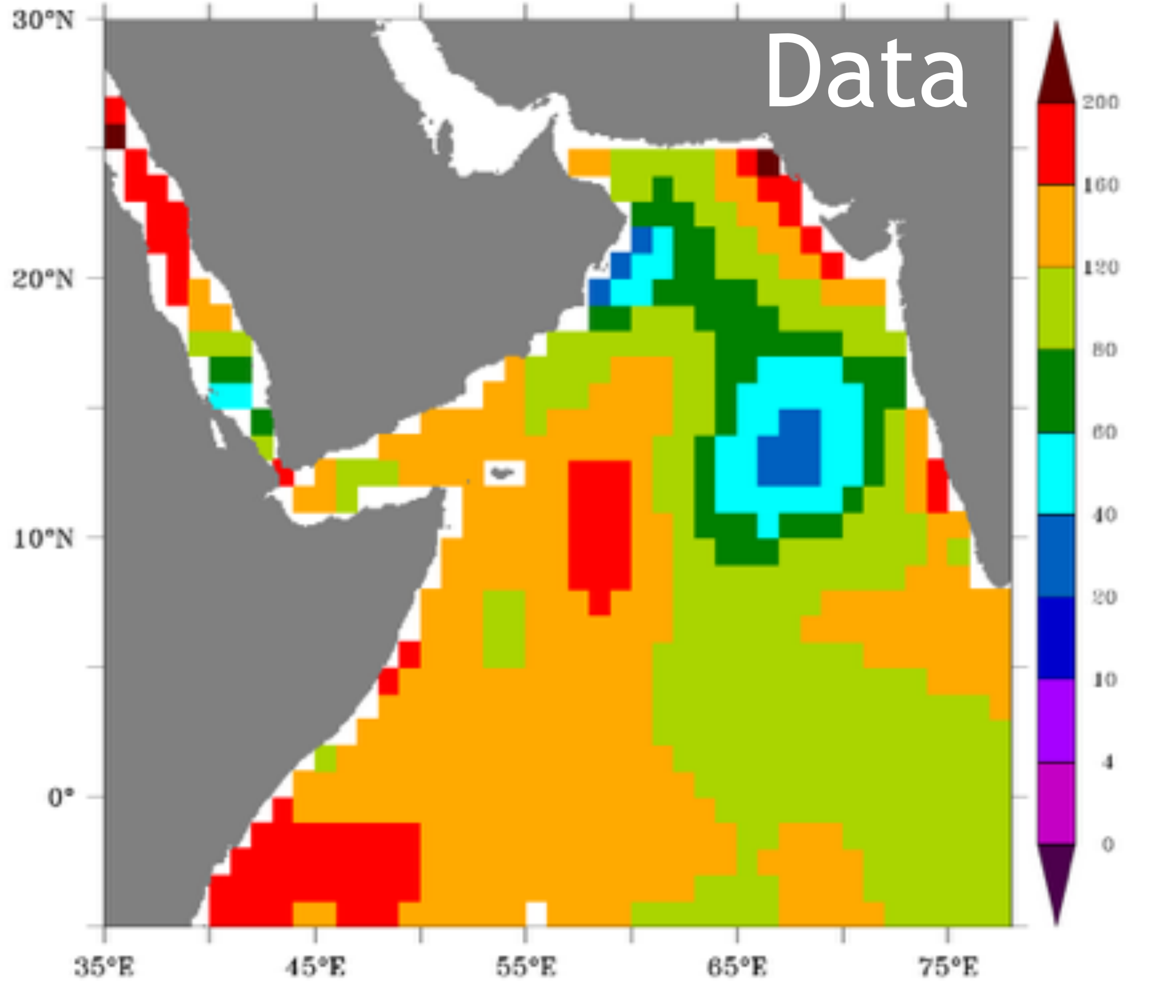
1/12º runs

What happens when resolution is systematically increased?

O_2 at 100m


1/3°
1/6°
1/12°
1/24°
200
160
120
80
60
40
20
10
4
0
30°N
20°N
10°N
0°
35°E
45°E
55°E
65°E
75°E

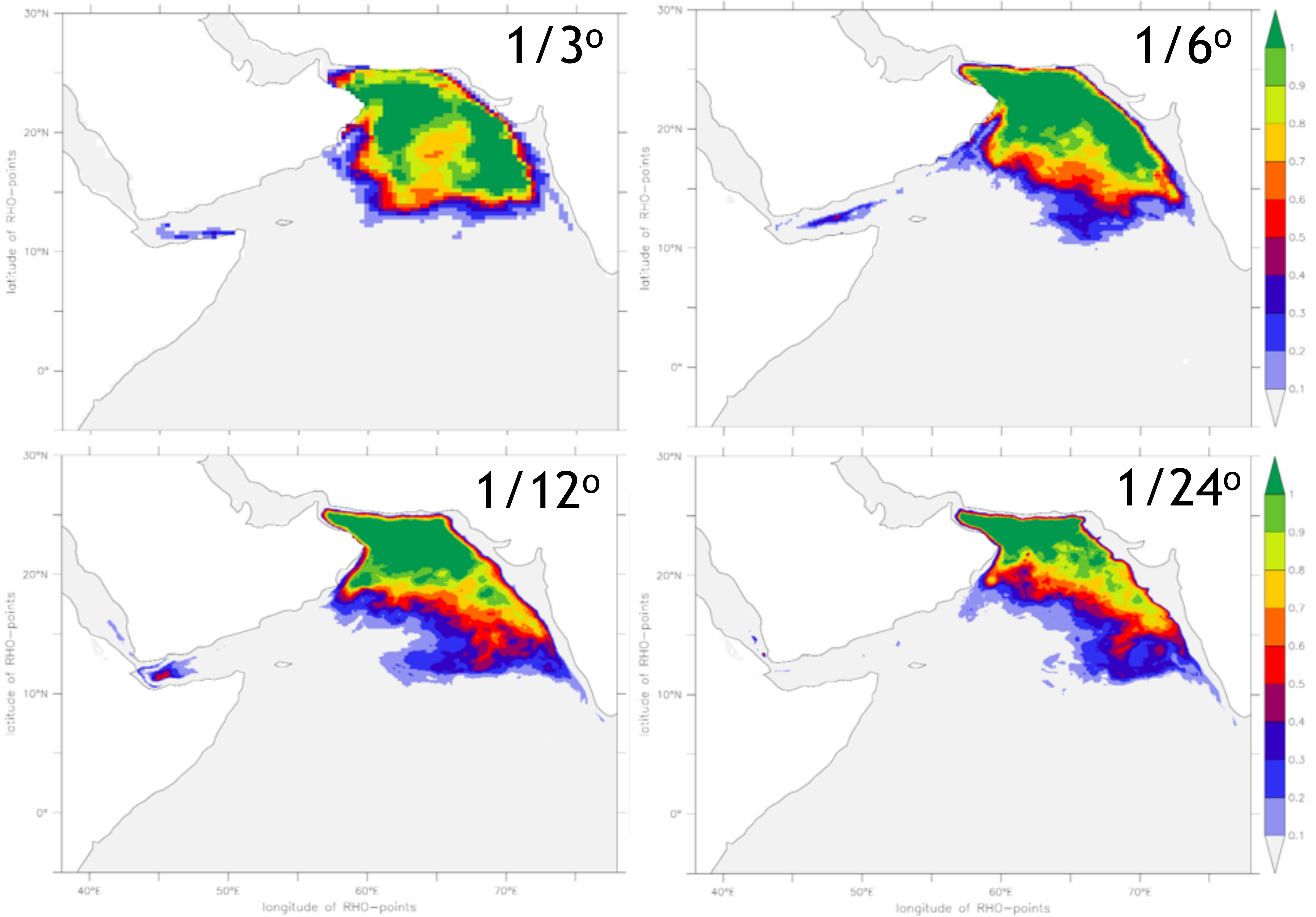
O_2 at 100m



Data
30°N
20°N
10°N
0°
35°E
45°E
55°E
65°E
75°E
200
160
120
80
60
40
20
10
4
0

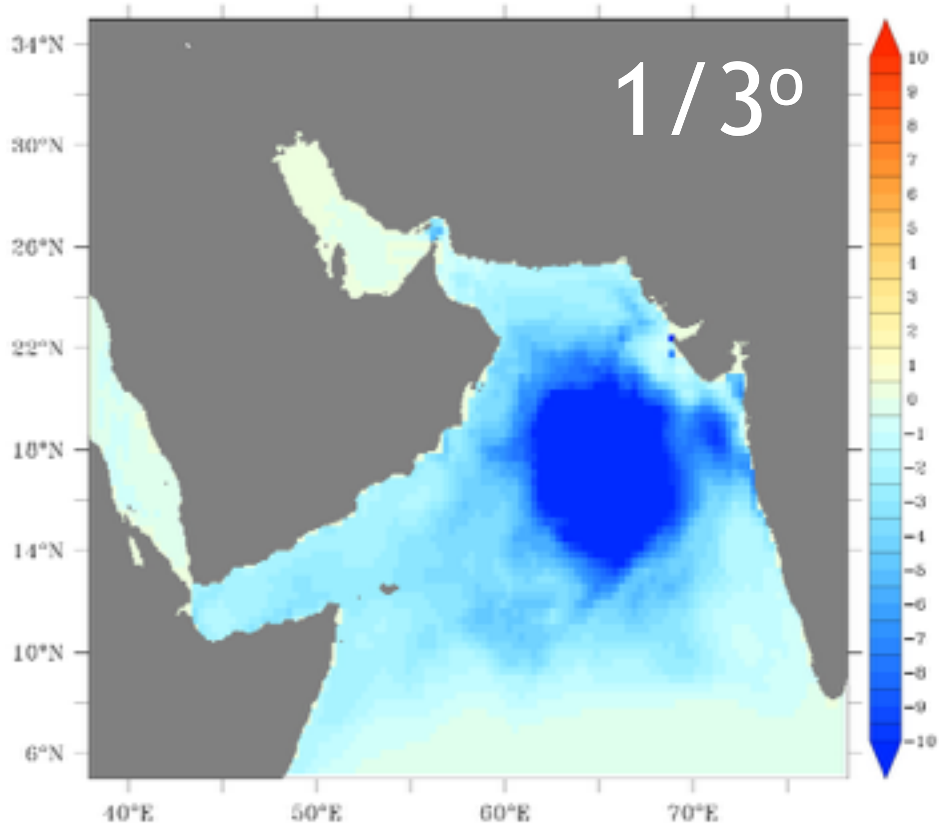
Denitrifcation rate (mol N m^2 yr^{-1})

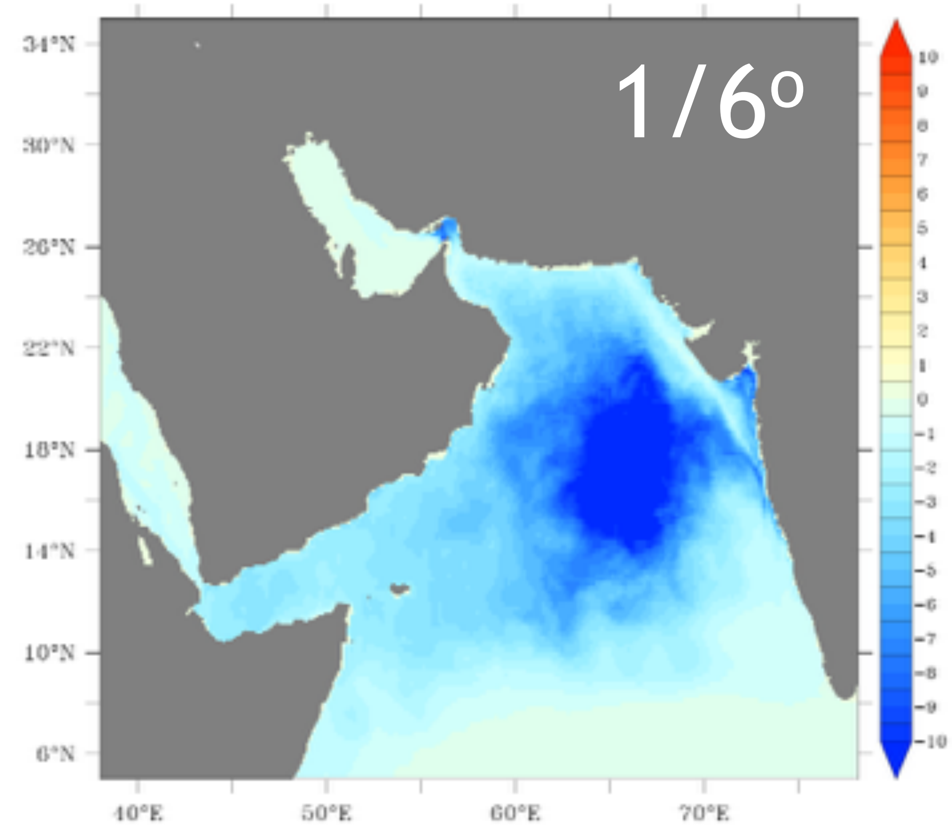
N^2PZD^2

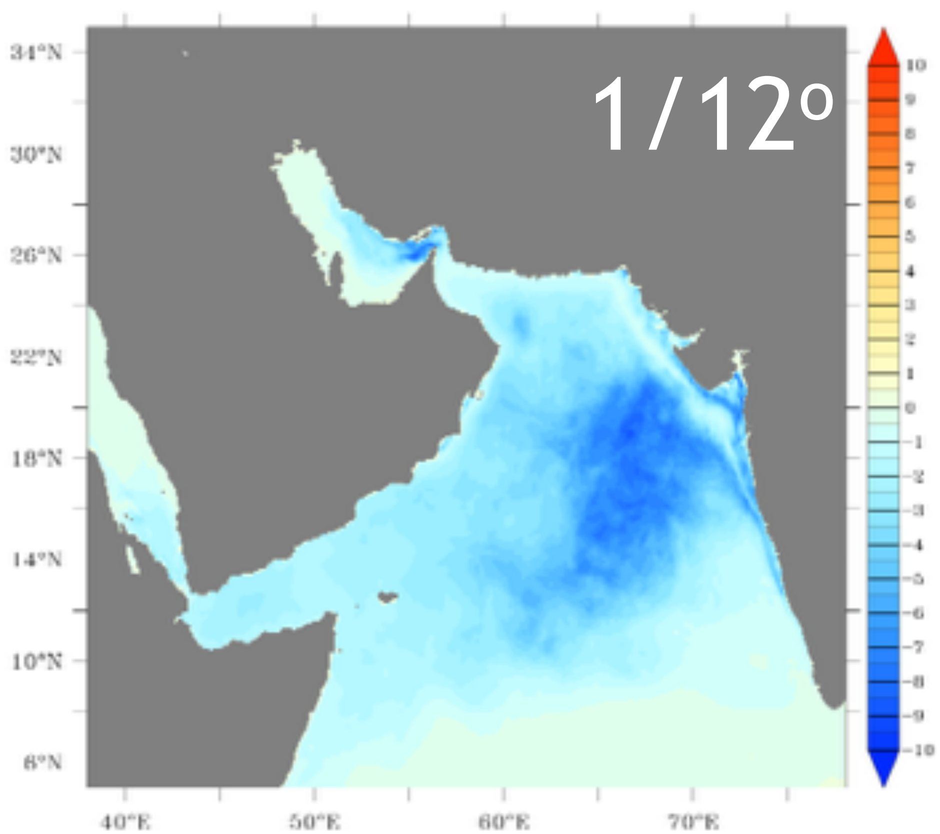


Denitrifcation induced NPP reduction (mol C m^2 yr^{-1})

N^2PZD^2







Difference in PP between simulations with O_2 and NO_3 coupled and uncoupled. With nitrate decoupled, denitrification cannot reduce PP. Moreover, because it's effect is bigger at low resolution there's a bigger decrease at low resolution

Changes to PP and O_2 with increased resolution

In addition to changes in denitrification, increasing resolution from $1/3^o$ to $1/12^o$:

- Moves OMZ downward but volume doesn't increase
- Increases PP monotonically

Increasing resolution from $1/12^o$ to $1/24^o$:

- Doesn't change PP
- Decreases volume of OMZ

No slides :(

Implications

Increasing resolution from $1/3^{o}$ to $1/12^{o}$:

- Ventilation increases with resolution, decreasing denitrification, thus increasing PP
- … but the increased respiration and increased ventilation compensate in their effect on oxygen, so there's no change in total OMZ volume.

Increasing resolution from $1/12^{o}$ to $1/24^{o}$:

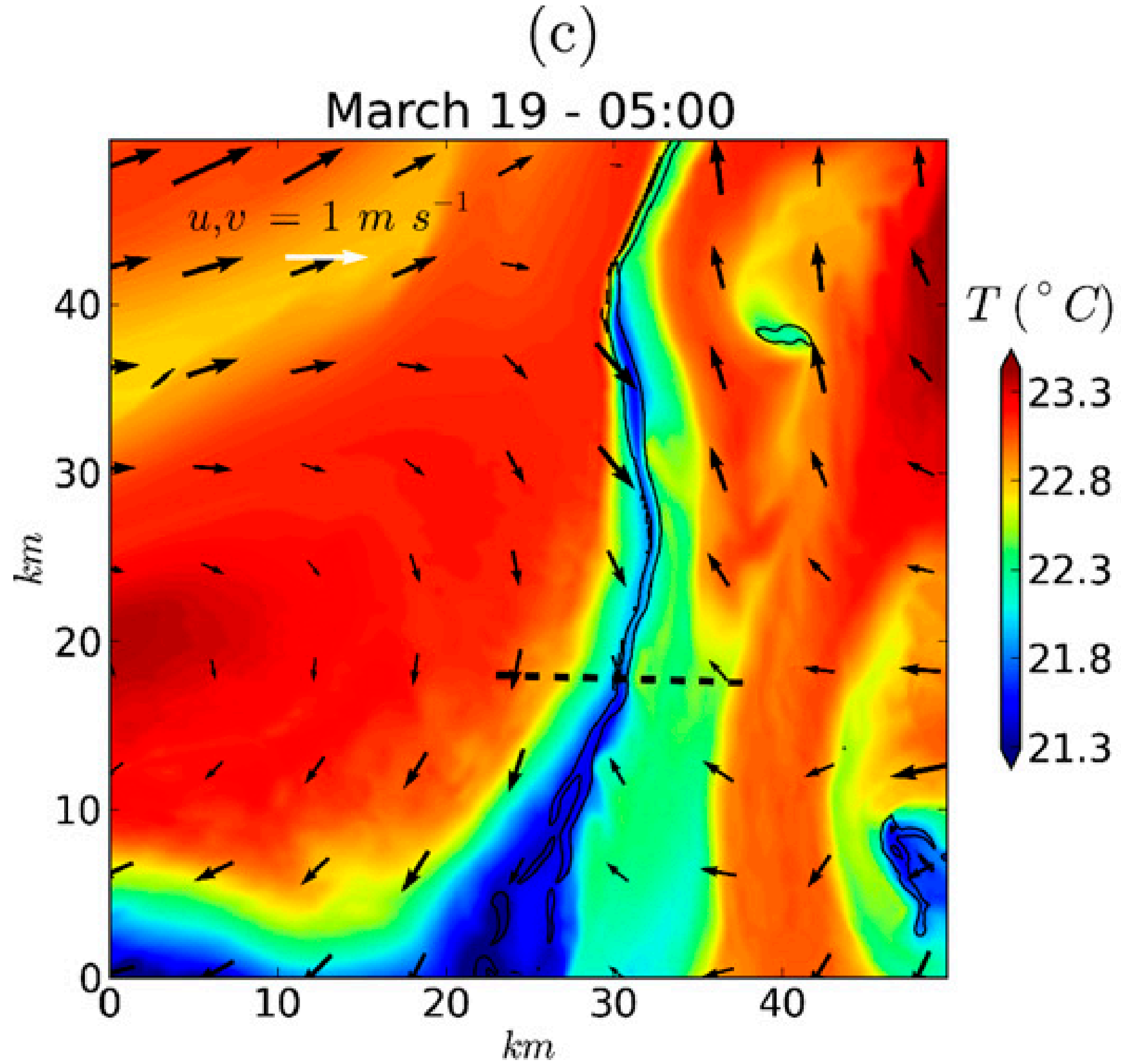
- As submesoscales start to be resolved, something changes: PP does not increase, and the OMZ decreases. We are trying to understand why.

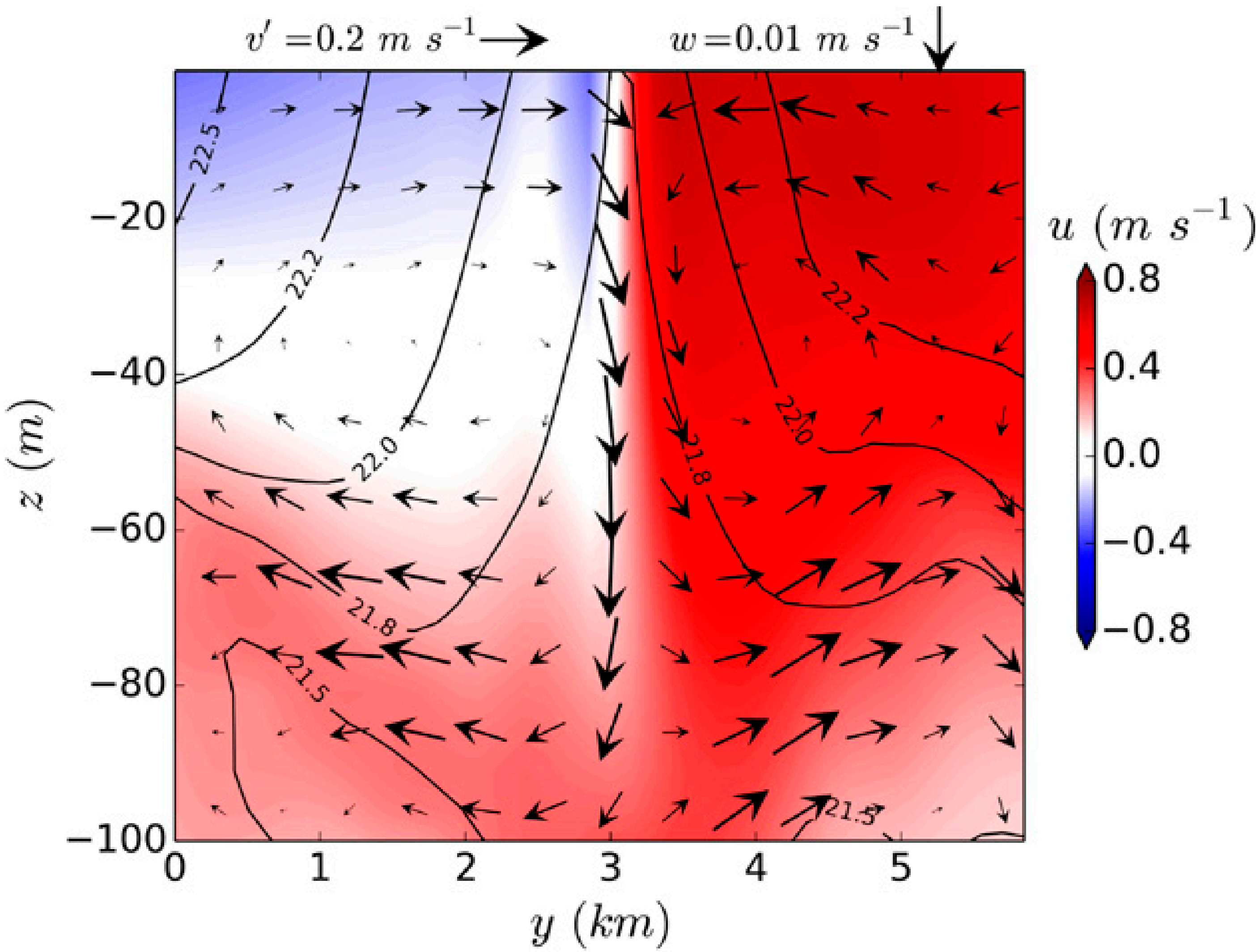
Hypotheses

1. As submesoscales are resolved, the active mixING layer increases in depth, and exceeds the depth of the euphotic zone, which decreases the net PP.
2. An asymmetry in the submesoscale vertical fluxes* allows ventilation to increase without a corresponding increase in the flux of nitrate to the surface layers, even though there's more nitrate at depth b/c of decreased denitrification.

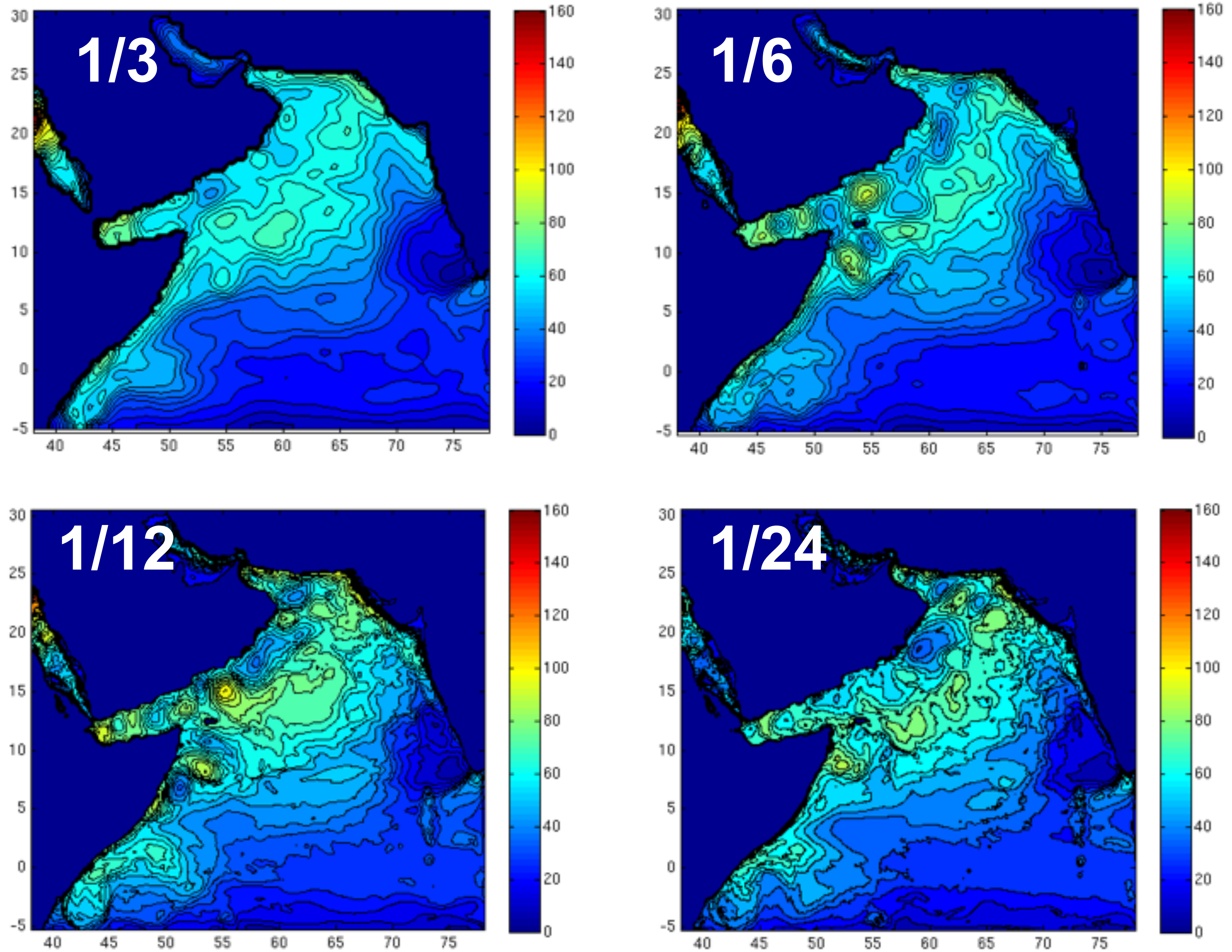
* This is perhaps consistent with Gula et al. (2014): cold filaments, with strong downward ageostrophic vertical velocities and diapycnal mixing, are more common than warm filaments.
See also Hakim et al. (2001) and Lapeyre et al. (2006)

Gula, Molemaker & McWilliams (2014 JPO)



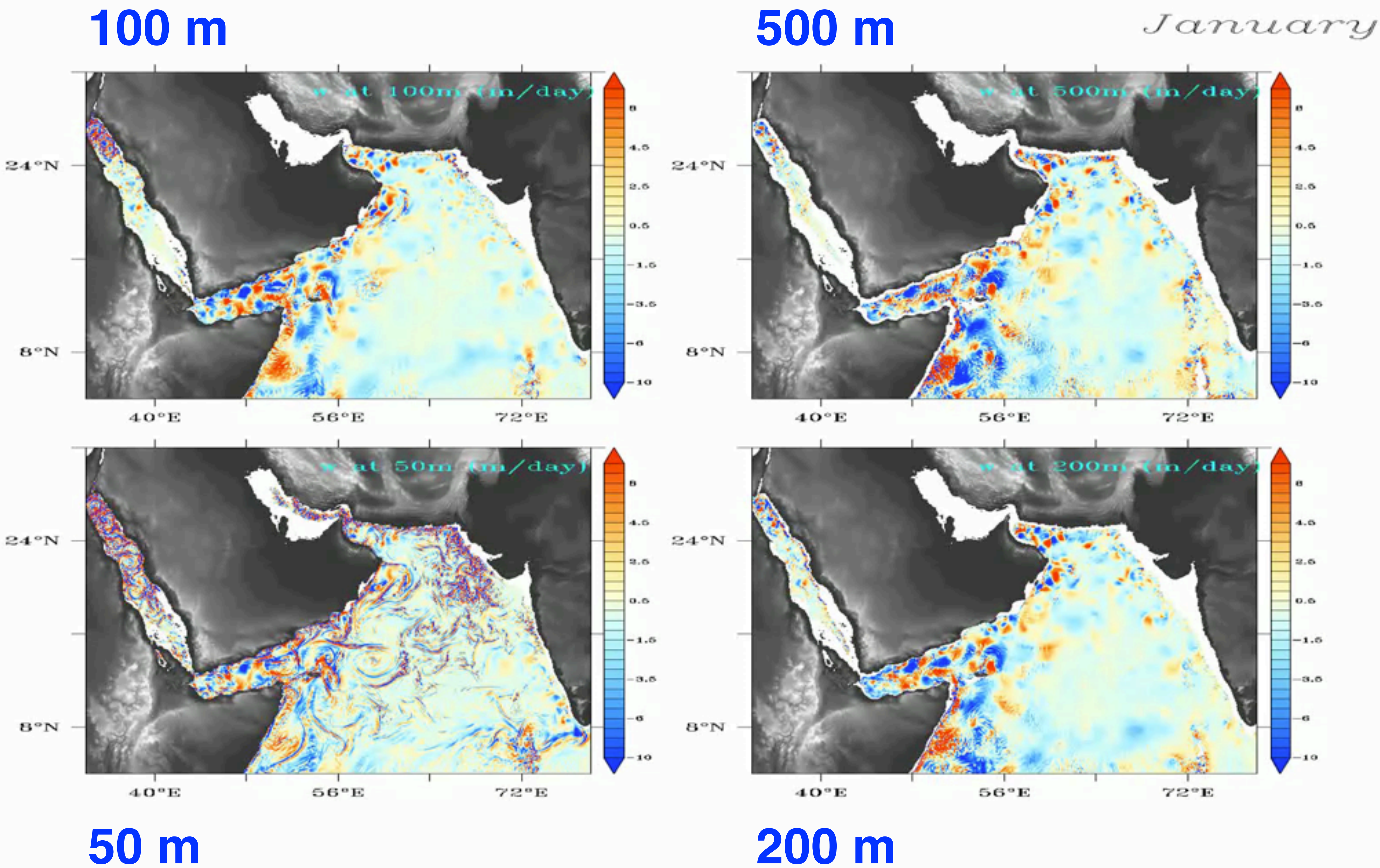


MixING layer depths



MLD deepens as resolution increases, then shallows at highest resolution: submesoscale restratification?

Vertical velocities (1/24°)



Histogram of <w'O_2'> at 200m