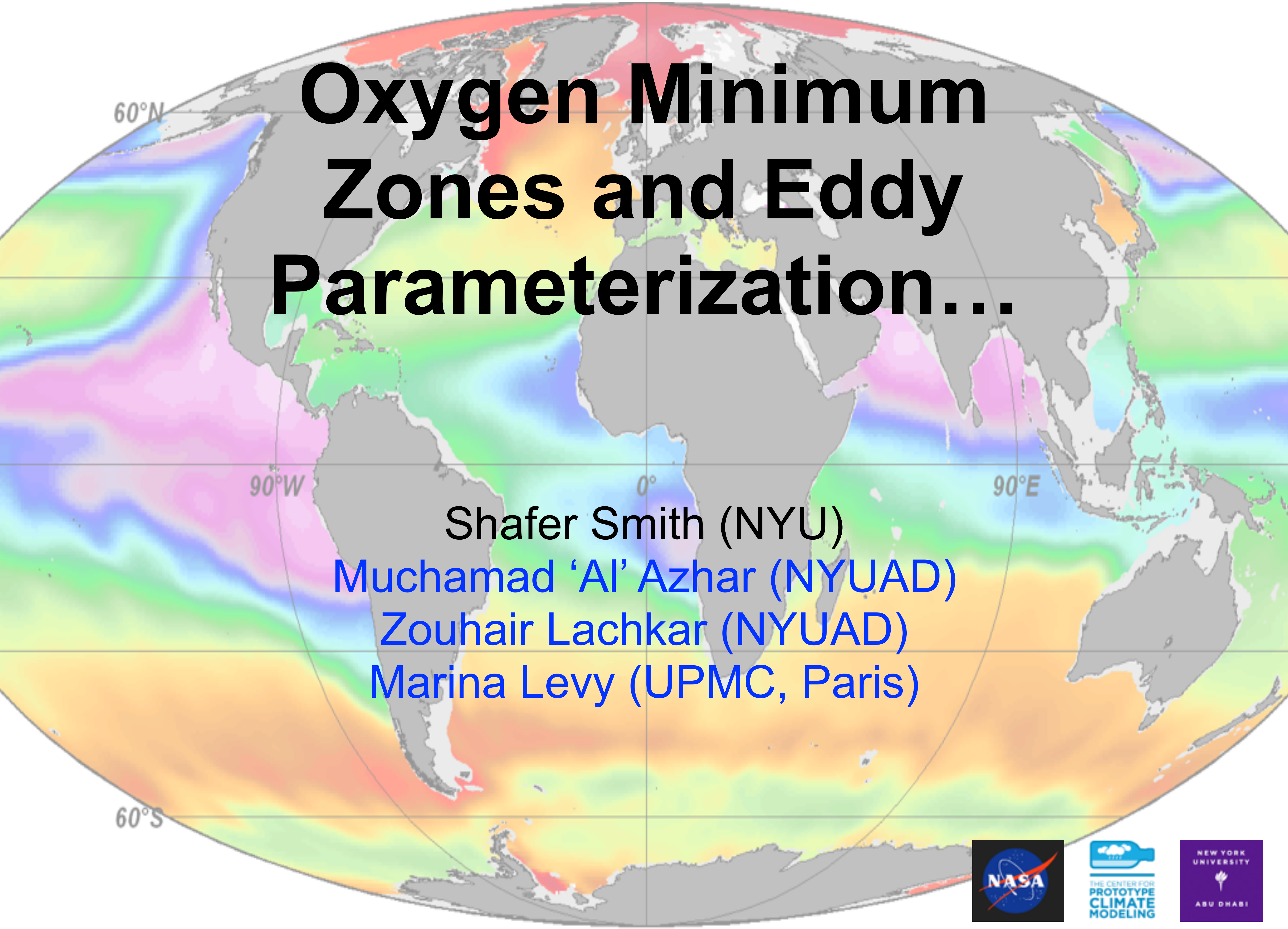


Oxygen Minimum Zones and Eddy Parameterization…

Shafer Smith (NYU)
Muchamad 'Al' Azhar (NYUAD)
Zouhair Lachkar (NYUAD)
Marina Levy (UPMC, Paris)

THE CENTER FOR
PROTOTYPE
CLIMATE
MODELING


Zouhair Lachkar


M. Al Azhar


Marina Levy

Outline

- Oceanic oxygen: How biology and physics compete to set subsurface oxygen levels and oxygen minimum zones (OMZs)

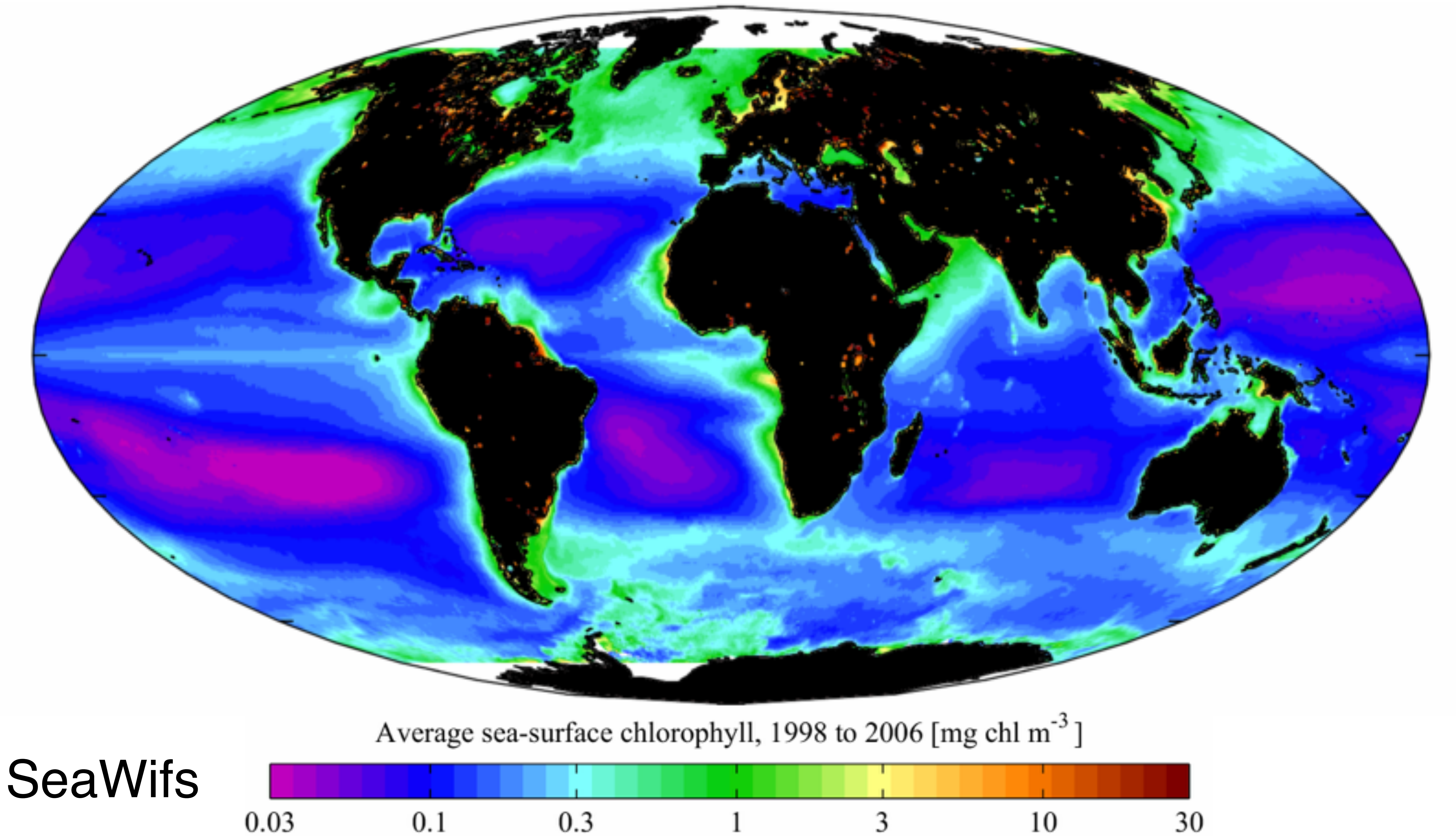
- The importance of the Arabian Sea OMZ, and how eddies influence it

- Parameterized oxygen fluxes in climate models generally too small

- Revisiting the eddy parameterization problem, suggesting a modest change to improve parameterized BGC tracer fluxes

Annual mean surface chlorophyll

Phytoplankton at the base of the food chain



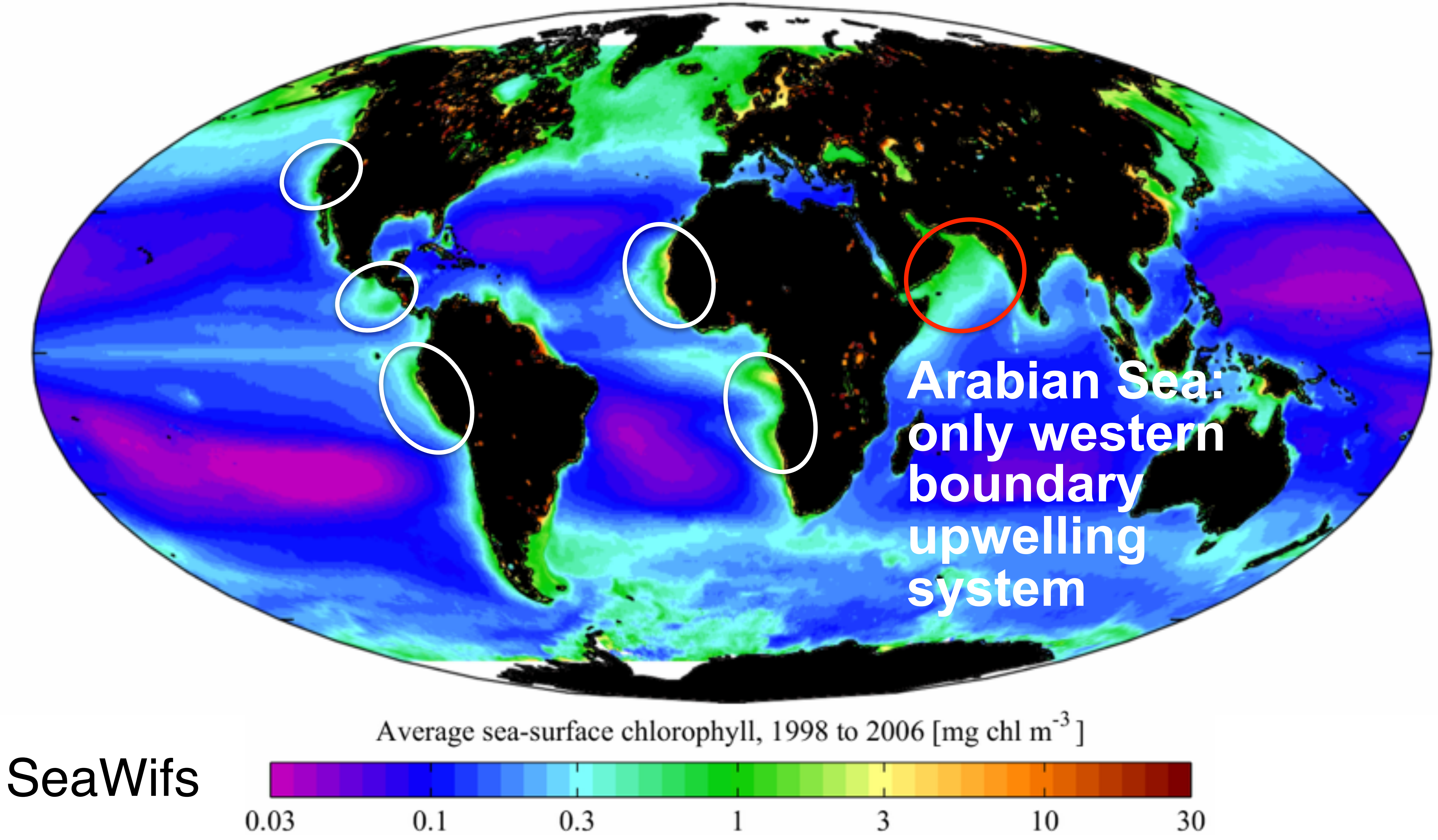
Average sea-surface chlorophyll, 1998 to 2006 [mg chl m^{-3}]

SeaWifs

Annual mean surface chlorophyll

Phytoplankton at the base of the food chain

— much produced in coastal upwelling systems



Arabian Sea: only western boundary upwelling system

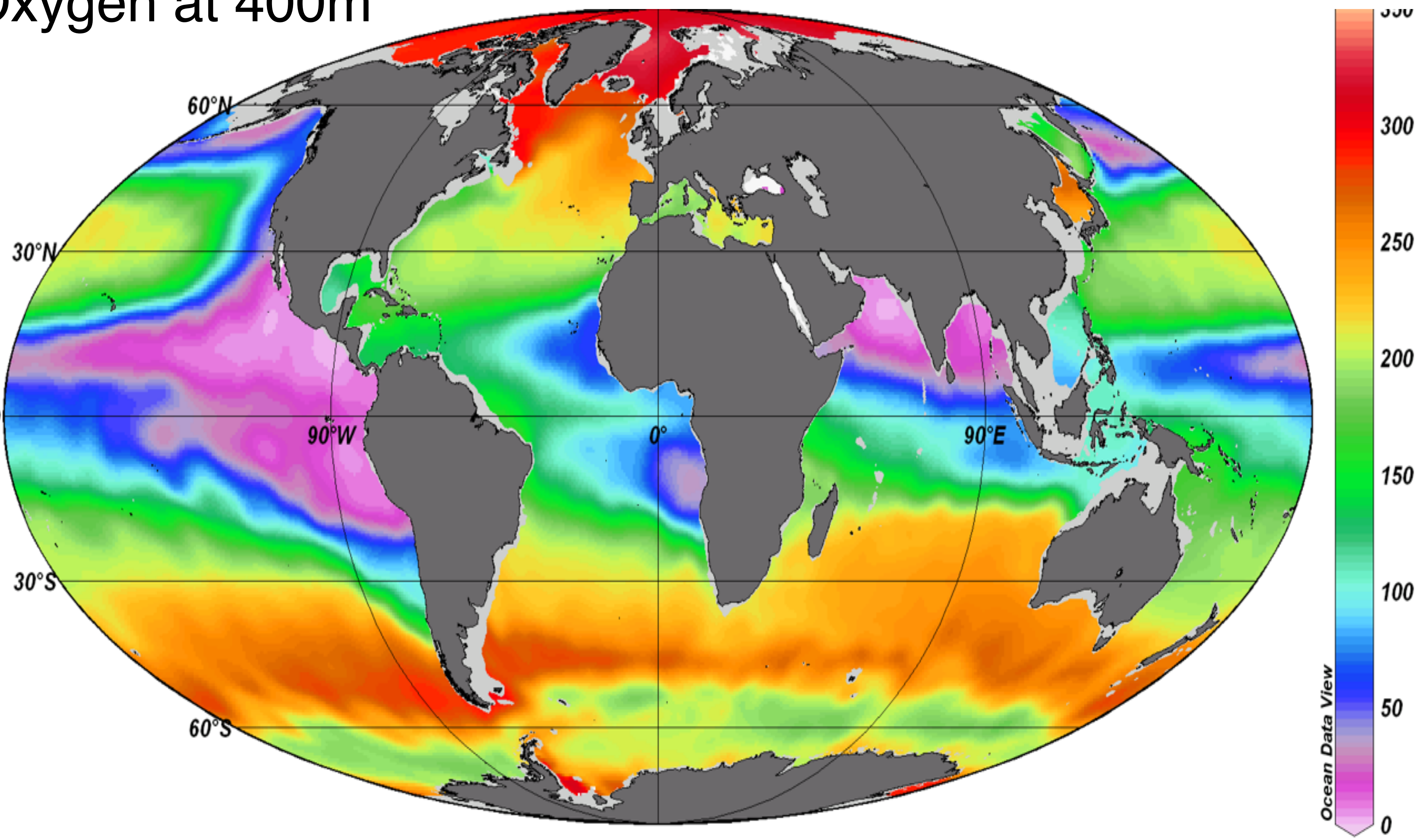
SeaWifs

Oxygen Minimum Zones (OMZs)

… mostly at eastern boundaries

Oxygen at 400m

(µmol/L)



WOA 2009

Oxygen Minimum Zones (OMZs)

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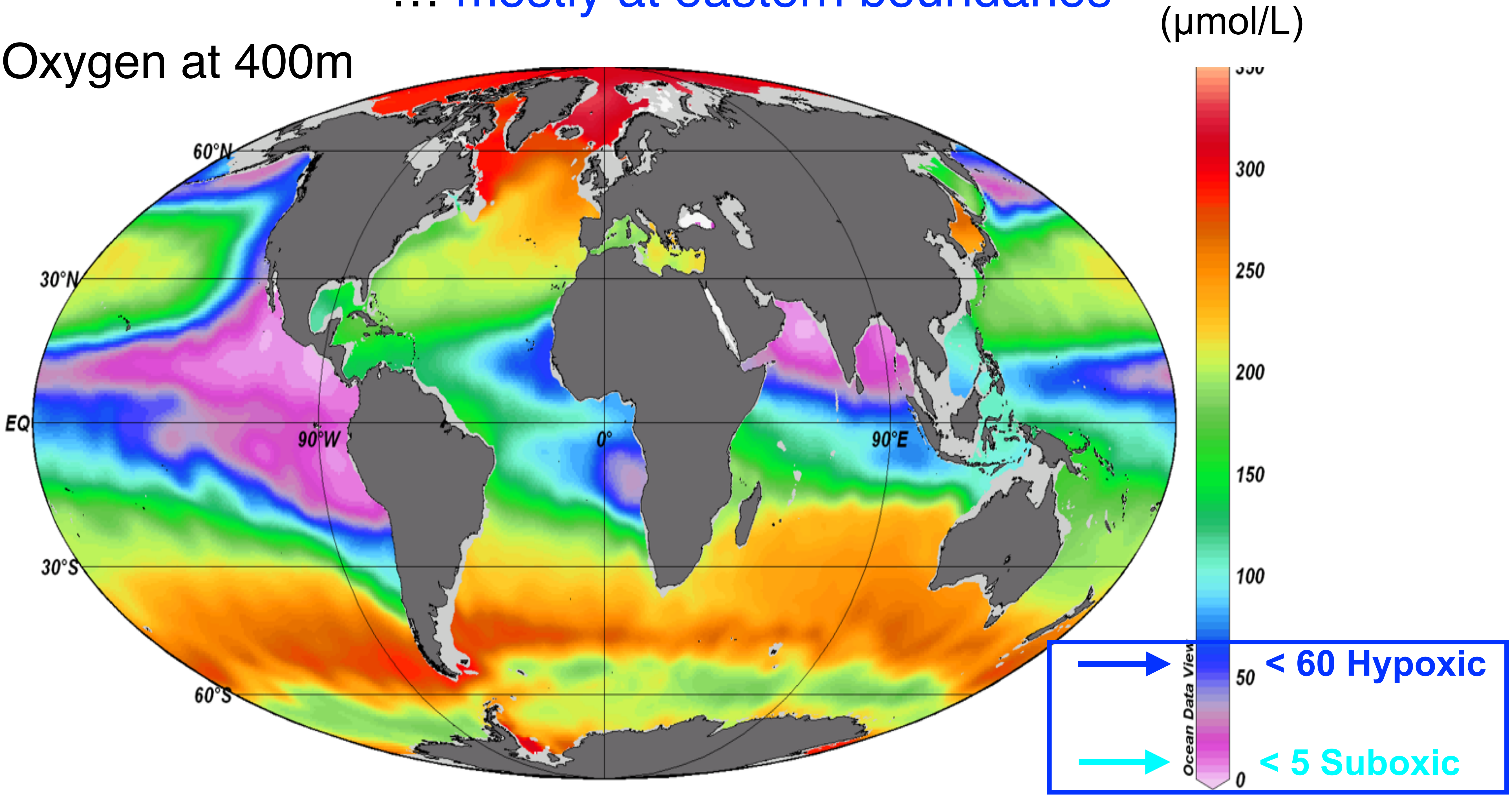


< 60 Hypoxic

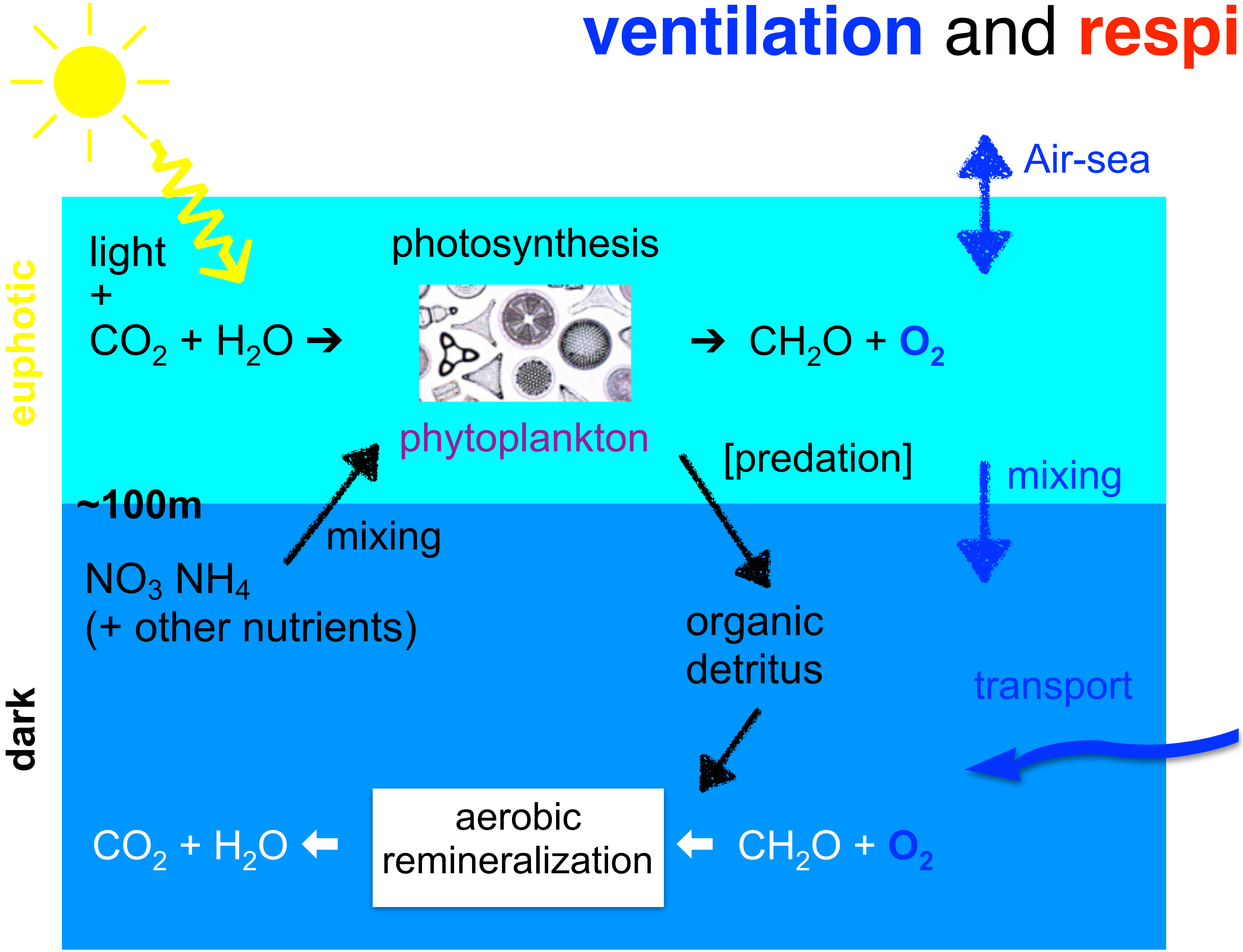
< 5 Suboxic

Hypoxic: lethal for many species

Suboxic: denitrification

WOA 2009

Oxygen at depth set by competition between **ventilation** and **respiration**



Air-sea

euphotic

light

+

$CO_2 + H_2O$ ➔

photosynthesis

➔ CH_2O + **O_2**

phytoplankton

[predation]

mixing

~100m

mixing

NO_3 NH_4

(+ other nutrients)

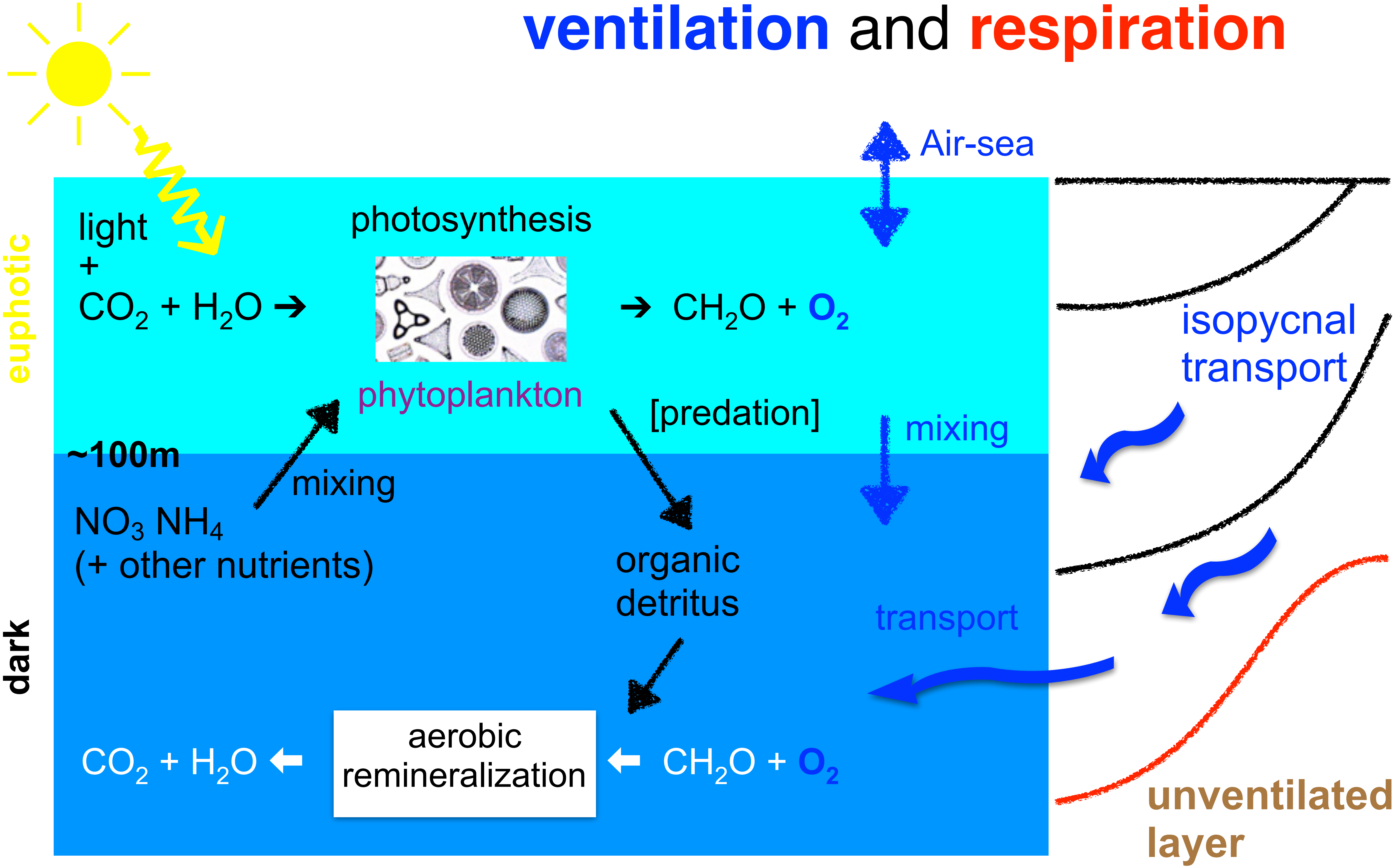
organic detritus

transport

dark

$CO_2 + H_2O$ ⬅ aerobic remineralization ⬅ CH_2O + **O_2**

Oxygen at depth set by competition between **ventilation** and **respiration**



euphotic

light
+
$CO_2 + H_2O$ ➔

photosynthesis

phytoplankton

➔ $CH_2O +$ **O_2**

Air-sea

[predation]

mixing

isopycnal
transport

~100m

mixing

NO_3 NH_4
(+ other nutrients)

organic
detritus

transport

dark

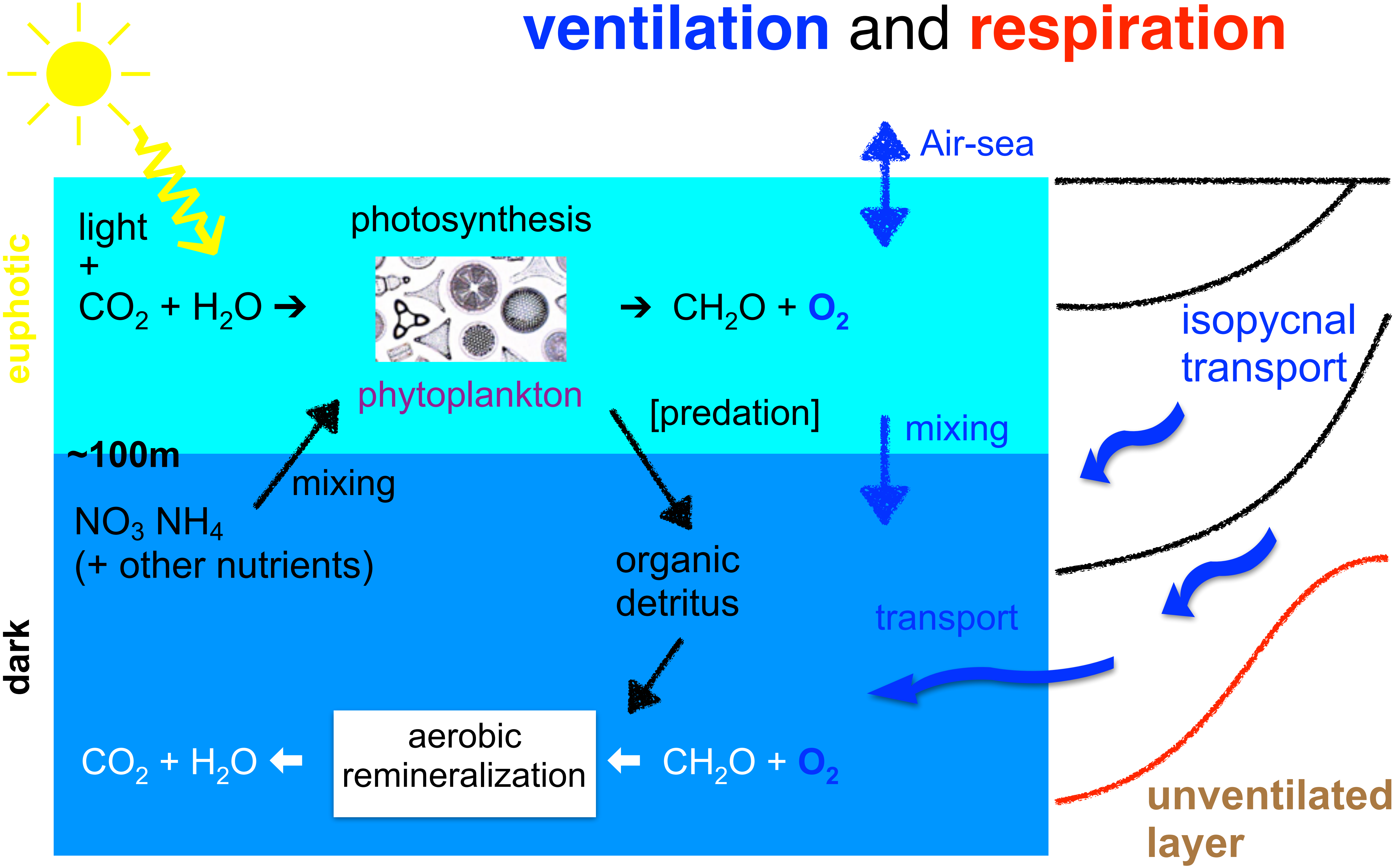
$CO_2 + H_2O$ ⬅

aerobic
remineralization

⬅ $CH_2O +$ **O_2**

**unventilated
layer**

Oxygen at depth set by competition between **ventilation** and **respiration**



euphotic

light + $CO_2 + H_2O$ ➔

photosynthesis

phytoplankton

➔ CH_2O + **O_2**

Air-sea

mixing

isopycnal transport

~100m

dark

mixing

NO_3 NH_4
(+ other nutrients)

[predation]

organic detritus

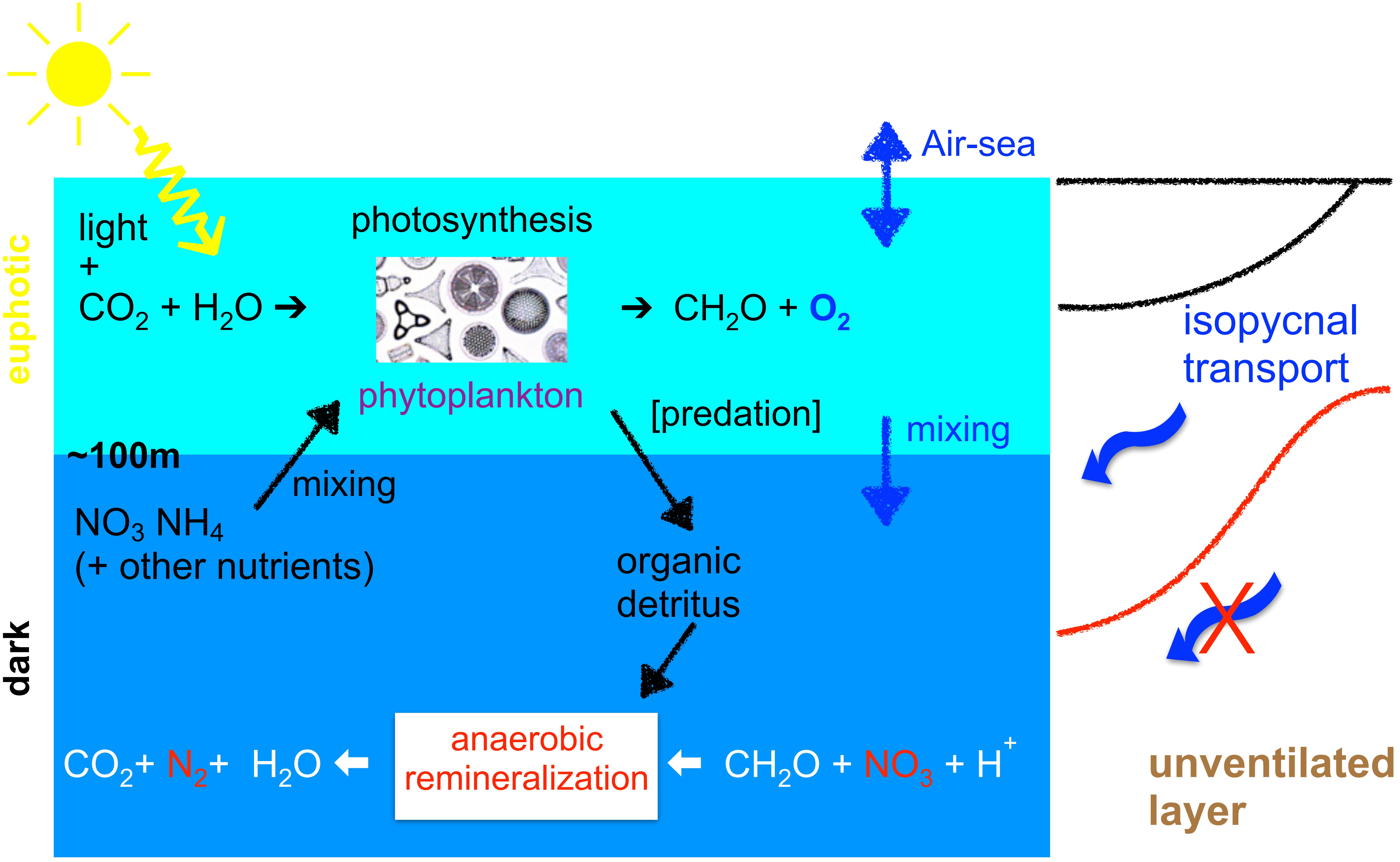
transport

$CO_2 + H_2O$ ⬅ aerobic remineralization ⬅ CH_2O + **O_2**

unventilated layer

Respiration << detrital flux << productivity << nutrient supply << mixing/transport

At suboxic levels, remineralization **denitrifies**

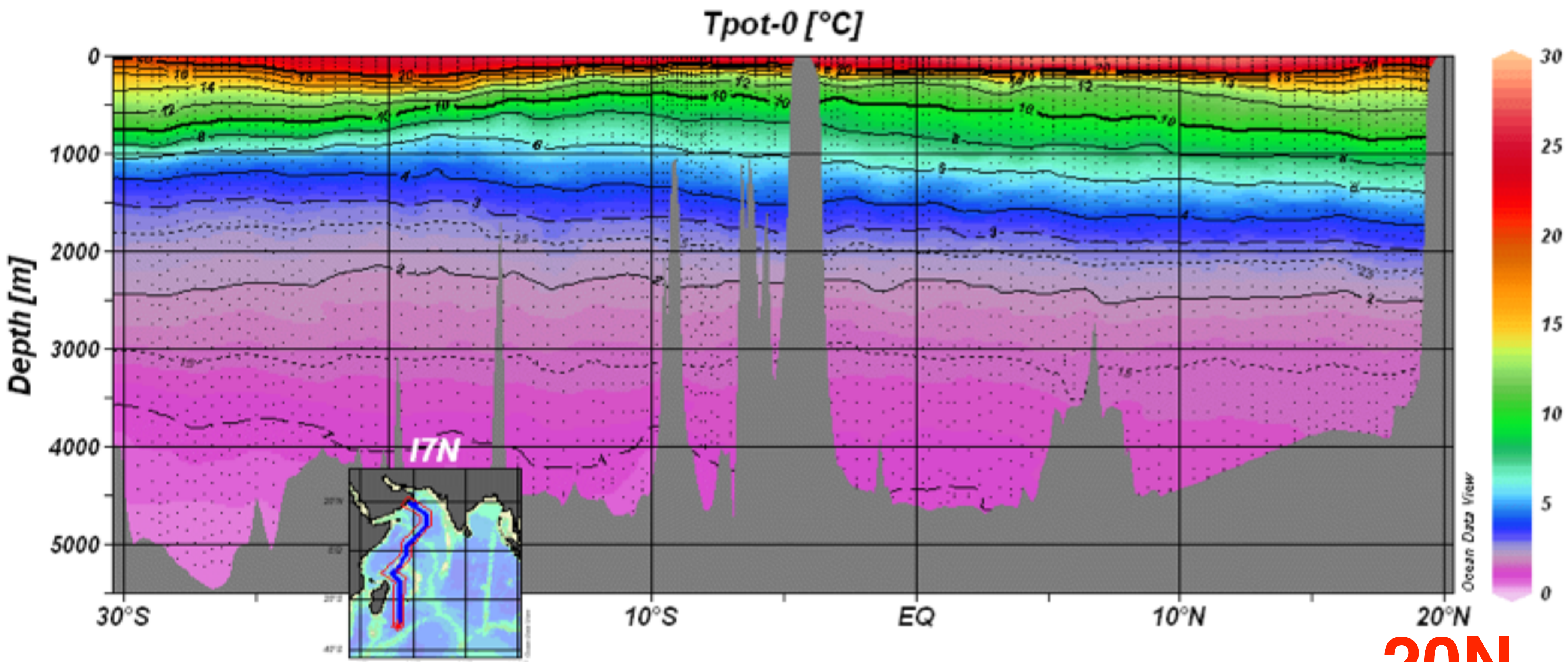


N_2 unavailable to most organisms

End result of nitrogen processes is release of N_2O: a strong greenhouse gas

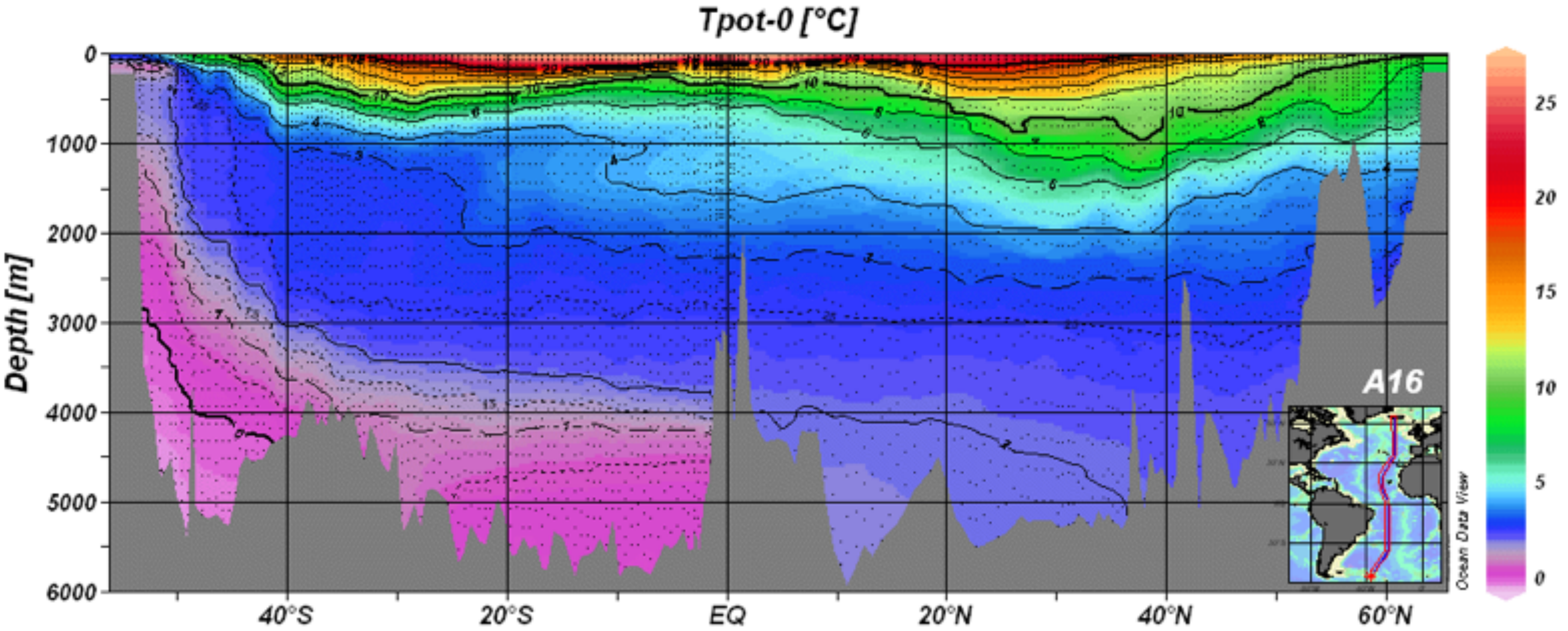
Indian Ocean: most isopycnals don't outcrop

Indian Ocean



20N

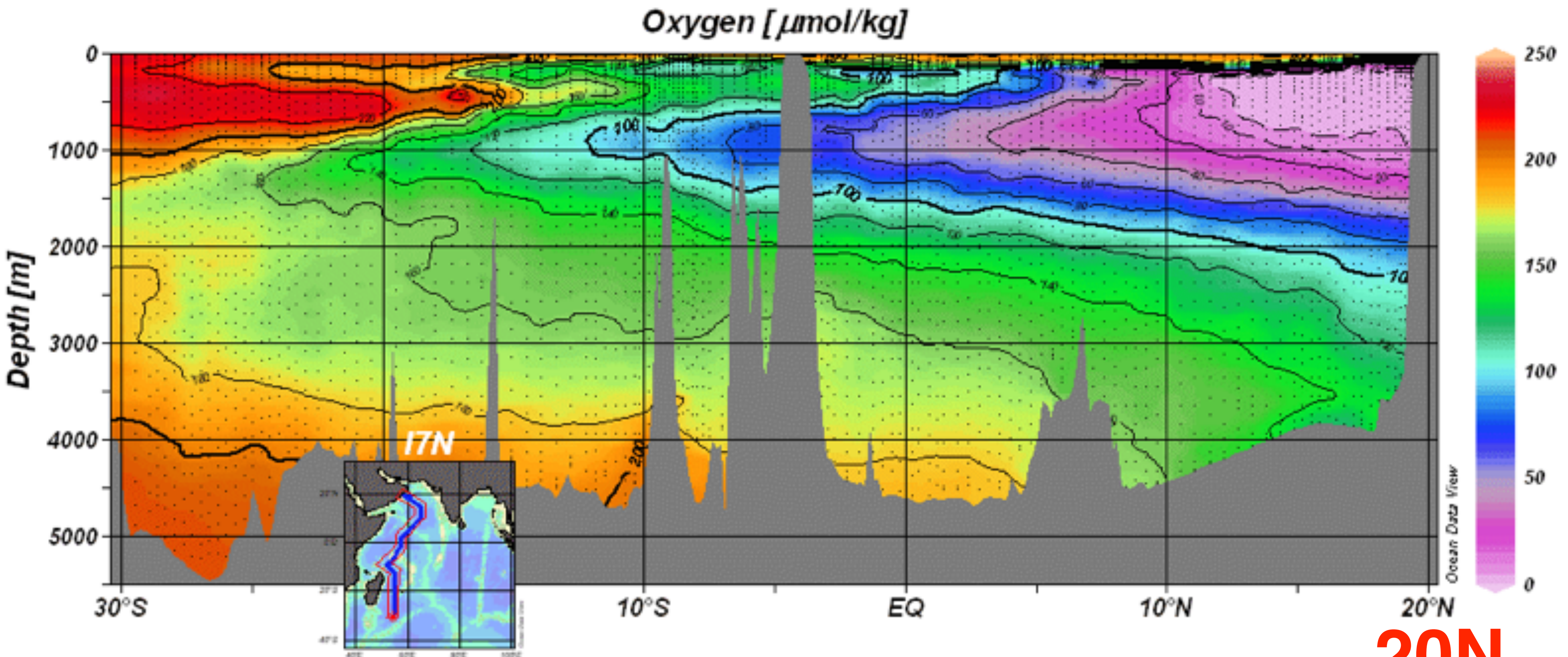
Atlantic Ocean



WOCE transects

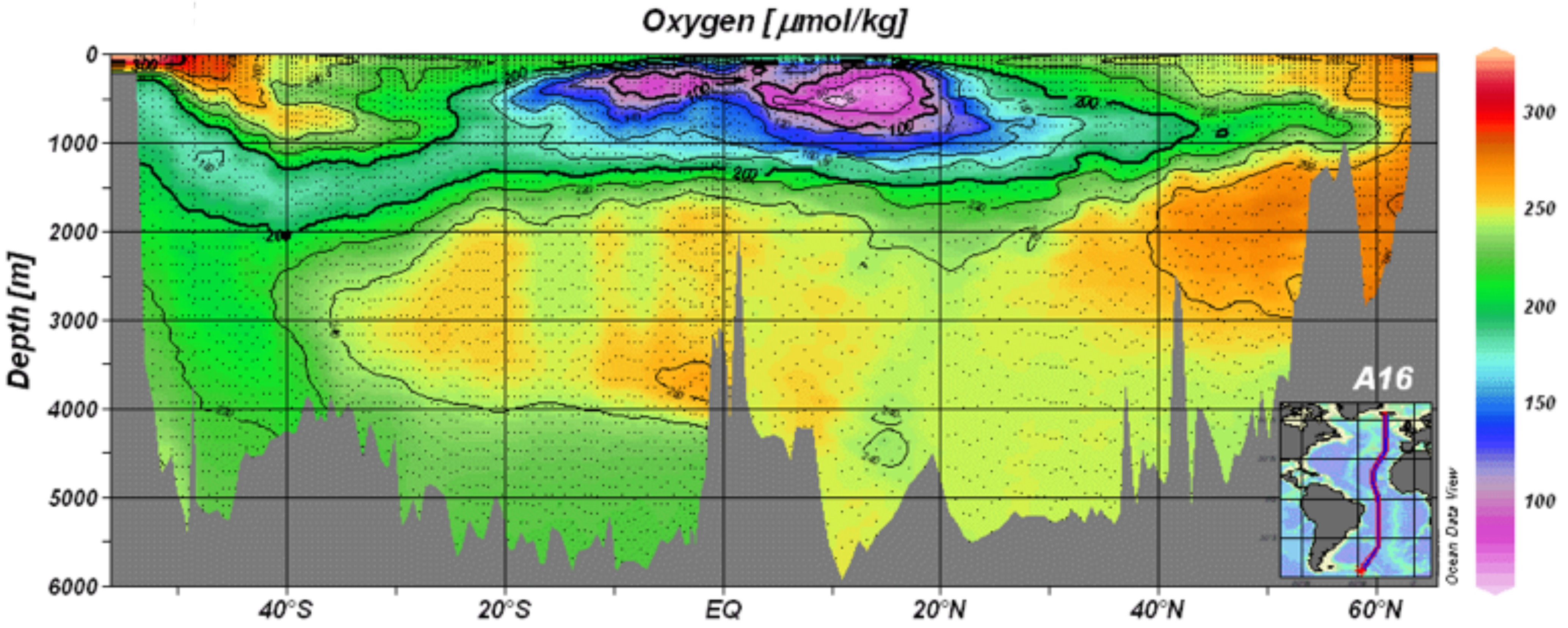
Indian Ocean: … and so less ventilated

Indian Ocean



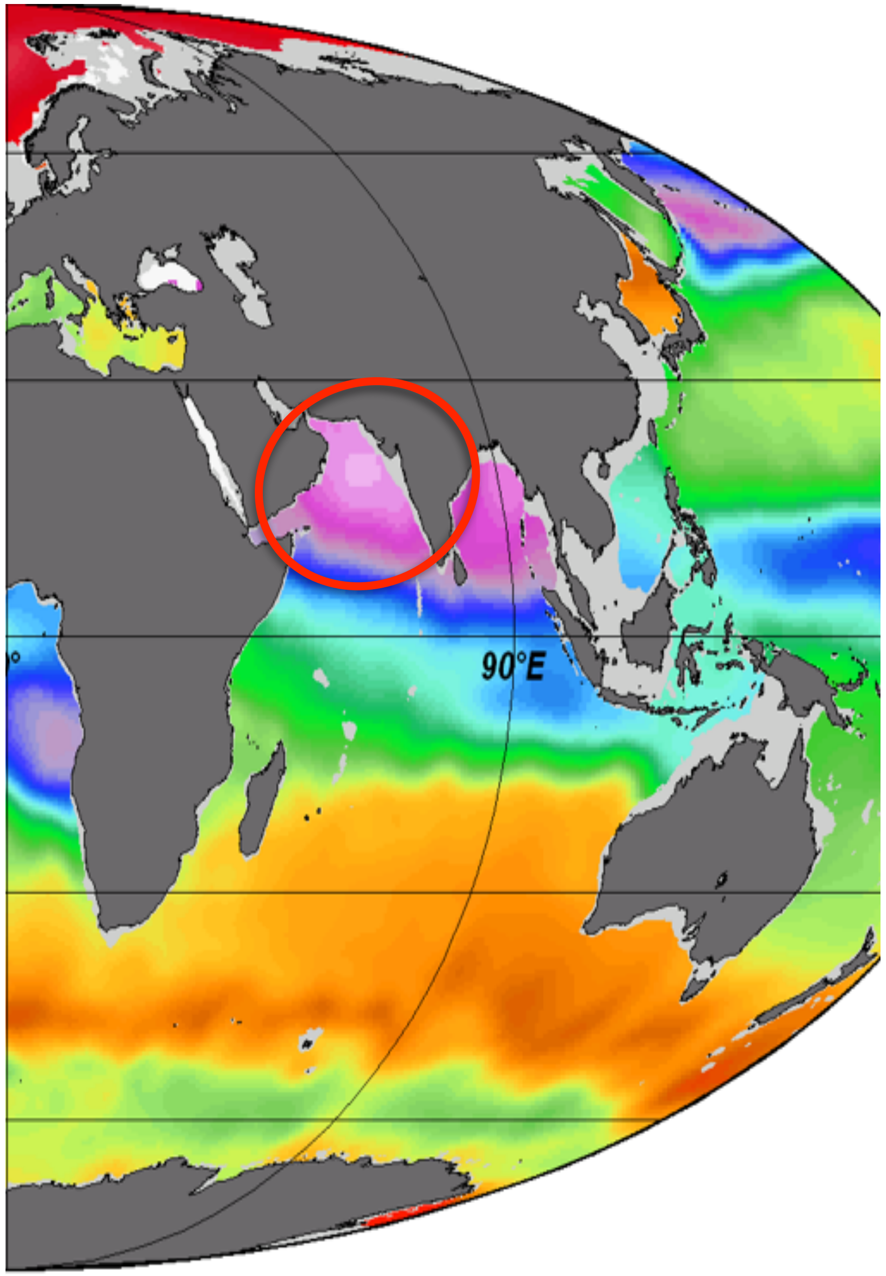
20N

Atlantic Ocean



WOCE transects

Focus on Arabian Sea .. why?



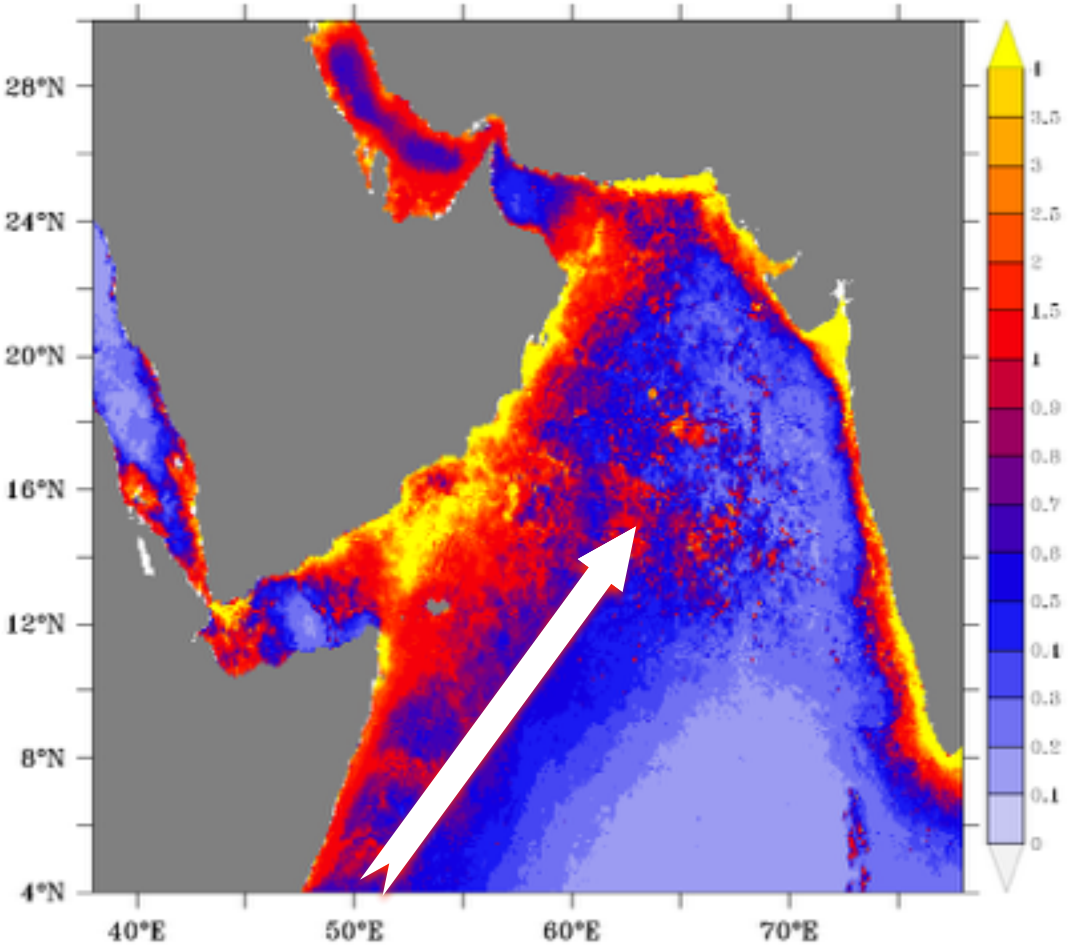
Oxygen at 400m

WOA 2009

- 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 (3rd most important LLGHG)
- Potential to modulate climate on geological timescales
- Extreme seasonality & complex dynamics (monsoon reversal, coastal upwelling, offshore advection, winter convection, eddies,…)
- Two blooms per year! …

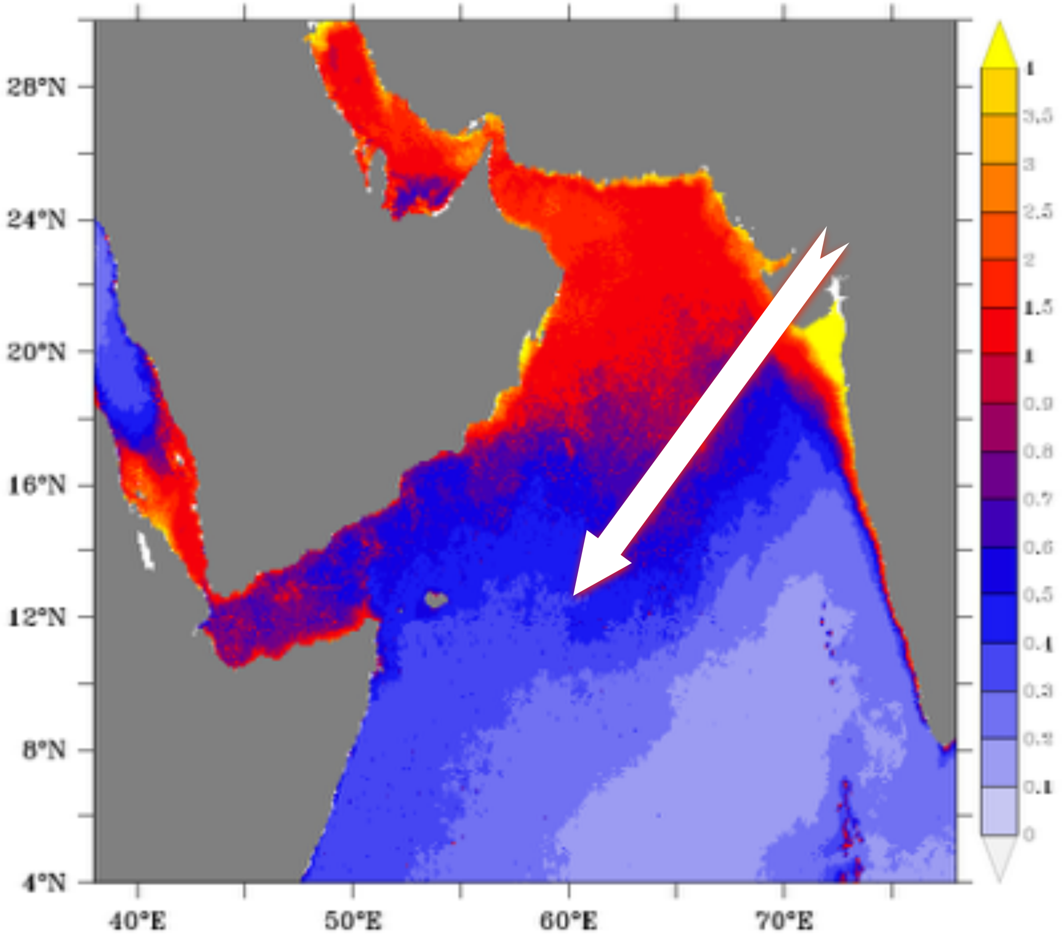
Arabian Sea: Two blooms per year

Summer



Summer monsoon winds drives upwelling along Somali coast

Winter



Winter monsoon winds drives convection at north of basin

SeaWifs

Changes in ventilation rates can have complicated responses:

Increased transport ➔ increased O_2 supply

But also:
Increased transport ➔ increased nutrient supply
➔ increased productivity ➔ increased remineralization
➔ decreased O_2

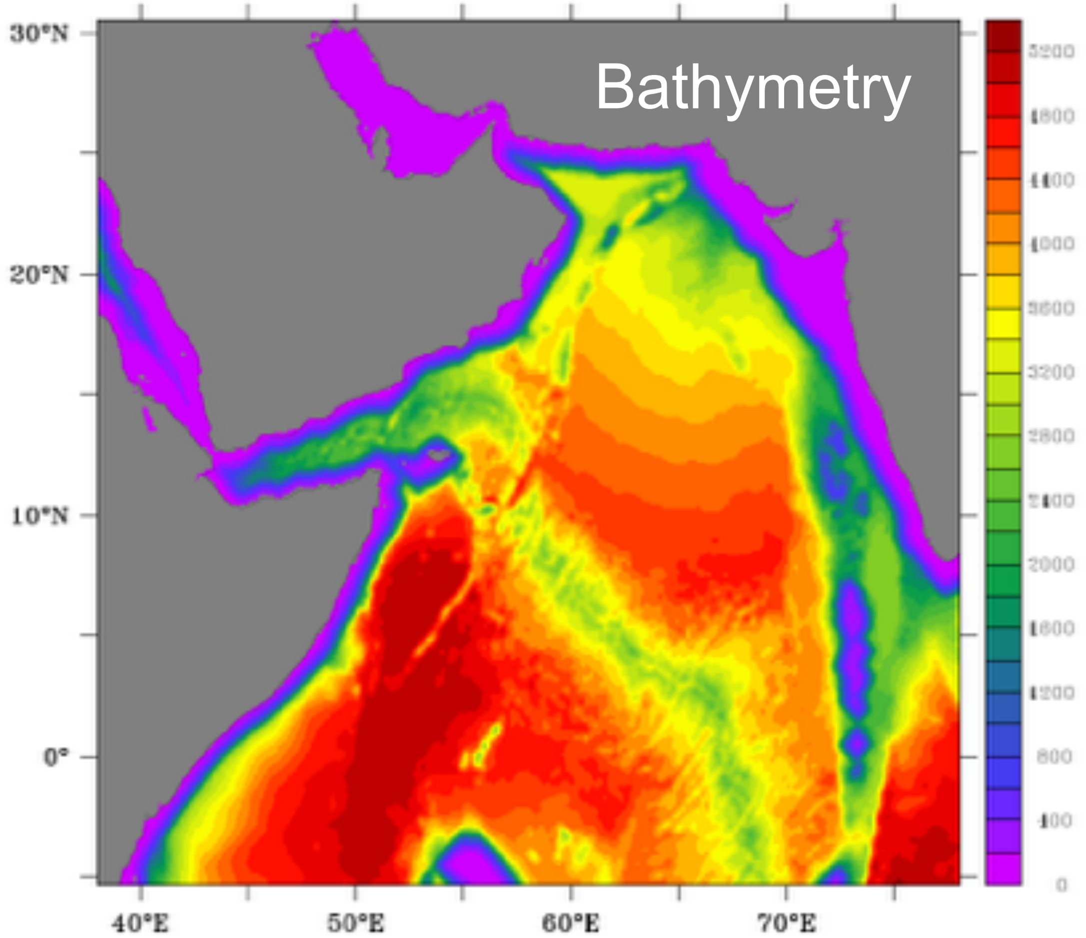
Moreover..
If increased transport increases O_2 & reduces suboxia
➔ decreased denitrification ➔ more NO_3
➔ more productivity ➔ less O_2!

➡ **Eddies reduce denitrification and compress habitats in the Arabian Sea**

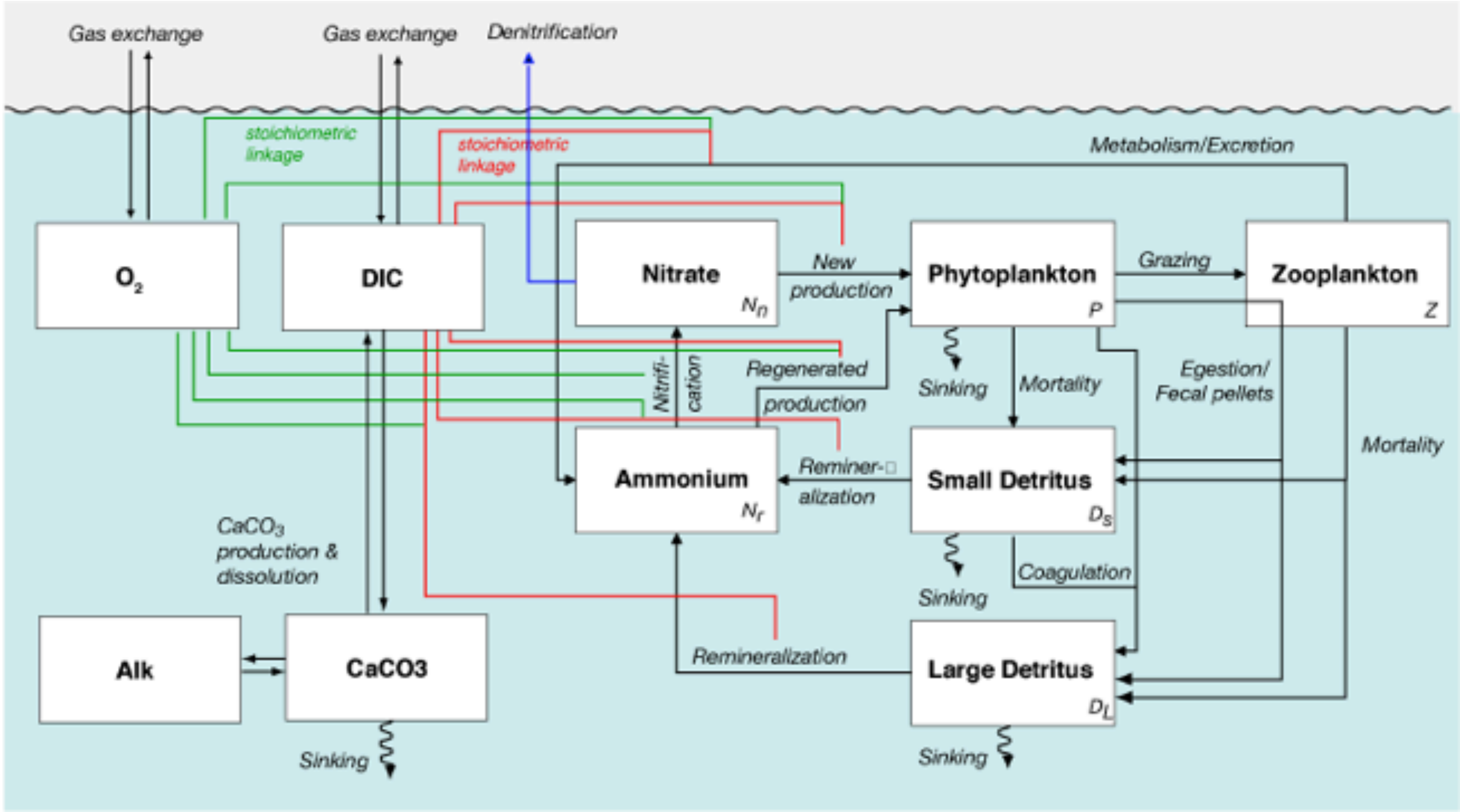
GRL 2016

Zouhair Lachkar[1], Shafer Smith[1,2], Marina Lévy[3], and Olivier Pauluis[1,2]

ROMS Simulations



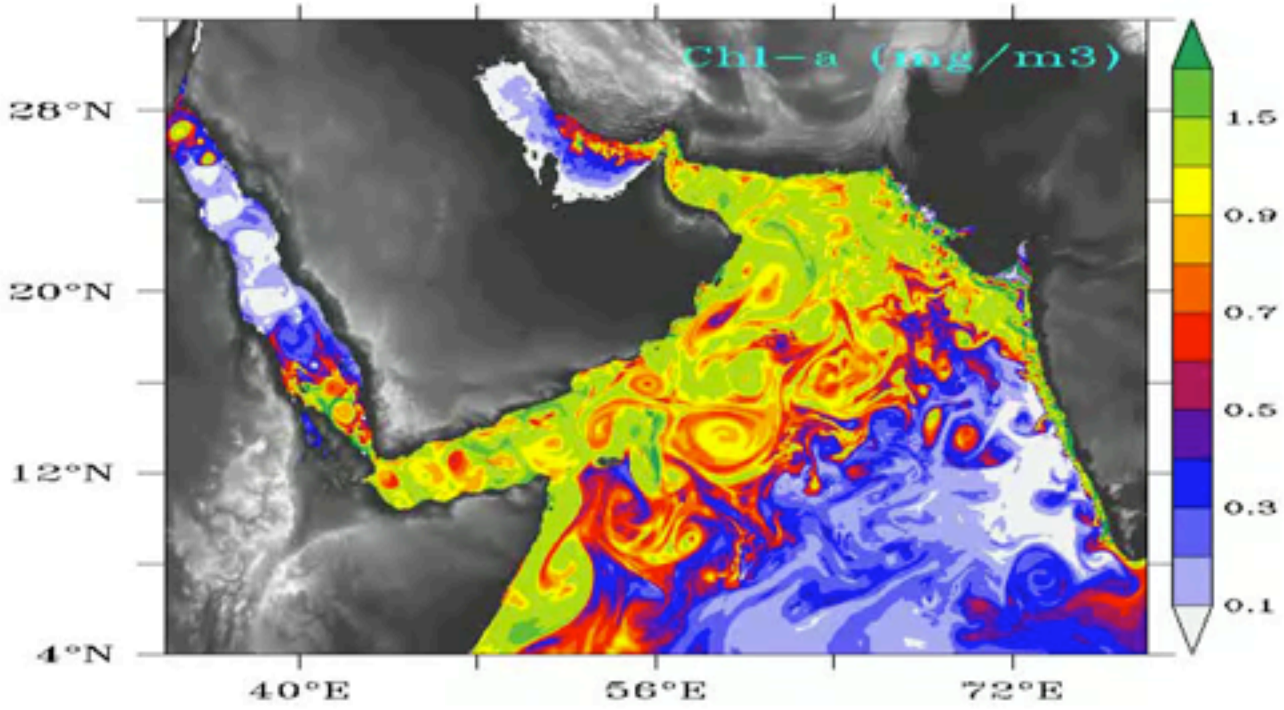
Res:	1/3°,1/6°,/12°,1/24° X 32
Forcing:	COADS, QuikSCAT
BC:	SODA reanalysis
Time:	12 yr spin-up, 8 yr analysis
Biology:	NH_4, NO_3, P, Z, D_s, D_l, **O_2**



BGC based on Gruber et al. (2006) [but no carbon cycle in these runs]

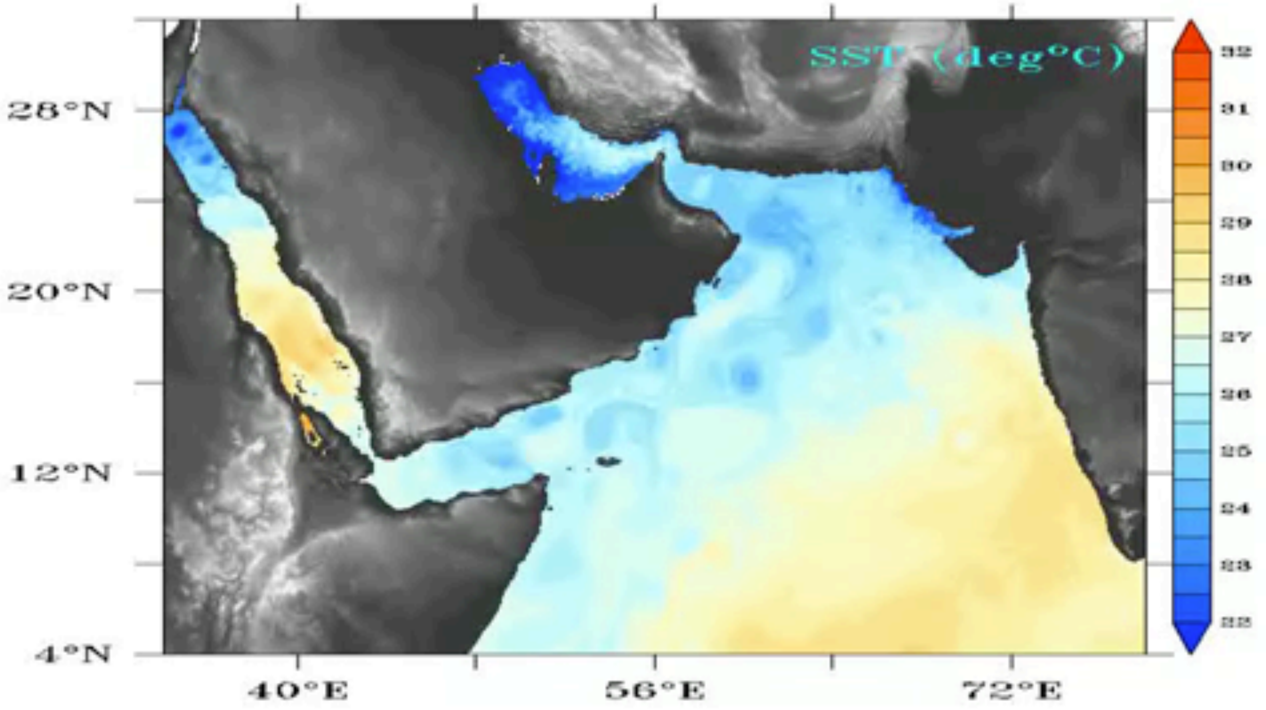
Model fields (1/24°) — surface

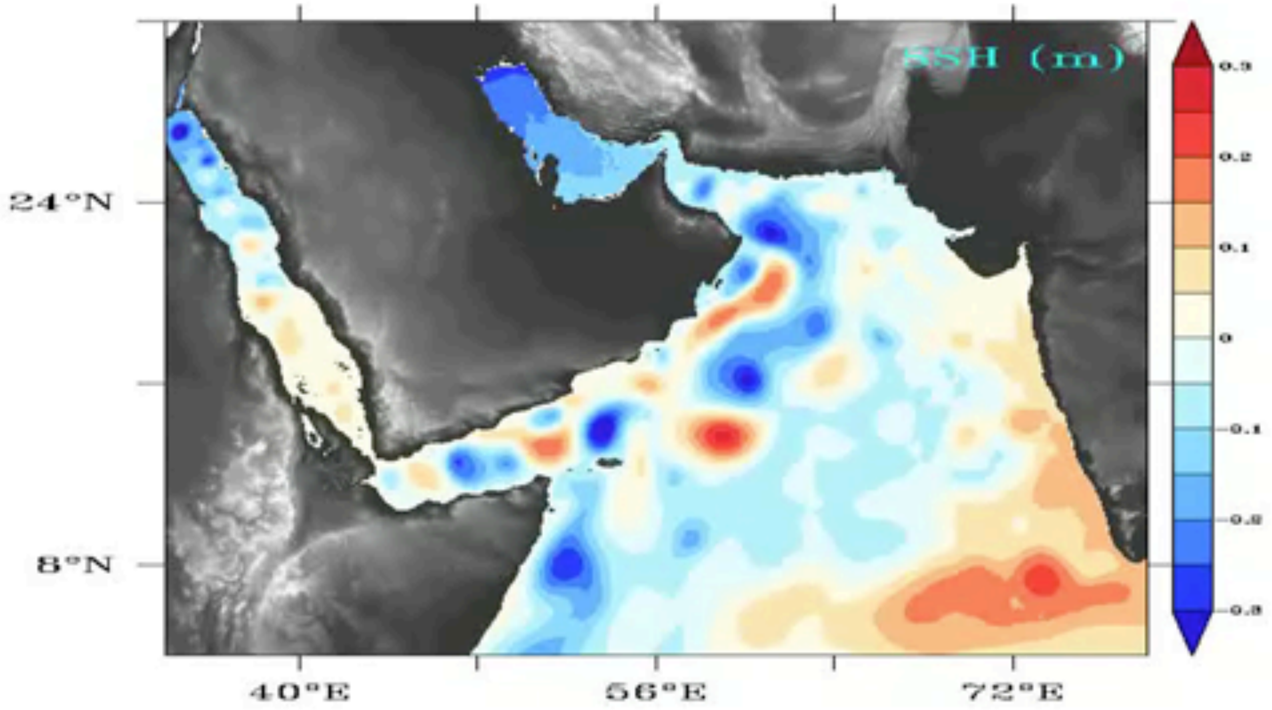
CHL



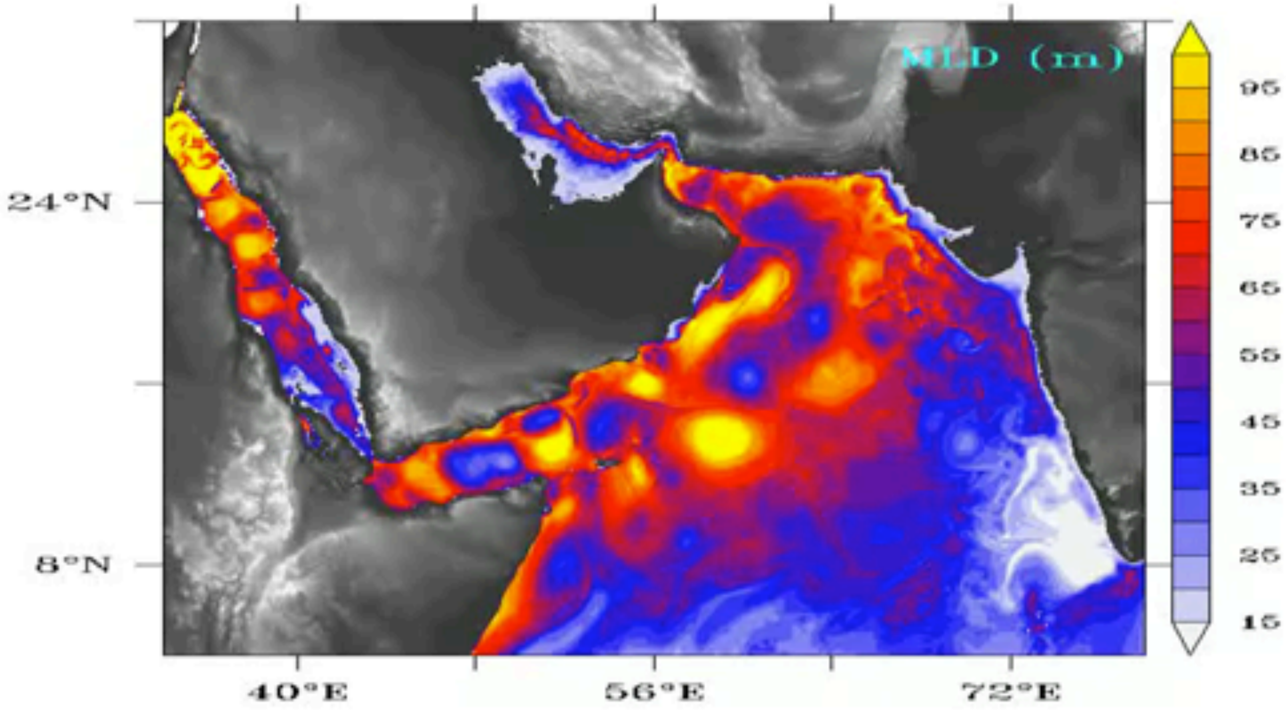
SST

January



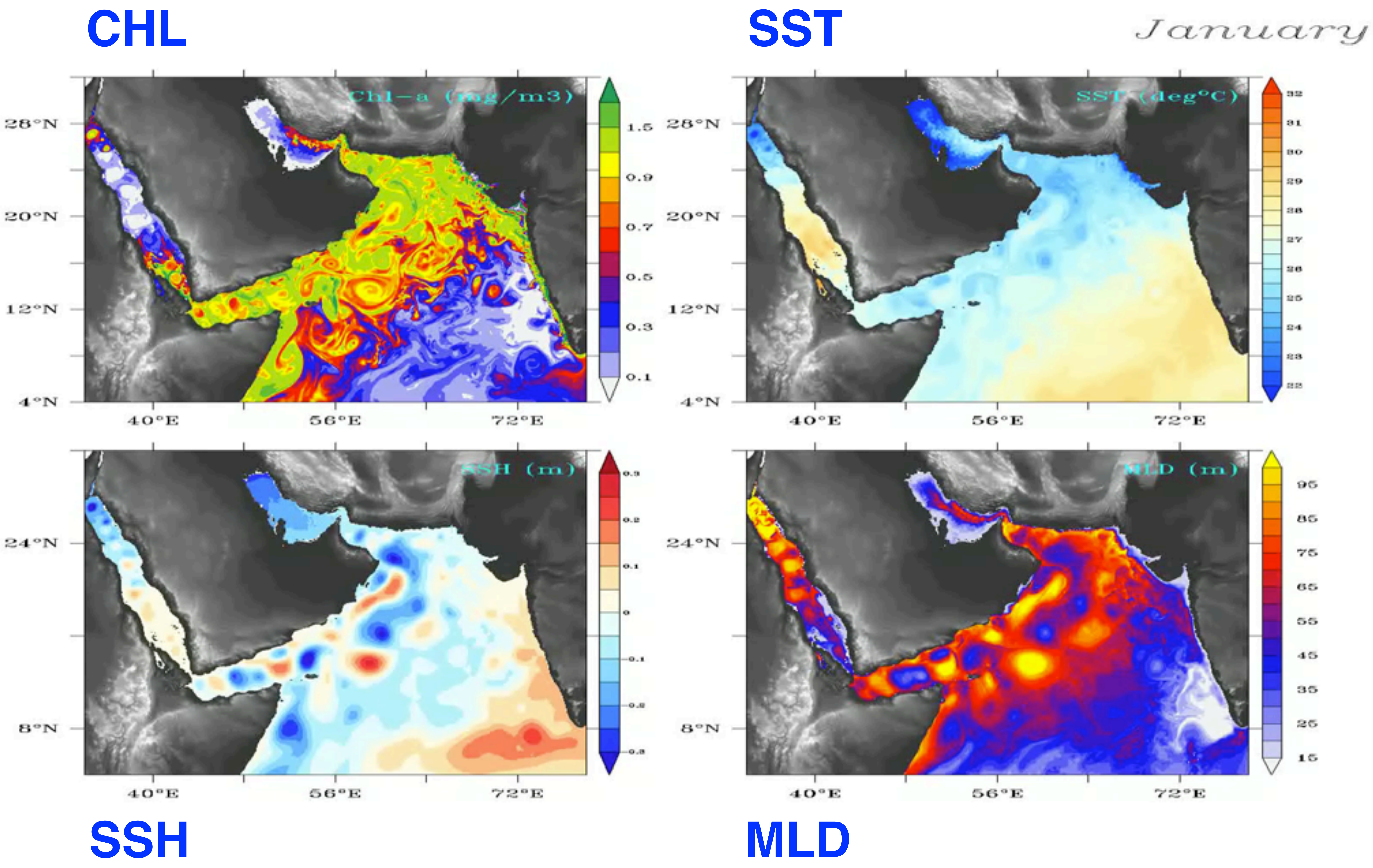


SSH



MLD

Model fields (1/24°) — surface



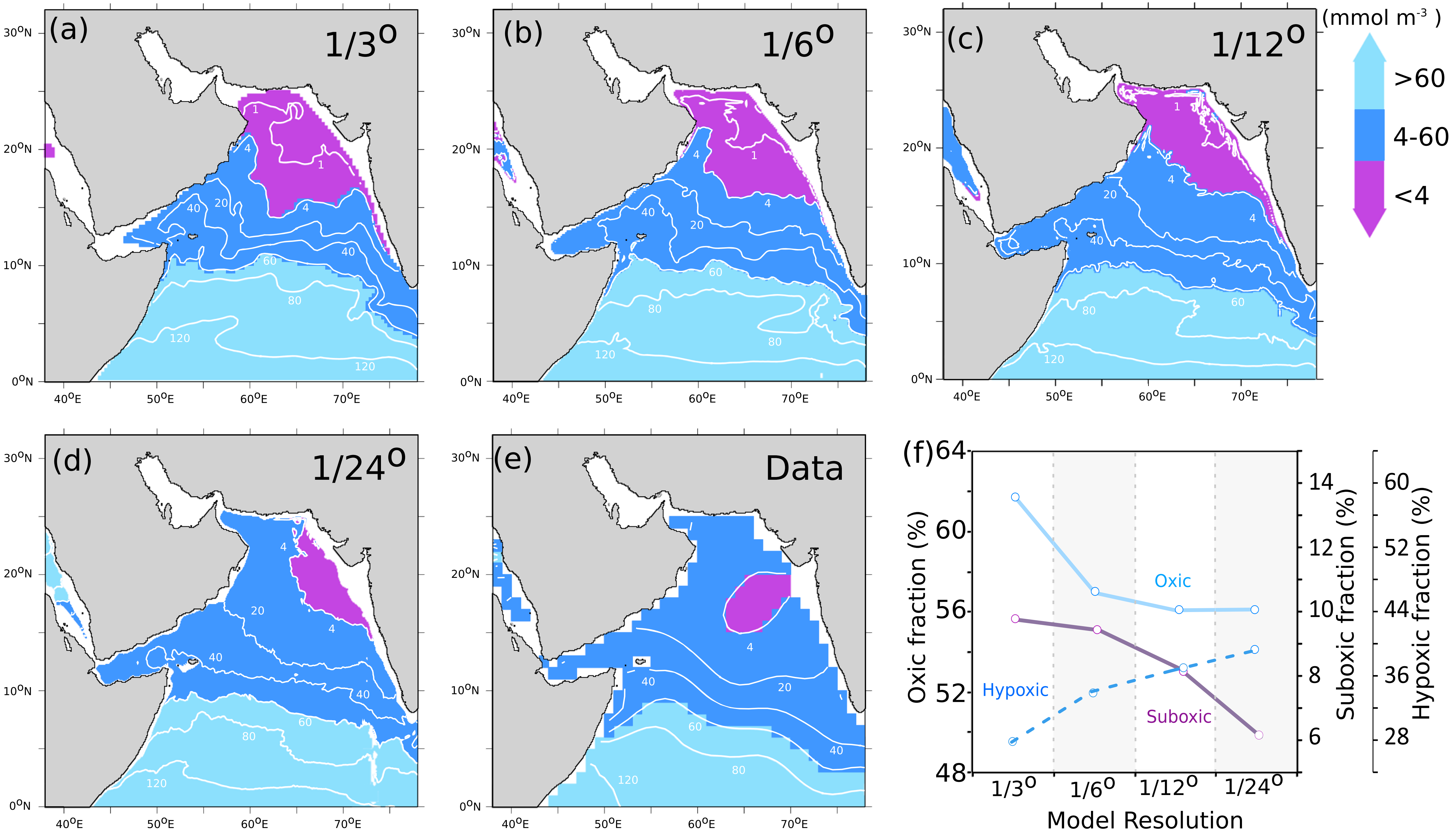
CHL

SST

SSH

MLD

Eddy fluxes shape the oxygen inventory



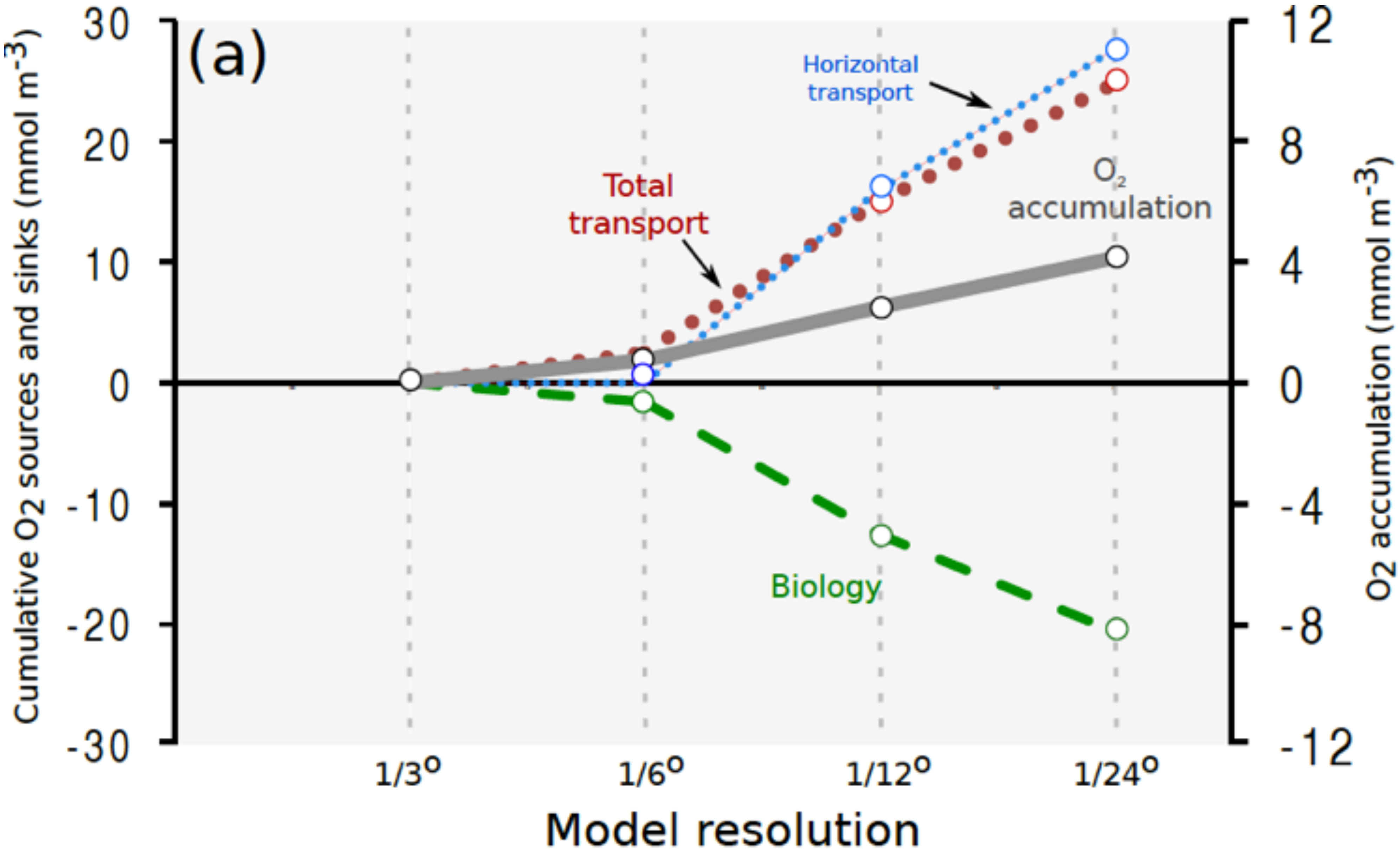
Eddies reduce denitrification and compress habitats in the Arabian Sea

GRL 2016

Zouhair Lachkar[1], Shafer Smith[1,2], Marina Lévy[3], and Olivier Pauluis[1,2]

Eddy fluxes shape the oxygen inventory

O2 accumulation driven mostly by increased lateral transport…



Oxygen is important.

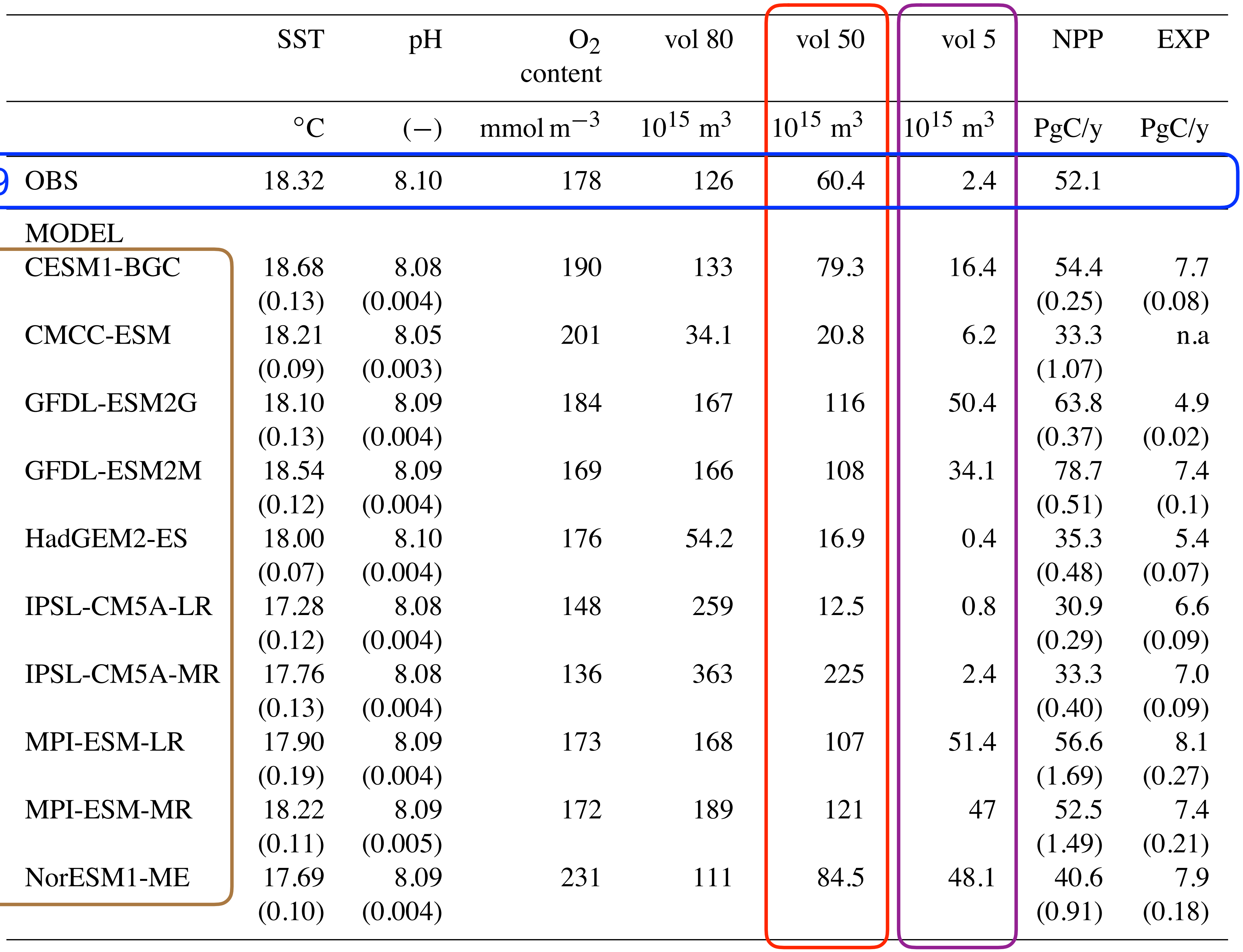
Crucial OMZ structure depends strongly on eddy fluxes.

Are eddy oxygen fluxes captured in climate models?

Earth system models are pretty bad at O_2

Bopp et al. (2013)

Present-day global average oxygen inventories



	SST	pH	O_2 content	vol 80	vol 50	vol 5	NPP	EXP
	°C	(−)	mmol m^{-3}	10^{15} m^3	10^{15} m^3	10^{15} m^3	PgC/y	PgC/y
OBS	18.32	8.10	178	126	60.4	2.4	52.1	
MODEL								
CESM1-BGC	18.68	8.08	190	133	79.3	16.4	54.4	7.7
	(0.13)	(0.004)					(0.25)	(0.08)
CMCC-ESM	18.21	8.05	201	34.1	20.8	6.2	33.3	n.a
	(0.09)	(0.003)					(1.07)	
GFDL-ESM2G	18.10	8.09	184	167	116	50.4	63.8	4.9
	(0.13)	(0.004)					(0.37)	(0.02)
GFDL-ESM2M	18.54	8.09	169	166	108	34.1	78.7	7.4
	(0.12)	(0.004)					(0.51)	(0.1)
HadGEM2-ES	18.00	8.10	176	54.2	16.9	0.4	35.3	5.4
	(0.07)	(0.004)					(0.48)	(0.07)
IPSL-CM5A-LR	17.28	8.08	148	259	12.5	0.8	30.9	6.6
	(0.12)	(0.004)					(0.29)	(0.09)
IPSL-CM5A-MR	17.76	8.08	136	363	225	2.4	33.3	7.0
	(0.13)	(0.004)					(0.40)	(0.09)
MPI-ESM-LR	17.90	8.09	173	168	107	51.4	56.6	8.1
	(0.19)	(0.004)					(1.69)	(0.27)
MPI-ESM-MR	18.22	8.09	172	189	121	47	52.5	7.4
	(0.11)	(0.005)					(1.49)	(0.21)
NorESM1-ME	17.69	8.09	231	111	84.5	48.1	40.6	7.9
	(0.10)	(0.004)					(0.91)	(0.18)

WOA 2009

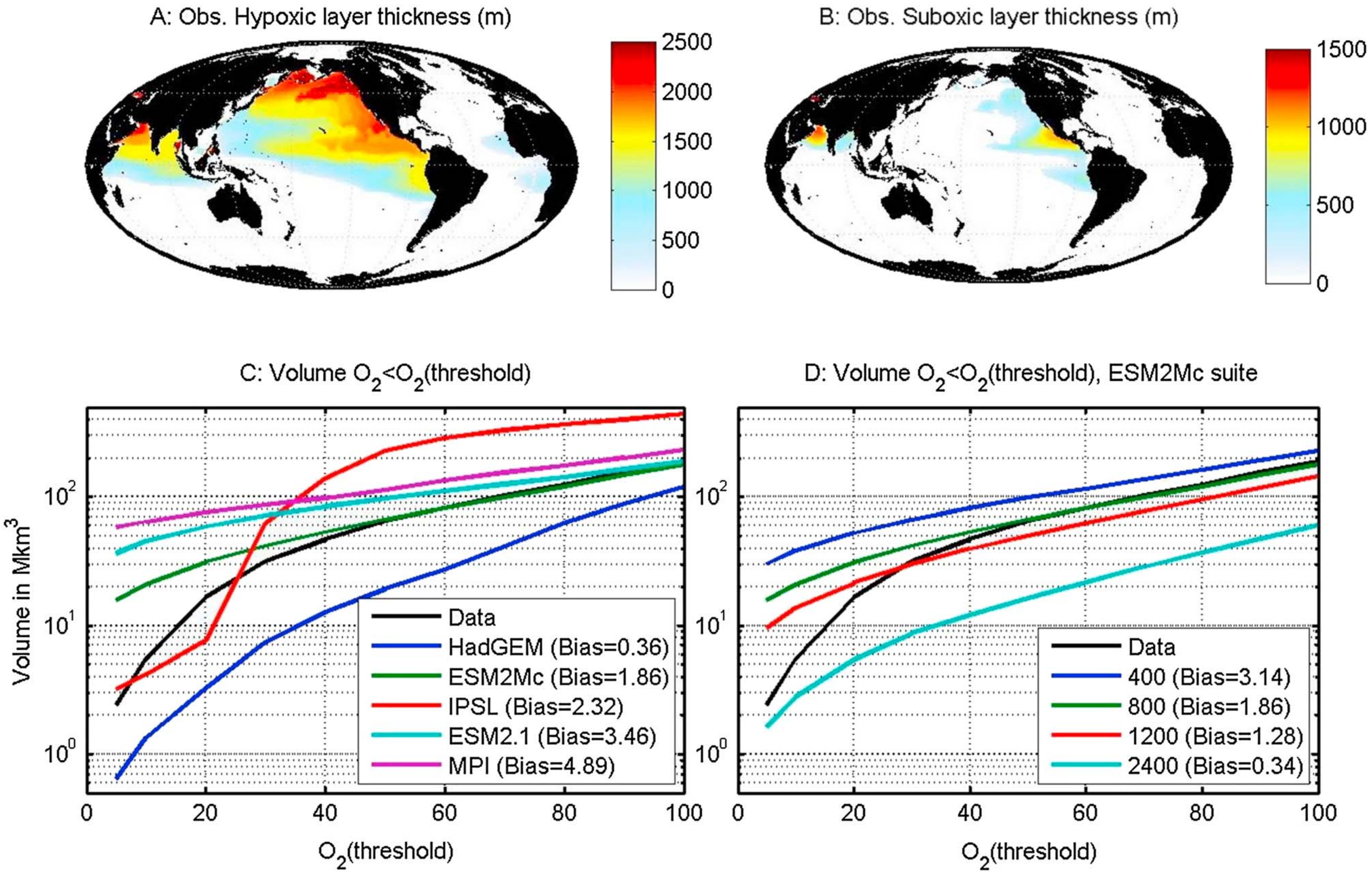
CMIP5

~hypoxic

~suboxic

Increasing isopycnal tracer diffusion helps

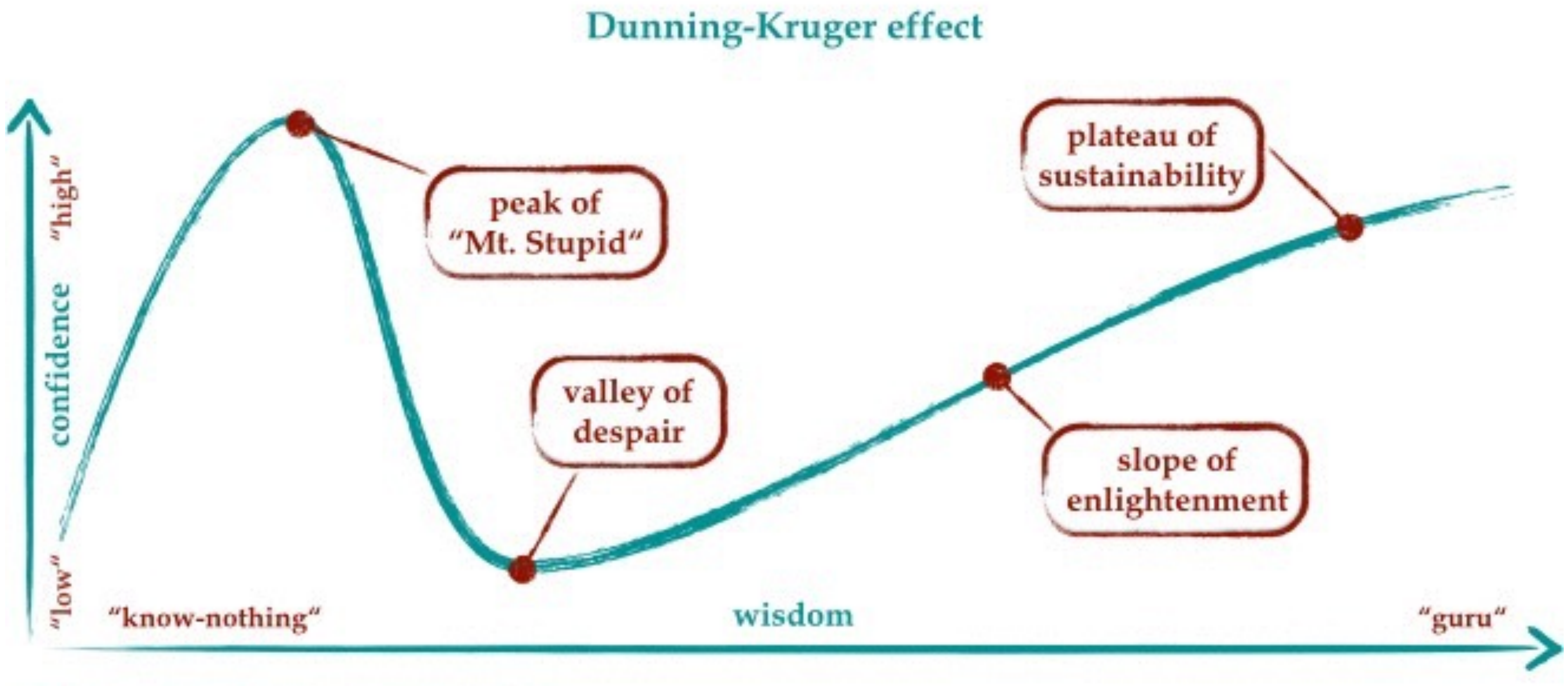
Gnanadesikan, Bianchi, Pradal (2013)



Implicates role of mesoscale eddy transport in structuring global oxygen

How can climate model representations of oxygen and other BGC tracers be improved?

Revisit the parameterization problem…



http://www.understandinginnovation.wordpress.com

Parameterized eddy fluxes …A brief history

Two major problems in early models:

- Water masses diffused away
- Isopycnals too steep

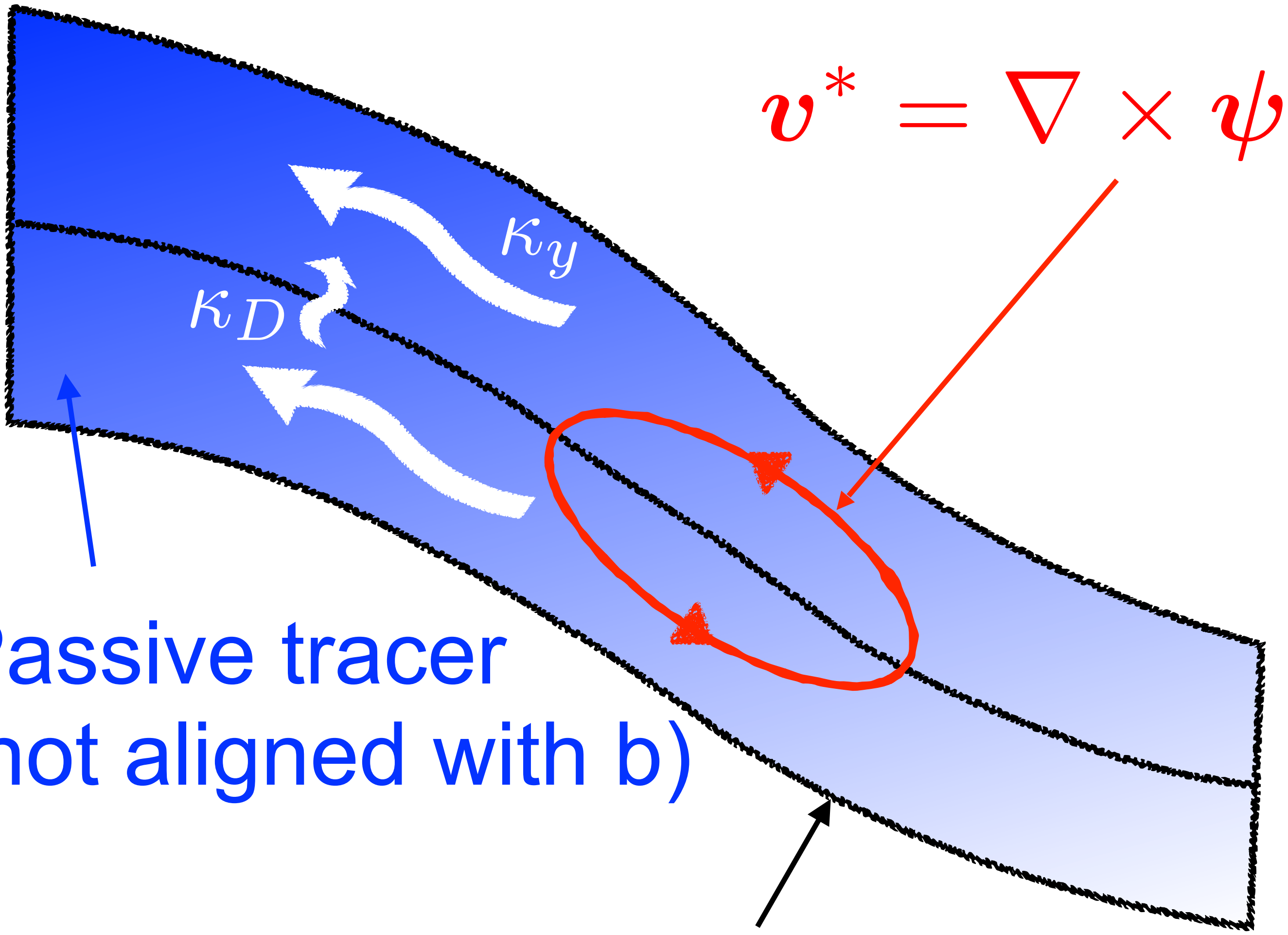
Solutions:

- Veronis (1975): Tracers diffuse along isopycnals, models const z
- Redi (1982): Rotated isopycnal mixing tensor (κ_{redi})
- Gent & McWilliams (1990): Adiabatic thickness diffusion ($\mathbf{v^*}$, κ_{gm})
- Visbeck et al. (1997) & others: Flow-dependent GM coefficient
- Griffies (1998): Redi & GM = symmetric and antisymmetric mixing tensors…

… and beautiful, efficient numerical form if we set $\boldsymbol{\kappa_{redi} = \kappa_{gm}}$

e.g. Gent (2011)

Parameterized eddy fluxes



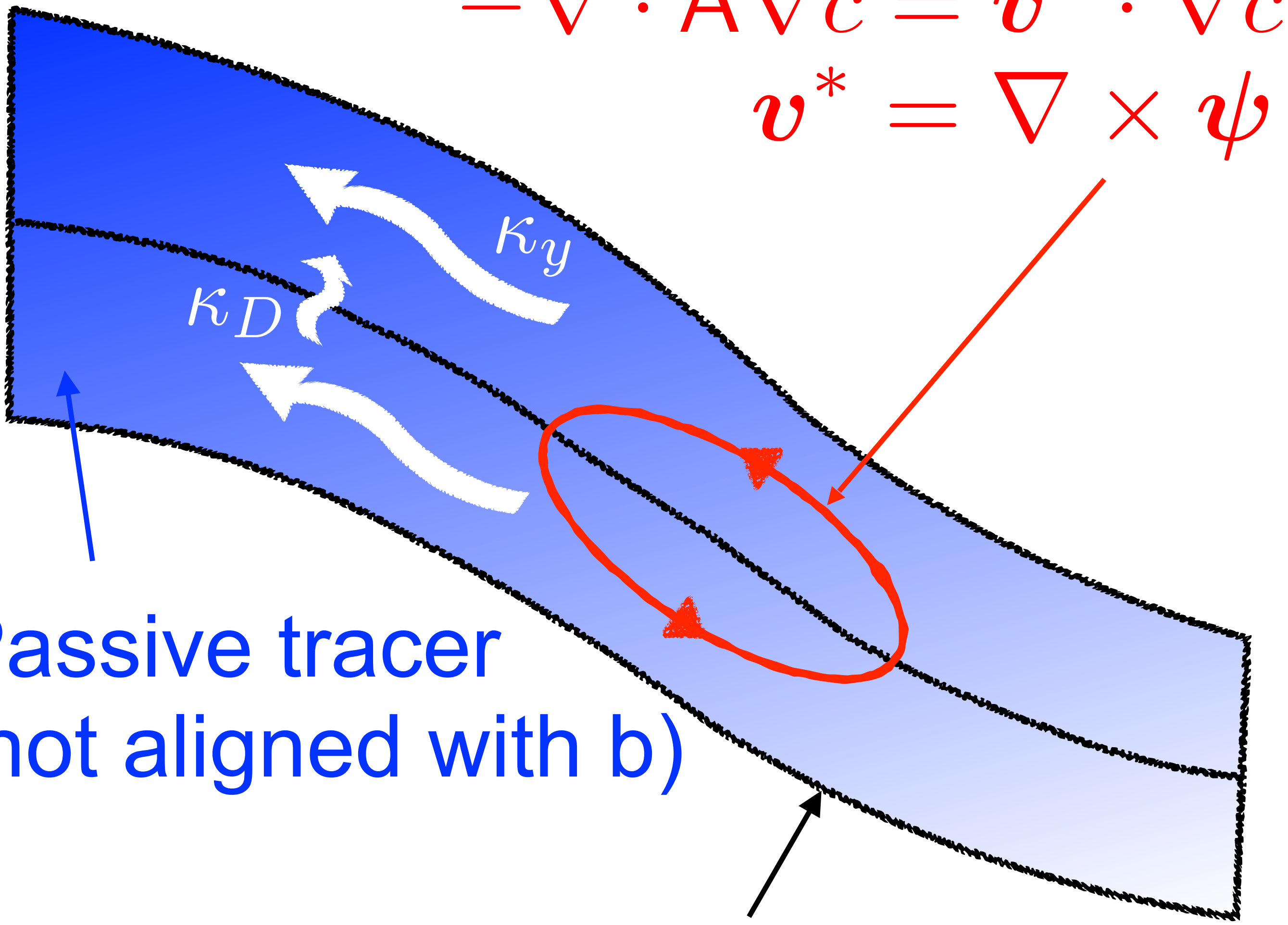
$\boldsymbol{v}^* = \nabla \times \boldsymbol{\psi}$

Passive tracer
(not aligned with b)

Isopycnal (b constant,
slope $\boldsymbol{s} = -\nabla_h b / \partial_z b$)

Parameterized eddy fluxes

$$-\nabla \cdot \mathsf{A}\nabla c = \boldsymbol{v}^* \cdot \nabla c$$
$$\boldsymbol{v}^* = \nabla \times \boldsymbol{\psi}$$



Passive tracer
(not aligned with b)

Isopycnal (b constant,
slope $\boldsymbol{s} = -\nabla_h b/\partial_z b$)

Tracer equation (c could be b)

$$\partial_t c + \boldsymbol{v} \cdot \nabla c = -\nabla \cdot \overline{\boldsymbol{v}'c'}$$
$$\equiv \nabla \cdot \mathsf{K}\nabla c$$

$$\mathsf{K} = \mathsf{A} + \mathsf{S}$$

antisymmetric symmetric

$$\mathsf{A} = \begin{bmatrix} 0 & \psi_3 & -\psi_2 \\ -\psi_3 & 0 & \psi_1 \\ \psi_2 & -\psi_1 & 0 \end{bmatrix}$$

$$\mathsf{S} = \mathsf{R}\begin{bmatrix} \kappa_x & 0 & 0 \\ 0 & \kappa_y & 0 \\ 0 & 0 & \boxed{\kappa_D} \end{bmatrix}\mathsf{R}^T$$

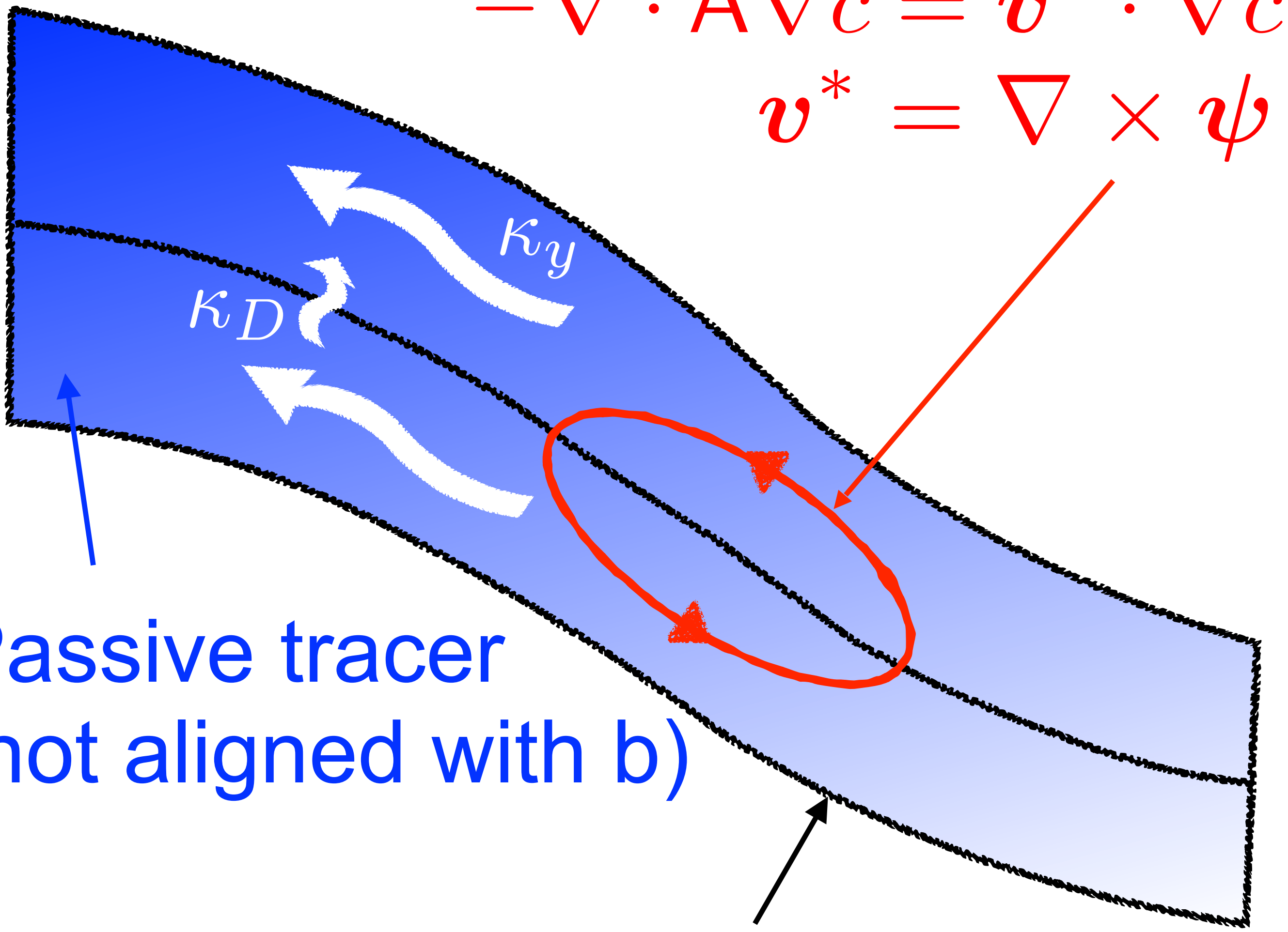
$\ll \kappa_x, \kappa_y$

rotation from isopycnal to geodesic coordinates

Parameterized eddy fluxes

$$-\nabla\cdot\mathsf{A}\nabla c = \boldsymbol{v}^{*}\cdot\nabla c$$

$$\boldsymbol{v}^{*} = \nabla\times\boldsymbol{\psi}$$



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slope $\boldsymbol{s} = -\nabla_h b/\partial_z b$)

Tracer equation (c could be b)

$$\partial_t c + \boldsymbol{v}\cdot\nabla c = -\nabla\cdot\overline{\boldsymbol{v}'c'}$$

$$\equiv \nabla\cdot\mathsf{K}\nabla c$$

$$\mathsf{K} = \mathsf{A} + \mathsf{S}$$

antisymmetric symmetric

$$\mathsf{A}_{\mathrm{gm}} = \begin{bmatrix} 0 & 0 & -\kappa_{\mathrm{gm}} s^x \\ 0 & 0 & -\kappa_{\mathrm{gm}} s^y \\ \kappa_{\mathrm{gm}} s^x & \kappa_{\mathrm{gm}} s^y & 0 \end{bmatrix}$$

$$\mathsf{S}_{\mathrm{redi}} = \mathsf{R}\begin{bmatrix} \kappa_{\mathrm{redi}} & 0 & 0 \\ 0 & \kappa_{\mathrm{redi}} & 0 \\ 0 & 0 & \boxed{\kappa_D} \end{bmatrix}\mathsf{R}^T$$

$$\ll \kappa_x, \kappa_y$$

rotation from isopycnal to geodesic coordinates

Parameterized eddy fluxes

Alternate derivation:

GM stirring = lateral downgradient buoyancy flux, with compensating vertical flux, to make b an adiabatic tracer:

$$\overline{\boldsymbol{v}'b'} \cdot \nabla b = \overline{\boldsymbol{u}'b'} \cdot \nabla_h b + \overline{w'b'} \partial_z b = 0$$

So

$$\boxed{\overline{\boldsymbol{u}'b'} \equiv -\kappa_{\mathrm{gm}} \nabla_h b \;\Rightarrow\; \overline{w'b'} = \kappa_{\mathrm{gm}} |\nabla_h b|^2 / \partial_z b}$$

And GM bolus velocity is

$$\boldsymbol{v}^*_{\mathrm{gm}} = -\partial_z (\kappa_{\mathrm{gm}} \boldsymbol{s}) + \hat{\boldsymbol{z}}\, \nabla_h \cdot (\kappa_{\mathrm{gm}} \boldsymbol{s})$$

Quasigeostrophic theory

Neglecting momentum flux, the QG PV flux, averaged horizontally over a patch of ocean:

$$\overline{\boldsymbol{u}'q'} \approx f\partial_z\left(\frac{\boldsymbol{u}'b'}{\partial_z b}\right)$$

Downgradient PV flux (neglecting β)

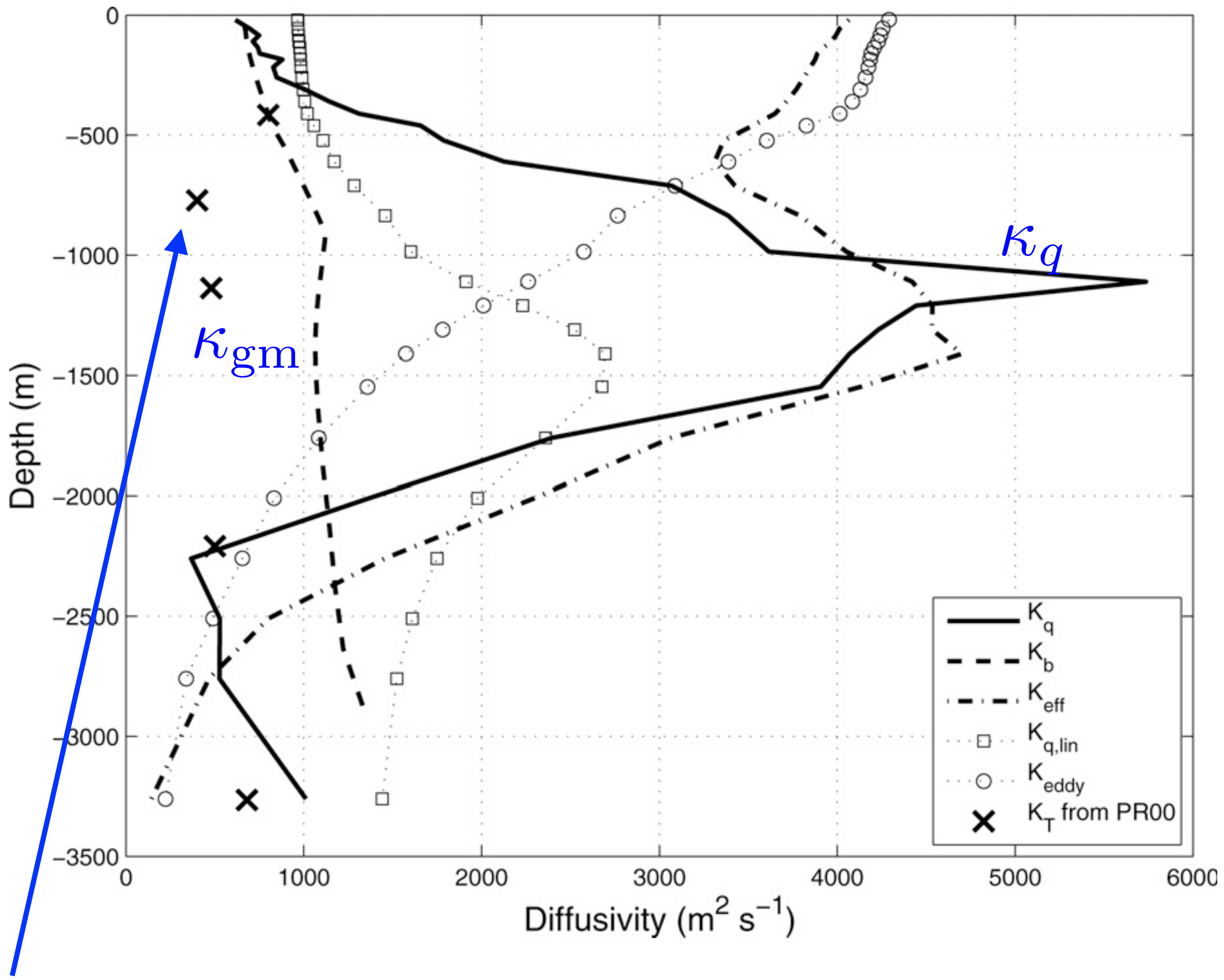
$$\boxed{\kappa_q\partial_z\boldsymbol{s} \approx \partial_z\left(\kappa_{\mathrm{gm}}\boldsymbol{s}\right)} \quad \bigstar$$

Smith & Marshall (2009). See also Killworth (1997), Treguier et al (1997)

Measuring eddy fluxes

Smith & Marshall (2009)

Test with periodic QG model
against eddy flux measurements



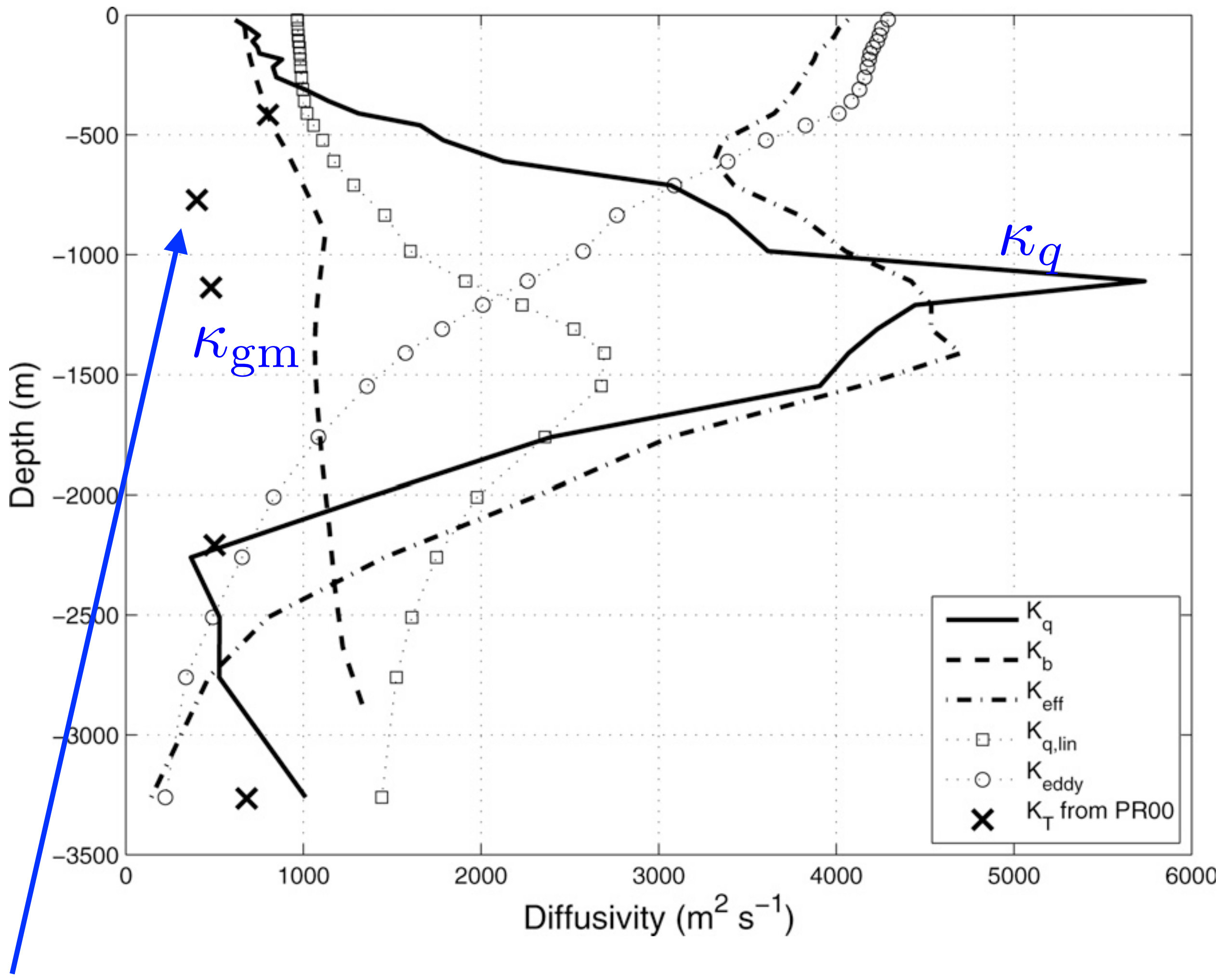
Solyan & Rintoul (2000) — eddy stress from moored array in S.O., near Tasmania

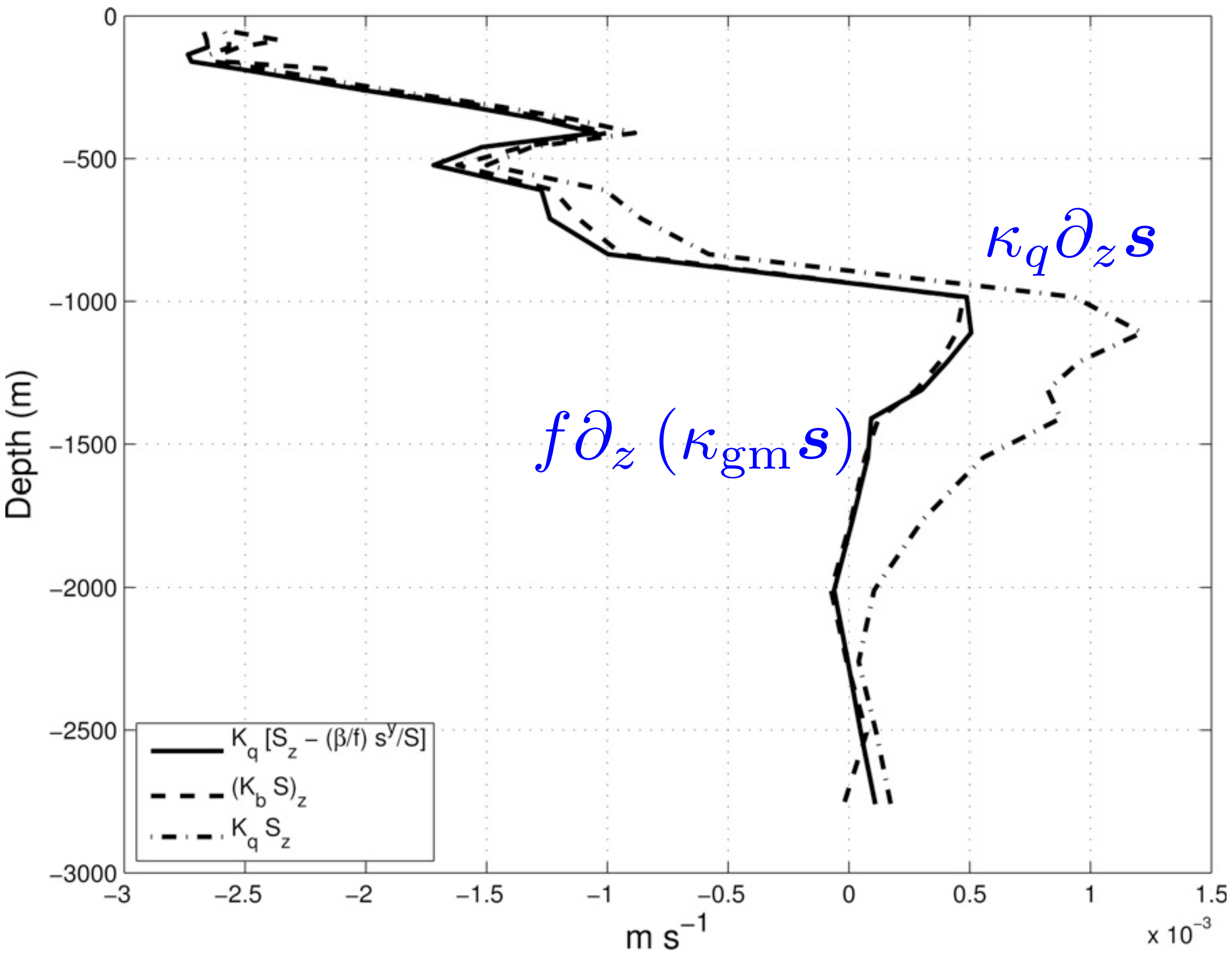
Measuring eddy fluxes

Smith & Marshall (2009)

Test with periodic QG model
against eddy flux measurements

$$\boxed{\kappa_q \partial_z \boldsymbol{s} \approx \partial_z \left(\kappa_{\mathrm{gm}} \boldsymbol{s}\right)}$$ ★





Solyan & Rintoul (2000) — eddy stress from moored array in S.O., near Tasmania

Measuring eddy fluxes

Abernathey, Ferreira, Klocker (2013)

Eddy fluxes from wind/buoyancy forced MITgcm channel model

Multiple-tracer method for zonal avg:

e.g. Plumb & Mahlman (87)
Bachman & Fox-Kemper (13)

$$\begin{bmatrix} \overline{v'c_1'} & \overline{v'c_2'} & \dots & \overline{v'c_6'} \\ \overline{w'c_1'} & \overline{w'c_2'} & \dots & \overline{w'c_6'} \end{bmatrix} = -\begin{bmatrix} K_{yy} & K_{yz} \\ K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} \partial\overline{c_1}/\partial y & \partial\overline{c_2}/\partial y & \dots & \partial\overline{c_6}/\partial y \\ \partial\overline{c_1}/\partial z & \partial\overline{c_2}/\partial z & \dots & \partial\overline{c_6}/\partial z \end{bmatrix}$$

Extract S and A from K:

$$\mathsf{S} = \frac{1}{2}(\mathsf{K} + \mathsf{K}^T) \qquad \mathsf{A} = \frac{1}{2}(\mathsf{K} - \mathsf{K}^T)$$

$$\mathsf{S} = \mathsf{U}\begin{bmatrix} \kappa_y & 0 \\ 0 & \kappa_D \end{bmatrix}\mathsf{U}^T \qquad \mathsf{A} = \begin{bmatrix} 0 & -\chi \\ \chi & 0 \end{bmatrix}$$

2D GM/Redi:

$$\boxed{\kappa_{\text{redi}} = \kappa_y \quad \kappa_{\text{gm}} = \chi/s}$$

Measuring eddy fluxes

Abernathey, Ferreira, Klocker (2013)

Eddy fluxes from wind/buoyancy forced MITgcm channel model

Multiple-tracer method for zonal avg:

$$\begin{bmatrix} \overline{v'c'_1} & \overline{v'c'_2} & \dots & \overline{v'c'_6} \\ \overline{w'c'_1} & \overline{w'c'_2} & \dots & \overline{w'c'_6} \end{bmatrix} = -\begin{bmatrix} K_{yy} & K_{yz} \\ K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} \partial\overline{c_1}/\partial y & \partial\overline{c_2}/\partial y & \dots & \partial\overline{c_6}/\partial y \\ \partial\overline{c_1}/\partial z & \partial\overline{c_2}/\partial z & \dots & \partial\overline{c_6}/\partial z \end{bmatrix}$$

e.g. Plumb & Mahlman (87)
Bachman & Fox-Kemper (13)

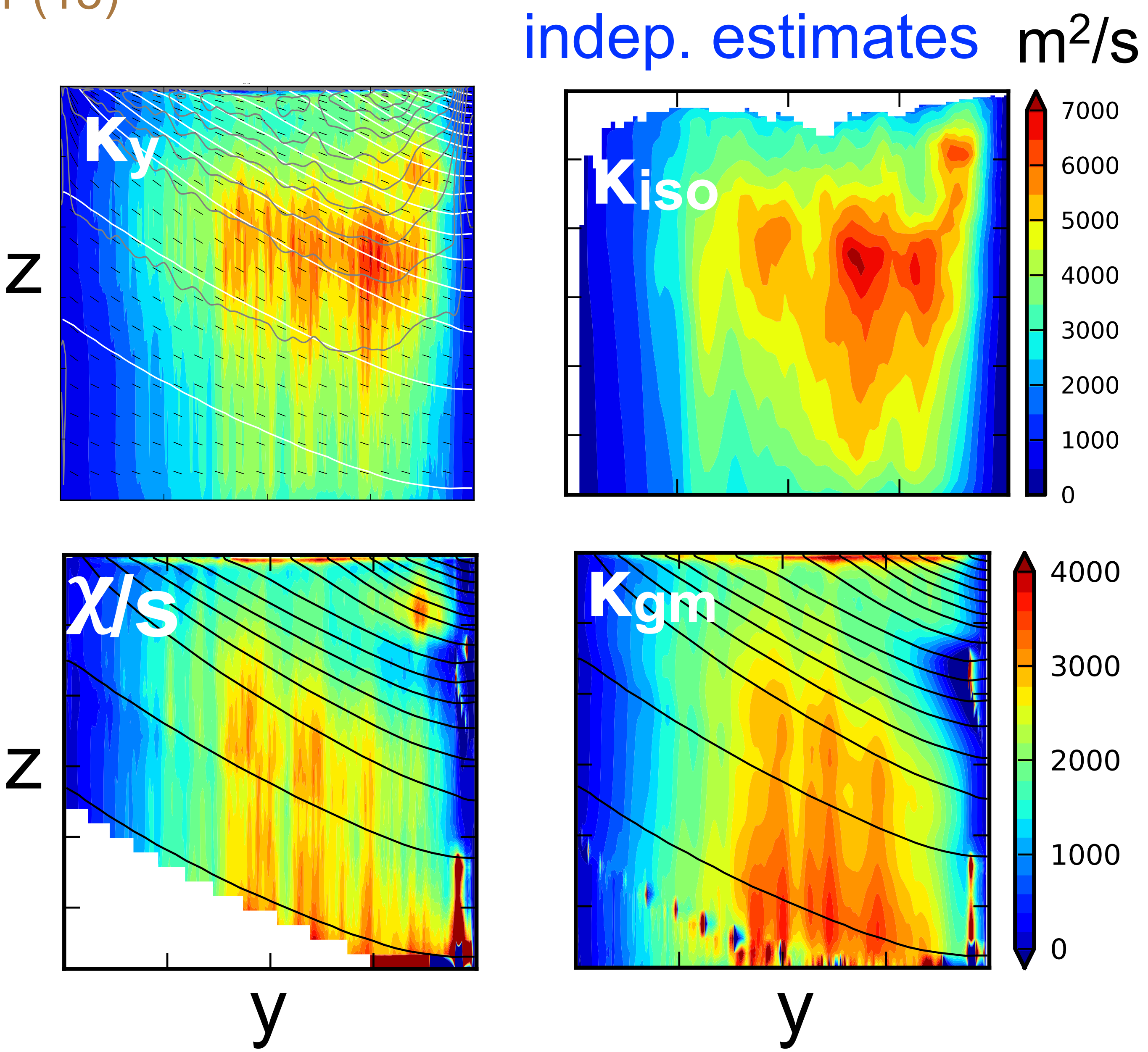
Extract S and A from K:

$$\mathrm{S} = \frac{1}{2}(\mathrm{K} + \mathrm{K}^T) \qquad \mathrm{A} = \frac{1}{2}(\mathrm{K} - \mathrm{K}^T)$$

$$\mathrm{S} = \mathrm{U} \begin{bmatrix} \kappa_y & 0 \\ 0 & \kappa_D \end{bmatrix} \mathrm{U}^T \qquad \mathrm{A} = \begin{bmatrix} 0 & -\chi \\ \chi & 0 \end{bmatrix}$$

2D GM/Redi:

$$\boxed{\kappa_{\mathrm{redi}} = \kappa_y \quad \kappa_{\mathrm{gm}} = \chi/s}$$



Measuring eddy fluxes

Abernathey, Ferreira, Klocker (2013)

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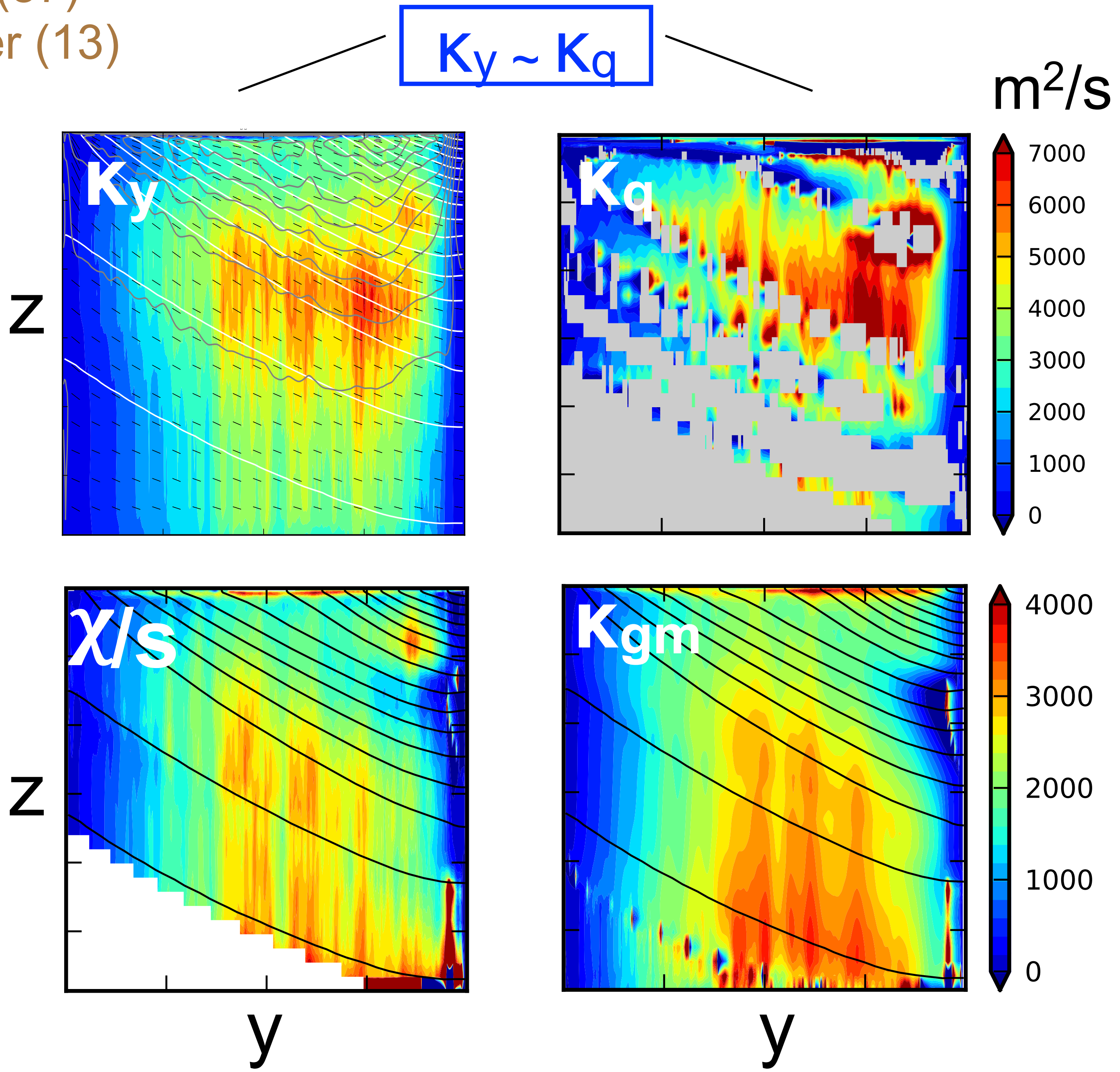

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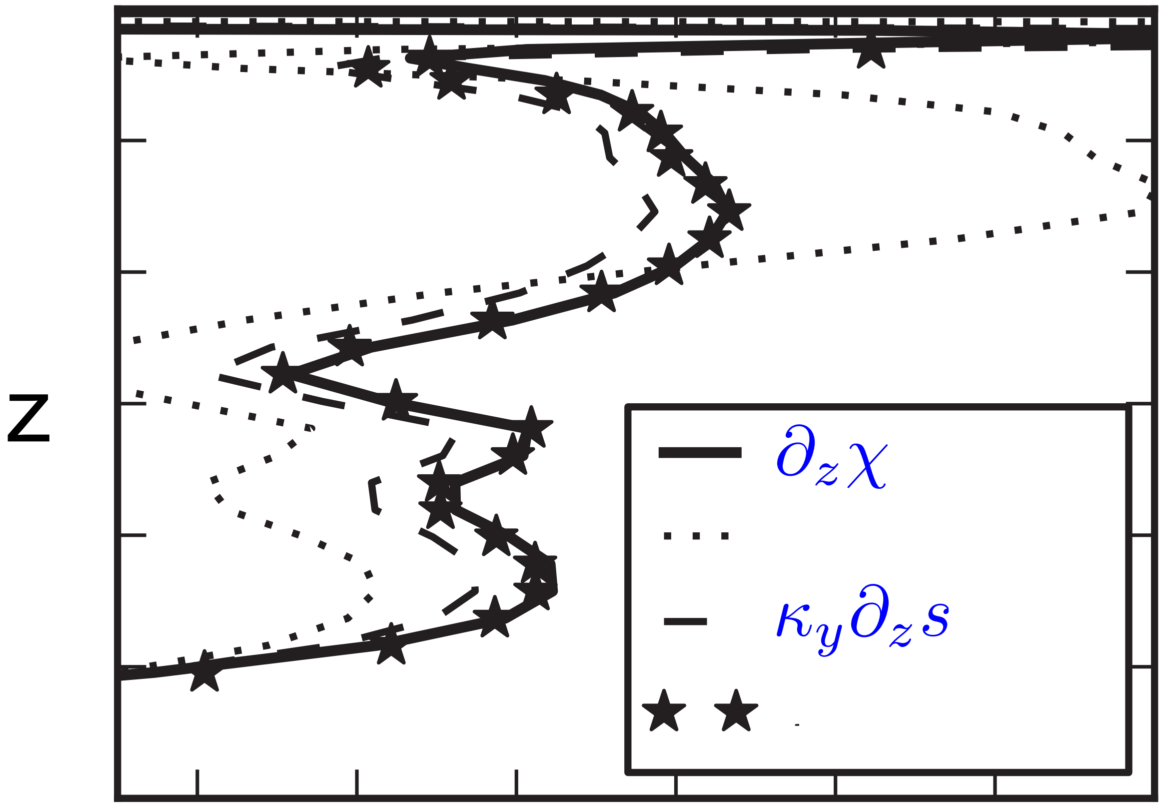

So $\kappa_y\partial_z \boldsymbol{s} \approx \partial_z\chi$

2D GM/Redi:

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→ $\boxed{\kappa_{\mathrm{redi}}\partial_z \boldsymbol{s} \approx \partial_z\left(\kappa_{\mathrm{gm}}\boldsymbol{s}\right)}$

Breadcrumb trail

- Need eddy fluxes to get oxygen (& other climate tracers) right
- Parameterized climate models with $\kappa_{\mathrm{redi}} = \kappa_{\mathrm{gm}}$ have κ_{redi} too small
- Tuning GCM to get stratification right requires $\kappa_{\mathrm{gm}} \sim 500\ \mathrm{m/s}^2$
- Tracer diffusivity estimates from models and obs: $\kappa_{\mathrm{redi}} \sim 5000\ \mathrm{m/s}^2$
- Model and obs: Both diffusivities strongly depth-dependent
- From above, $\kappa_{\mathrm{redi}} \partial_z \boldsymbol{s} \approx \partial_z \left(\kappa_{\mathrm{gm}} \boldsymbol{s} \right)$ and $\kappa_{\mathrm{redi}} \approx \kappa_q$

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- ➔ Set κ_{redi} via theory for QGPV flux, and integrate to get κ_{gm}

$$\boxed{\kappa_{\mathrm{gm}}(z) \boldsymbol{s}(z) = \kappa_{\mathrm{gm}}(0) \boldsymbol{s}(0) - \int_z^0 \kappa_{\mathrm{redi}}(z') \partial_z \boldsymbol{s} \, dz'}$$

Current work to test this idea

Using Arabian Sea simulations to estimate κ_{redi} and κ_{gm}:

- ZL continued 1/12^o AS sim to 62 years.
- Made series of 20 1-year runs (years 40-59), each restarted with biology switched off — biological variables become passive tracers
- Use multiple tracer method to extract S and A:

➡ $S = UDU^T$ >>> downgradient diffusion directions and diffusivities [encouraging]

➡ Extracting κ_{gm} from A … [blackboard!]

Other projects at CPCM

- Oxygen in the Arabian Sea vs. Bay of Bengal: similar geometry, but no suboxia in BoB. River outflow in BoB > more sediment > faster detrital sinking (Azhar, Lachkar, Levy & Smith 2017 GRL — full IO model)
- Models show monsoonal winds may intensify with global warming. Increased winds > increased productivity > increased OMZ (Lachkar, Levy & Smith 2018 Biogeosciences)
- Interannual variability of oxygen in the Indian Ocean (ongoing)
- Importance of Saharan dust deposition in biogeochemistry of AS (ongoing)
- GM-parameterized ROMS simulation of IO (ongoing)
- Carbon cycle and acidification in AS (starting)