Tropical Ocean Dynamics related to equatorial upwelling and oxygen minimum zones

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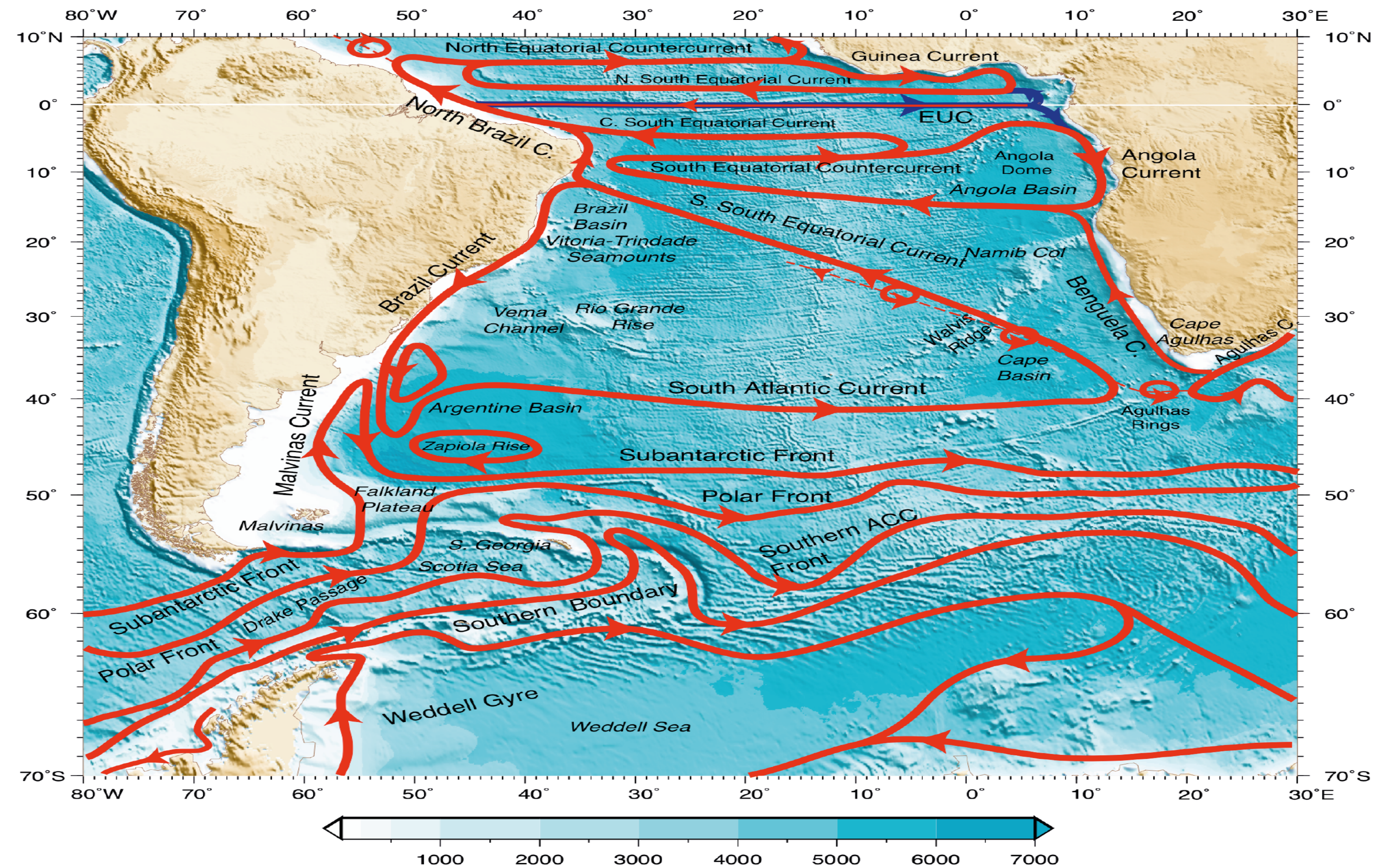
- Introduction to tropical Atlantic circulation
  - Wind-driven circulation
  - Thermohaline circulation
  - Subtropical Cells
- Dynamics of equatorial upwelling
  - Equatorial Undercurrent
  - Seasonality of mixing and upward nutrient supply
- Tropical oxygen minimum zones and marine ecosystem threats

Tropical and South Atlantic Circulation

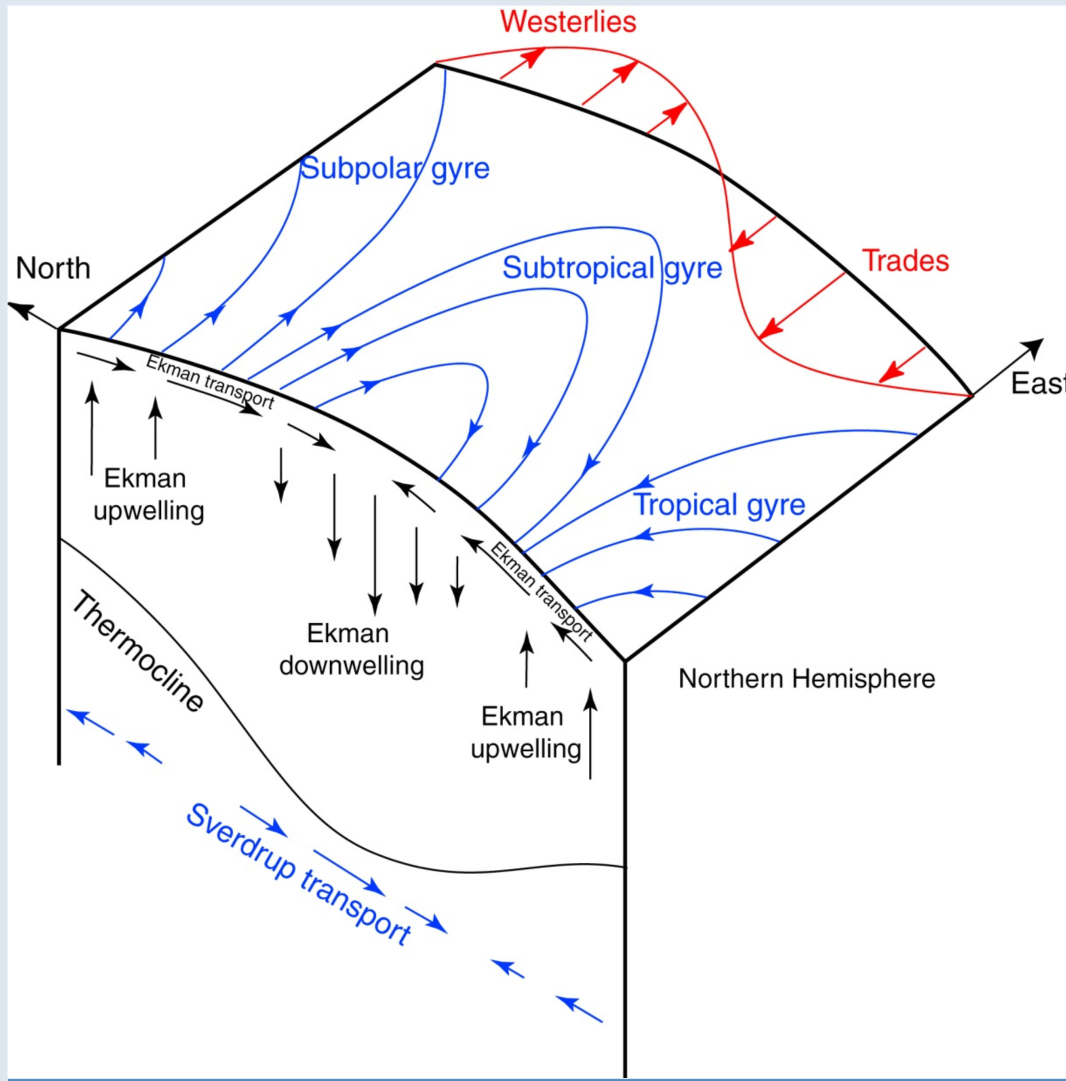


Talley et al., Descriptive Physical Oceanography: An Introduction, 2011

Wind-driven Circulation: Sverdrup Balance

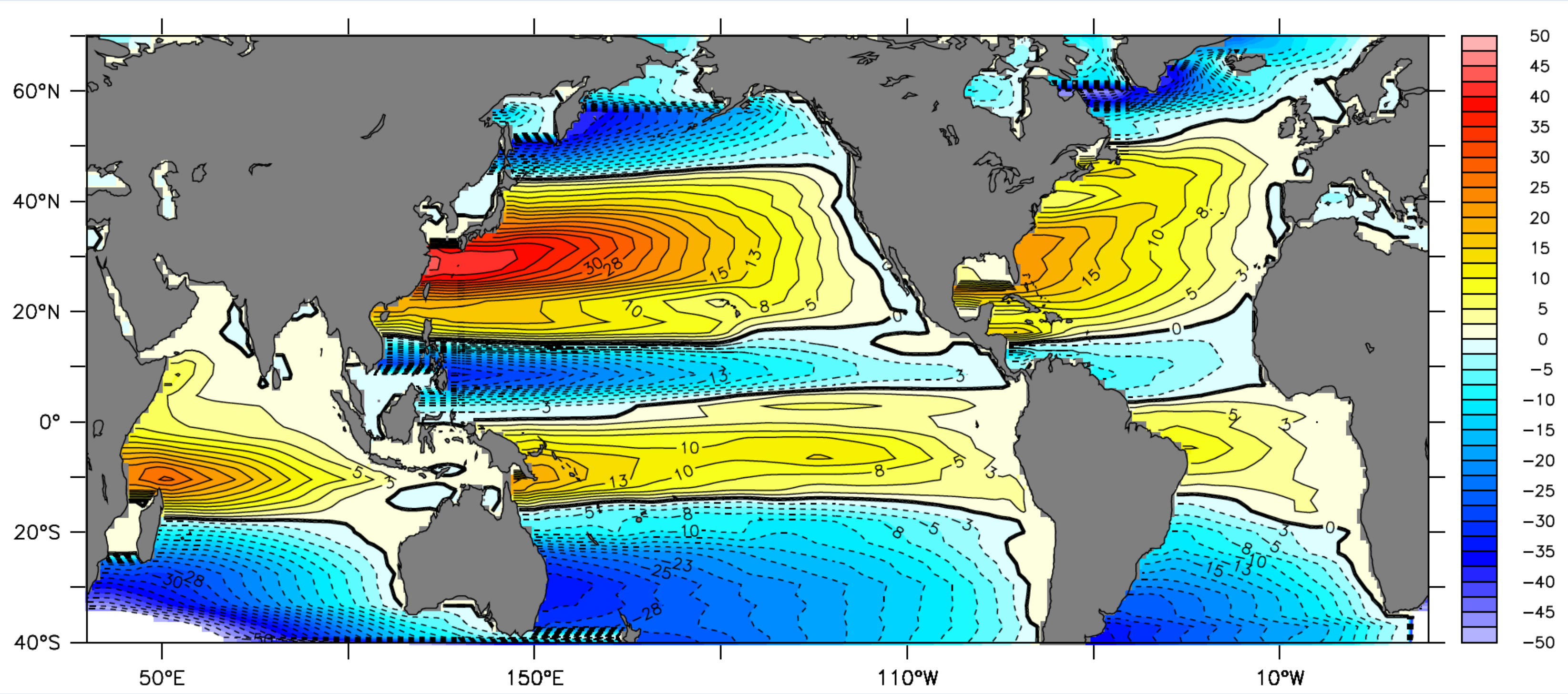
- Westerly and trade winds force Ekman transport with Ekman convergence in the subtropics and divergence in subpolar and tropical regions
- Ekman downwelling and upwelling results
- Sverdrup mass transport:

$$= \frac{\times \vec{\tau}}{\beta}$$



Talley et al., DPO, 2011

Sverdrup Stream Function [Sv]



For a subtropical gyre to expand poleward, a poleward shift of the wind system is required.

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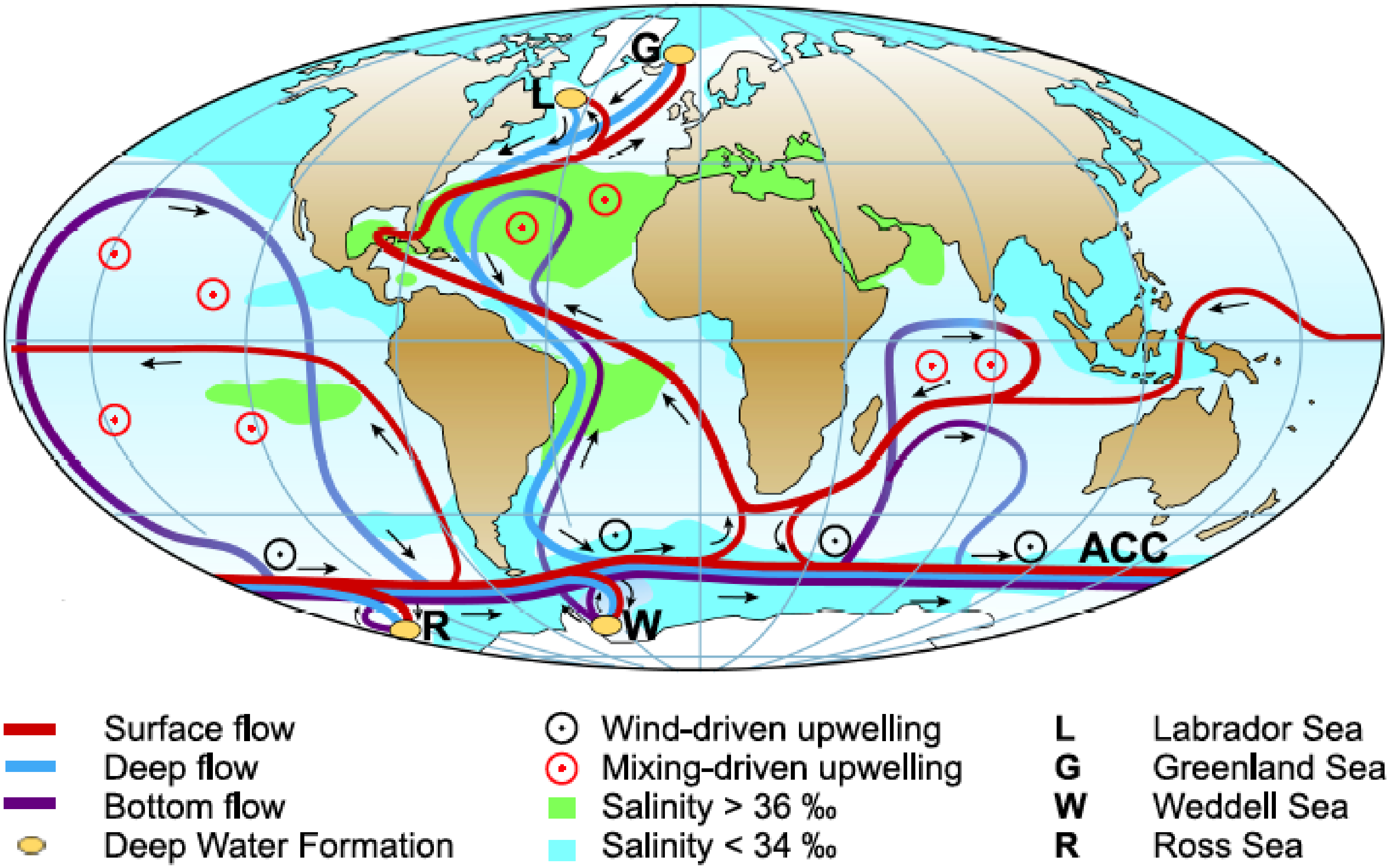
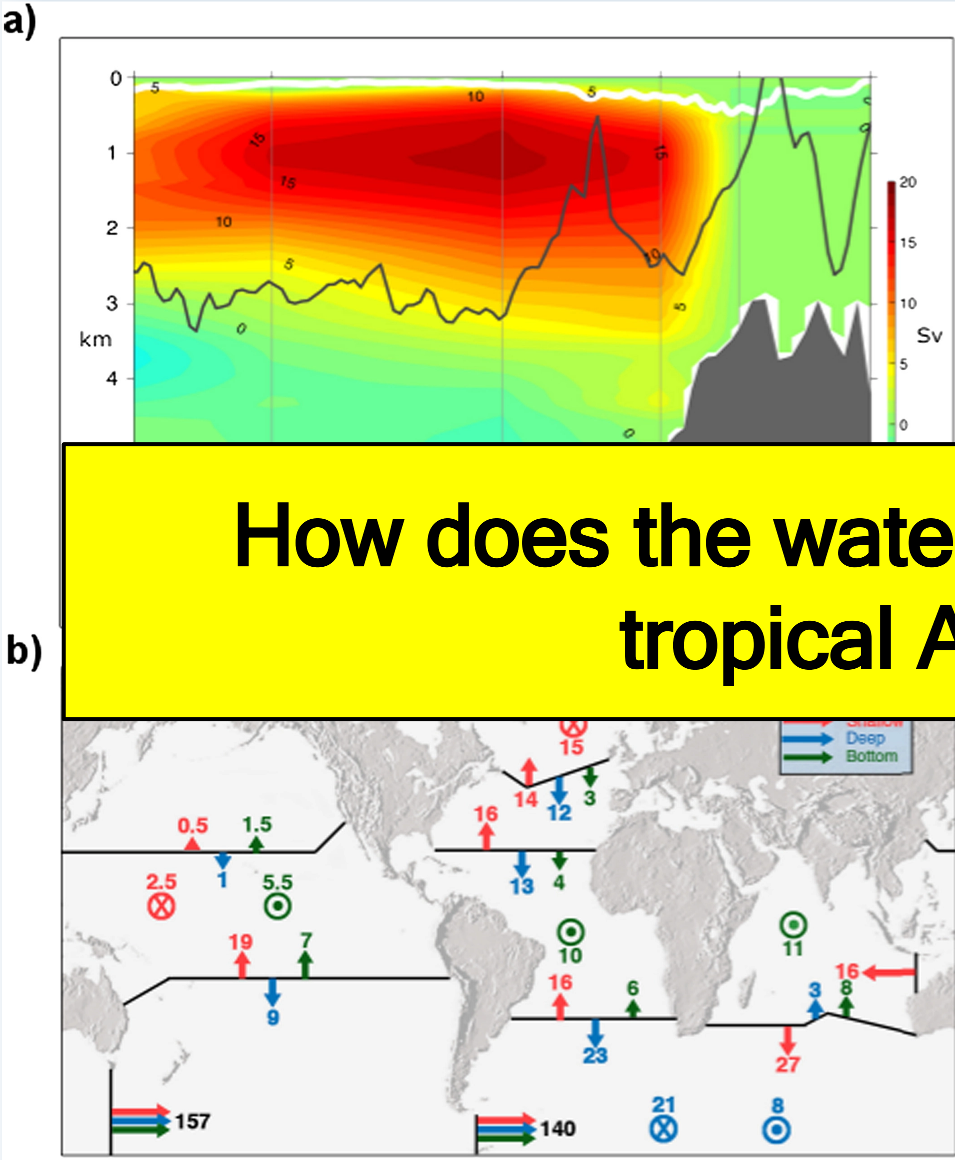
Olbers et al., Ocean Dynamics, 2012

Large Scale Buoyancy Driven Ocean Circulation



Kuhlbrodt et al., 2007

Atlantic Meridional Overturning Circulation



AMOC streamfunction (shading) and crest of the Mid-Atlantic Ridge (black line)

MOC is a 2D-simplification of a complex 3D circulation derived by zonal averaging

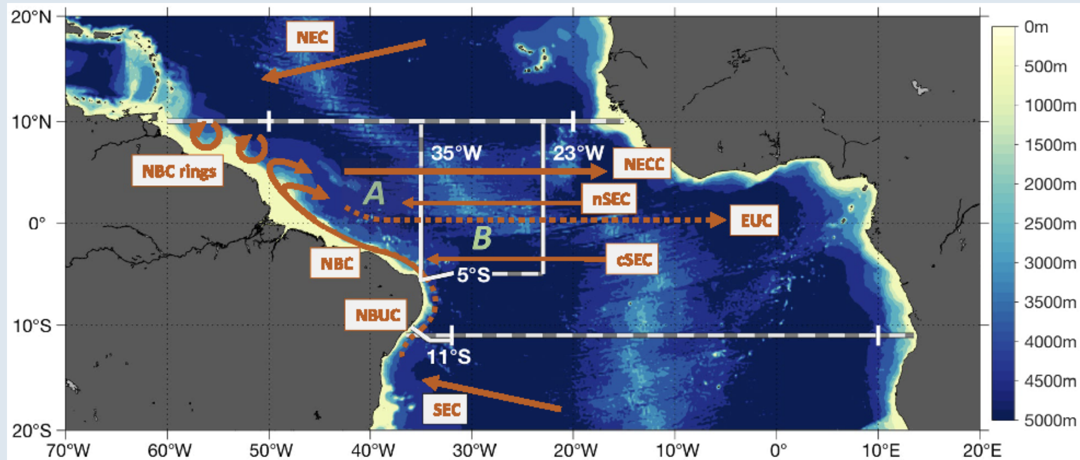
How does the water flow through the tropical Atlantic?

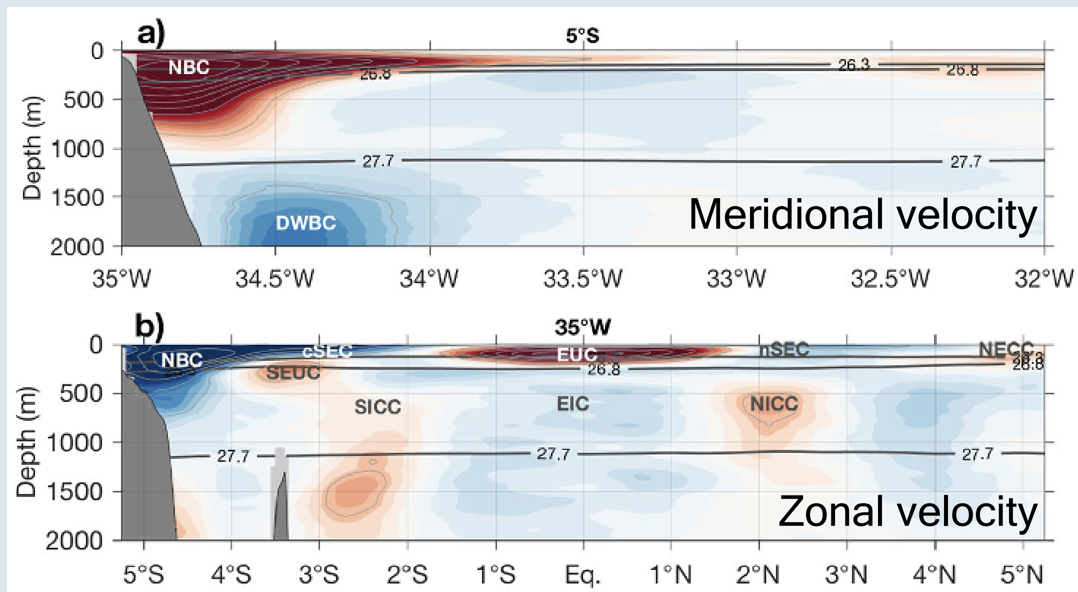
three layers: shallow (red, <2 km), deep (blue, 2-4 km), and bottom (green, >4 km)

after Lumpkin and Speer (2007) and Ganachaud and Wunsch (2000)

Tropical Atlantic Circulation

- Western boundary: northward North Brazil Current and southward Deep Western Boundary Current
- Interior: strong east- and westward wind-driven and eddy-driven zonal currents
- Northward AMOC return flow (above 27.7 kgm^{-3}) has to pass through the equatorial current system

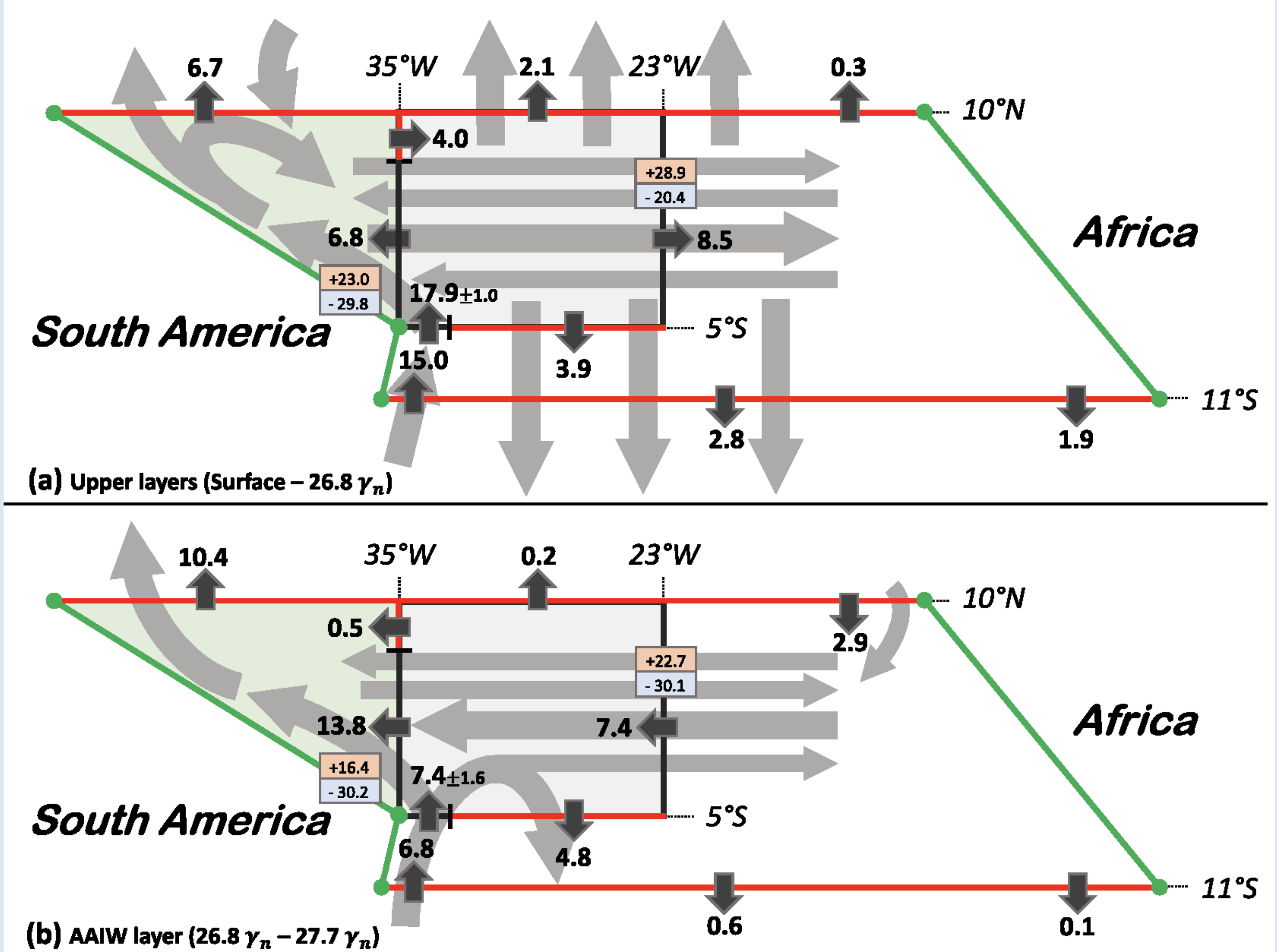




Tuchen et al., 2022

AMOC-related Tropical Atlantic Circulation

- Pathways
- Upper ocean:
  - Western boundary
  - EUC/NECC, equatorial upwelling and northward Ekman transport
- Intermediate Layer
  - Western boundary
  - Return flow at the eastern boundary



Tuchen et al., 2022

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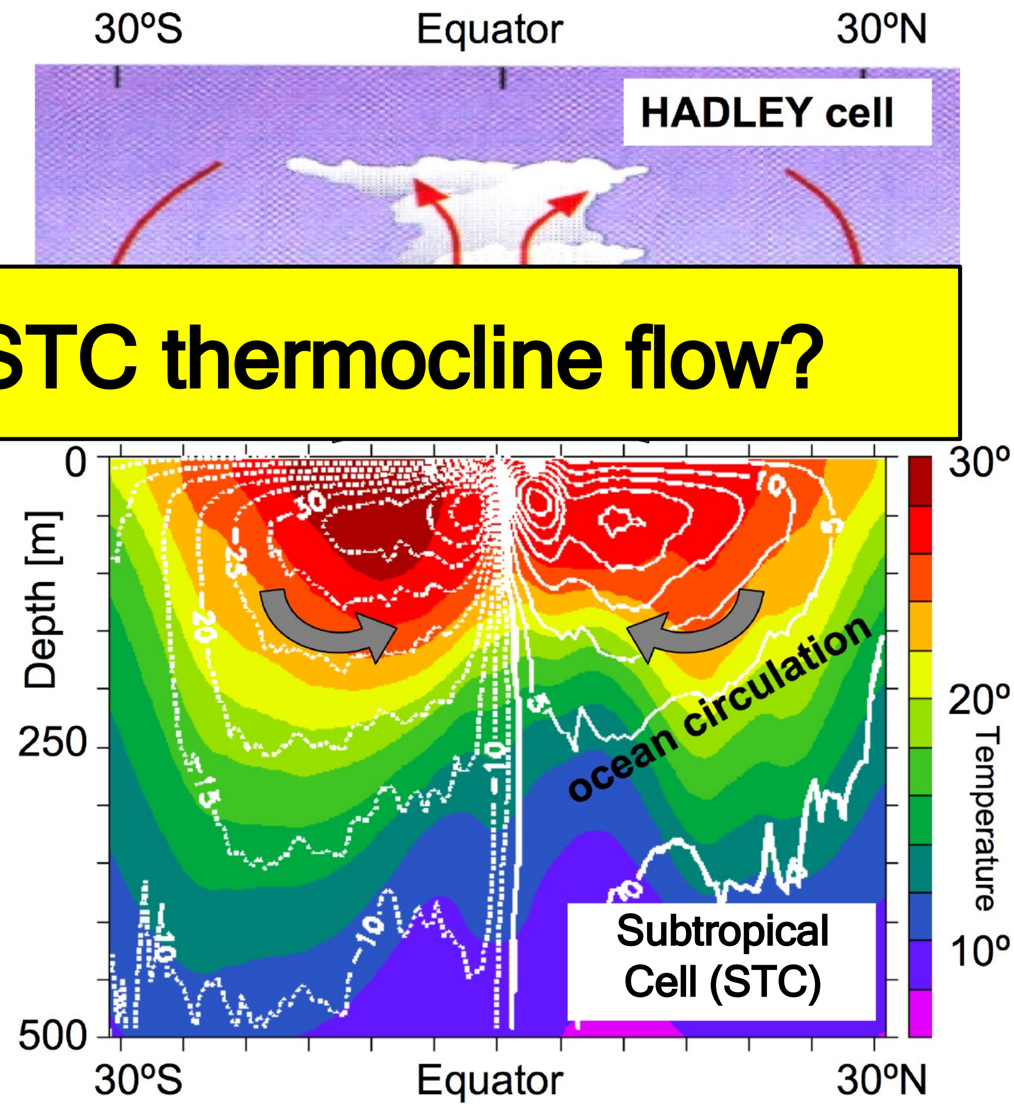
Shallow Overturning: Subtropical Cells (STCs)

- STCs are shallow meridional circulation cells that connect the
- equatorial or eastern boundary upwelling regions via the equatorial eastward currents
- STCs are closed by poleward surface flow

What drives the STC thermocline flow?



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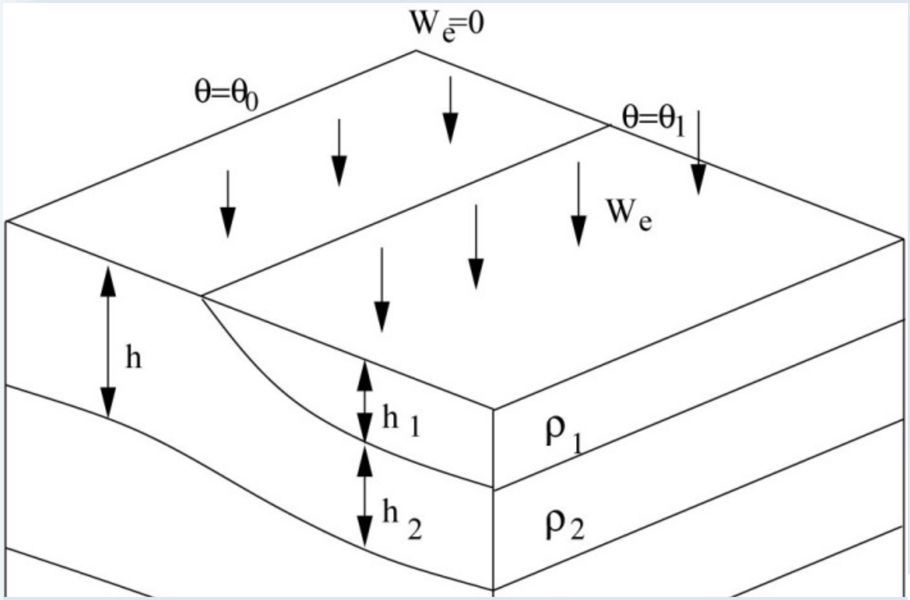
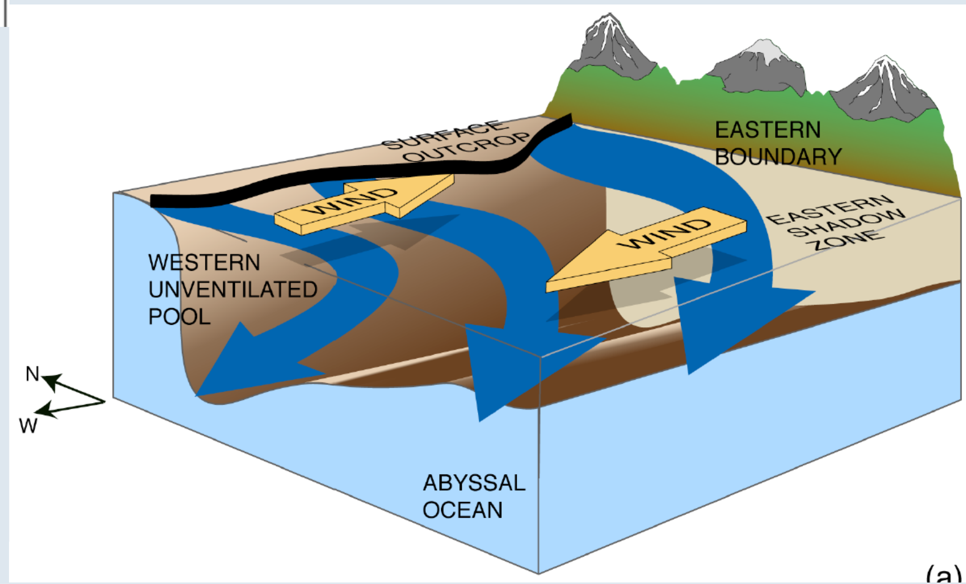
Ventilated Thermocline



Luyten, Pedlosky, Stommel (1983)

- ocean interior & eastern boundary
- Ekman pumping w_e due to wind curl
- geostrophy (potential vorticity conservation)
- no diapycnal mixing

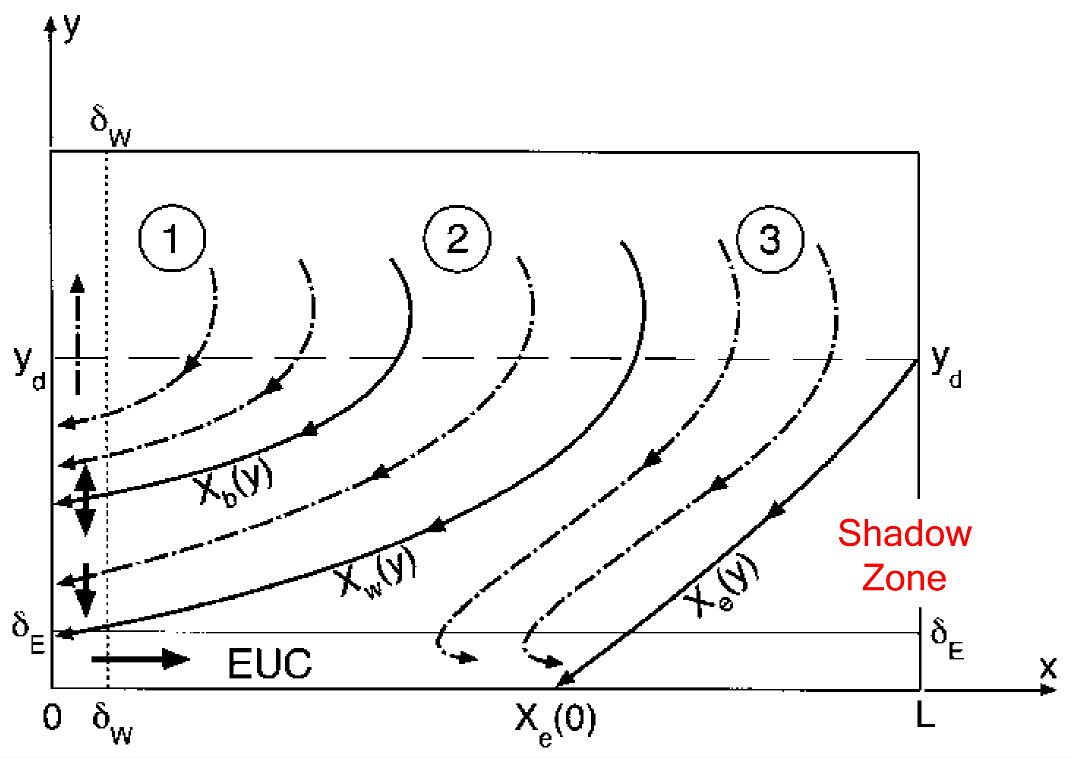
- constant layer thickness at the eastern boundary:
- increase of layer thickness toward west due to Ekman pumping
- flow follows contours contours
- eastern boundary no streamline - shadow zone as



Connection between the tropical and subtropical thermocline

- Thermocline waters subducted in the subtropics flow equatorward and westward
- The three different exchange windows in the subtropics and between the subtropics and the tropics that are possible for subducted water

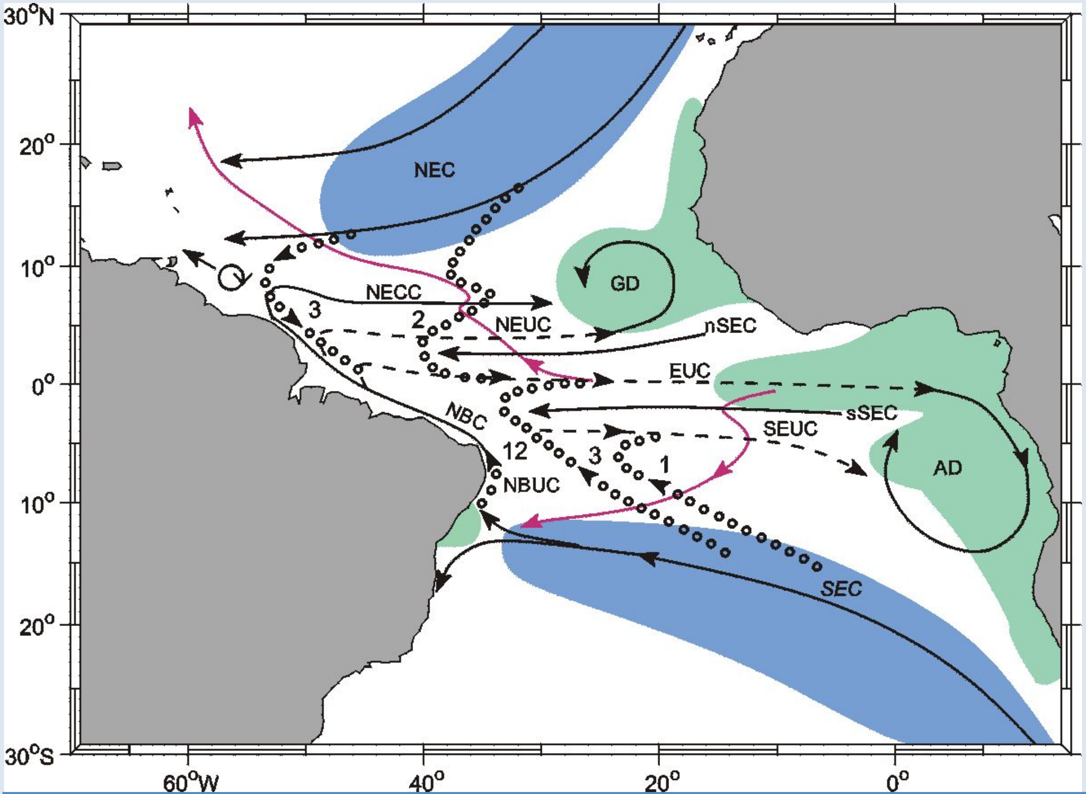
1. Recirculating window
2. Western boundary exchange window
3. Interior exchange window



Malanotte-Rizzoli et al., 2000

The Atlantic’s STC

- Subduction due to anticyclonic wind stress curl in the subtropics (blue)
- Equatorward and westward thermocline transport (dotted) dominantly from the South
- Eastward transport with Equatorial Undercurrent (EUC) and NEUC/SEUC
- Upwelling at the equator and eastern boundary (green)
- Poleward Ekman transport in the surface layer (red)



Schott et al., 2004

The Atlantic's STC & AMOC

- Subduction due to anticyclonic wind stress curl in the subtropics (blue)
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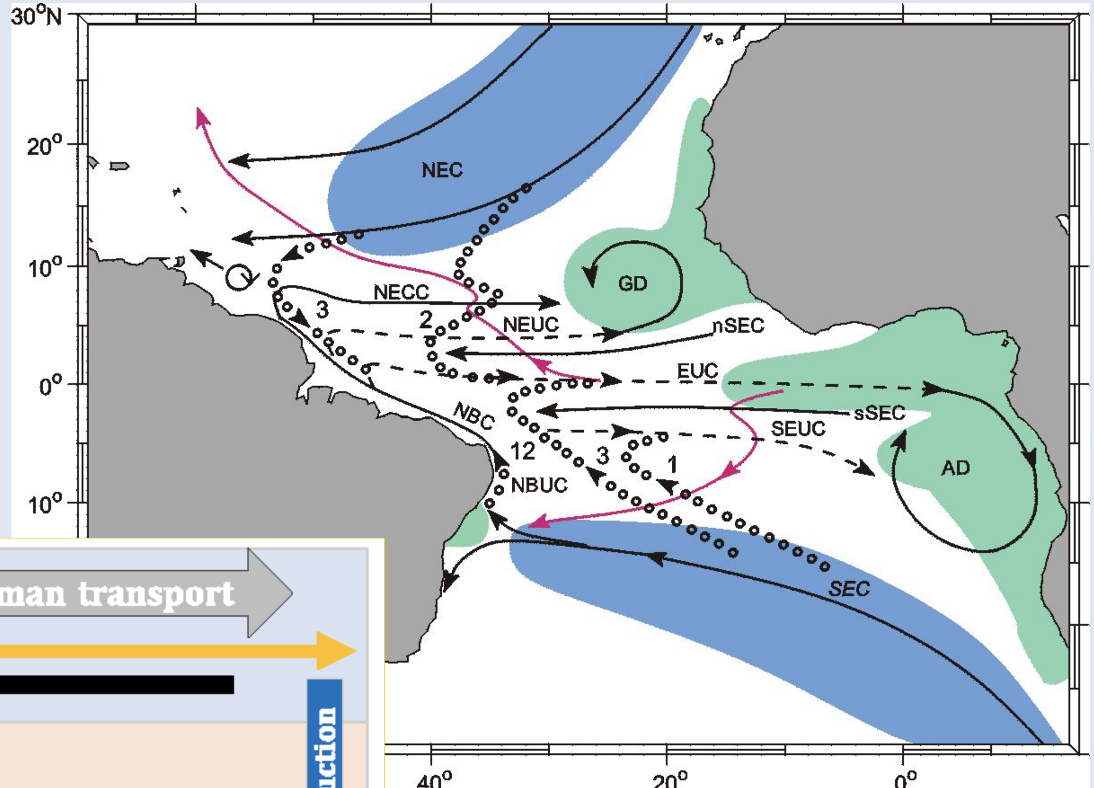

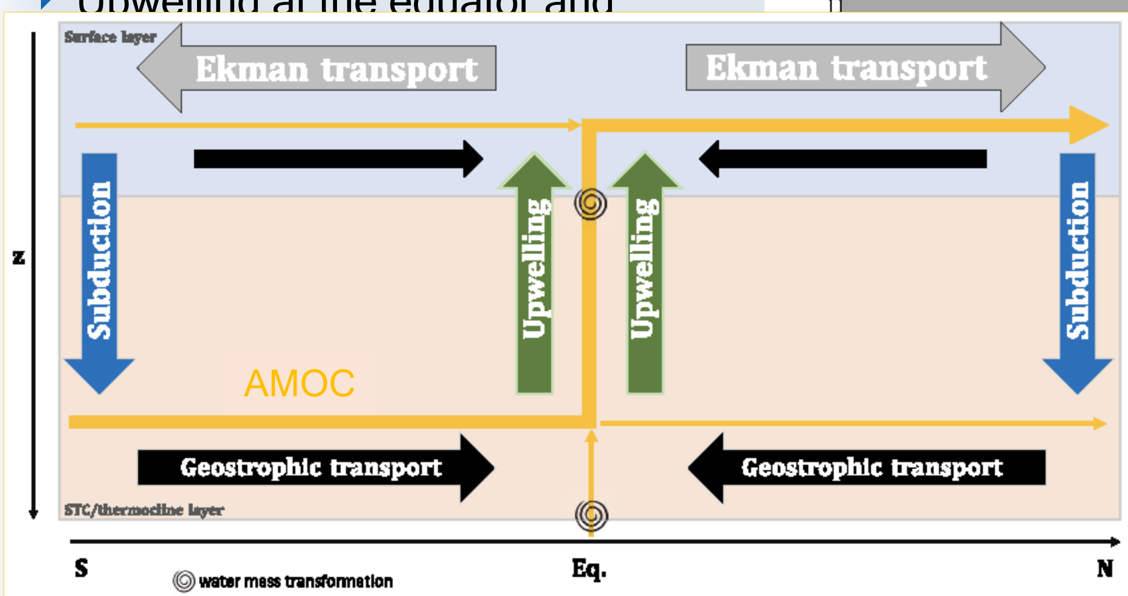

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AMOC superimposed on STC results in asymmetric STC

Tuchen et al., 2019, 2022

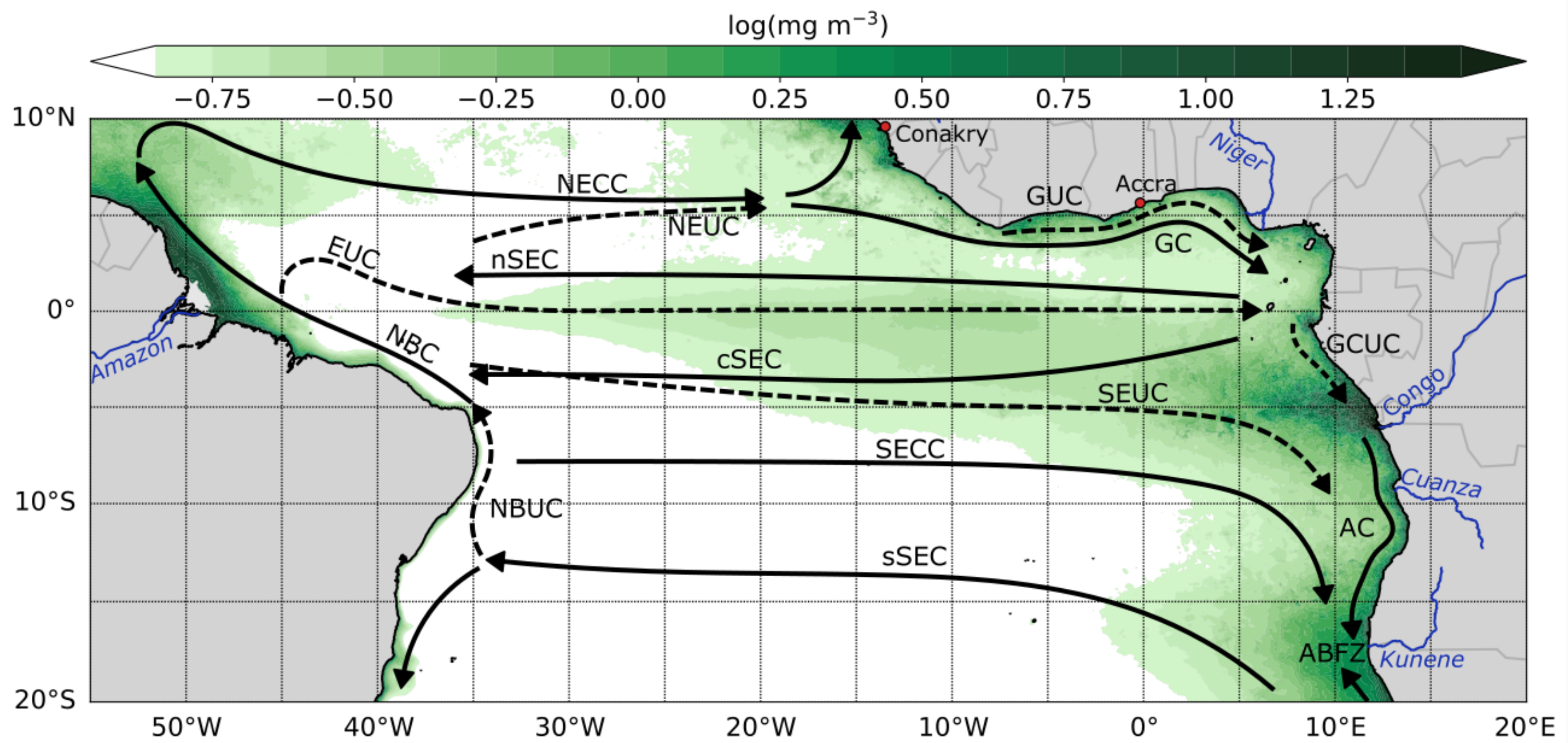
Main Points Part I

- Sverdrup balance and subtropical gyres
- Atlantic meridional overturning circulation
- Complex superposition of wind-driven and buoyance-driven circulation in the tropical Atlantic
- Ventilated thermocline
- Asymmetric Atlantic Subtropical Cells

Now, more to the Equatorial Undercurrent

Tropical Atlantic Circulation and Biological Productivity

- Enhanced productivity at the eastern boundaries, near the Amazon and Congo river mouths and along the equator
- Equatorial Undercurrent (EUC) among strongest currents with velocities larger than 1 m/s supplies equatorial upwelling



Chl-a and circulation scheme

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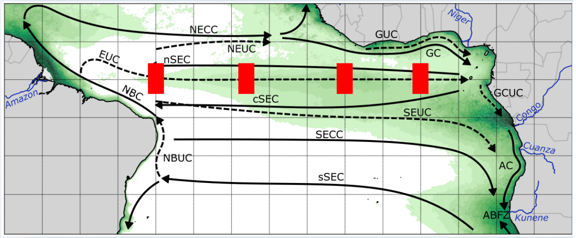
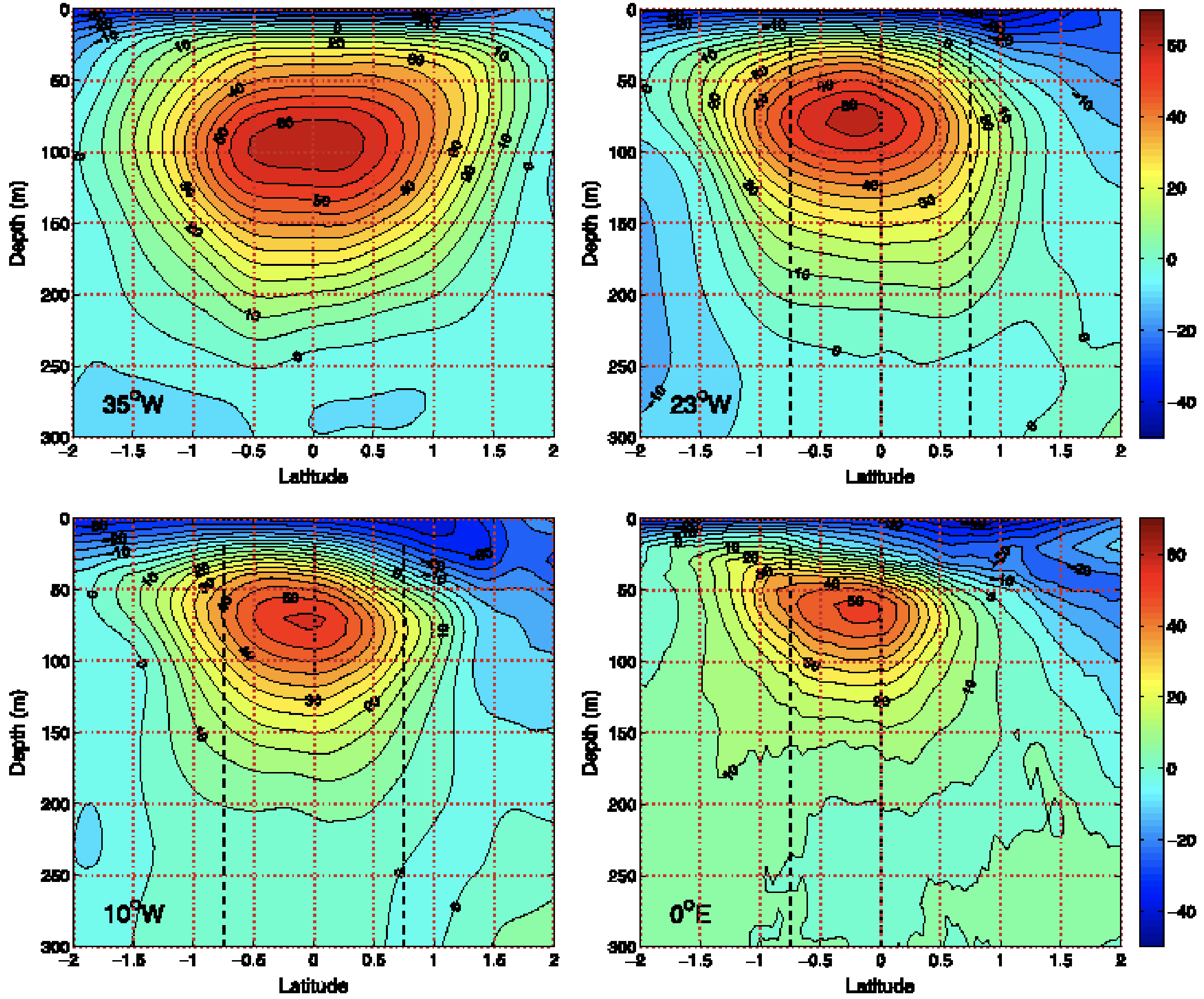
Equatorial Undercurrent (EUC)

- Mean zonal velocity in the western, central, and eastern Atlantic from direct velocity measurements
- EUC decreases in strength and shallows toward east





Johns et al., 2014

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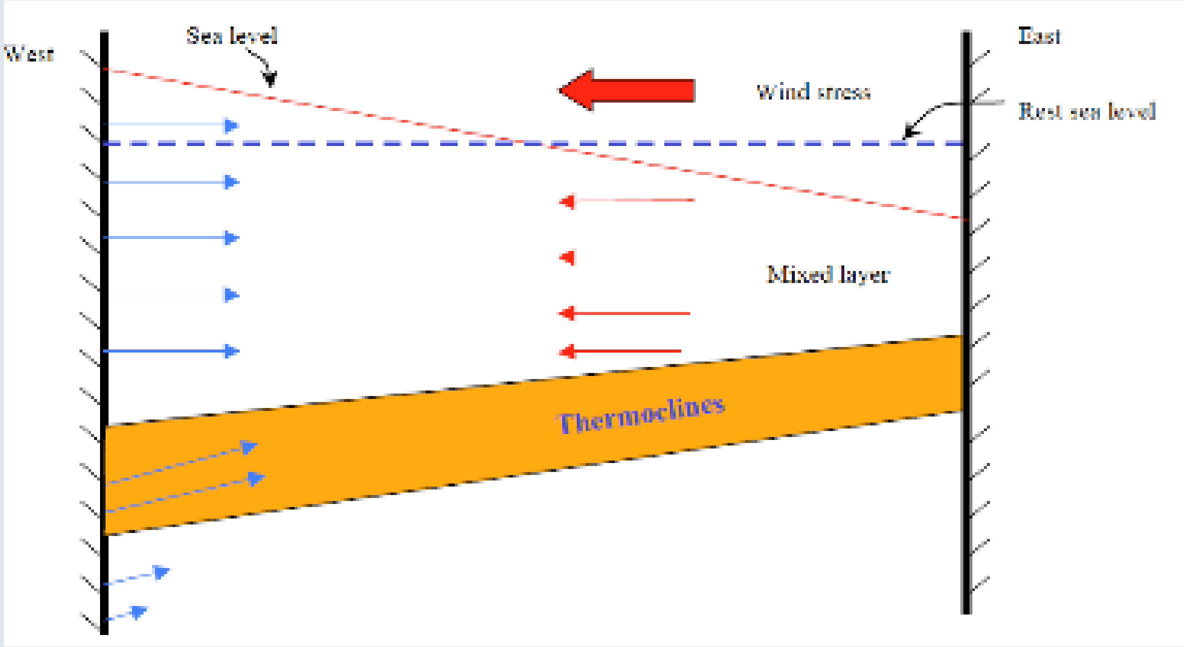
EUC Equilibrium Response

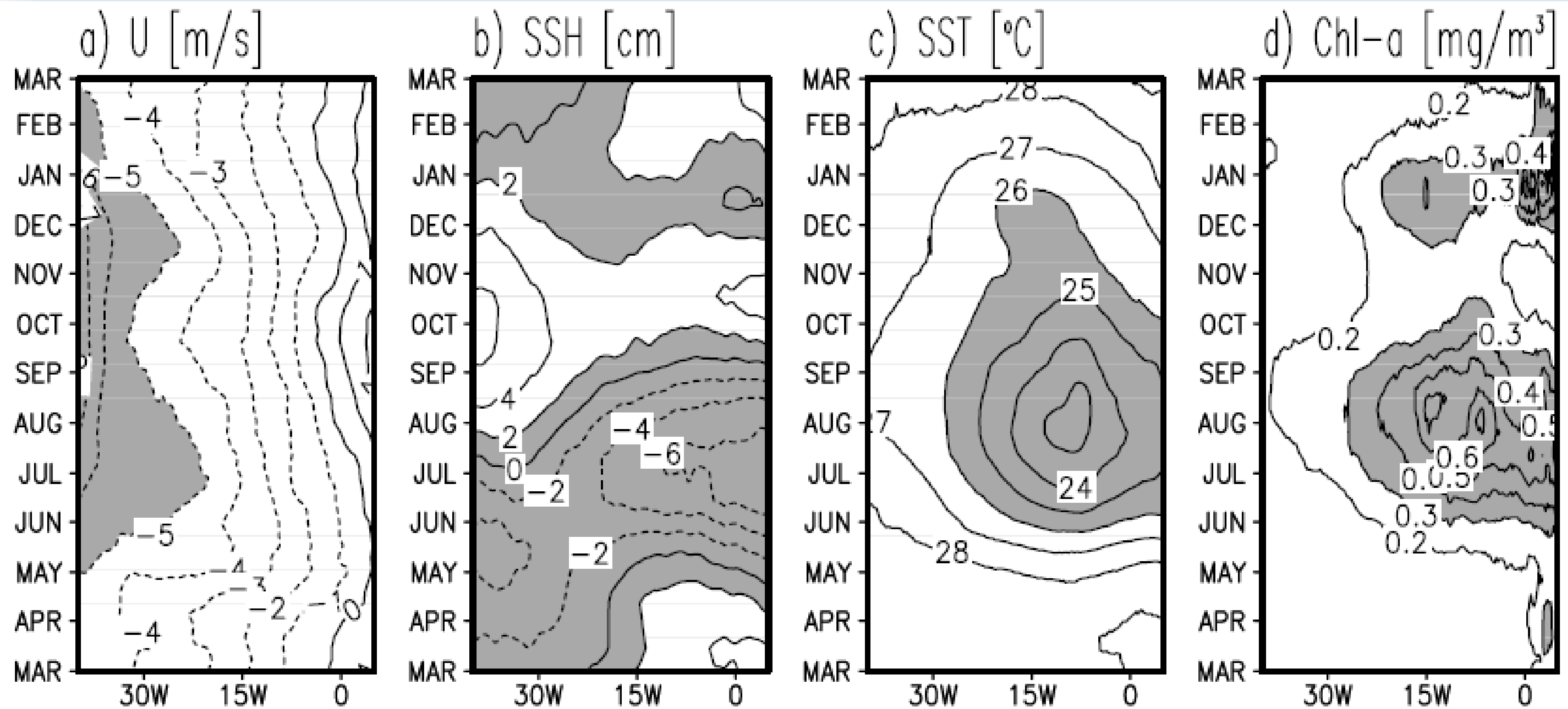
- EUC is forced by the westward wind stress at the equator that results in equatorial upwelling, tilted thermocline, westward surface flow, and reversely-tilted sea level
- At the surface, westward wind stress is balanced by eastward zonal pressure gradient
- At thermocline depth zonal pressure gradient produces eastward flow (EUC) that is balanced by friction



Do represent seasonal EUC variations an equilibrium response to the wind stress?

Seasonal Cycle of Equatorial Upwelling

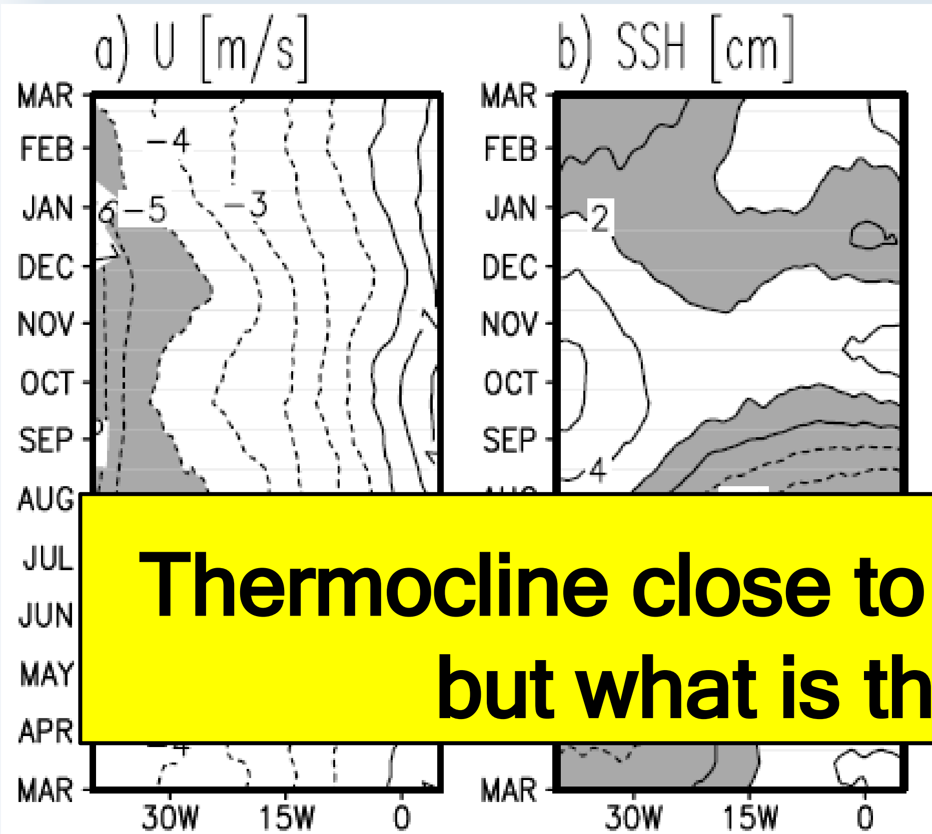
- Seasonal cycle of equatorial (a) zonal winds, (b) sea surface height, (c) sea surface temperature, and (d) chlorophyll-a



Grodsky et al., 2008

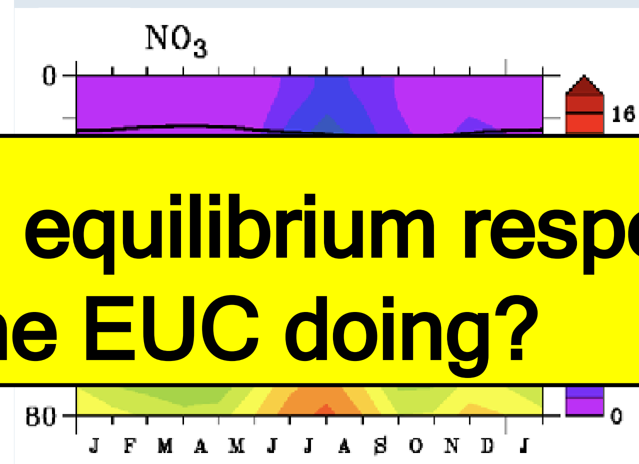
Seasonal Cycle of Equatorial Upwelling

- Seasonal cycle of equatorial (a) zonal winds, (b) sea surface height
- Nitrate from model simulation (right)



Grodsky et al., 2008

High nitrate levels closest to the surface in July and December corresponding to low sea level during upwelling conditions



Radenac et al., 2020

20°C isotherm as

20-5°W.

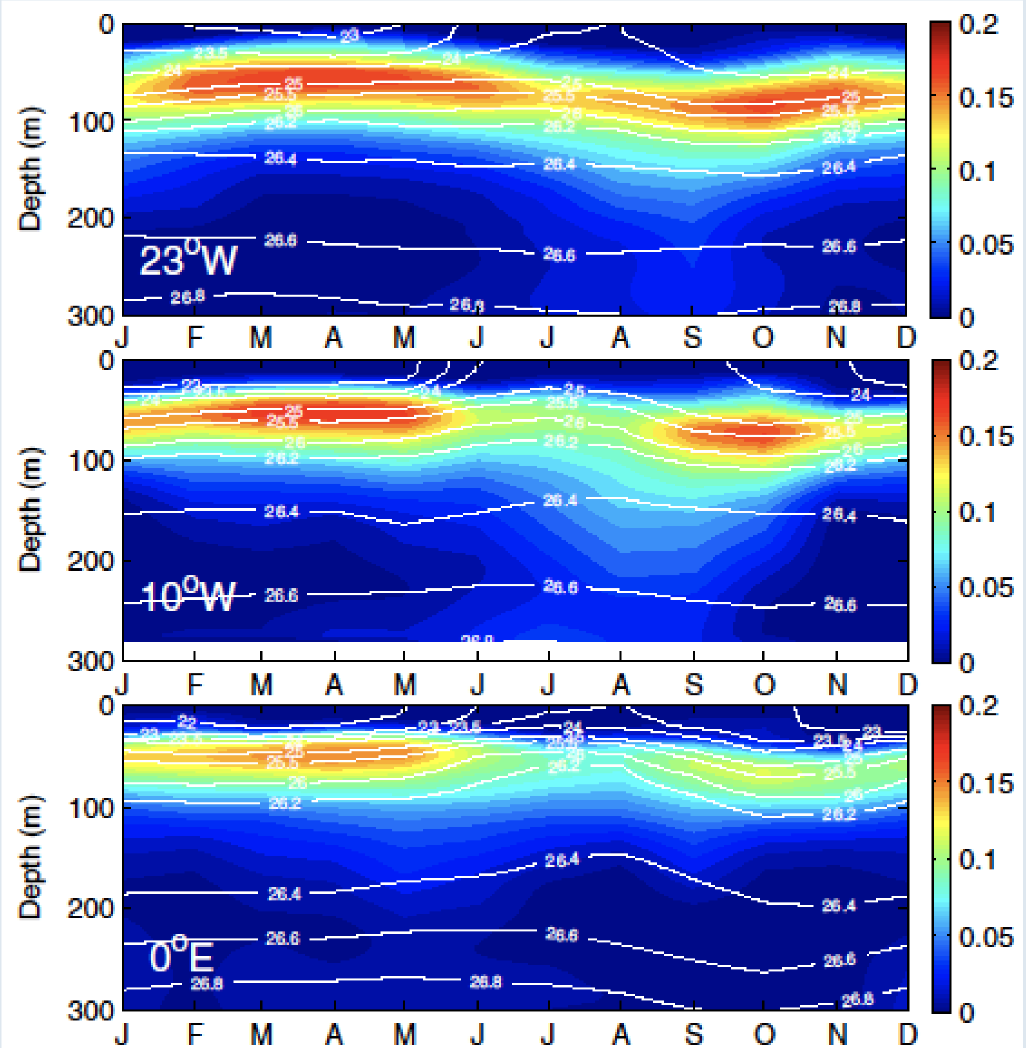
Thermocline close to equilibrium response, but what is the EUC doing?

EUC Transport Profiles

- Moored observations show weakest EUC thermocline transport during July/August and December, i.e., when the easterlies are strong

$$(z)=\int_{-}^{0} \left(\quad , \quad \right)$$

Monthly-mean EUC transport profiles (Sv/m) at 23°W, 10°W, and 0°E with density contours



Johns et al., 2014

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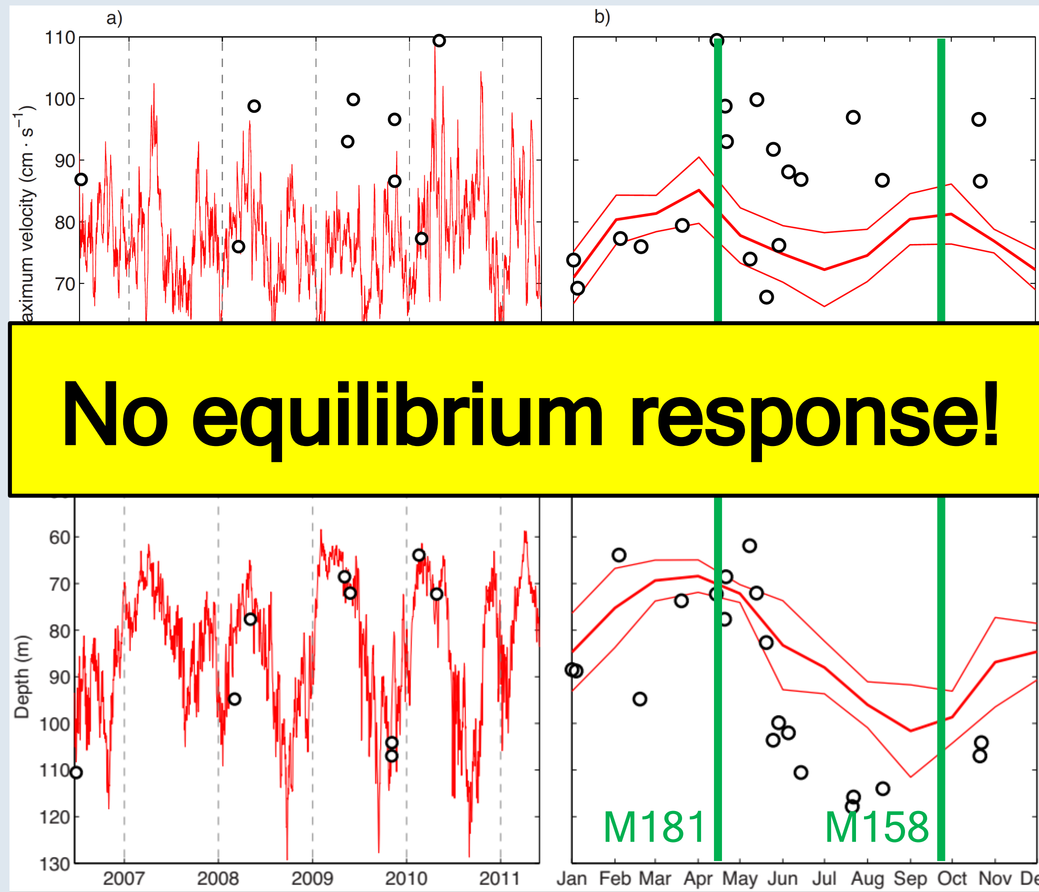
EUC Core Velocity and Depth

- Moored observations at 23W show semi-annual cycle of EUC core velocity with maxima in boreal spring and autumn
- Annual cycle of EUC core depth with minimum in boreal spring and maximum in autumn
- Explained by resonant equatorial wave response (Brandt et al. 2016):
  - 2nd baroclinic mode semi-annual cycle
  - 4th baroclinic mode annual cycle



Brandt et al., 2014

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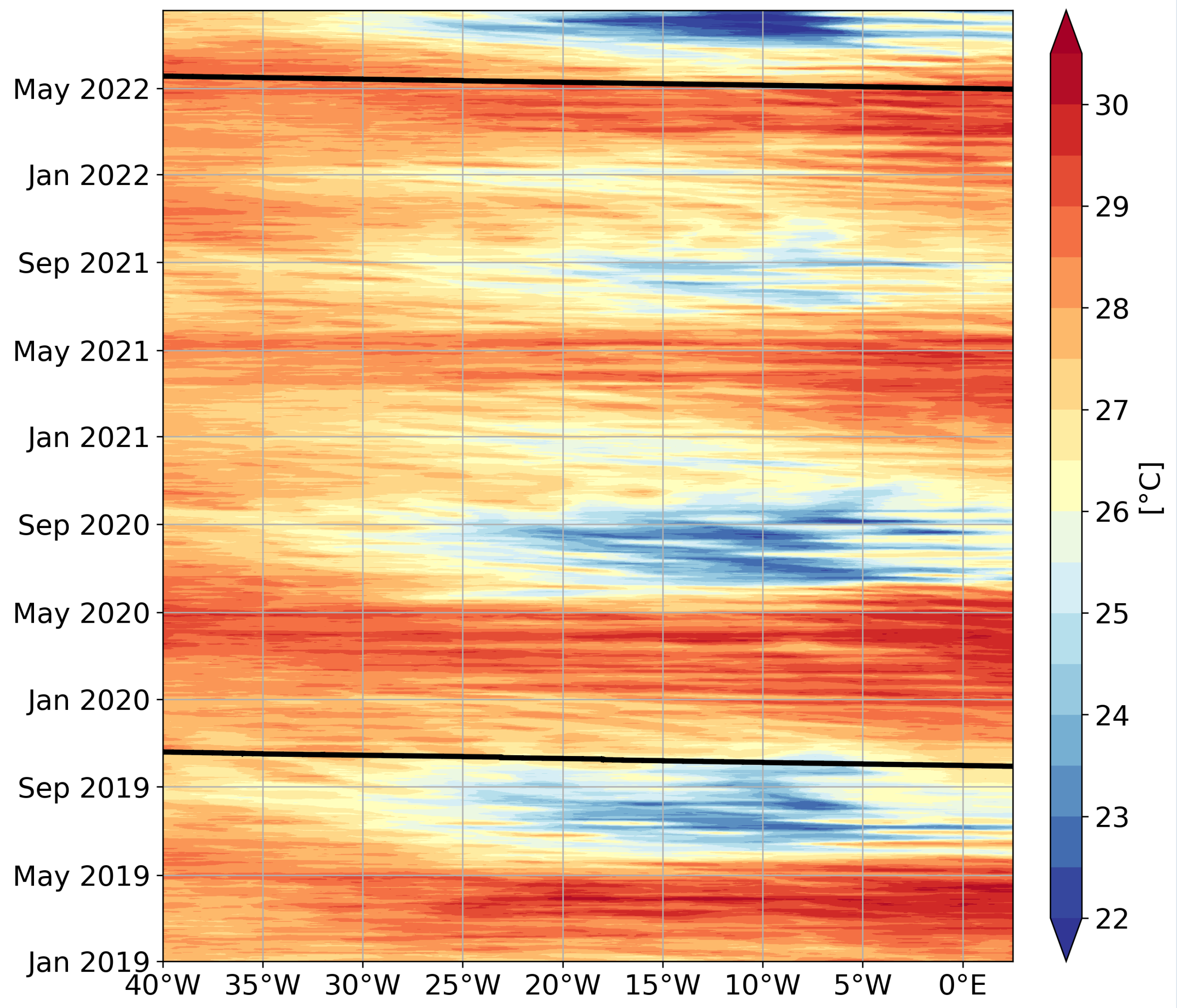
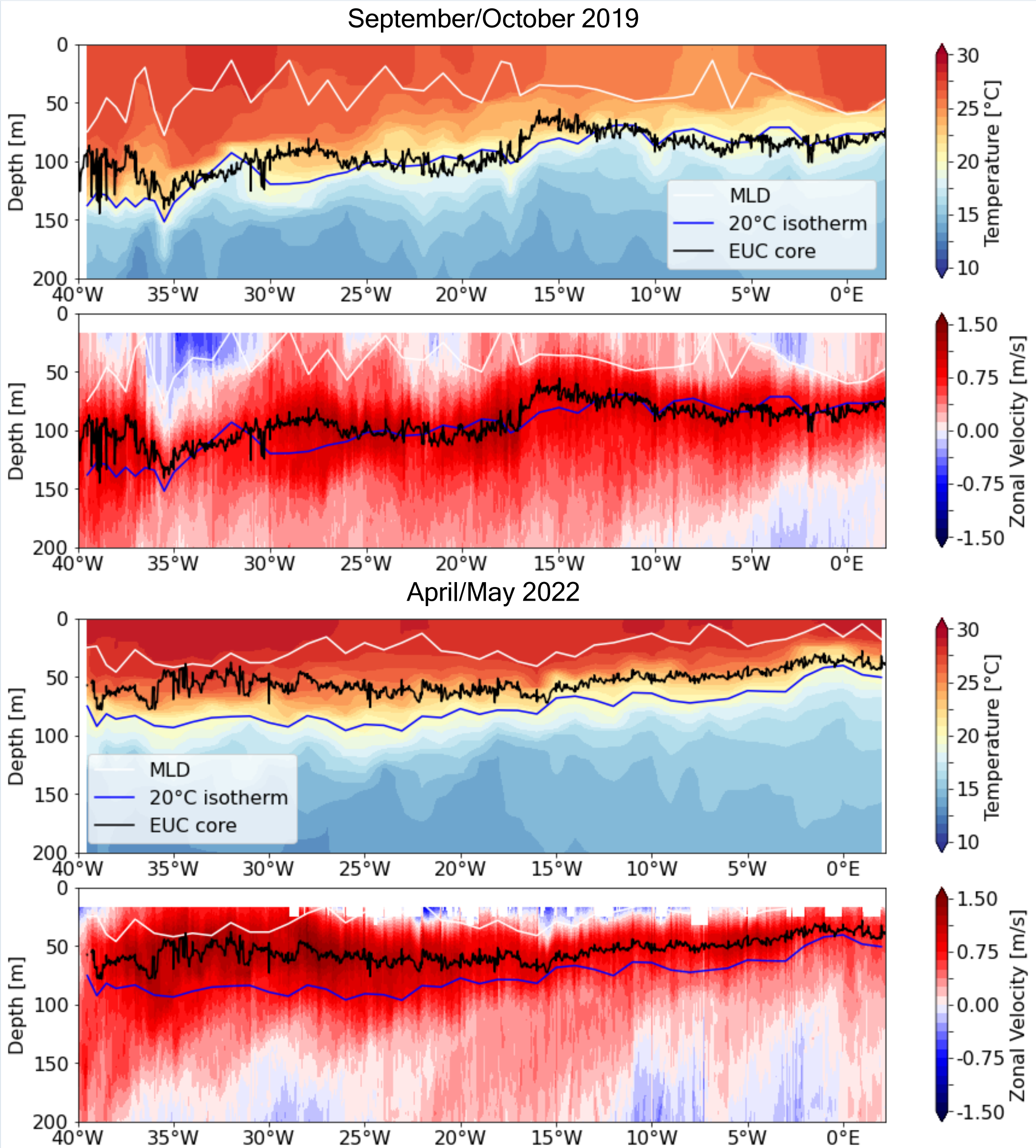
Trans-Atlantic Equatorial Cruises I&II

- RV Meteor cruises:
  - M158: Sep./Oct 2019 at end of the Cold Tongue season
  - M181: Apr./May 2022 at end of warm season



Temperature and Zonal Velocity during TRATLEQ I&II

- EUC core velocity during both cruise partly > 1m/s
- Deep EUC in Sep./Oct. and shallow EUC in Apr./May: resonant basin mode response
- EUC core (black line) shallower than 20C isotherm (blue line) during Apr./May and appr. at same depth during Sep./Oct.



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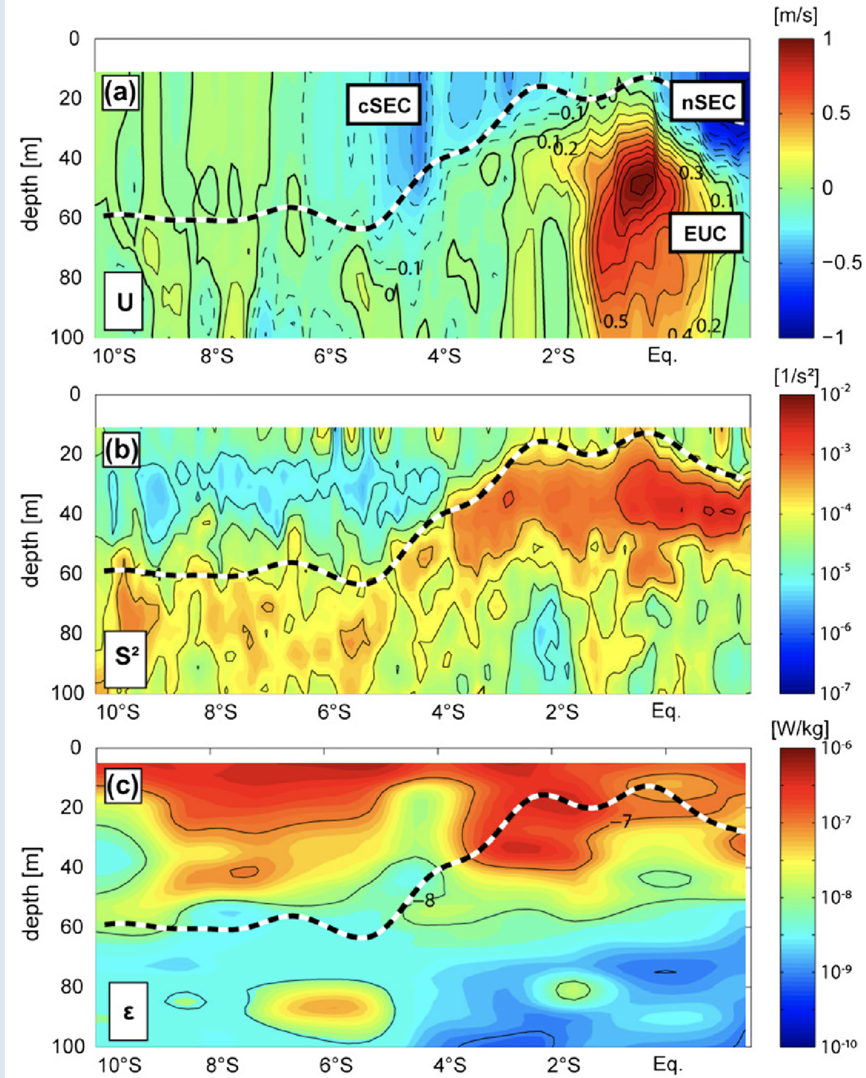
EUC and Mixing at 10W

- Mixing derived from shipboard microstructure measurements: Diapycnal diffusion coefficient

$$= \frac{\Gamma}{\quad^{2}}$$

... mixing efficiency
... dissipation rate
... buoyancy frequency

- High mixing, in the shear zone above the EUC
- Low mixing in the EUC core

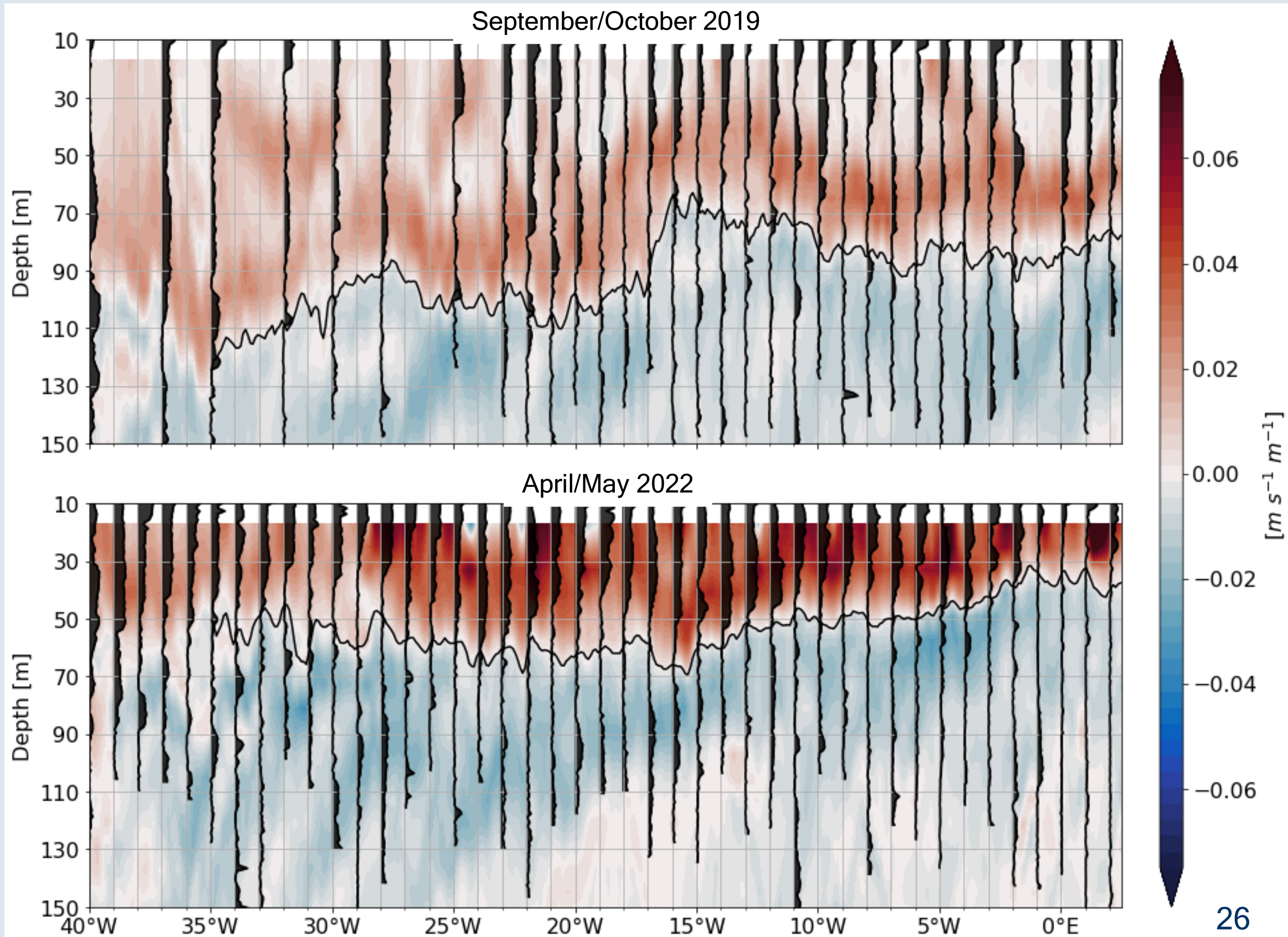


(a) Zonal velocity, (b) squared shear, (c) turbulence dissipation rate, , along 10°W in June 2006.The black and white line denotes the MLD.

Hummels et al., 2003

Zonal Shear and Mixing

- Shear zone above EUC with elevatad turbulence dissipation rate, , reach down to >90m during Sep./Oct.
- Stronger shear and dissipation rate during Apr./May, but only above 50m
- Sep./Oct. was period with strong TIWs - more scattered mixing events



Nutrients and Mixing

- Nutrient levels are similar during both seasons, but more deep mixing events during Sep./Oct. suggesting upward nutrient flux
- In Apr./May high nutrients at shallow depths in the far East – plankton bloom
- Nutrient flux:

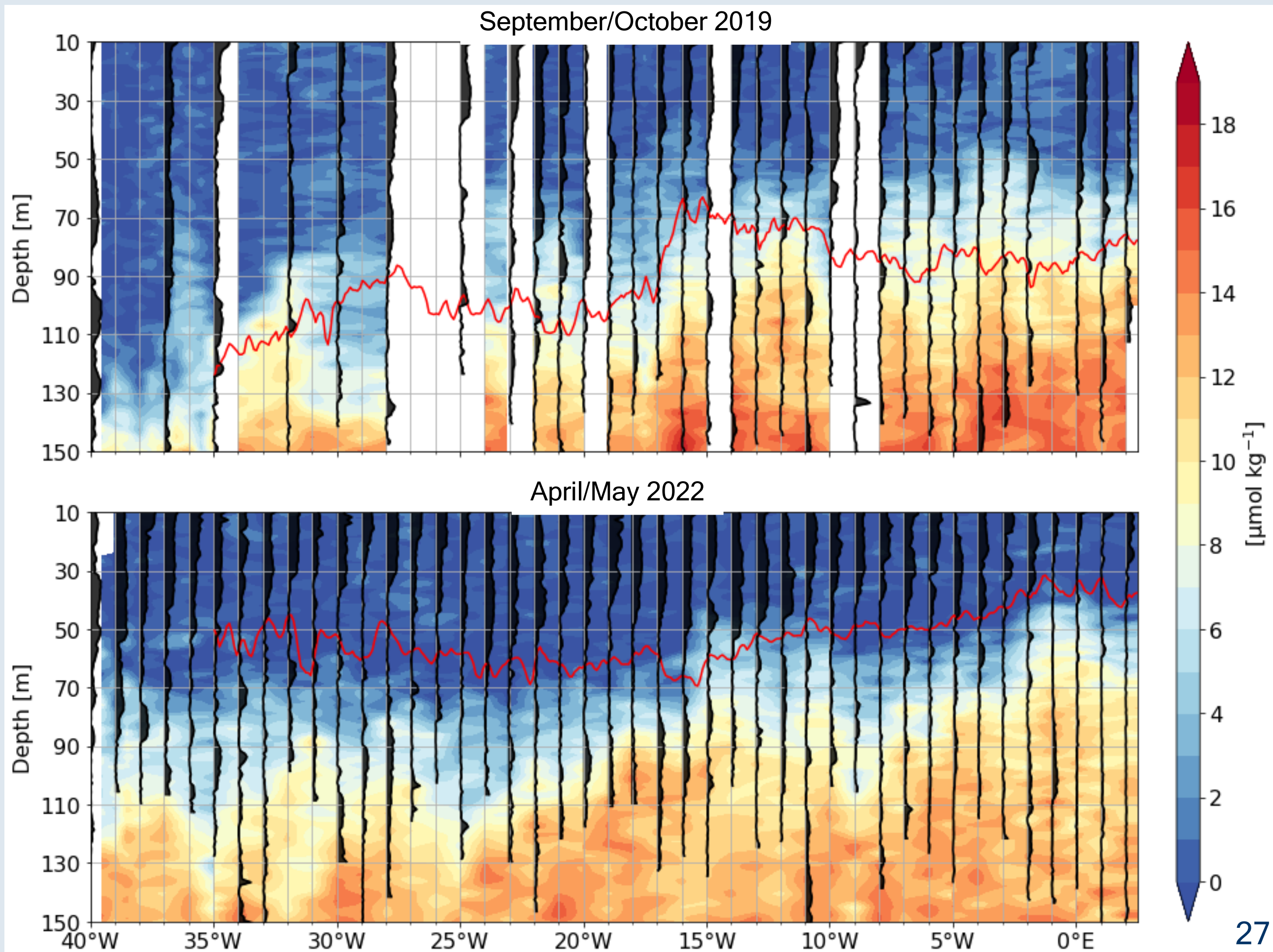
$$ _3 = \frac{\quad 3}{} $$

and

with

$$ = \frac{\Gamma}{\quad 2} $$

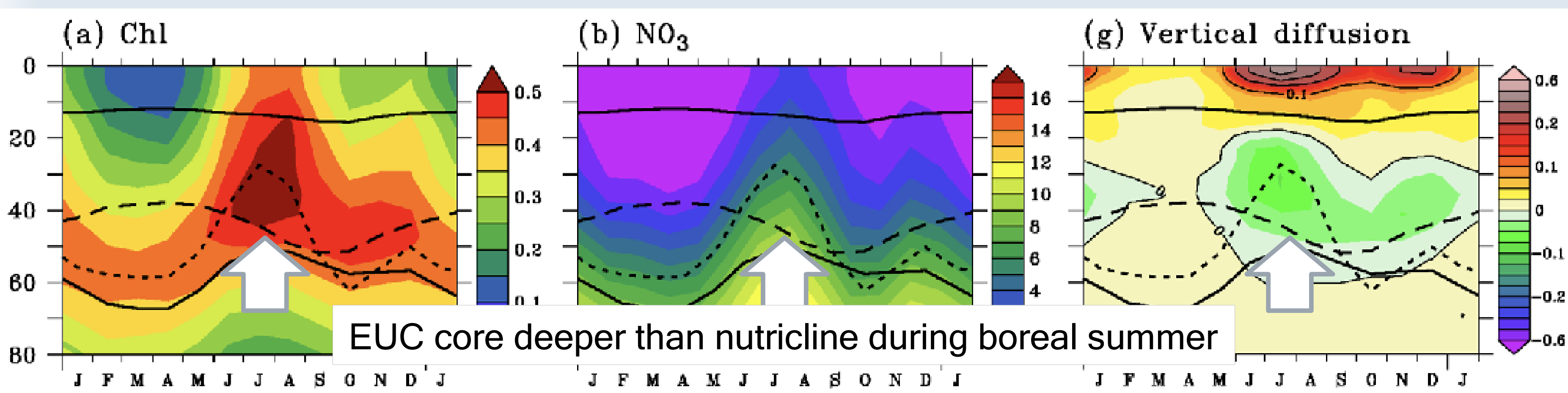
…iciency
… dissipation rate
… buoyancy frequency



Modelling Nitrate Seasonality

- Nitrate reach shallowest levels in July and December
- Vertical diffusion and meridional advection shaping bloom
- EUC does not follow the thermocline within the seasonal cycle: equatorial wave dynamics are important

Seasonal cycle of vertical profiles of (a) chlorophyll, (b) nitrate, (g) vertical diffusion averaged in 1.5°S-0.5°N, 20-5°W.
Depths of the mixed layer (upper solid line), of the euphotic layer (lower solid line), of the EUC core (dashed line), and of the 20°C isotherm as proxy of the nutricline (dotted line).



Radenac et al., 2020

Summary Part II

- Equatorial productivity requires supply of nitrate into the euphotic layer/surface mixed layer
- Upward nitrate supply is determined by
  (1) upward nitrate advection associated with vertical thermocline/nitracline movements
  (2) upward mixing of nitrate in the shear zone above the EUC core only during periods when EUC core is deeper than nitracline
- Thermocline shoaling can be largely understood as an equilibrium response to a strengthening of the easterly wind stress along the equator
- Instead, EUC vertical migration and transport changes are associated with equatorial wave response and cannot be understood as an equilibrium response to local wind stress

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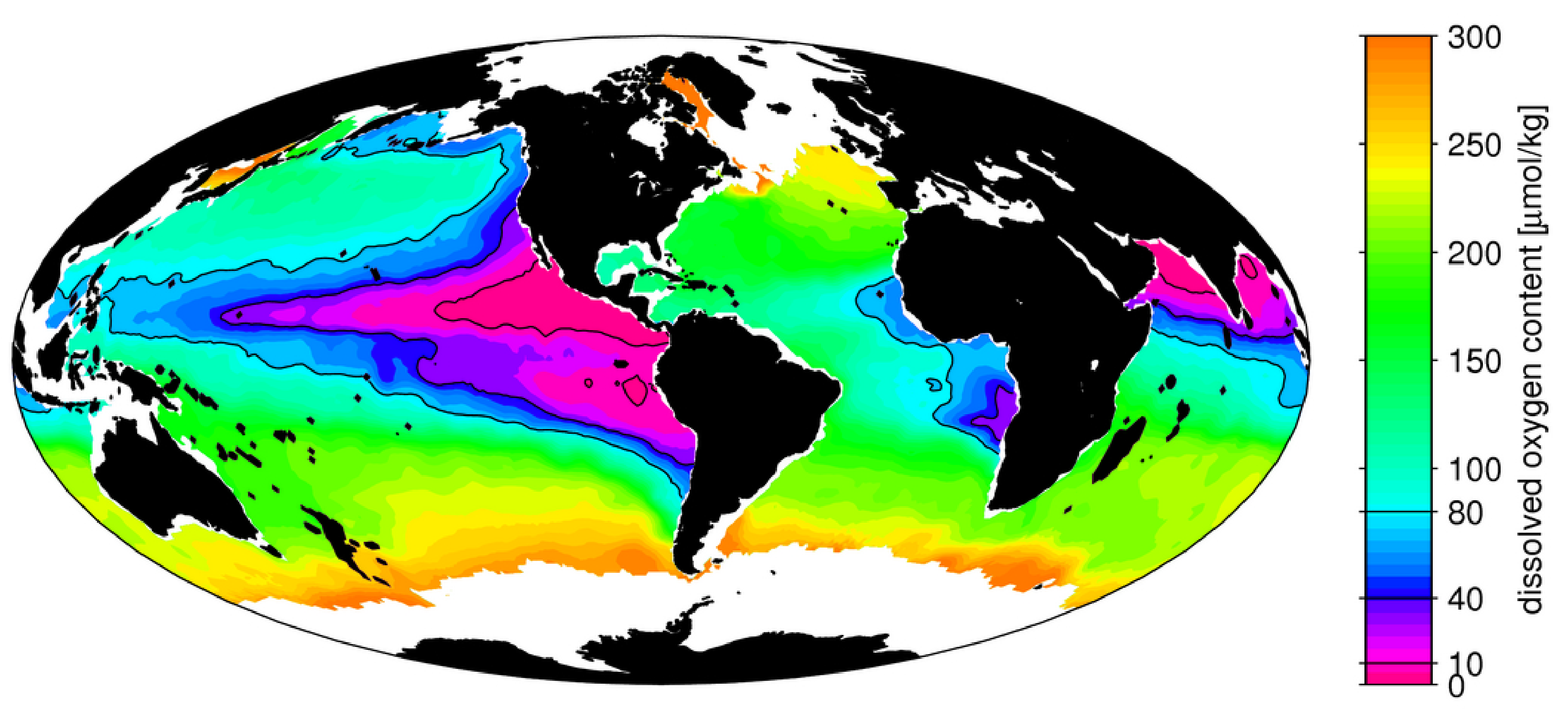
Open Questions Part II

- Momentum balance of the EUC from observations particularly in the eastern basin is not solved
- How important are near-surface processes? Diurnal cycle of near-surface stratification, velocity and turbulence in the upper few meters; wind power input into the equatorial ocean
- What drives the mixing? Role of tropical instability waves, deep cycle turbulence, other processes
- How important are nitrate changes in source waters?
- Dynamics of eddy-driven circulation and its long-term changes

EUC and eastward oxygen supply?

Mean Oxygen Distribution

- Tropical oxygen minimum zones
  - Eastern Pacific and Atlantic (lower oxygen in the Pacific)
  - Northern Indian Ocean



Oxygen on isopycnal 26.9 kg/m3 (300-600 m depth, outcropping in the subpolar regions)

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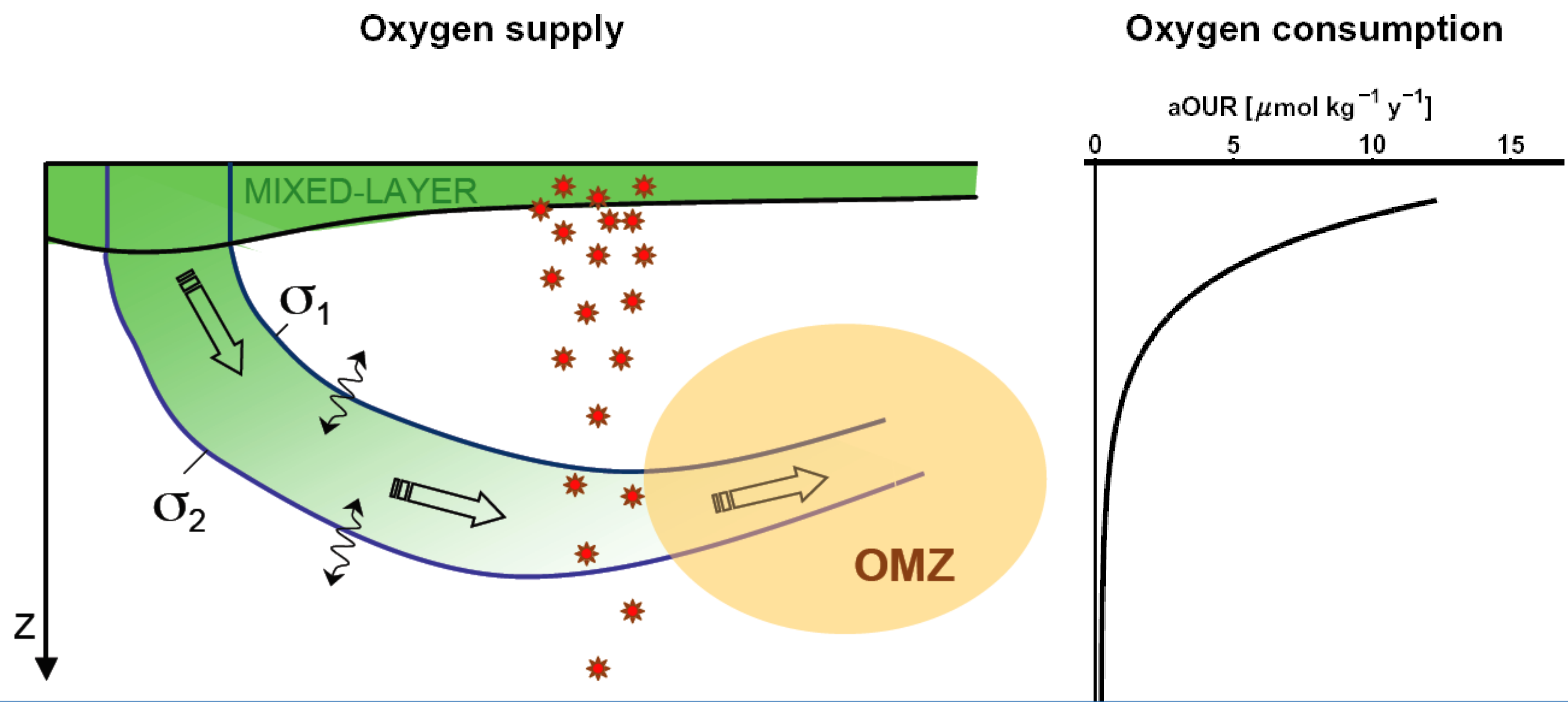
Ventilation versus Respiration

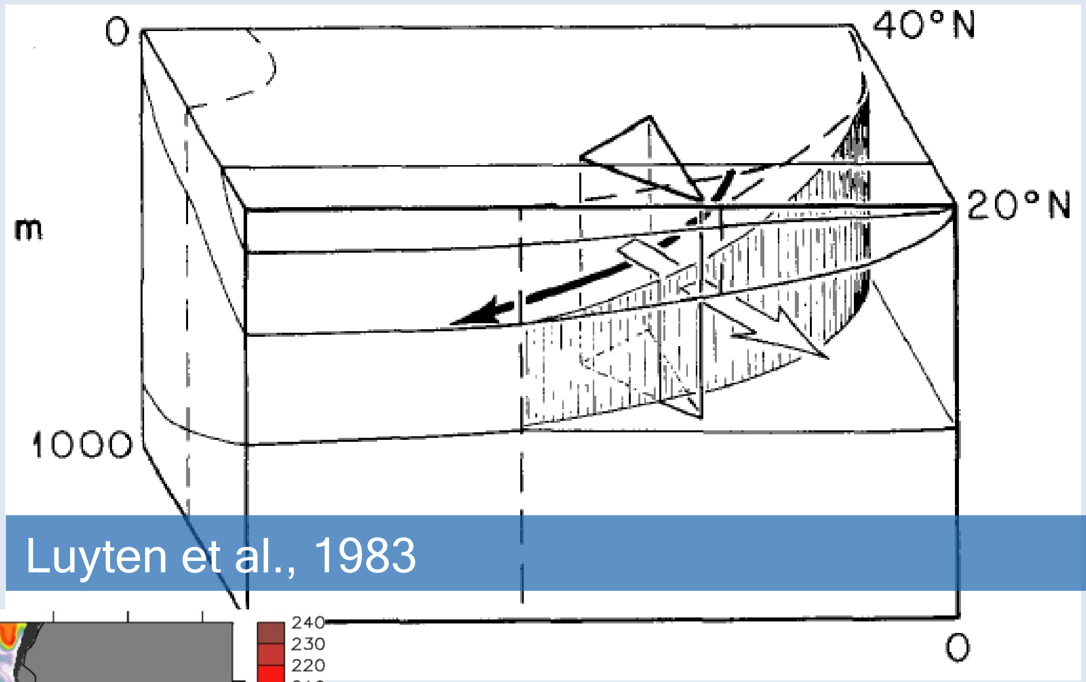
- Oxygen supply along isopycnal surfaces
- In general weak diapycnal mixing.
- Oxygen consumption via heterotrophic respiration



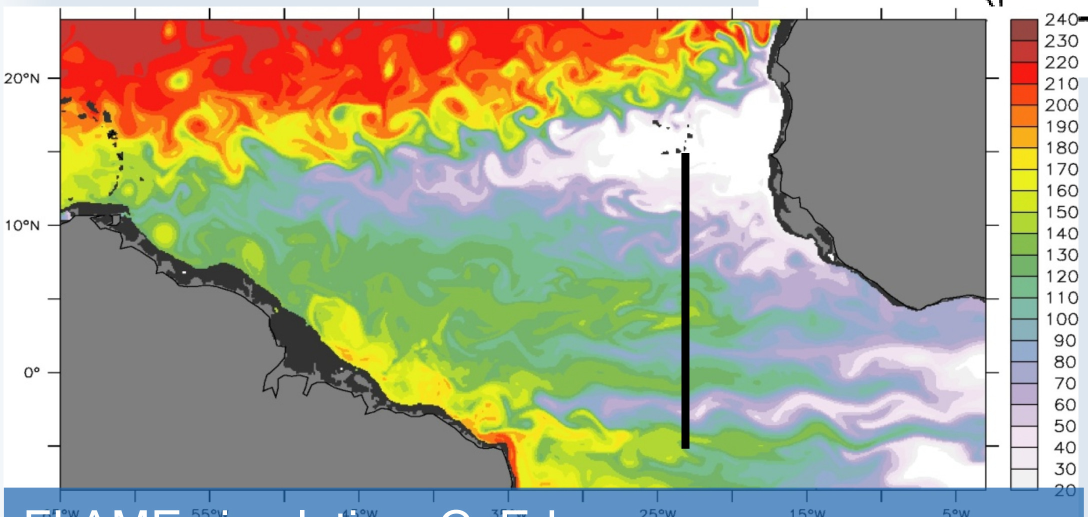
Karstensen et al., 2008

Ventilated Thermocline: Luyten, Pedlosky, Stommel model

Transport processes at the boundary between ventilated and unventilated thermocline: advection (solid arrow) and diffusive flux (open arrow)



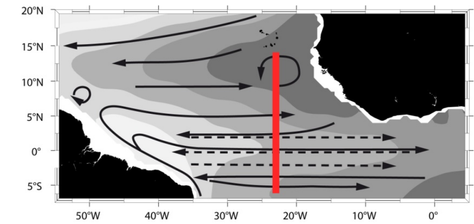
Luyten et al., 1983



FLAME simulation, C. Eden

Simulation of OMZs involve physical processes from large to small scales: circulation, jets, eddies, filaments, turbulent mixing.

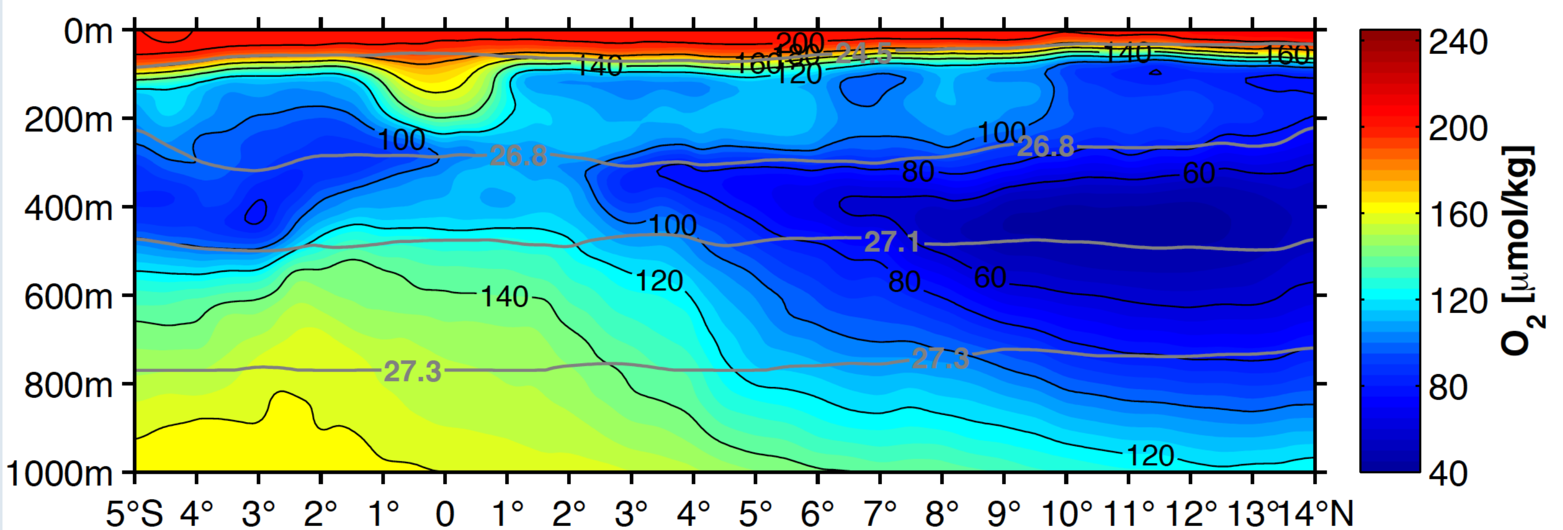
Mean 23W Section

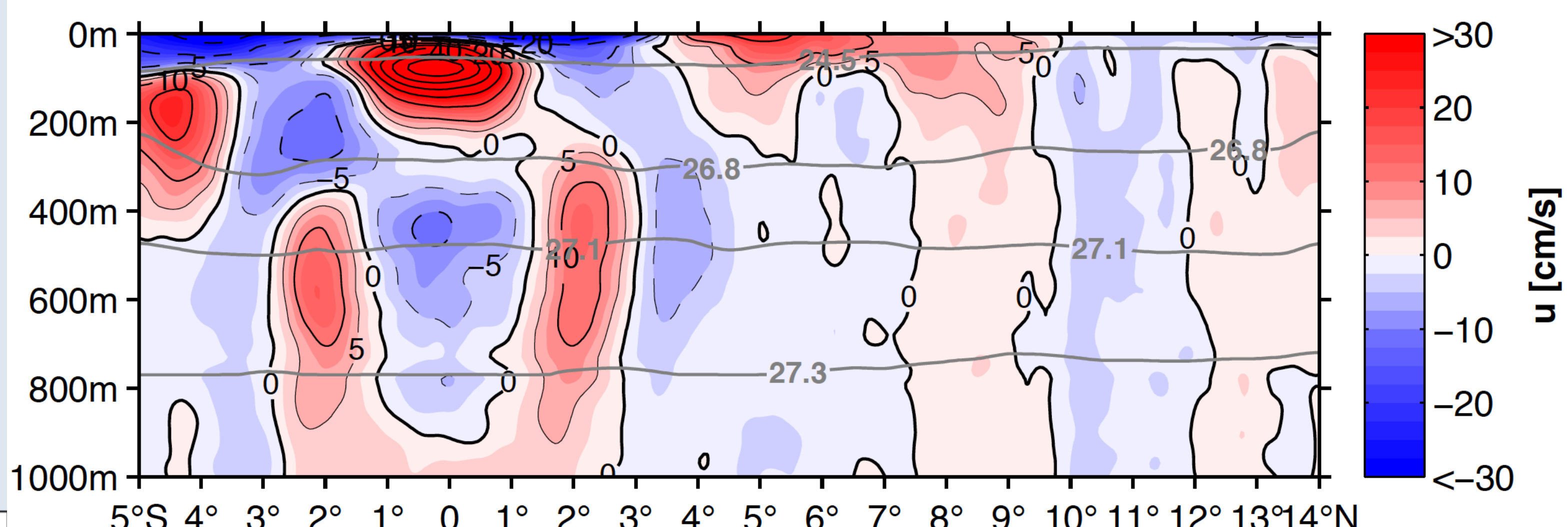


Equatorial oxygen maximum

Deep oxycline at about 300m or σ_θ=26.8 kg/m³

OMZ is ventilated from the west by zonal currents





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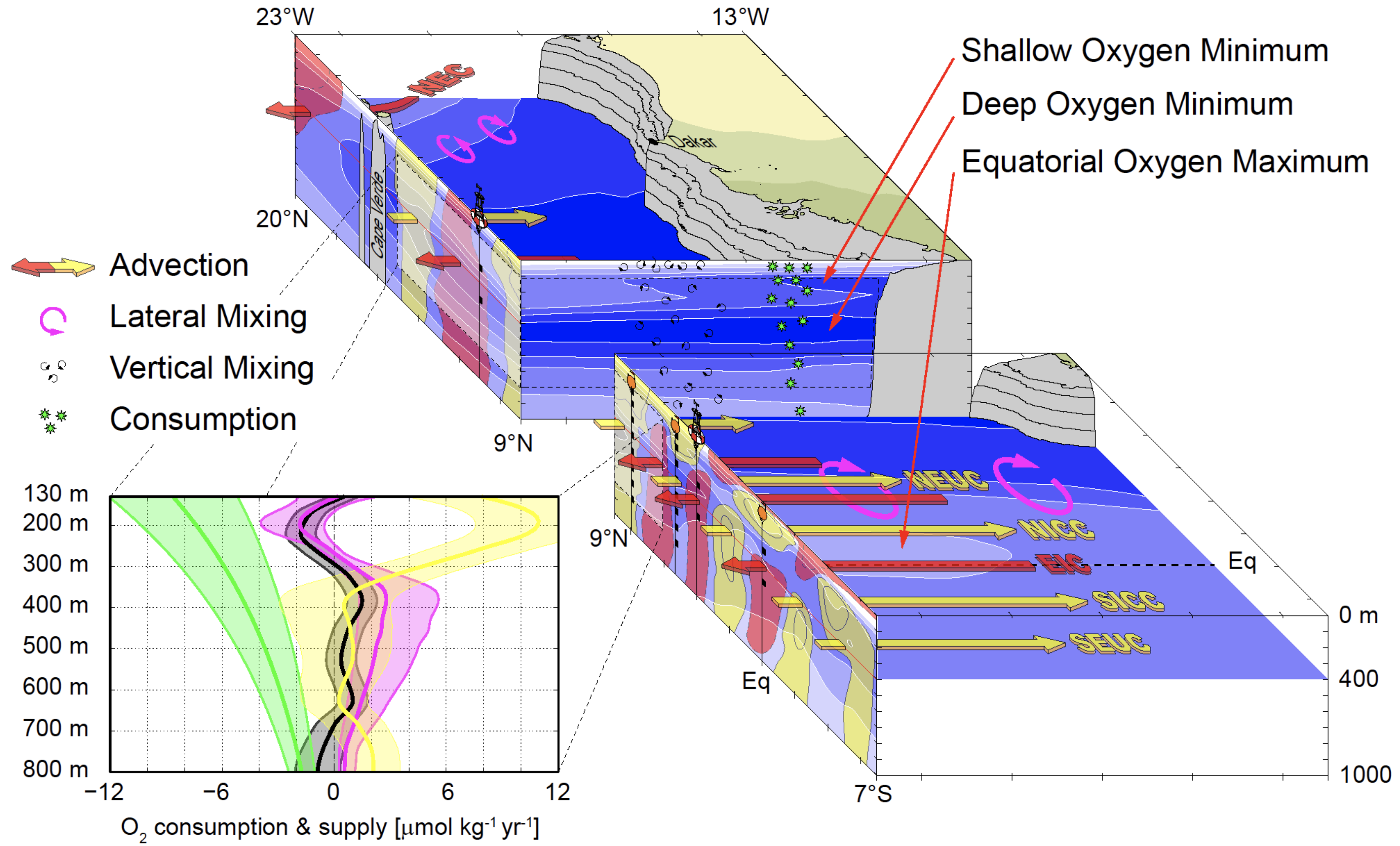
Functioning of Oxygen Mininum Zone



Brandt et al., 2015

Marine Ecosystem Threats

Climate Change related threats

- Warming
- Deoxygenation
- Acidification
- Sea level rise

Other anthropogenic threats

- Pollution (run-off, NOx/SOx, plastics, oil, …)
- Dredging, mining

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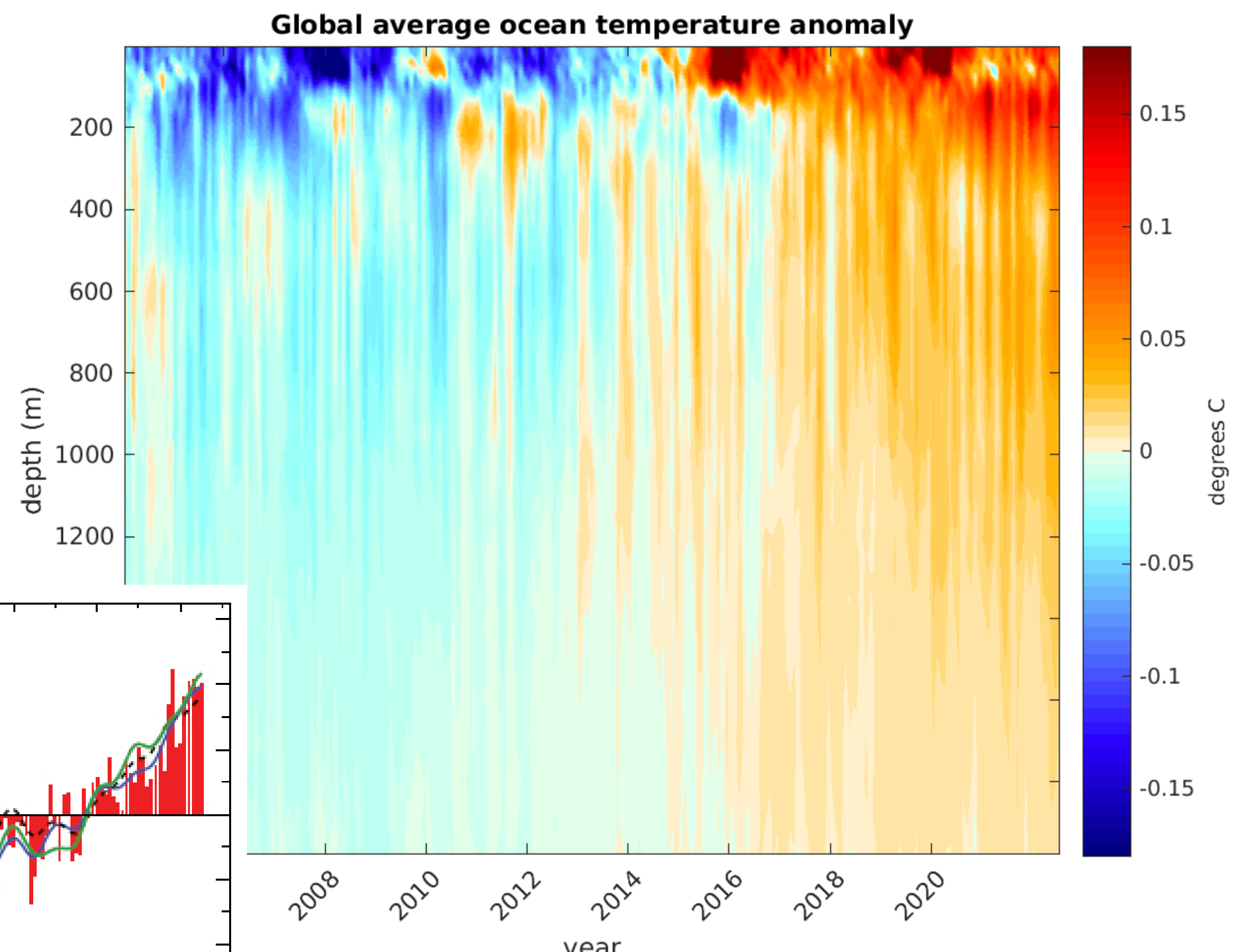
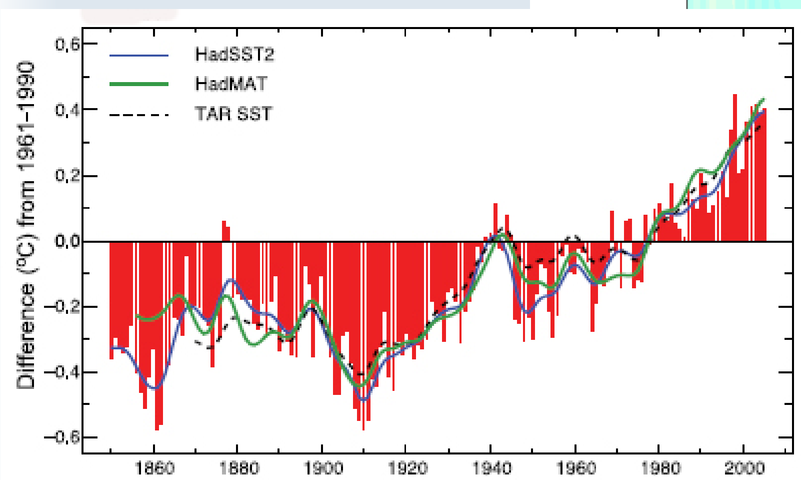
Ocean Warming



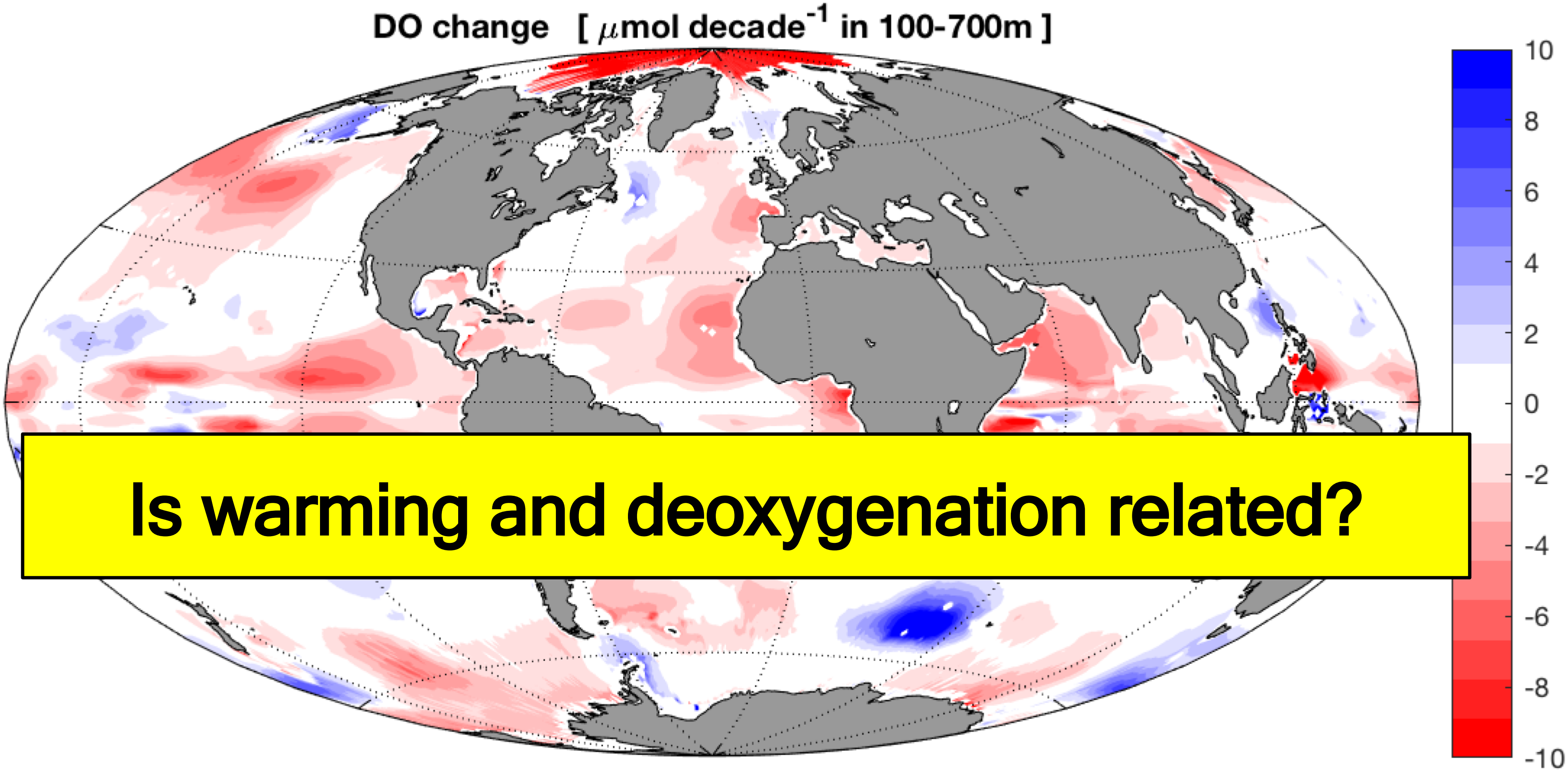


Global Sea Surface Temperature - IPCC 4th Report

2.whoi.edu/site/argo/impacts/warming-ocean/

Oxygen Change in the Ocean (1960-2010)

- Deoxygenation particularly in tropical oxygen minimum zones



Is warming and deoxygenation related?

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Oxygen Change in the Ocean (1960-2010)

- Global oceanic oxygen content decreased by more than 2% since 1960
- About 50% of changes in the upper 1000m can be explained due to warming induced solubility changes
- Other 50% may have their origin in stratification changes (reduced or shallower ventilation) and a potential increase in biological consumption
- Other processe such as basin-scale multidecadal variability or oceanic overturning slow-down might play a role as well

Schmidtko et al., 2017

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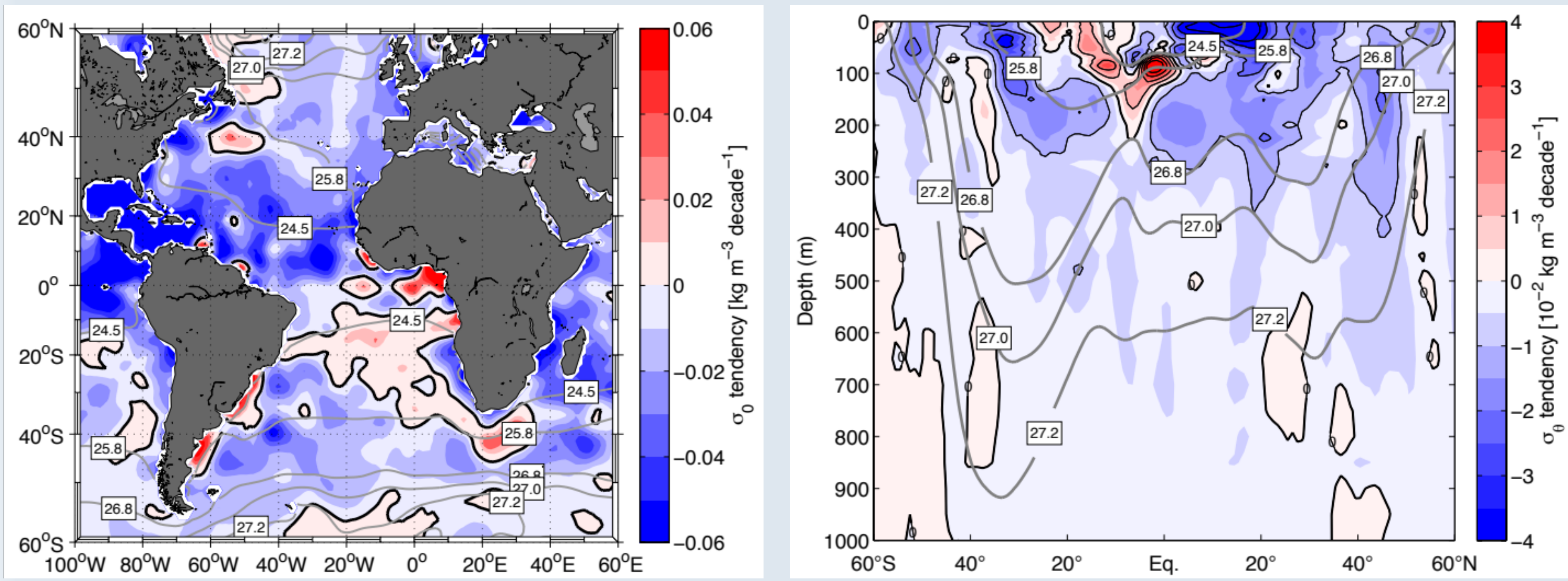
Density change in the Atlantic (1960-2010)

- Surface density reduces due to global warming
- Density changes reduces with depth resulting in increased thermocline stratification



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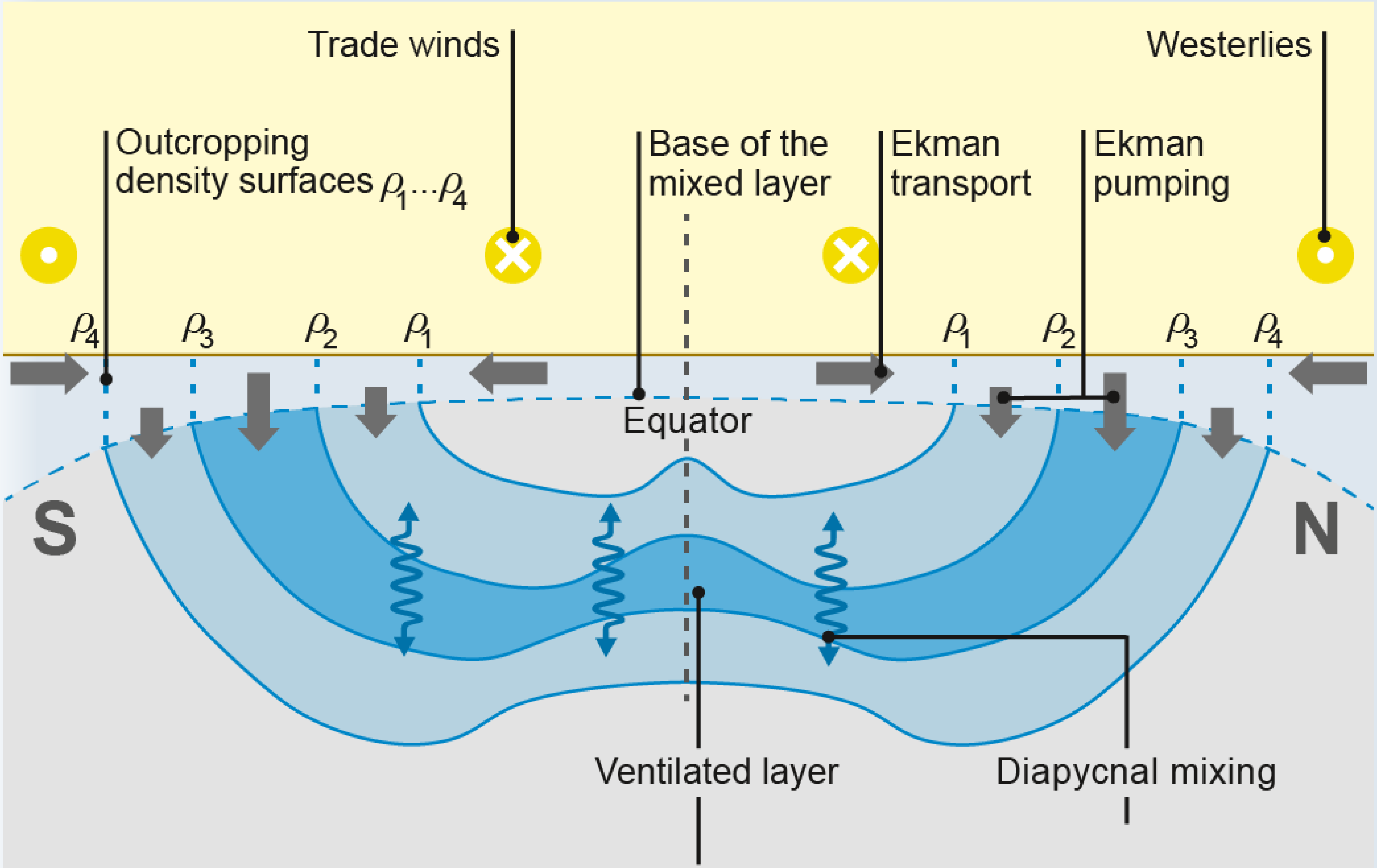
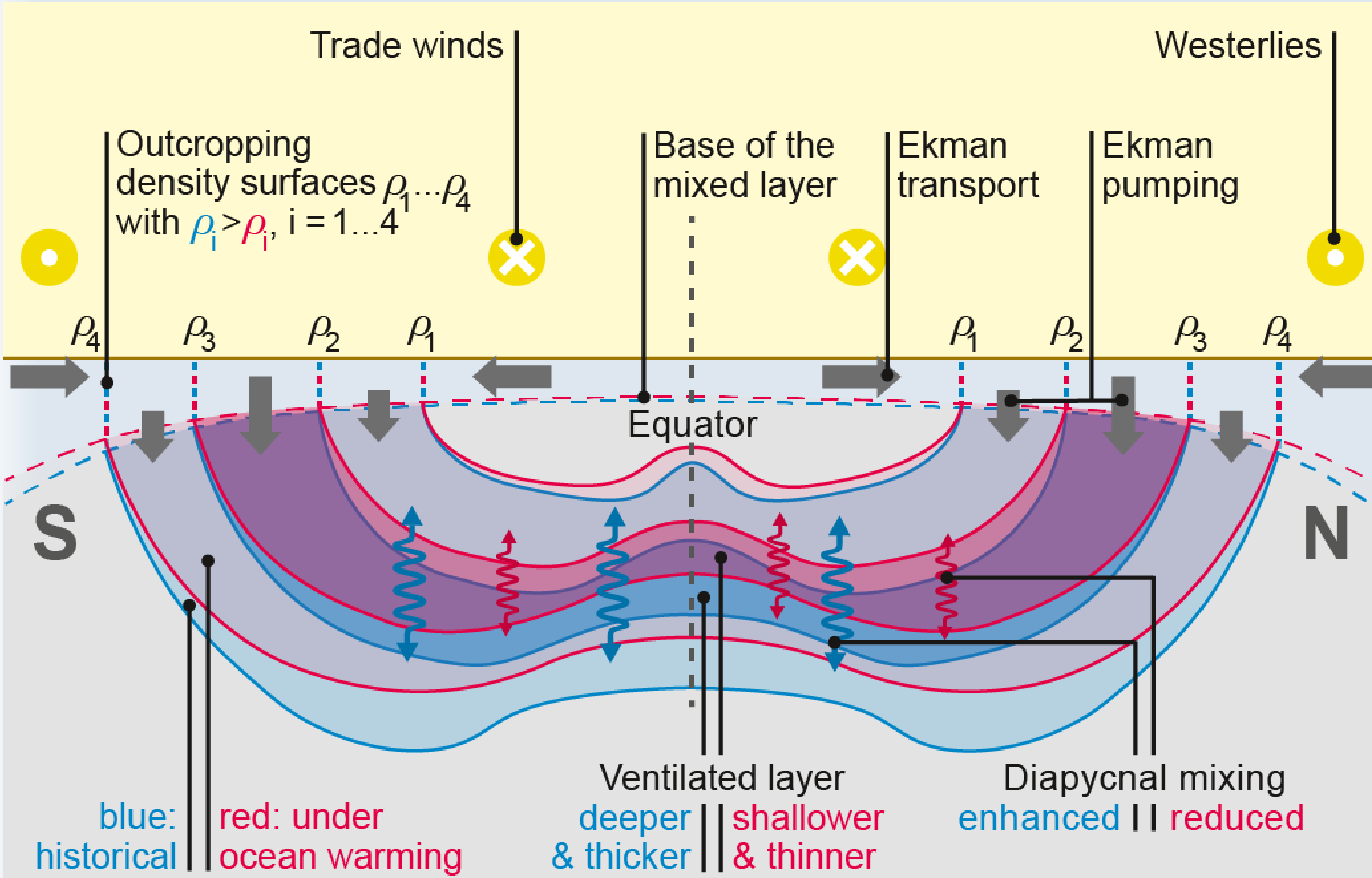
Mechanisms of Thermocline Oxygen Changes



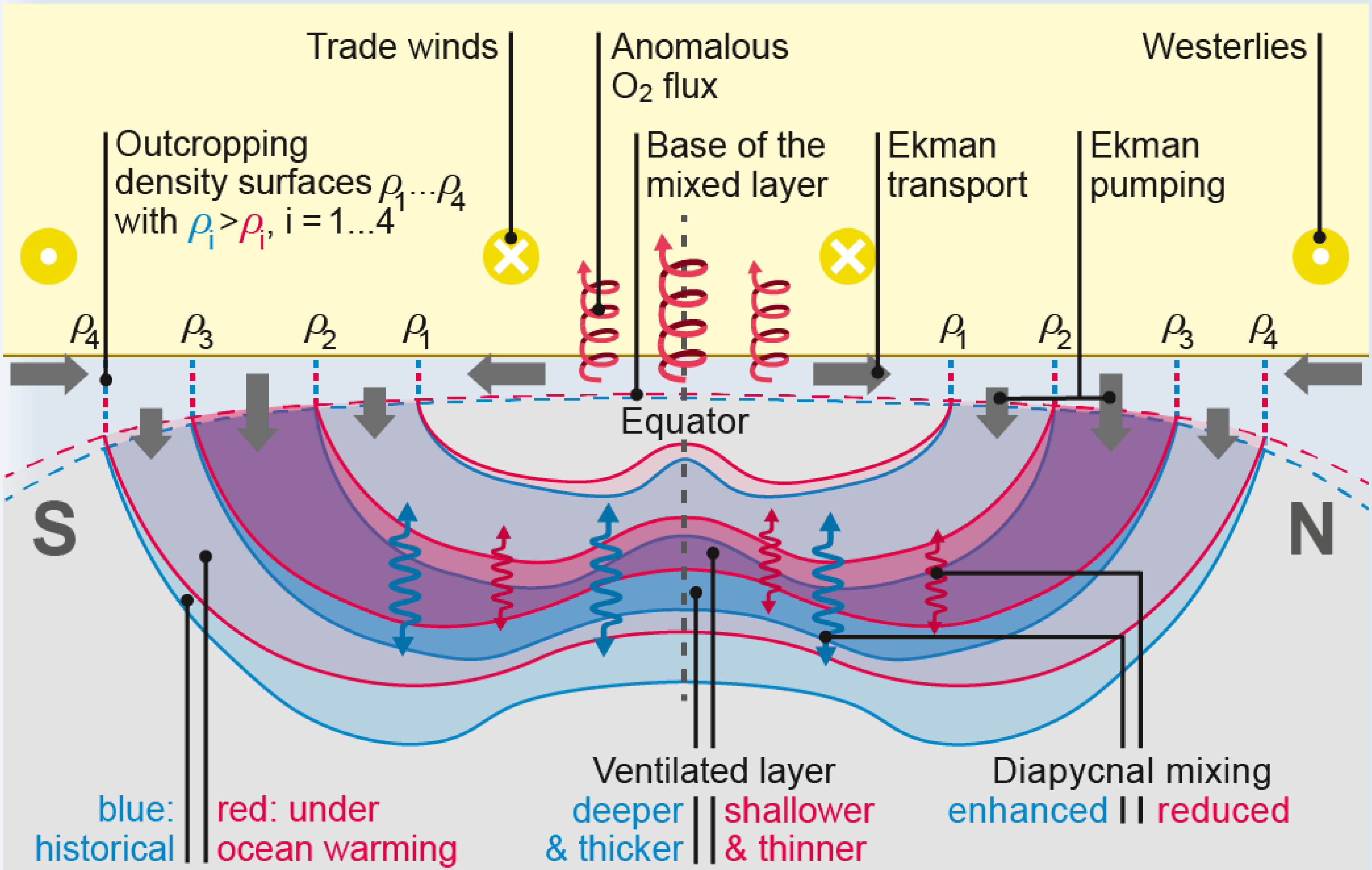
Oschlies et al., 2018

Mechanisms of Thermocline Oxygen Changes



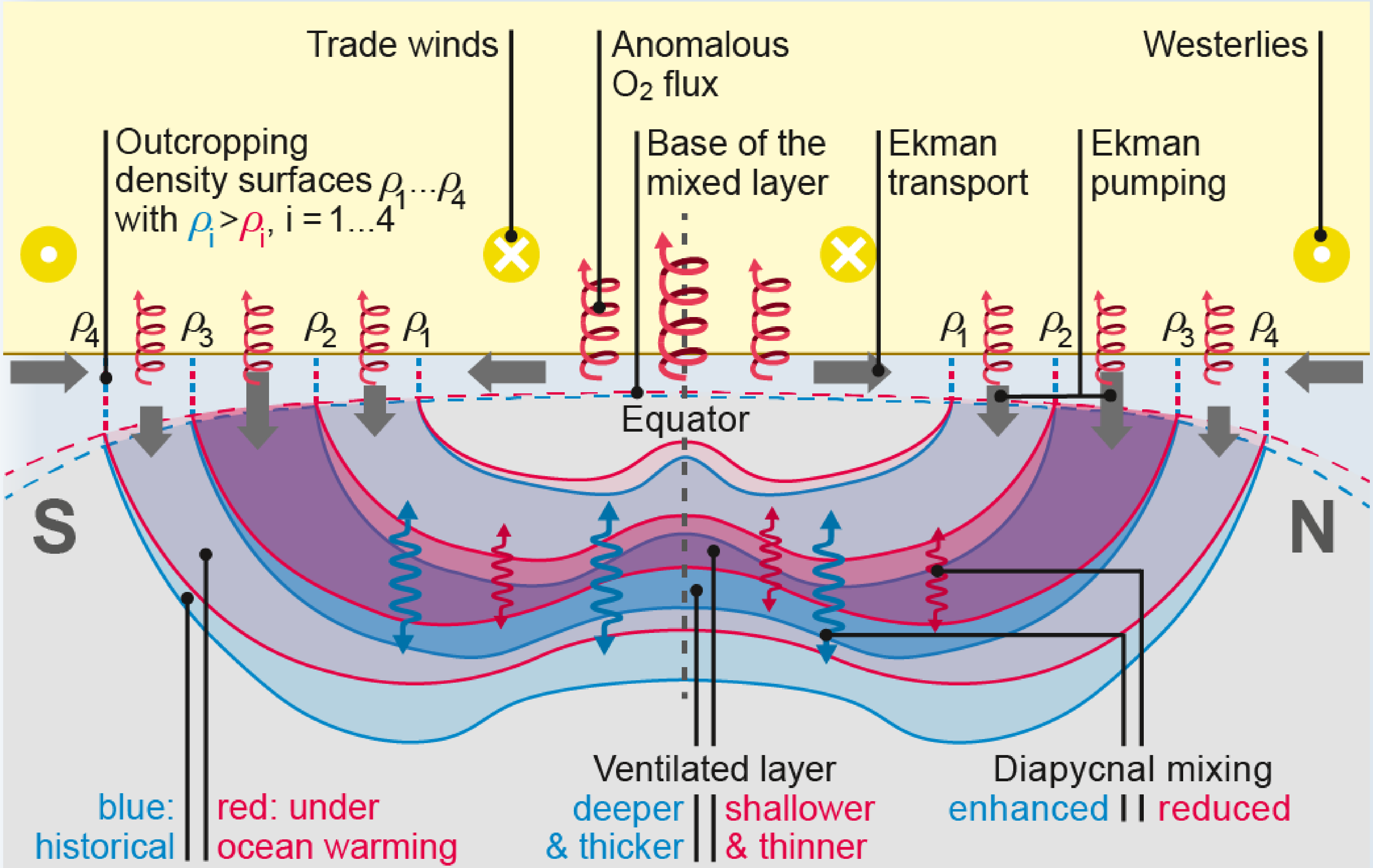
Oschlies et al., 2018

Mechanisms of Thermocline Oxygen Changes



Oschlies et al., 2018

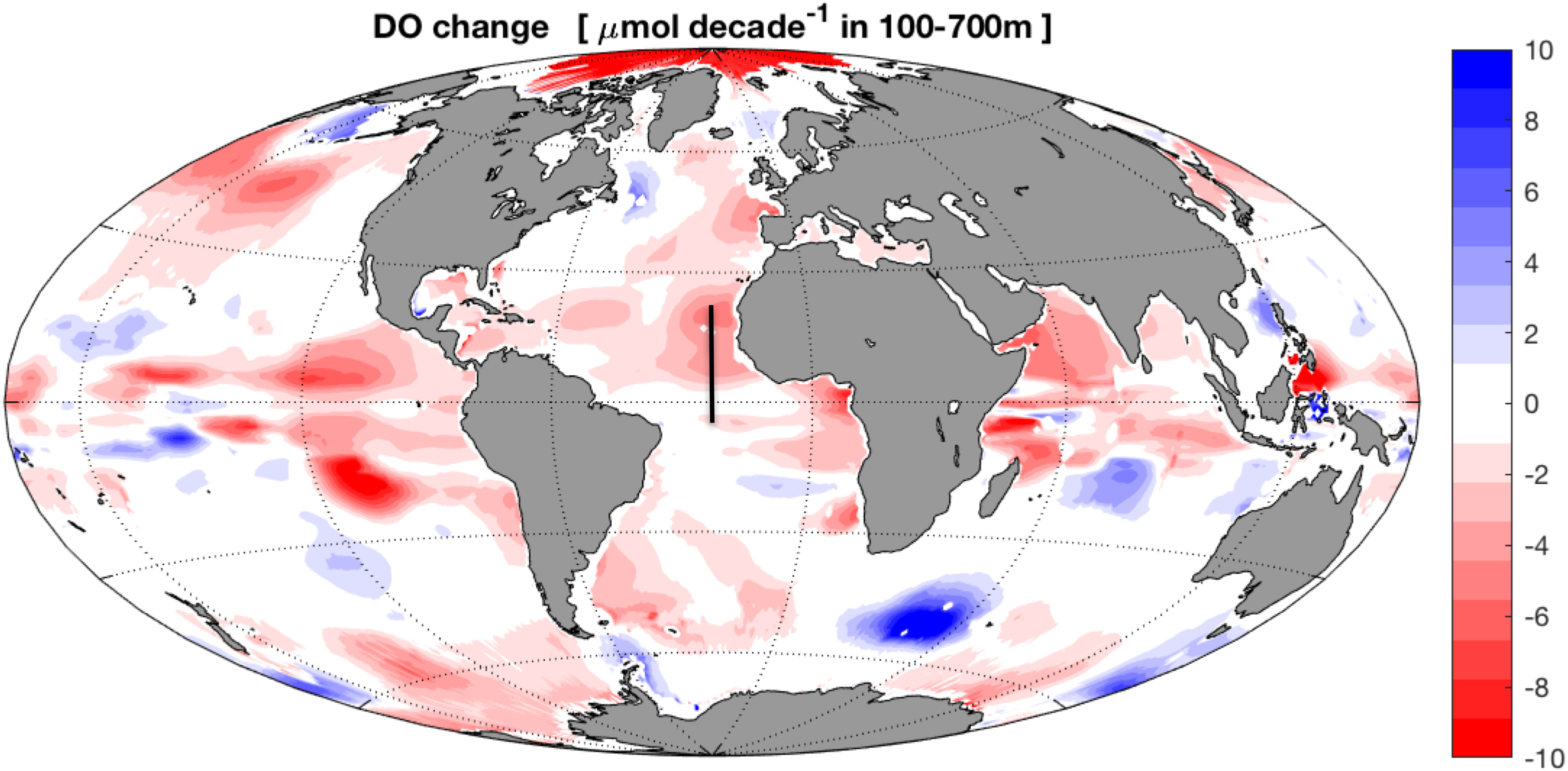
Mechanisms of Thermocline Oxygen Changes



Oschlies et al., 2018

Oxygen Change in the Ocean (1960-2010)

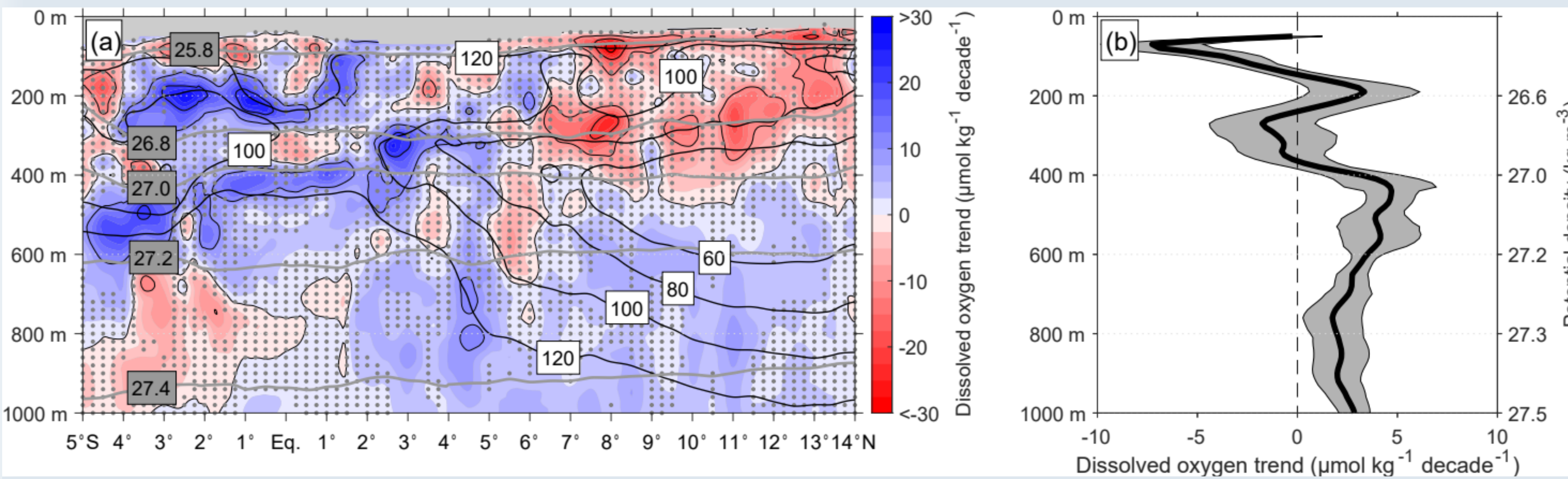
- Deoxygenation particularly in tropical oxygen minimum zones



- Since 2006 focus on 23°W section

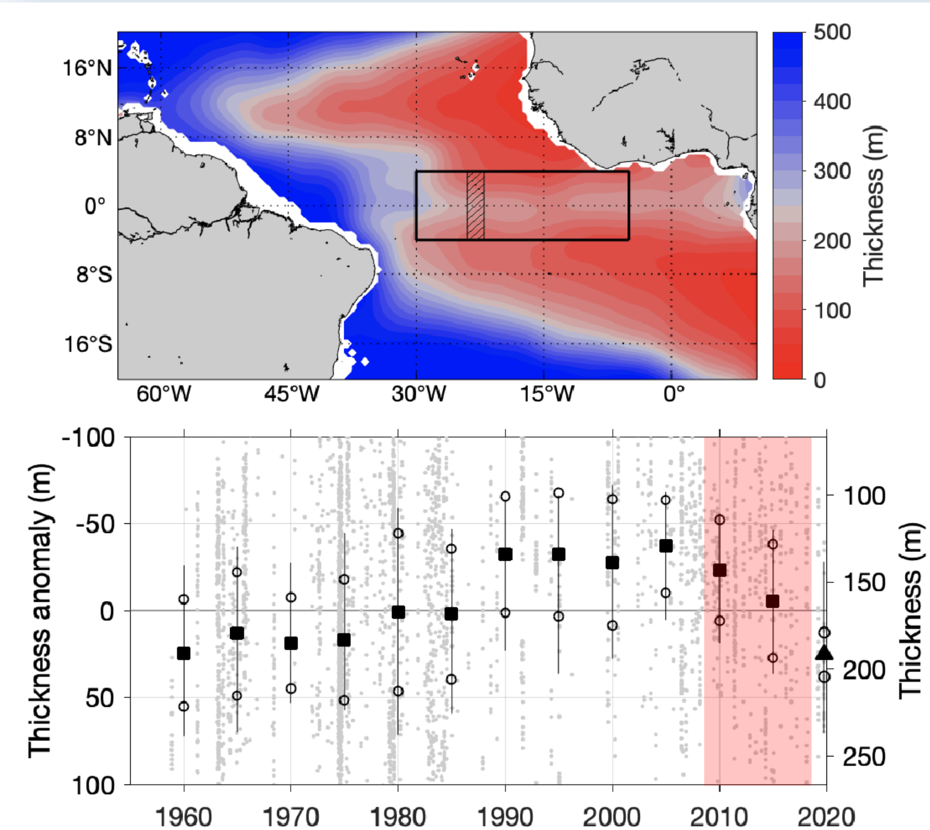
Oxygen Change along 23W (2006-2018)

- Meridional mean shows oxygen increase at 200m and decrease at 300m : in agreement with shallowing of STCs. However
- Observed oxygen pattern often more complicated likely associated with climate variability: oxygen increase/decrease south/north of 5N
- Below likely changes of eddy-driven circulation

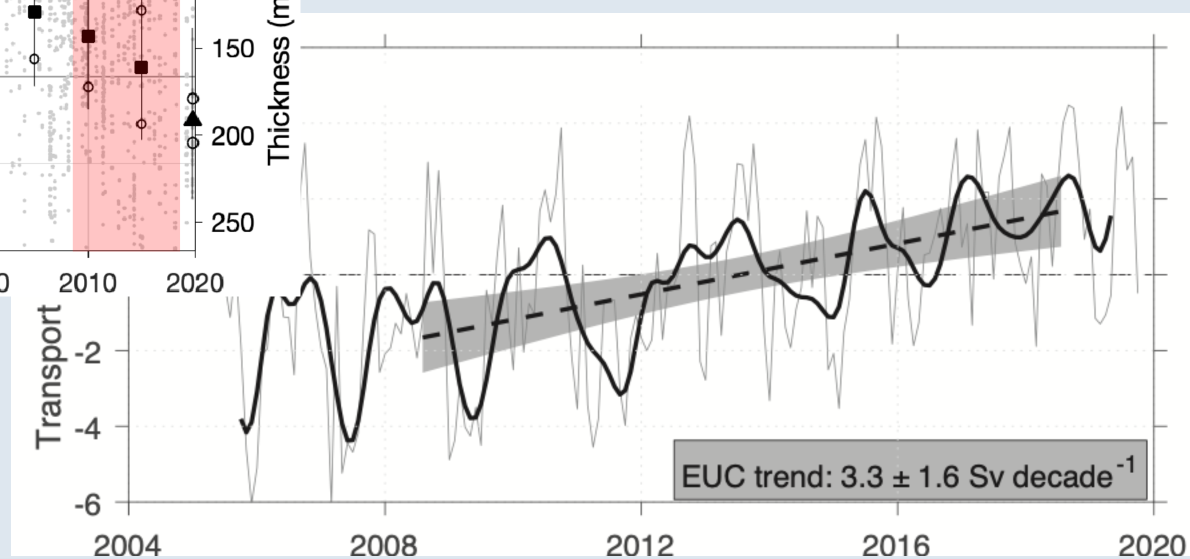


a) Linear oxygen trend along 23°W for 2006-2018 (colorbar), mean oxygen distribution (black contours) and isopycnal surfaces (grey contours).
b) Profile showing meridionally averaged trend.

Oxygen Change associated with climate variability



- EUC intensification associated with oxygenation of upper equatorial ocean: increased upper ocean oxygenated layer thickness
- Multidecadal variability likely associated with wind variability of the AMO



Equatorial Undercurrent variability from long-term moored observatory

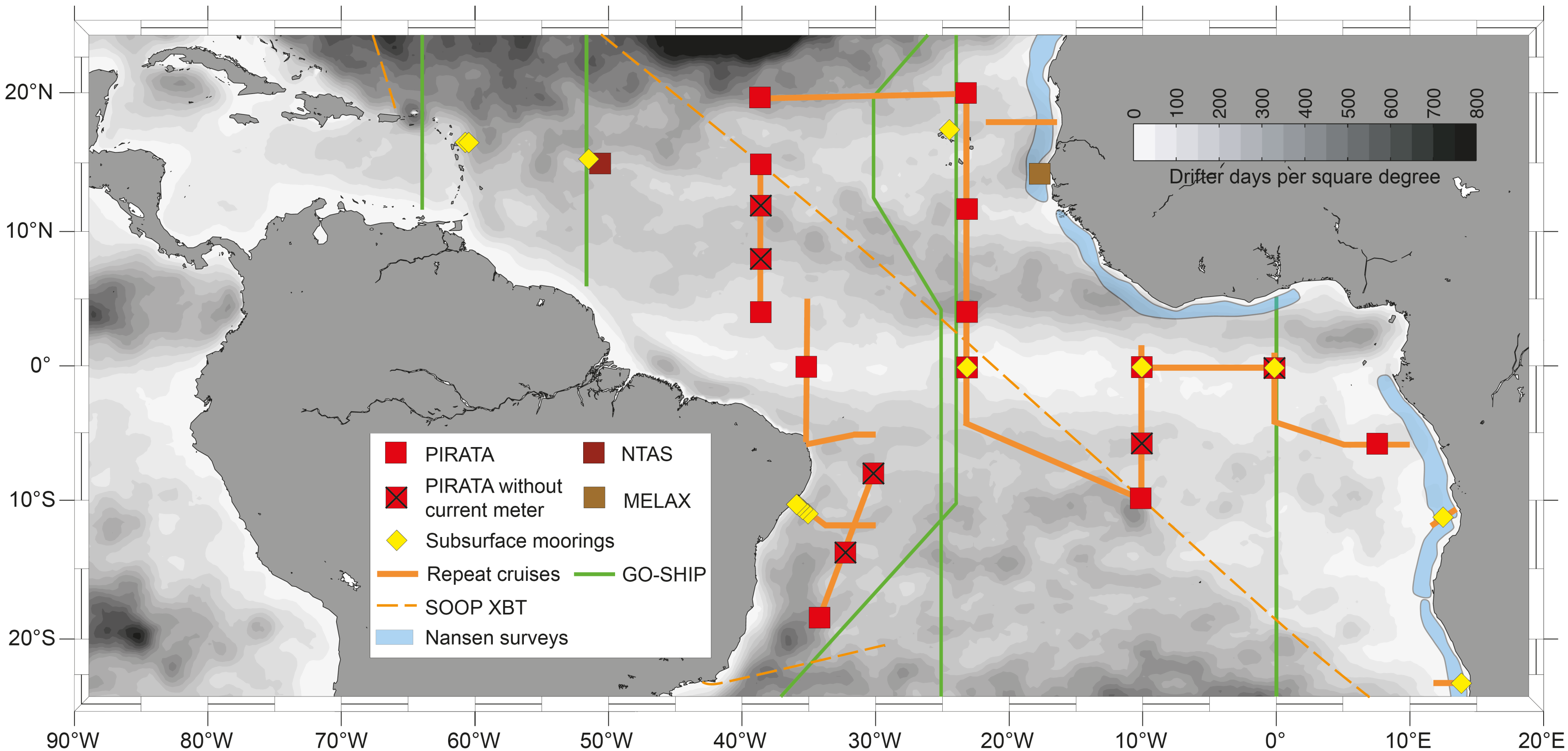
Brandt et al., 2021

GEOMAR

Summary Part III

- Oceanic oxygen distribution is a subtle balance between mostly physical supply and heterotrophic respiration (state-of-the-art models show large biases)
- Marine ecosystem threats include 1) warming and increased stratification and 2) deoxygenation
- Stressors for marine life and/or reduction of habitat
- Observed time series are affected by interannual, decadal und multidecadal variability superimposed on trends related to climate-warming
- Requirement to sustain/improve the observing system 1) to better understand and quantify relevant processes and 2) to obtain the necessary long-term datasets for model validation and improvement

Tropical Atlantic Observing System



Foltz et al., 2019