Examples of biogeochemical studies using ROMS/CROCO-PISCES

Vincent Echevin and colleagues

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Examples of biogeochemical studies using ROMS/CROCO-PISCES

3 examples from the Peru upwelling system:

- Long-term trends (1973-2008) in the oxygen minimum zone
- Impacts of climate change under RCP8.5 “worst-case” scenario
- Submesoscale dynamics

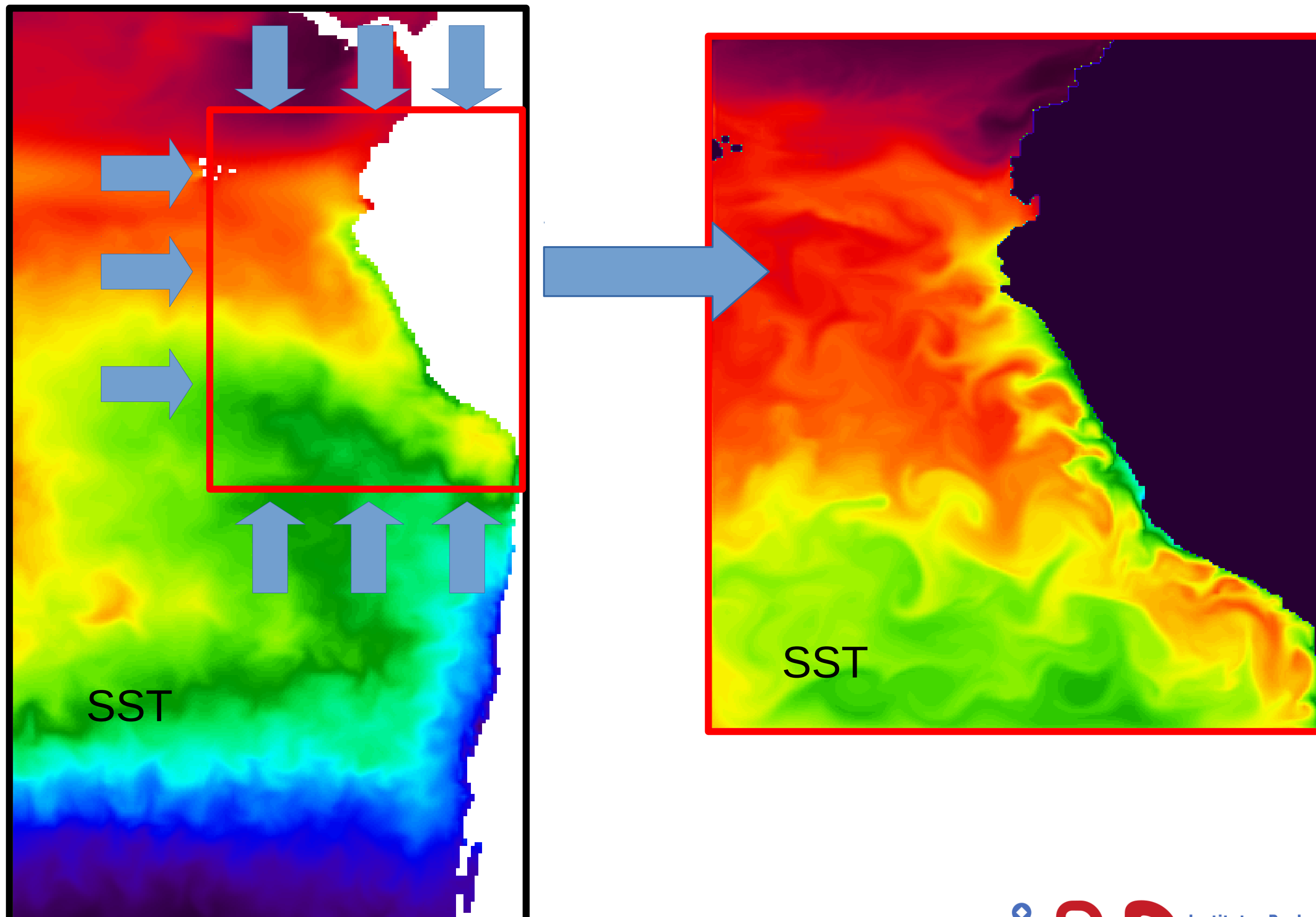
CROCO model configurations: the example of the Peru upwelling system

Open Boundary Conditions

Physics : global models (1/12°, 1/4°, 2°)

Biogeochemistry : climatologies (CARS, WOA, GLODAP, Fe from ORCA-PISCES)

CROCO-PISCES (**1/9°~12 km**)



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First step for each BGC study: model evaluation of the physics

Evaluation of the physics (sea level, temperature, currents, mixed layer depth,...)

=> very important step : realism of biogeochemical fields depend strongly on realism of the physics

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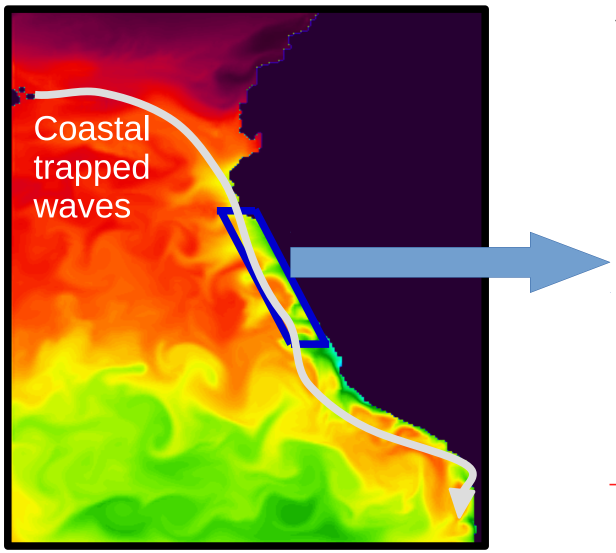
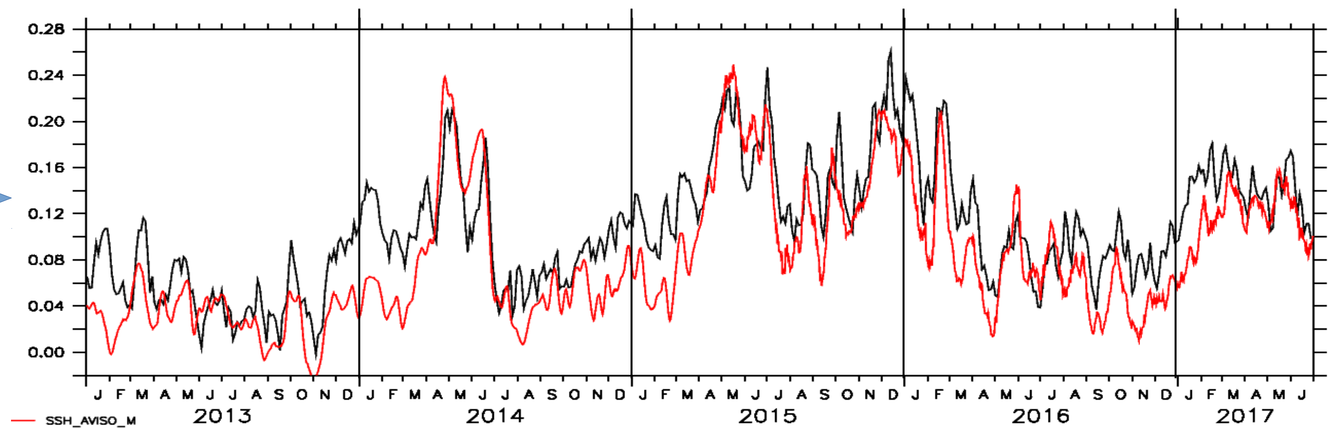


SSh in coastal band of 24 km between 6°S and 12°S (ROMS, AVISO obs)



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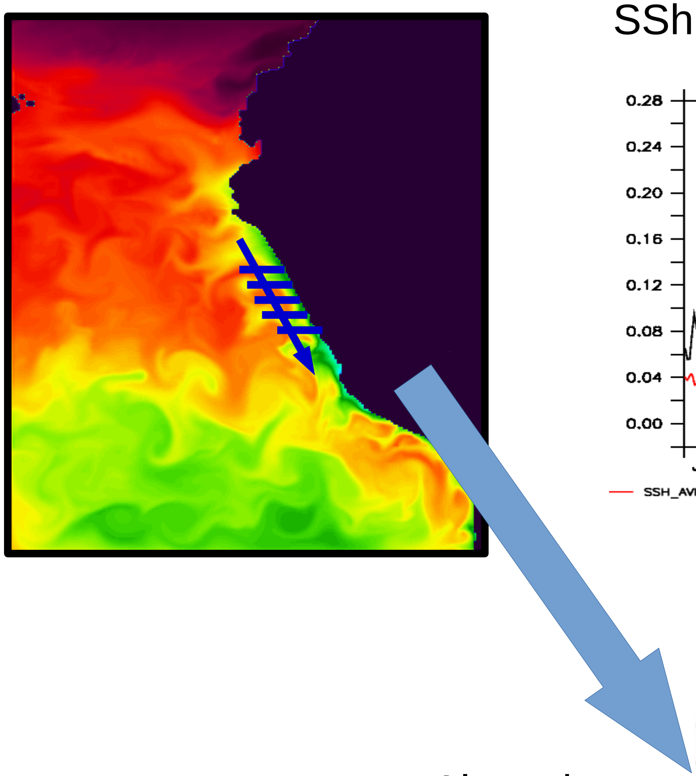

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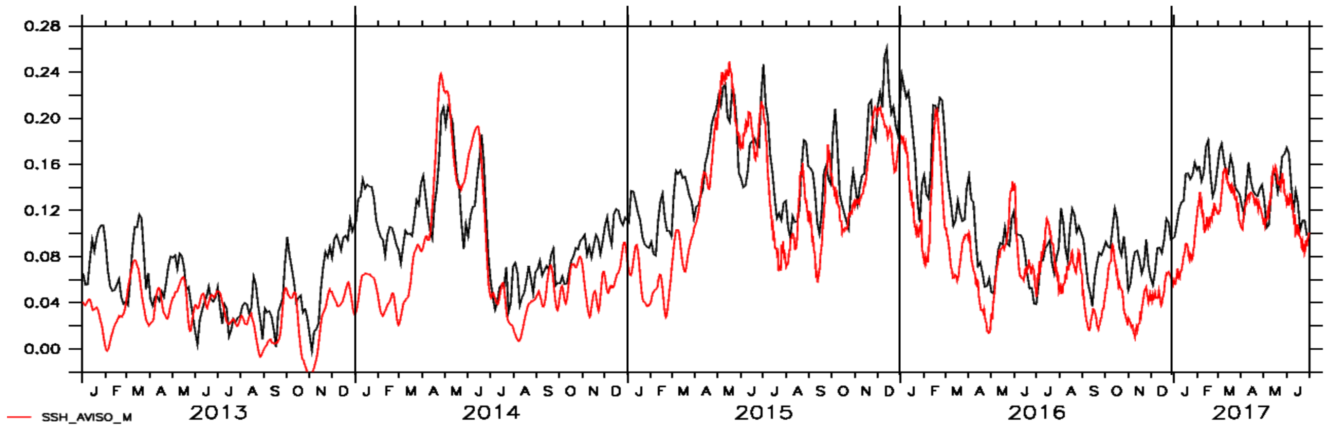
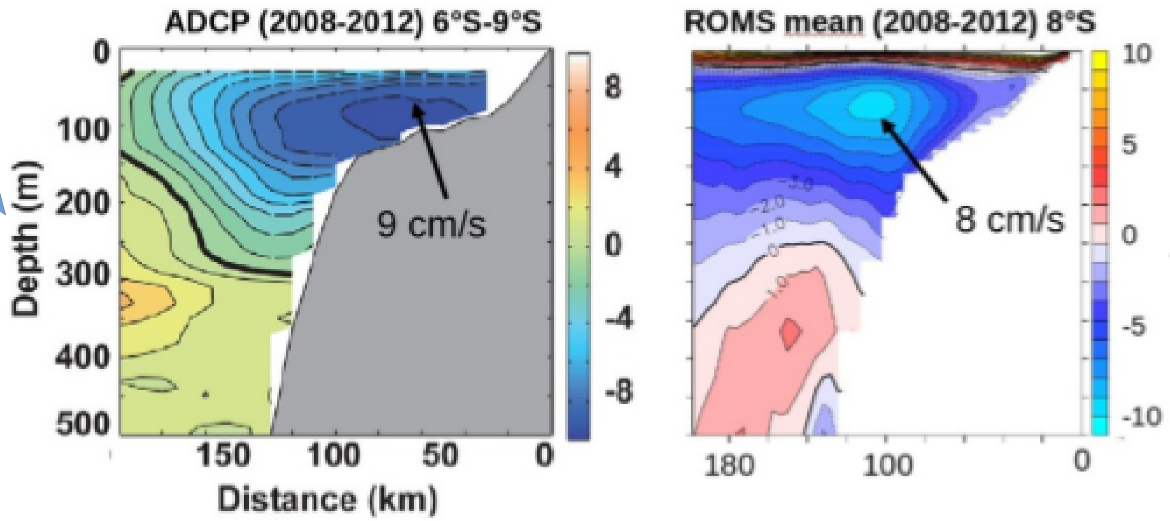
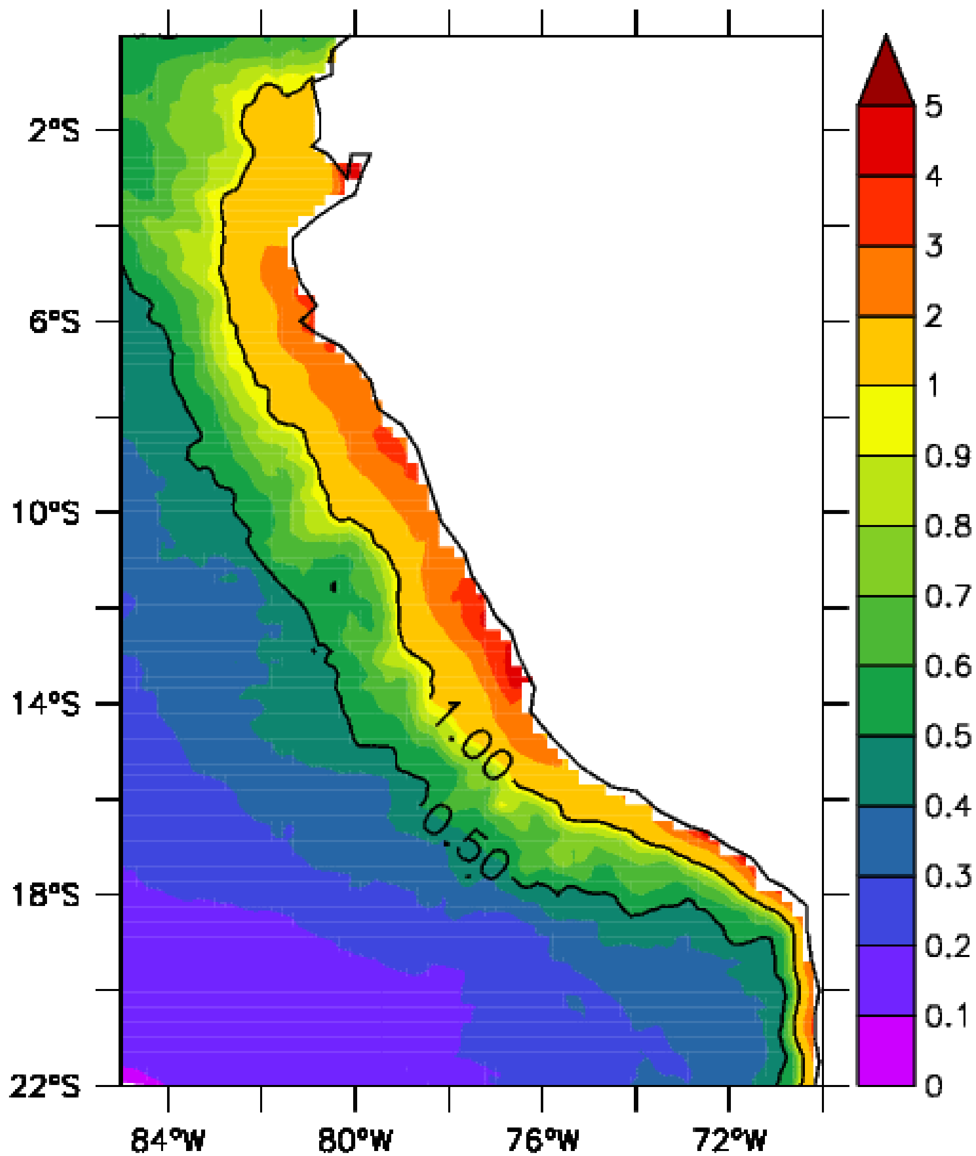


Alongshore poleward current

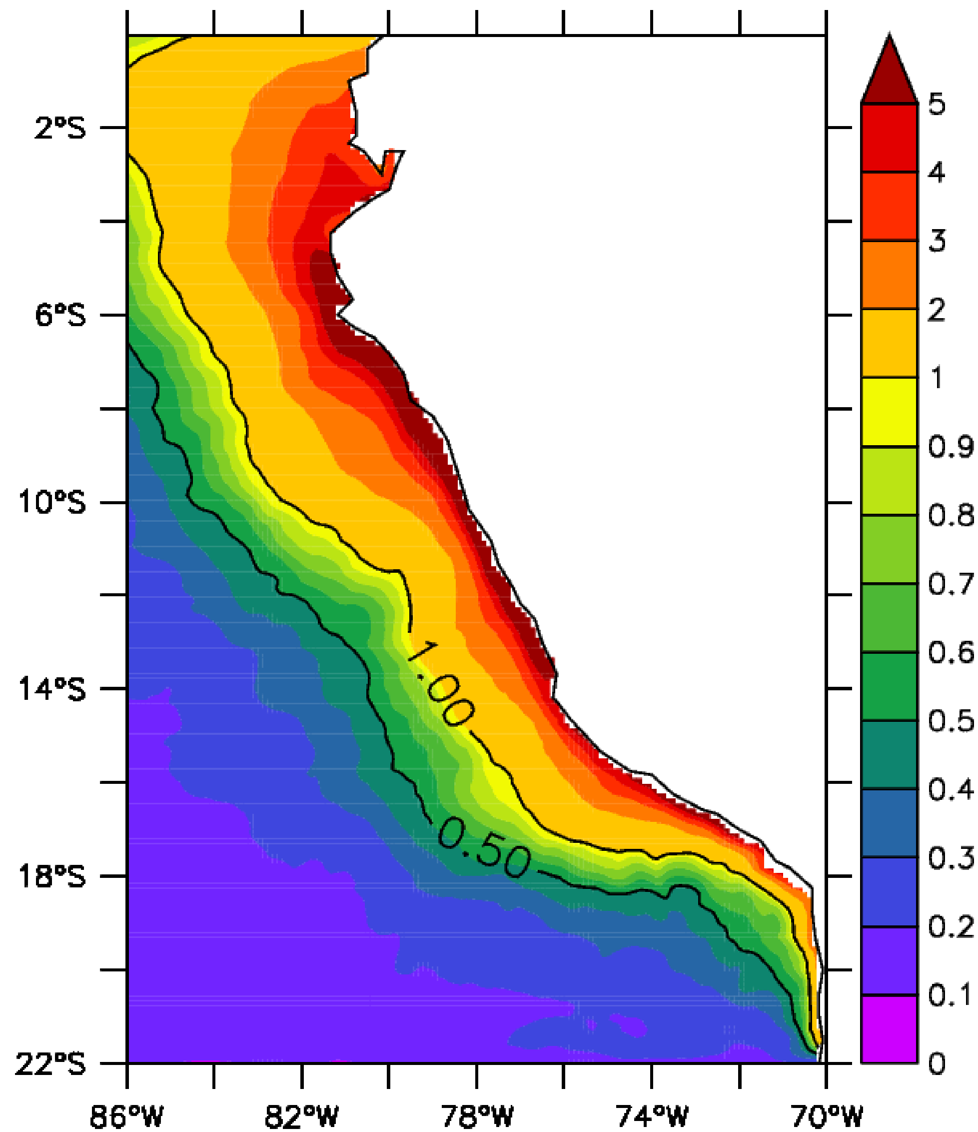


model evaluation of the BGC: surface chlorophyll

MODIS (sat) chl (2013-2016)



Model chl (2013-2016)



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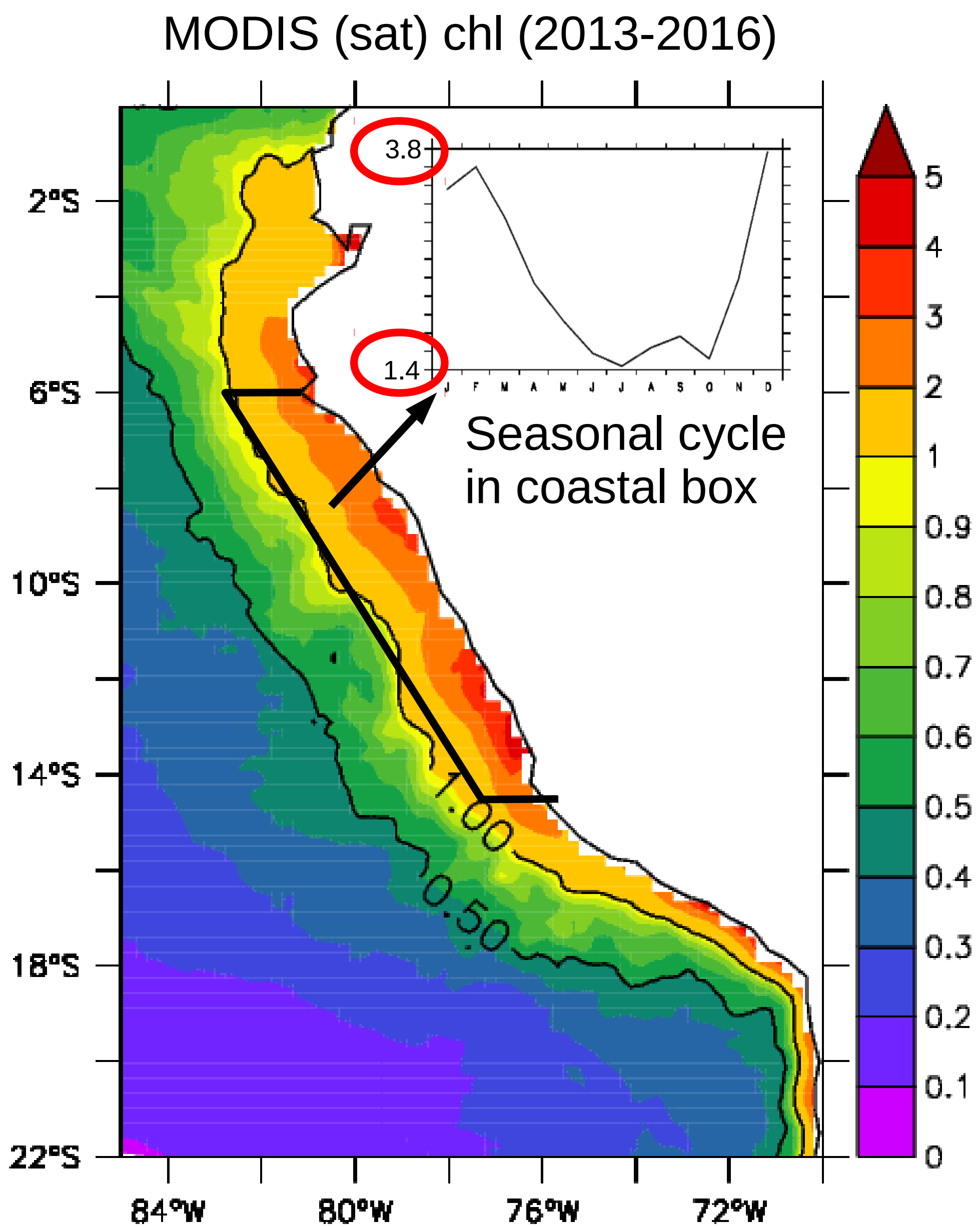
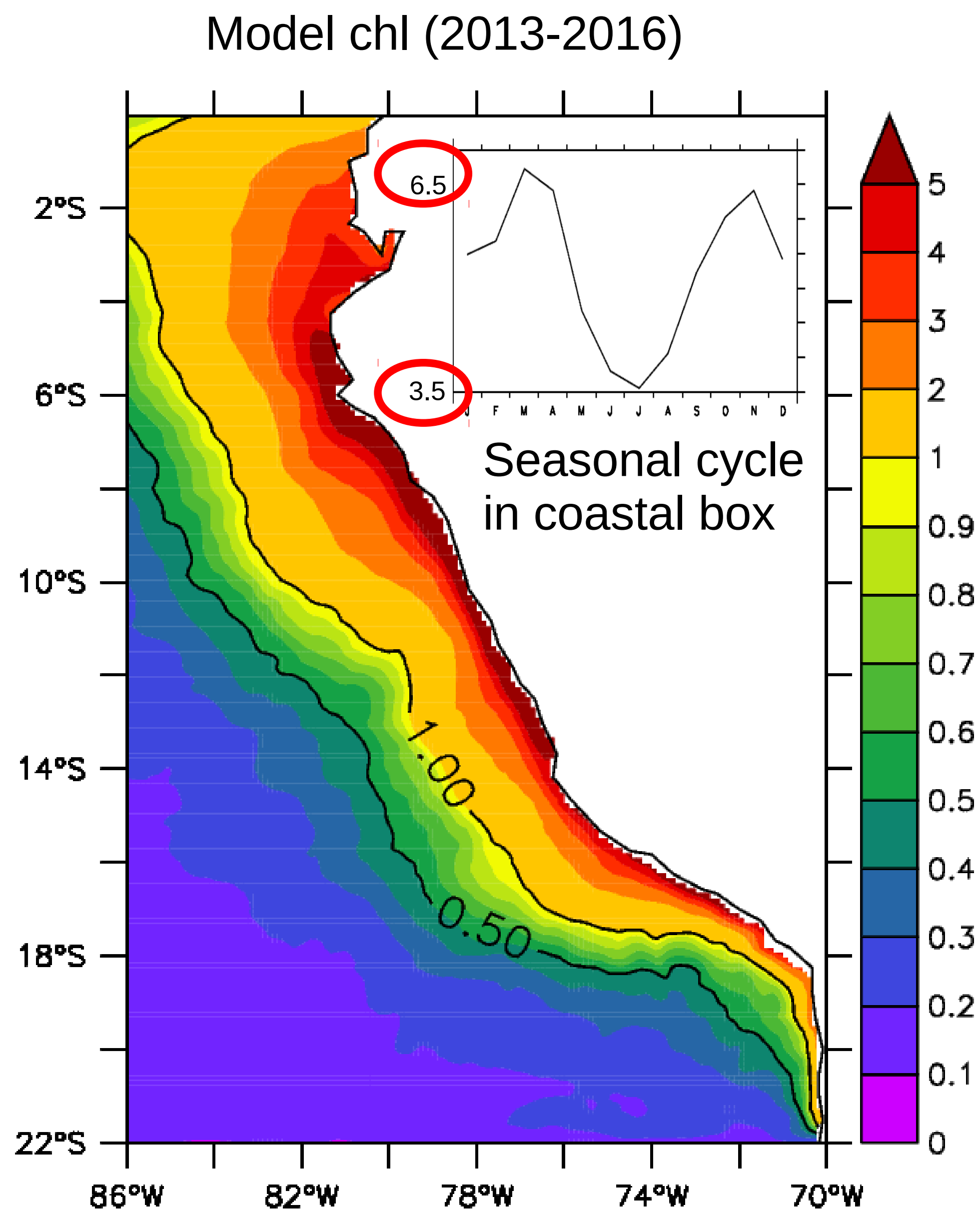
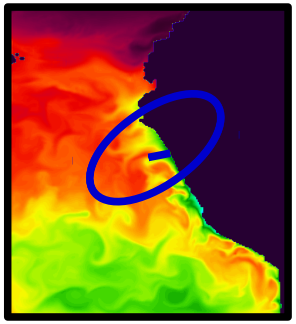




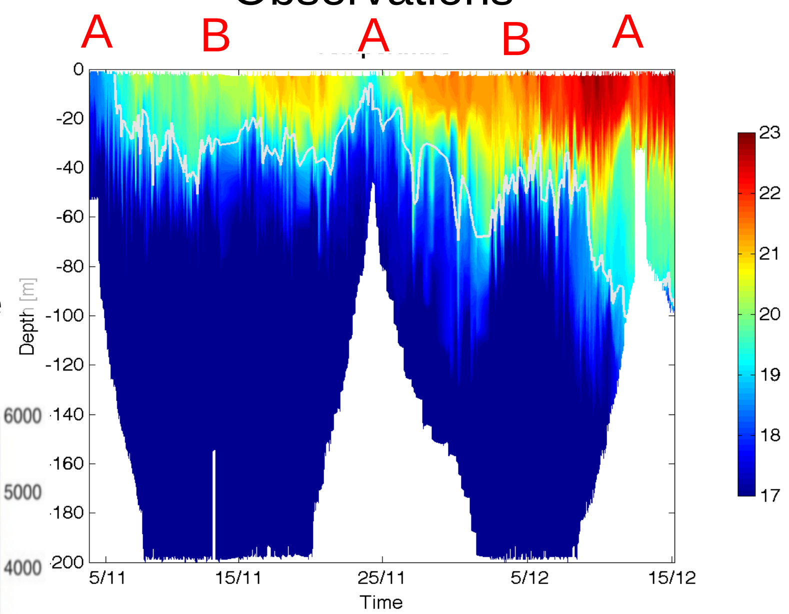
model evaluation using glider data

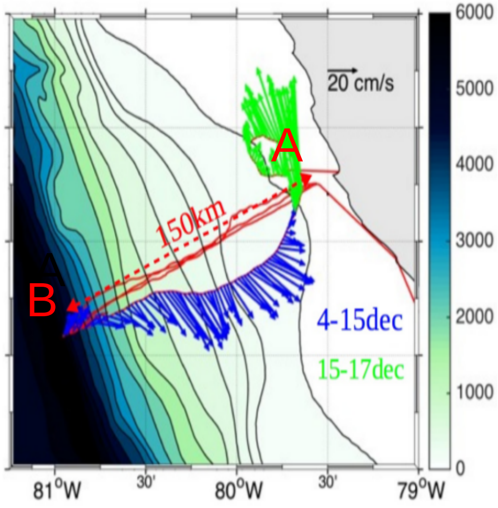
Comparison with a glider section north of Peru in November-December 2015



Temperature

Observations





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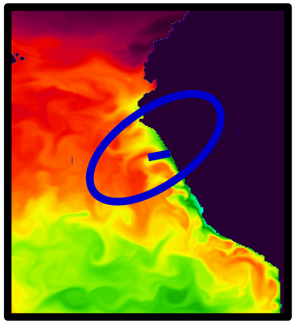

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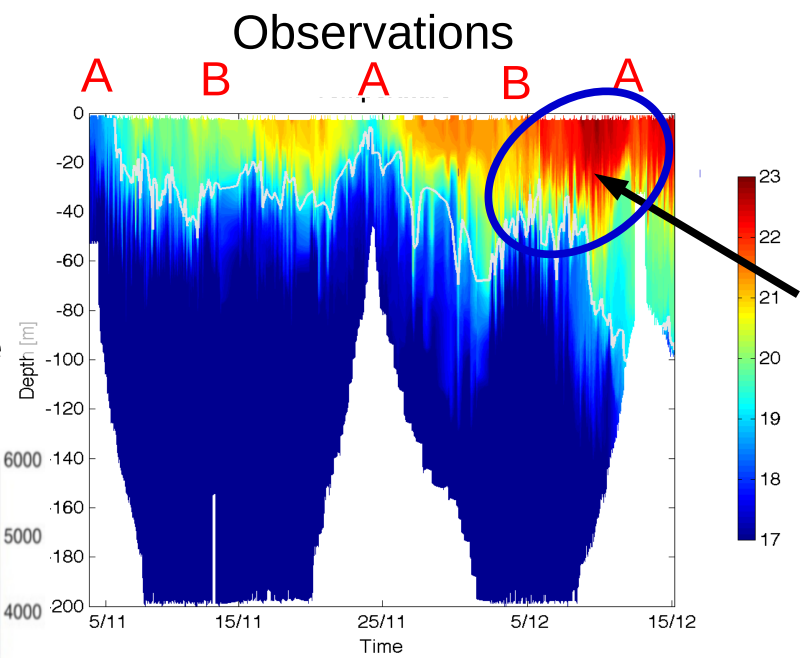
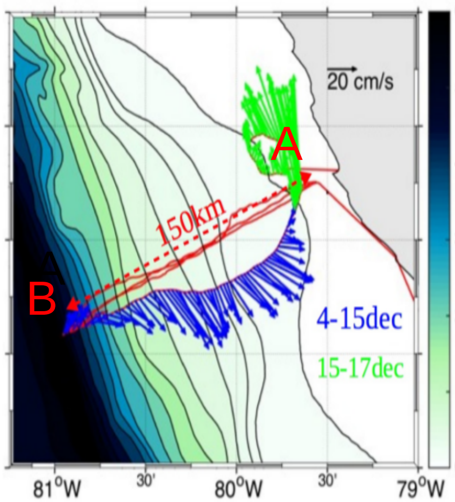


nearshore

warming

(El Niño)



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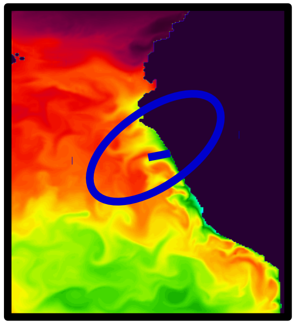

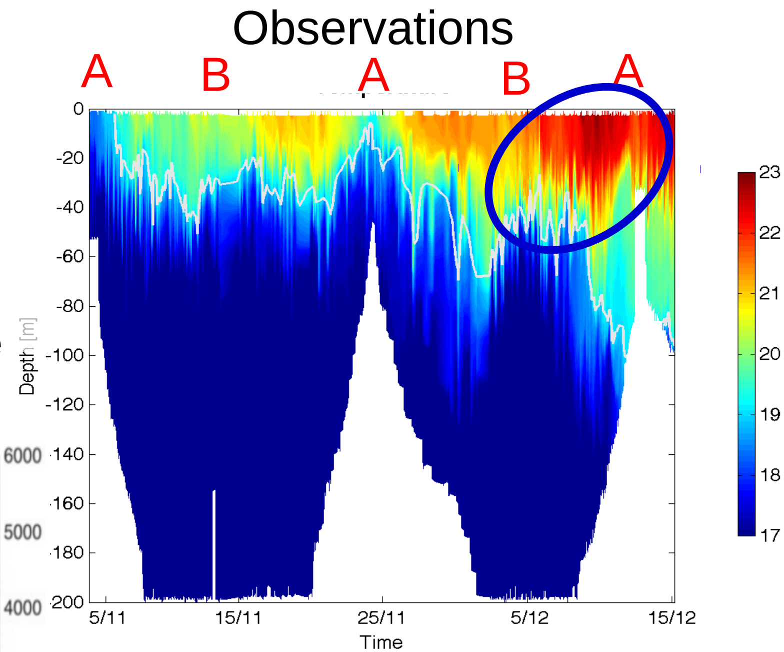

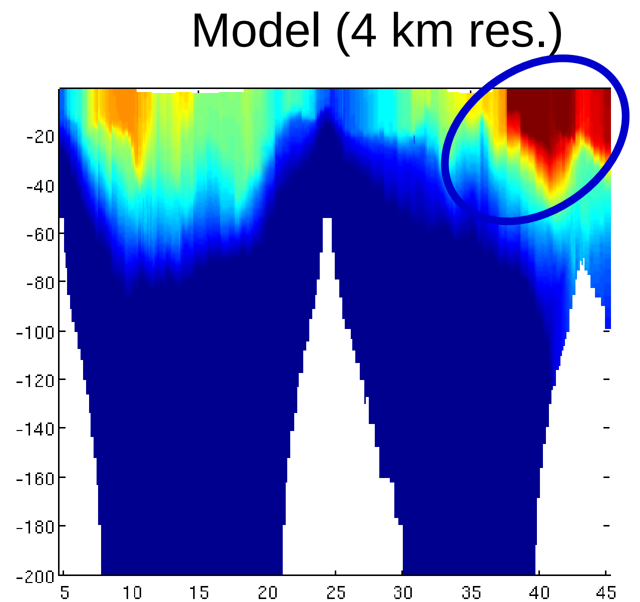

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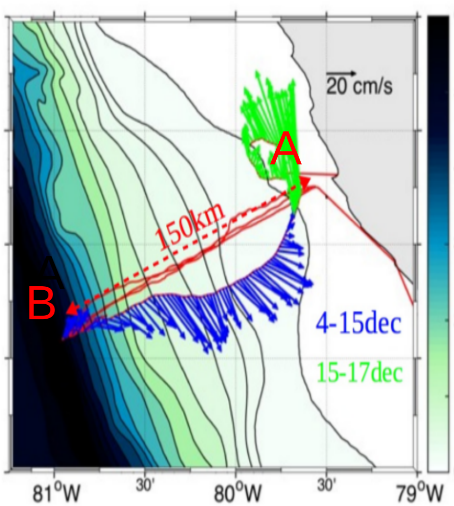

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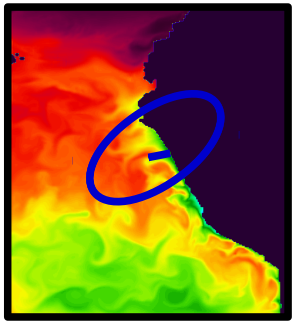

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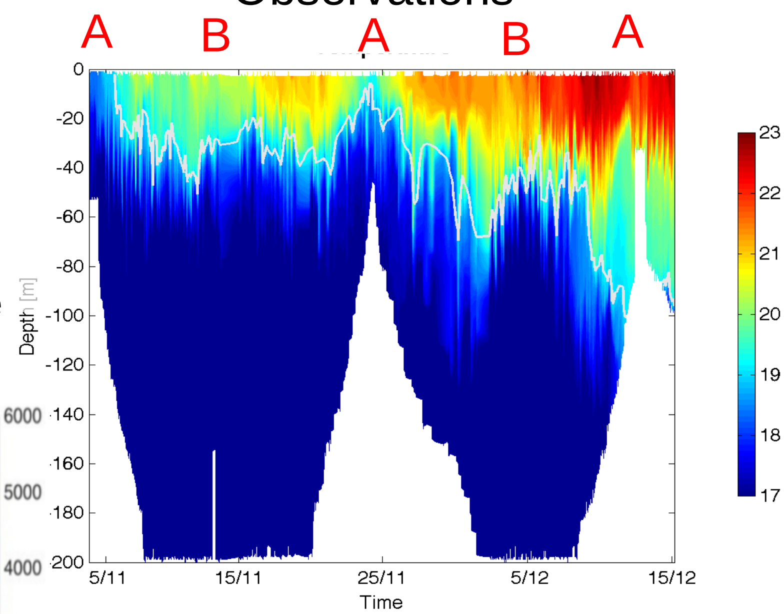
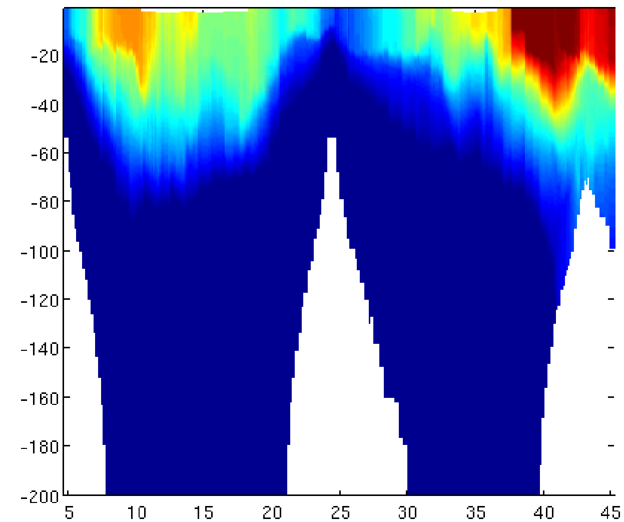
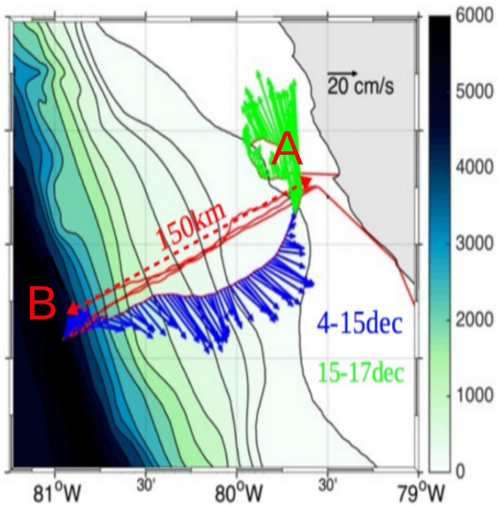


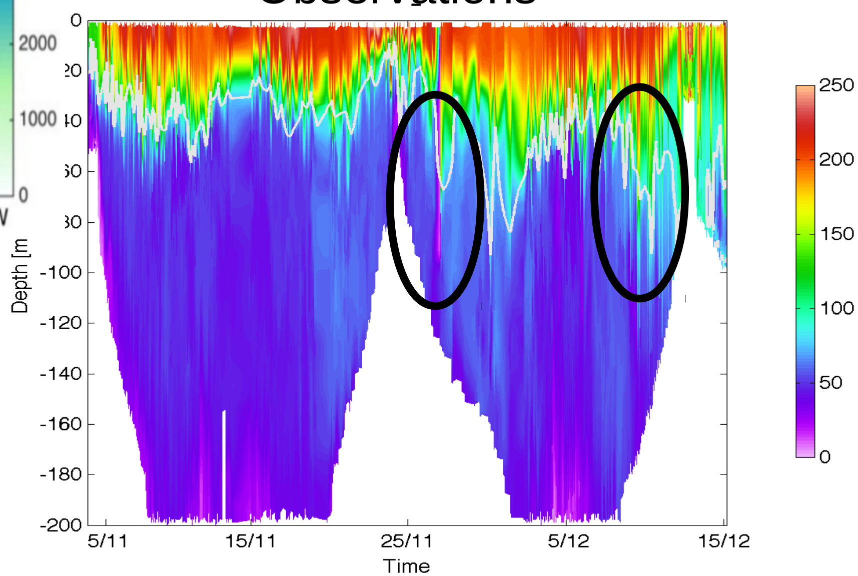
Model (4 km res.)





Oxygen

Observations



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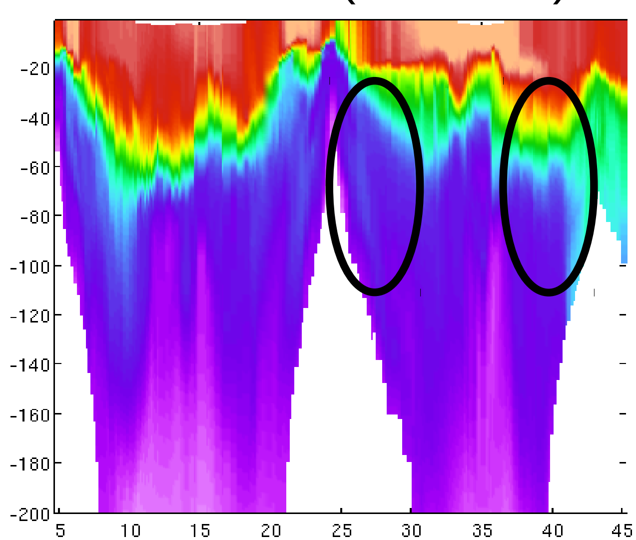

Oxygen long term trends in the Peru OMZ

- What drives oxygen variations in the Peru upwelling systems?

El Nino/La Nina: Espinoza-Morriberon et al, (2019), Frontiers in Marine Sciences

Long-term trends: Espinoza-Morriberon et al.(2021), Scientific Reports

Model configuration of this study:

- ROMS-PISCES model (1/6°~ 20 km), 1958-2008 period
- SODA global model for physical open boundaries
- CARS climatology O2 + nutrients for bgc open boundaries
- atmospheric forcings: NCEP, CFSR,...

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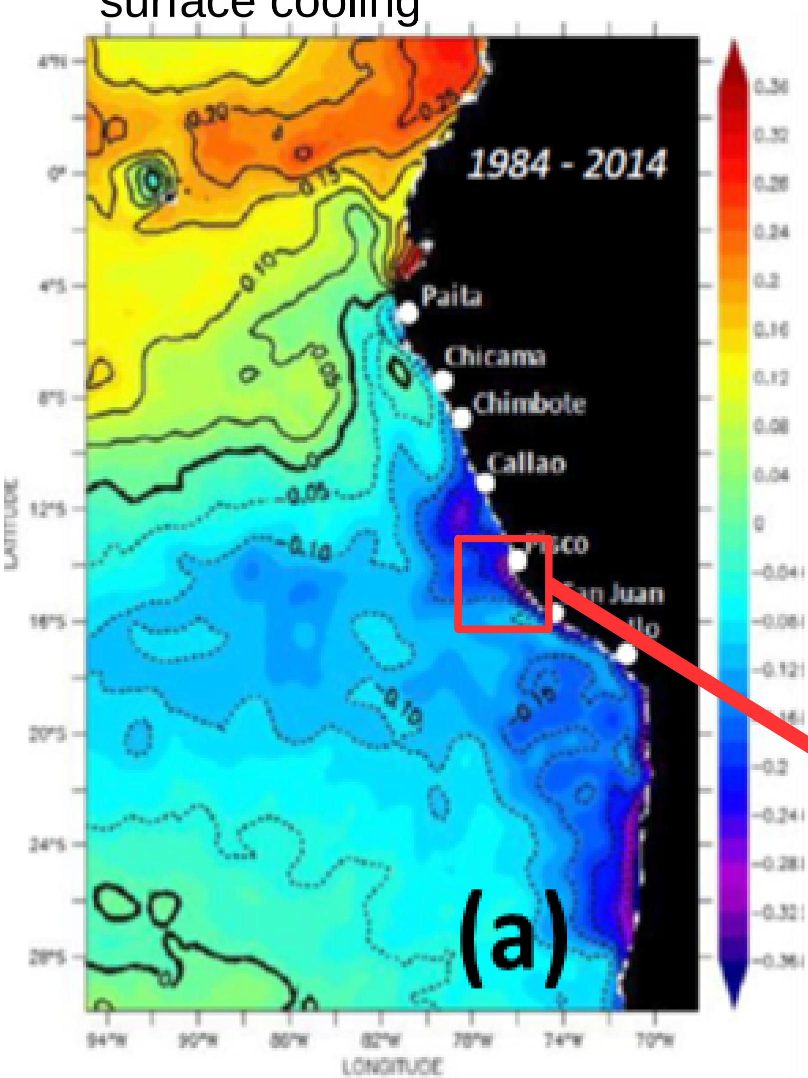
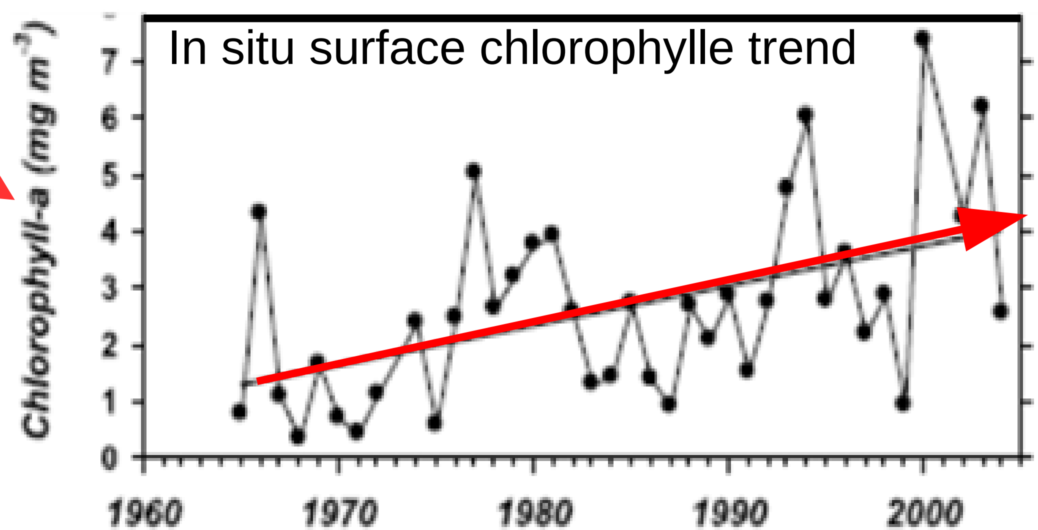
Trends in the Peru-Chile region

AVHRR SST trend (1984-2014)
surface cooling





Gutierrez et al. (2011)

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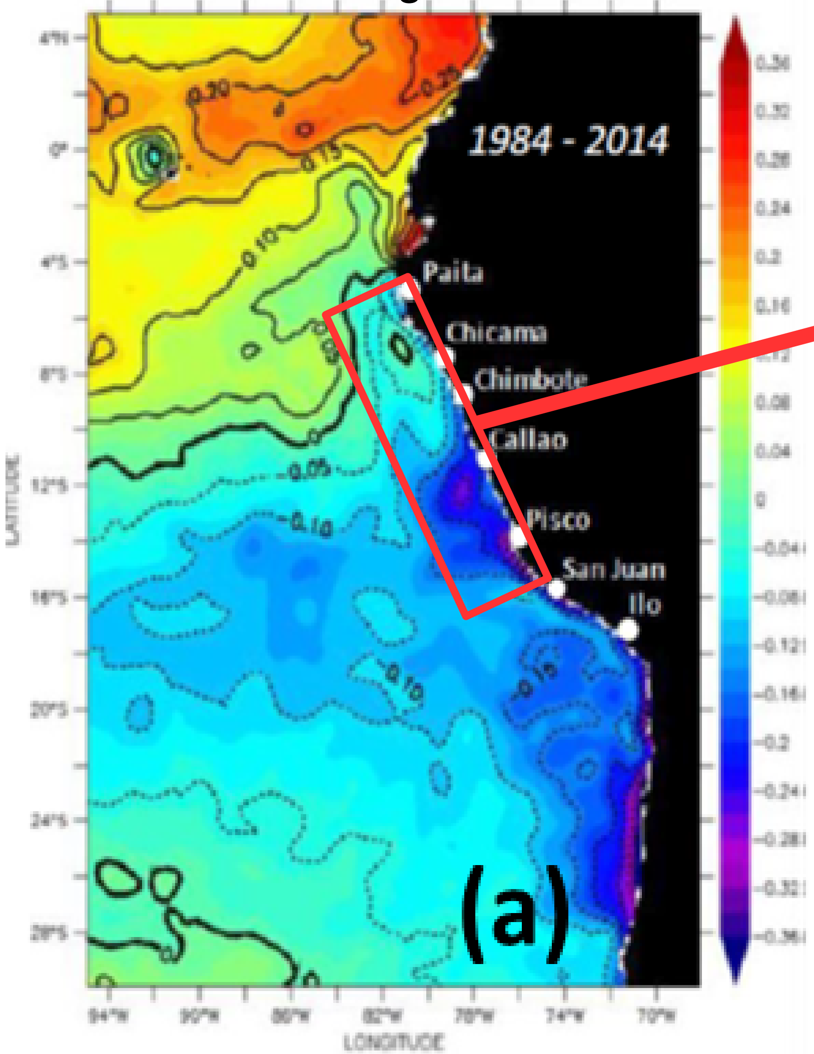
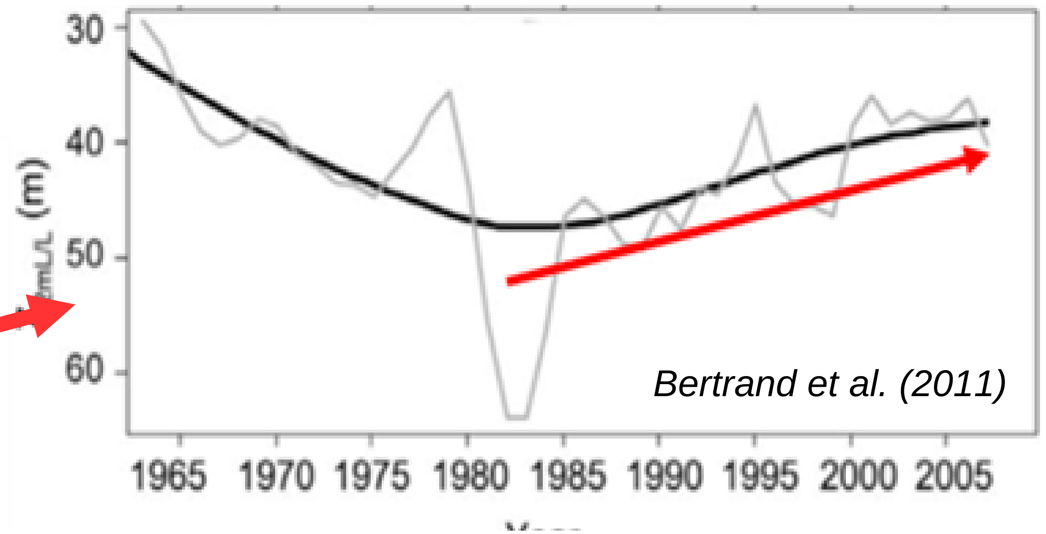
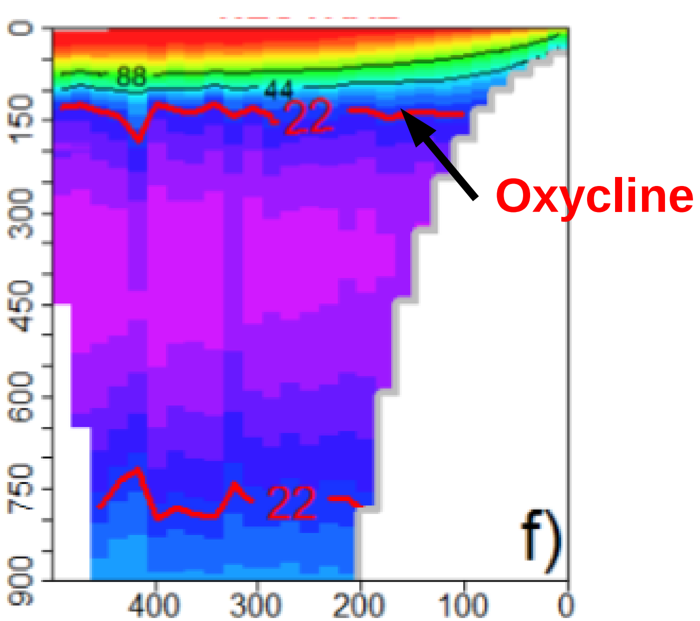


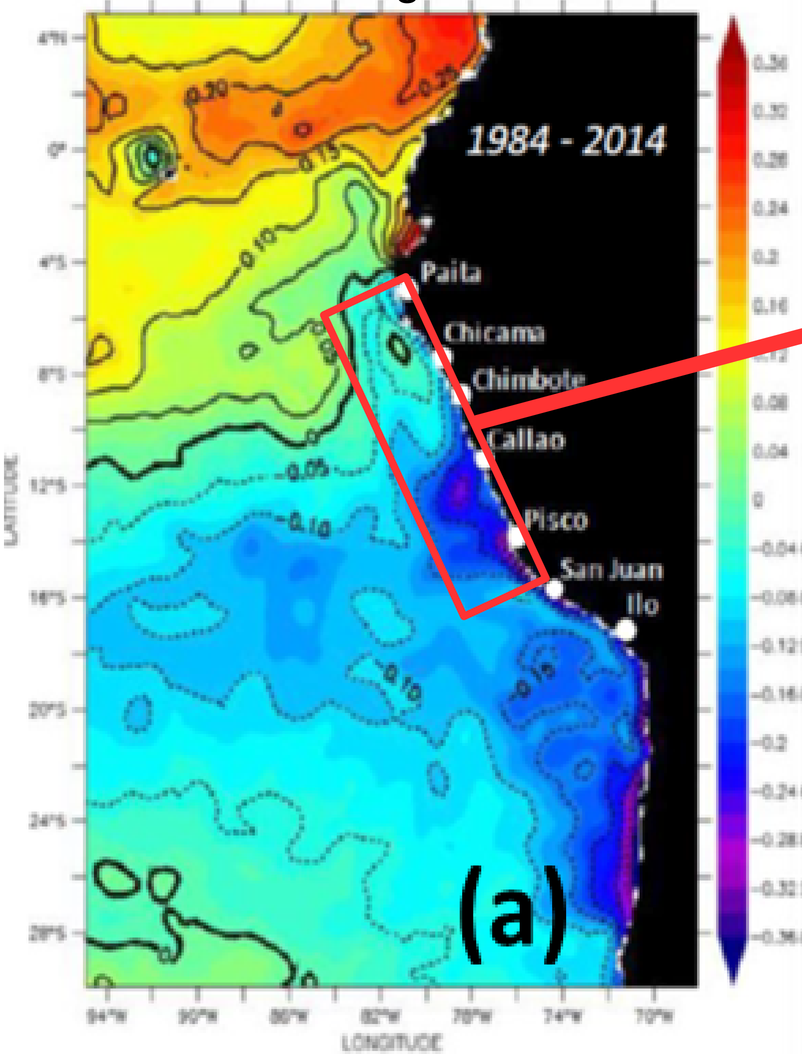
Oxycline (~90 µmol.l⁻¹) shoaling in 1980-2008





Recent observed trends in the Peru-Chile region

AVHRR SST trend (1984-2014)
surface cooling



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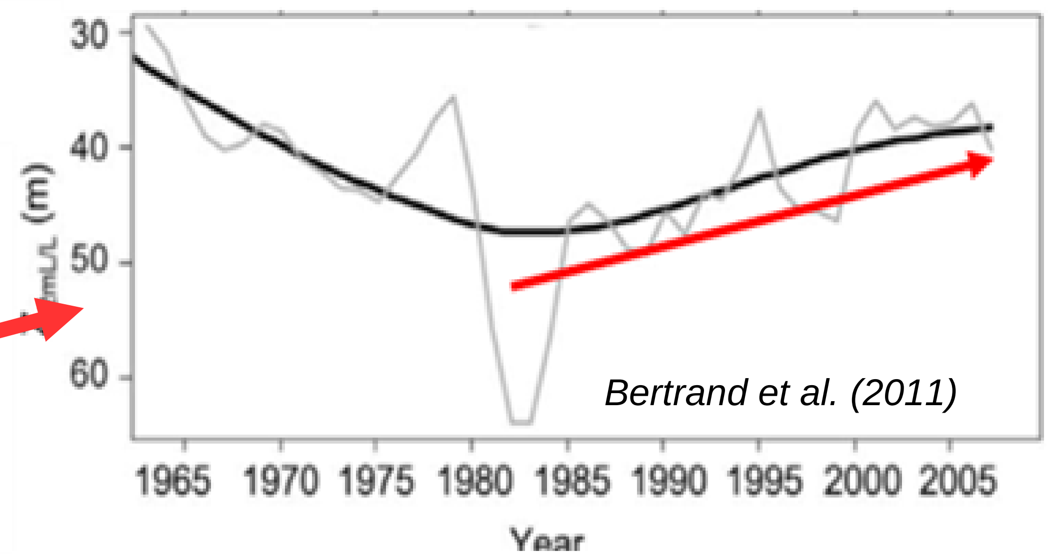

Consistent trends in SST, oxycline and Chl :

=> What is the forcing of these trends ?

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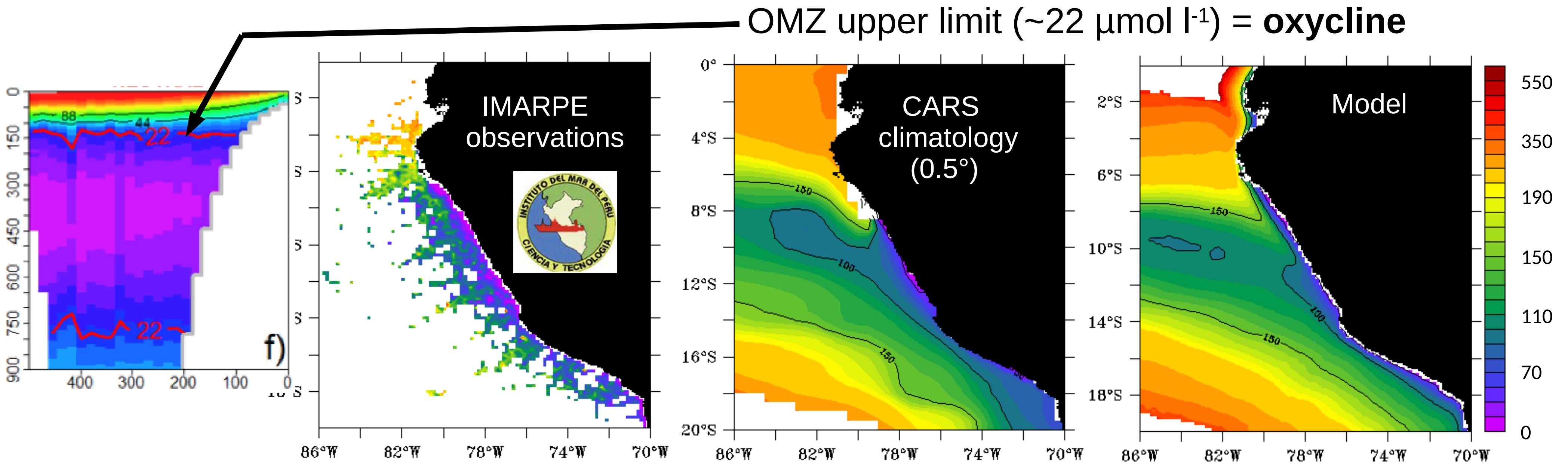
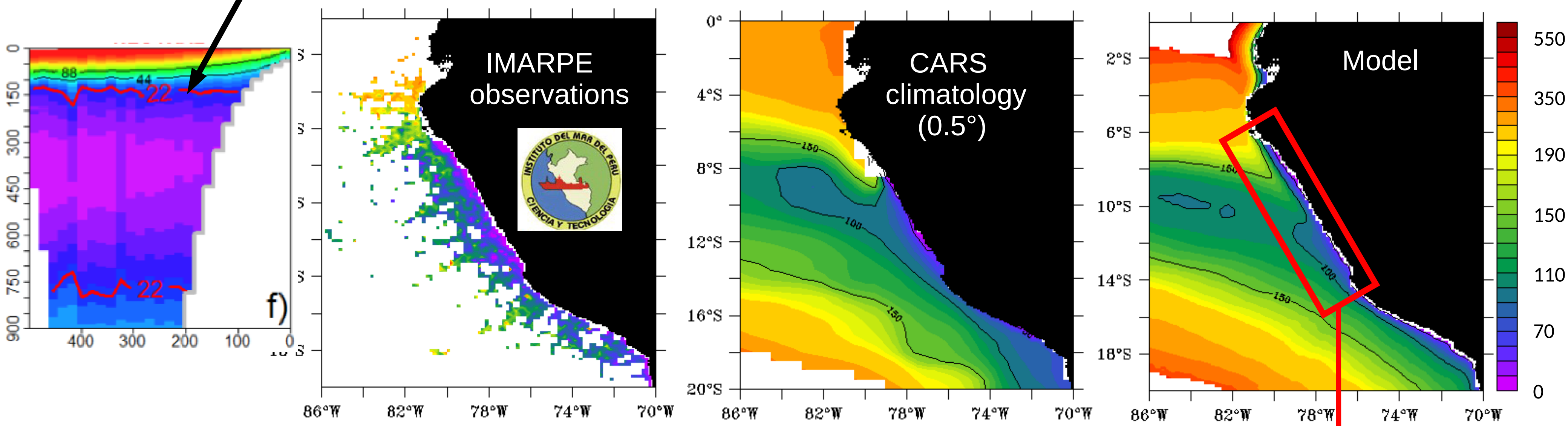
Evaluation of Interannual variability of the OMZ



Espinoza-Morriberon et al., 2019

Evaluation of Interannual variability of the OMZ

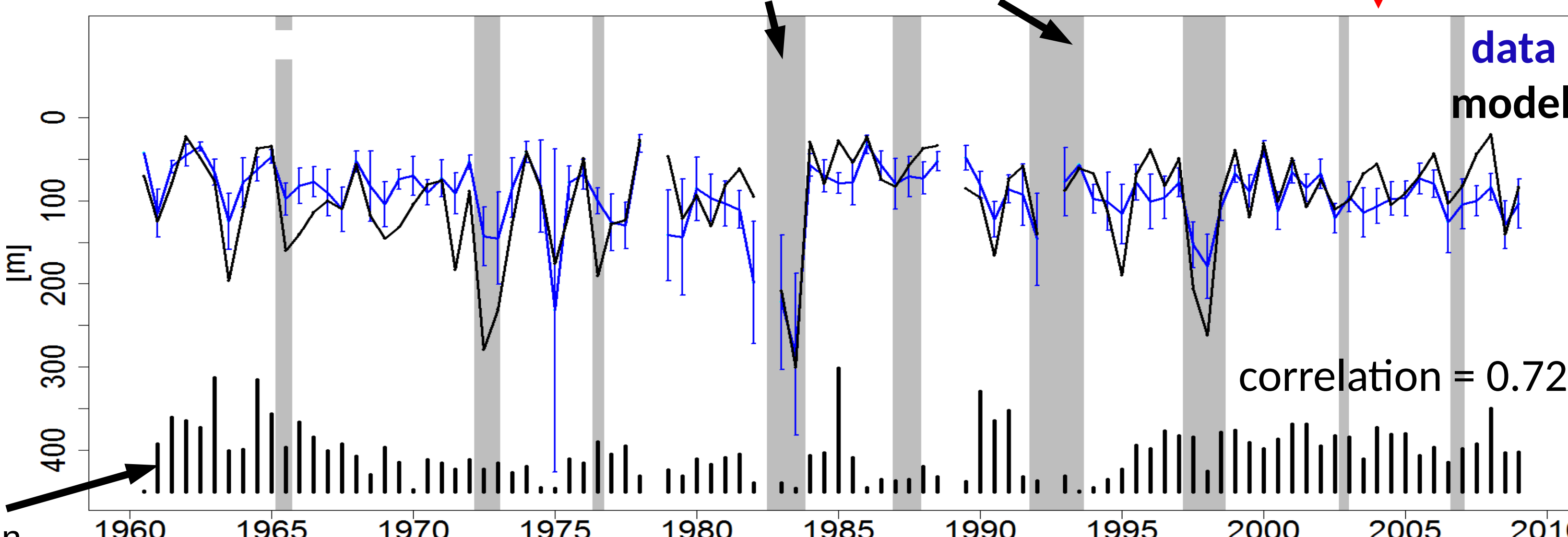
OMZ upper limit (~22 μmol l^{-1}) = **oxycline**



Espinoza-Morriberon et al., 2019

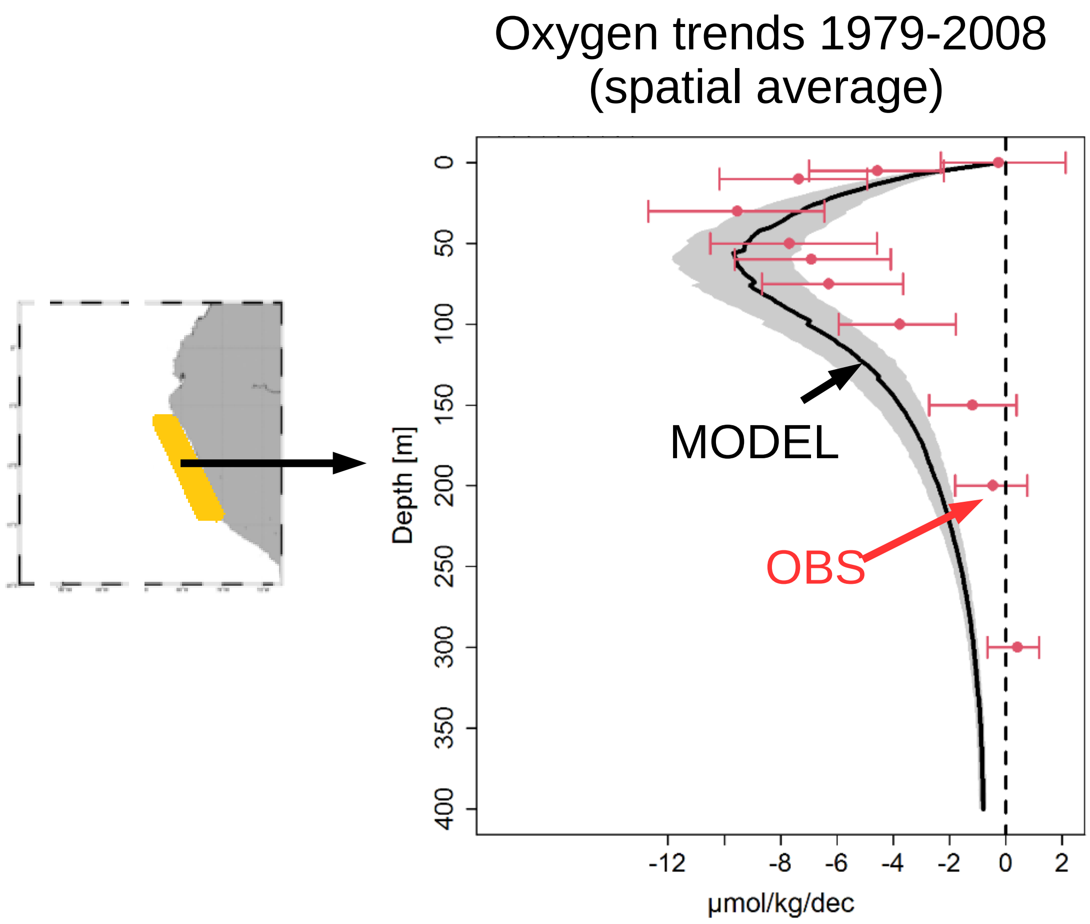
Variation of oxycline in 1960-2008

El Niño events (gray bars)



number of data points in each bin

Long-term variability of the OMZ



- decreasing oxygen trends between 10 m and 150 m depth in observations and model

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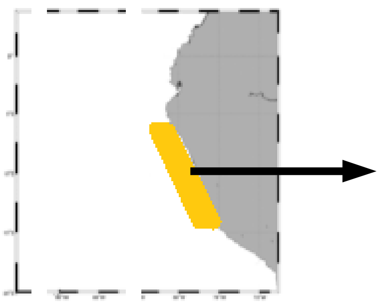
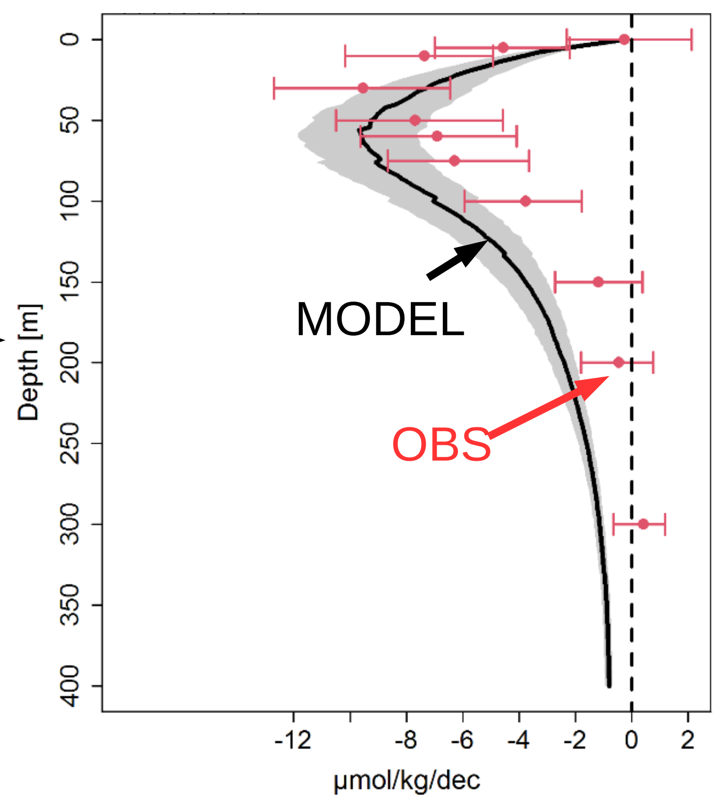
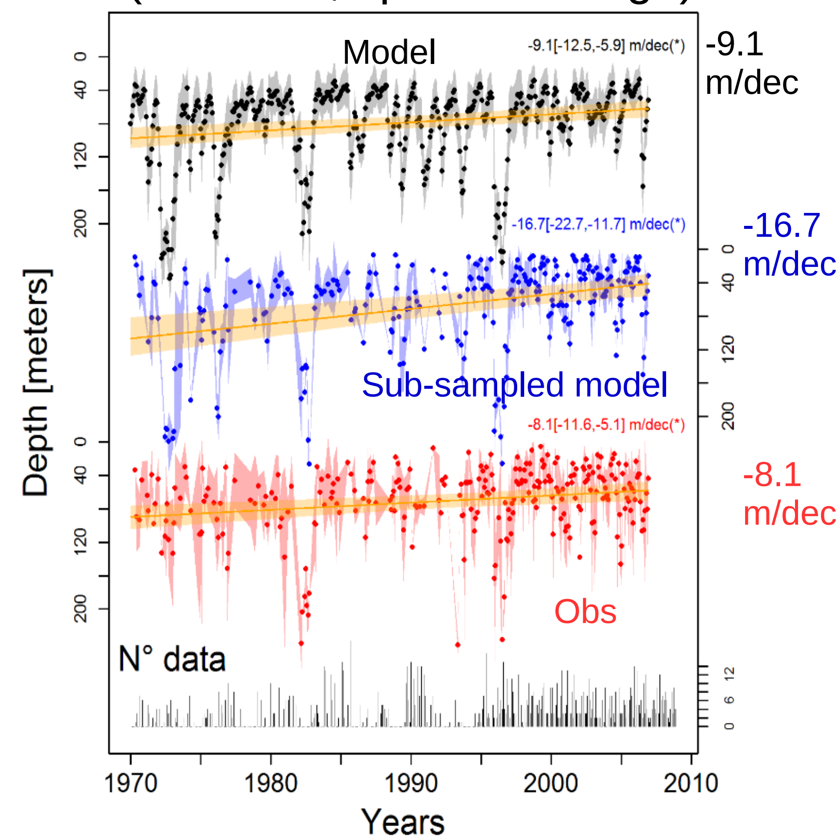


Oxygen trends 1979-2008
(spatial average)



Oxycline trend 1979-2008
(10S-13S, spatial average)



- decreasing oxygen trends between 10 m and 150 m depth in observations and model

- model reproduces oxycline shoaling trend (~ -10 m/decade)

- subsampling the model results leads to overestimation of trend

 => observed trend could be weaker than the real trend !

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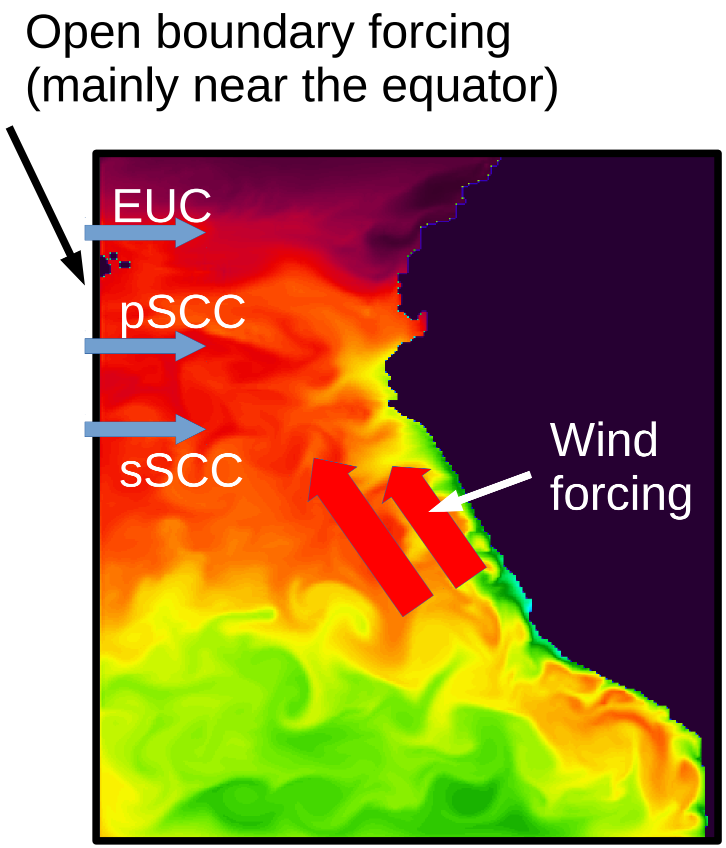
Investigating the forcing of the OMZ long-term variability

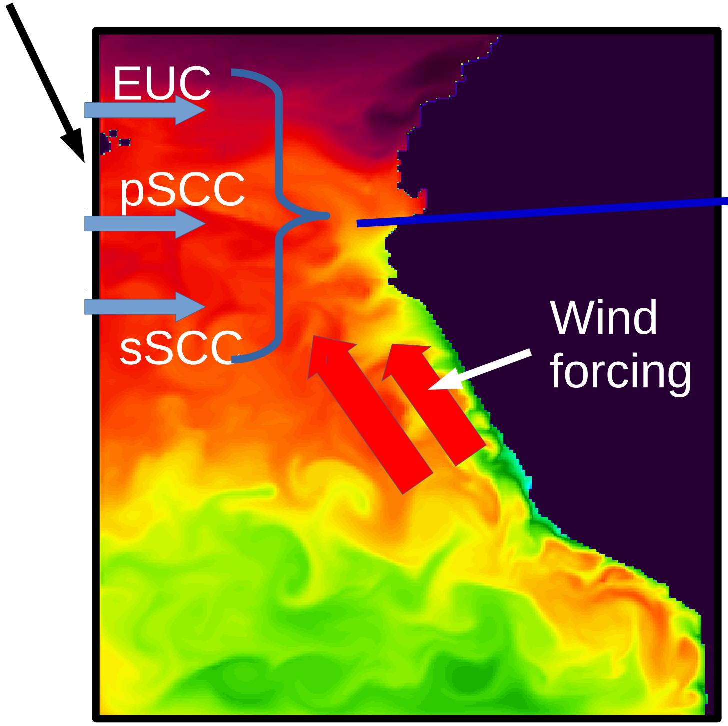
Source of variability : equatorial currents and/or local wind stress ?



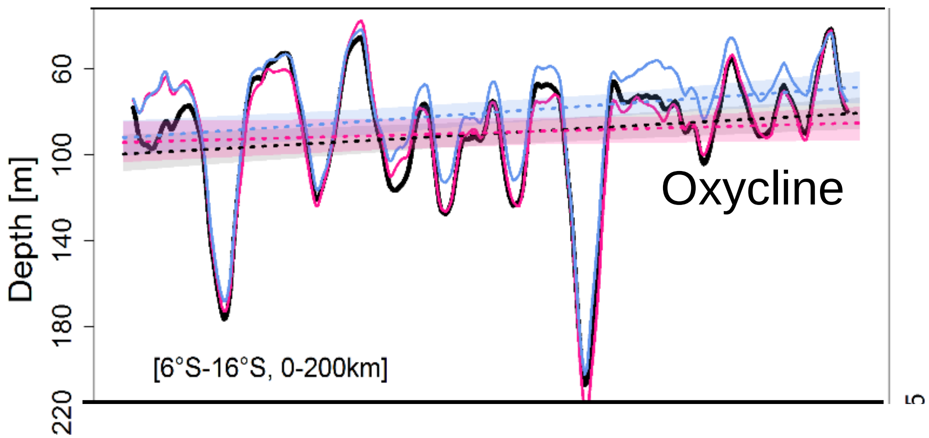
Investigating the forcing of the long-term variability

Source of variability : equatorial currents and/or local wind stress ?

Open boundary forcing
(mainly near the equator)



Different **climatological** wind forcing
+ **interannual boundary conditions**



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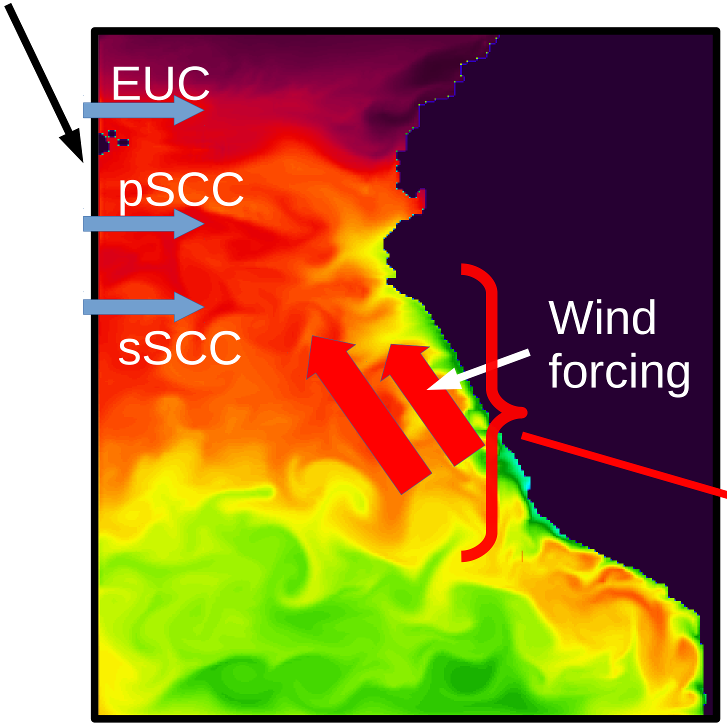

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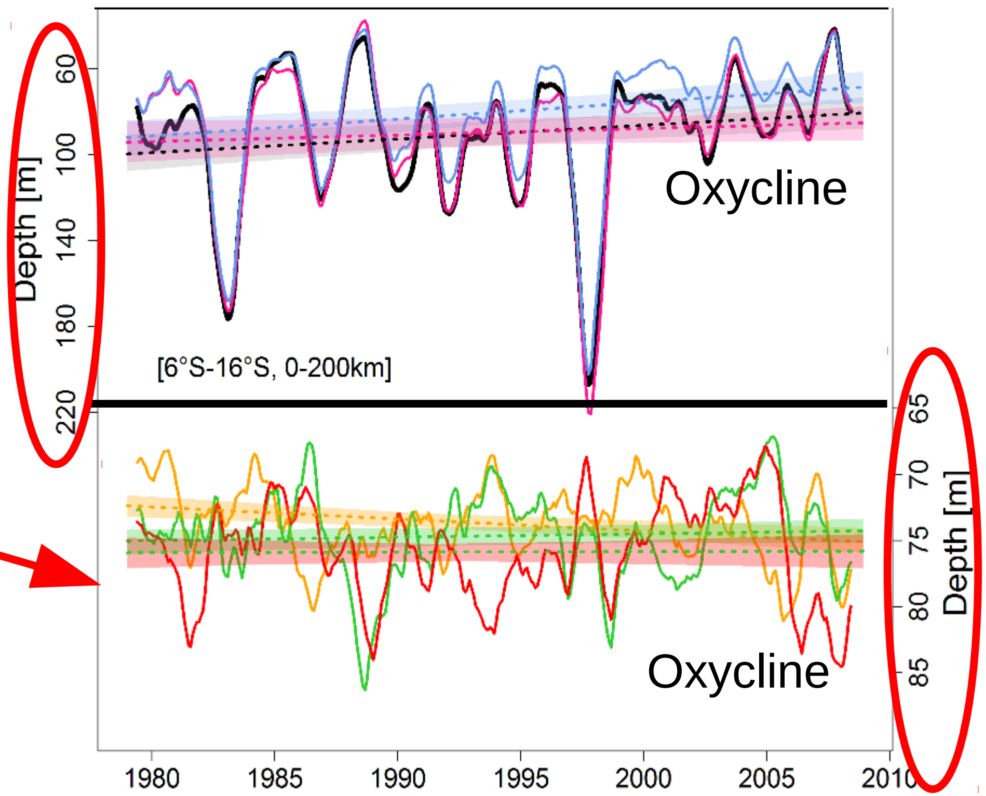

Different **interannual** wind forcing
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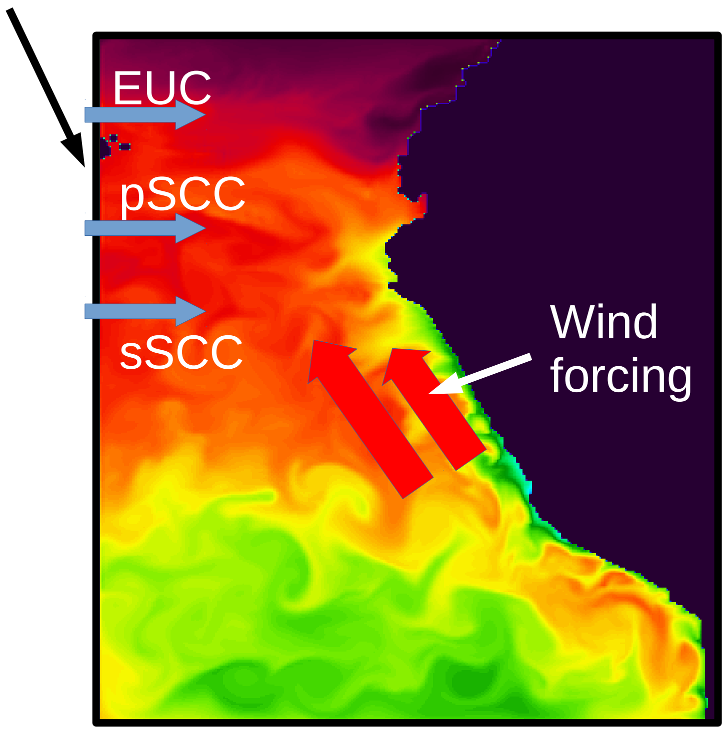

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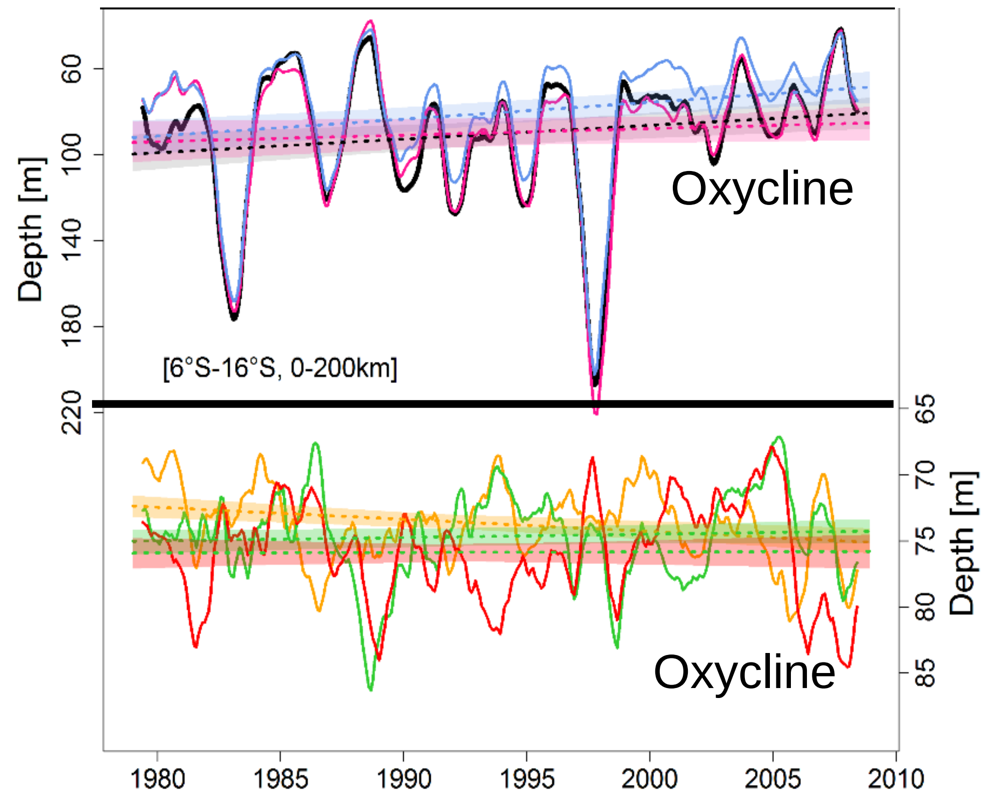


Different **interannual** wind forcing
+ **climatological** boundary conditions

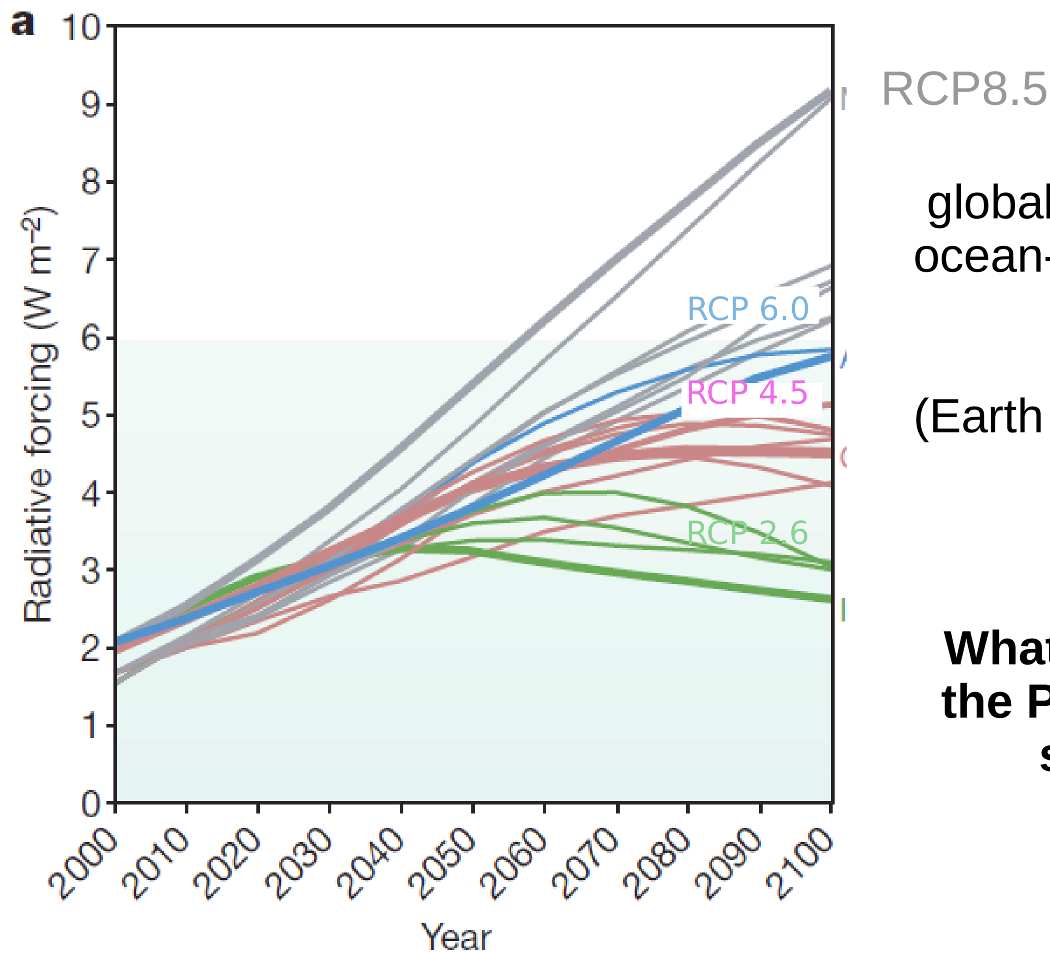
=> Reducing oxygen flux by equatorial currents (ventilation)
drives deoxygenation in 1970-2008 period

Investigating the forcing of the long-term variability: climate change

Impact of climate change on the Peruvian Upwelling system :

Echevin et al., Biogeoch. Discuss., 2020

CMIP5 climate scenarios



global, large scale ocean-atmosphere-BGC Models

(Earth System Models=ESM)

What is the impact in the Peruvian upwelling system BGC ?

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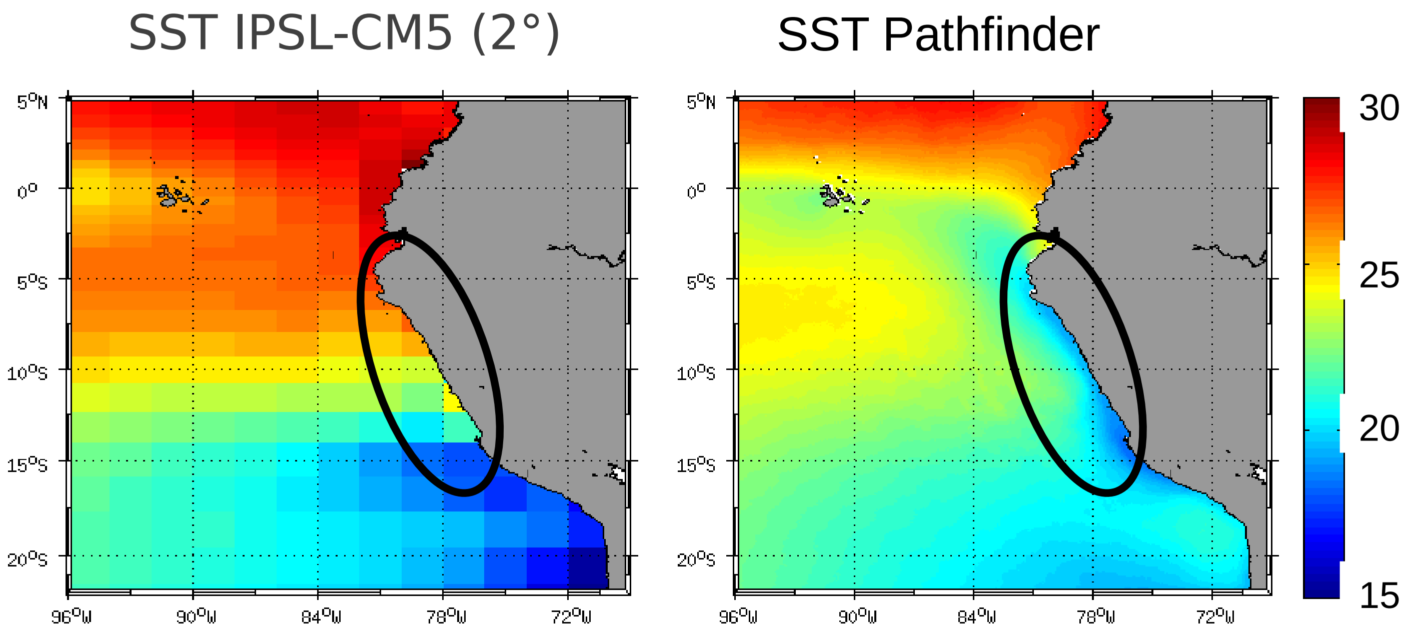
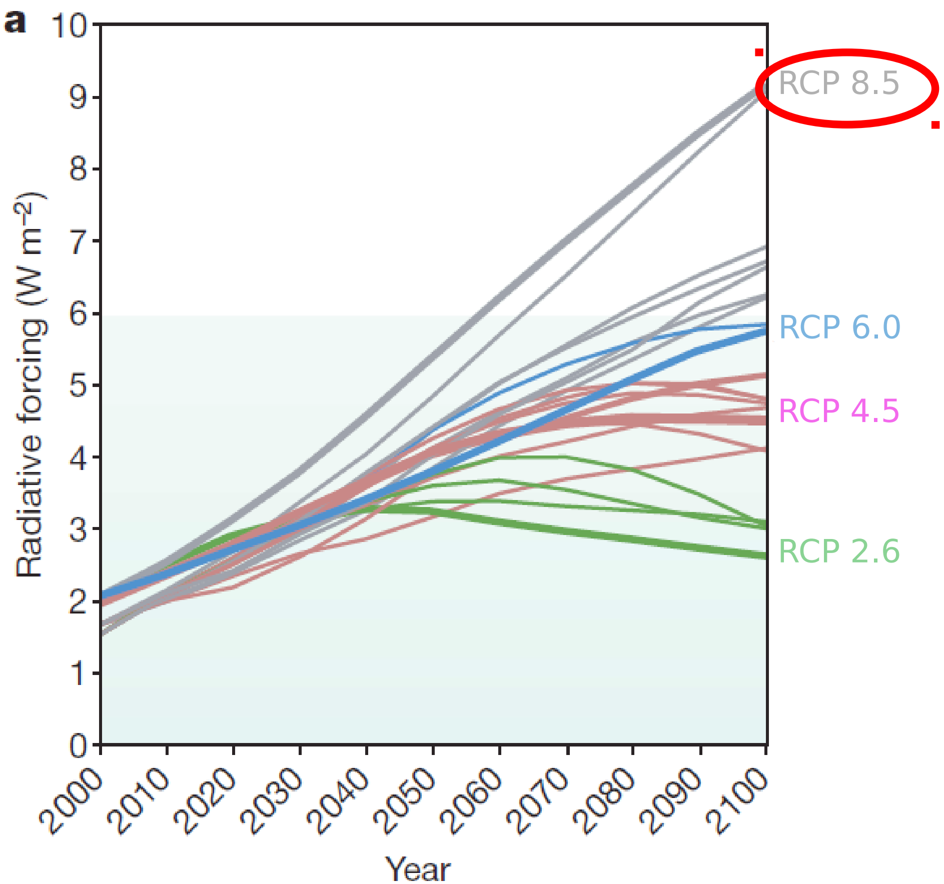
Investigating the forcing of the long-term variability: climate change

- strong model bias in CMIP5 ESM



- no/weak coastal upwelling in ESM => necessary to use regional models
to downscale climate and BGC signals

Investigating the forcing of the long-term variability: climate change



Moss et al., 2010

RCP8.5 = worst case scenario

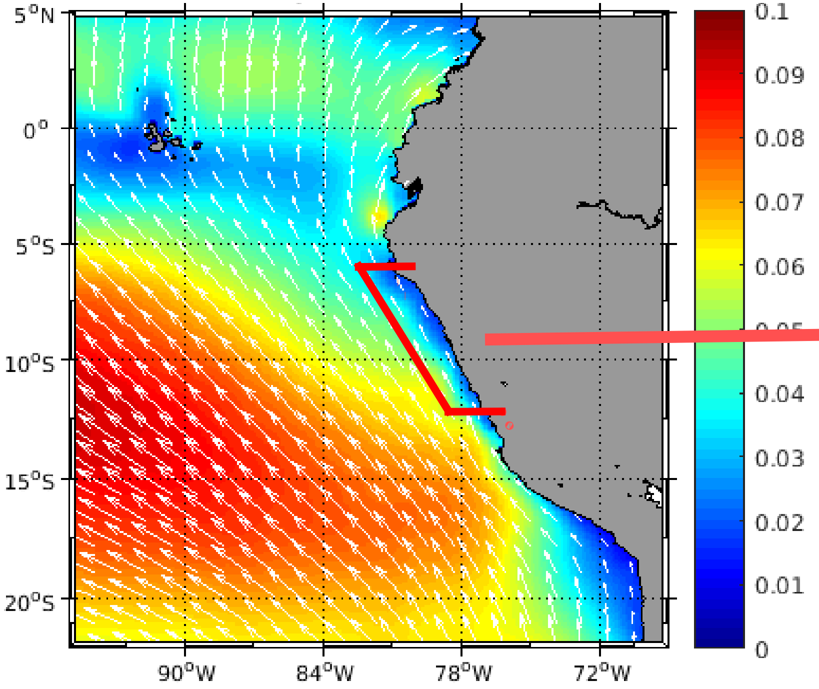
Downscaling of 3 ESM models (Phy & BGC)

CNRM-CM5, GFDL-ESM2M, IPSL-CM5A-MR

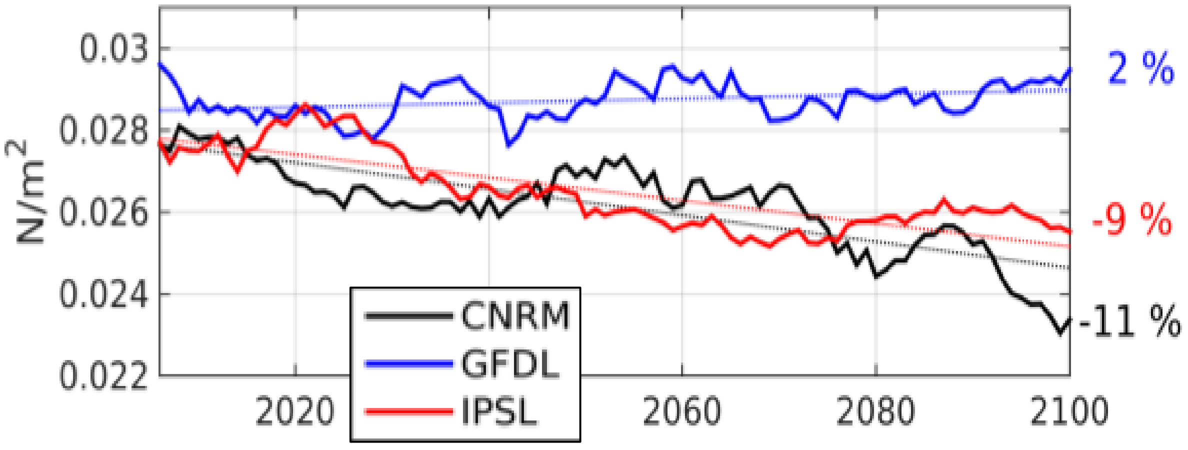
ROMS – PISCES (dx = 1/9° ~ 10 km)

Investigating the forcing of the long-term variability: climate change

Mean wind stress



Alongshore wind stress in coastal box



Dotted lines = linear trends

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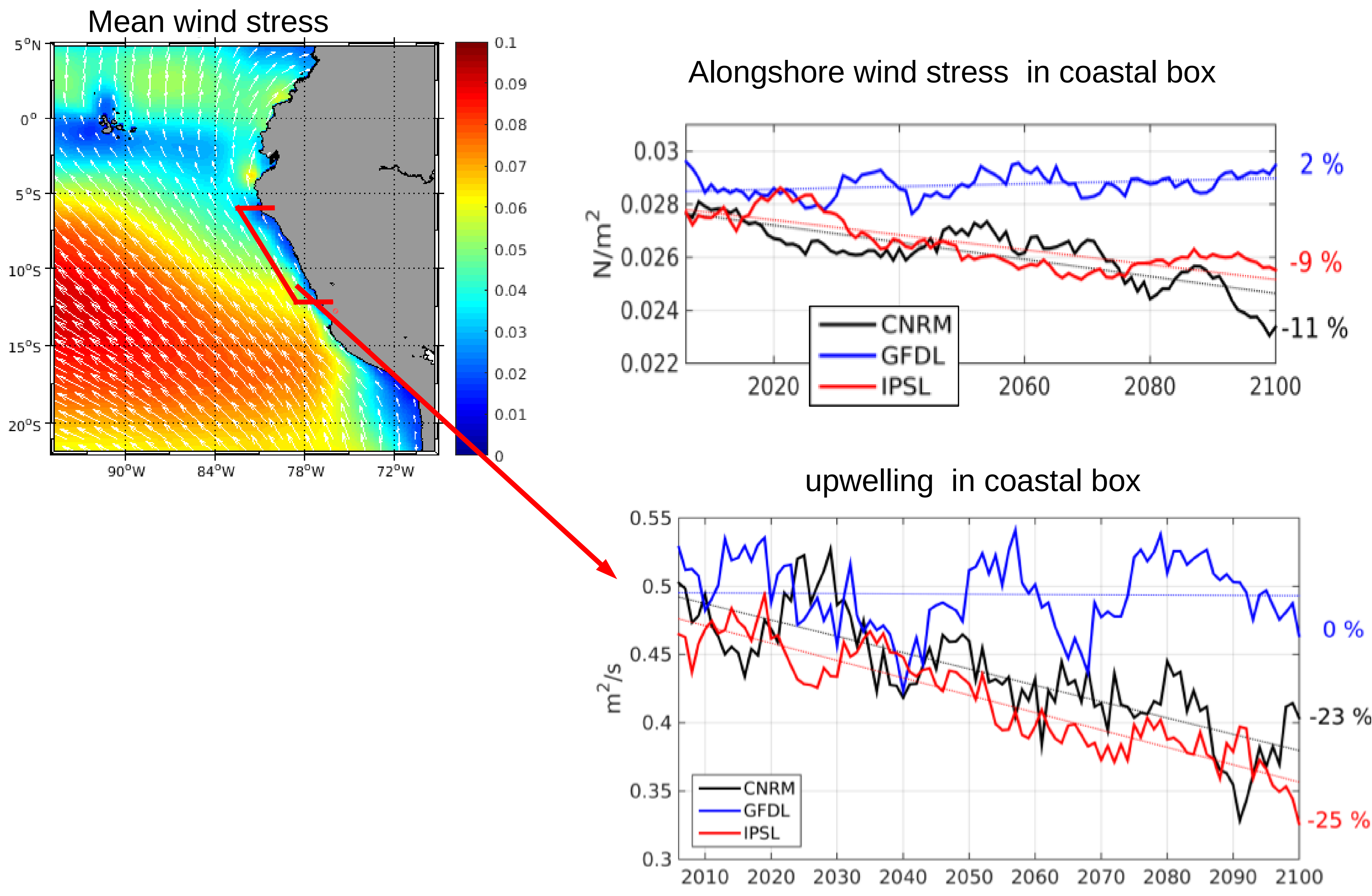
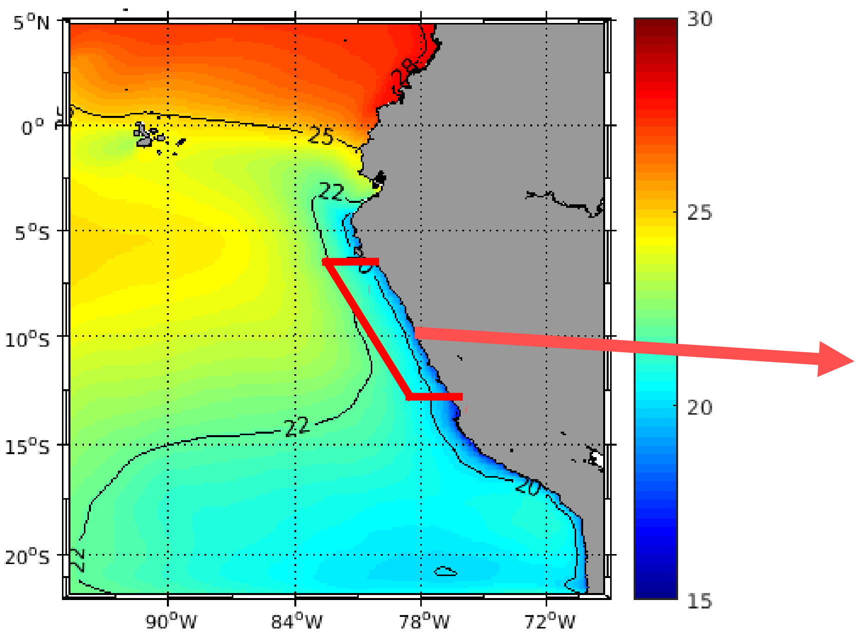
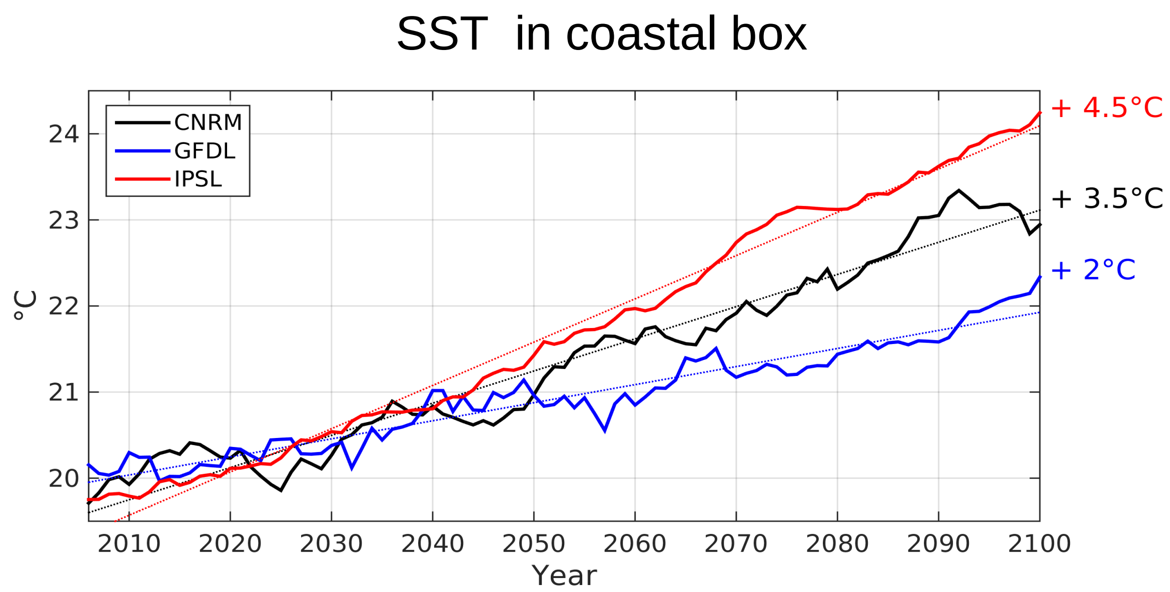
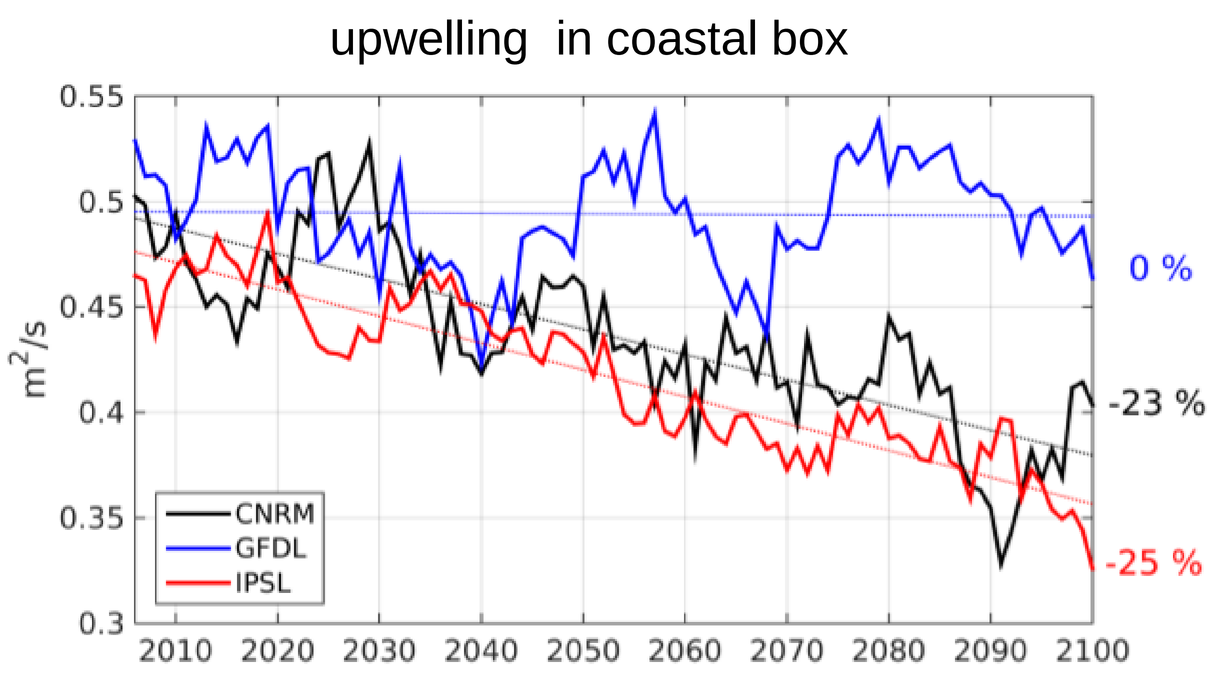
Investigating the forcing of the long-term variability: climate change



Investigating the forcing of the long-term variability: climate change







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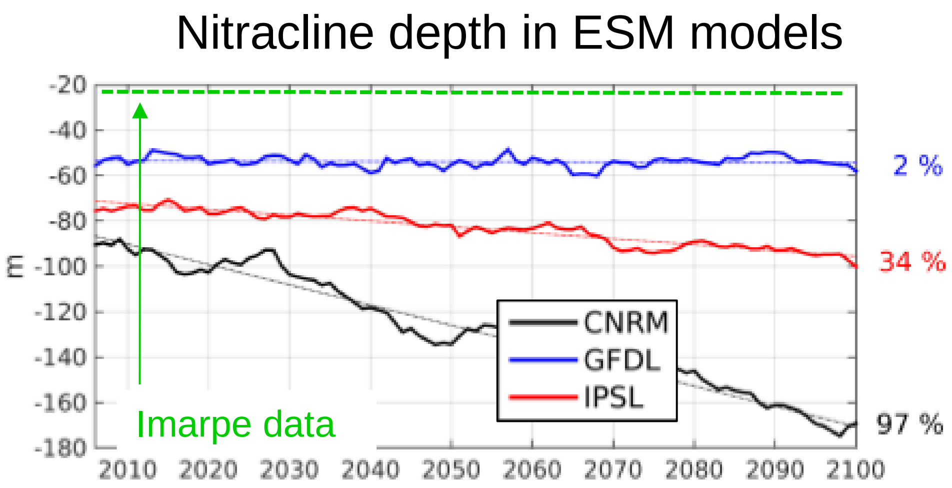
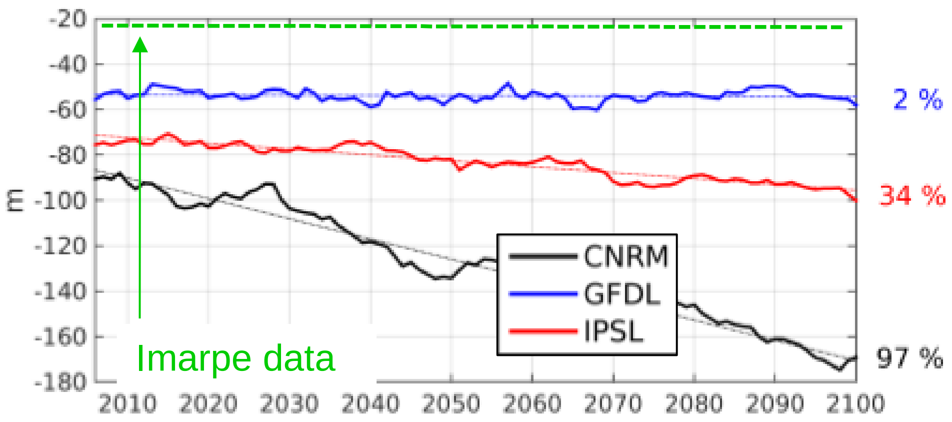


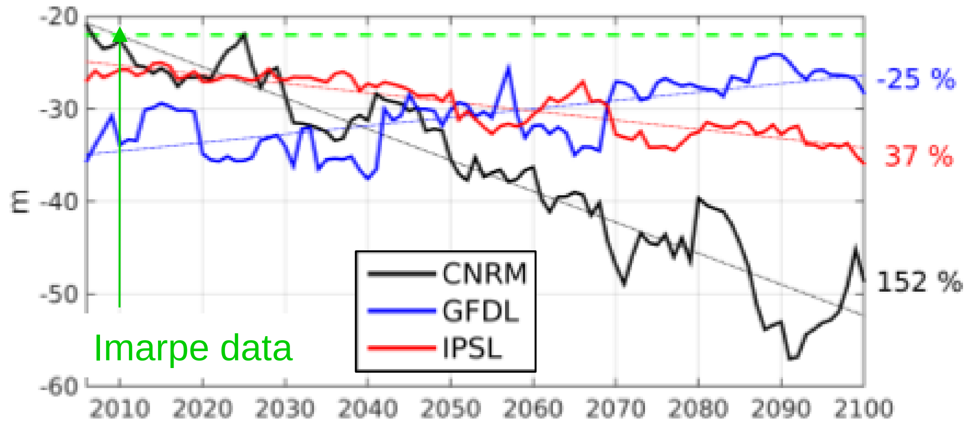
- strong bias in nitracline depth in ESM

Investigating the forcing of the long-term variability: climate change

Nitracline depth in ESM models



Nearshore nitracline depth in ROMS-PISCES



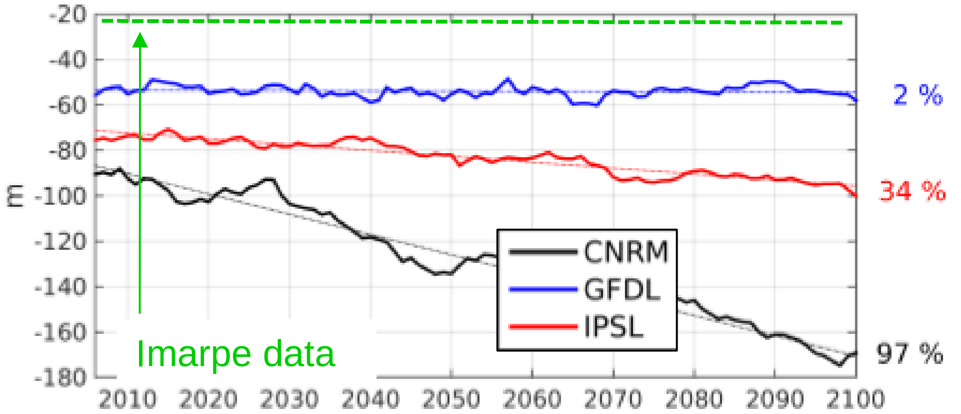
- strong bias in nitracline depth in ESM

- regional downscaling corrects part of the bias

Institut de Recherche pour le Développement FRANCE
Instituto francés de Investigación para el Desarrollo

Investigating the forcing of the long-term variability: climate change

Nitracline depth in ESM models



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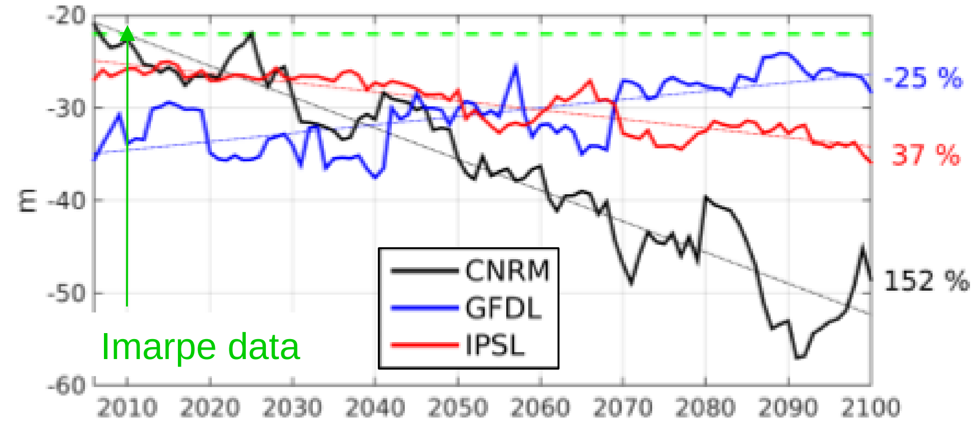
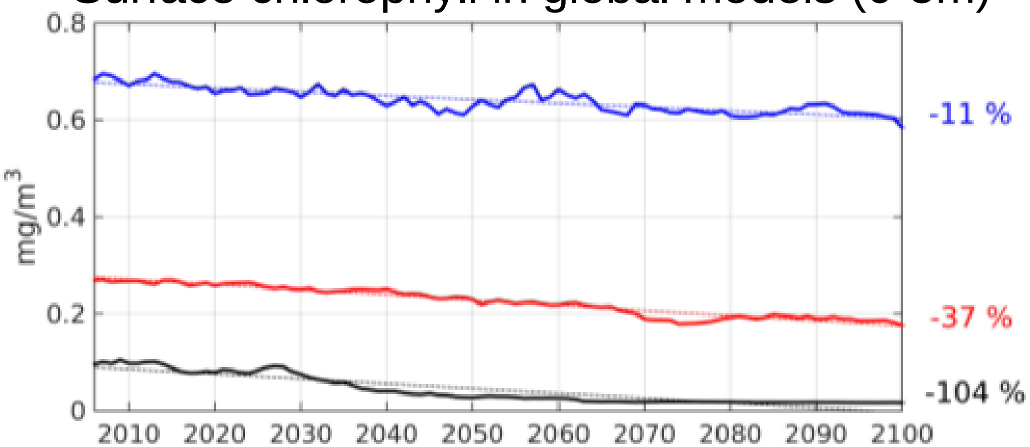
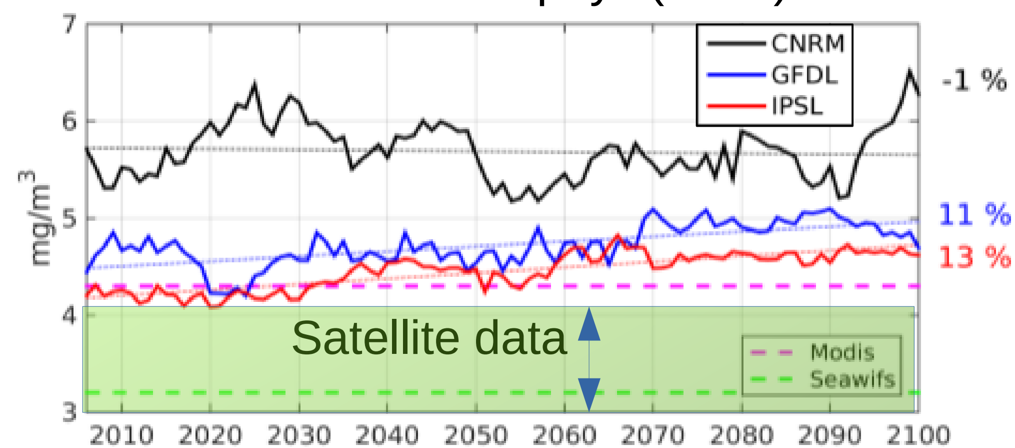


Surface chlorophyll in global models (0-5m)



Surface Chlorophyll (0-5m)



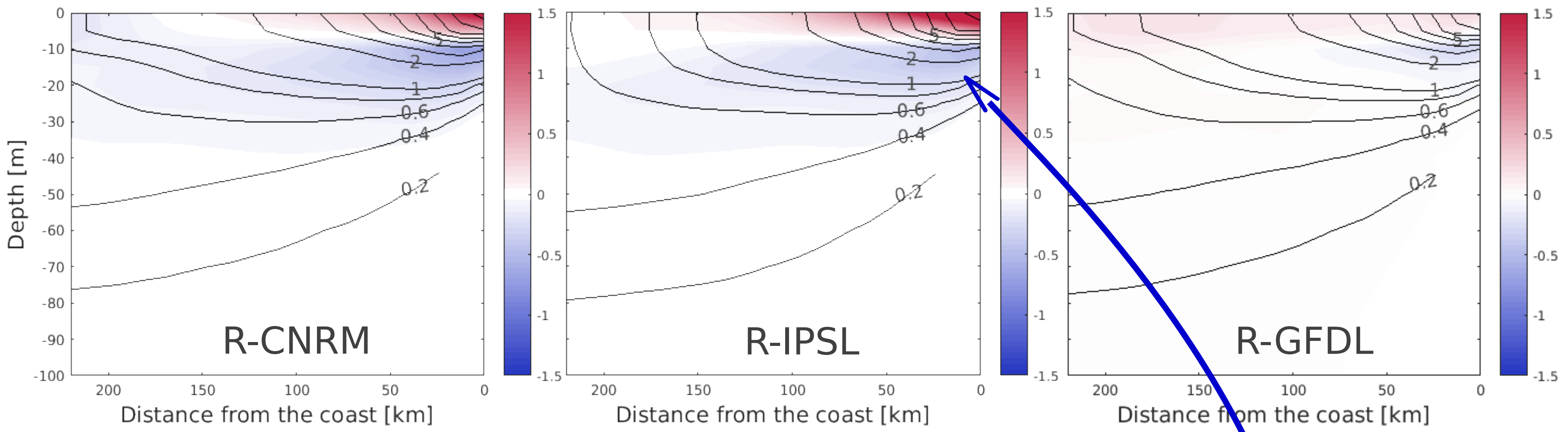
=> ROMS-PISCES surface chlorophyll range is correct ≠ global models

=> surface chl trends are very differents from those in the global models

=> weak surface chl trends in ROMS-PISCES in spite of nutricline deepening

Investigating the forcing of the long-term variability: climate change

Chlorophyll trend vertical structure



Less nutrients in subsurface layers but :

- less upwelling => less offshore transport

=> more retention near the coast

- more stratification & shallower mixed layer

=> stable phytoplankton concentration at surface and reduction below

CROCO-PISCES: tool to understand mechanisms

- What is the impact of small scale (submesoscale) dynamics in the Peru upwelling system?

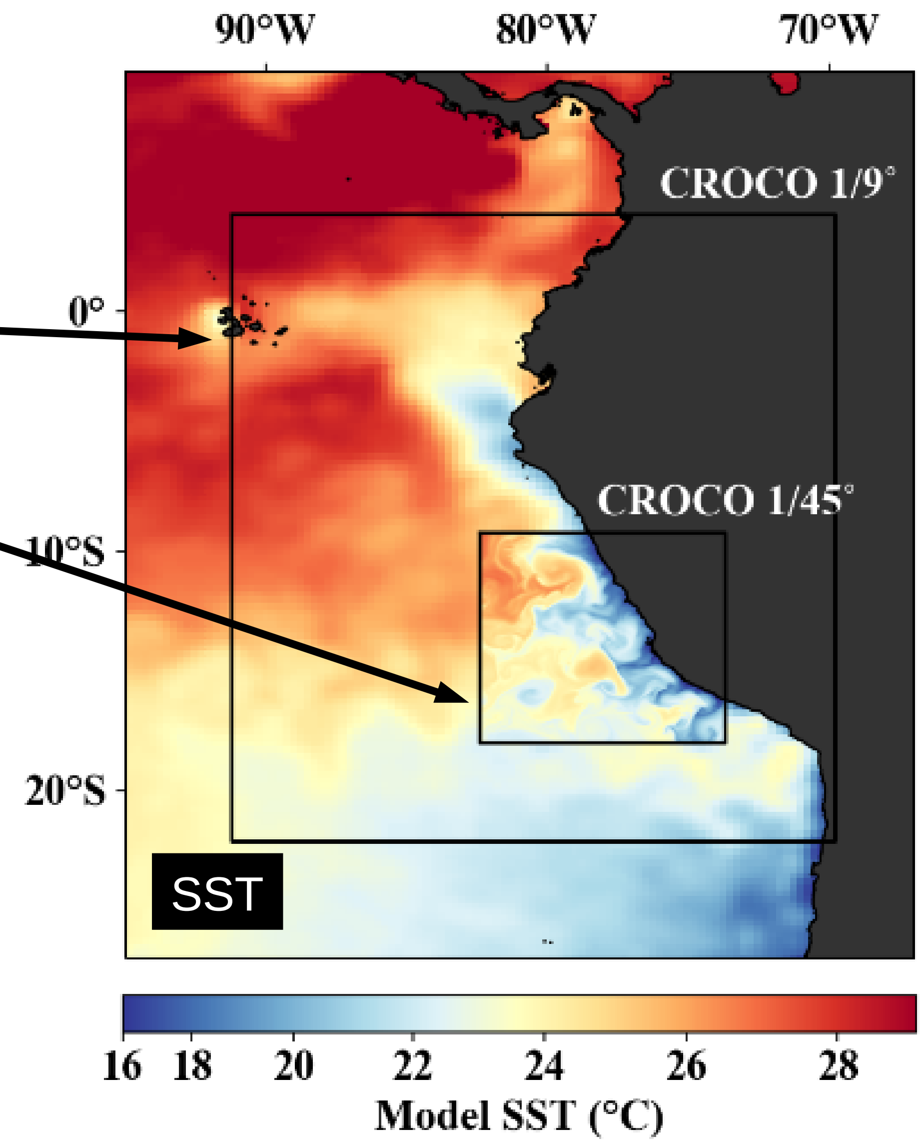
Thomsen et al. (2016), Geophysical Res. Let.

Hauschildt et al.,(2021), Biogeochemical cycles.

Model configuration

CROCO-PISCES model (1/9°~13 km)

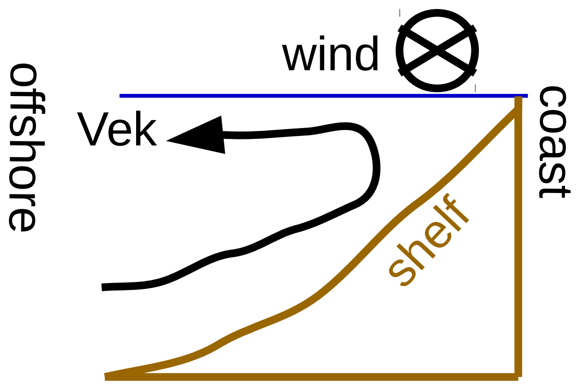
+ offline zoom (1/45°~2.6 km)



Impact of submesoscale dynamics in the Peru upwelling system

- there is a lot of subduction in upwelling systems!

« classical view »



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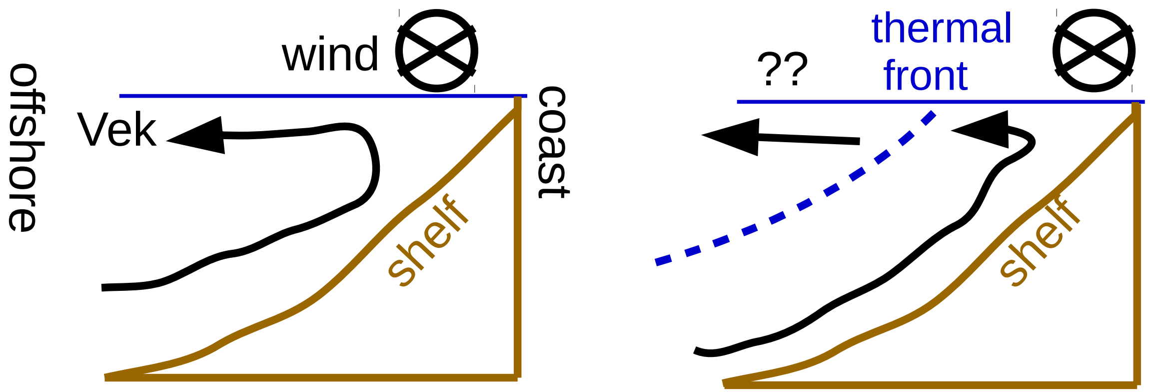
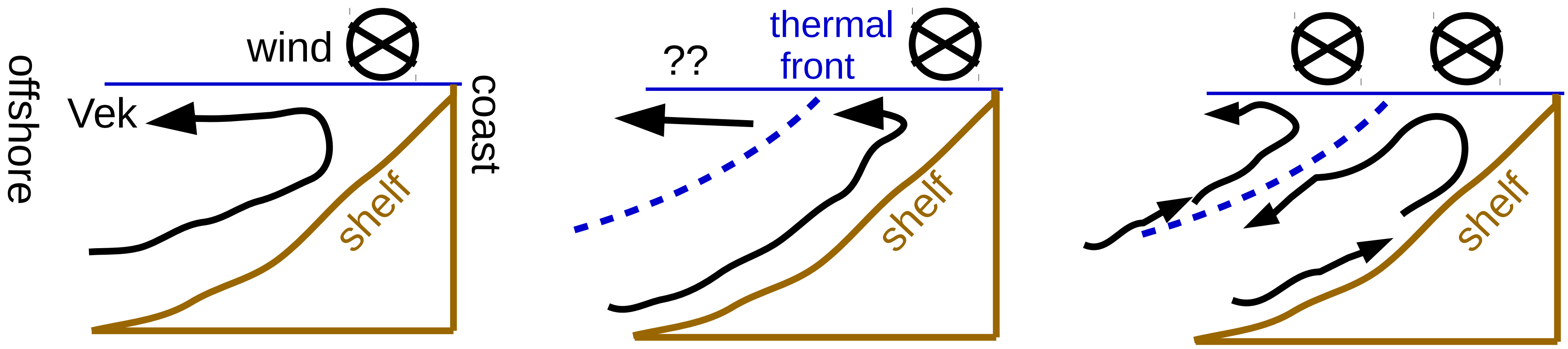


Impact of submesoscale dynamics in the Peru upwelling system

- there is a lot of subduction in upwelling systems!

« classical view »

Subduction (downwelling) on the cold side of the front, upwelling on the warm side



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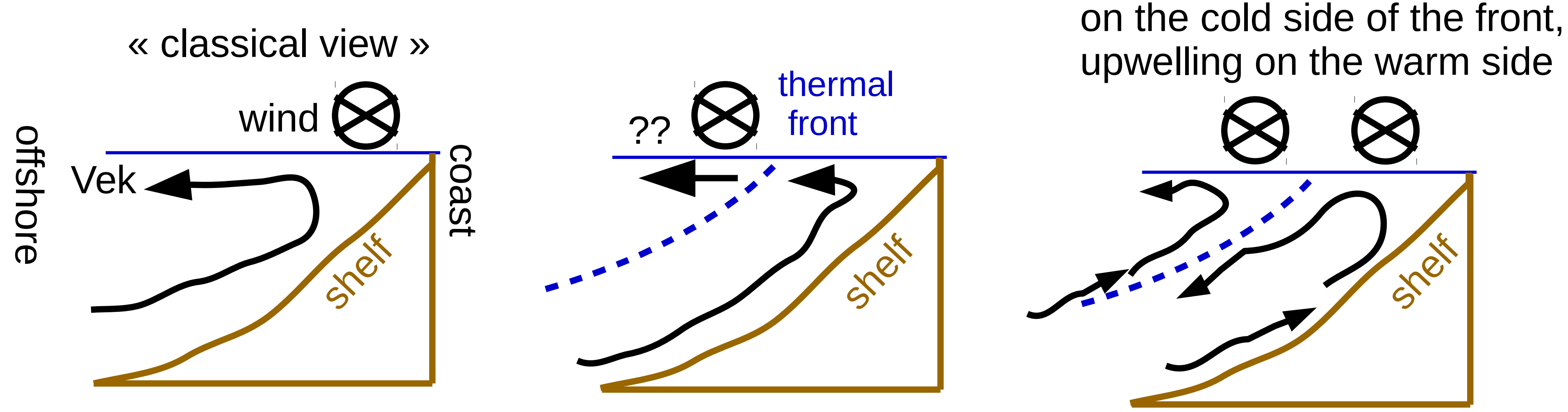
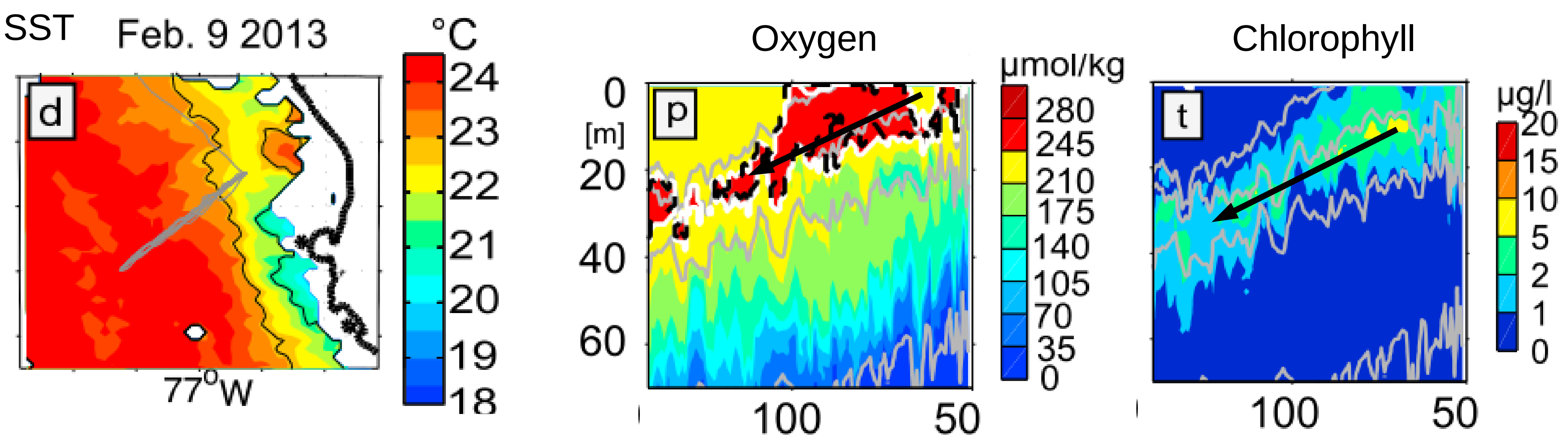
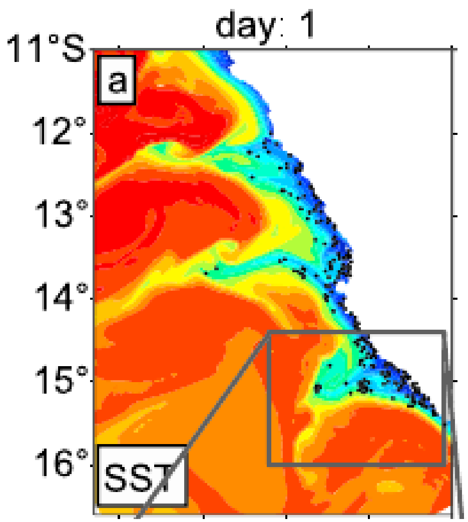


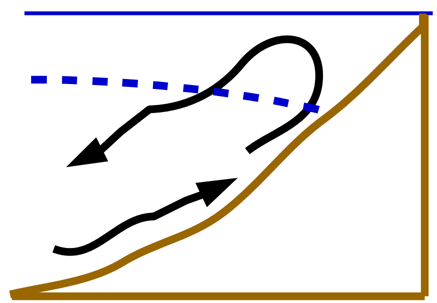


Thomsen et al., 2016

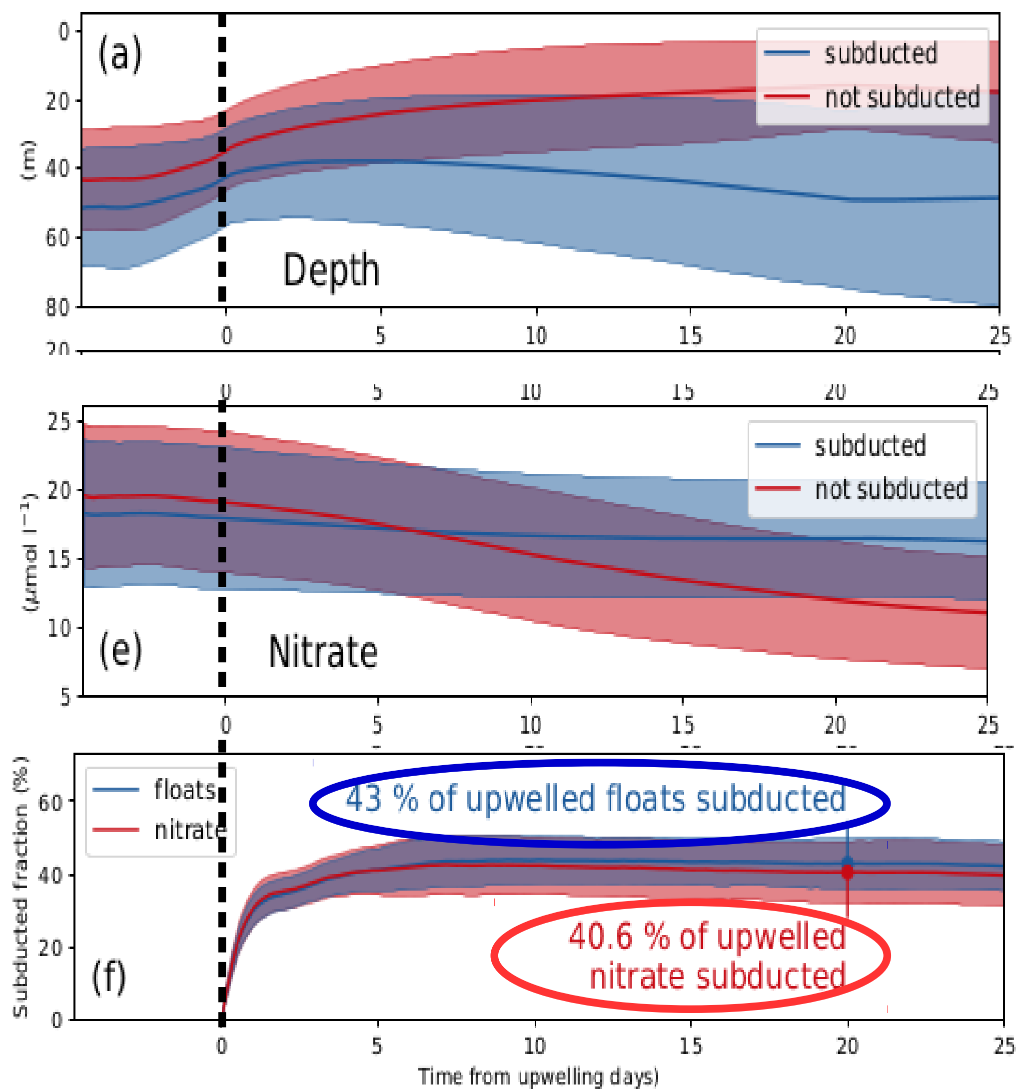
Impact of submesoscale dynamics in the Peru upwelling system

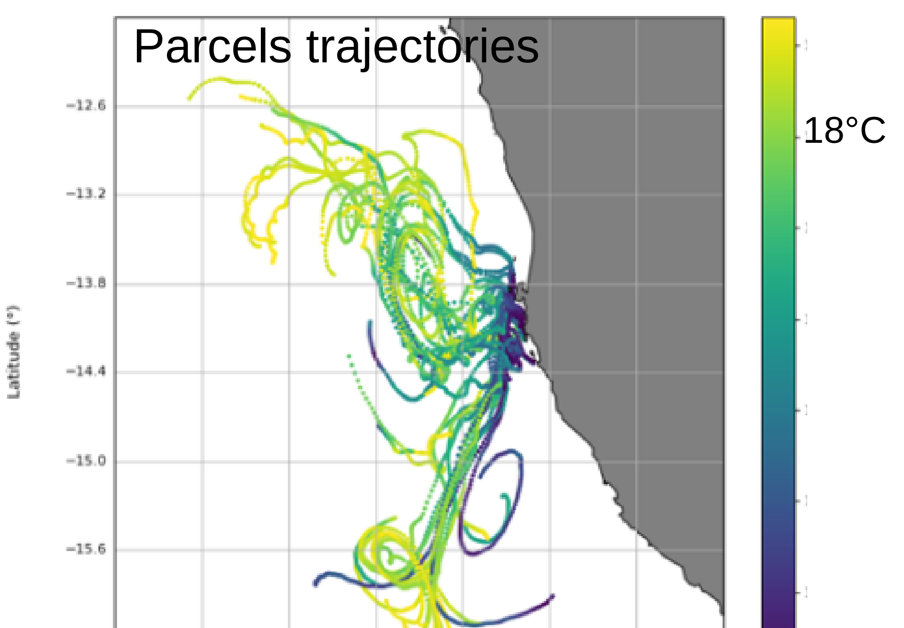
Lagrangian approach (ROMS offline) : what are the characteristics of upwelled water parcels ?





Subducted parcels = upwelled into the mixed layer and then leave the mixed layer





Hauschildt et al., 2021

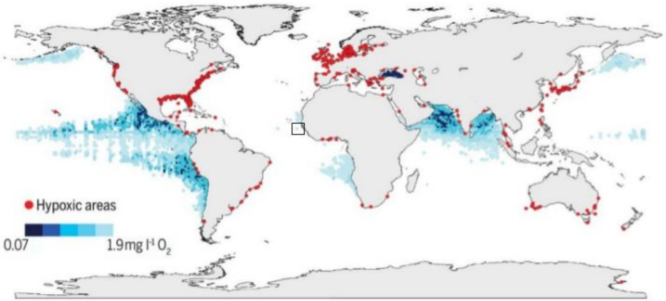
Modelling the dissolved oxygen cycle on the Senegalese shelf: physical and biogeochemical processes, and Lagrangian analyses

Abdoul Wahab Tall, Vincent Echevin,
Eric Machu and Xavier Capet

Why study dissolved oxygen (DO) in the Senegalese shelf ?

Deoxygenation trends

(Breitburg et al., 2018)



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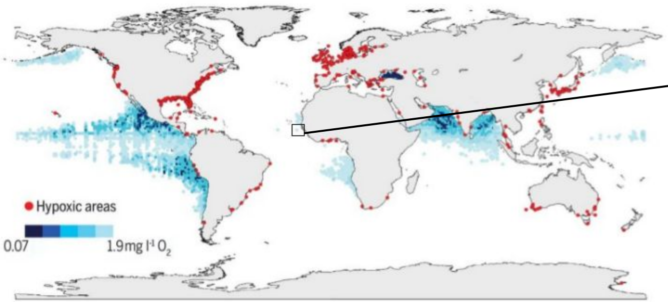
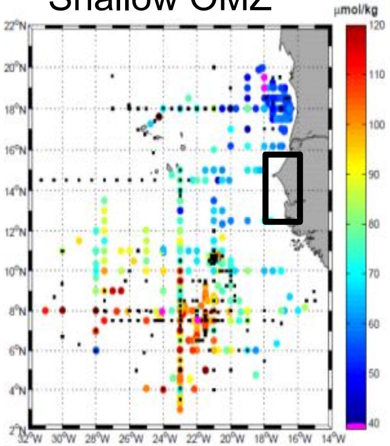


Shallow OMZ



Brandt et al. (2015)

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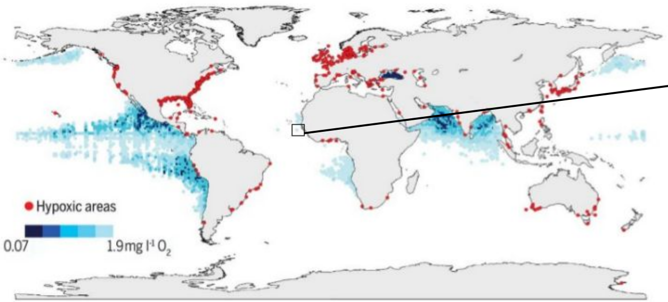

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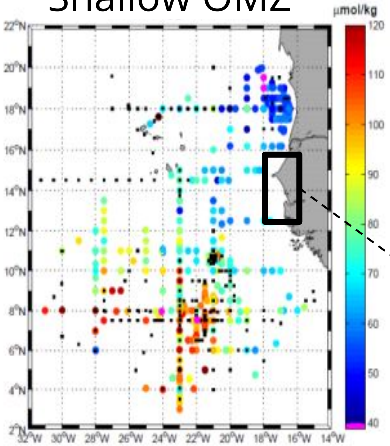
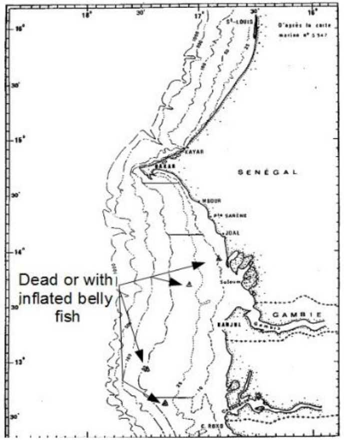


Brandt et al. (2015)

Serranidae (fish) mortality attributed to low oxygen concentrations

(Caverivière & Touré, 1990)



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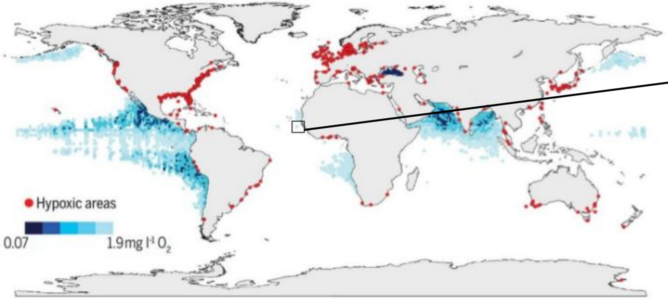

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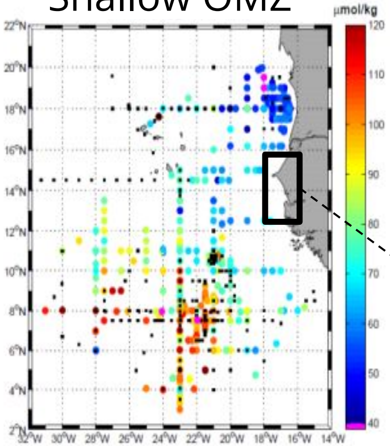

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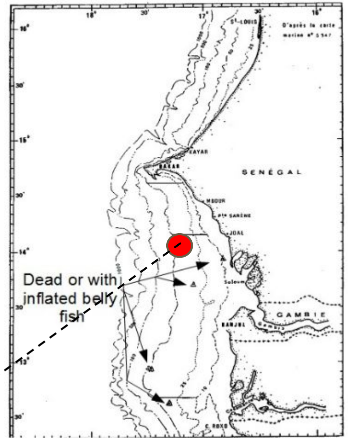

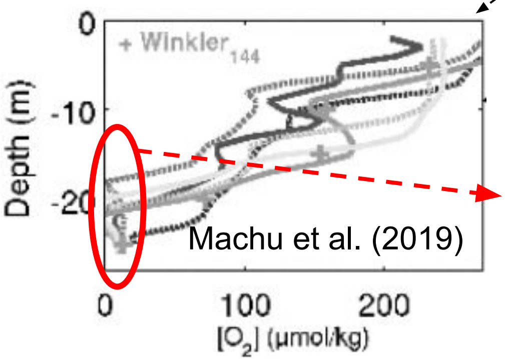

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First measurement of anoxia over the Senegalese shelf during upwelling season (March 2012)

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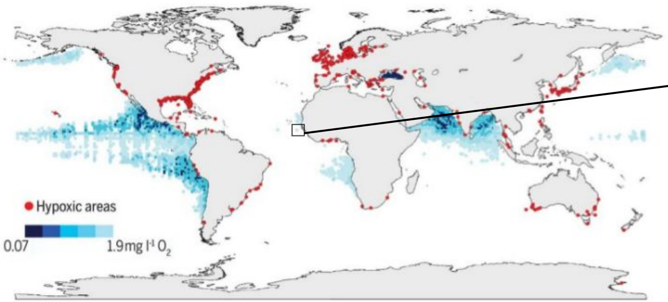

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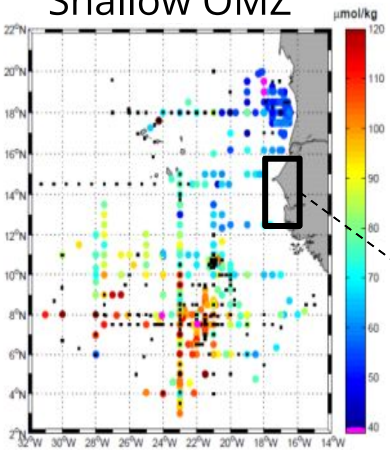

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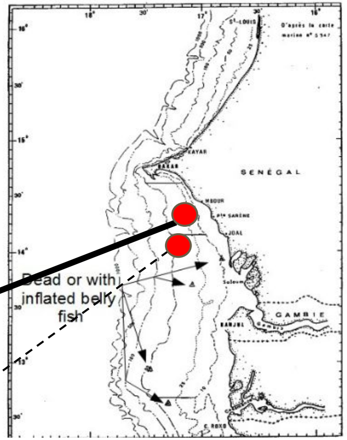
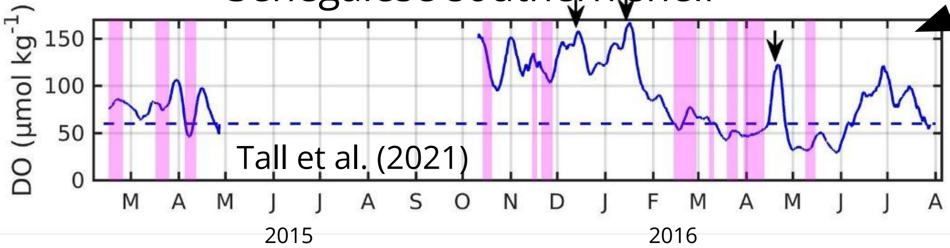
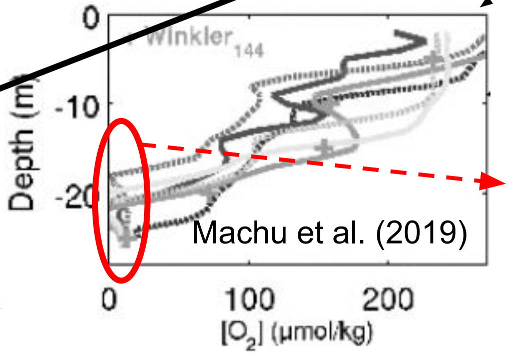


DO times series at the bottom layer over Senegalese southern shelf



Tall et al. (2021)



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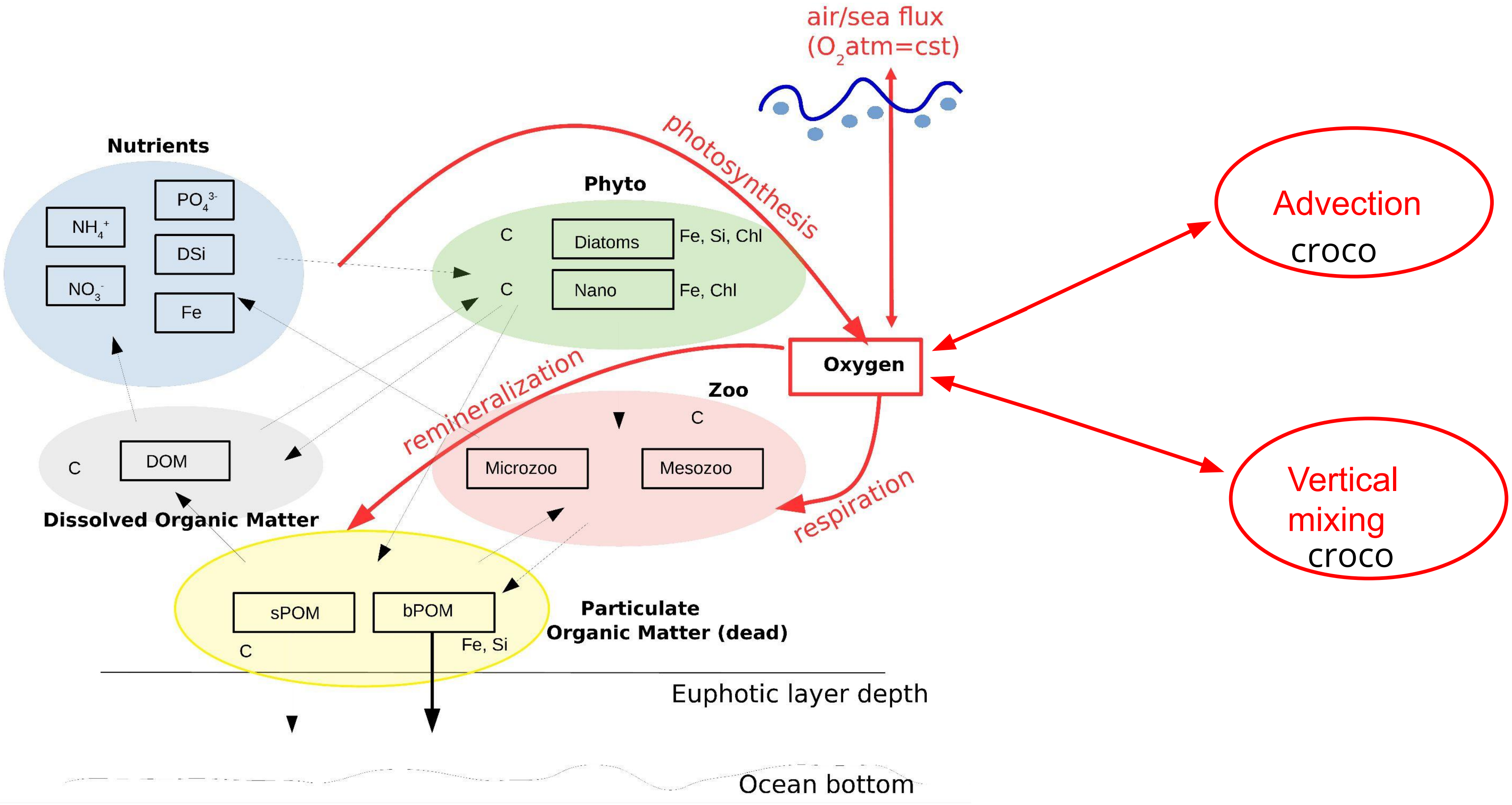
Objectives

Study bottom DO variability during the upwelling season over the Senegalese shelf using a regional model:

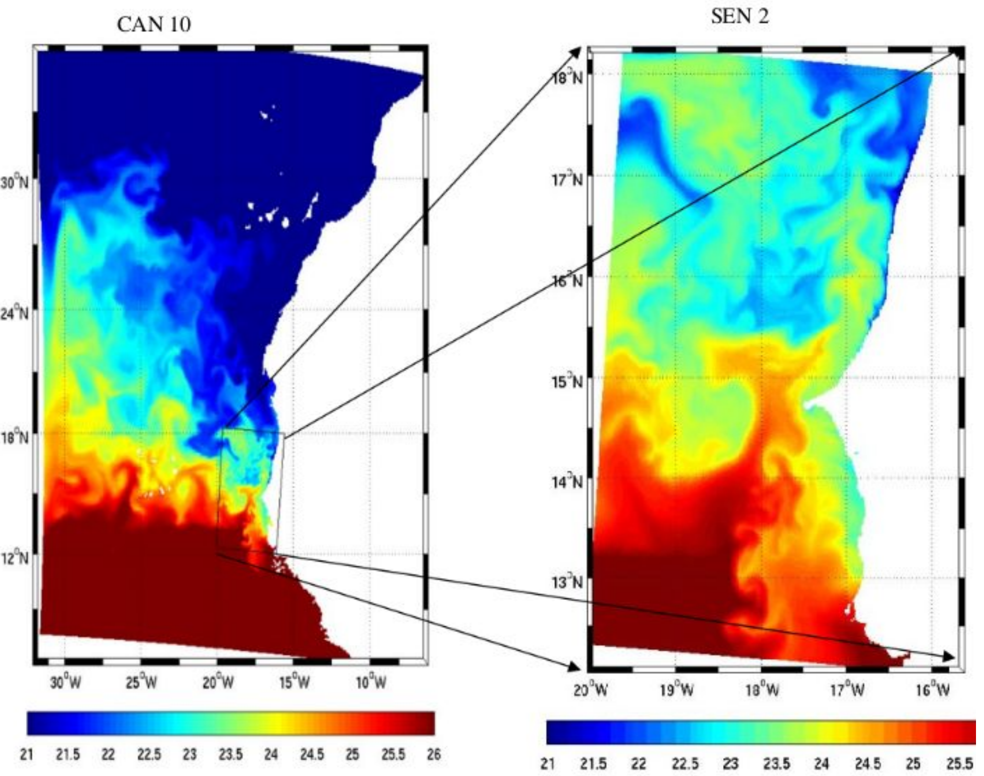
- Understand the role of the physical and biogeochemical processes controlling the DO budget

- Study the characteristics of the upwelled source waters using a Lagrangian approach

Modelling the DO cycle : CROCO-PISCES model architecture



modelling the DO cycle : CROCO-PISCES model characteristics



10 km, 50 vertical levels, 225x290 grid points

2 km, 50 vertical levels, 201x302 grid points

- Forcings:
  ASCAT wind stress (daily, 2014-19)
  Climatological heat/freshwater fluxes (COADS)
  PISCES: dust deposition (Iron) climato

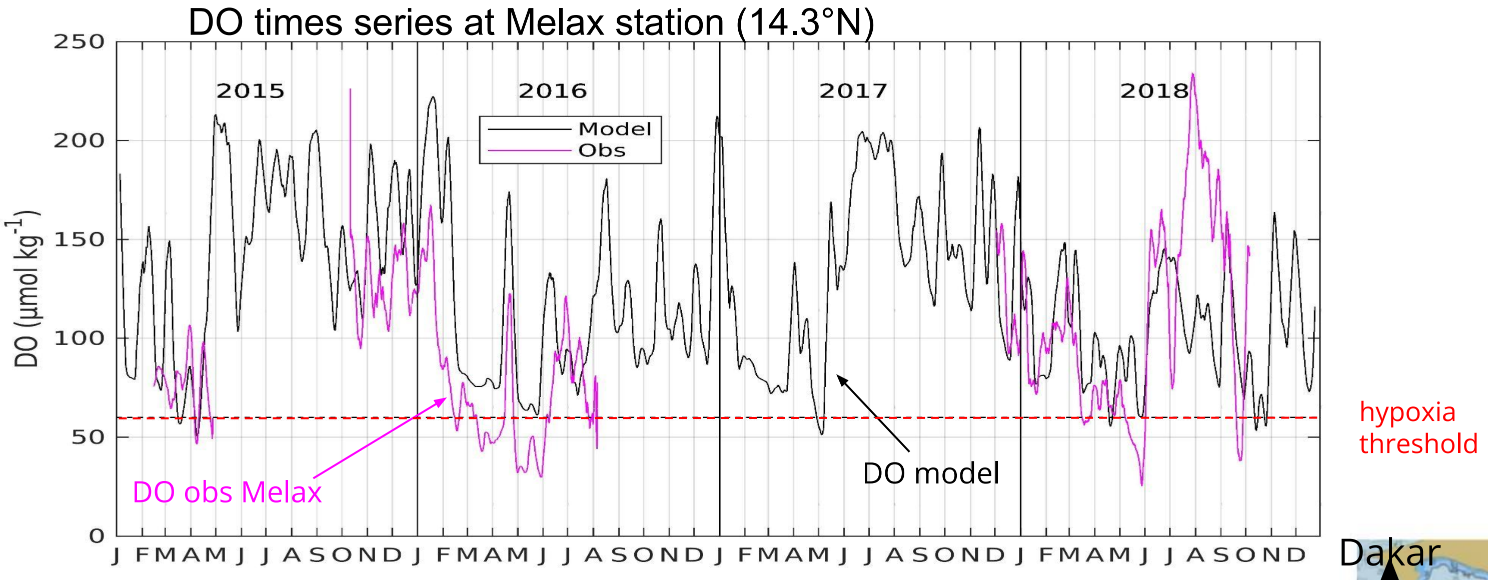
- Initial/Boundary Conditions :
  Mercator (1/12°)
  PISCES: WOA, GLODAP

- BGC model PISCES:

  - Oxygen budget

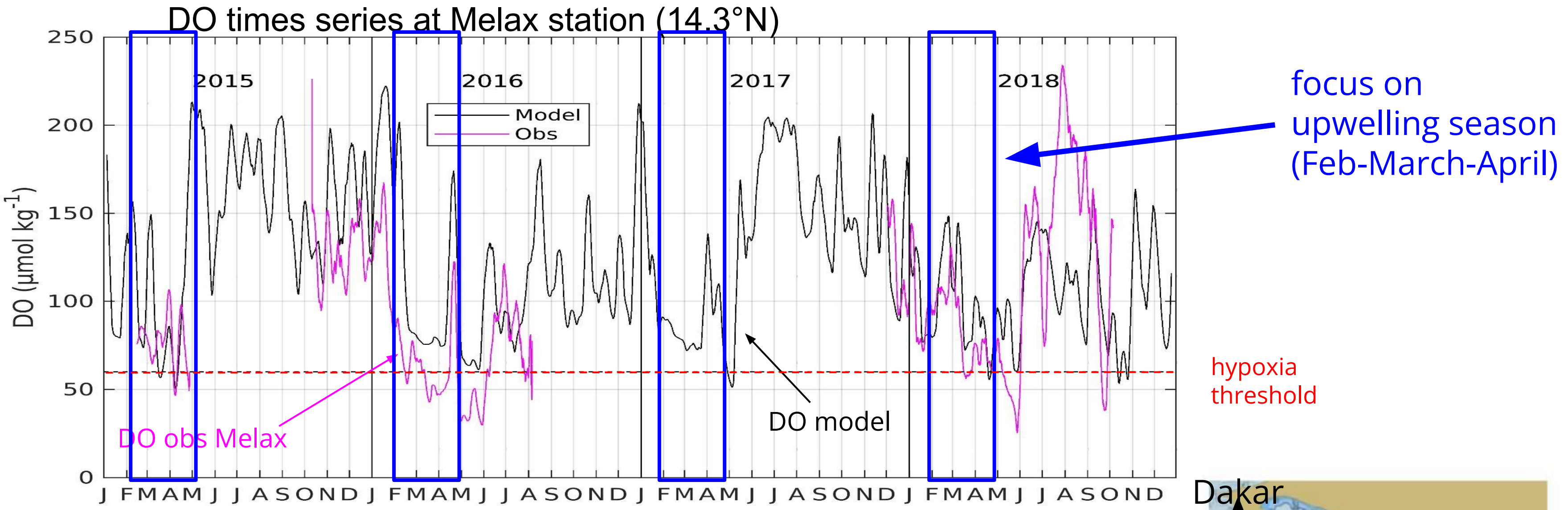
  - BGC diagnostics (Primary production, export,...)

DO Budget : CROCO-PISCES model validation



- Seasonal variability with low DO during upwelling season
- Strong intra-seasonal fluctuations related to synoptic wind events
- DO occasionally below hypoxic threshold
- Good match between modelled and observed DO

DO Budget : CROCO-PISCES model validation



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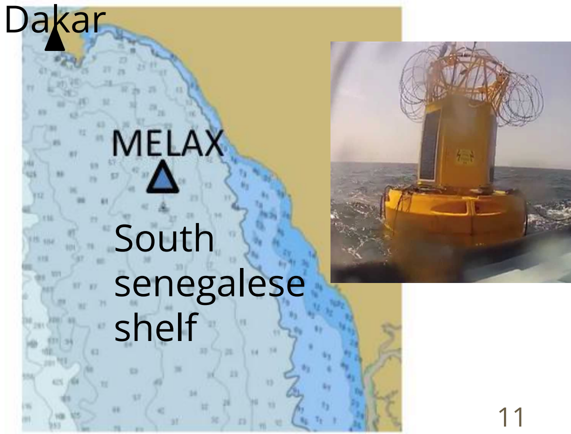
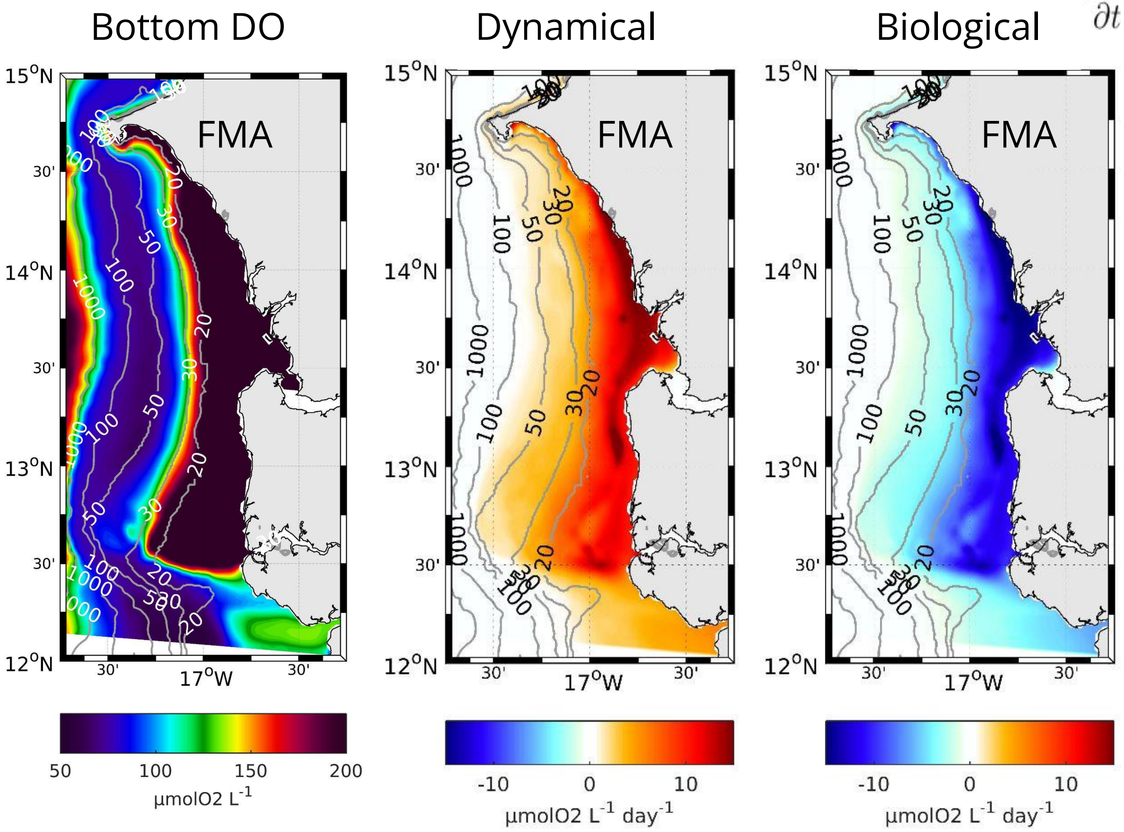


DO Budget : Physical and biogeochemical processes

Average over upwelling season (Feb-Mar-Apr=FMA)

$$\frac{\partial O_2}{\partial t} = \overbrace{\boxed{\left(\frac{\partial O_2}{\partial t}\right)_{Bio}}}^{\text{Biological sources and sinks}} + \overbrace{\boxed{\left(\frac{\partial O_2}{\partial t}\right)_{Dyn}}}^{\text{Dynamical transport}}$$



Biological sources and sinks

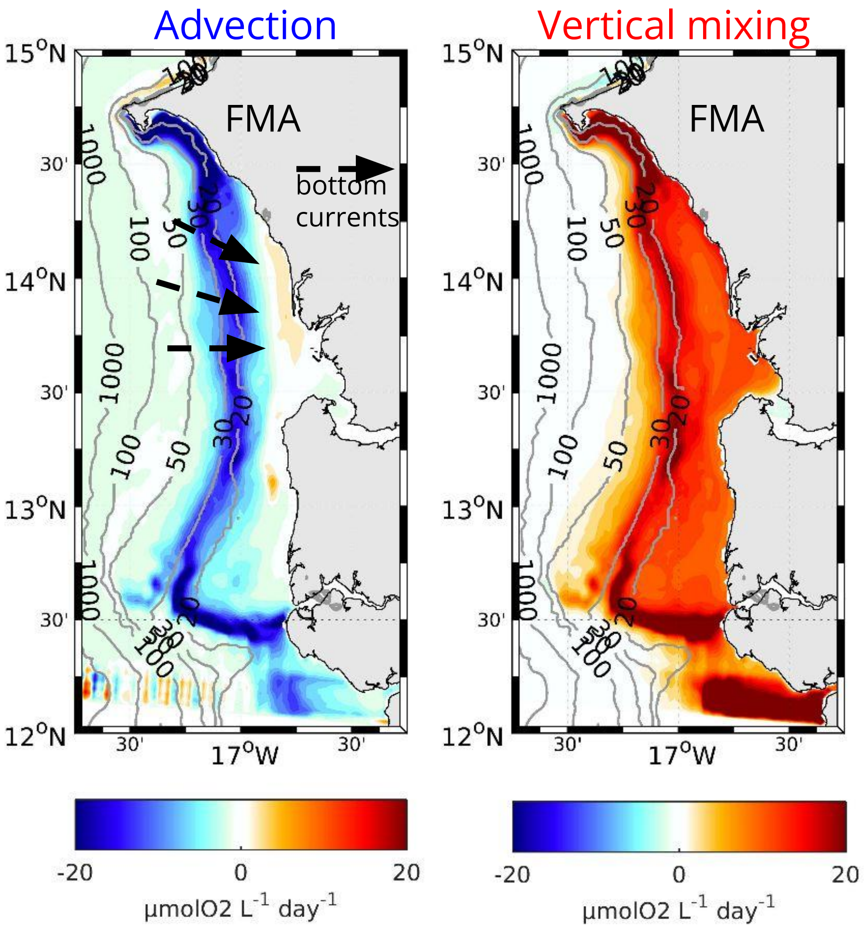
Dynamical transport

- DO: strong cross-shelf gradient
- Dynamical = source of DO
- BGC = sink of DO

Oxygen Budget : focus on physical processes

$$\left(\frac{\partial O_2}{\partial t}\right)_{Dyn} = \boxed{\overbrace{-u_H \nabla_H O_2}^{\text{Horiz. advection}} \quad \overbrace{-w \nabla_z O_2}^{\text{Vert. advection}}} + \boxed{\overbrace{\frac{\partial K_z \partial O_2}{\partial z^2}}^{\text{Vert. mixing}}}$$

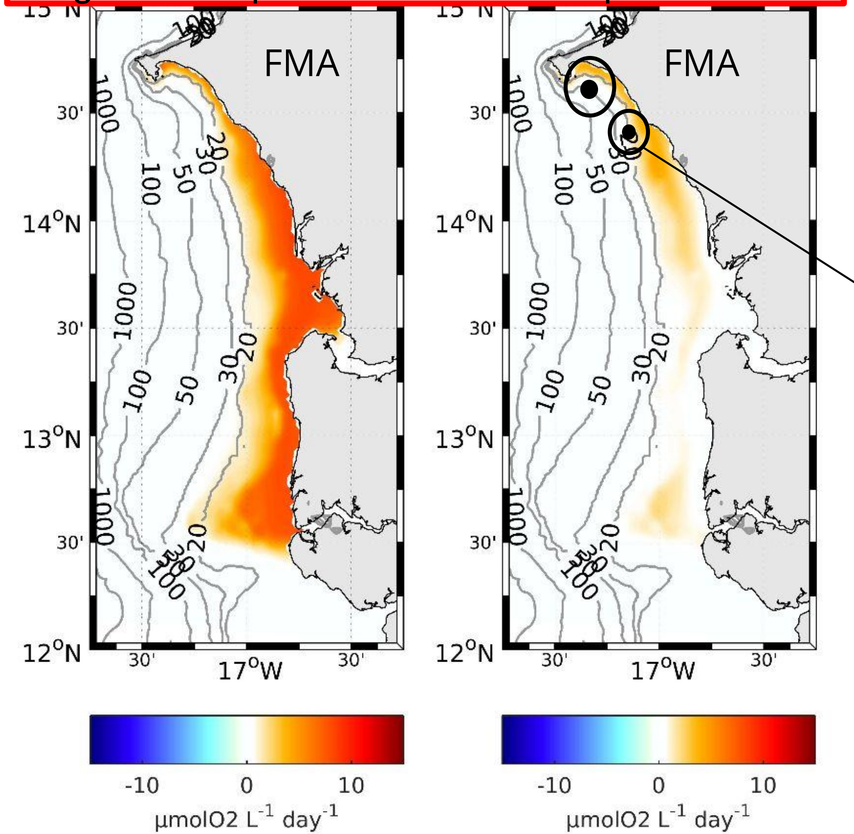
- Transport of poorly oxygenated water by the onshore currents on the shelf
- Maximum advection due to strong DO gradient near 20-30 m isobaths
- Ventilation of the bottom layer by vertical mixing of surface oxygenated water and low DO bottom water



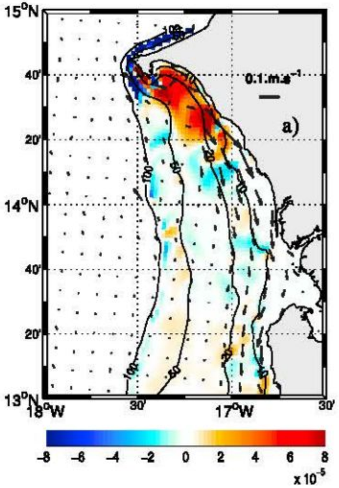
Oxygen Budget : focus on biogeochemical processes

Photosynthesis ⇒ sources

Regenerated production New production

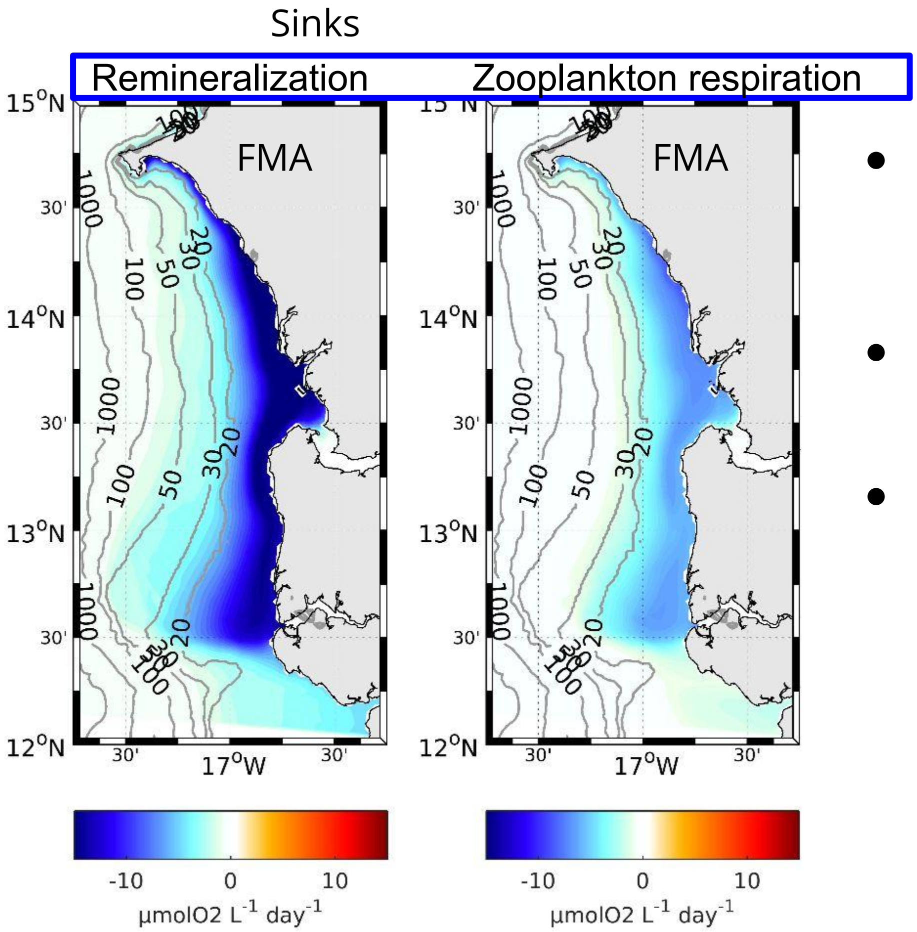


- Regenerated production significantly higher than new production over entire shelf
- New production strong in the north where the upwelling of subsurface nitrate is located



Near-bottom vertical velocity during upwelling season (Ndoye et al., 2017 **using the same model**)

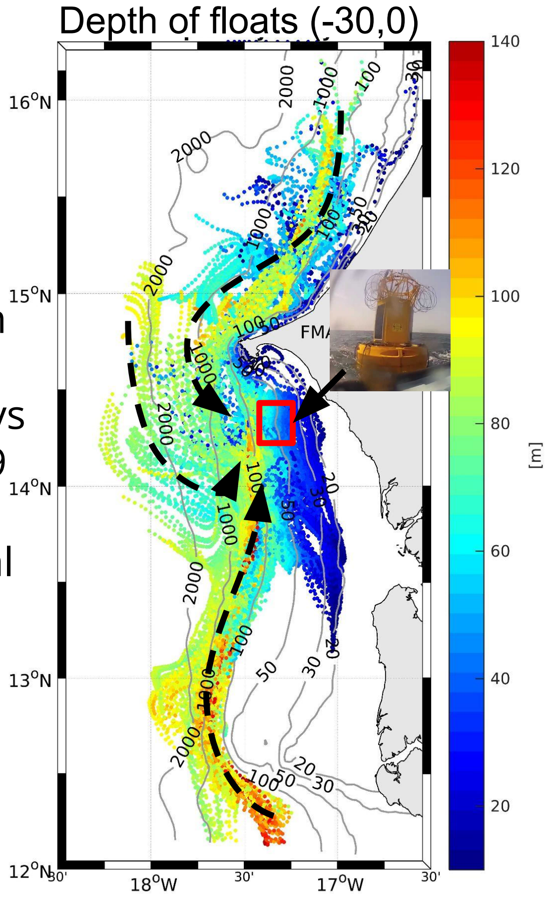
Oxygen Budget : focus on biogeochemical processes

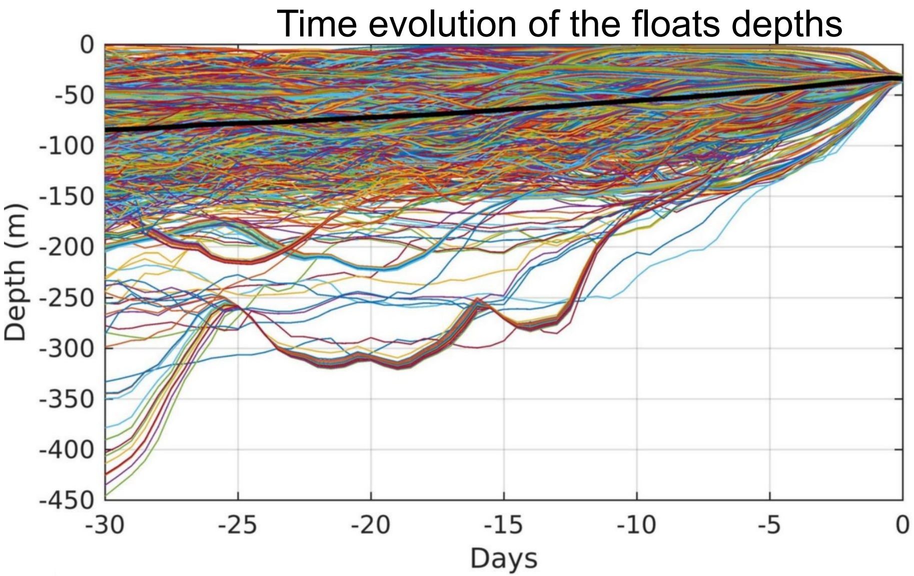


- DO BGC consumption = OM remineralization, which largely compensates production by photosynthesis
- Zooplankton (microzoo + mesozoo) respiration levels lower than OM remineralization
- Mesozooplankton respiration dominates microzooplankton respiration.

Analysis of the water masses reaching the shelf : methodology

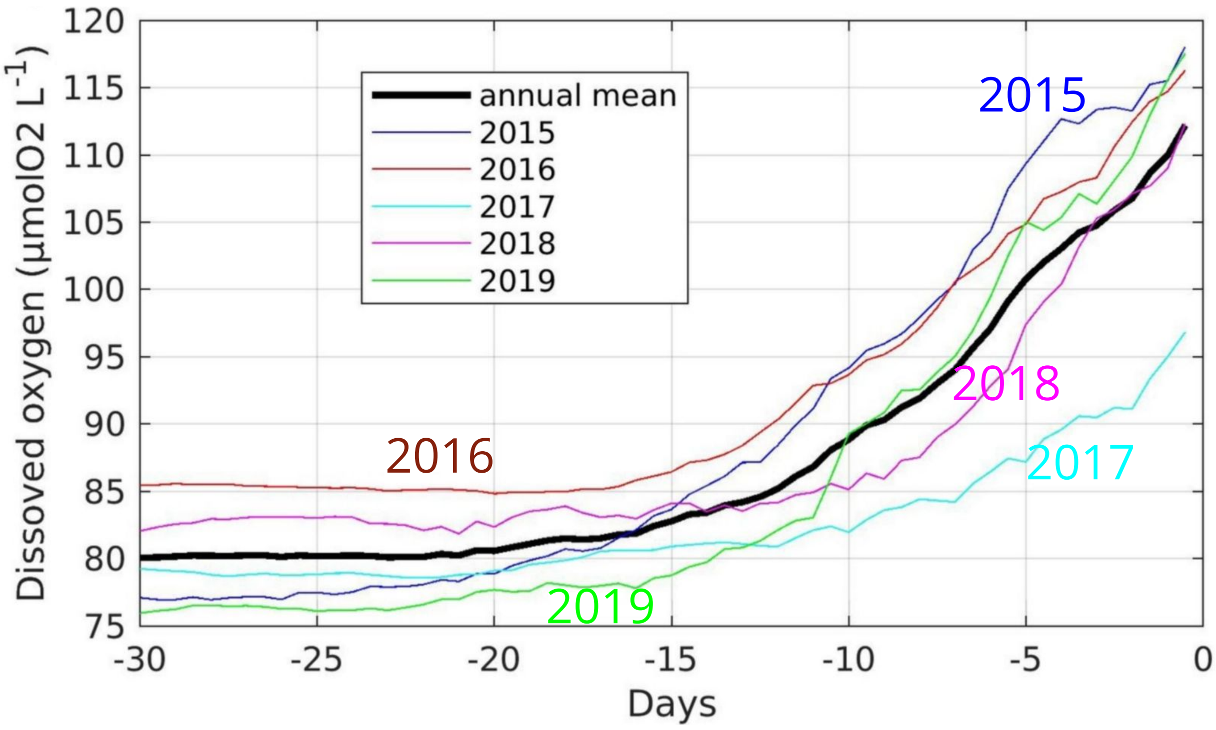
- floats transported backwards in time for 30 days
- 500 floats released between 30 & 40 m around Melax station, every 5 days (Feb-April), 2015-19
- 45000 floats in total
- DO, depth, vertical mixing, BGC terms registered along each trajectory





Lagrangian analysis : interannual variability

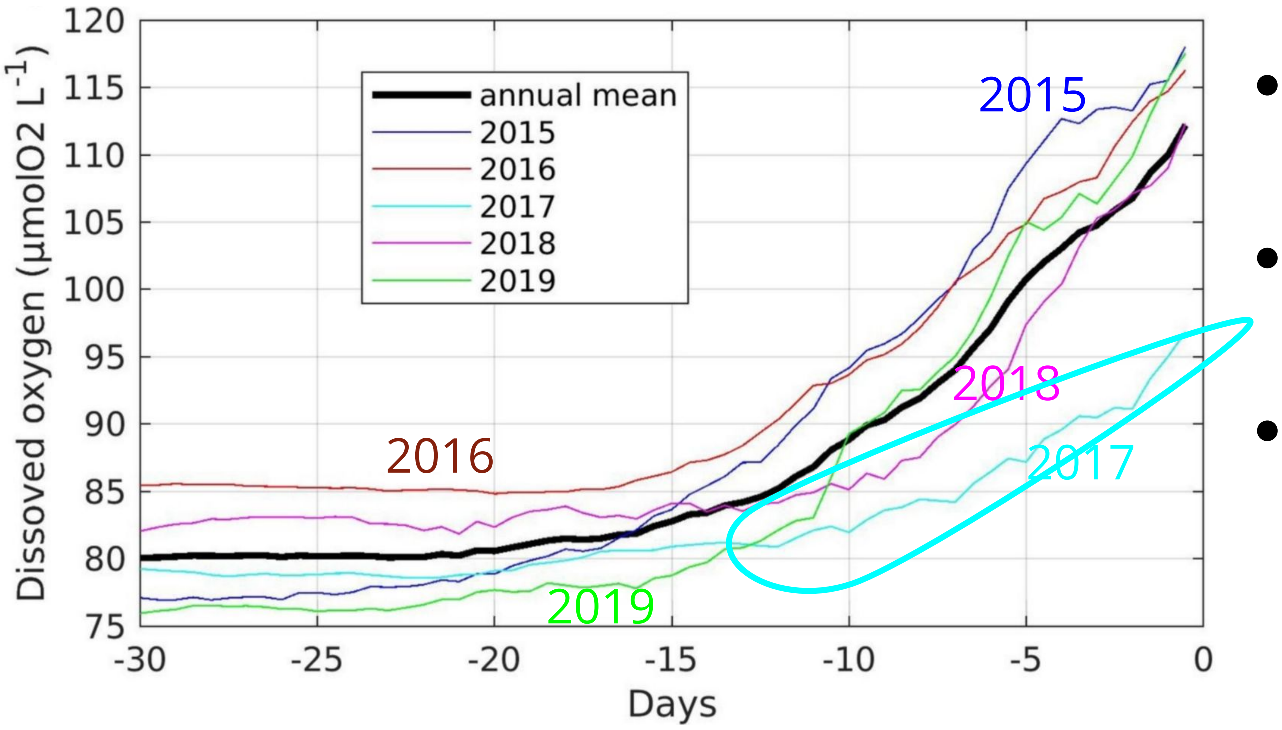
Interannual variability of DO along the pathway



- Increase of DO during one month
- weak change during the first 15 days
- Strong change during the last 15 days

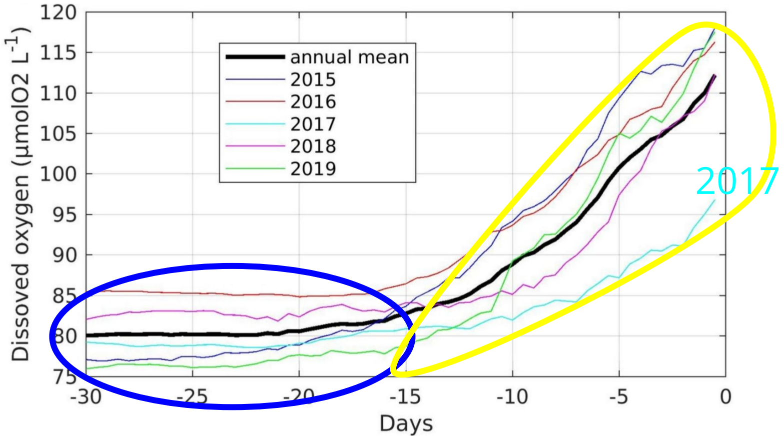
Lagrangian analysis : interannual variability

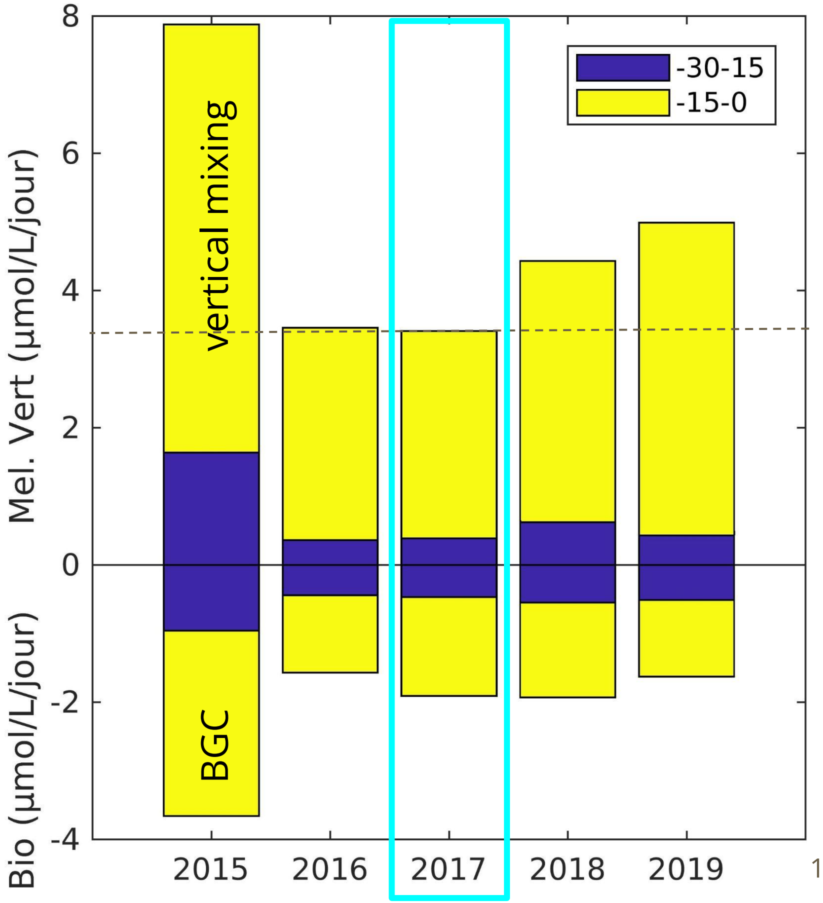
Interannual variability of DO along the pathway



- Strong interannual variability
- Lower DO in 2017 in last 15 days
- Why ?

Lagrangian analysis : why 2017 is more deoxygenated ?





- Low DO supply by vertical mixing in 2017 and 2016

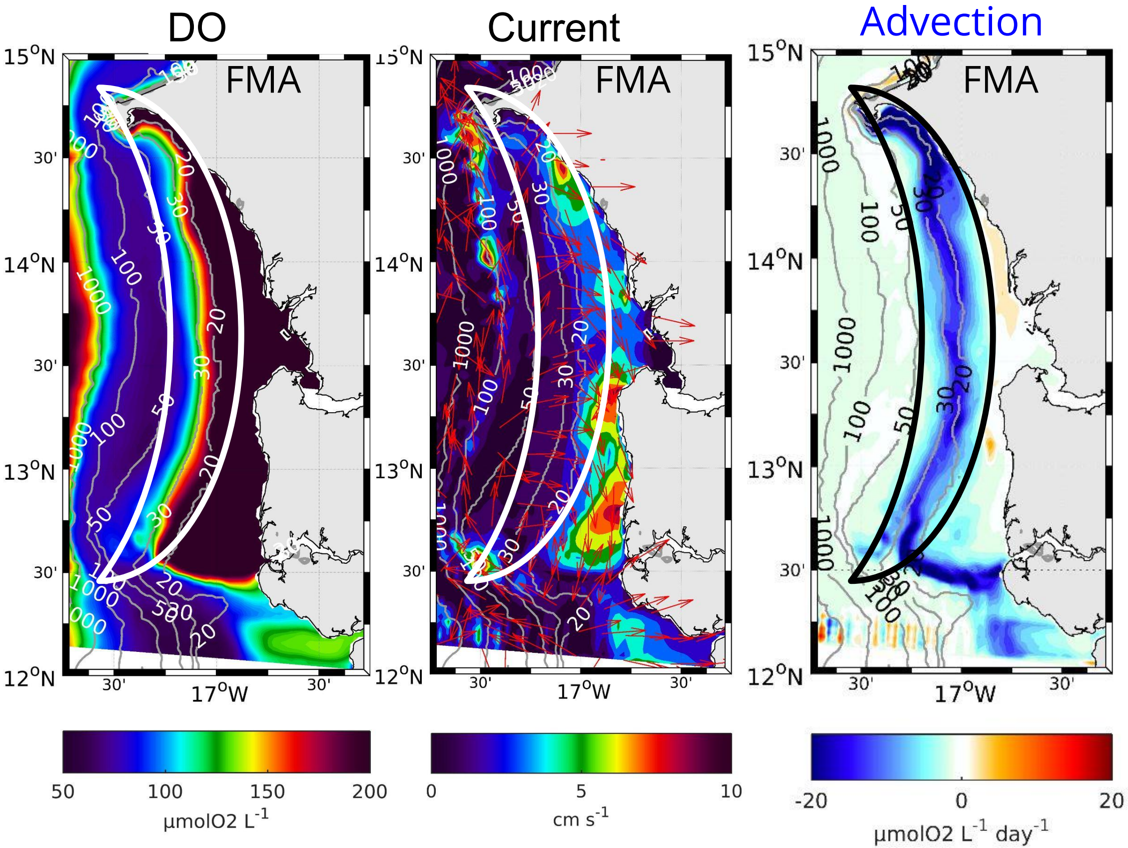
- Low DO consumption by BGC in 2016

- Very strong mixing and consumption in 2015 because of shallow source waters

Conclusions

- Physics brings DO and biology consumes DO in the bottom layer on the continental shelf during the upwelling season
- Advection decreases DO by transporting low DO subsurface water onto the shelf
- Vertical mixing ventilates the bottom layer
- Consumption of DO by remineralization of organic matter strongly compensates production of DO by photosynthesis in the bottom layer
- The source waters show high interannual variability, with the lowest oxygen levels encountered in 2017 associated with reduced vertical mixing

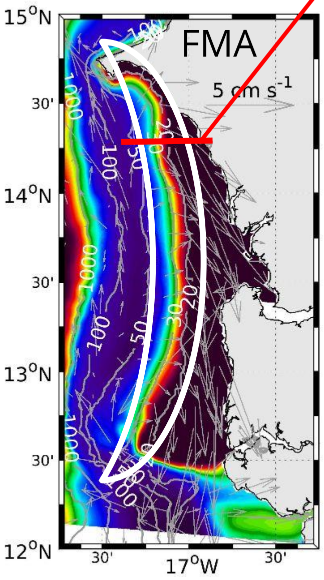
Oxygen Budget : focus on physical processes (total advection)

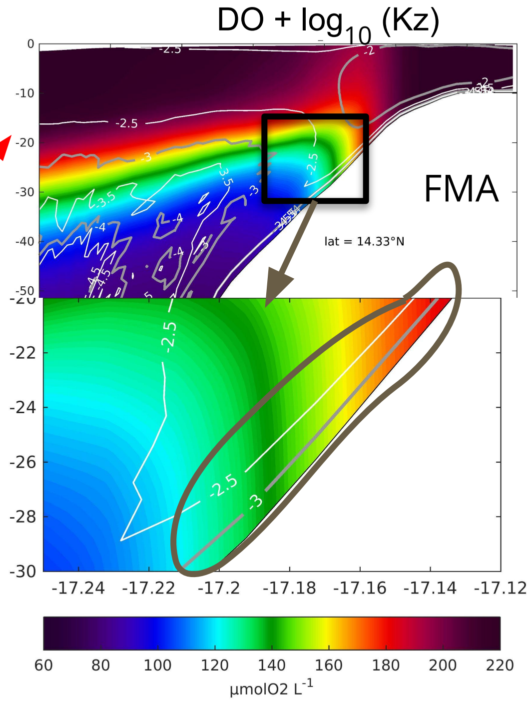


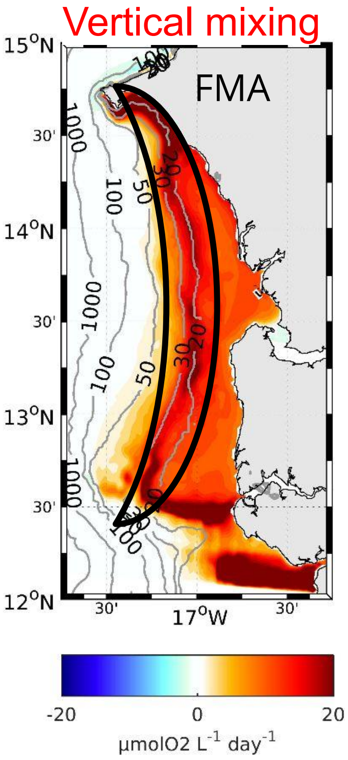
- Currents flow towards the coast
- Low DO deep waters transported on the shelf
- Strong horizontal DO gradient between 20-30 m isobaths
- Maximum advection near 20-30 m isobaths

Oxygen Budget : focus on physical processes (vertical mixing)

$$\underbrace{\frac{\partial K_z \partial O_2}{\partial z^2}}_{\text{vertical mixing}}$$







- Strong vertical Kz gradient between 20-30 m isobaths

- The greater vertical mixing between 20-30 m isobaths is due to a DO influx from the oxygenated layers above by friction on the bottom combined with the strong vertical gradient.

characteristics of the source waters one month before reaching shelf

Floats position (t=-30 d) Depth (t=-30 d) DO (t=-30 d)