The role of bottom enhanced turbulence and non-linear internal waves on the diapycnal velocities and cross-slope circulation in upwelling regions.

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Peculiarities of tropical upwelling regions

Marcus Dengler[1], Marin Visbeck[1], Kevin Lamb[2], Toste Tanhua[1], Jan Lüdke[1], Thilo Klenz[3]

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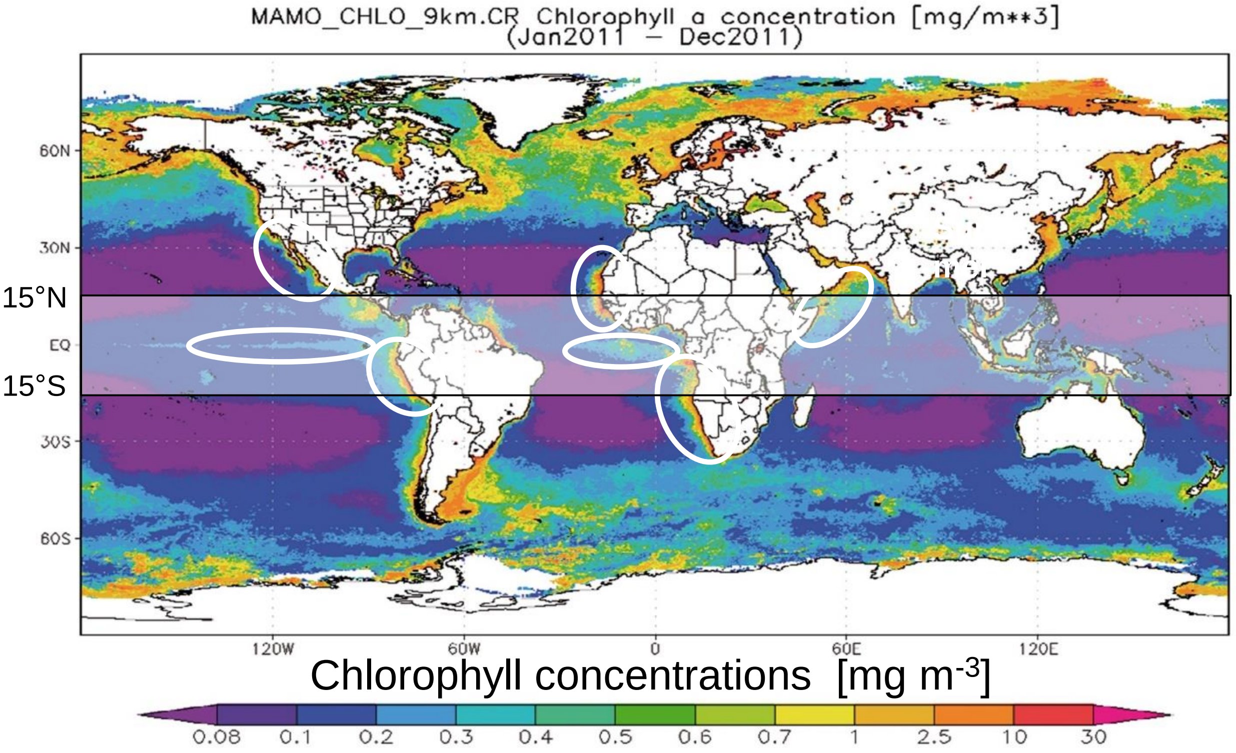
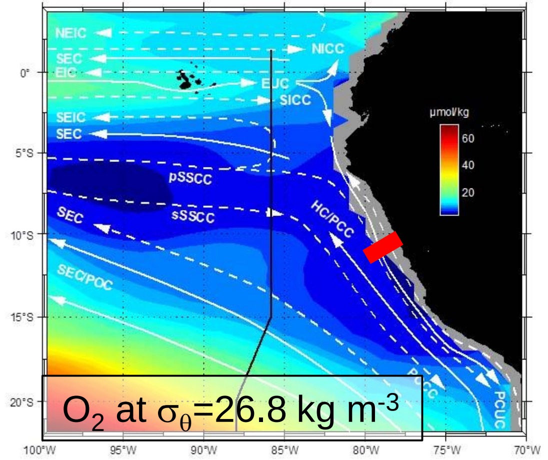
Major Oceanic Upwelling Regions



Capone and Hutchins (2013)

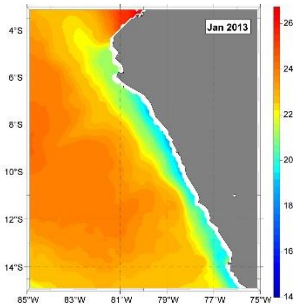
- Coastal upwelling is predominately forced by alongshore winds and wind curl.
- However, coastal upwelling in tropical regions (<15°) often exhibit seasonal upwelling maxima out of phase with seasonal wind forcing variability.

Motivation: Peruvian upwelling region (<15°S)

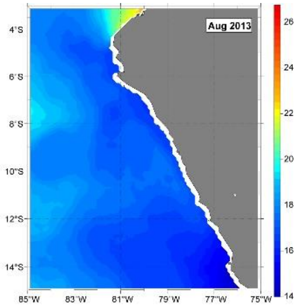


(Brandt et al., 2015)

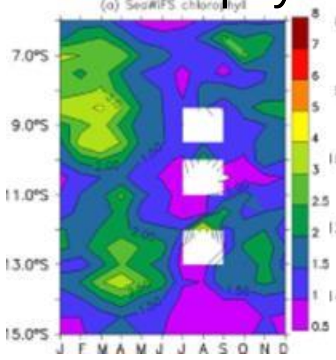
SST January



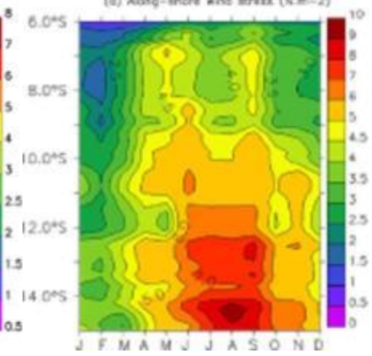
SST August



Chlorophyll



Wind stress



(Echevin et al., 2008)

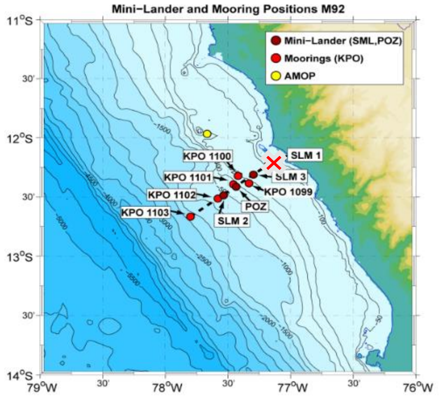
“Upwelling season” - Austral summer

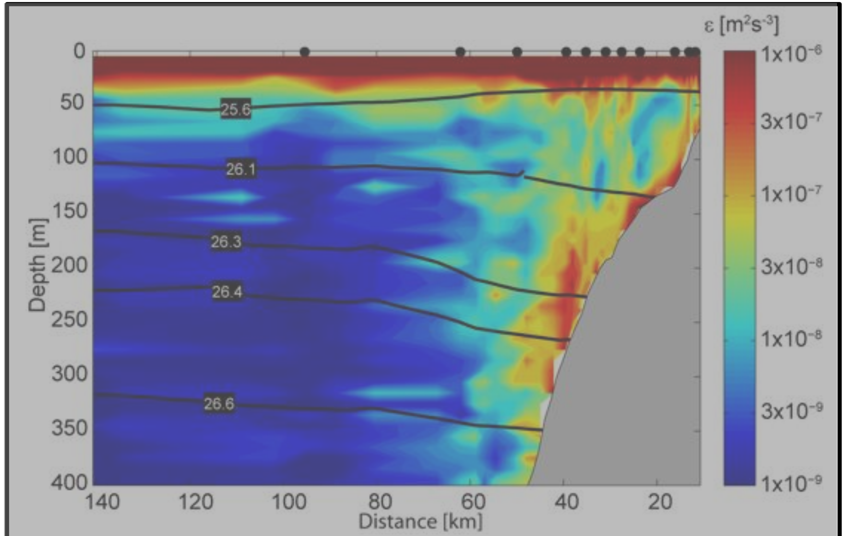
- Seasonal minimum of alongshore winds & curl
- Chlorophyll maximum
- Maximum in SST
- Maximum cross-shore SST gradient

“Non-upwelling season” - Austral winter

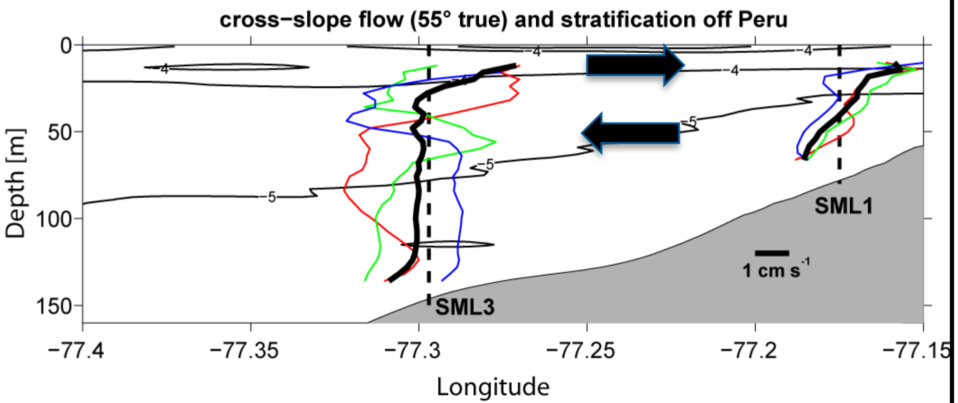
- Seasonal maximum of alongshore winds & curl
- Chlorophyll minimum
- Minimum in SST
- Minimum in cross-shore SST gradient

Observations from the Peruvian upwelling regions at 12°S





- Dissipation rates of turbulent kinetic energy suggests bottom enhanced mixing above the continental slope/shelf



- 30-day average cross-slope velocity from the continental slope indicate near-surface onshore flow

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Measurement program off Peru in austral summer

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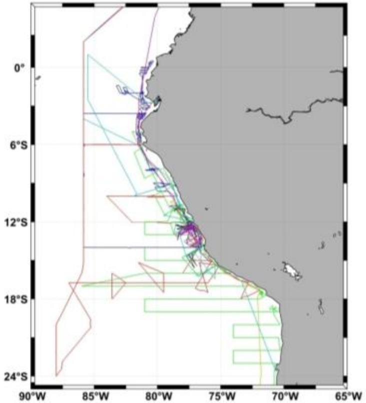
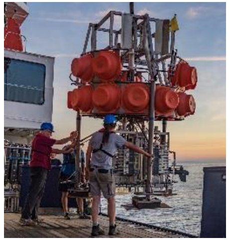
FS Meteor cruise M90-M93, M135-138 (2013 and 2017)

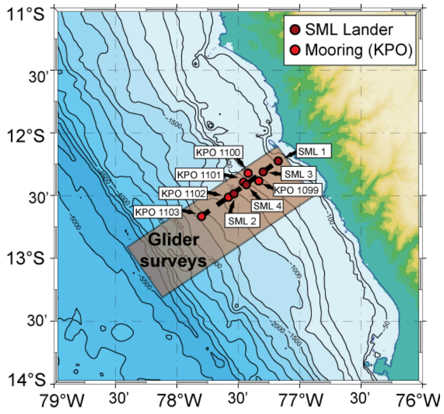
CTD / turbulence measurements



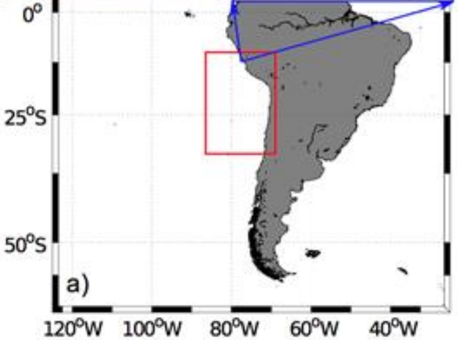
benthic flux measurements



Mooring program



Tracer release experiment



Cross-slope velocity on the Peruvian shelf

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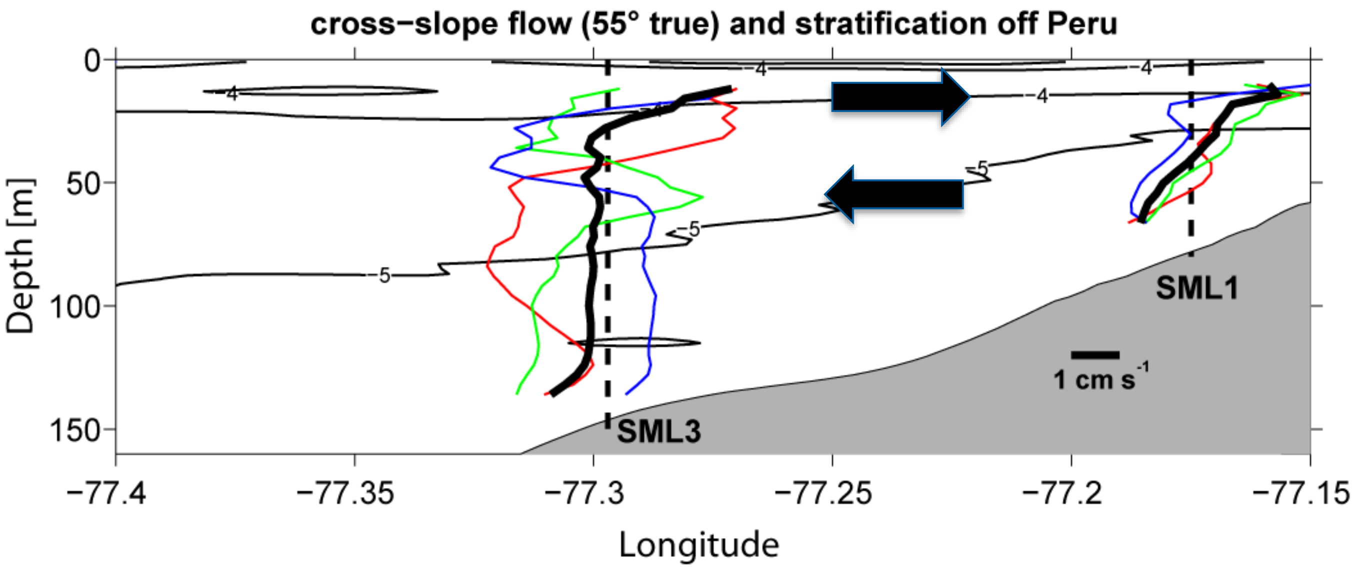
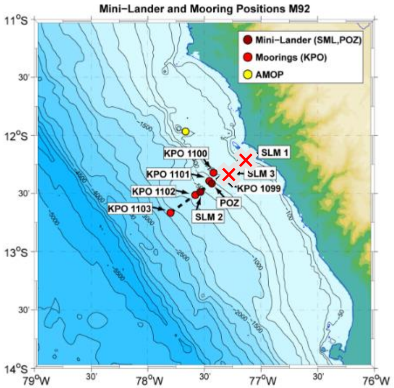
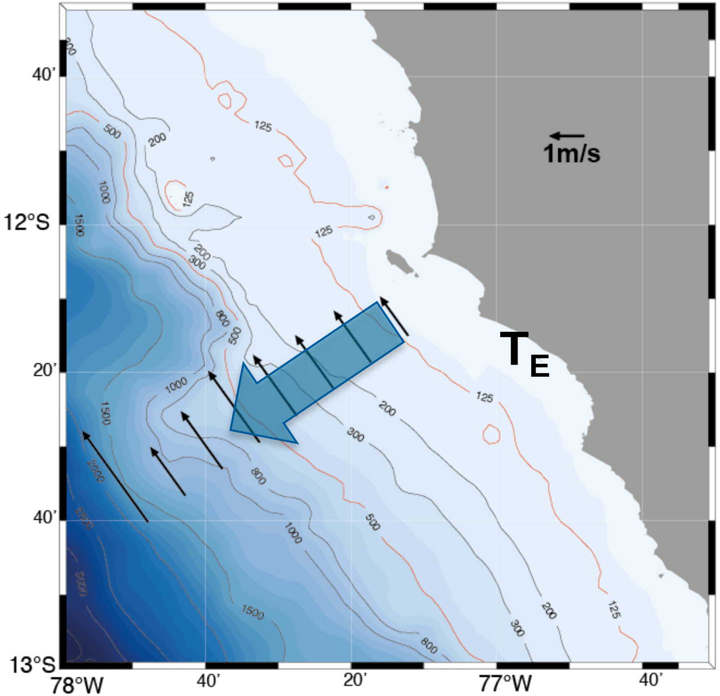




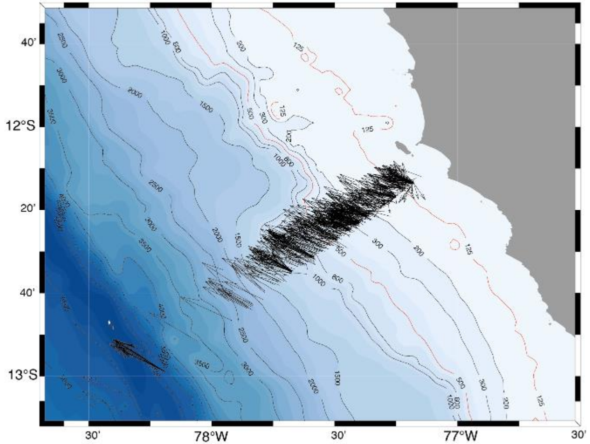
Winds and Ekman transport

Average alongshore winds Jan. 2013



Wind speeds (10m height) were 2-5 ms^{-1} (1-3 Bft.)

Hourly winds off Peru from Jan. 5 to Feb. 3, 2013



Water Depth	Ekman transport (T_E)
<125m	0.16 m^2s^{-1}
<500m	0.24 m^2s^{-1}
all	0.26 m^2s^{-1}

Currents on the Peruvian shelf

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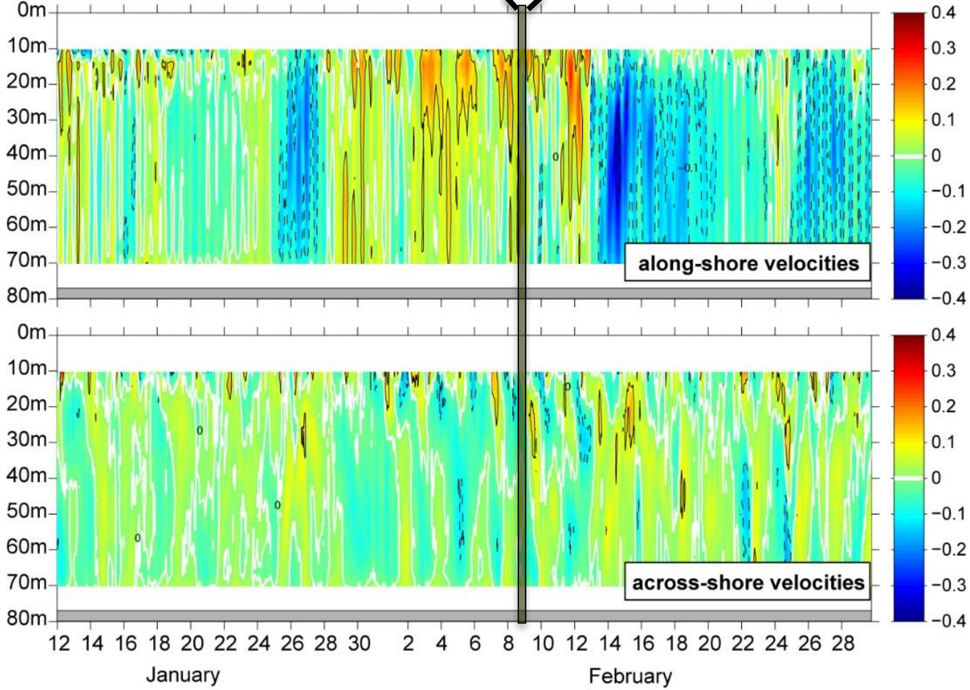
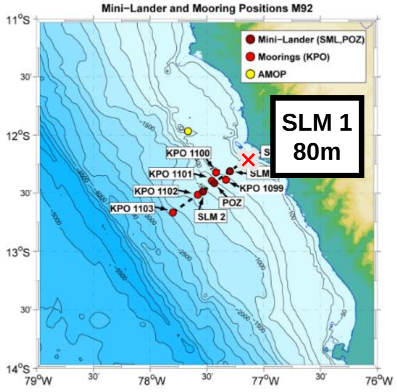
Velocity time series from 80m depth

February 8, 3:00 7:00





SLM 1
80m

- Variable currents on the Peruvian shelf

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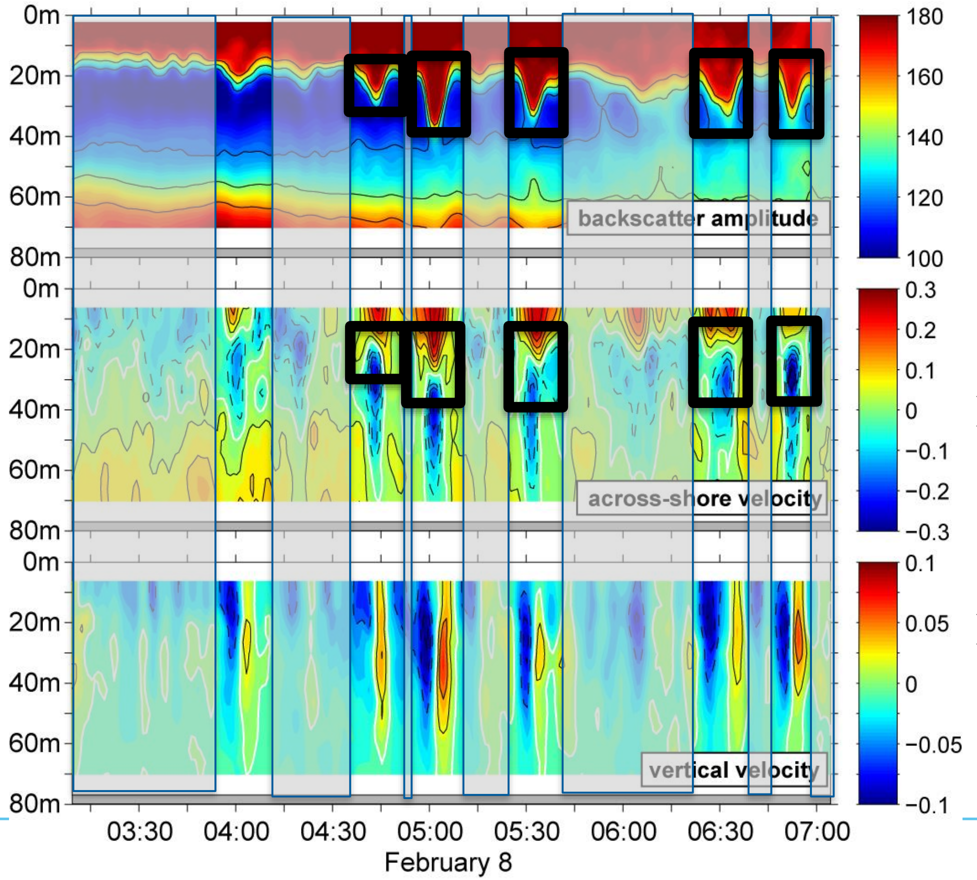
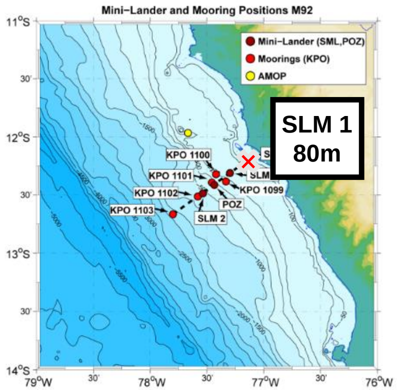
Bores on the Peruvian shelf





- sequences of strong baroclinic across-shore velocity pulses of 5-10 min. duration occur every 12 hours.
- pulses are associated with elevated vertical velocity displacing solutes from near-surface to 30-40m depth

Very-high resolution simulation of velocity variability generated by the barotropic tide impinging on the shelf

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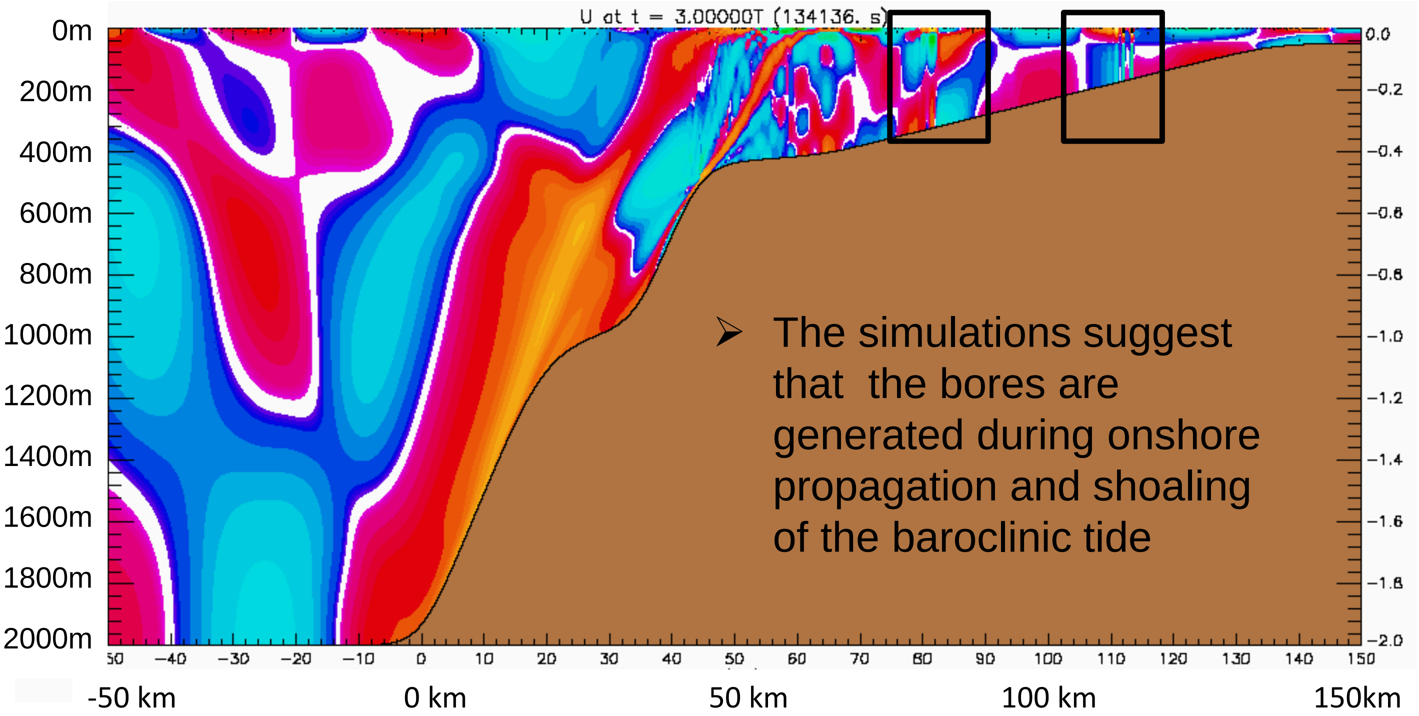


- The simulations suggest that the bores are generated during onshore propagation and shoaling of the baroclinic tide

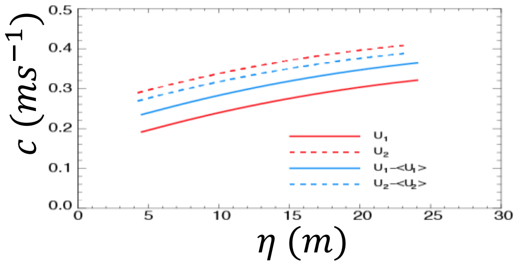
Onshore transport by NLIWs due to Stokes drift

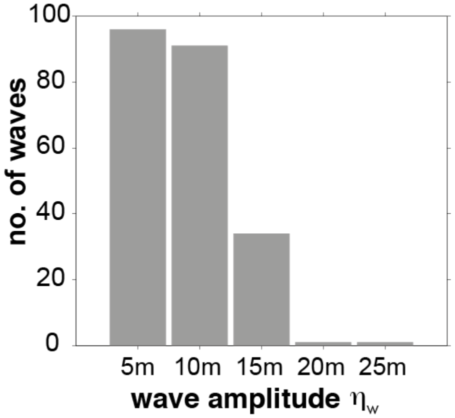
$$T_{NLIW} = \int \frac{\Delta(z)}{\tau(z)} dz, \quad \Delta(z) = \int_{x'}^{x_{end}} \frac{U_w(x,z)}{c - U_w(x,z)} dx$$

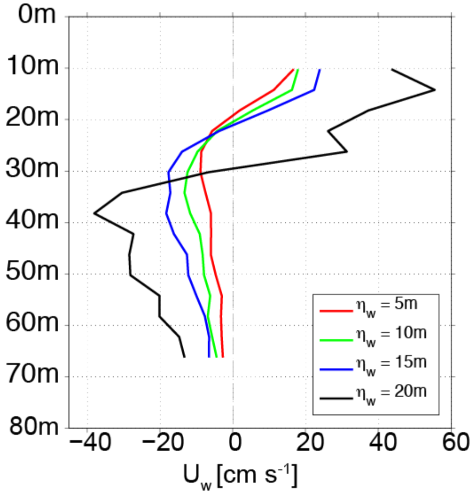
(e.g. Huthance, 1995; Lamb, 1997)

$\tau(z)$	is the wave duration time
$\Delta(z)$	is particle transport distance due to Stokes drift
c	phase speed of the NLIW
U_w	particle velocity

c was determined from Dubreil-Jacotin-Long model







(Long, 1953; Stastna and Lamb, 2002)

NLIW onshore transport due to Stokes drift

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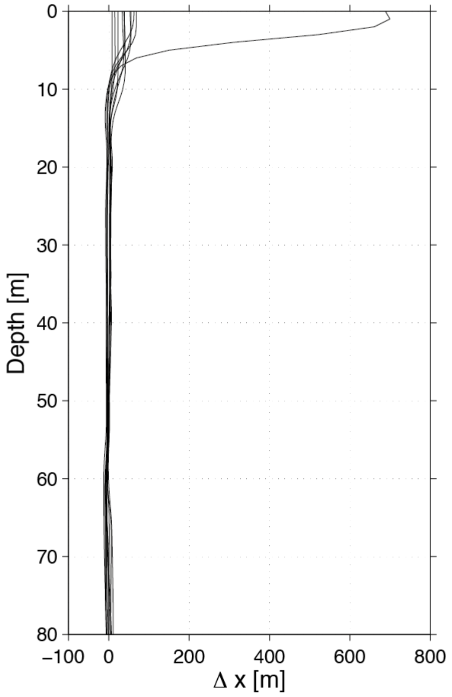
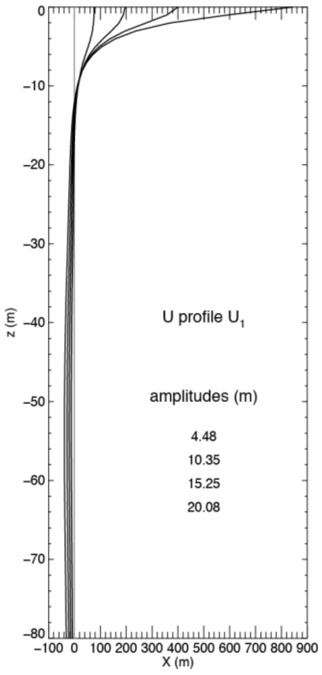
Particle displacement from observations



Particle displacement from model

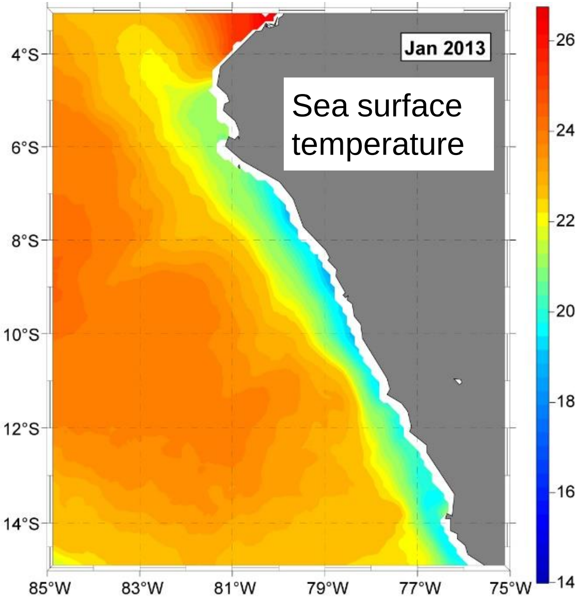


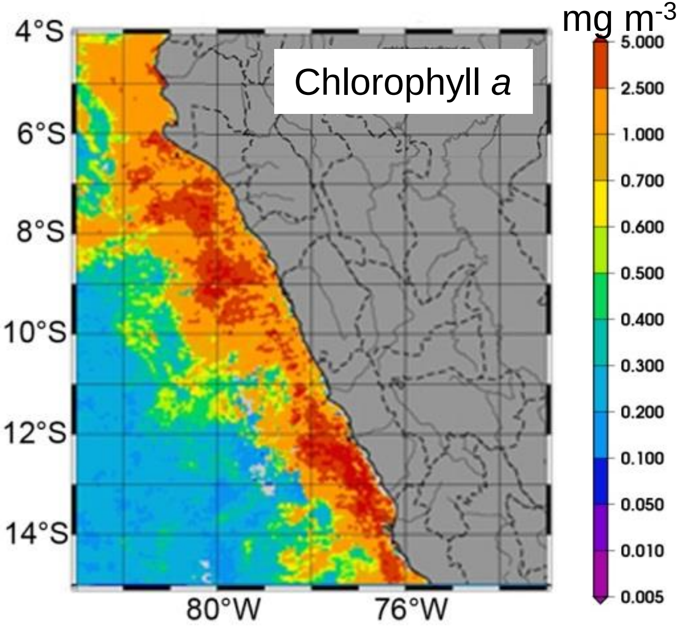
- Average onshore transport in the upper 10m of the water column at 80m water depth:

T_{NLIW} = 0.24 m^2s^{-1}

water depth	Ekman transport (**T_E**)
<125m	0.16 m^2s^{-1}
<500m	0.24 m^2s^{-1}
all	0.26 m^2s^{-1}

Conclusion I





courtesy A. Bracher (AWI)

- Coastal “upwelling” of Peru during upwelling season is likely not related to offshore Ekman transport
- Instead, net onshore transport due to nonlinear internal waves may occur

Motivation of the tracer release experiment

Artificial tracer (SF_5CF_3) represents nutrients from anoxic sediments

Nutrient flux from the sediments are potentially important for the development of oxygen minimum zone

Picture from Madeline Freund

<u>Objective:</u>

- ➢ Investigate spreading pathways and *fate of nutrients released from the sediments*
- ➢ **Study exchange between the continental margin and ocean interior**

Tracer release experiment at the continental slope off Peru 2015-2017

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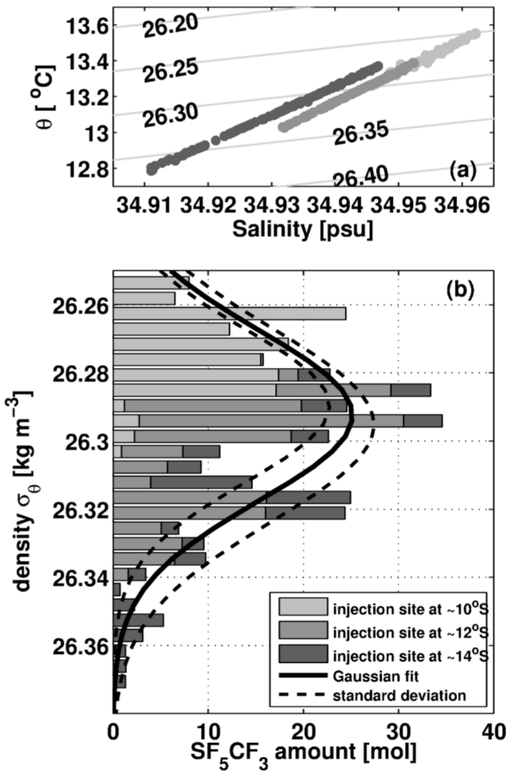

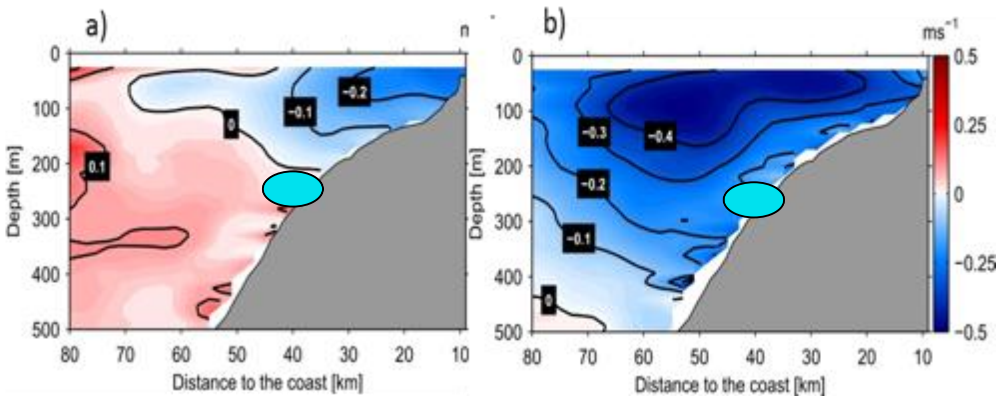

Alongshore velocity at 12°S in April, 2017 (a) and May, 2017 (b)

(Lüdke et al., 2020)

- About 70 kg of SF_5CF_3 were injected into the bottom boundary layer of the Peruvian continental slope in October 2015.
- Tracer was released at three sites at 250m depth and sampled 17 month later.

Temperature, salinity and density during injection of the tracer.

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Tracer survey cruise on RV METEOR

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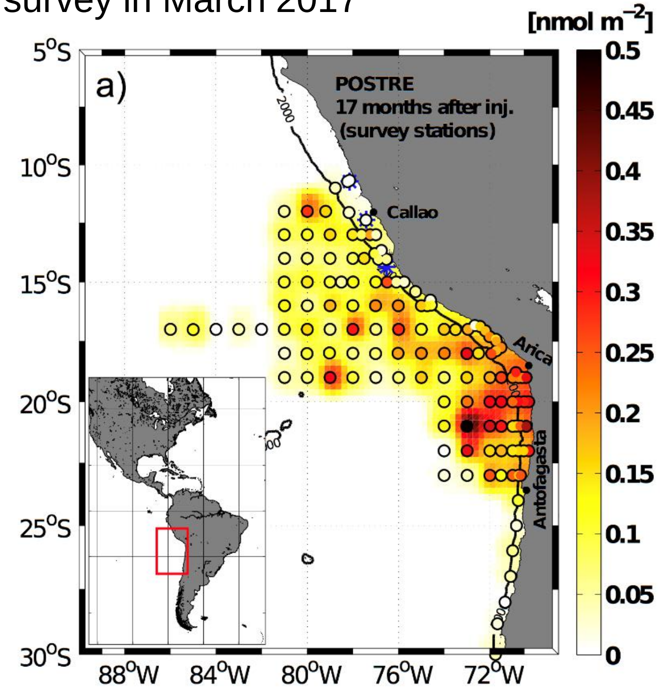
Depth-integrated tracer concentrations from survey in March 2017



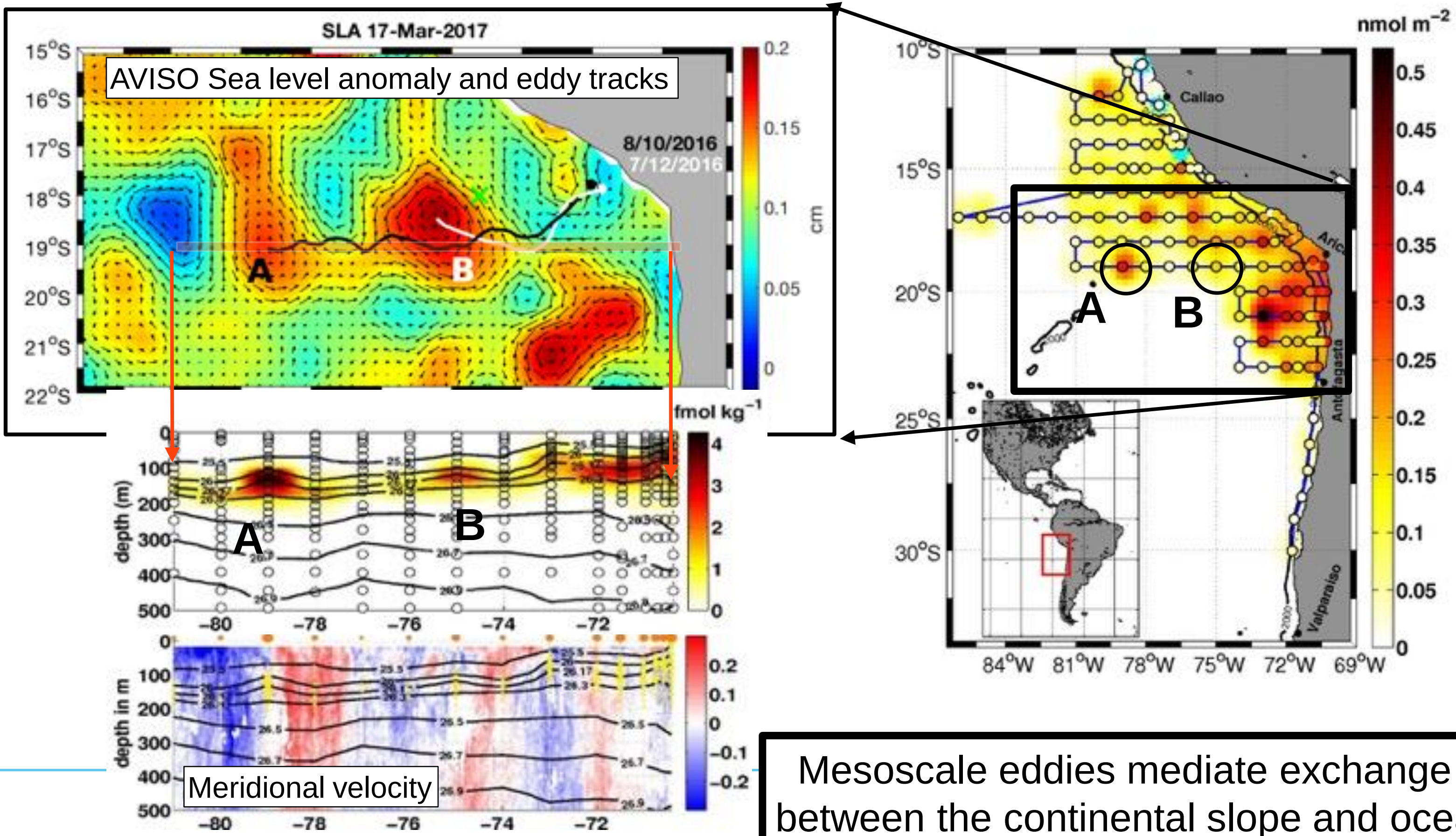
Tracer survey:

- March 2017, ~17 months after injection
- 132 stations (10-30°S, coast to 86°W)

Results:

- ~40±10% of tracer found
- 2000 km southward and 1400 km offshore of release site
- more than $2 \cdot 10^6$ km^2 covered

Exchange of tracer between the continental slope and ocean interior



Mesoscale eddies mediate exchange of tracer between the continental slope and ocean interior

Density change / vertical displacement of the tracer's center of mass

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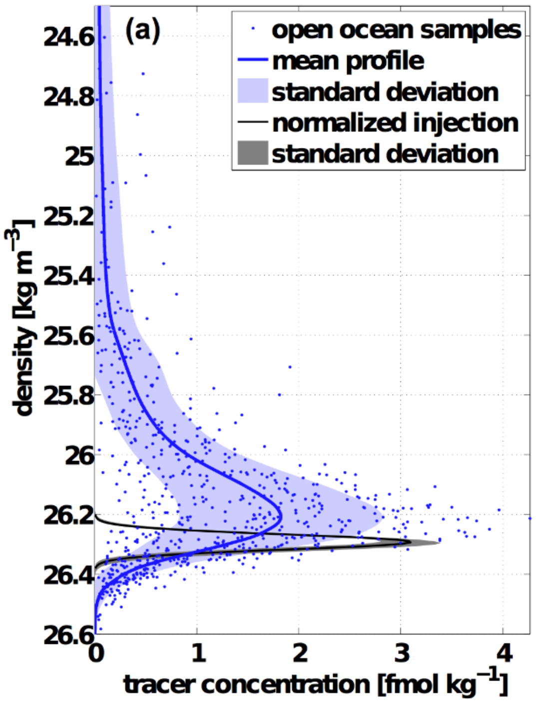
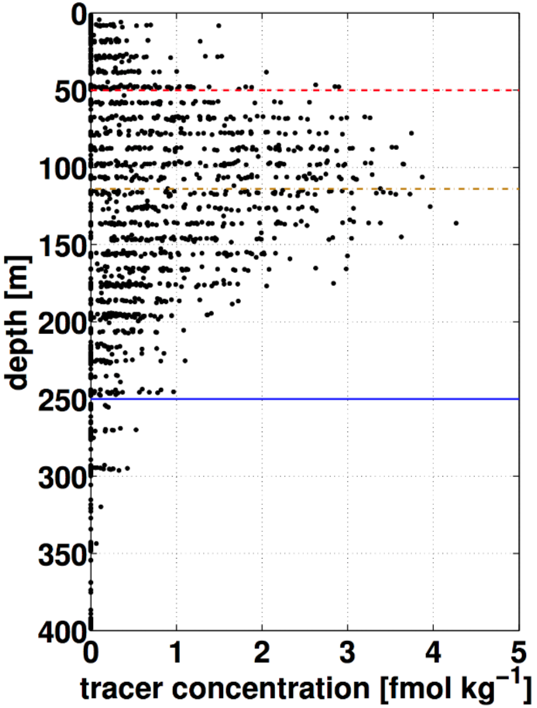
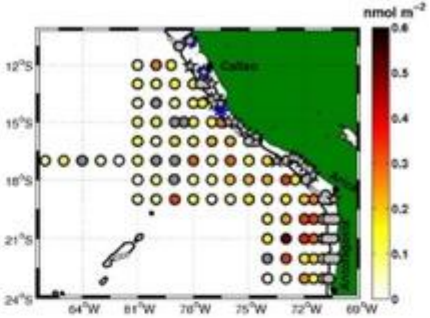
Concentration vs. density



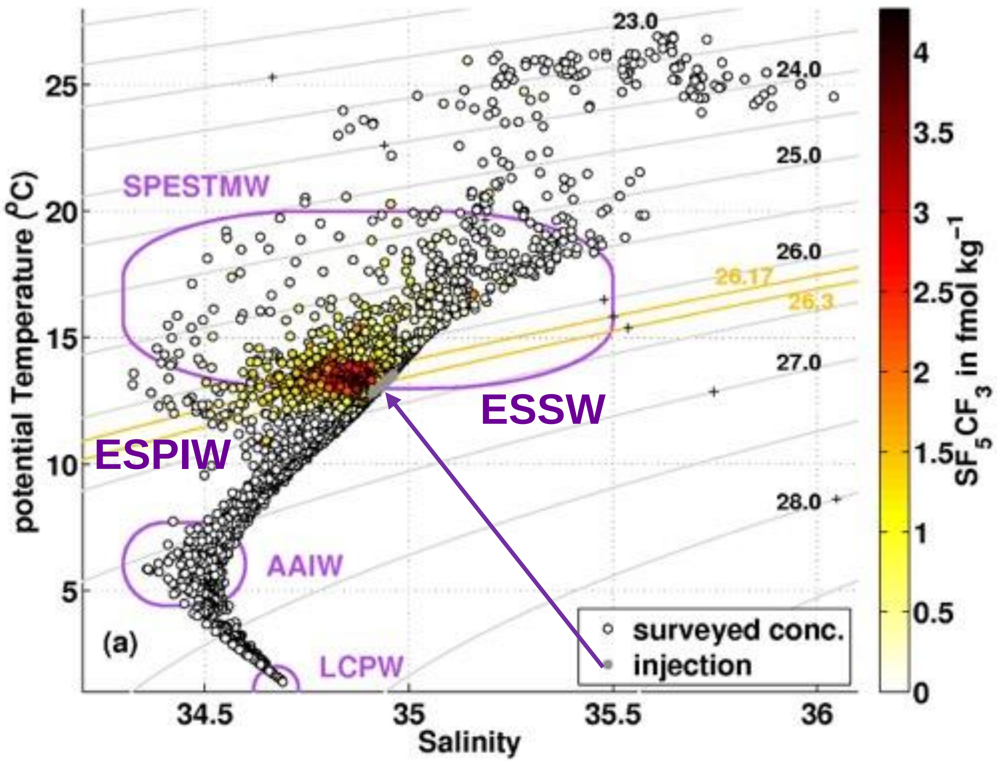
Concentration vs. depth





- Density of tracer's center of mass decreased by 0.13 kgm^{-3}.
- Corresponds to an upward displacement of about 70m
- Density change / vertical displacement is independent of region!

Tracer distribution in Θ-S space and related water masses



ESSW - Equatorial Sub-Surface Water with linear Θ-S, transported by PCUC

ESPIW – Eastern South Pacific Intermediate Water, low salinity (~150m)

SEPSTMW - South Pacific Eastern Sub-Tropical Mode Water

AAIW - Antarctic Intermediate Water

Density of the tracer's center of mass density decrease (0.13 kg/m^3) due to

- warming by 0.28°C
- freshening by 0.10 g/kg

Diapycnal mixing processes at the Peruvian continental margin

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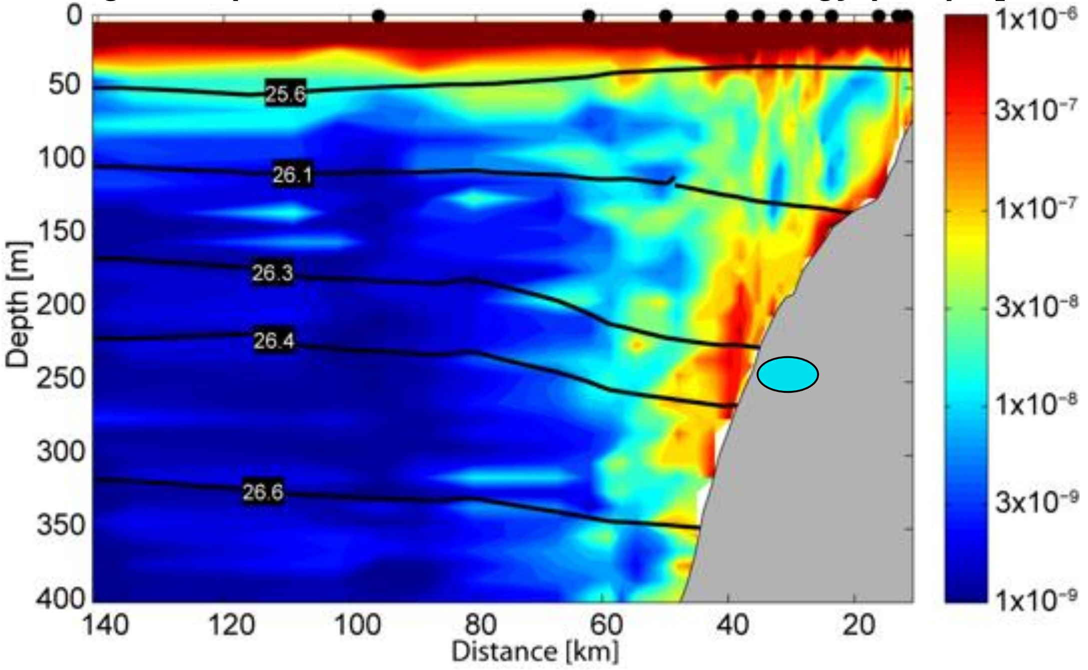
Average dissipation rate of turbulent kinetic energy (TKE) ε [m²s⁻³]



- TKE dissipation rates determined from **1300 loosely-tethered microstructure** profiles collected along the continental margin of Peru during 8 cruises (2013-2017)
- Near-bottom mixing is enhanced by an order of magnitude

Diapycnal mixing processes at the Peruvian continental margin

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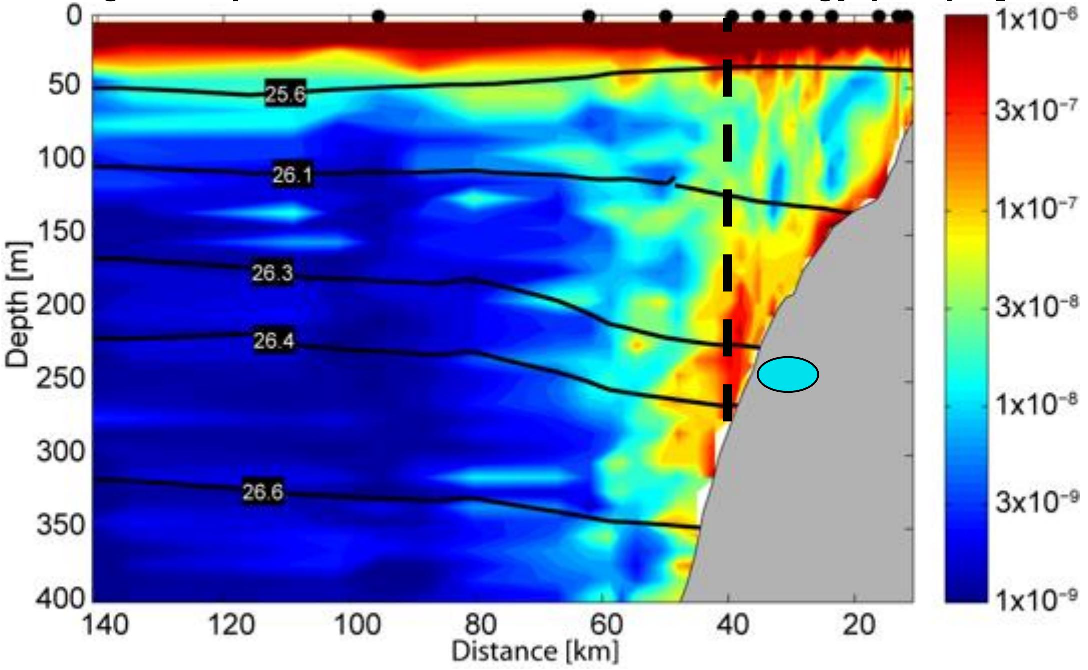
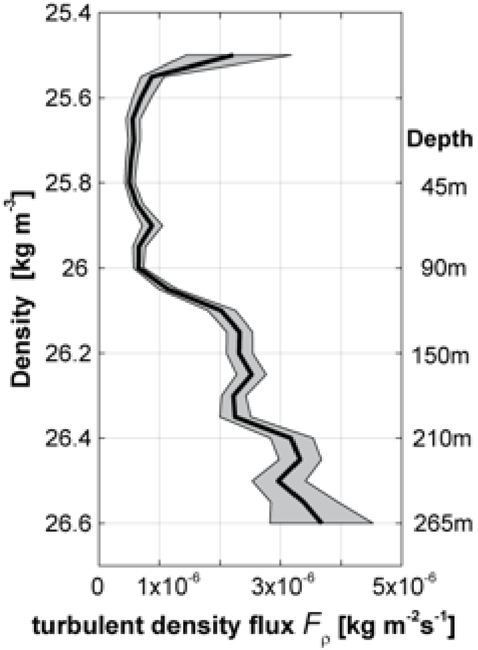
Average dissipation rate of turbulent kinetic energy (TKE) ε [m^2s^{-3}]



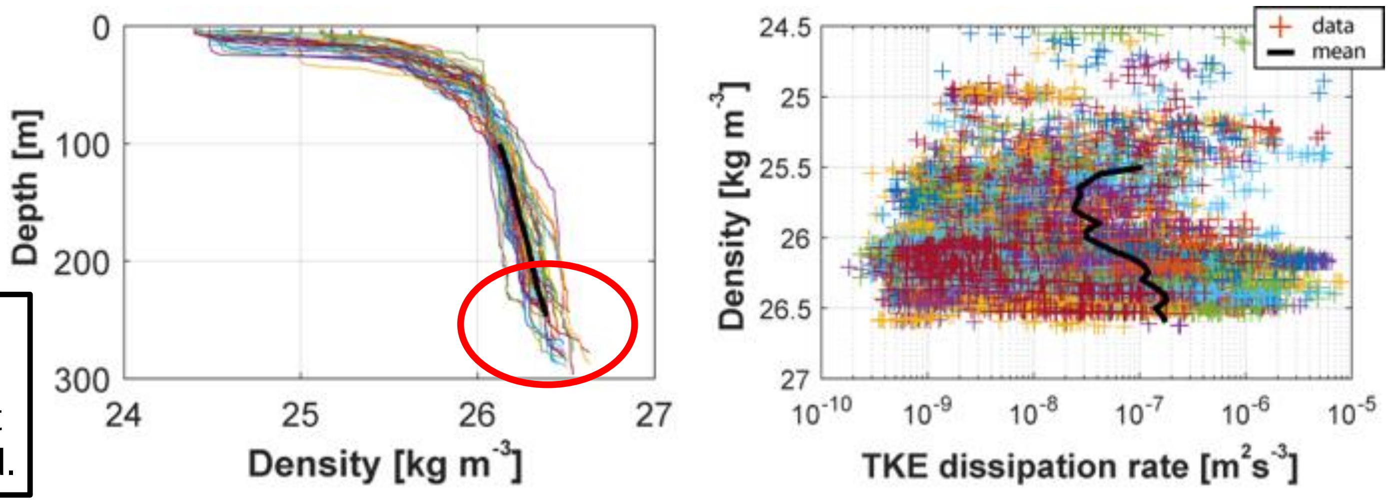
Turbulent density flux at 250m depth



➢ Vertical density flux convergence leads to downward diapycnal velocities (Ferrari et al., 2016)

Evaluating upward along-slope diapycnal velocities

Bottom boundary layer is not pronounced.



- We assumed that diapycnal downwelling $\boldsymbol{\varepsilon_{SML}}$ in the stratified mixing layer induces diapycnal upwelling $\boldsymbol{\varepsilon_{BBL}}$ in the BBL
- Evaluating $\overrightarrow{\boldsymbol{\varepsilon_{SML}}} \cong -\rho_0 g^{-1}\Gamma\frac{\partial\epsilon}{\partial\rho}\overrightarrow{\boldsymbol{n_z}}$ from microstructure profiles collected between bottom depth of 200m and 280m yields: $\boldsymbol{\varepsilon_{SML}}$ ≈ - **0.5 m day^{-1}.**

Residence time of the tracer at the eastern boundary

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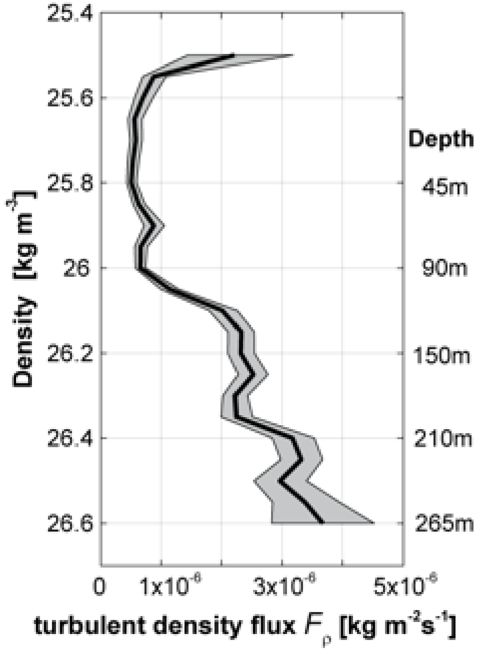
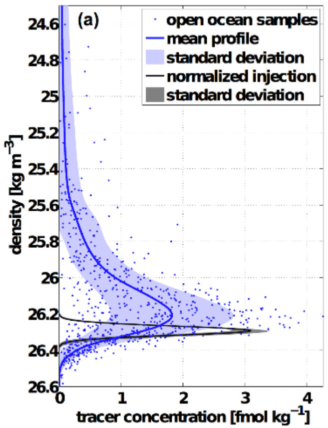
Density flux determined from all profiles measured at bottom depth between 200m and 280m.

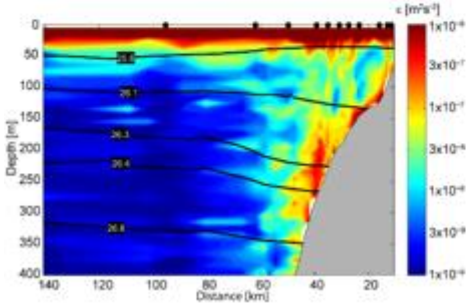


- Assuming $\varepsilon_{SML} = -\varepsilon_{BBL}$ yields diapycnal upwelling velocities of 0.5 m day^{-1} in the BBL.
- **A residence time in the BBL requires to be about 1.5 to 3 month** to explain the density change of the tracer's center of mass of 0.13 kg m^{-3}

Caveat:

- Vertical distribution of the density flux does not decrease near the bottom (vanishing flux at the bottom is required)
- A BBL is not obvious in the data!





Conclusion II

- At the Peruvian continental slope, turbulent mixing processes exhibit a near-bottom maximum that is estimated to drive a diapycnal downwelling of 0.5 m day^{-1} in the lower 50-100m of the water column.
- Diapycnal upwelling in the bottom boundary layer can explain the density decrease of the tracer's center of mass, requiring a BBL residence time of the tracer of 1.5 to 3 month.

Upwelling in the bottom boundary layer provides a direct pathway for nutrients released from the sediment to contribute to primary production in upwelling region.

An International Field Campaign (about 2025)
- Documenting a whole year of Canary Upwelling

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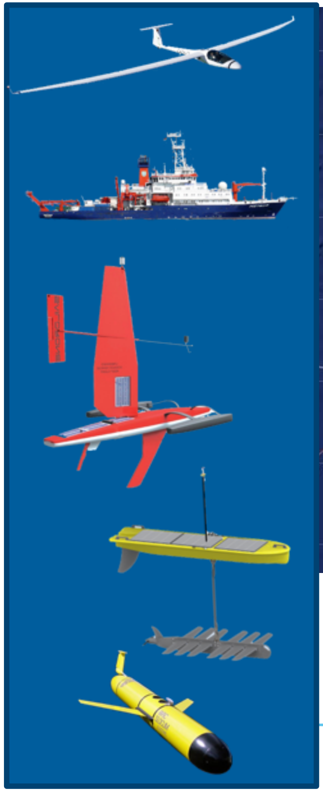
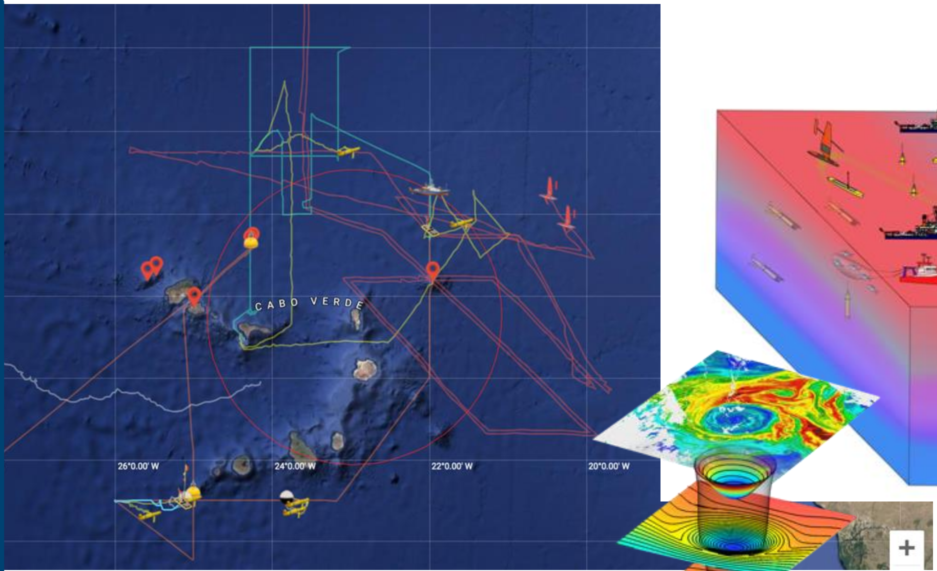
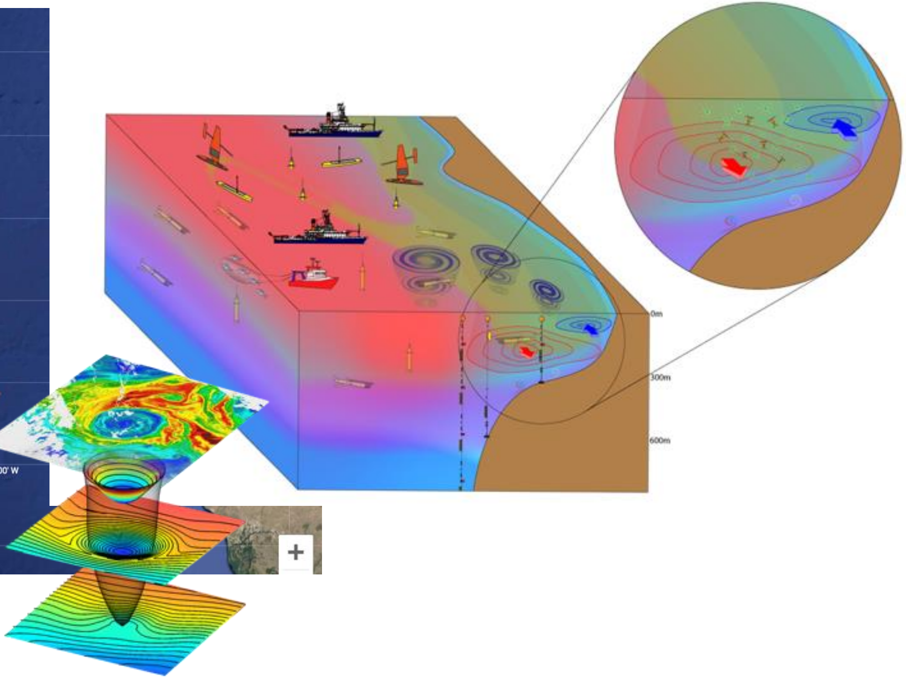
Perform concerted multi-disciplinary, multi-parameter, multi-platform study







Take full advantage of robotics