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Estimating Eddy Buoyancy Fluxes in Eastern-Boundary Upwelling Systems

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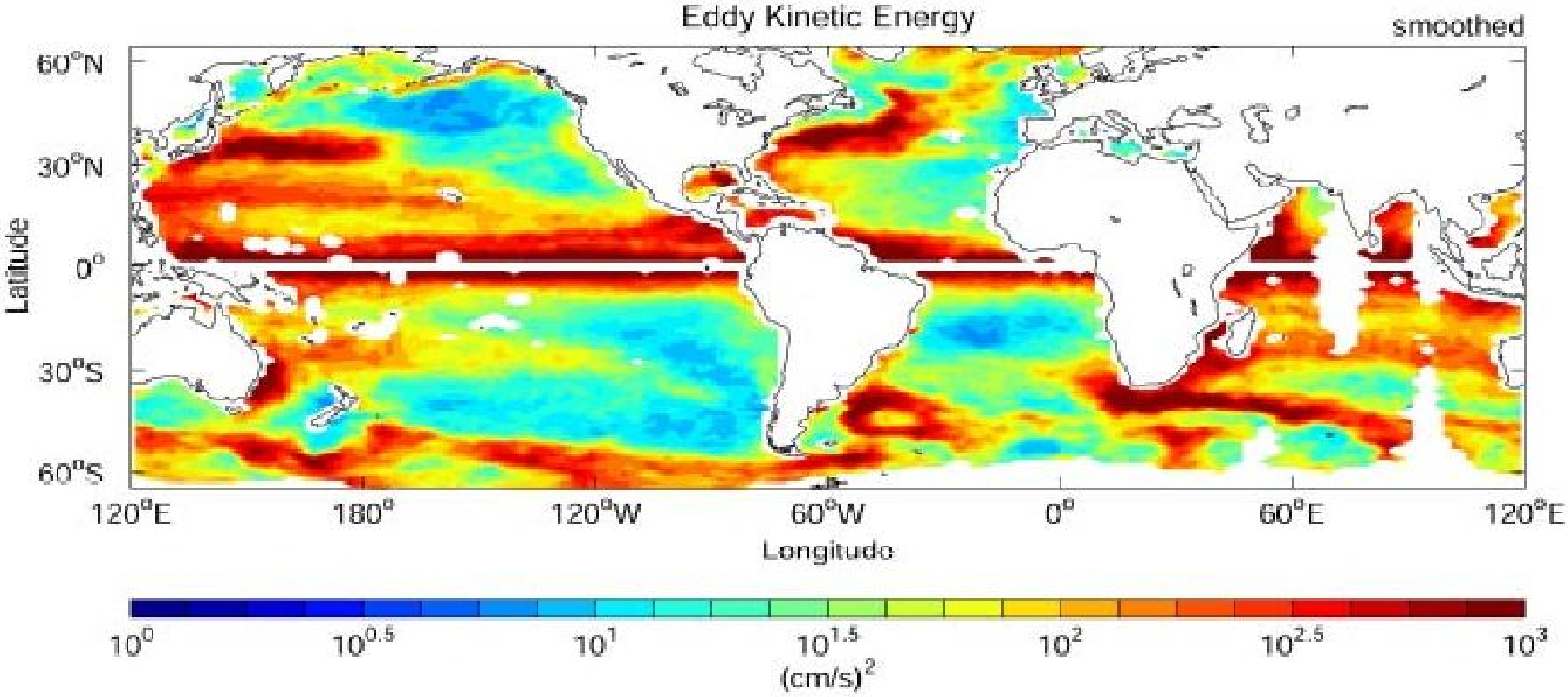
- Climate Heat Balance off Peru
- Eddy Advection - Diffusion Decomposition
- Surface-Layer vs. Pycnocline Fluxes

EDDY KINETIC ENERGY



Surface geostrophic eddy kinetic energy estimated from the TOPEX/Poseidon-Jason1 tandem altimeter mission. Note the logarithmic scale ⇒ non-uniform eddy amplitudes. Resolved mesoscale eddies are $\geq$ Rossby radius in size. (Stammer, 2008)

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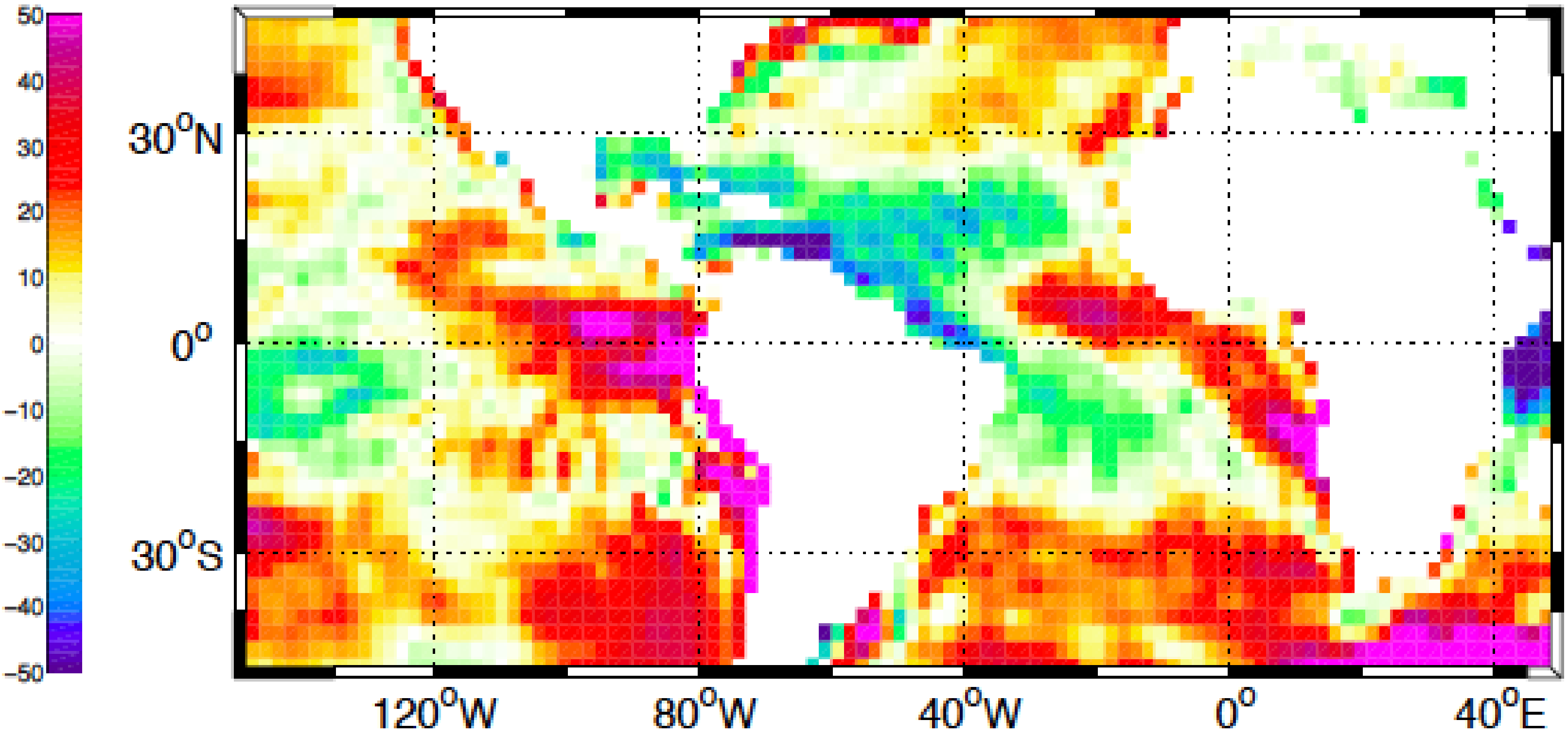
SURFACE HEAT FLUX



Annual mean net air-sea heat flux difference [W m^{-2}] between COADS and the NCEP reanalysis climatologies. Discrepancies are large in eastern boundary regions, and mesoscale eddy processes may contribute.

WHAT DO WE THINK EDDIES DO TO CIRCULATION?

1. Extract available potential energy through baroclinic instability by eddy buoyancy b flux and eddy-induced circulation:

$$\langle\, \mathbf{u}'b' \,\rangle = \boldsymbol{\Psi} \times \boldsymbol{\nabla} b + \mathbf{F}_b$$

$$\boldsymbol{\Psi} = -\,\frac{\langle\, \mathbf{u}'b' \,\rangle \times \boldsymbol{\nabla} b}{|\boldsymbol{\nabla} b|^2}\,, \qquad \mathbf{u}^* = \boldsymbol{\nabla} \times \boldsymbol{\Psi}\,, \qquad \boldsymbol{\nabla} \cdot \mathbf{u}^* = 0$$

$$\boldsymbol{\nabla} \cdot \langle\, \mathbf{u}'b' \,\rangle = \mathbf{u}^* \cdot \boldsymbol{\nabla} b + \boldsymbol{\nabla} \cdot \mathbf{F}_b\,, \qquad \mathbf{F}_b = \frac{\langle\, \mathbf{u}'b' \,\rangle \cdot \boldsymbol{\nabla} b}{|\boldsymbol{\nabla} b|^2}\, \boldsymbol{\nabla} b\,.$$

2. Mix material concentrations c:

$$\langle\, \mathbf{u}'c' \,\rangle = \boldsymbol{\Psi} \times \boldsymbol{\nabla} c + \mathbf{F}_c$$

$$= \text{eddy advection} + \text{eddy diffusion}$$

$\mathbf{F}_c$ is “mixing” if $\mathbf{F}_c \cdot \boldsymbol{\nabla} c < 0 \;\Rightarrow\; \mathbf{F}_c = -\,K \boldsymbol{\nabla} c$ with $K > 0$.

The “adiabatic” dynamical hypothesis is that $\mathbf{F}_b = 0$ in the stratified interior, while $|\mathbf{F}_c \cdot \boldsymbol{\nabla} b|$ is often large ($i.e.$, isopycnal mixing).

3. Restratify the turbulent surface boundary layer:

$$\langle\, w'b' \,\rangle > 0 \qquad \text{with} \qquad w^*\,,\ \langle\, w'c' \,\rangle \neq 0\,.$$

Many other roles are possible but not yet known to be so important.

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WHY DO WE KNOW SO LITTLE ABOUT REAL EDDY FLUXES?

Sampling Limits: Given time series $a(t)$, spectrum $A(\omega)$, variance $\sigma^2 = \int A \, d\omega$, sampling interval T, eddy decorrelation time t_c,

error in $\langle\, a \,\rangle$: $\sim \left(\frac{A(0)}{T}\right)^{1/2}$

error is $\langle\, a'^2 \,\rangle$: $\sim \sigma^2 \left(\frac{t_c}{T}\right)^{1/2}$

error in $\langle\, a'b' \,\rangle$: $\sim \sigma_a \sigma_b \left(\frac{t_c}{T}\right)^{1/2}$

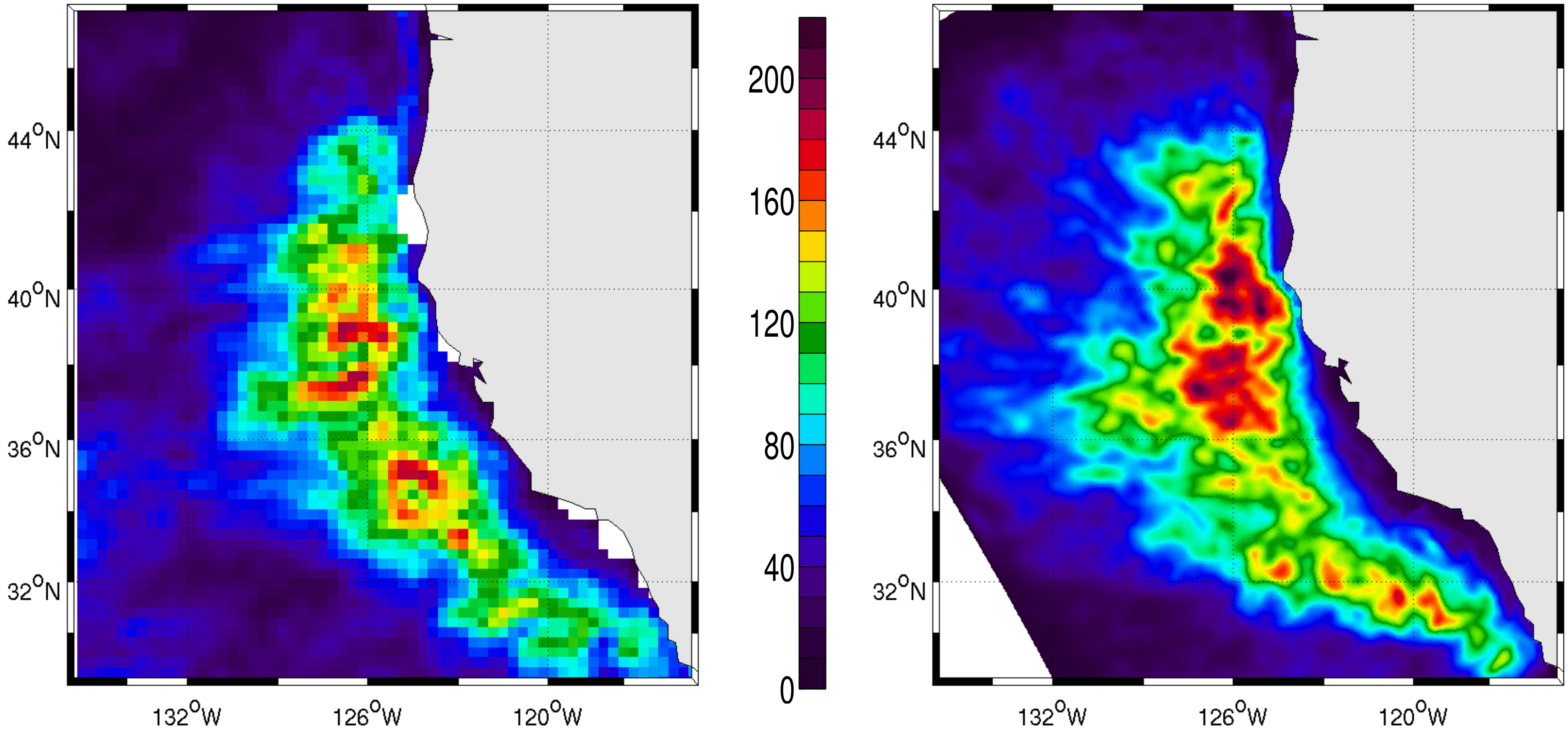
Difficulties are (1) eddies have broad-band spectra; (2) $\sigma \gg \langle\, a \,\rangle$ is common; (3) t_c is not short ($\sim$ month), so $T = N t_c$ is long to have $N^{-1/2} \ll 1$; and (4) $\langle\, a'b' \,\rangle$ is typically small compared to $\sigma_a \sigma_b$ ($\sim 10\%$).

⇒ It takes decades, if not centuries, for an accurate flux at a single point.

Computational Limits: Turbulent eddies are intimately related to their mean flow. In OGCMs eddy resolution is marginally adequate with $dx \approx 10$ km. Local models can have small dx but an ill-determined mean flow.

⇒ Multi-scale grid nesting with skillful open boundary conditions.

EDDY KINETIC ENERGY OFF CALIFORNIA

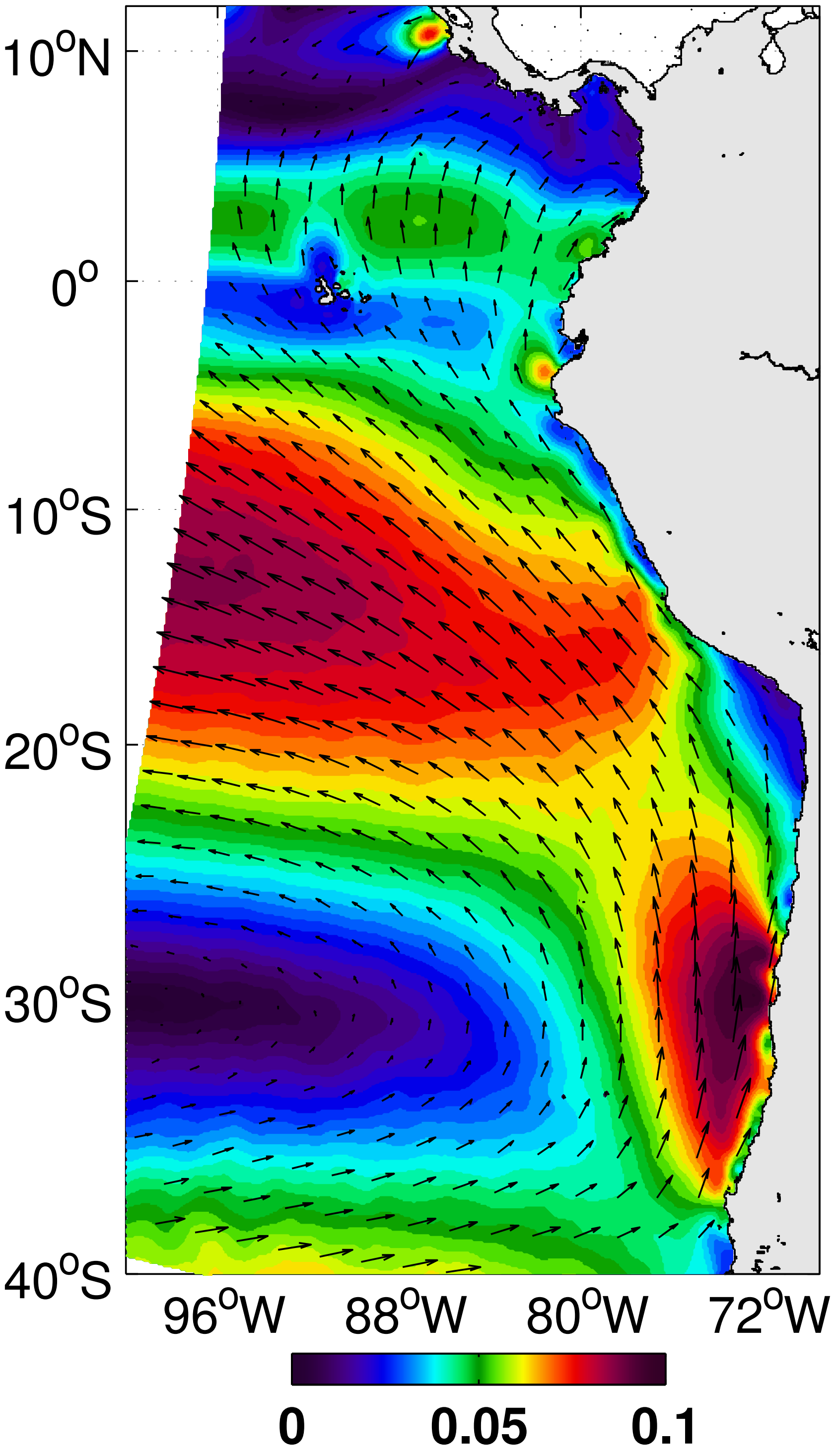


AVISO (altimetry)

simulation

Annual mean surface eddy kinetic energy [cm^2 s^{-2}] in the California Current System.
The simulation is with a nested regional grid.
The spatial fine structure is more an indication of sampling estimation uncertainty than true detail.

The simulation has plausible realism by this measure.

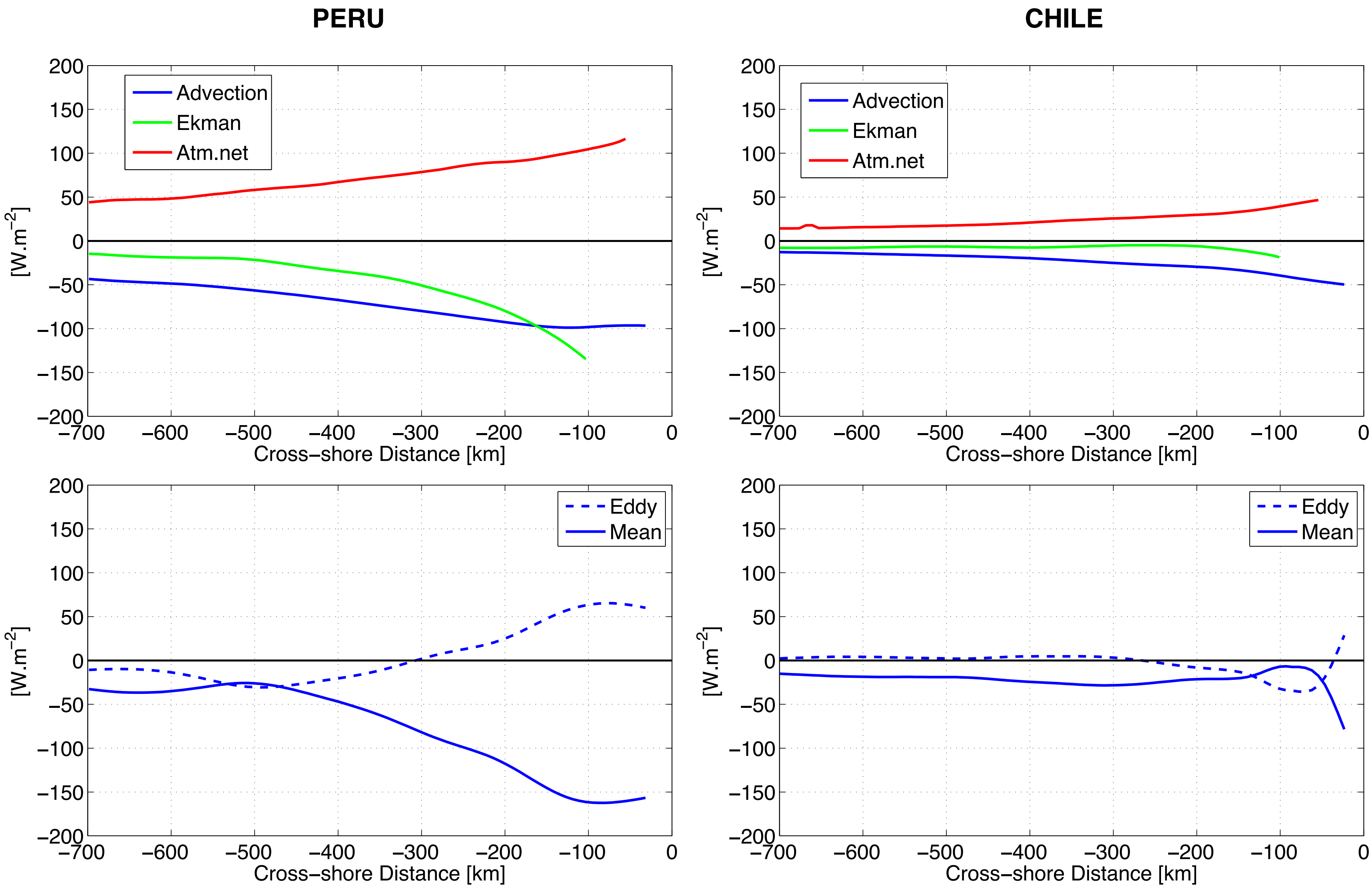


WIND FORCING

Measured mean wind stress [N m^{-2}] off South America from scatterometry (SCOW). Notice alongshore direction and sharp coastal transition. A broad stratus cloud deck covers the ocean from the coast to $\sim$ 1000 km offshore.

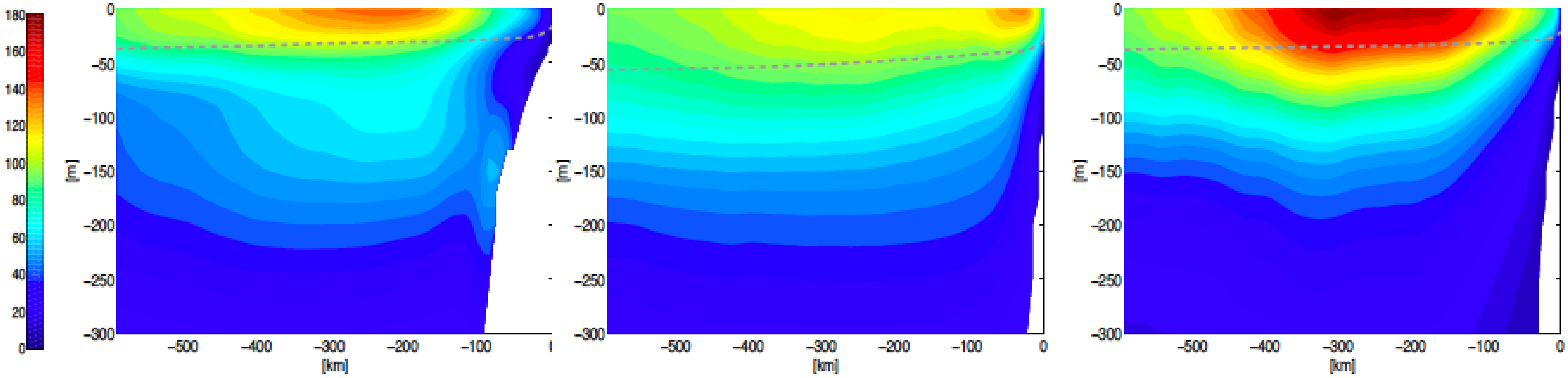
How does the surface remain cold enough in the presence of air $\longrightarrow$ sea heat flux?

OCEANIC HEAT BALANCE



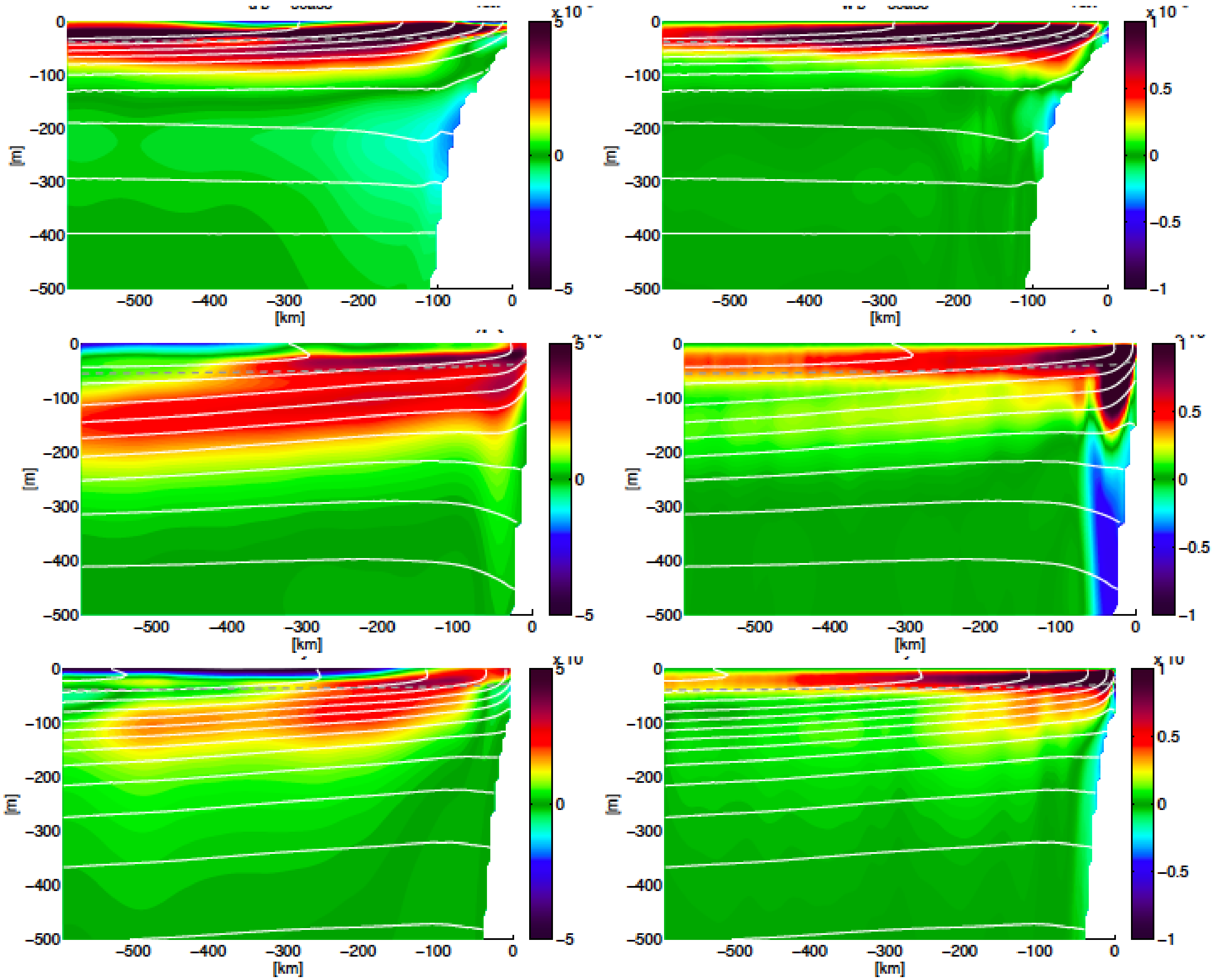
Simulated vertically-integrated mean heat balance off Peru and Chile.
Mean and eddy lateral advection balance the air-sea warming.
Eddy advection is large and broadly cooling off Peru.
Eddy and mean advection oppose each other in the coastal upwelling zone.

VERTICAL STRUCTURE OF KINETIC ENERGY



Alongshore- and time-averaged eddy kinetic energy [cm^2 s^{-2}]
in cross-shore sections off Peru, Chile, and California.
Dashed lines indicate the surface boundary layer depth.

EDDY BUOYANCY FLUX



Alongshore- and time-averaged $\langle\, u'b' \,\rangle$ [left; 10^{-5} $\mathrm{m^2s^{-3}}$] and $\langle\, w'b' \,\rangle$ [right; 10^{-8} $\mathrm{m^2s^{-3}}$] in cross-shore sections off Peru (top), Chile (middle), and California (bottom).

Fluxes are mainly shoreward and upward.

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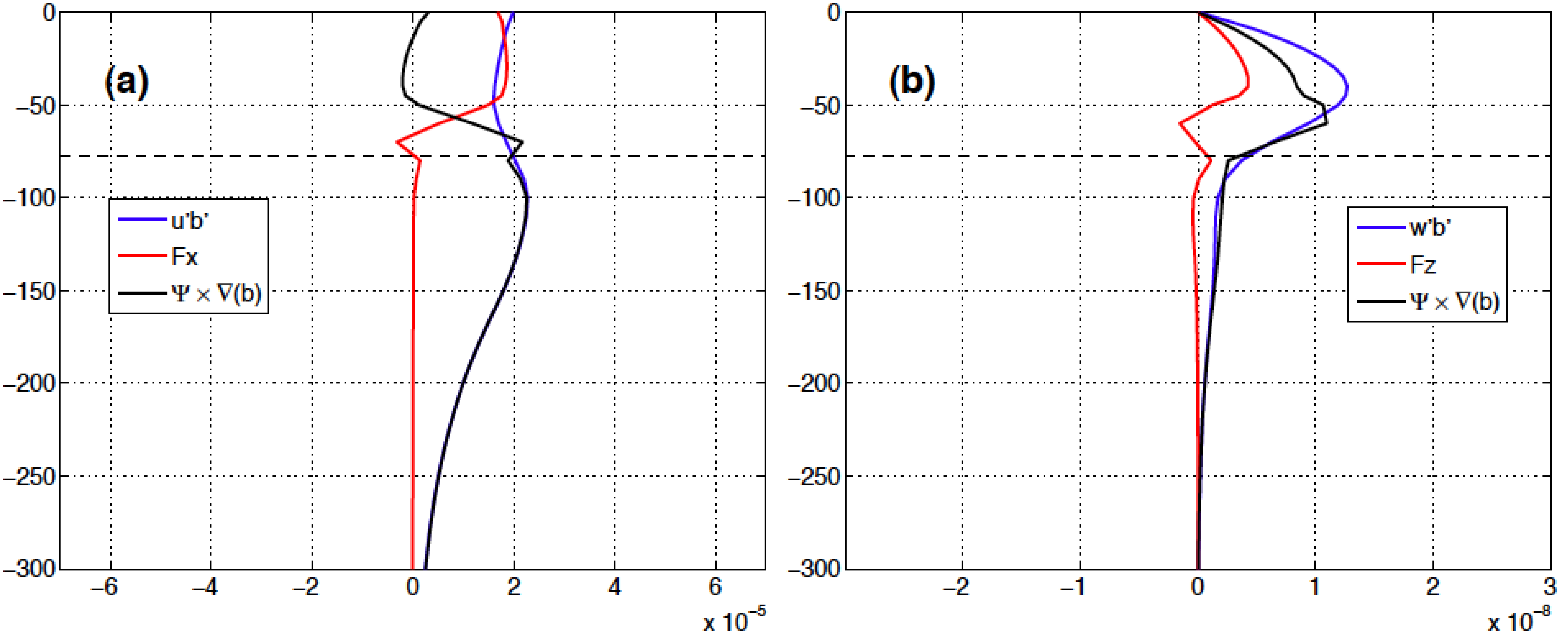
EDDY ADVECTION - DIFFUSION DECOMPOSITION: CHILE



Area-averaged profiles of cross-shore (left) and vertical (right) eddy buoyancy flux [m^2s^{-3}] decomposed into their advective and diffusive components for winter off Chile.

Below the surface boundary layer the flux is almost entirely advective.

The advective flux structure is different in the surface layer and pycnocline.

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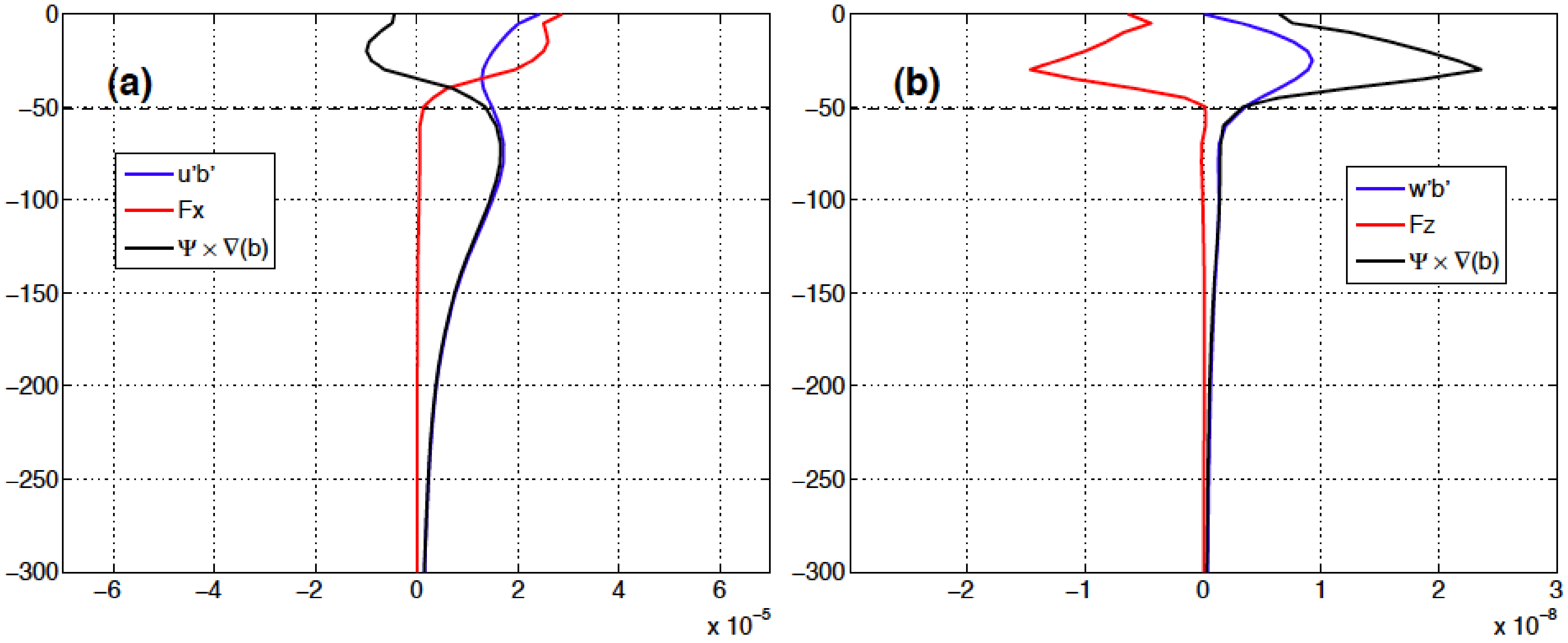
EDDY ADVECTION - DIFFUSION DECOMPOSITION: CALIFORNIA

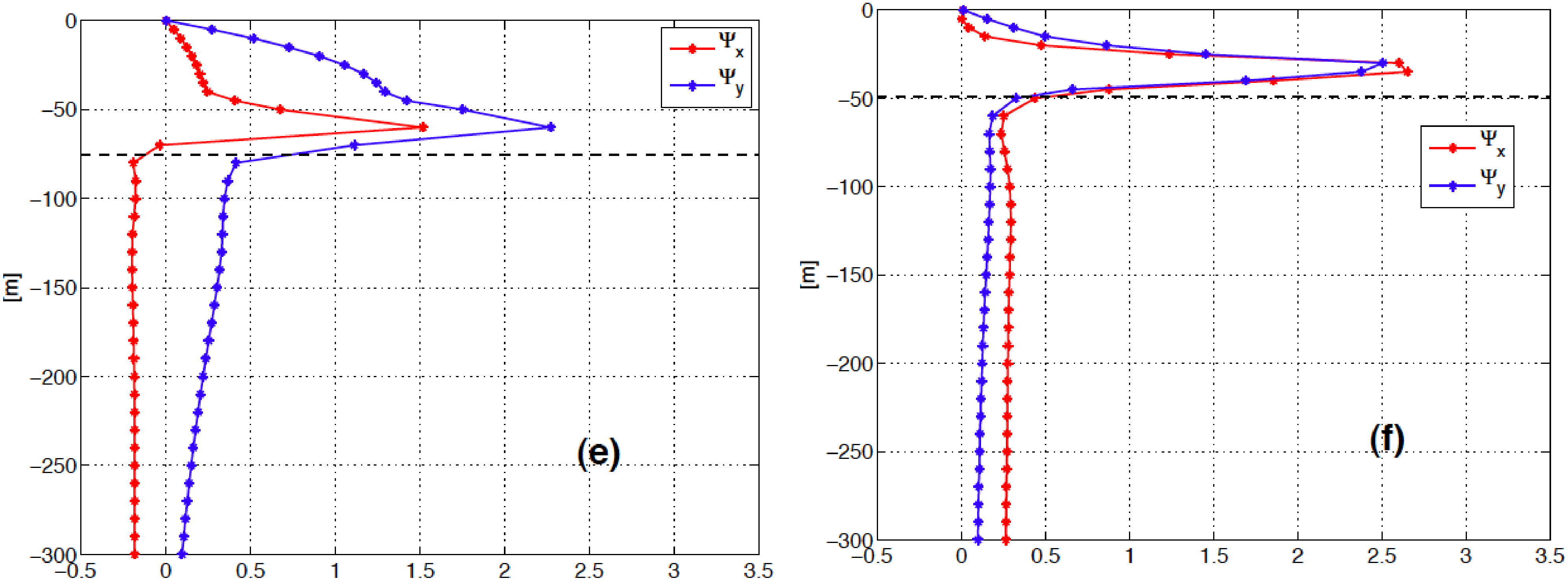


Area-averaged profiles of cross-shore (left) and vertical (right) eddy buoyancy flux [m^{2}s^{-3}] decomposed into advective and diffusive components for winter off California.

Below the surface layer the flux is almost entirely advective ($i.e.$, adiabatic).

The advective flux structure is different in the surface layer and pycnocline.

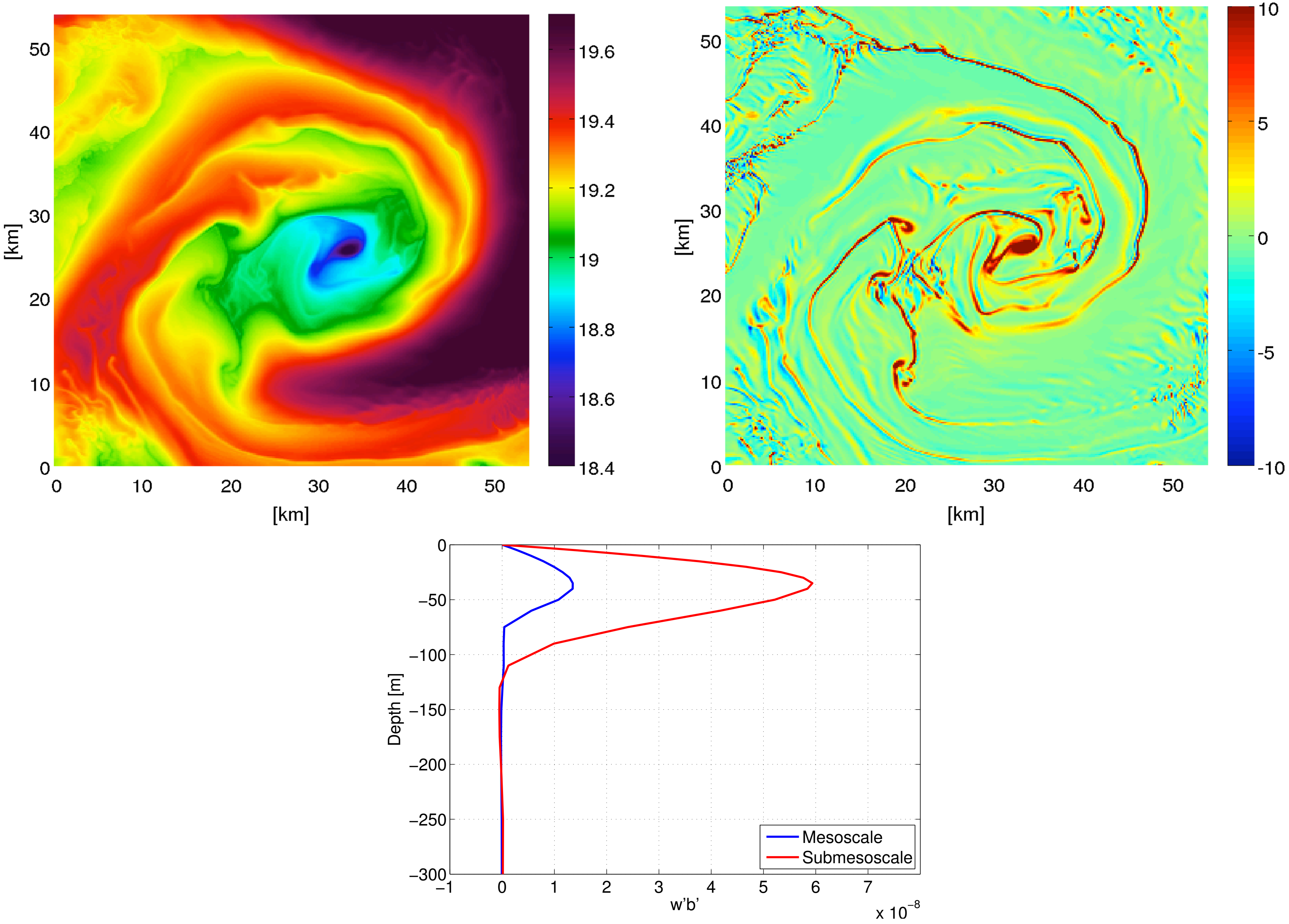
EDDY-INDUCED STREAMFUNCTION



Area-averaged profiles of the eddy-induced streamfunction [m^{2}s^{-1}] for Chile (left) and California (right) in winter. Flow in the cross-shore plane is controlled by Ψ_y, alongshore by Ψ_x:

$$u^* = -\,\partial_z \Psi_y \qquad v^* = \partial_z \Psi_x \qquad w^* = \partial_x \Psi_y - \partial_y \Psi_x \, .$$

Again notice the distinctive surface-layer and pycnocline structures.
In Chile the primary cell is cross-shore (shoreward at surface);
in California the cross-shore cell is similar but the alongshore cell is stronger.



Emergence of submesoscale filaments and spiral eddies in SST [C] and (vertical vorticity)/f (top) and their associated vertical eddy buoyancy flux [$m^2 s^{-3}$] (bottom) off Peru.

Summary

- Mesoscale (and submesoscale) eddies are everywhere in the ocean.
- Their buoyancy and material fluxes are probably important almost everywhere, but sampling and computational limits are severe.
- With nested regional grids and spatial averaging, accurate fluxes can be determined.
- In subtropical eastern boundary systems eddy buoyancy fluxes are mostly shoreward and upward, counter to the mean upwelling circulation. But alongshore fluxes are important, especially off California.
- Off Peru eddy heat fluxes importantly cool the offshore region under the stratus cloud deck and large air-sea heating.
- The adiabatic dynamical hypothesis of primarily eddy buoyancy advection $\mathbf{\Psi}$ in the pycnocline is confirmed. In the surface layer eddy advection and diffusion $\mathbf{F}_b$ both occur. Submesoscale eddies dominate $\langle\, w'b' \,\rangle$ in the surface layer.
- In comparison to the GM parameterization formula,

  $$\mathbf{\Psi} = -\,K\;\hat{\mathbf{z}} \times \frac{\boldsymbol{\nabla} b}{N^2}\,,$$

  Fitted K values are $10^3 - 10^4$ m^{2}s^{-1}, as expected, but the profiles are not confirmed.
- Spatial refinement (as far as feasible), dynamical interpretation, and parameterization assessment all remain to be done.