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Mesoscale Eddy-Induced Sharpening of Oceanic Tracer Fronts and its Parameterization

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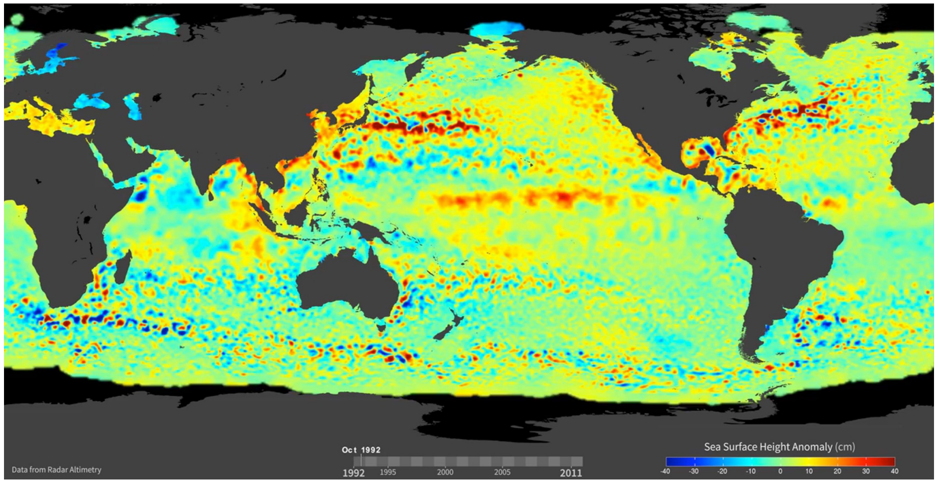
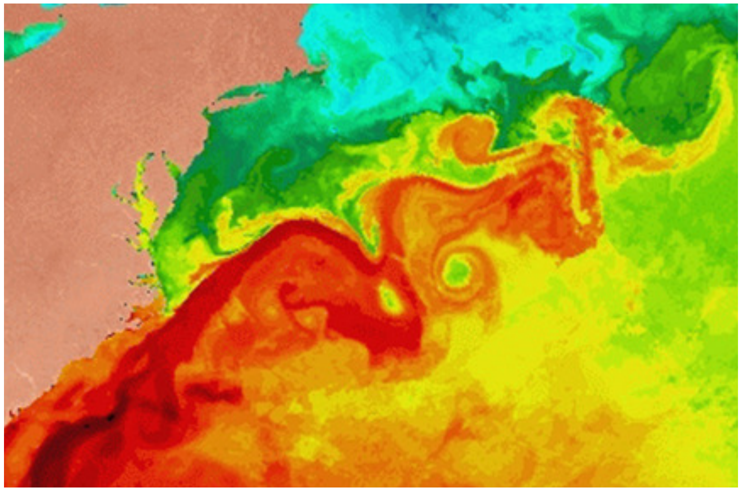
Mesoscale eddies

- Stirring and mixing along isopycnals
- Important for tracer (e.g., carbon, heat) distributions
- E.g., can generate and sharpen the fronts via strain *(e.g., Berloff 2005; Waterman & Jayne 2011)*

Observed SSH anomaly (PODAAC)

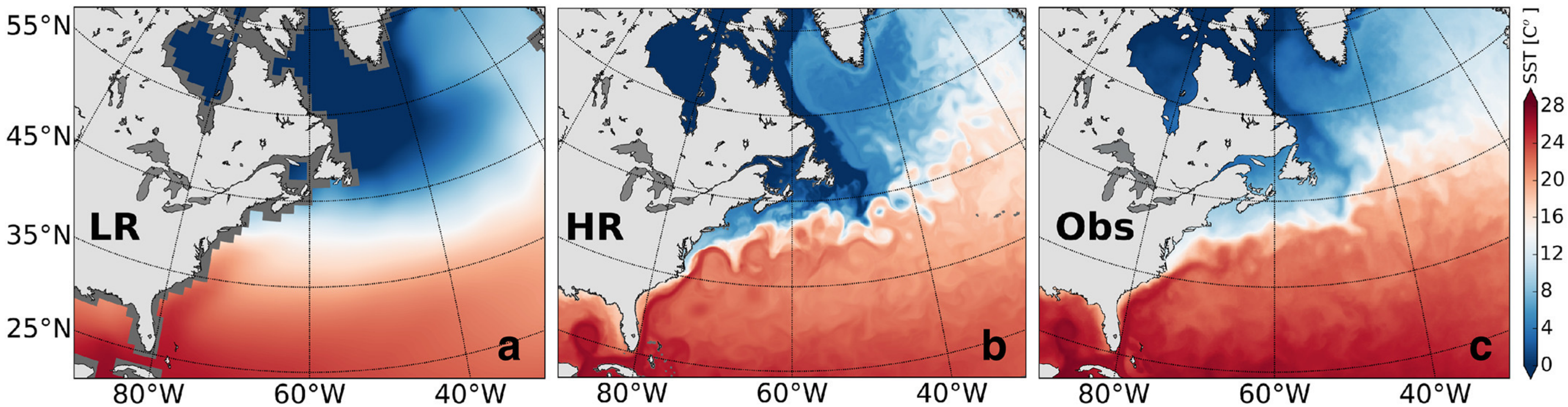


AVHRR SST showing an **elongated front** along the Gulf Stream



Ocean fronts in non-eddy-resolving models

- Much weaker SST fronts in non-eddy-resolving models than in eddy-resolving models or observations (e.g., *Kirtman et al. 2012; Siqueira & Kirtman 2016*)



Snapshots of monthly-mean **SST**. LR: 1° ocean; HR: 0.1° ocean; in CCSM4 (*Siqueira & Kirtman 2016*)

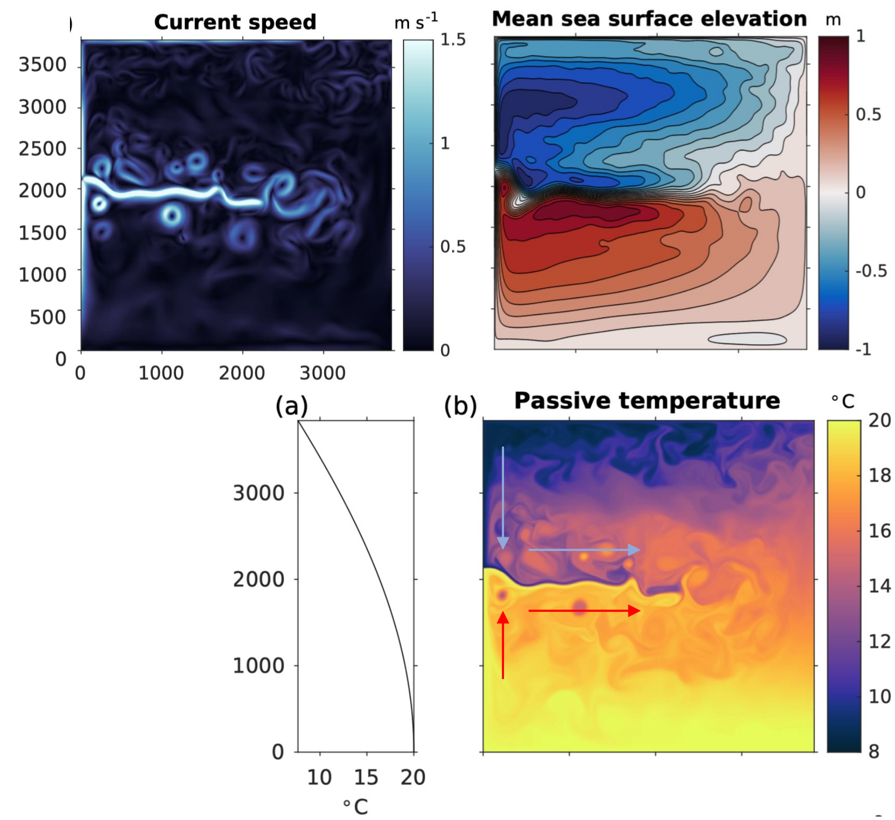
Our objective: to examine the role of mesoscale eddies in the formation of the **elongated front** of *passive* tracer along the western boundary current extension

Double-gyre model

- Three-isopycnal-layer, wind-driven, shallow water model by MOM6
- Beta-plane; 2^{nd} deformation radius = 25 km; L = 3840 km
- Run a **fine grid dx = 3.75 km**; also consider a **coarse grid dx = 60 km.**
- Equation of tracer c in a layer h:

  $$\partial_t(hc) + \nabla\cdot(\mathbf{U}c) = A + R$$

  where horizontal mass flux $\mathbf{U} = \mathbf{u}h$, subgrid diffusion A and relaxation R
- An elongated **front** of **passive temperature** forms along the "Gulf Stream" (GS)



(Top) Flow speed & time-mean sea surface elevation. (Bottom) Initial tracer (**passive temperature**) and its solution at day 730. All in the upper layer.

The eddy effects on tracer - “eddy forcing”

- The low-resolution tracer equation:

$$\partial_t(h_L c_L) + \nabla_L \cdot (\mathbf{U}_L c_L) = EF + A + R,$$

where L denotes fields on coarse grid, $\mathbf{U}_L$ is the large-scale mass flux, h_L is solved from continuity using $\mathbf{U}_L$, EF is a tracer “**eddy forcing**” that quantifies the eddy effects on tracer.

- Coarse graining $\langle\cdot\rangle$ the high-resolution equation and let $c_L = \langle c \rangle$, we get EF:

$$EF = \partial_t(h_L\langle c\rangle - \langle hc\rangle) + \nabla_L \cdot (\mathbf{U}_L\langle c\rangle) - \langle \nabla \cdot (\mathbf{U}c)\rangle + res.$$

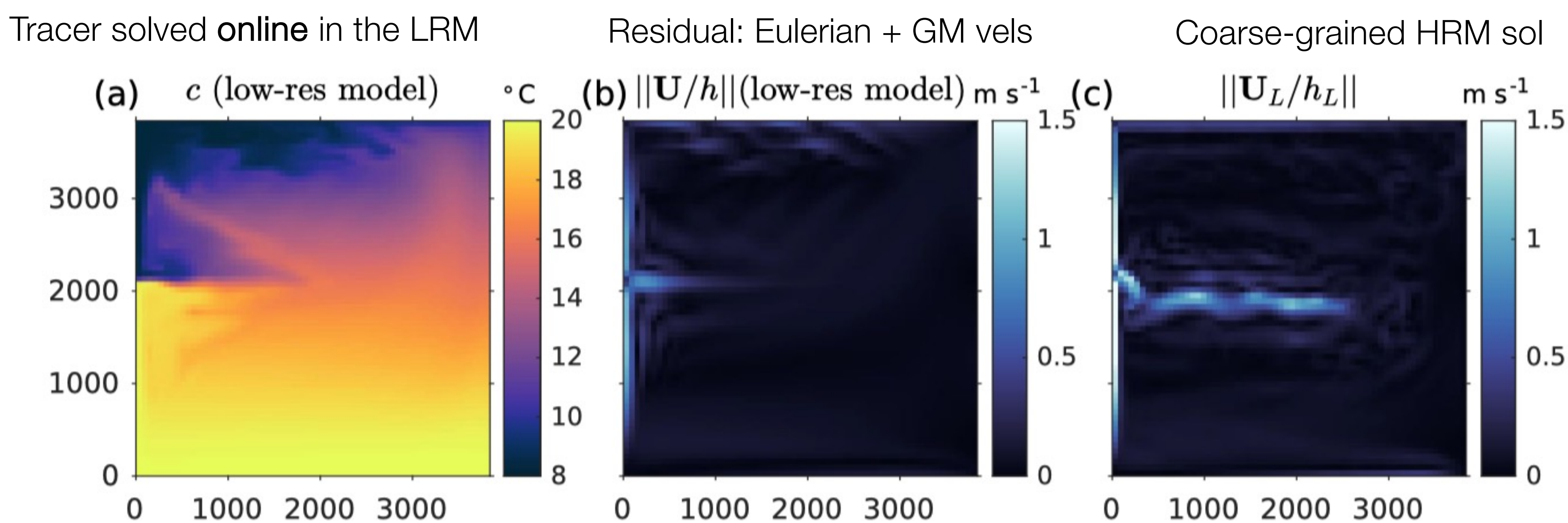
- In this study, we **derive $\mathbf{U}_L$ from high-resolution solution** and use it to advect tracer (**offline**):

$$\mathbf{U}_L = \langle \overline{\mathbf{U}} \rangle,$$

where overbar is a 180-day time average which helps remove the mesoscale variability.

Why solve tracer offline (by prescribing U_L)?

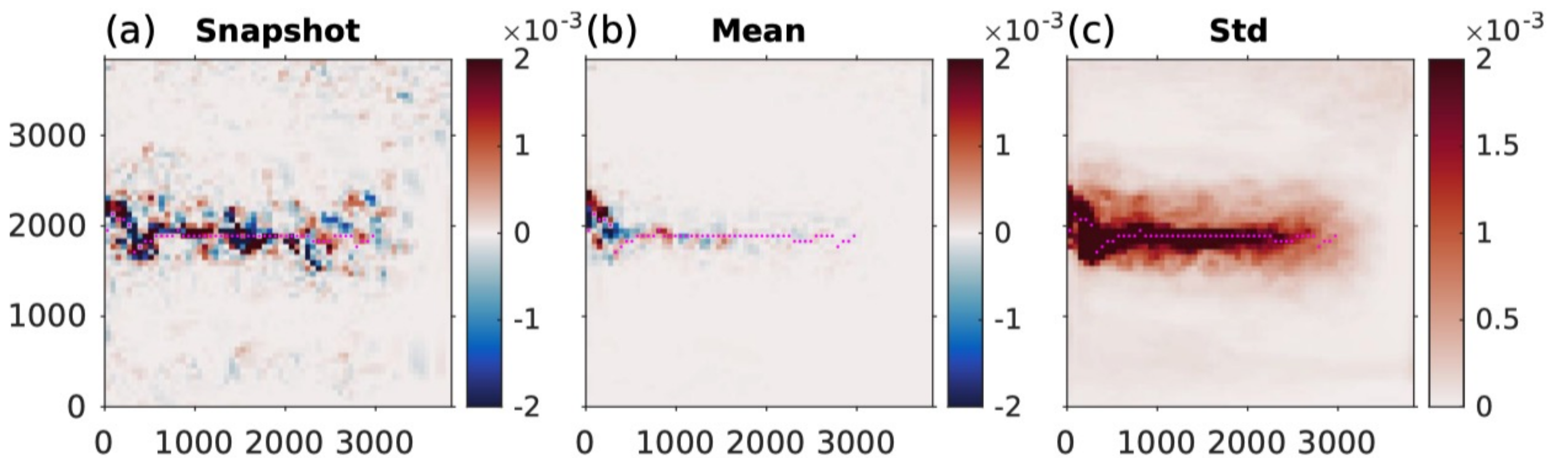
- To focus on the role of *EF*, and to avoid the tracer bias due to errors in the residual velocity (Eulerian + GM) solved by the coarse grid model
- Backscatter parameterizations *(e.g., Yankovsky et al. 2024)* are promising to generate a correct Eulerian flow (e.g., reproduce the jet extension), but are not considered here



A GM coef. = 400 m^2/s & a selective Smagorinsky eddy viscosity are used in the LRM (60 km)

Statistics of *EF*

- *EF* concentrates in the frontal region along the jet of strong eddy activities



Statistics of $\mathcal{D}_e$ [°C m s^{-1}] in the upper layer on the coarse grid (60 km).
Dots are the GS core

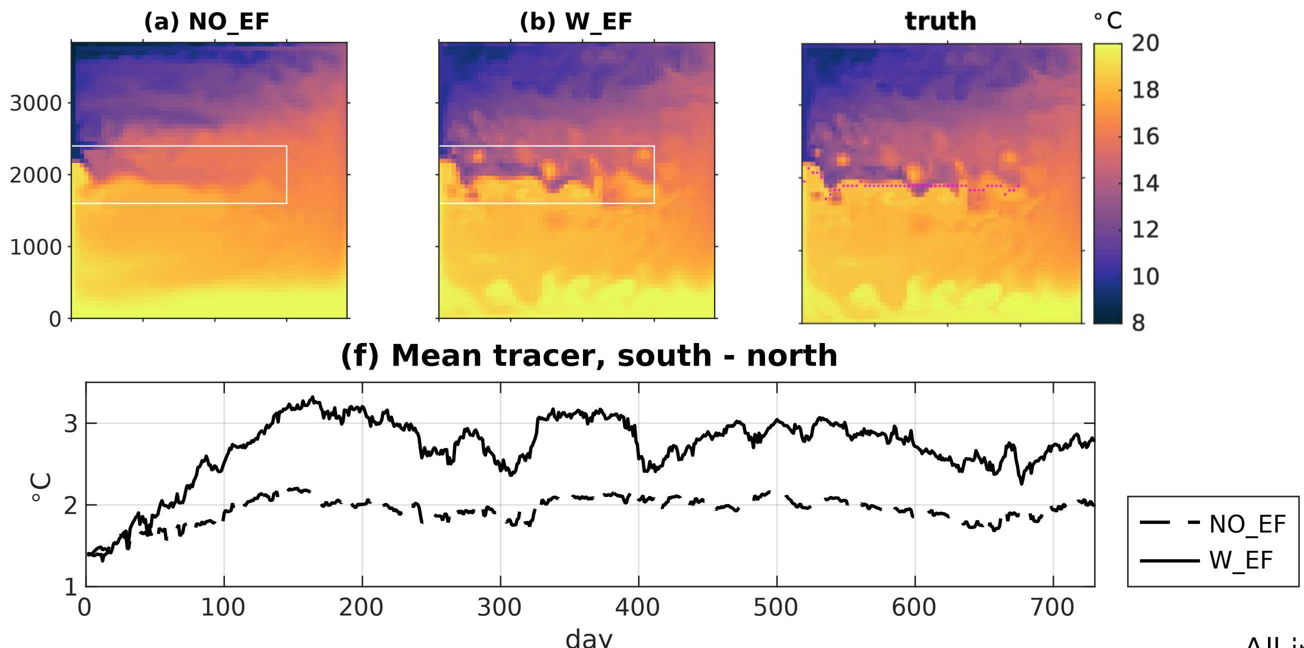
Eddy-induced frontogenesis

- Tracer experiments with different forcing $\mathcal{D}$ **on the coarse grid**:

$$\partial_t(h_L c) + \nabla_L \cdot (\mathbf{U}_L c) = \mathcal{D} + A + R$$

- *EF* augments the solution toward the **truth** (coarse-grained fine-grid solution)
- The front is ~50% stronger in the presence of eddy effects (W_EF) than NO_EF

NO_EF: $\mathcal{D} = 0$
W_EF: $\mathcal{D} = EF$



Front magnitude: difference between tracers averaged in the S and N of GS core (magenta dot)

All in the upper layer

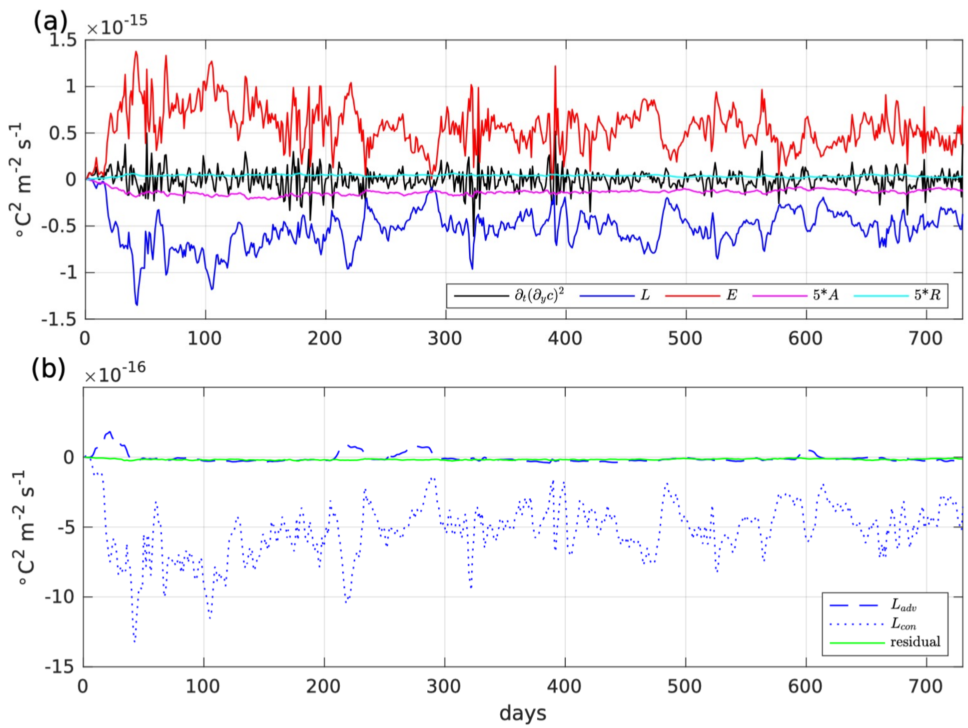
Competition with large-scale currents

- Frontogenesis equation:

$$\partial_t(\partial_y c)^2 = L + E + A + R$$

L: large-scale (residual) flow ($\mathbf{u}_L = \mathbf{U}_L/h_L$) effect on front, *E*: eddy effect (*EF*), *A*: diffusion, *R*: relaxation.

Terms averaged in the frontal region vs. time



E > 0: sharpening front (frontogenesis)

L < 0: weakening front (frontolysis)

$L = L_{adv} + \mathbf{L_{con}}$

$L_{adv} \sim \mathbf{u}_L \cdot \nabla_L (\partial_y c)^2 \sim 0$

$\mathbf{L_{con}} \sim \partial_y \mathbf{u}_L < 0$: proportional to the large-scale velocity gradient (strain)

Effective eddy-induced velocity

- Eddy-induced frontogenesis is an **advective** process
- Describe it by a recently proposed approach (*Lu et al. 2022*):

$$EF = \kappa h_L \nabla_L^2 c - \boldsymbol{\chi} \cdot h_L \nabla_L c$$

where κ a diffusivity, and $\boldsymbol{\chi}$ an eddy-induced velocity (separate from GM velocity)

- Only the component perpendicular to the tracer contours are significant for tracer

$$EF = \kappa h_L \nabla_L^2 c - \chi_\perp h_L |\nabla_L c| \delta_c$$

where $\chi_\perp = \boldsymbol{\chi} \cdot \boldsymbol{n} \delta_c$ is an **effective eddy-induced velocity** (EEIV) -- the speed at which $\boldsymbol{\chi}$ moves tracer contours, ***n*** is the unit vector along tracer gradient.

- δ_c is a sign function ensuring:
  - $\chi_\perp > 0$: $\boldsymbol{\chi}$ has a northward component
  - $\chi_\perp < 0$: $\boldsymbol{\chi}$ has a southward component

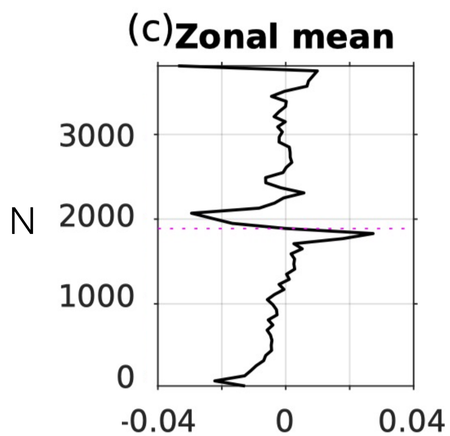
Mechanism of eddy-induced frontogenesis

In the north (south) of the jet, the negative (positive) $\chi_\perp$

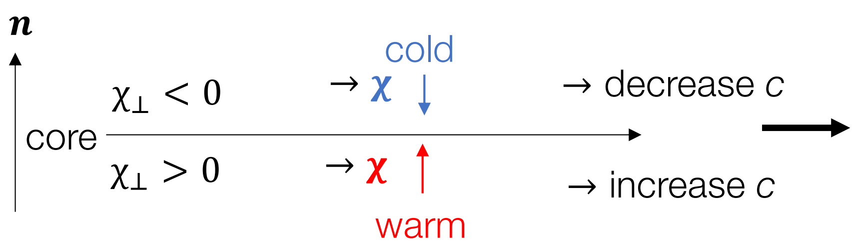
→ implies southward (northward) $\boldsymbol{\chi}$, which

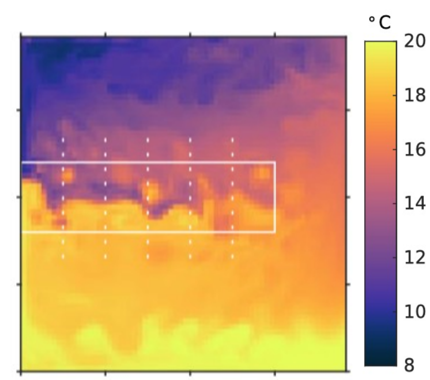
→ squeezes cold (warm) contours southward (northward)

→ sharpens tracer gradients - frontogenesis



Time- & zonal-mean of $\chi_\perp$ diagnosed from *EF*. Dots are GS core.





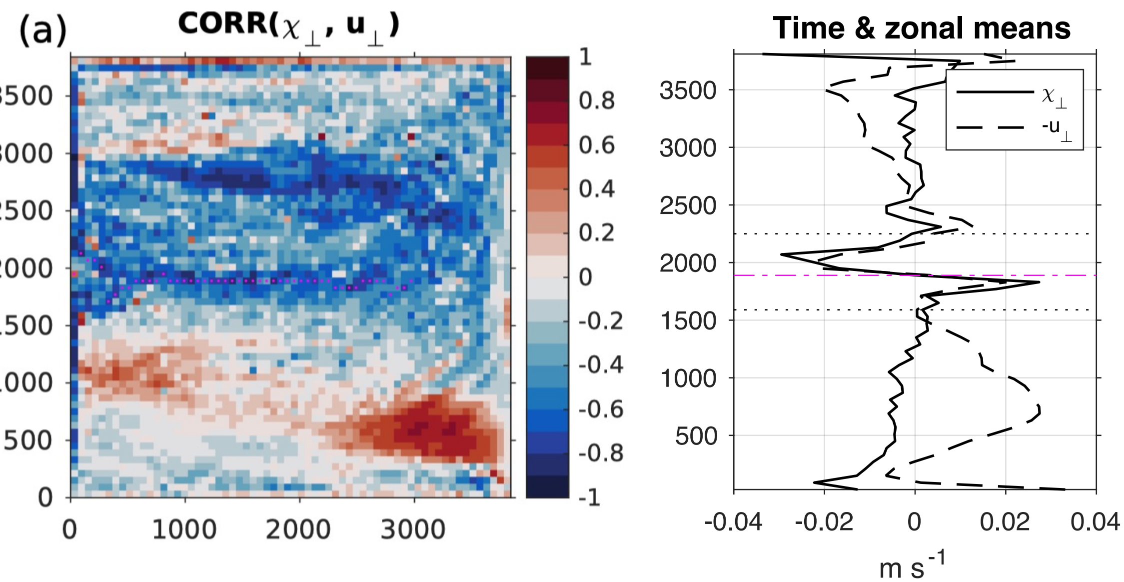
Consistent with the eddy-induced frontogenesis revealed by the experiments and frontogenesis equation.

Closure of $\chi_\perp$

- EEIV is **negatively related** to the effective large-scale velocity (ELSV) →

$$\chi_\perp(y) = -\alpha u_\perp(y)$$

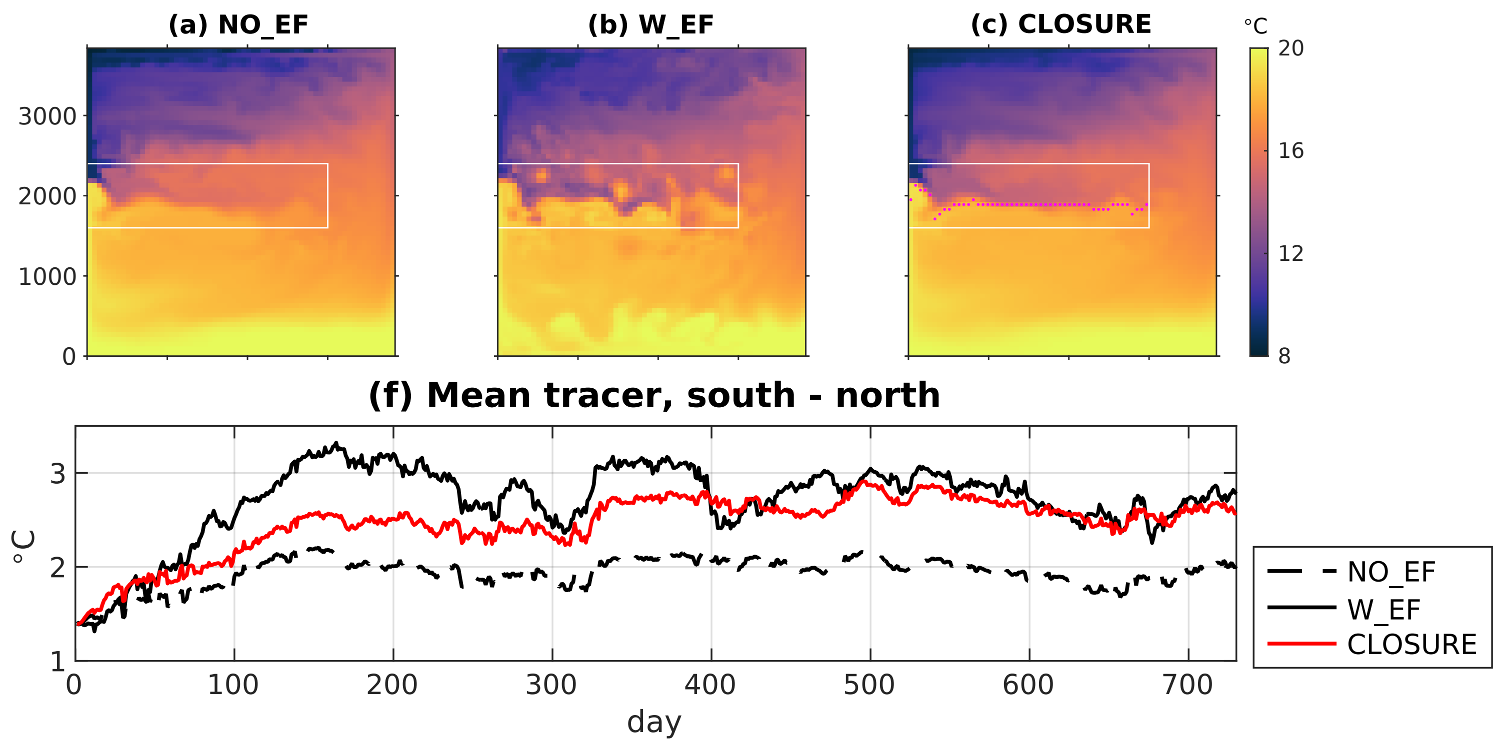
with $u_\perp = \mathbf{u}_L \cdot \boldsymbol{n}\delta_c$ and coefficient α quantifies the compensation between large-scale and eddies



(a) Correlations between $\chi_\perp$ and $u_\perp$ over 2 yrs.
(b) Time-zonal-mean $\chi_\perp$ and $-u_\perp$, which fit well in frontal region 1600 < y < 2400 km

Application to offline coarse-resolution tracer model

- (**CLOSURE**) $\mathcal{D} = \kappa h_L \nabla_L^2 c + \alpha \bar{u}_\perp^{xt} |h_L \nabla_L c| \delta_c$
- $\kappa = 400$ m²/s from an estimate of the domain-mean κ and $\alpha = 2$ by tunning
- $\bar{u}_\perp^{xt}$ is the time- zonal- mean ELSV → predict the time-mean $\chi_\perp$



Summary

- Mesoscale eddies sharpen a **large-scale front** along the eastward jet (e.g., Gulf Stream) by squeezing tracer contours via **eddy-induced advection**
- The large-scale flow counteracts this effect - related to the strain of large-scale velocity
- This compensation leads to a closure for the *effective* eddy-induced velocity in terms of the effective large-scale velocity
- The closure can reproduce the eddy-induced frontogenesis in a coarse-resolution offline tracer model

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