Oceanic Phenomena & Dynamics at the Submesoscale

Jim McWilliams, UCLA

Rotation and stratification matter but are not asymptotically overwhelming (not QG).

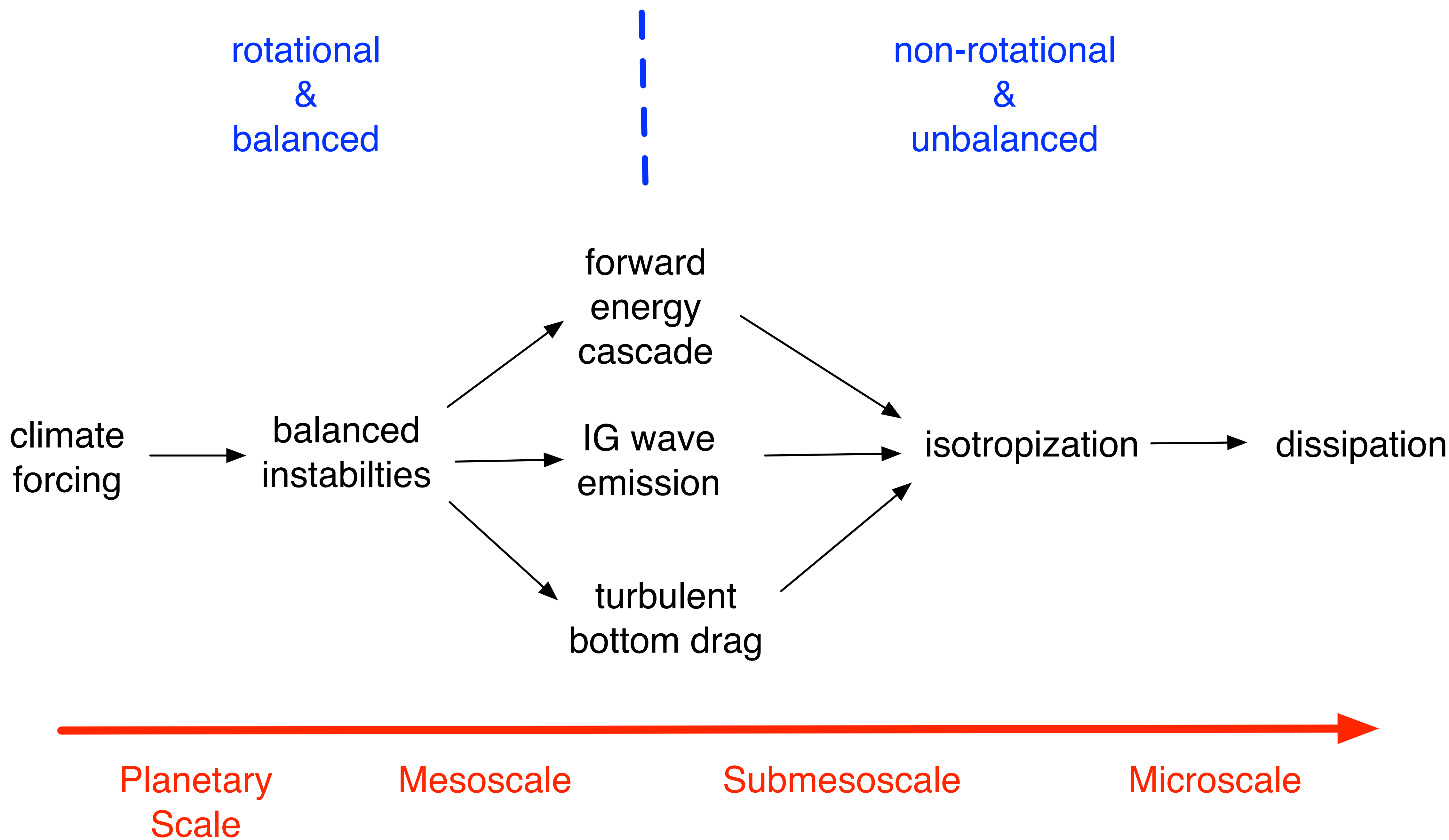
characteristic scales: L ~ 10 m - 10 km
H ~ 10 - 100s m
t ~ hours - days (sometimes much longer in coherent vortices)

- arise out of mesoscale eddies and boundary currents.
- flow structures: surface-layer fronts, filaments, topographic wakes, coherent vortices.
- forward cascades of energy & tracer variance to microscale mixing and dissipation.
- dynamics are mostly advective and partly "balanced" with $Ro = V/fL$, $Fr = V/NH \lesssim 1$.
- strong surface convergences and vertical velocity, hence vertical fluxes.

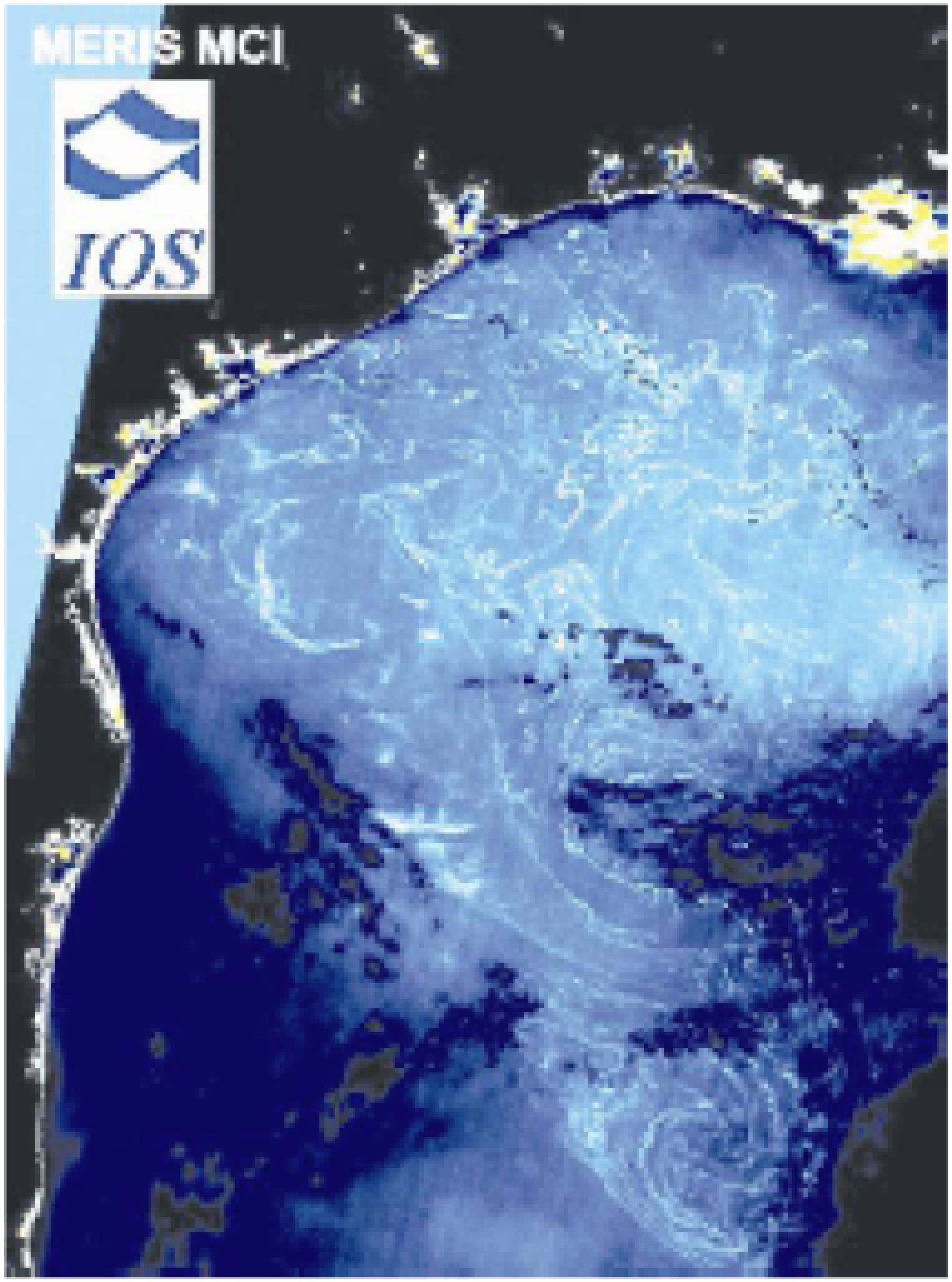
These scales overlap with IGW, which have $V/c < 1$ and completely different energy sources: tides, BL turbulence, wind fluctuations, and sometimes topographic flows.

For years people have falsely imagined this range is mostly IGW and hypothesized strong IGW-mesoscale eddy coupling (e.g., spontaneous emission), but it has been and continues to be illusive, i.e., usually weak.

The Flow of Energy and Information in the Oceanic General Circulation

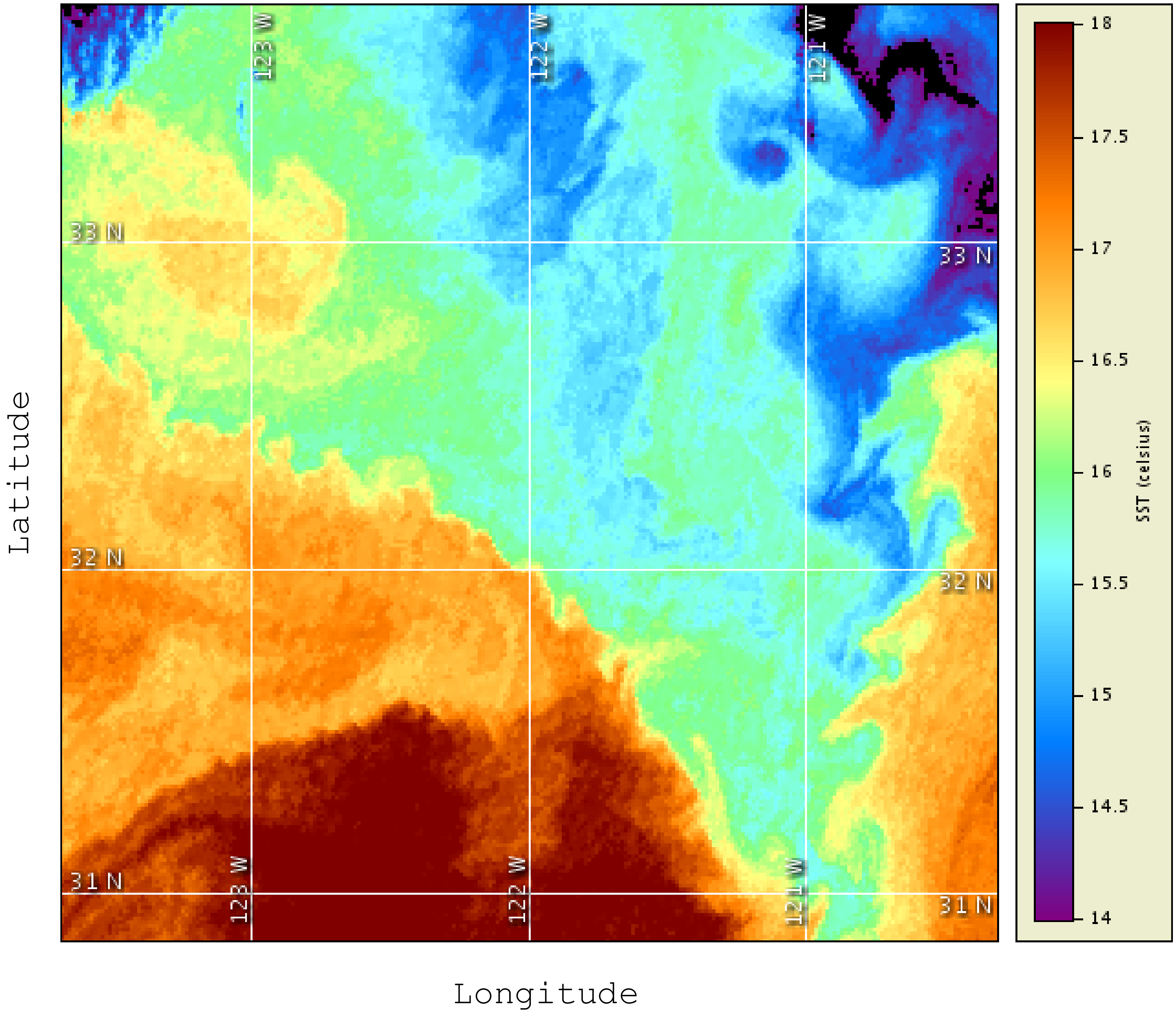


Observed Submesoscale Phenomena



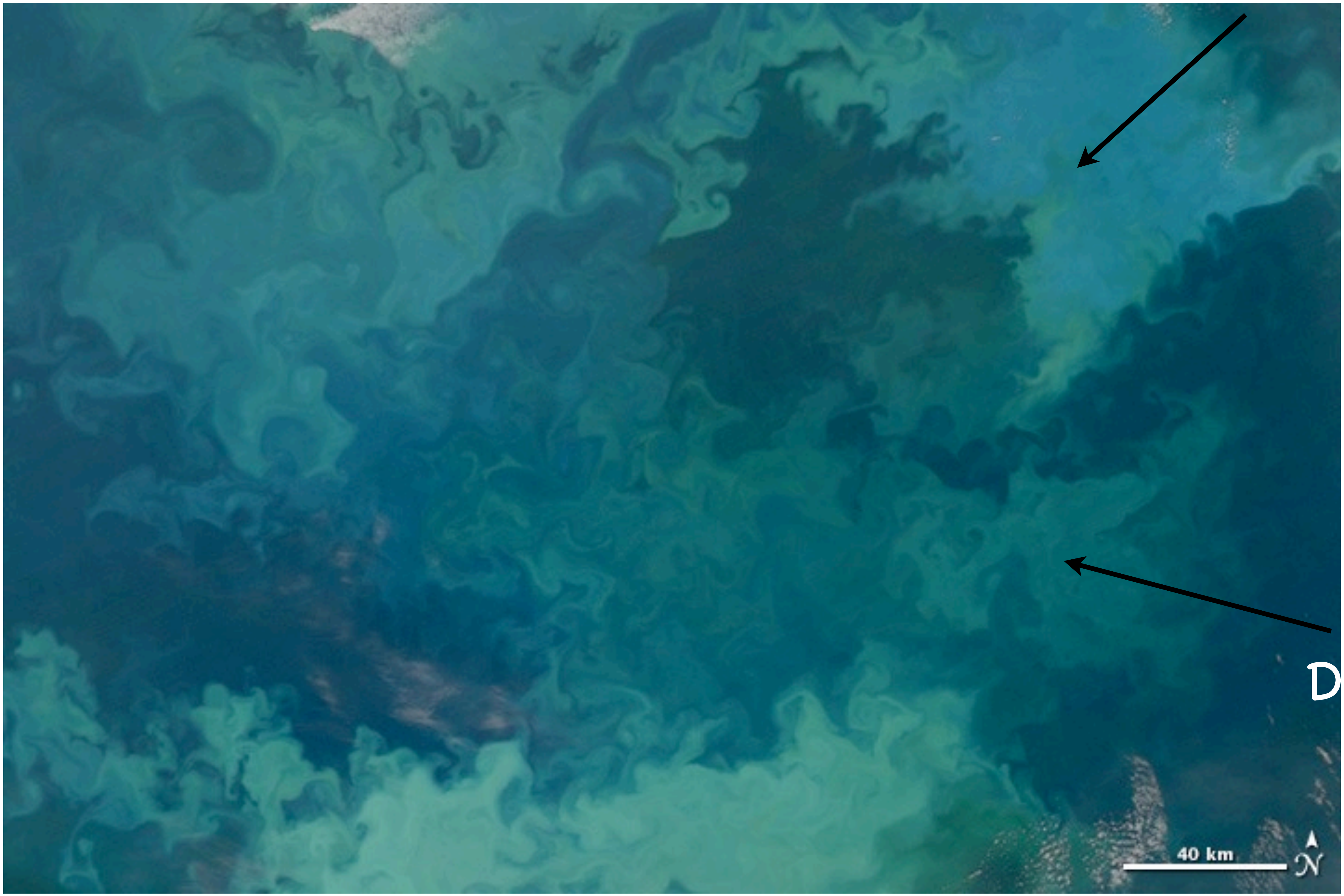
Sargassum lines in a MERCI MCI (Maximum Chlorophyl Intensity) image on June 2, 2005 in the Gulf of Mexico (Gower et al., 2006).

They illuminate abundant submesoscale surface convergence lines especially on the edges of the mesoscale eddies.



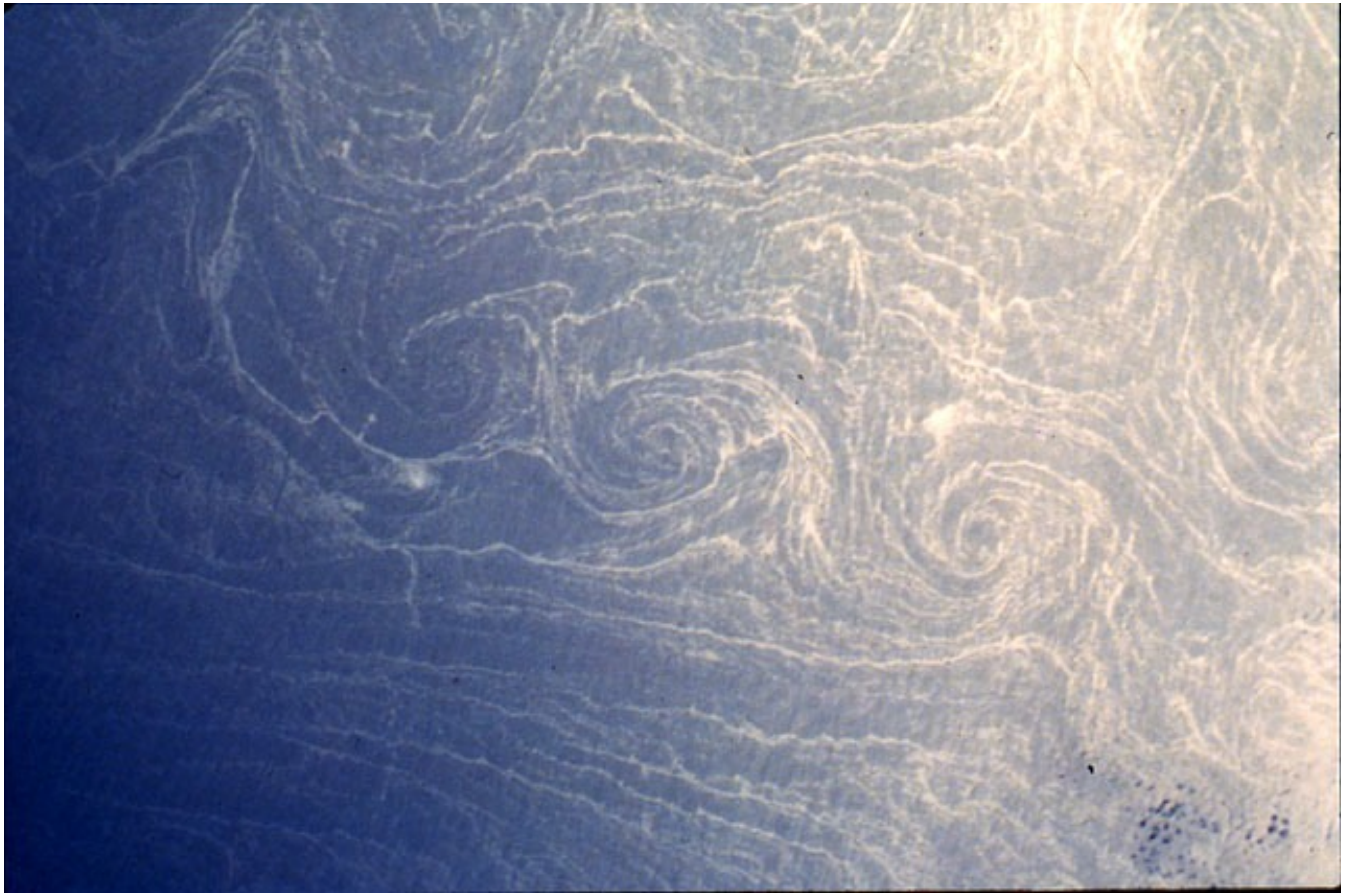
SST [^{o}C] off California (NOAA COASTWATCH): $\lesssim 10$ km submesoscale **fronts, instabilities, and cyclonic vortices** surrounding ~ 100 km mesoscale eddies.

Submesoscale Phytoplankton Structure



Modis (on Terra), August 31, 2010, Barents Sea

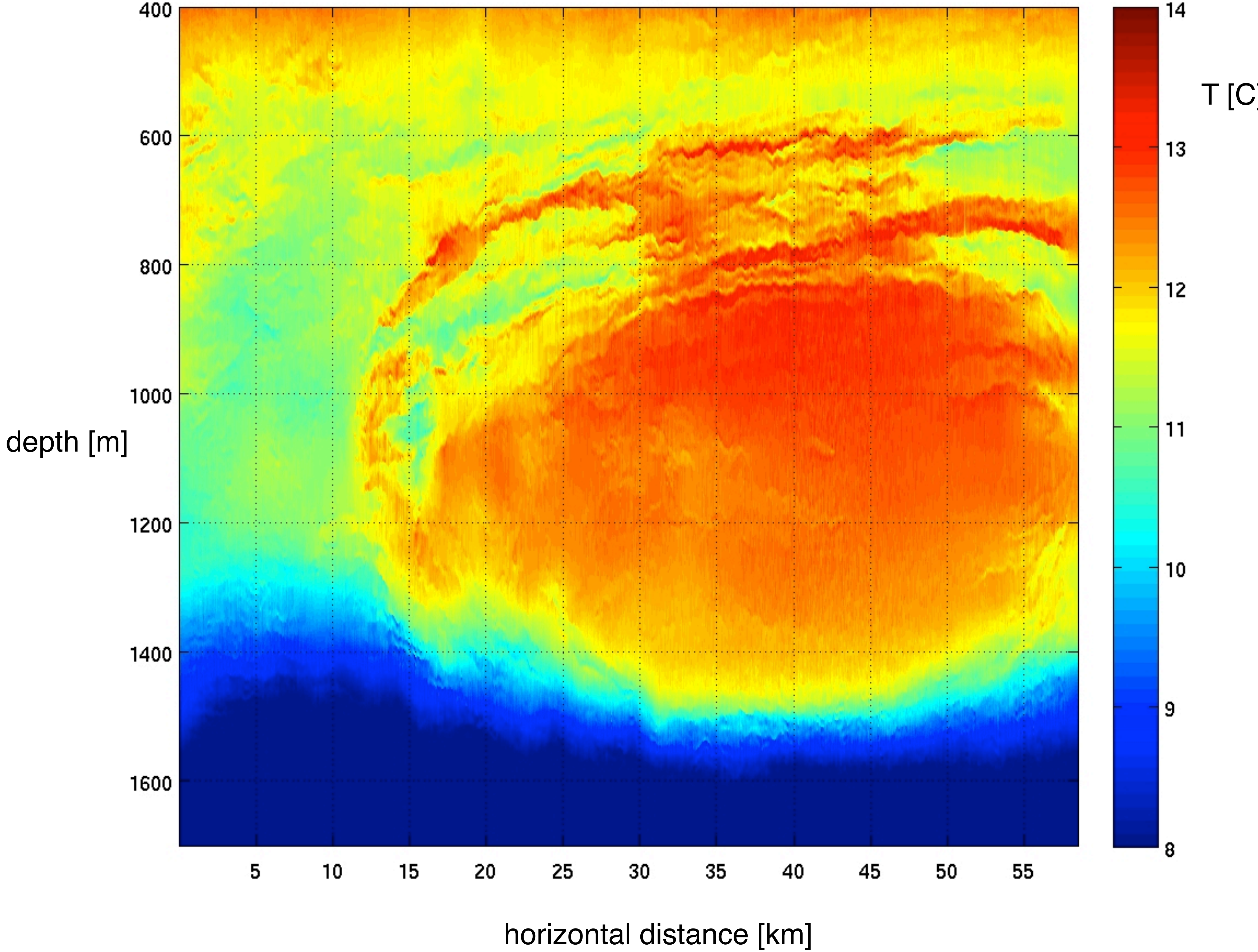
Filaments and Spirals on the Sea

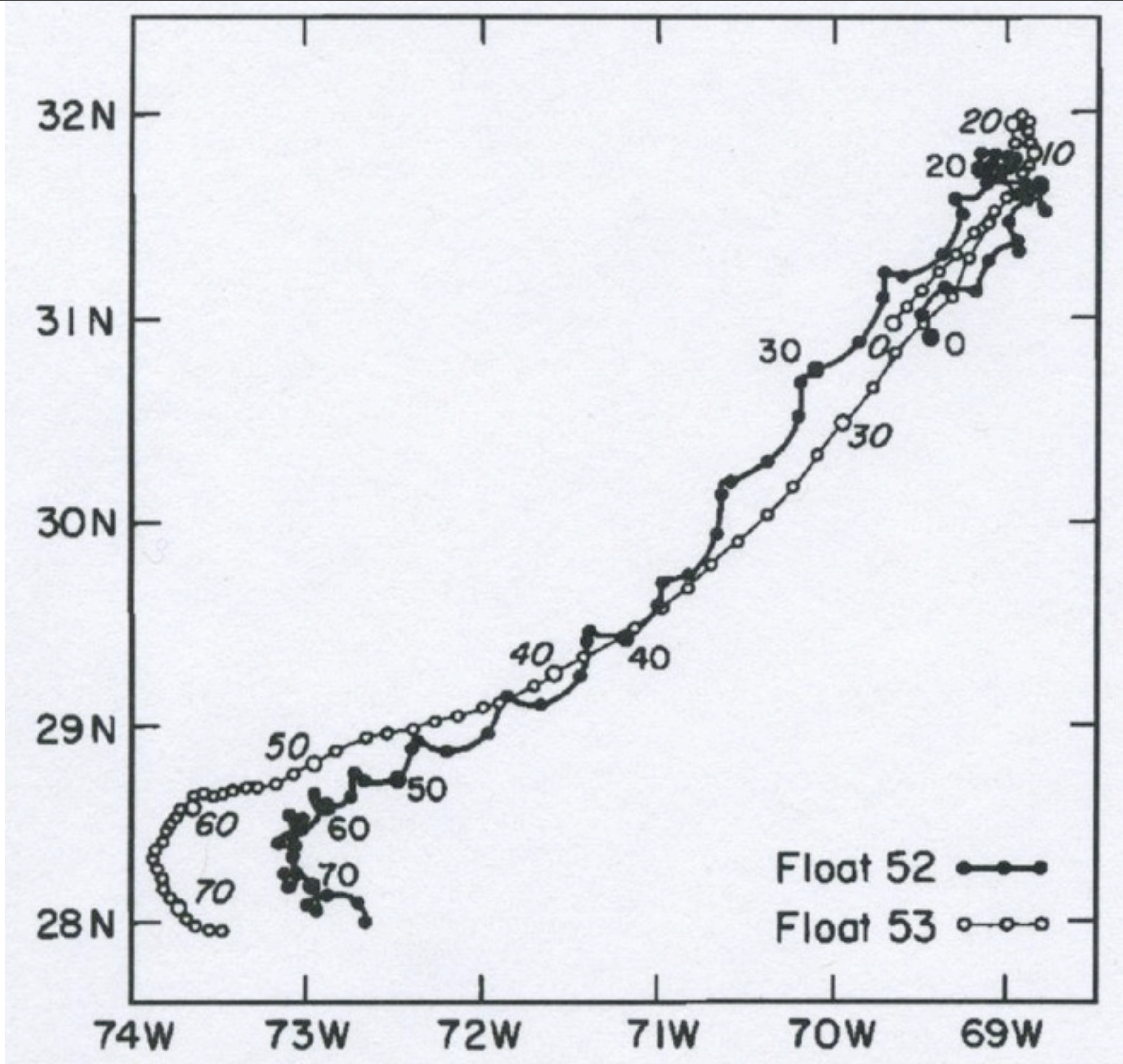


Photograph of a cyclonic spiral-eddy street off the coast of the Egyptian/Libyan border. Eddy radii are ~ 5 km, and scum convergence lines are ~ 100s m wide. The configuration suggests a recent vortex roll-up from an unstable submesoscale shear layer (a cold filament?). [Scully-Power, 1986]

Deepwater Horizon oil trapped in surface convergence lines
in the Gulf of Mexico (see boat for scale)

Mediterranean Submesoscale Coherent Vortex in North Atlantic





Two-month trajectories for 2 isobaric floats at 700 m depth in the Subtropical North Atlantic (Riser et al., 1986). Float 52 is trapped in a small anticyclonic Submesoscale Coherent Vortex (SCV) with ~10 km swirls, while the nearby Float 53 is not. The chemically anomalous water mass in this SCV is preserved in a long lifetime (yrs) and travel distance (1000s km).

Submesoscale Roles in GFD
and
Methodology

Inferences of the Existence of the Submesoscale from its Roles

Forecast Initialization and Balance: Recall Richardson's first NWP failure due to spurious gravity wave initialization. Later NNMI was developed to achieve asymptotically perfect balance, but it often fails to converge. (Present NWP uses ad hoc temporal filters to be "balanced enough".) We now know that the "slow manifold" does not exist, and evolution breaks balance, mostly not by IGW generation but by transfer into partly unbalanced SM eddies.

Geostrophic and Stratified Turbulence: Charney (1971) identified an energy spectrum E(k) $\sim k^{-3}$ at large k without small scale sources, and an inverse energy transfer function, Π (k) < 0. Lilly (1983) conjectured $\Pi < 0$ and $E \sim k^{-5/3}$ with balanced flow and a small scale source (deep convection in the atmosphere). Both are wrong in nature. Spontaneous SM emergence gives $\Pi > 0$ and $E \sim k^{-2}$ (surface fronts/filaments) or $k^{-5/3}$ (interior).

Global Energy Cycle: Planetary scale generation must connect to microscale viscous dissipation. This cannot happen with $\Pi < 0$. Vertical turbulent boundary layers are not enough. Energy transfer to IGW seems to be not enough (except perhaps in ACC). => SM route to dissipation.

Thermohaline Circulation: Sustaining global rate of 10s Sv requires interior diapycnal mixing $\kappa > 10^{-5}$ m^2 s^{-1}. Breaking IGWs do some of this, but probably so does the SM $\Pi > 0$.

Global Model Regularization: No general circulation model can be run stably without mixing and dissipation provided by "eddy diffusion" κ usually chosen in an hoc way for acceptable smoothness. For a coarse climate model, κ represents the mesocale, and for eddy-resolving models, the SM effects.

...and, with lesser force, sustained ecological productivity by SM vertical flux across the nutricline.

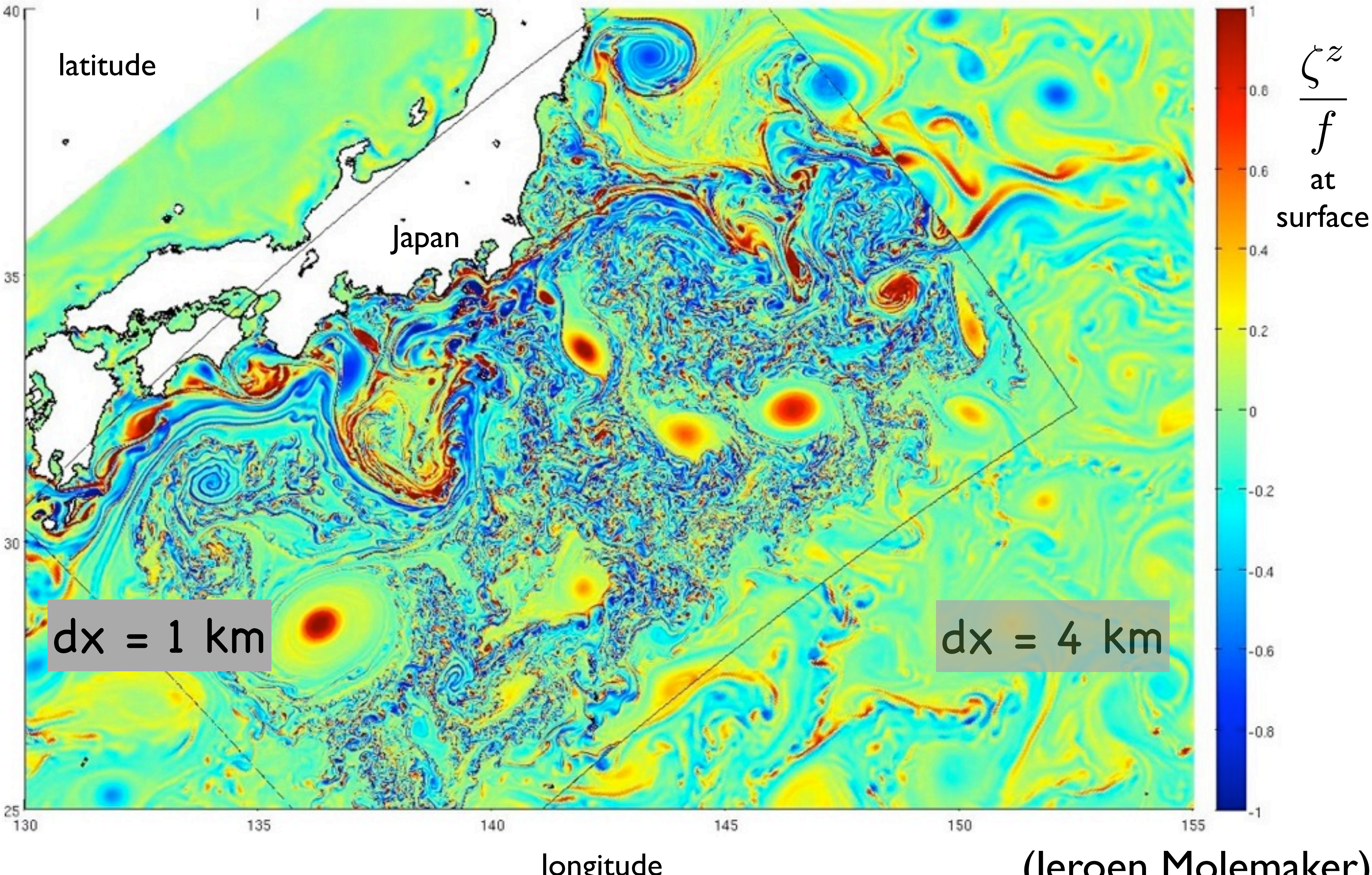
Accepting the incompleteness of present and probably future measurements for the SM, this brings us to **theory** and **modeling**.

Pure theory is limited, as all pure theories of turbulence are, but modeling is very powerful.

The key computational technology is multiply-nested, open-boundary grids run to a statistical equilibrium to be able to combine the necessary larger- and mesoscale dynamical controls --- usually starting on the basin scale --- with consistent finer scales of the SM.

The common experience is that SM currents spontaneously emerge when the grid resolution is increased in rotating, stratified flows.

Winter time Kuroshuo: Increased resolution



(Jeroen Molemaker)

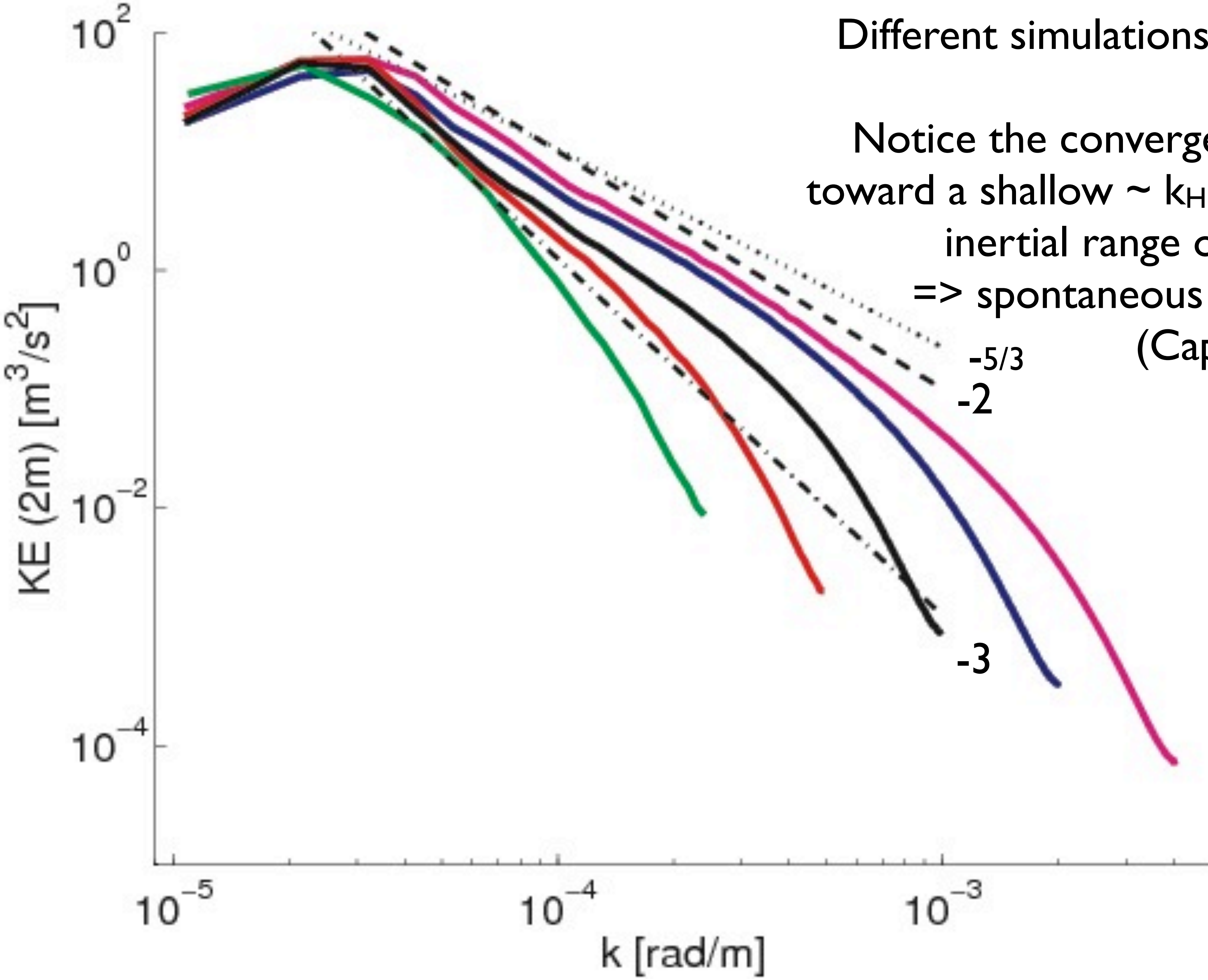
Breakdown of Geostrophic Turbulence

How do Submesoscales Break Geostrophic Turbulence?

Horizontal kinetic energy spectra near the surface in an idealized eastern boundary upwelling current system.

Different simulations with dx = 12, 6, 3, 1.5, 0.75 km.

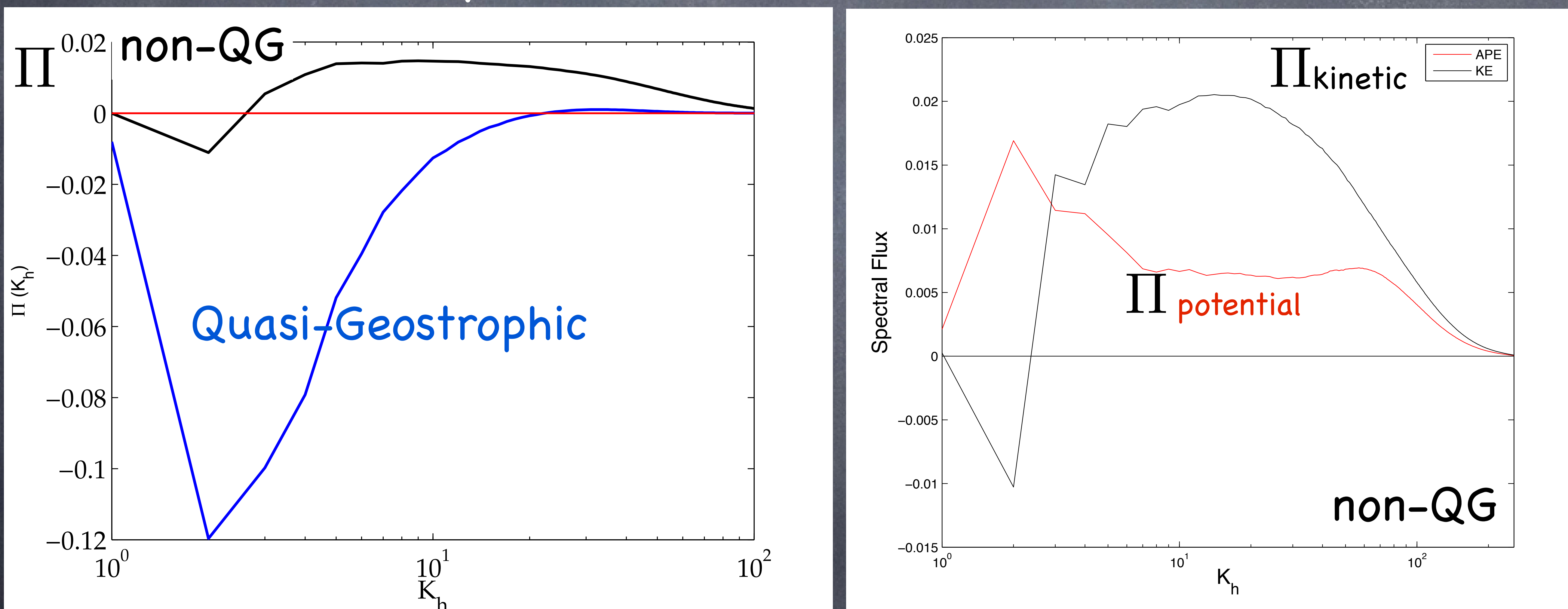
Notice the convergence with increasing resolution toward a shallow ~ k_H^{-2} shape, not the ~ k_H^{-3} enstrophy inertial range of geostrophic turbulence.
=> spontaneous loss of balance with $\prod$ > 0.
(Capet et al., 2008)



[In flows without surface fronts, the SM spectrum shape is ~ $k_H^{-5/3}$]

Why are submesoscales important?

Ageostrophic currents provide a forward cascade of energy towards dissipation in an equilibrium Eady U(z) flow



Spectral flux of energy for QG and non-QG turbulence

(Molemaker et al., JFM 2010; Molemaker & McWilliams, JFM 2010)

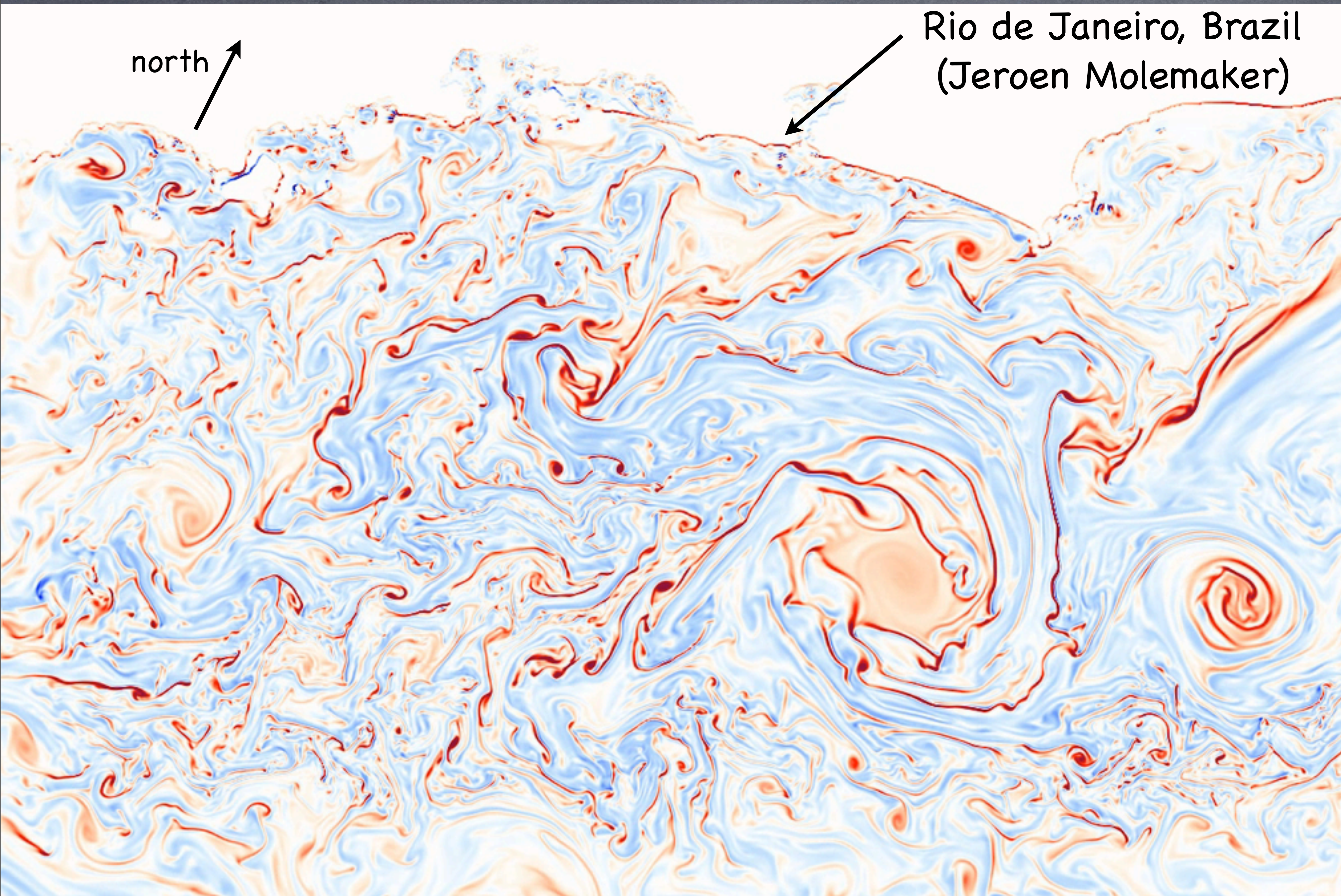
Submesoscales in Motion

Simulated Surface Relative Vorticity

north

Rio de Janeiro, Brazil
(Jeroen Molemaker)

Simulated Surface Relative Vorticity



Uniformly released surface particles + SST evolving over 10 days in the winter Sargasso Sea
=> trapping into submesoscale frontal convergence lines between mesoscale eddies

(Molemaker et al., 2013)

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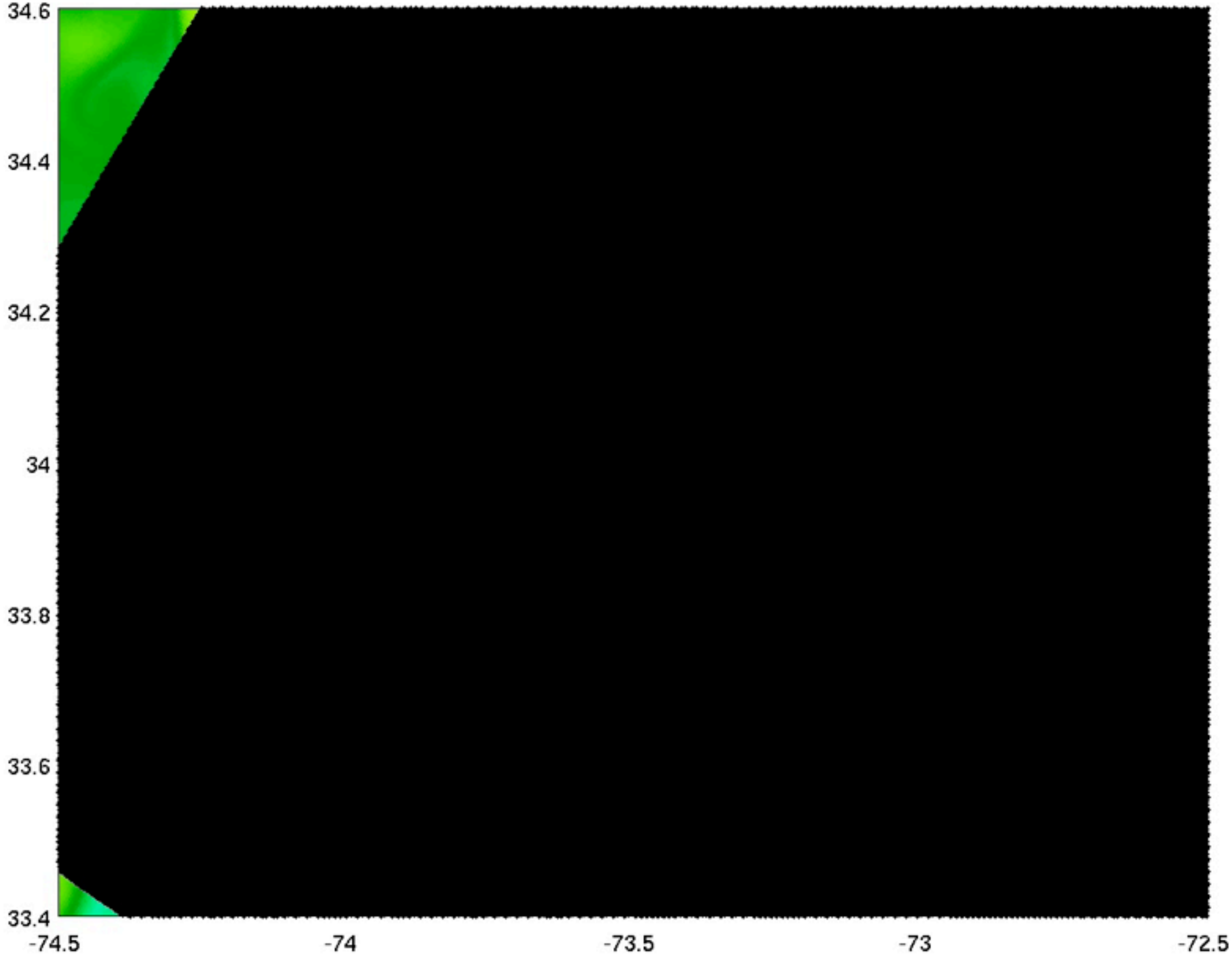


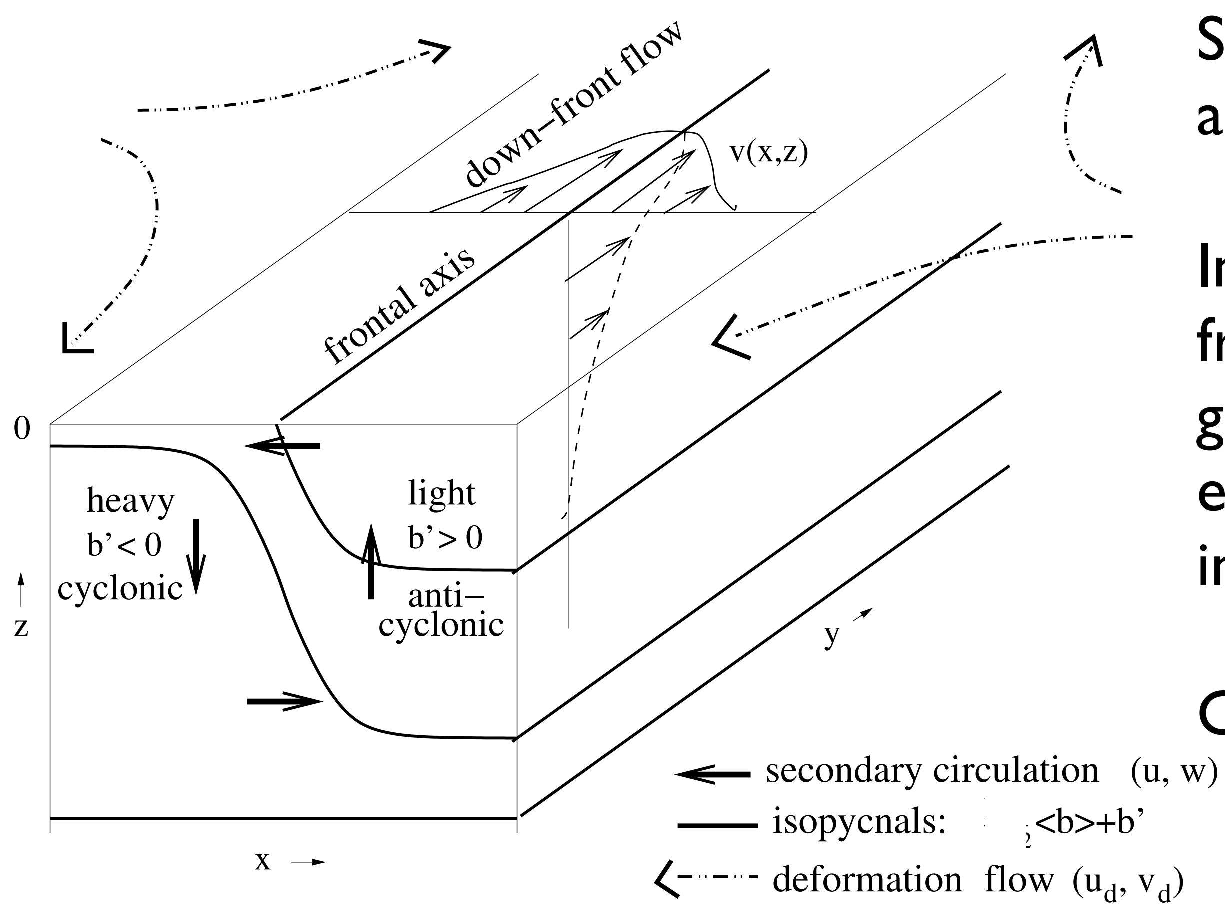
(Molemaker et al., 2013)

Frontal and Filamentary Processes

Schematic depictions of the flow and buoyancy structure associated with **fronto-** and **filamento-gensis**.

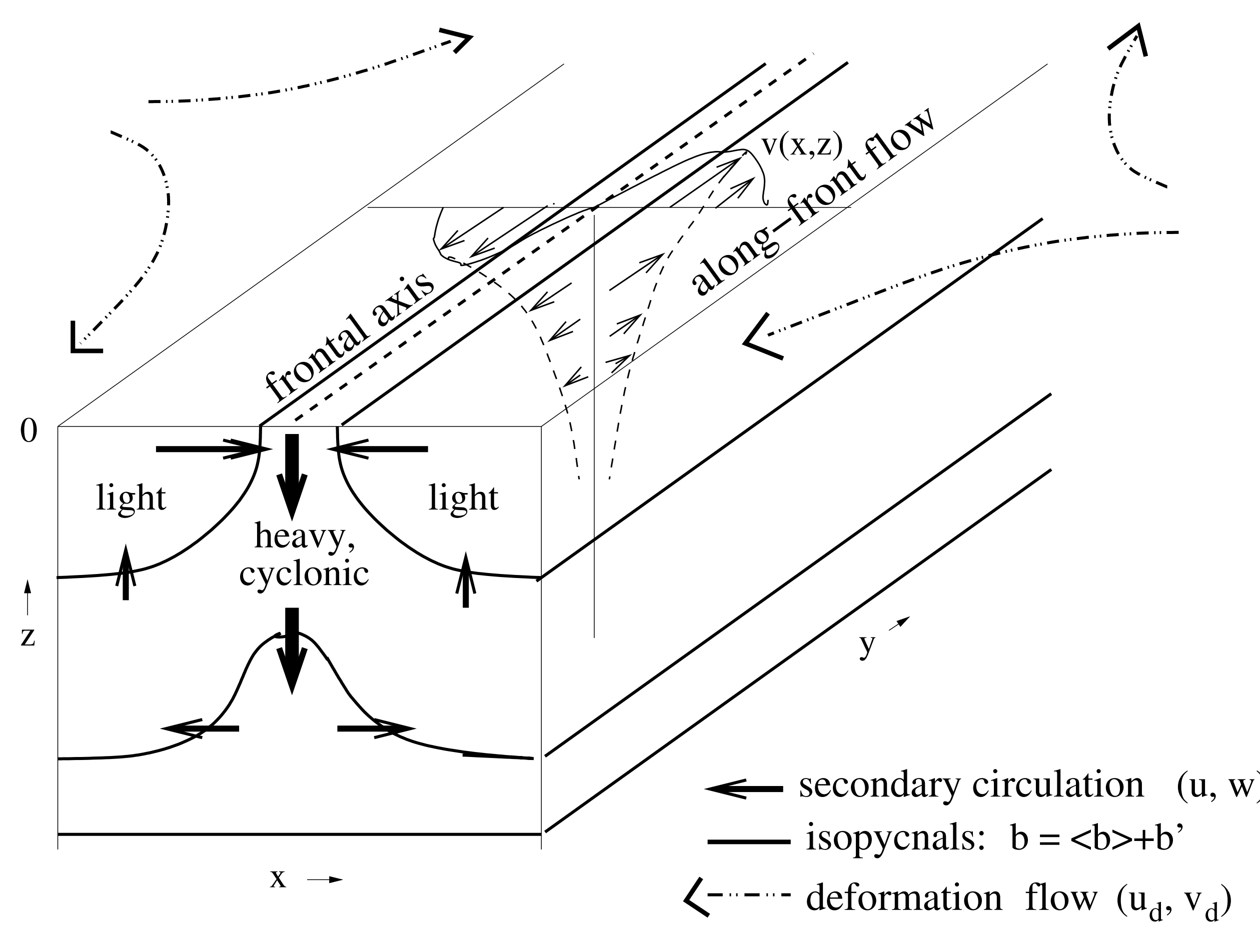
In the presence of a confluent deformation flow, a cross-frontal secondary circulation spins up & buoyancy gradients and velocity shear sharpen at a super-exponential rate in time until limited by some arresting instability and turbulent equilibration.

Cyclonic ζ^z and downward w are favored, & $\overline{wb} > 0$.



front

filament



Turbulent Thermal Wind

$$-fv = \frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(K\frac{\partial u}{\partial z}\right)$$

$$fu = \frac{\partial p}{\partial y} + \frac{\partial}{\partial z}\left(K\frac{\partial u}{\partial z}\right)$$

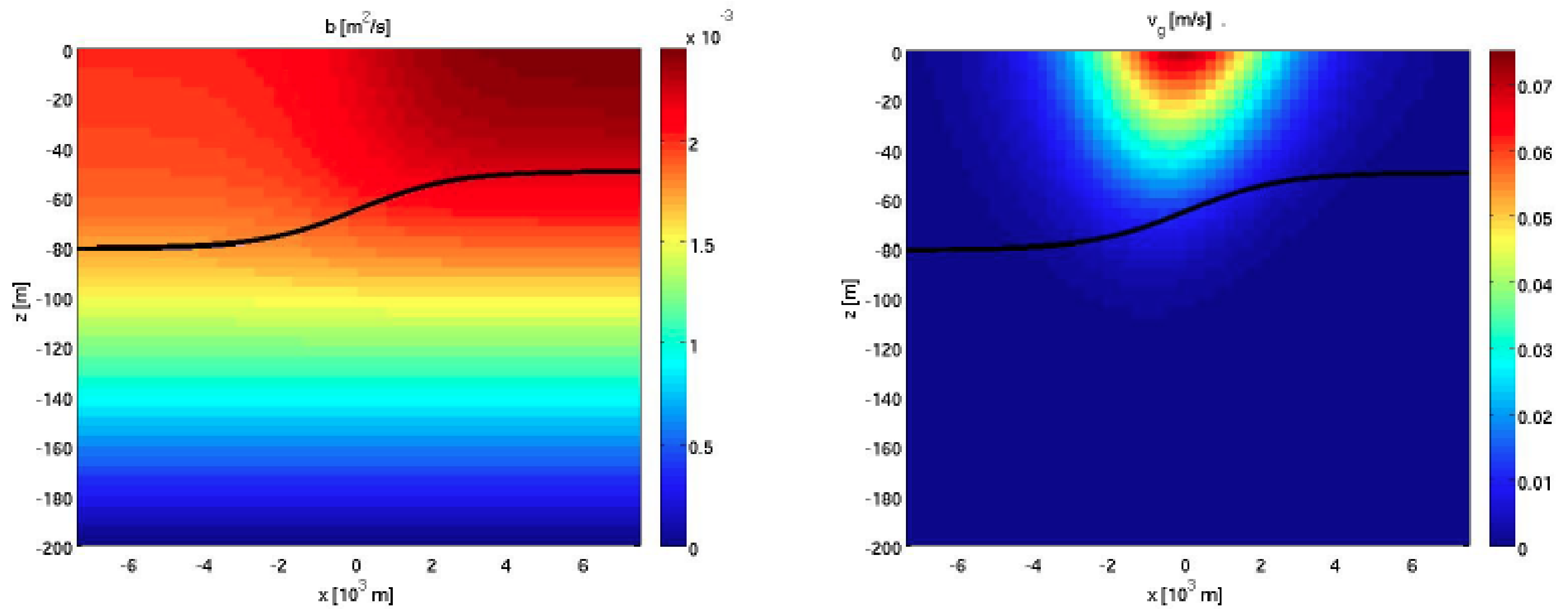
$$\frac{\partial p}{\partial z} = b$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

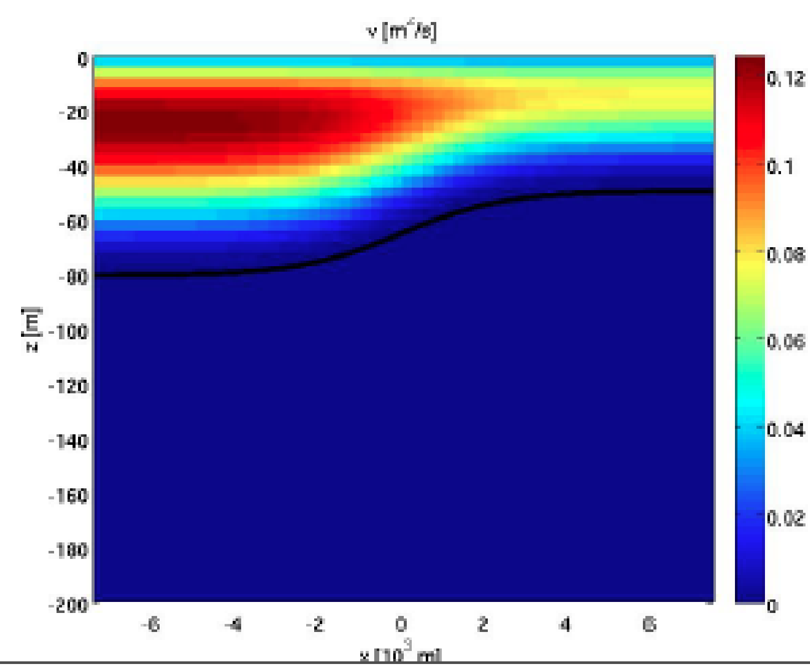
For a given b(x,z) near the surface and BL turbulence with eddy viscosity K, an ageostrophic (u,v)(x,z) will be generated in addition to thermal wind v(x,z). Its horizontal divergence will generate a w(x,z) that mimics the secondary circulation pattern for a front or filament in a deformation flow, even without that flow; e.g., downwelling in a cold filament.

Illustrations for a Straight Front

Define a $b(x,z)$ and $(\nu,\kappa)(x,z)$ based on a boundary layer depth $z = -h(x)$ where the stratification transitions from strong in the interior to weak in the surface layer.



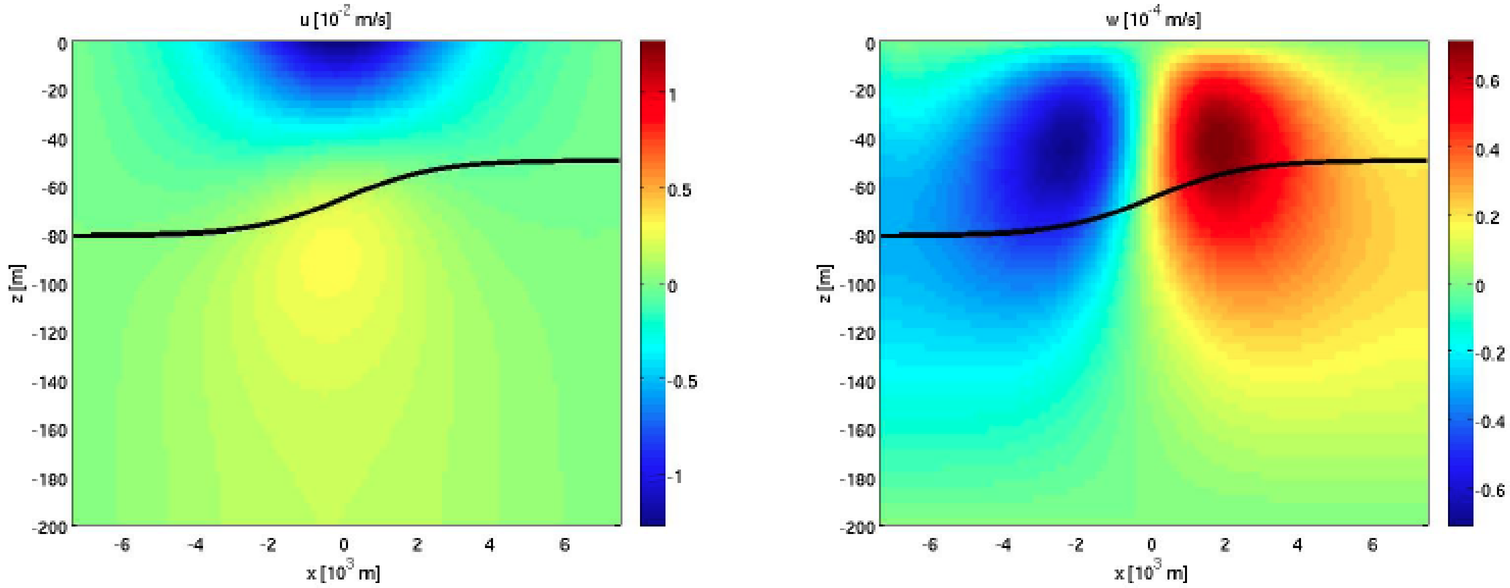
$b(x,z)$ [m s^{-2}] and alongfront geostrophic velocity $v_g(x,z)$ [m s^{-1}]. The black line denotes the boundary layer base at $z = -h(x)$.



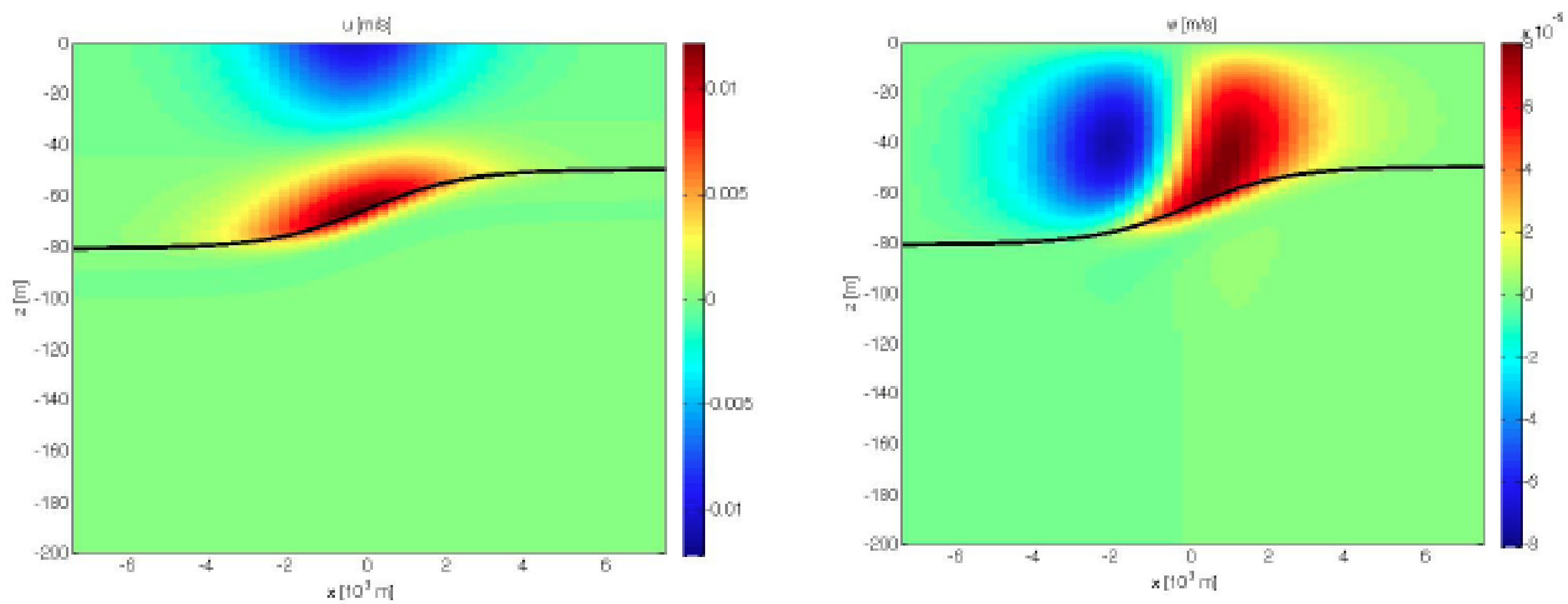
Eddy viscosity across a front based on a K-Profile Parameterization scheme with $K = \nu(x,t)$ = u* h G(z/h).

h is deeper on the dense side because the stratification is weaker there.

Secondary Circulation around a Front

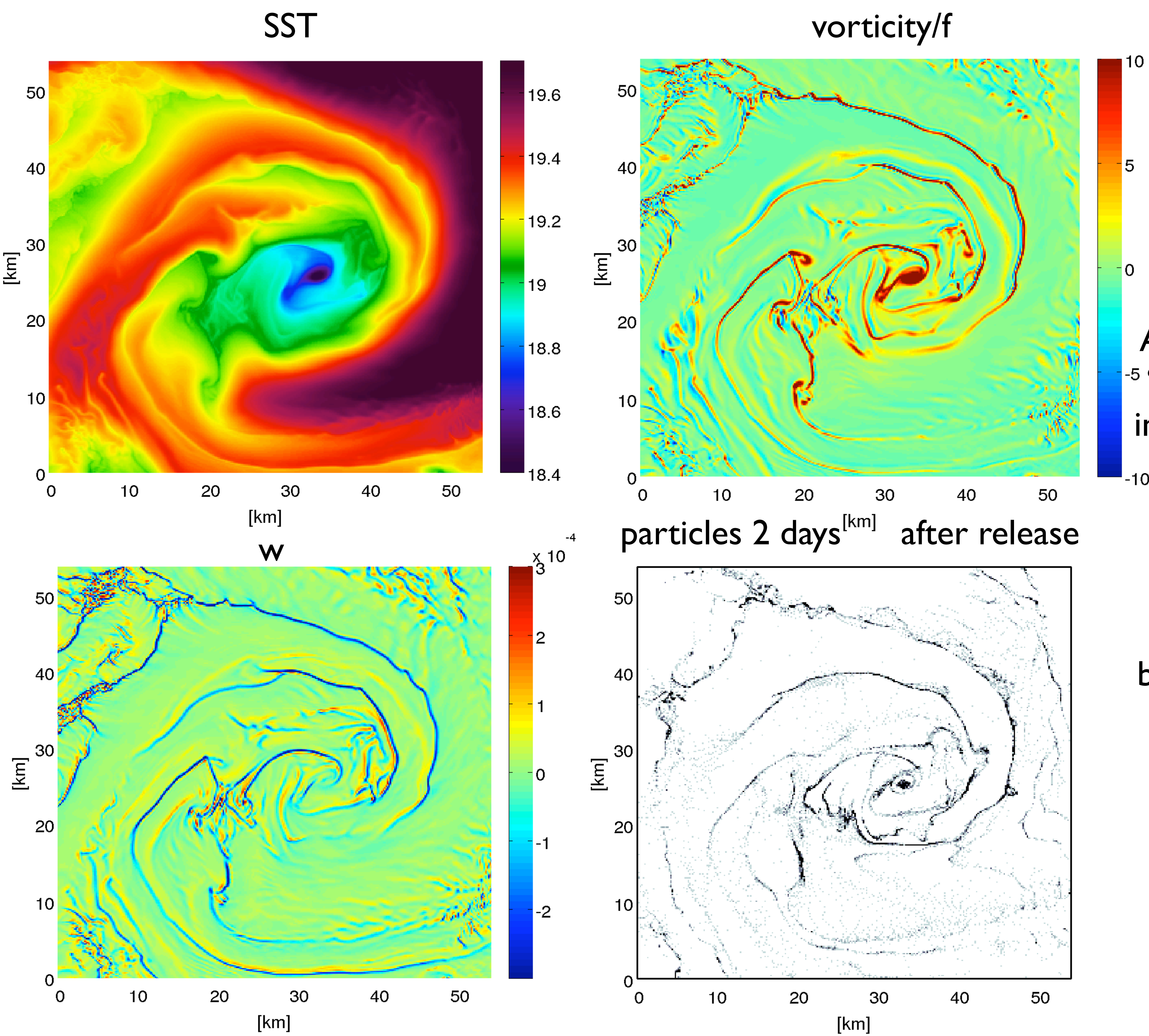


Secondary circulation [ms^{-1}] for a front in an external deformation flow with $\alpha = 1 \times 10^{-5}$ s^{-1}. The black line denotes the boundary-layer base at $z = -h(x)$.



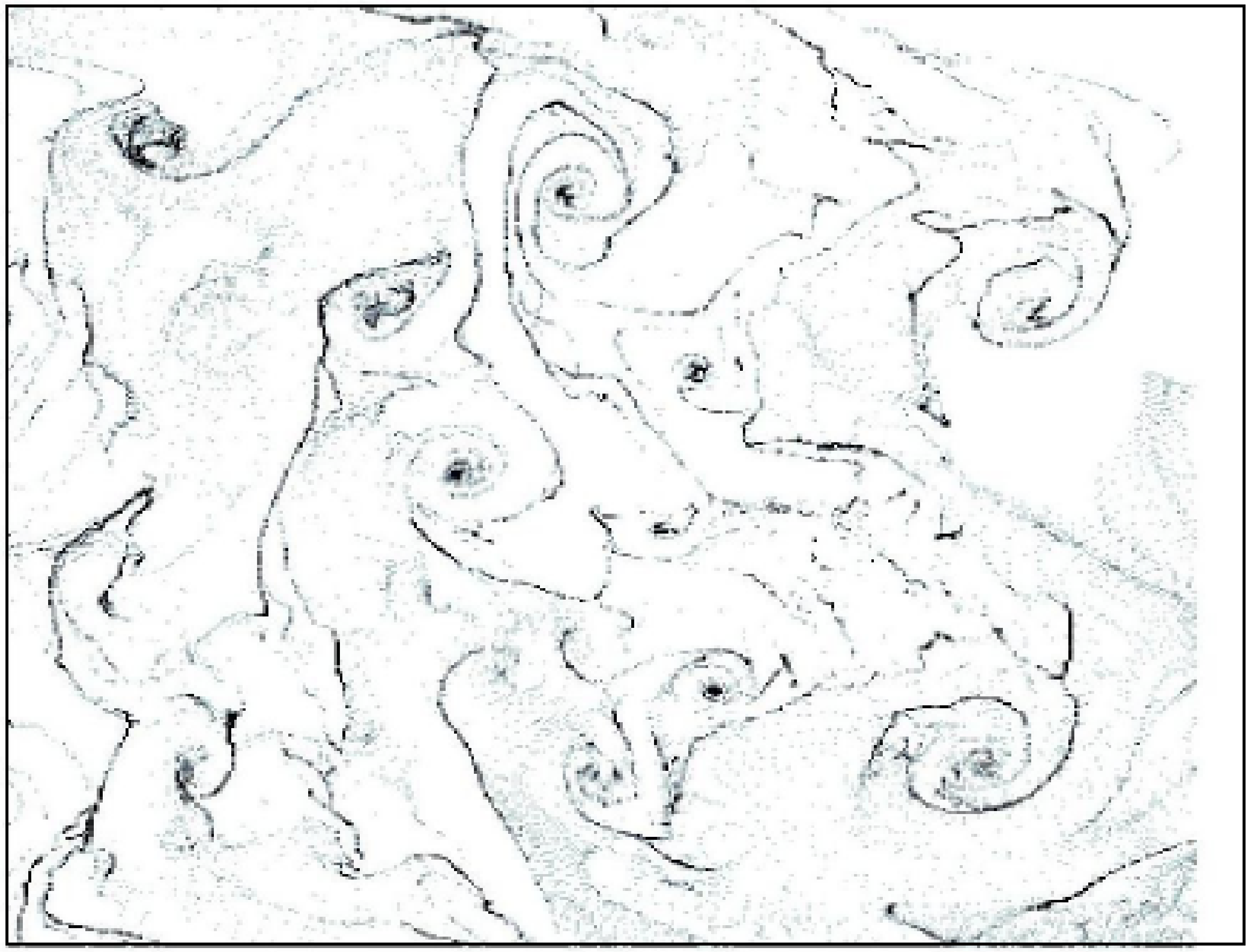
Secondary circulation [ms^{-1}] for a front with the spatially variable eddy viscosity, $K = \nu(x,t)$.

Peruvian Filaments and Spiral Vortices

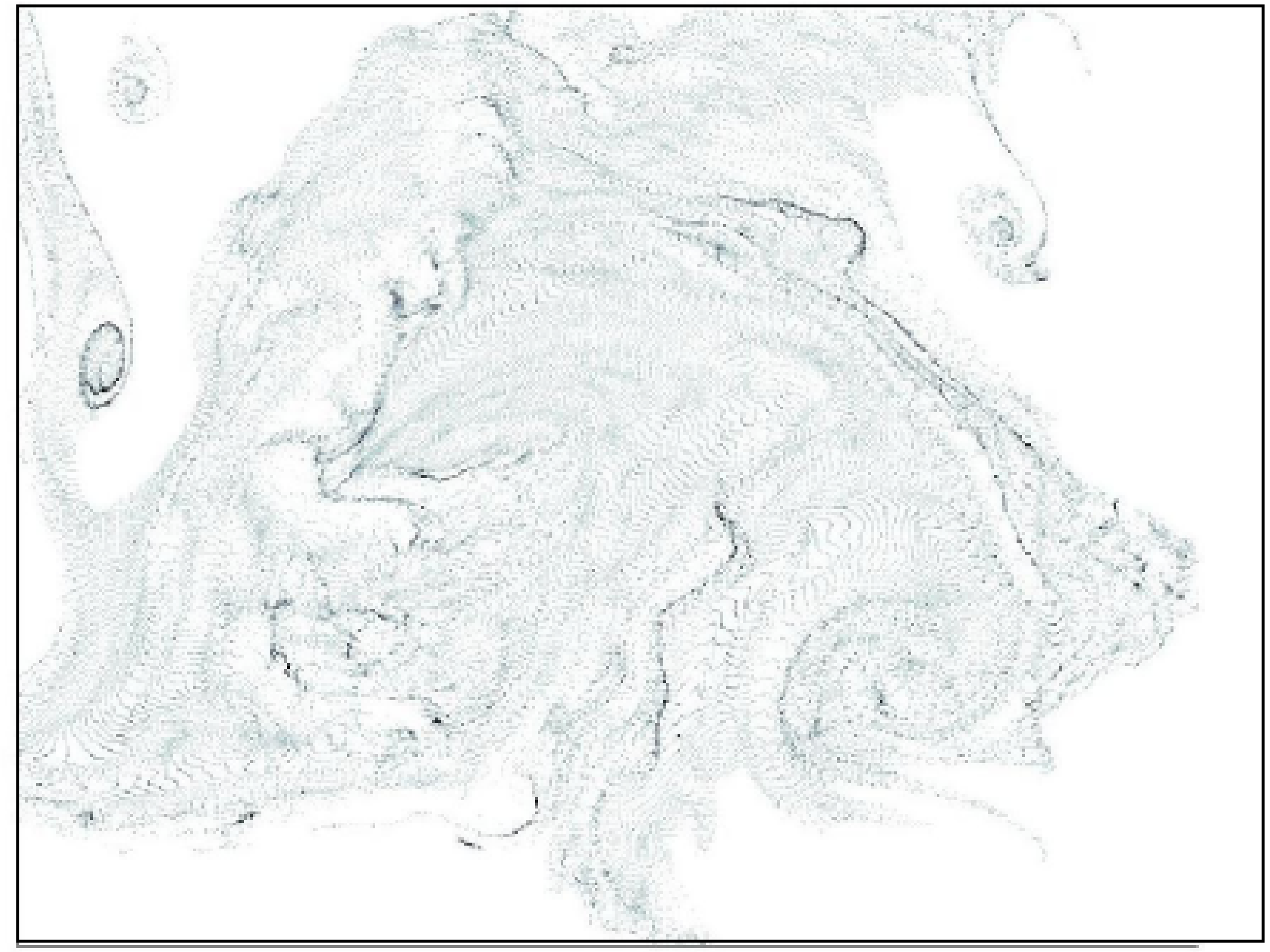


A spontaneously arising "**spiral on the sea**" in the Humbolt Current: a submesoscale cyclonic vortex with cold-filamentary spiral arms, downwelling w, buoyant surface particle convergence into the arms.
(Colas et al., 2013)

Peru - Winter

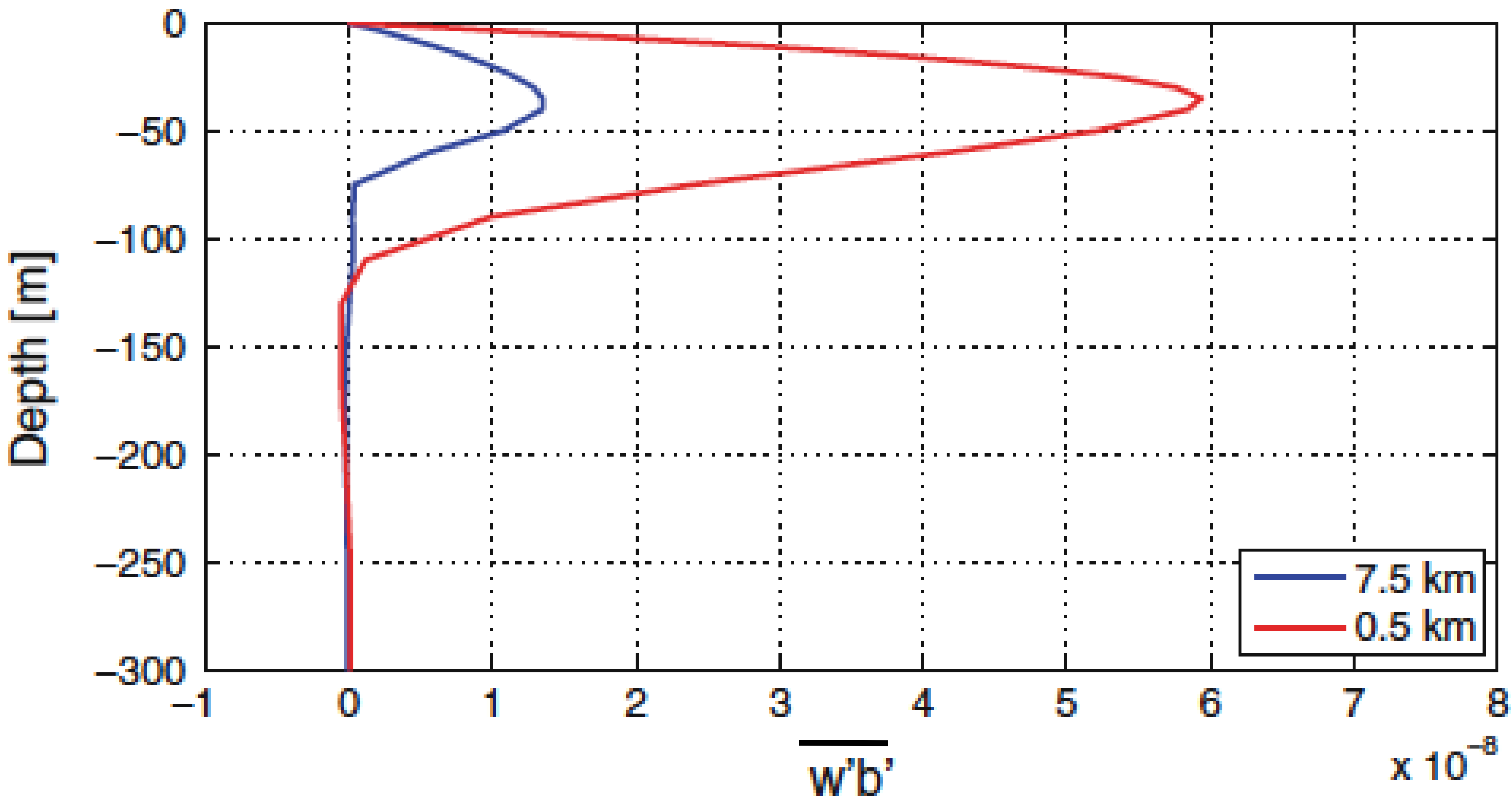


Peru - Summer



Randomly released buoyant **particle convergence** into surface filaments and spirals in the Humbolt Current.

Notice the big **seasonal contrast** in submesoscale activity associated with depth of mixed layer: more SM in the winter with bigger h. (Colas et al, 2013)



Vertical profiles of vertical buoyancy flux [m^2s^{-3}] in July off Peru in two simulations with mesoscale or submesoscale grid resolution, dx = 7.5 or 0.5 km, showing emergence of submesoscale **restratification** flux (Colas et al, 2011). Surface-layer buoyancy balance:

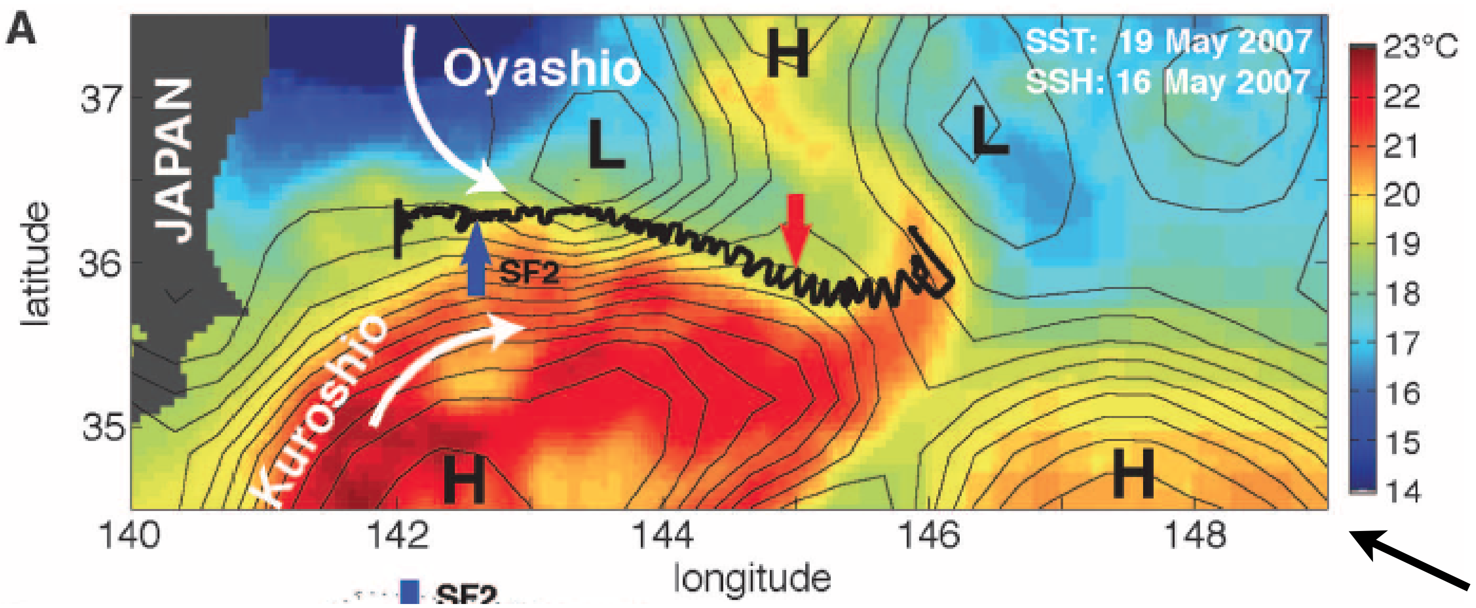
$$\partial_t \overline{b} = \mathrm{BL\ turbulence}\ -\ \partial_z \overline{w'b'}\ + \mathrm{Ekman\ pumping}$$

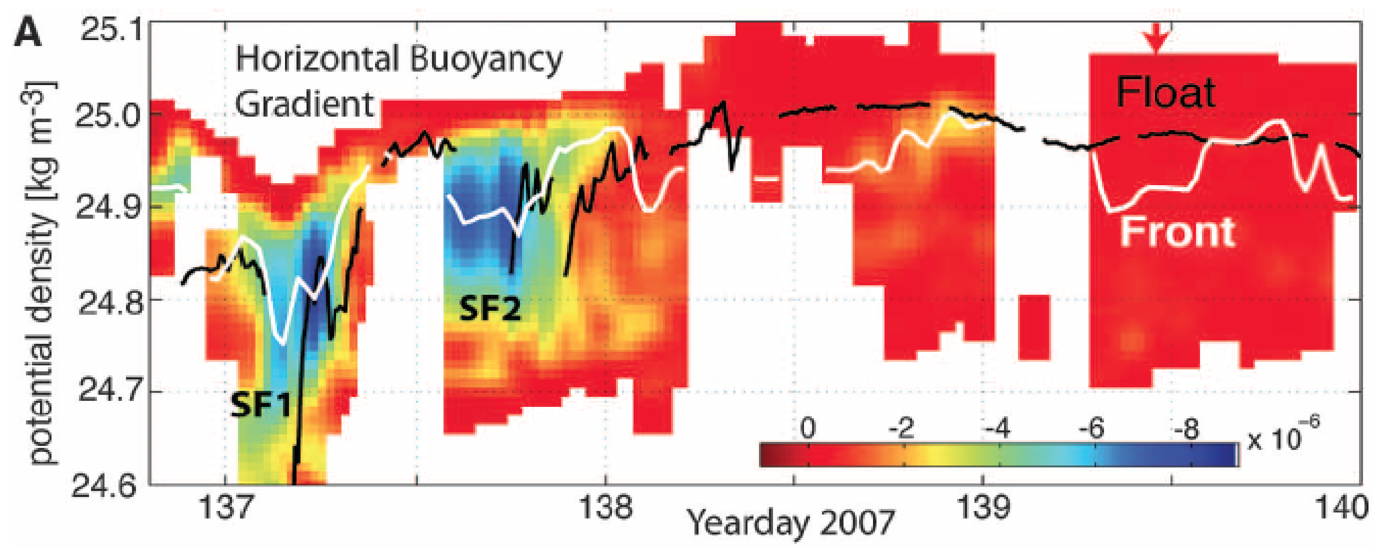
This is a equivalent to a buoyancy advection by a shallow overturning cell of eddy-induced Lagrangian mean flow (**bolus velocity**) [cf., mesoscale eddy cells in the pycnocline].

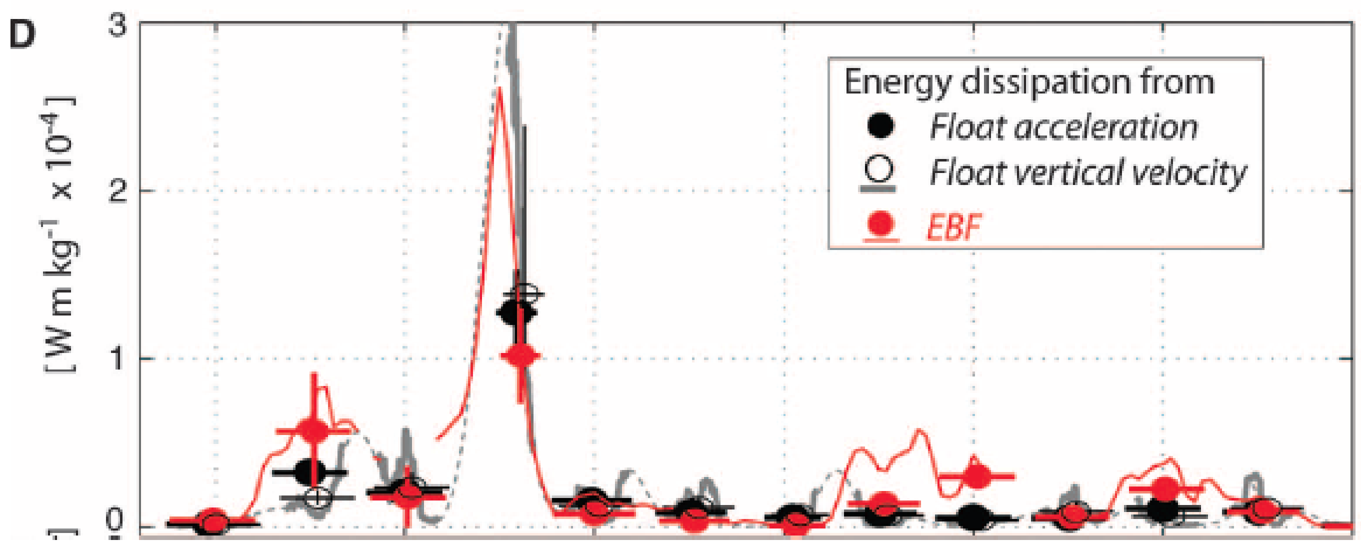
Other materials also have big SM fluxes in the surface layer.

Submesoscales in Strong Currents

Measured Kuroshio frontogenesis and frontal instability







The near-boundary confluent strain sharpens the buoyancy gradient at its northern edge into a front ~ 1 km wide and ~ 30 m deep.

front-following ship track on SSH and SST snapshots.

frontal strength $|\nabla b|(t)$ at its center.

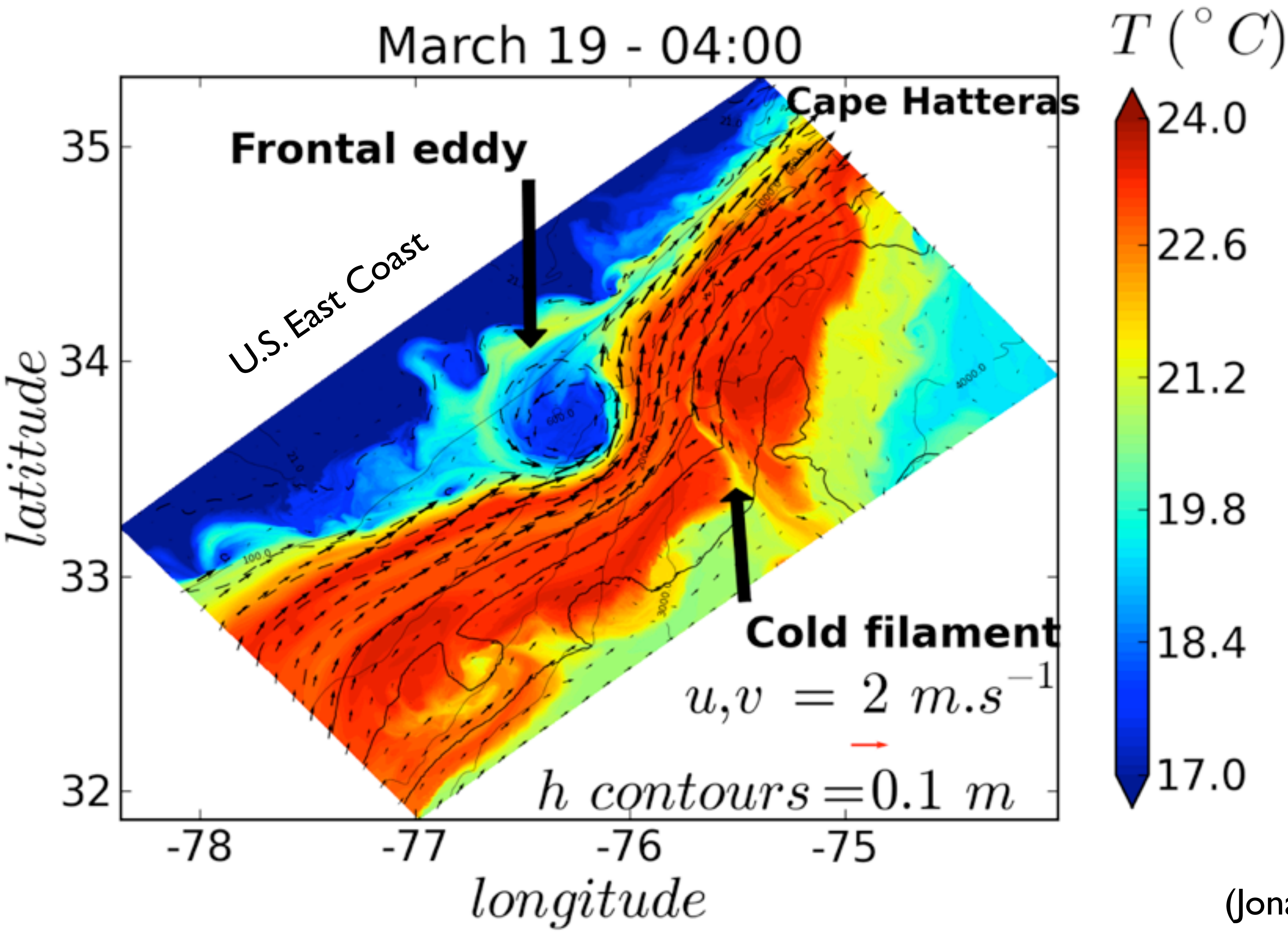
depth-averaged energy dissipation rate by three methods

Downstream, a down-front wind influxes negative potential vorticity, which catalyzes a centrifugal instability that weakens the front through several episodes of ageostrophic energy cascade and a very high dissipation rate. (D'Asaro et al, 2011)

Gulf Stream South of Cape Hatteras

[a regional nest with dx = 0.5 km inside an Atlantic basin simulation with dx = 7 km]

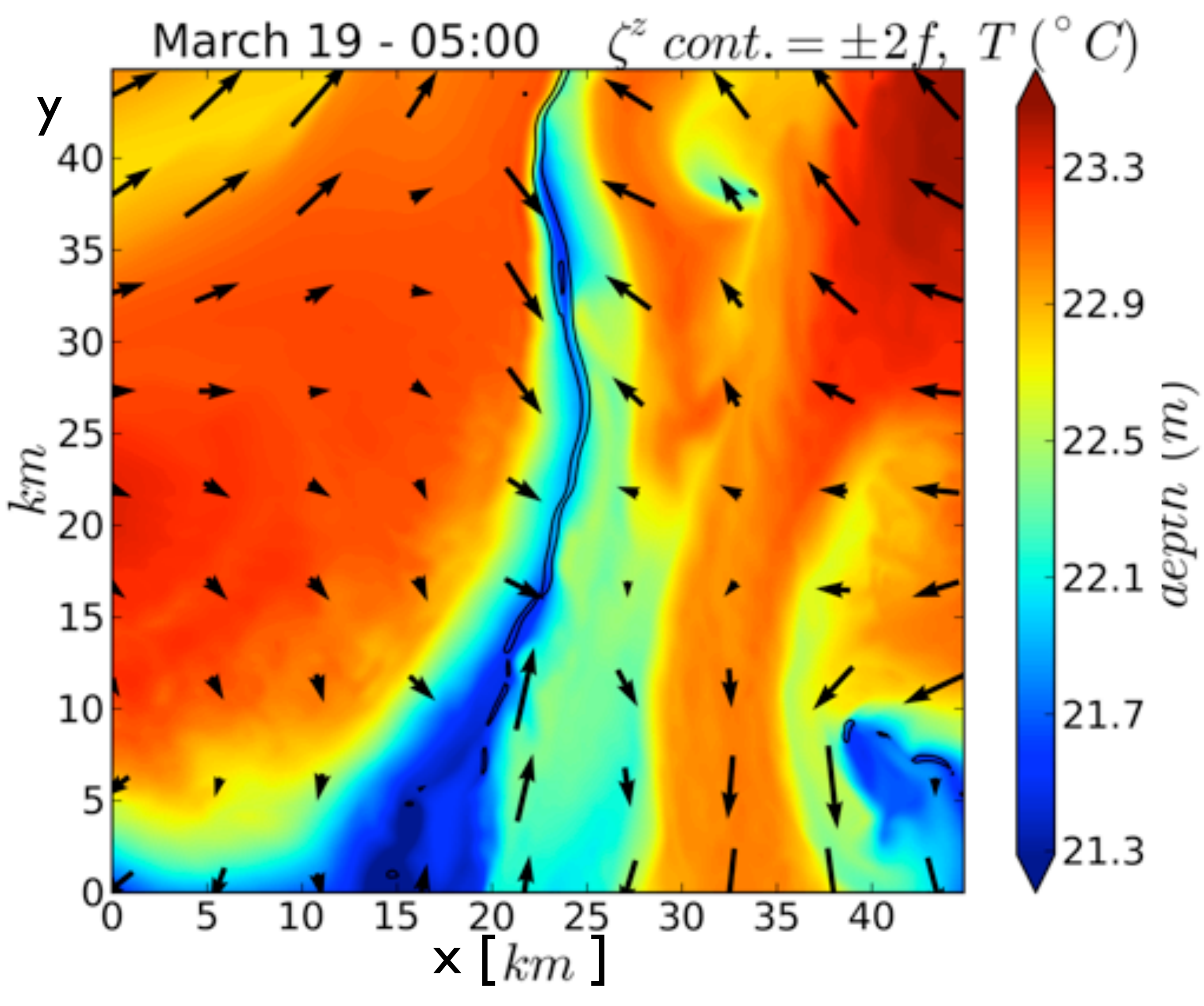
Snapshot with small mesoscale cyclonic frontal eddy (a.k.a. shingle eddy) and submesoscale cold filament:



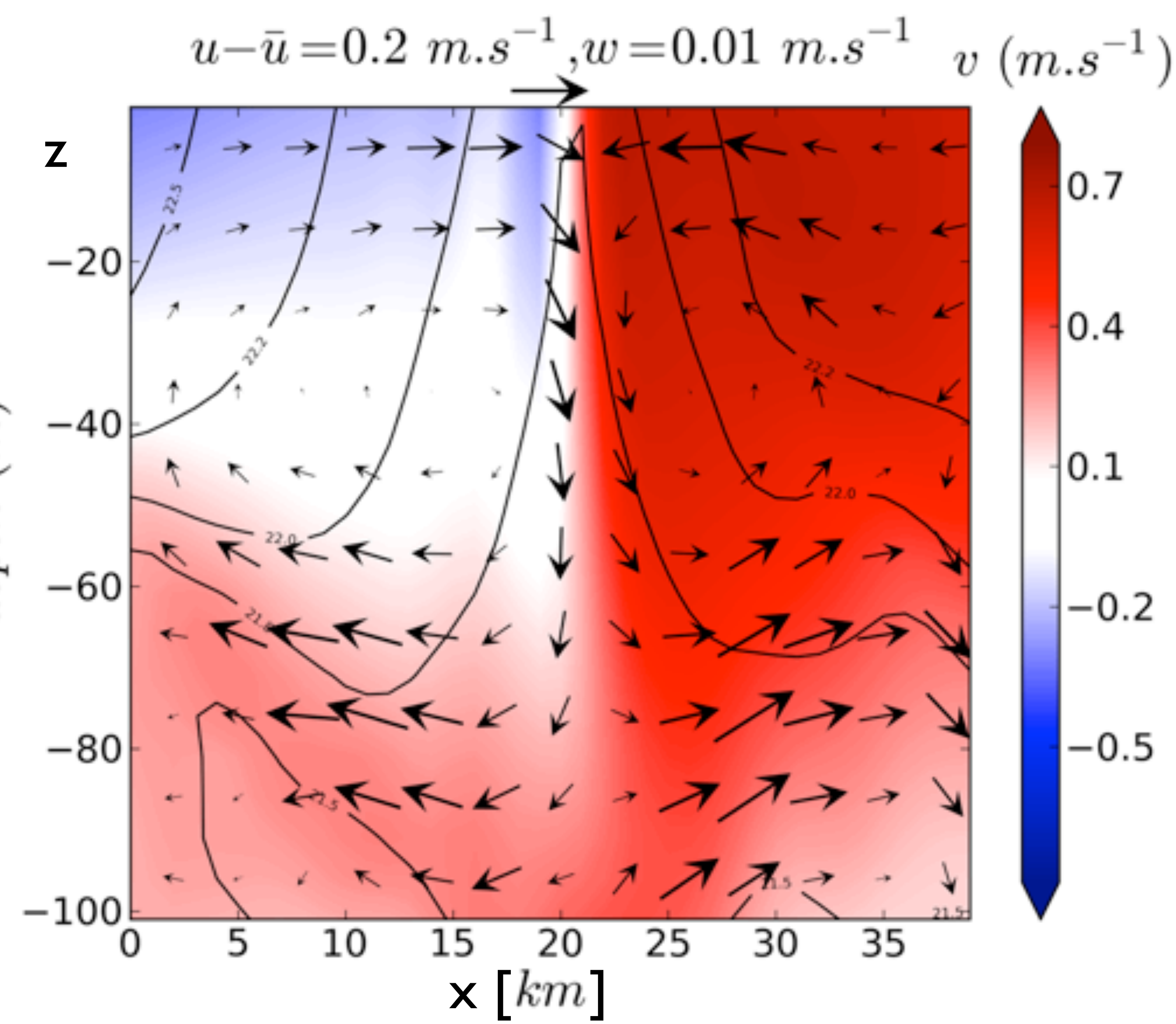
(Jonathan Gula)

Surface-Horizontal and Vertical Structure of Gulf Stream Filament

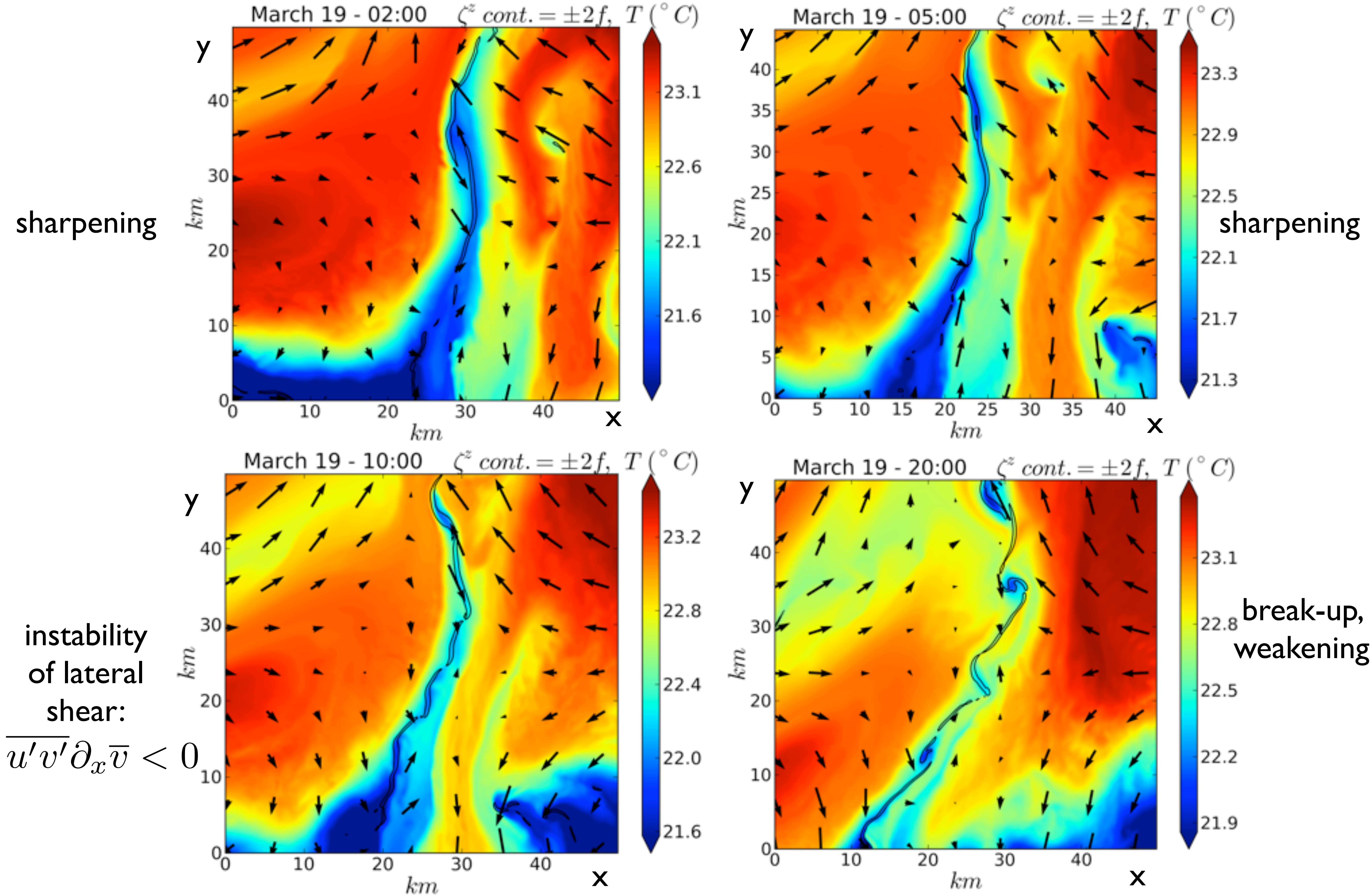
SST, vorticity, relative velocity



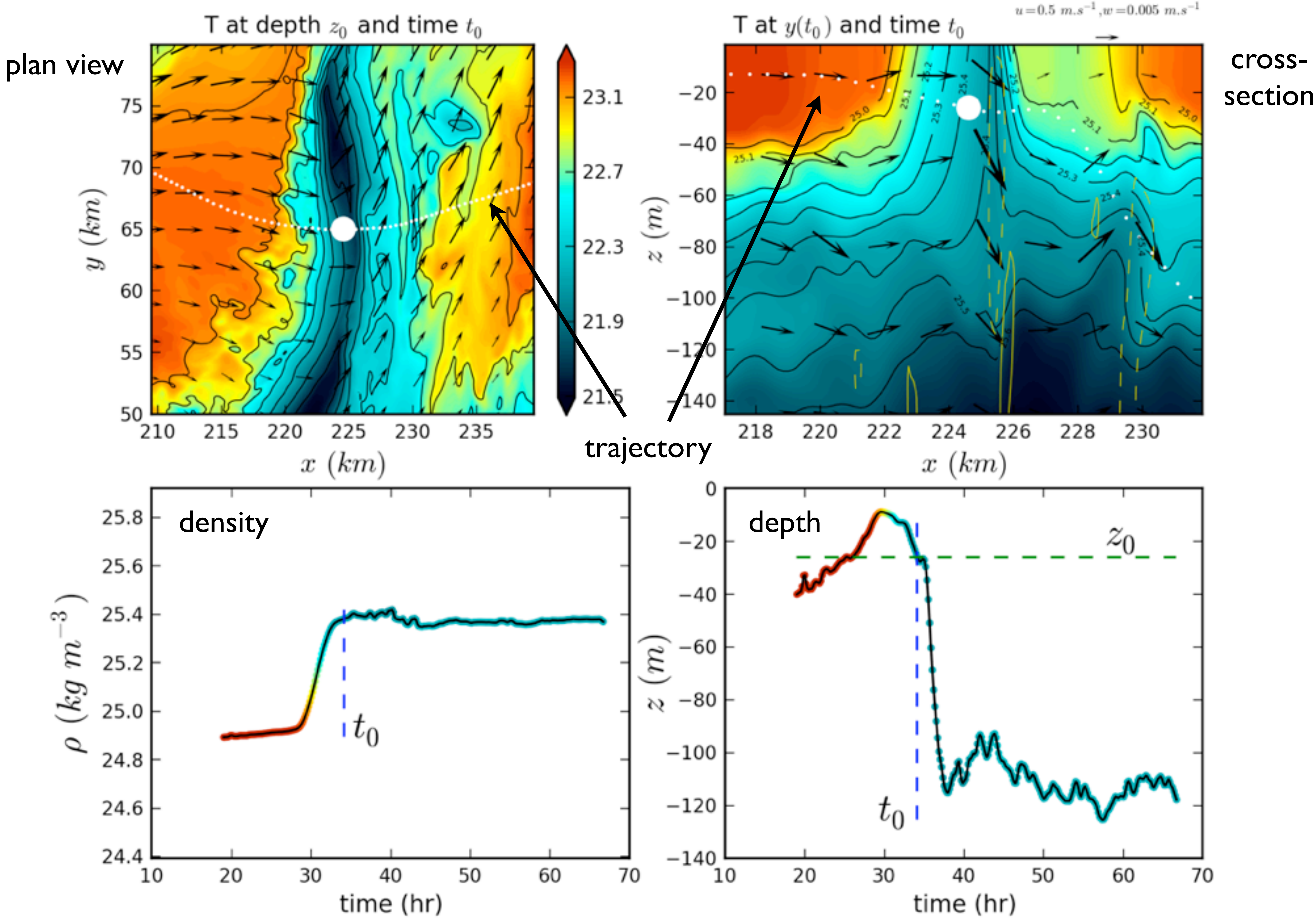
ρ, down-filament v (color),
secondary circulation u,w(arrows)



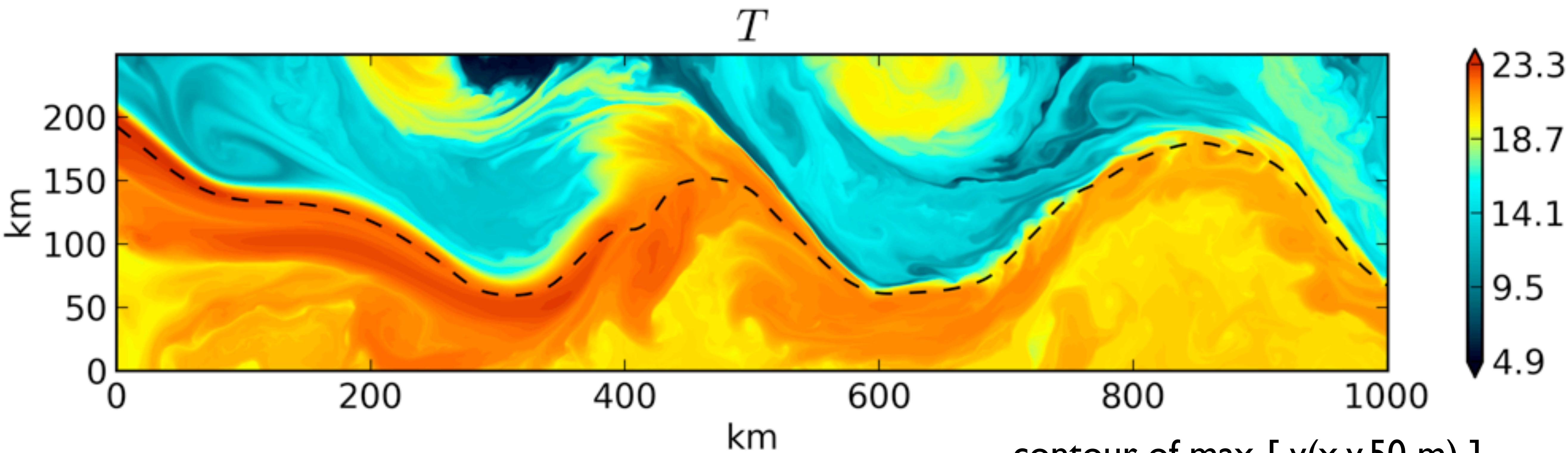
Evolution of a Gulf Stream Filament over 18 Hours



Diabatic mixing as a near-surface particle crosses the filament front:



The Gulf Stream after Separation: Instantaneous SST near the North Wall



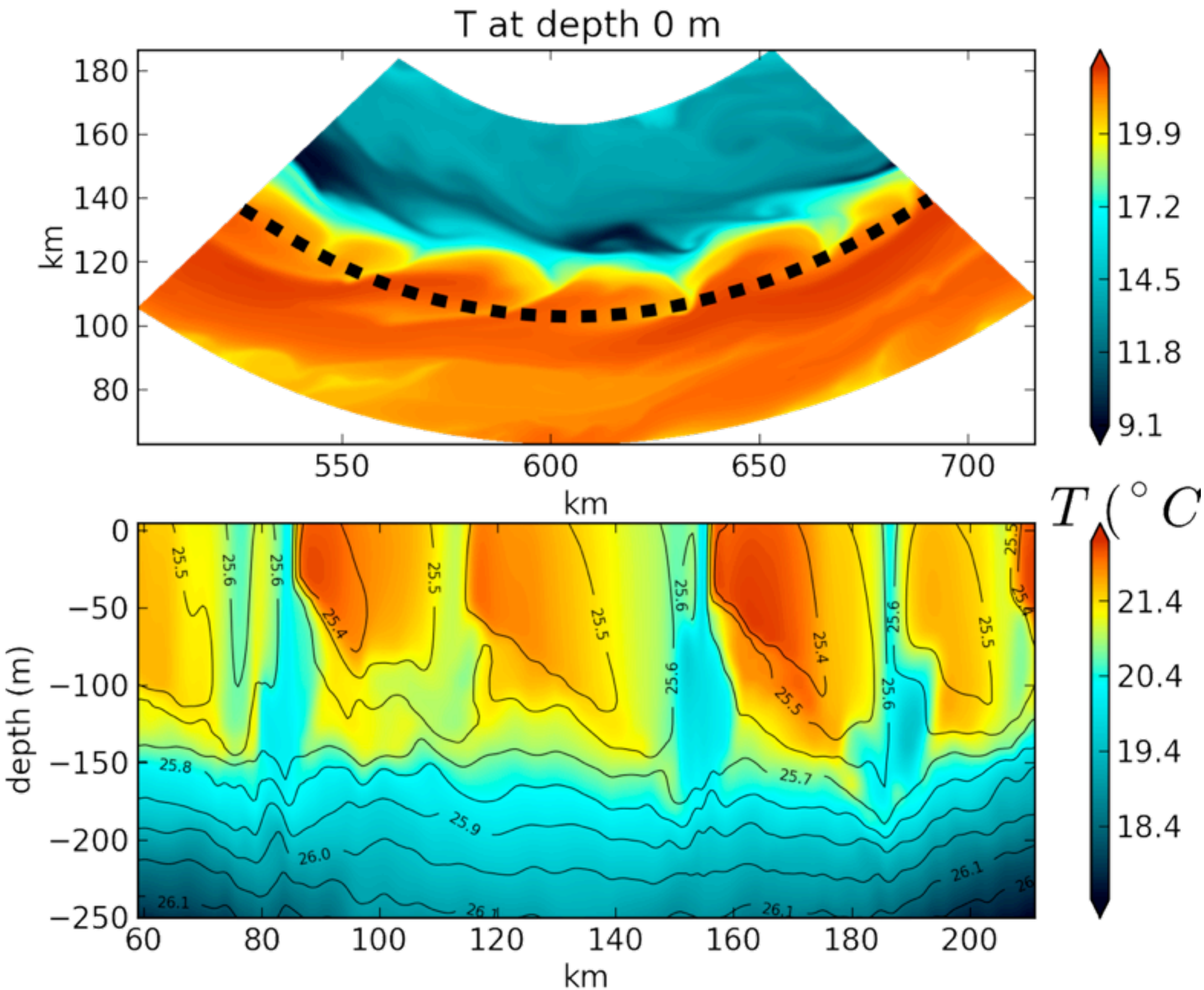
- - - contour of $\max_x$[v(x,y,50 m)]

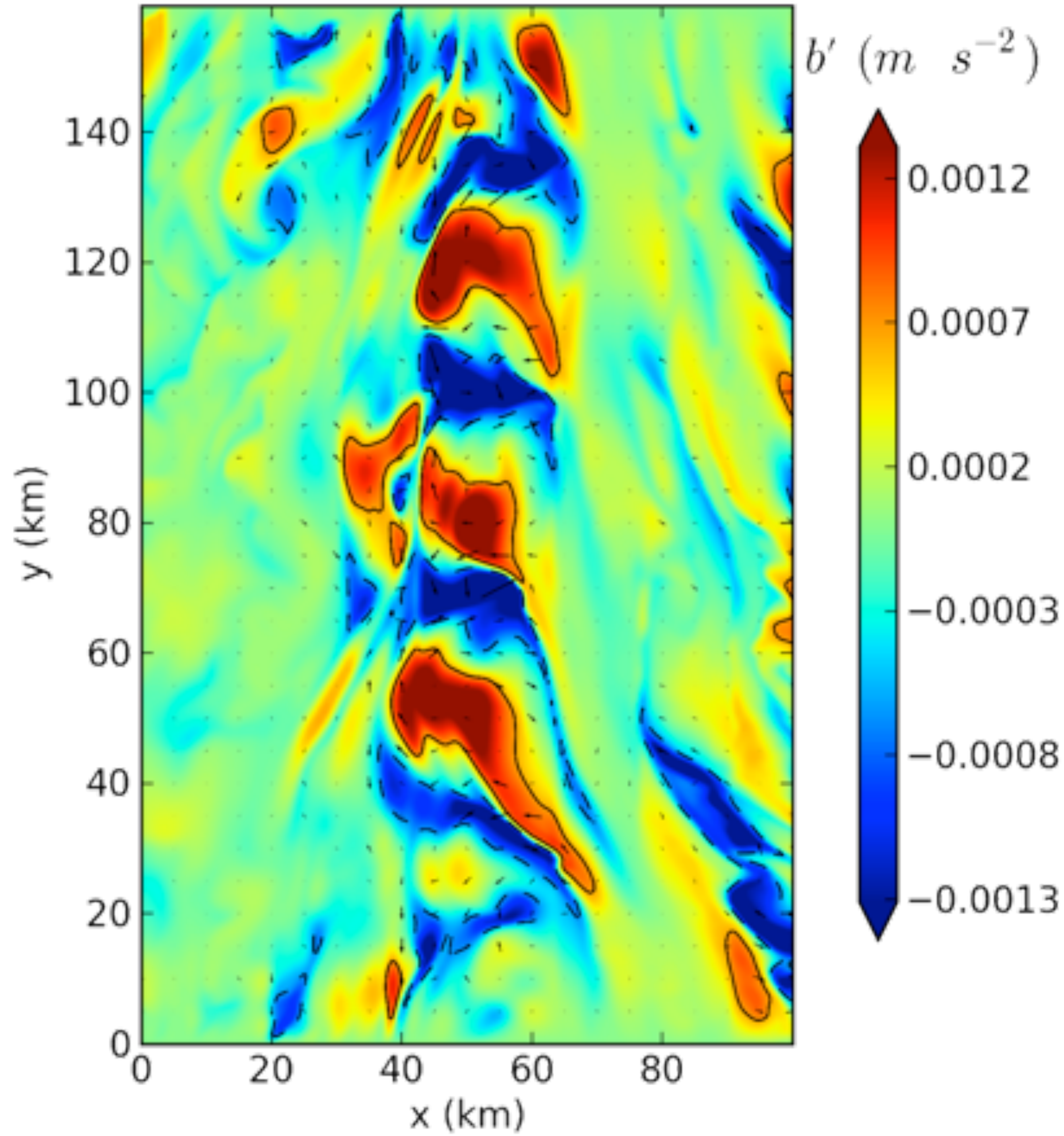
ROM SST
12/19/XX :

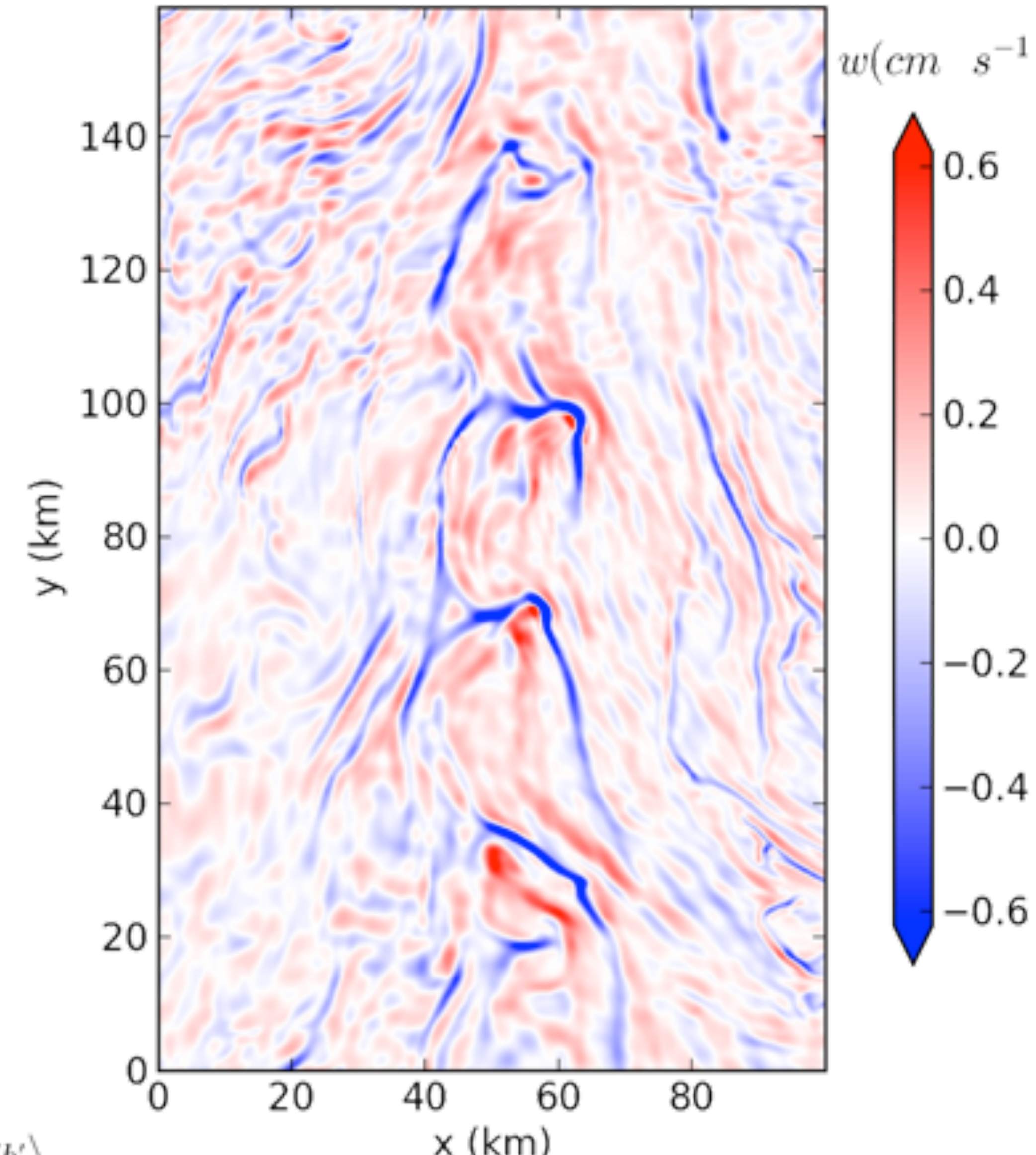
warm GS core
meanders
warm Rings
[“wonder eddies”]
sharp north wall
[esp. downstream faces]

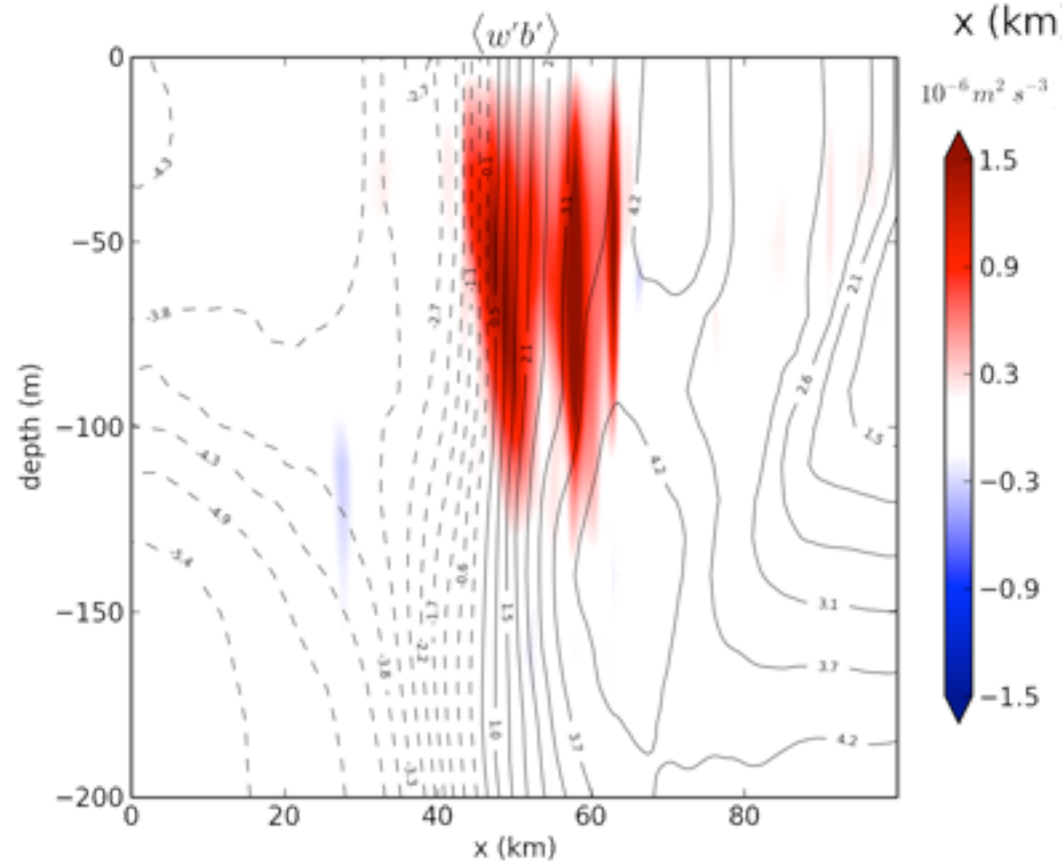
cold filaments
[esp. south wall]
north wall comma instabilities
[esp. upstream faces]
north wall streamers
[crests & upstream faces]

Comma Instability on the GS North Wall (especially at through - upstream face)



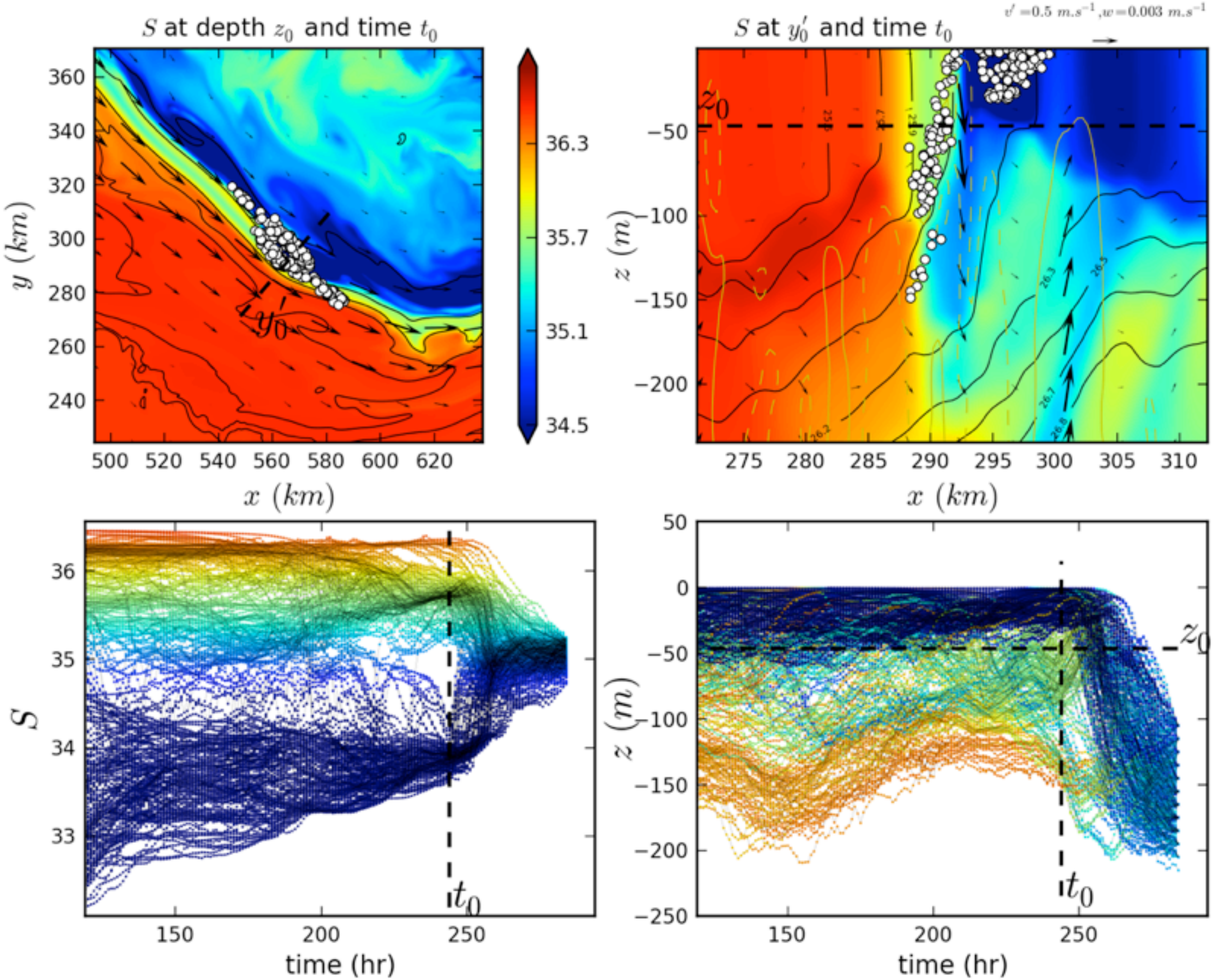






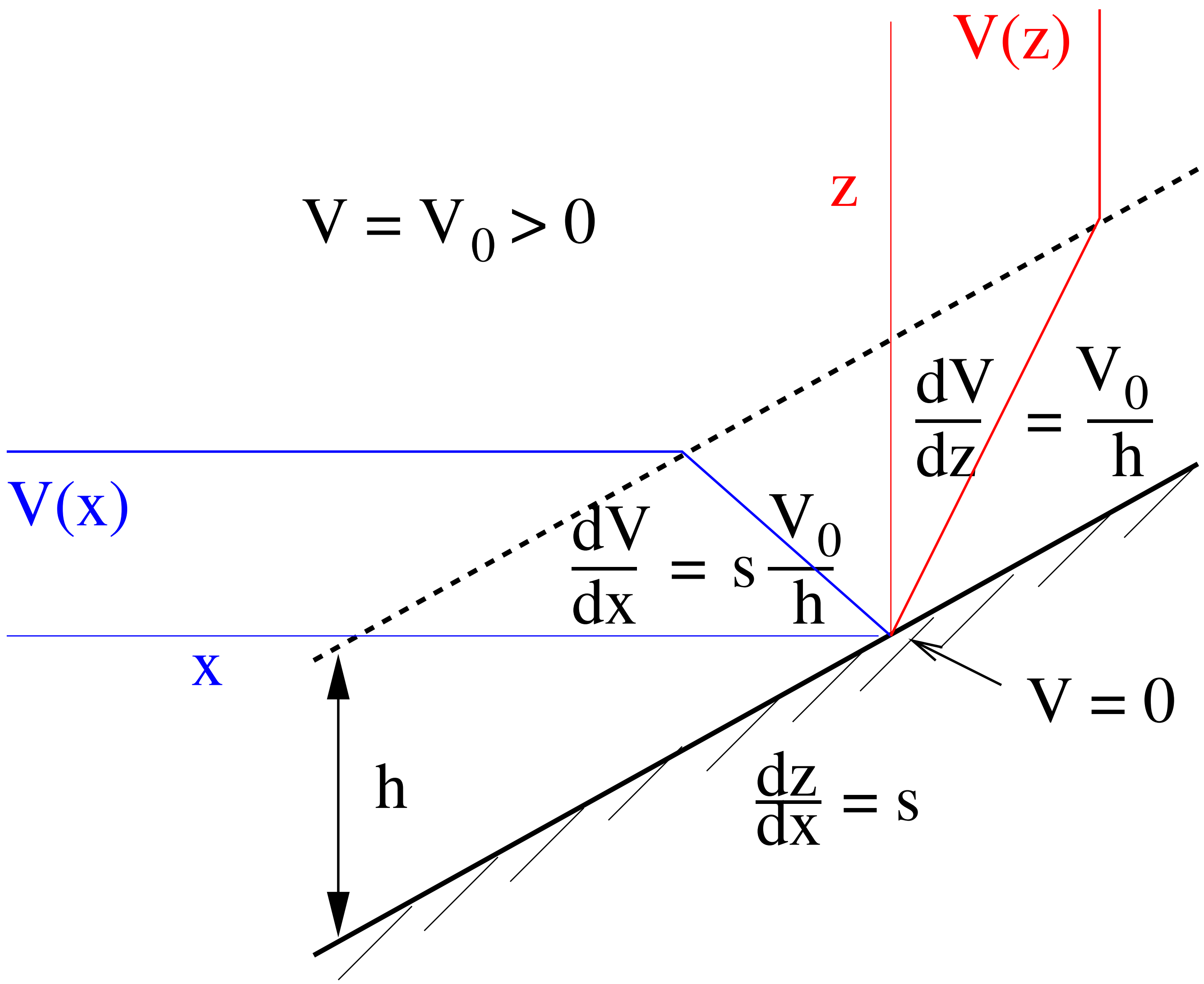
Comma instability:
eddy b’(x,y,0) & w’(x,y,50 m)
and <w’b’>(x,z) > 0
energy conversion:
surface layer baroclinic
instability of the sharp north wall
with finite-amplitude
cold-filamentary arms.

Particle mixing across the north wall generates pycnocline intrusions



Submesoscales and Topography: “Wakes”

Vorticity Generation by Flow Along a Sloping Bottom

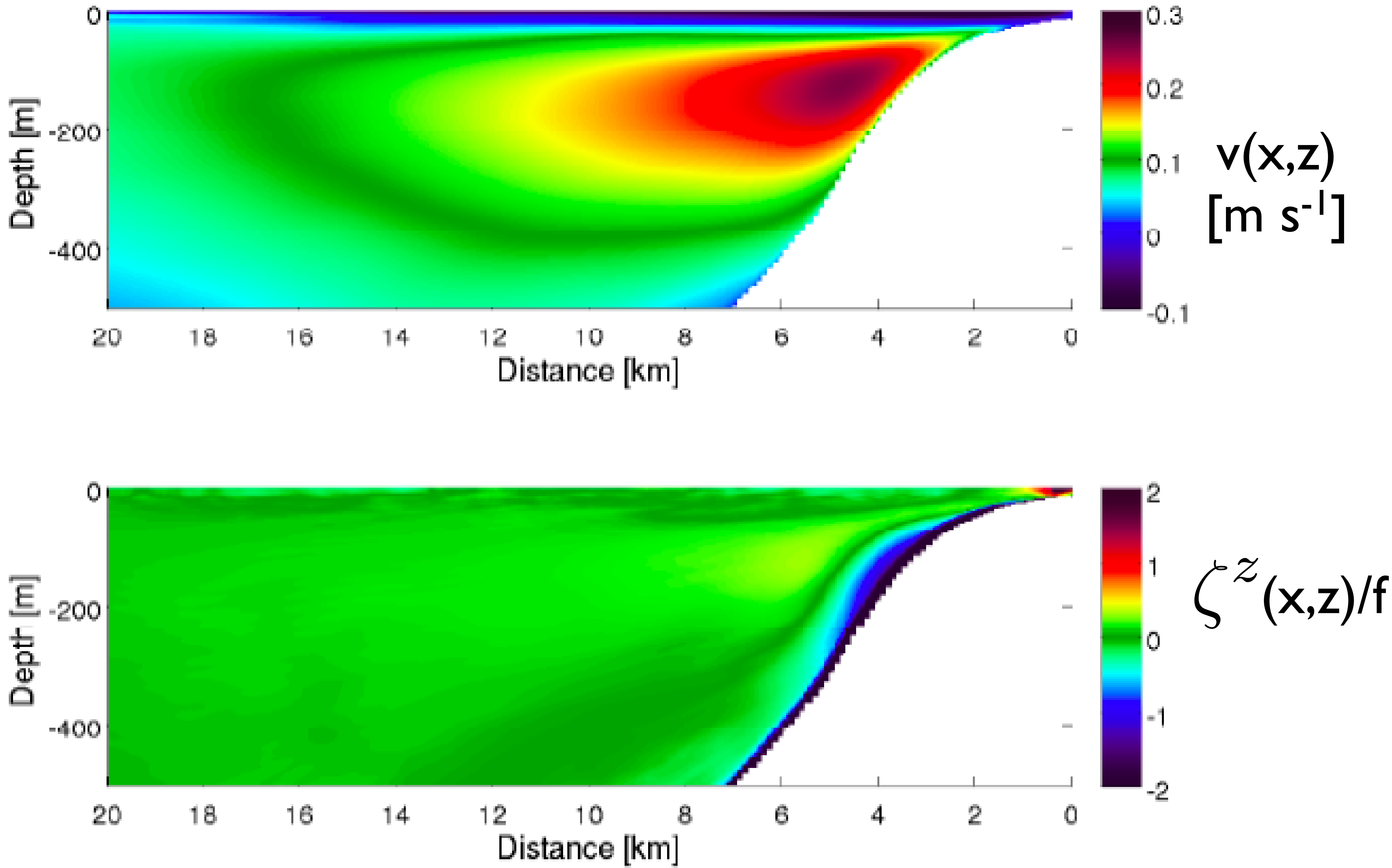


Vertical shear ∂_zV in the bottom boundary layer => large ∂_xV and ζ^z even for moderate V_0 values, set by h and s, not f.

It is easy to cross the thresholds for **ageostrophic instability** (i.e., $f + \zeta^z < |\nabla \mathbf{u}|$) and **centrifugal instability** (i.e., ζ^z < -f and fQ < 0), which may be locally suppressed by the adjacent boundary.

Subsequent flow separation generically => "**wake**" instability, either mesoscale or submesoscale.

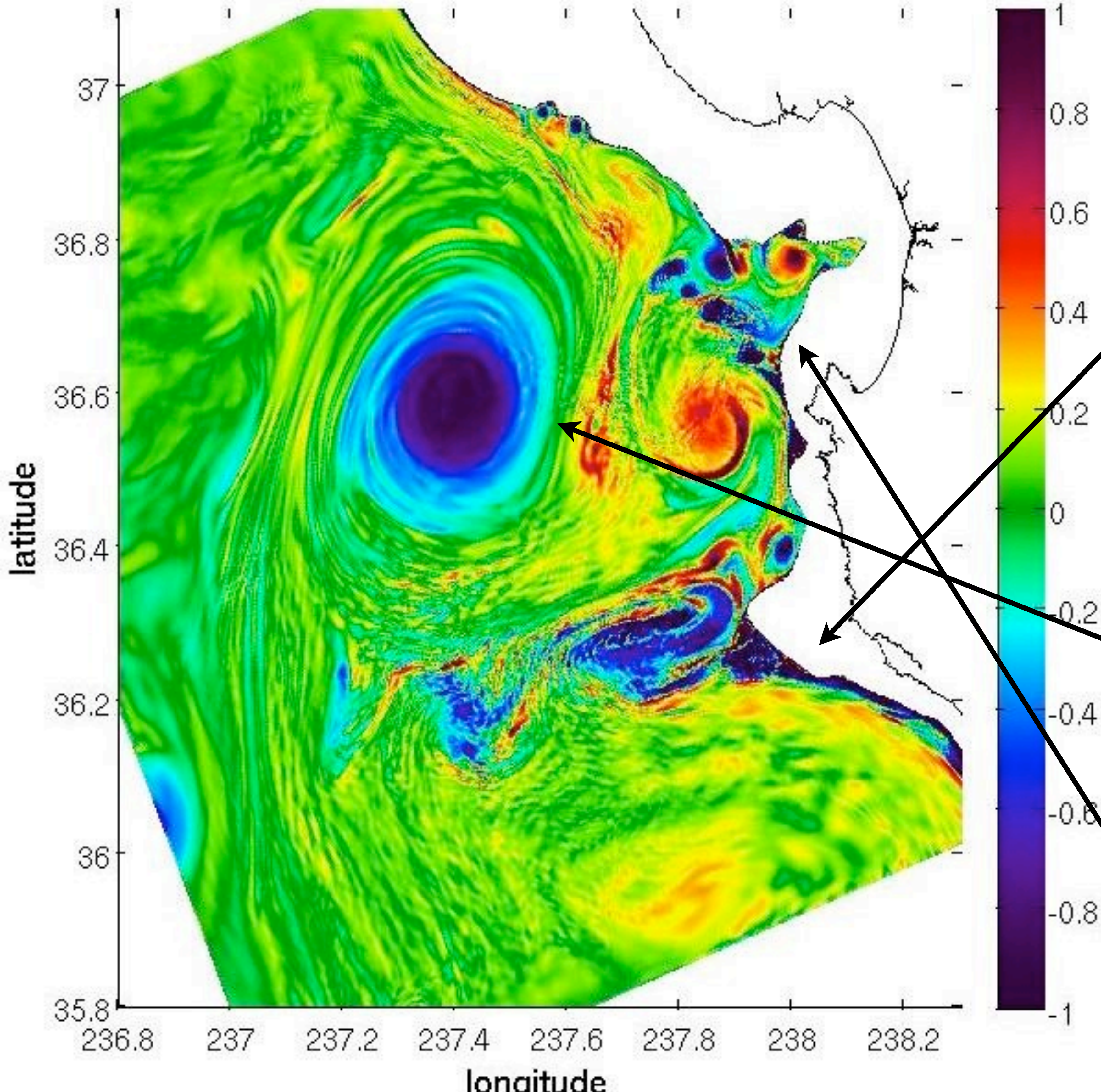
California Undercurrent Separation => Cuddy Generation



Alongshore summer-mean current v and normalized vertical vorticity for the California Undercurrent upstream of Monterey Bay and Pt. Sur. This is in a nested simulation with the finest dx=150 m.

(Molemaker et al, 2012)

Snapshot of $\zeta^z(x,y)$ at 250 m depth off Monterey Bay, CA



The poleward Undercurrent **separates** from the slope at Pt. Sur (36.3°N).

With ζ^z < - f, this leads to **centrifugal instability**, submesoscale turbulence, diapycnal mixing, and then **upscaling** into coherent "Cuddy" SCVs (e.g., a previously generated one seen here, with ζ^z/f = - 0.9), commonly seen off the U.S. West Coast (Collins et al, 2012)

Other SM eddy generation in Monterey Canyon.

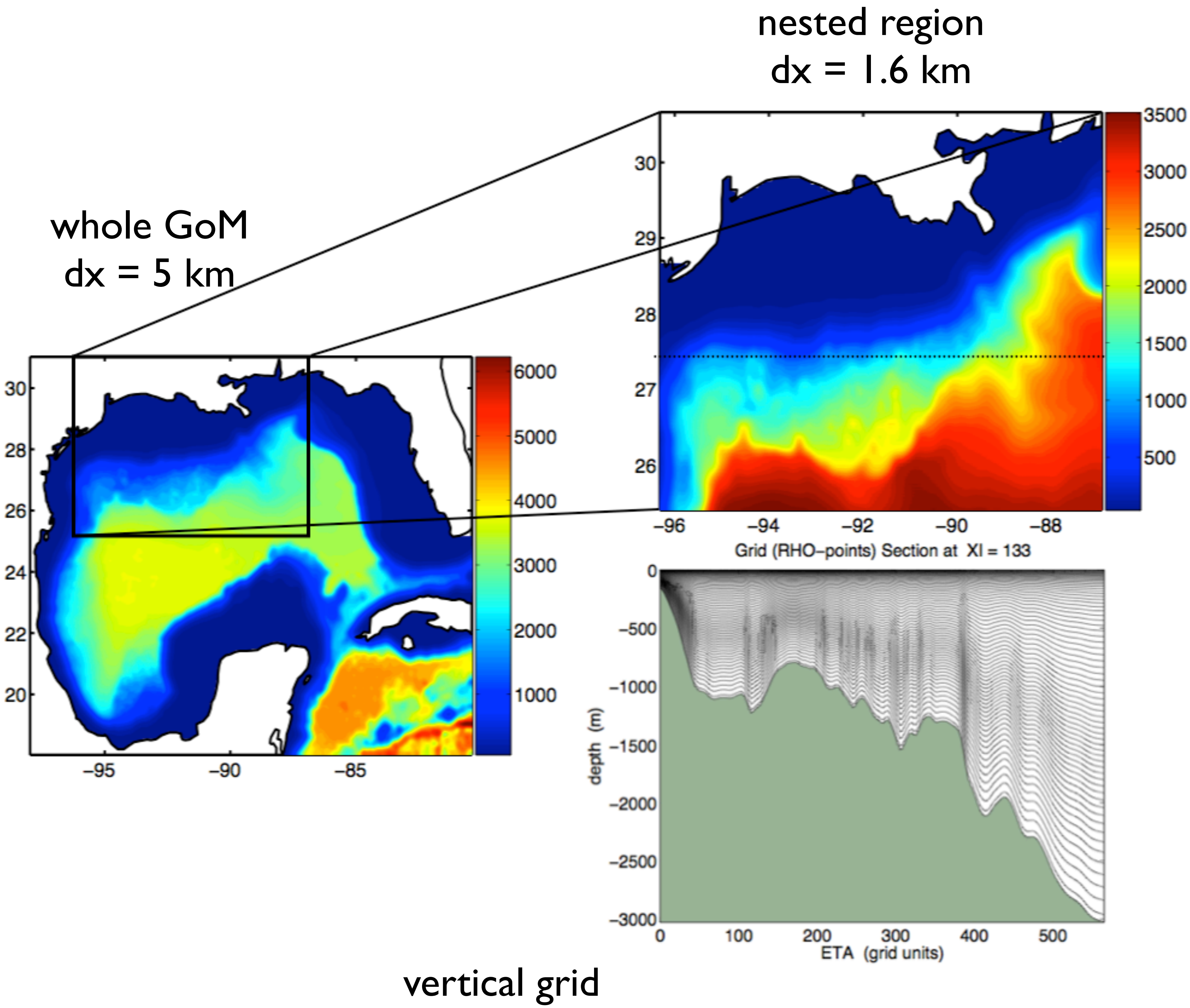
Summary of Submesoscale Dynamics

- SM outbreaks are widespread: convergence lines, fronts, & filaments in the surface layer & in strong currents; coherent vortices at all depths
- SM generated by surface layer, topographic, and ageostrophic "instability" of mesoscale eddies and boundary currents
- loss of full balance & forward cascade of energy in rotating and/or stratified turbulence → energy dissipation & diapycnal mixing
- big w → density restratification & other vertical fluxes in the surface layer, connecting mixed layer with pycnocline
- lateral mixing at intermediate scales, 100 m - 10 km
- SM dynamics provides a rational basis for initialization & mixing-parameterization schemes

Gulf of Mexico

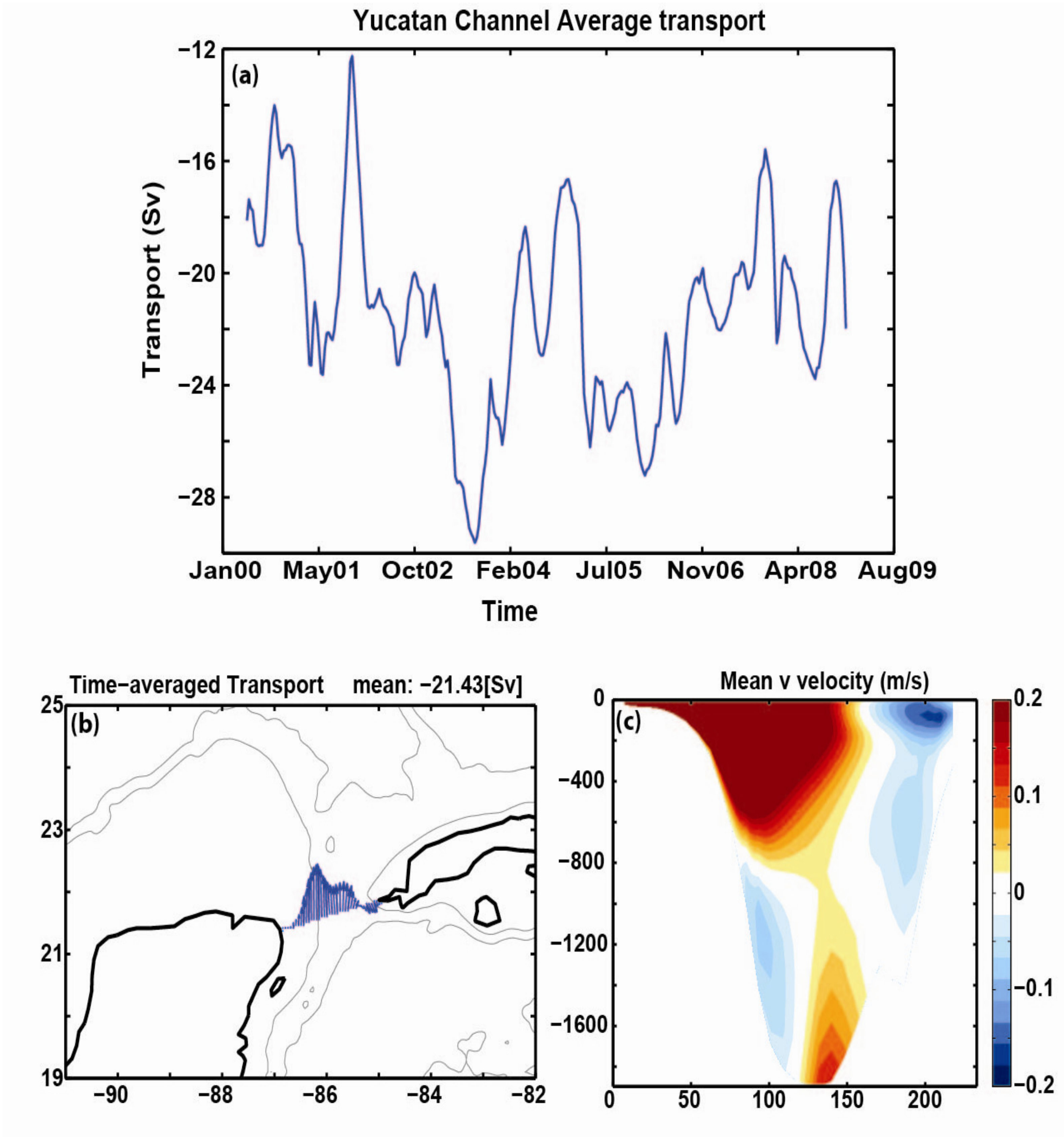
Gulf of Mexico Model Configuration

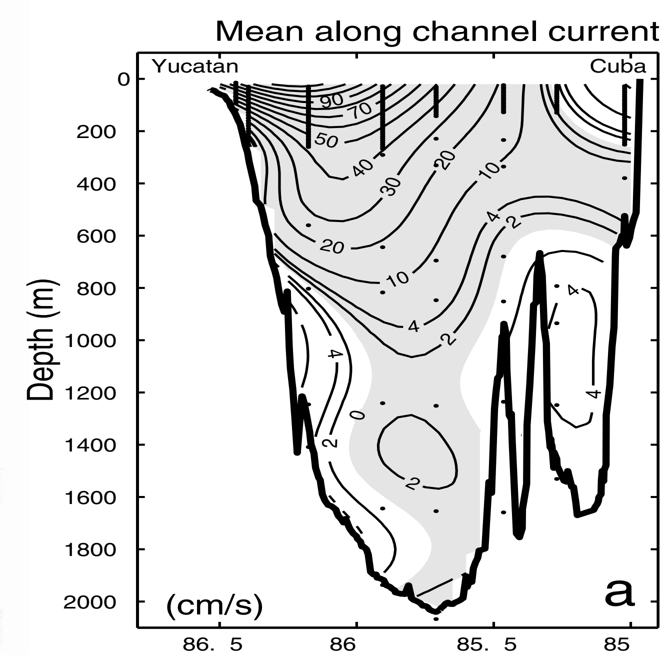
[A. Bracco et al.]



- ROMS Agrif
- 70 (or 35) vertical layers
- Two-way nesting. Parent grid horizontal resolution 5km; child grid 1.6km.
- Six-hour atmospheric forcings (NCEP and Quickscat from 2000 to 2008; ERA-interim for 2009-2012)
- SODA monthly varying boundary conditions 2000 – 2008; SODA climatologies for T/S and HYCOM U and V for 2009-2012
- Rivers by nudging T,S to monthly climatology

averaged transport (2000 – 2010): 21.4 +/- 0.1 Sv against 23.8 +/- 1 Sv during 10 months of observations in 1999 – 2000 (Sheinbaum et al., 2002)

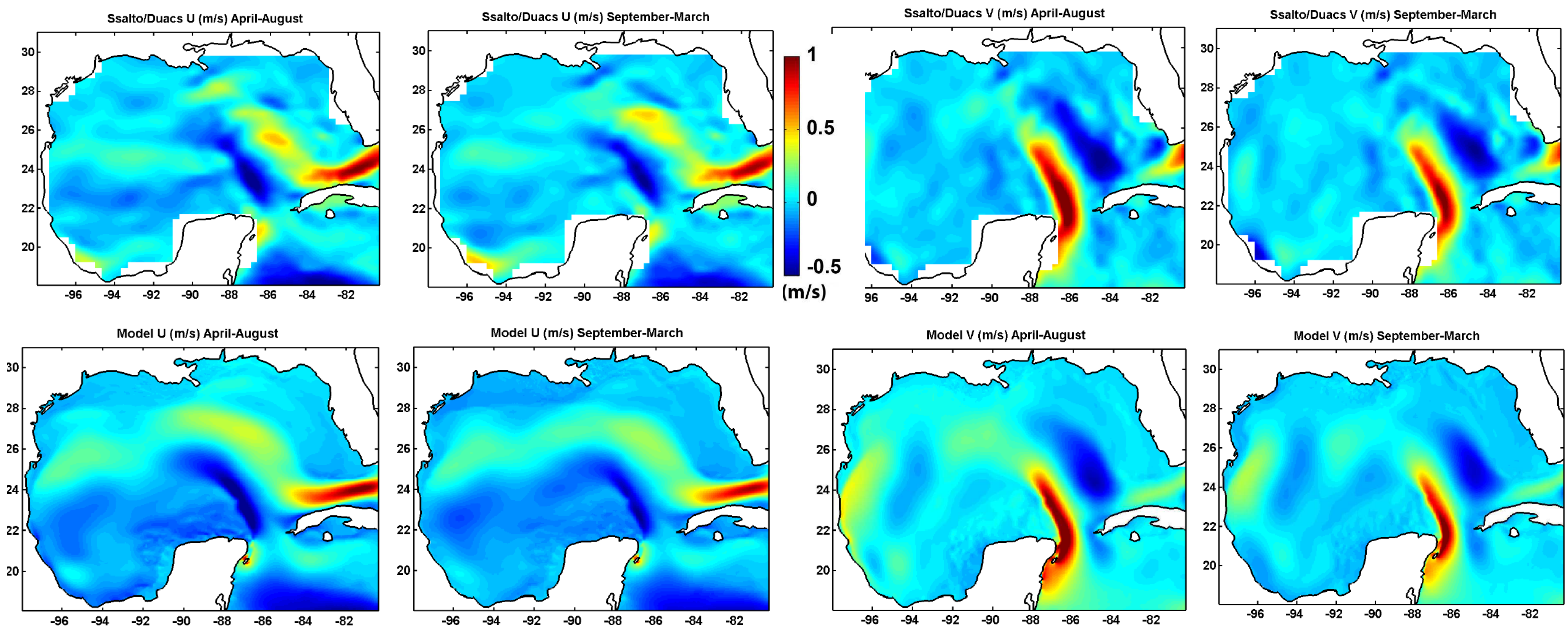




Mean Surface Velocity

seasons: warm (left) and cool (right)
Aviso (top) and ROMS (bottom)

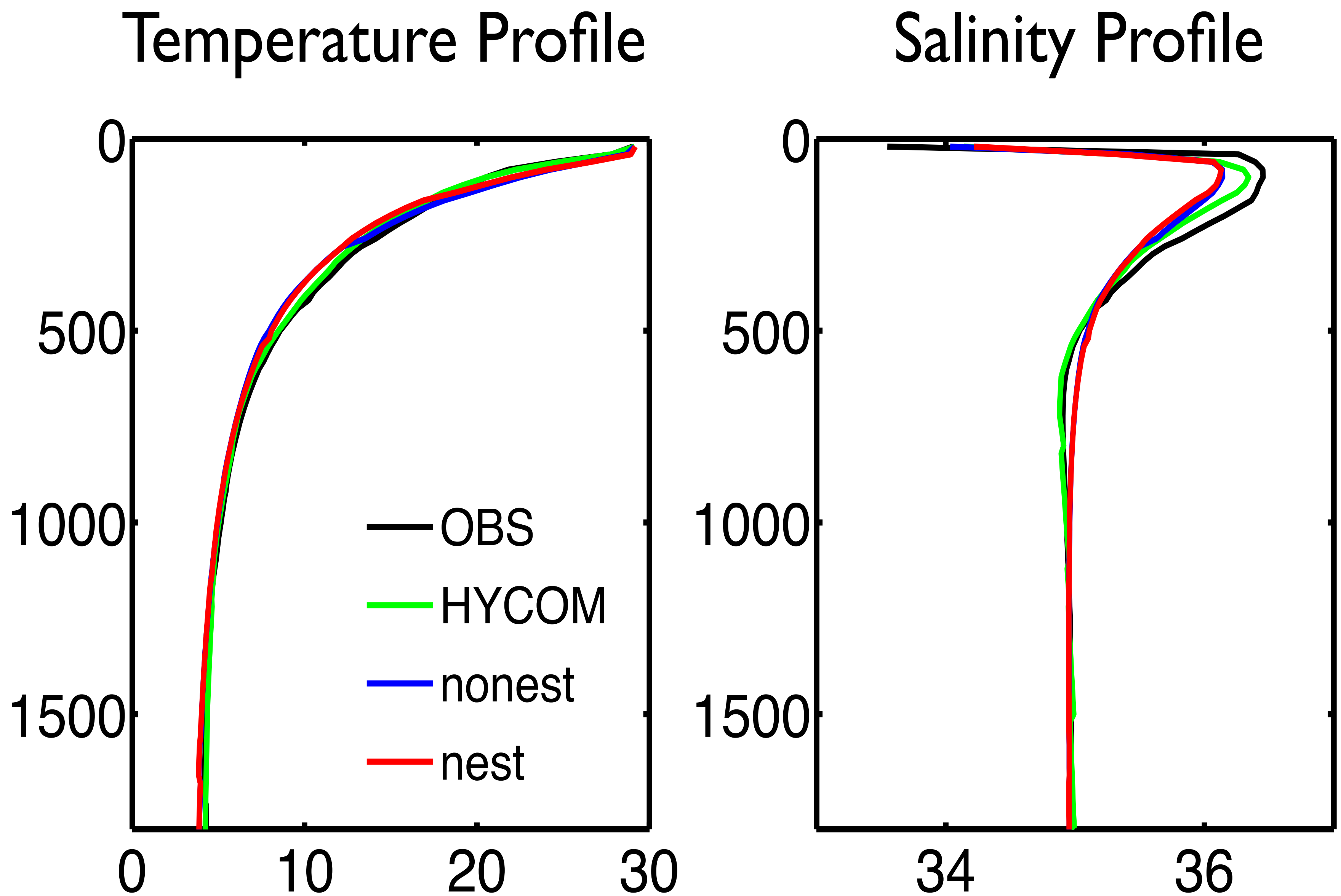
U V



Mean Stratification

Averaged over 18 CTD casts taken within the nested area in summer 2010-12.

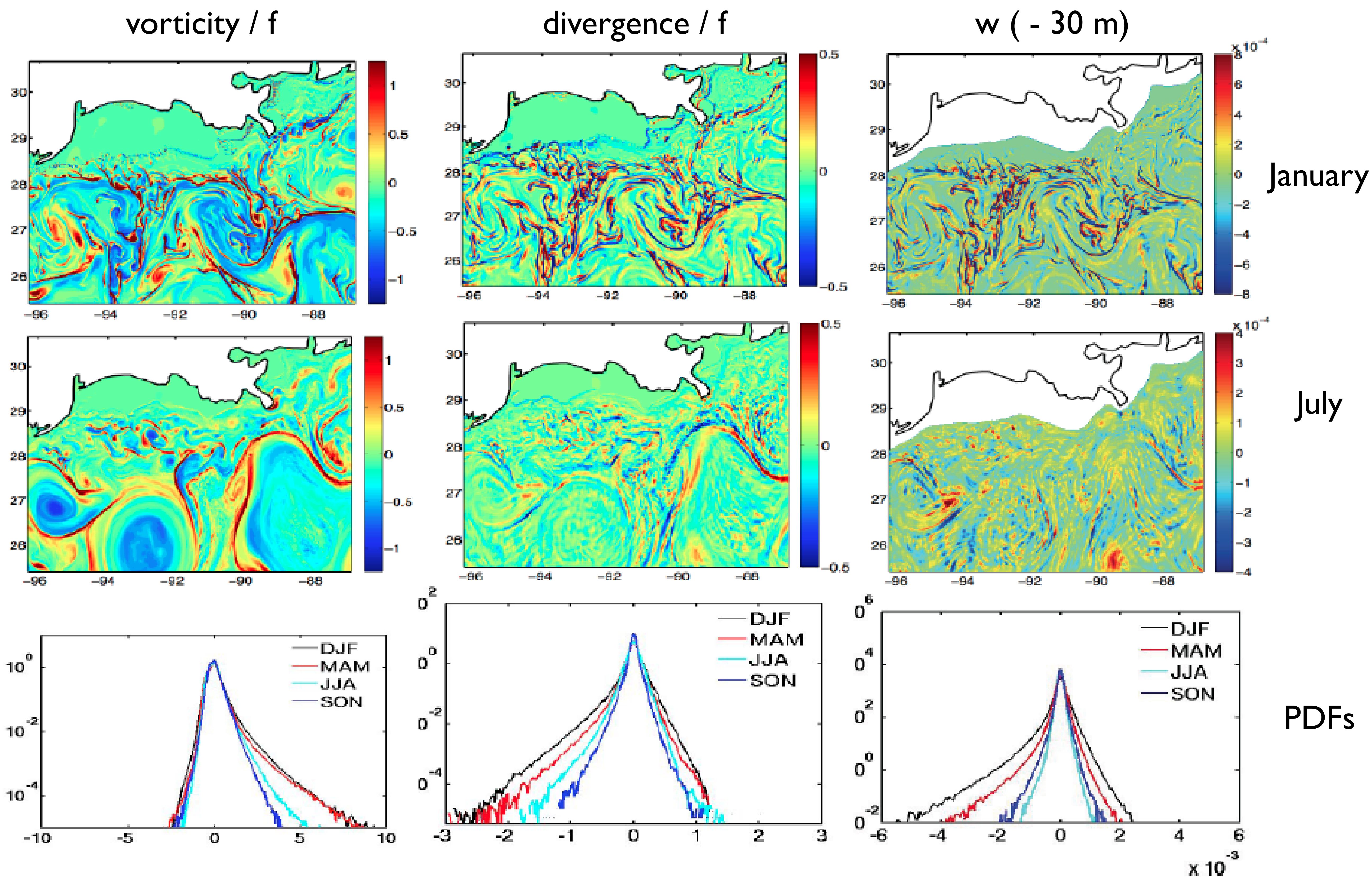
HYCOM assimilates hydrography.



Surface Submesoscale Fields

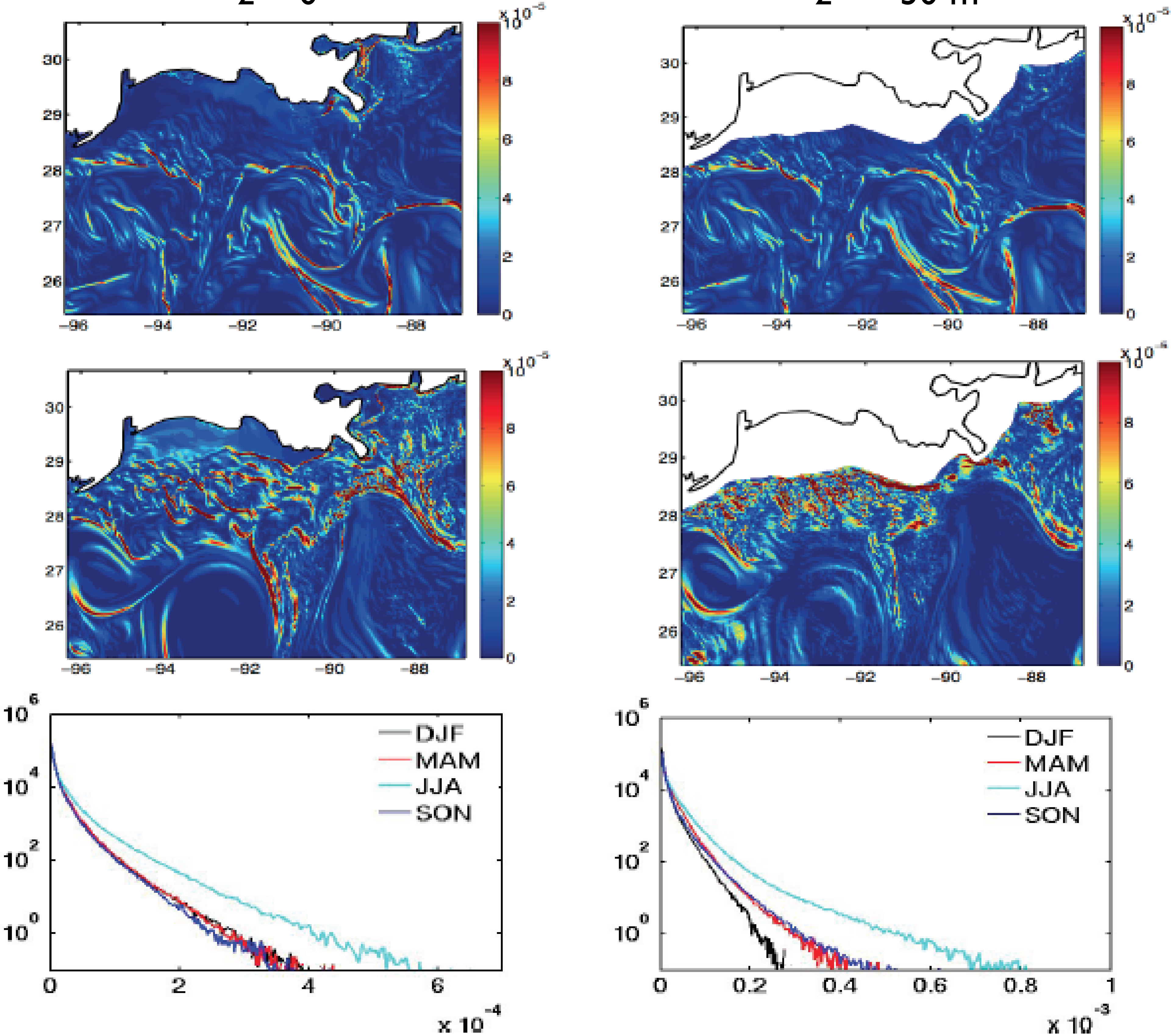
Stronger around Rings and the Loop Current. Weaker on the shelf (sometimes?), but not on the slope.

Notice the wintertime maxima: deeper mixed layer.



Submesoscale Horizontal Density Gradient

z = 0 | z = - 30 m



January

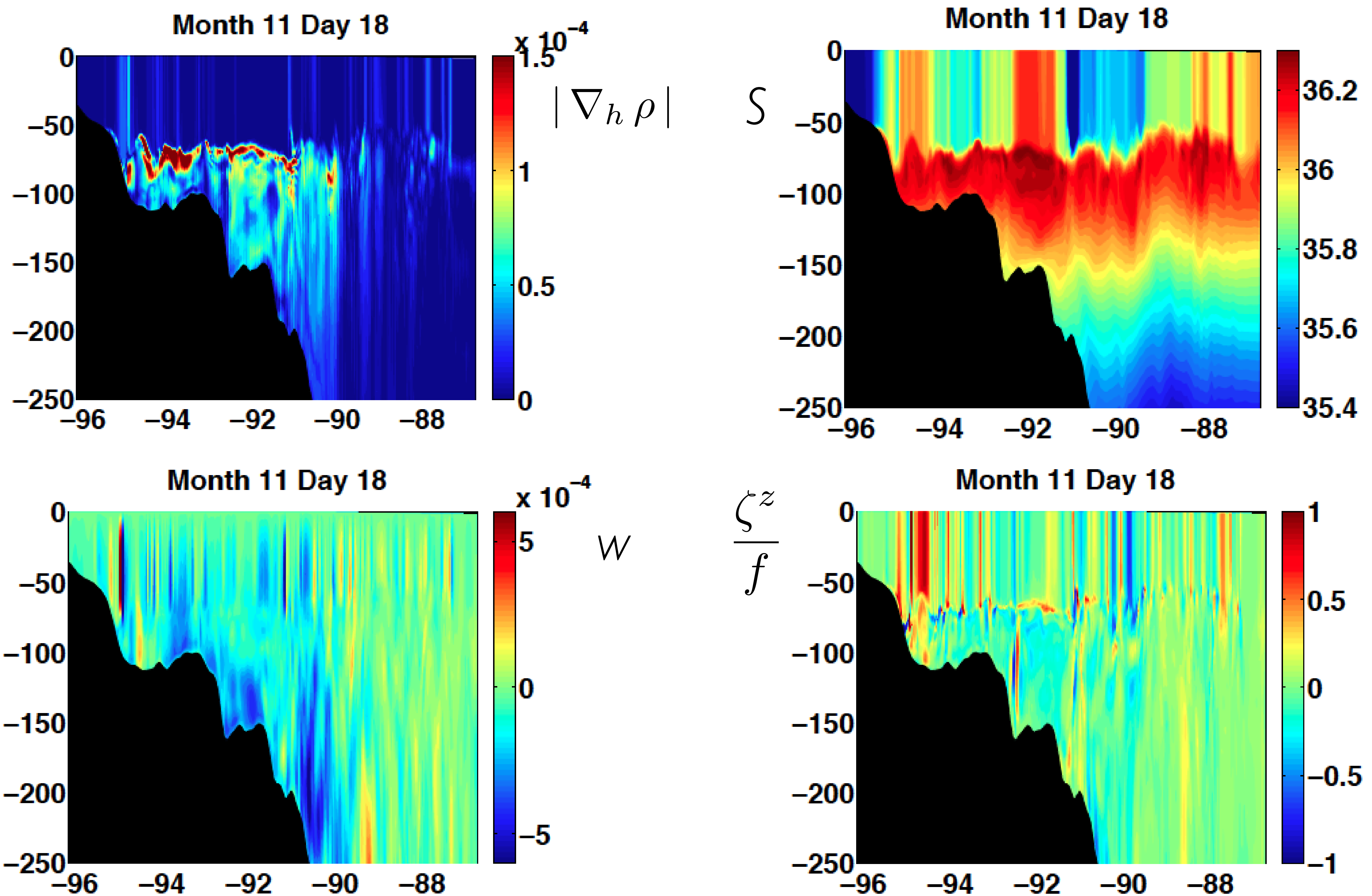
Notice the summertime maxima: river inflow baroclinicity?

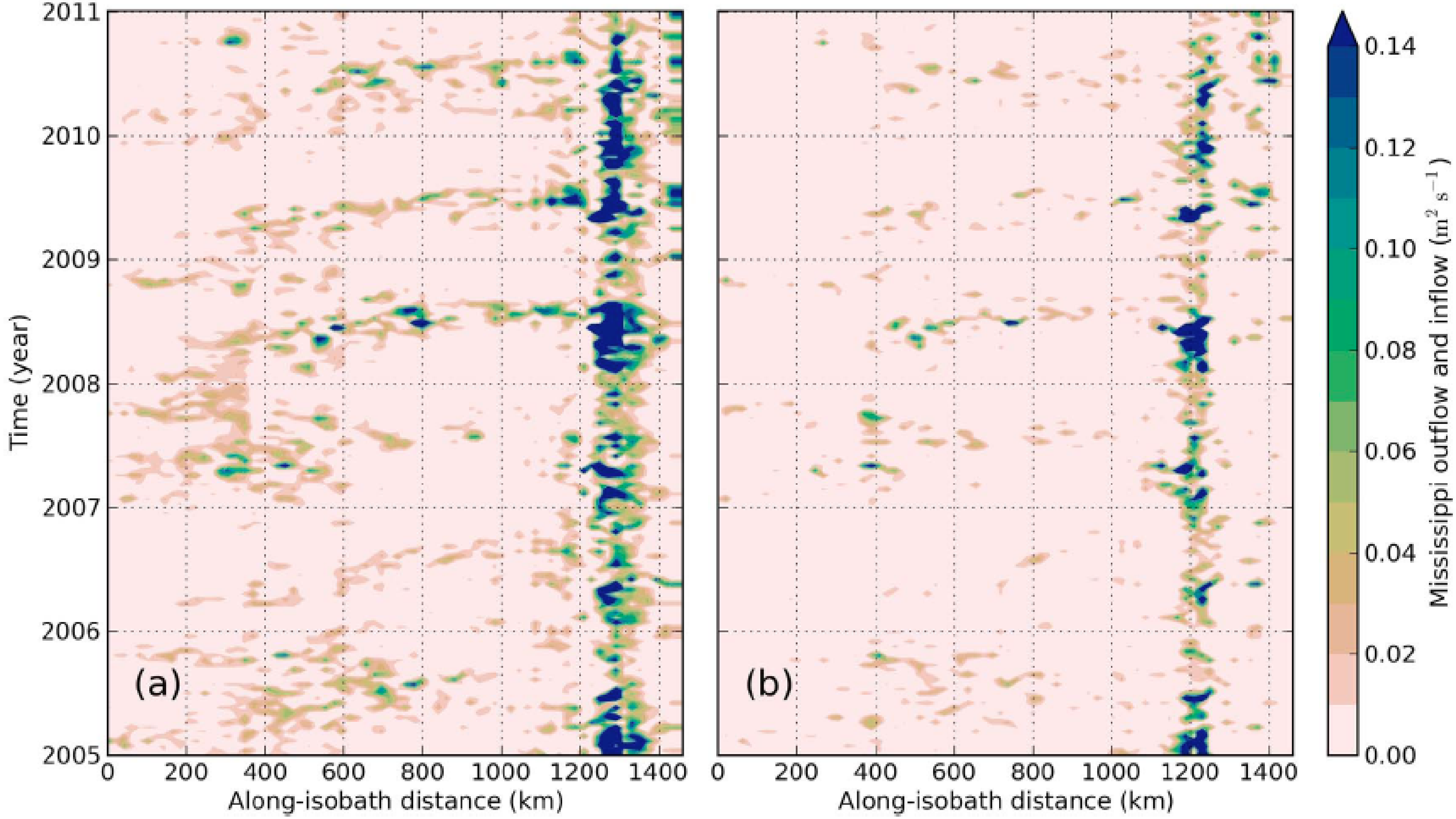
July

Penetration onto the shelf especially around rivers

PDFs

Submesoscale Activity over the Slope: a section along 28N





Modeled Mississippi freshwater (a) outflow and (b) inflow across the shelf-edge 100 m isobath. Much of the flux is associated with high-frequency (& small scale?) currents. (Zhang et al., 2012)

Future Directions for CARTHE:
Submesoscale Currents and Transport

More aggressive nesting down to dx ~ 100 m: what's there?

Lateral dispersion in the presence of strong surface convergence lines.

Filaments and instabilities on the north wall of the Loop Current and edges of Warm Rings.

Slope topographic "wake" generation of submesoscale currents.

Generation and penetration of submesocale currents in the shelf and littoral zones.

River outflow plume instability and mixing (warm season).

Chemically active materials in boundary-layer and submesoscale turbulence.

Better understand and model dynamics of fronts, filaments, and coherent vortices.