Submesoscale Currents:
Surface and Topographic Populations

J. McWilliams, UCLA

Distinctive submesoscale currents are essentially ubiquitous:

1. Near the surface with relatively greater size and strength when horizontal density gradients and/or boundary layer depths are large, with an energy source from mesoscale available potential energy.

2. Near topography where mean or mesoscale currents drag against a sloping bottom in the presence of stratification, generate vertical and potential vorticities, then transiently separate into unstable vortical wakes.

Primary Properties

Scales: horizontal ~ 10 m — 10 km; vertical ~ 10 m — 1 km; time ~ hours — days.
(Note the overlap with IGW scales.)

Patterns are surface fronts & dense filaments, topographic wakes, and coherent vortices.

Most evident in vertical vorticity, vertical velocity, and horizontal density gradient, in which they stand out from their mesoscale analogs.

Main effects are

* spontaneous, intrinsic emergence from the mesoscale as a systematic advective transfer of energy to smaller scales;

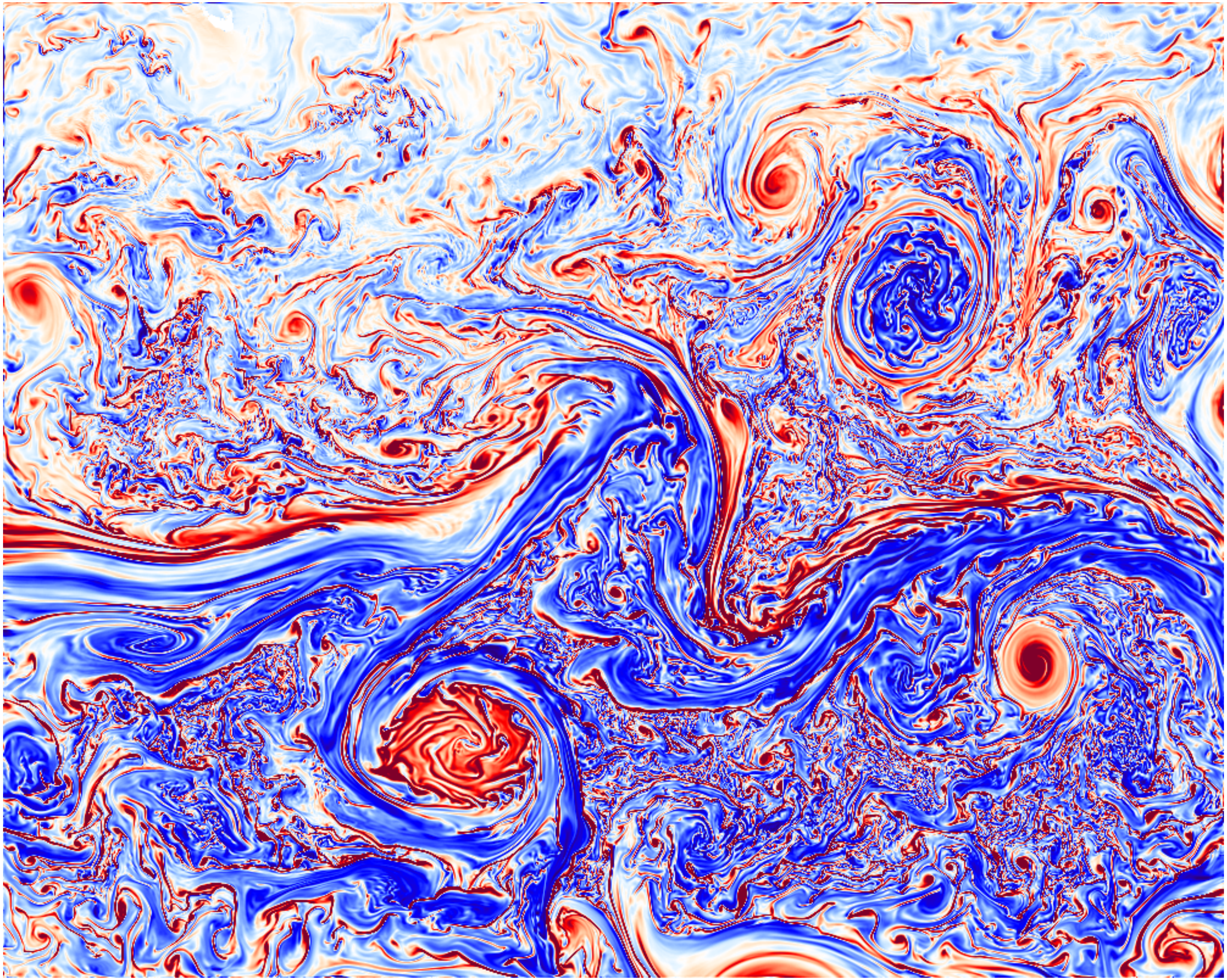
* breakdown of geostrophic, hydrostatic balance;

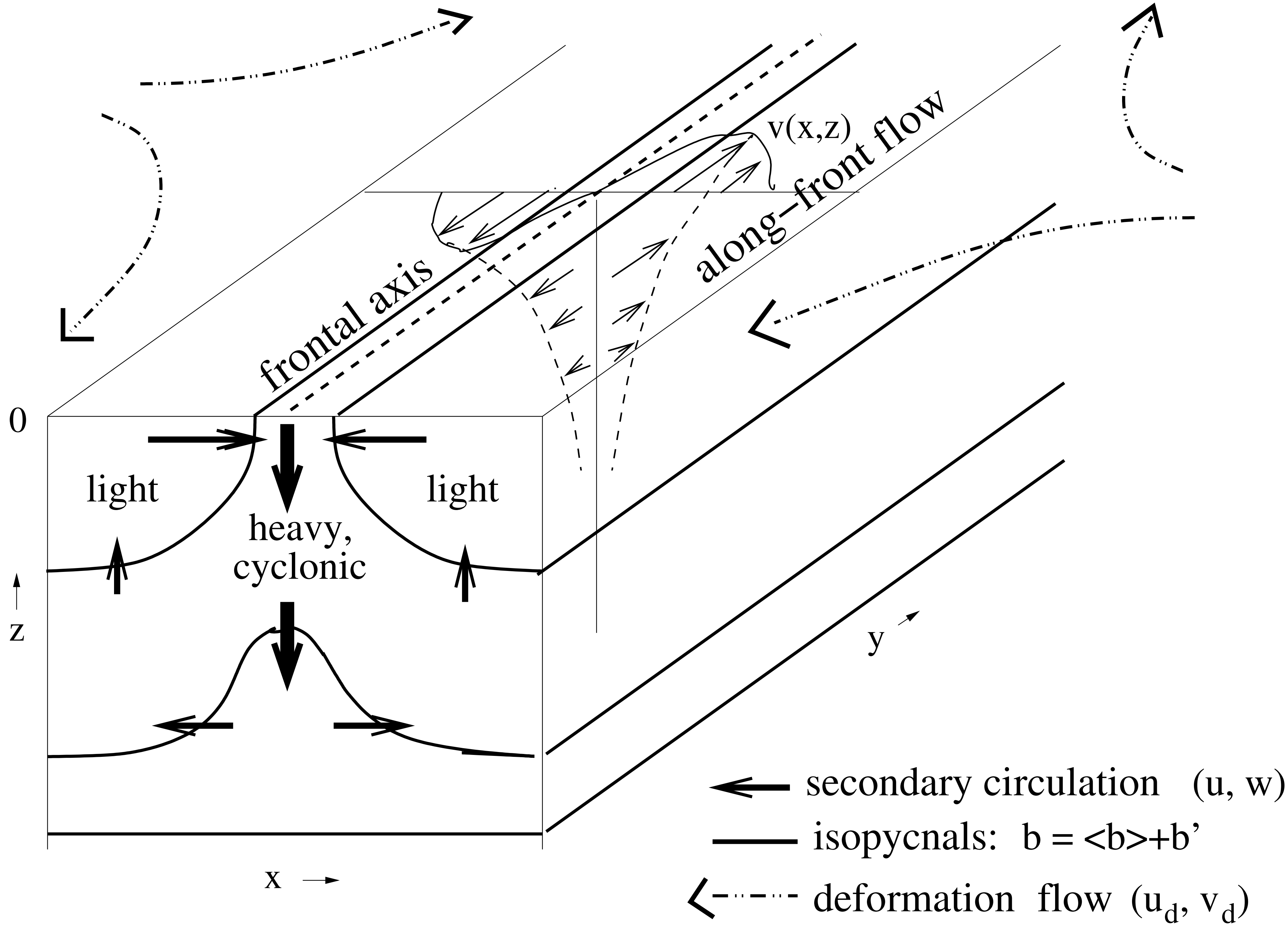
* lateral material mixing on intermediate lateral scales (or larger in long-lived vortices);

* vertical material fluxes near the top and bottom boundaries;

* route to energy dissipation for the general circulation that instigates diapycnal mixing.

Separated Gulf Stream in Winter: surface vorticity

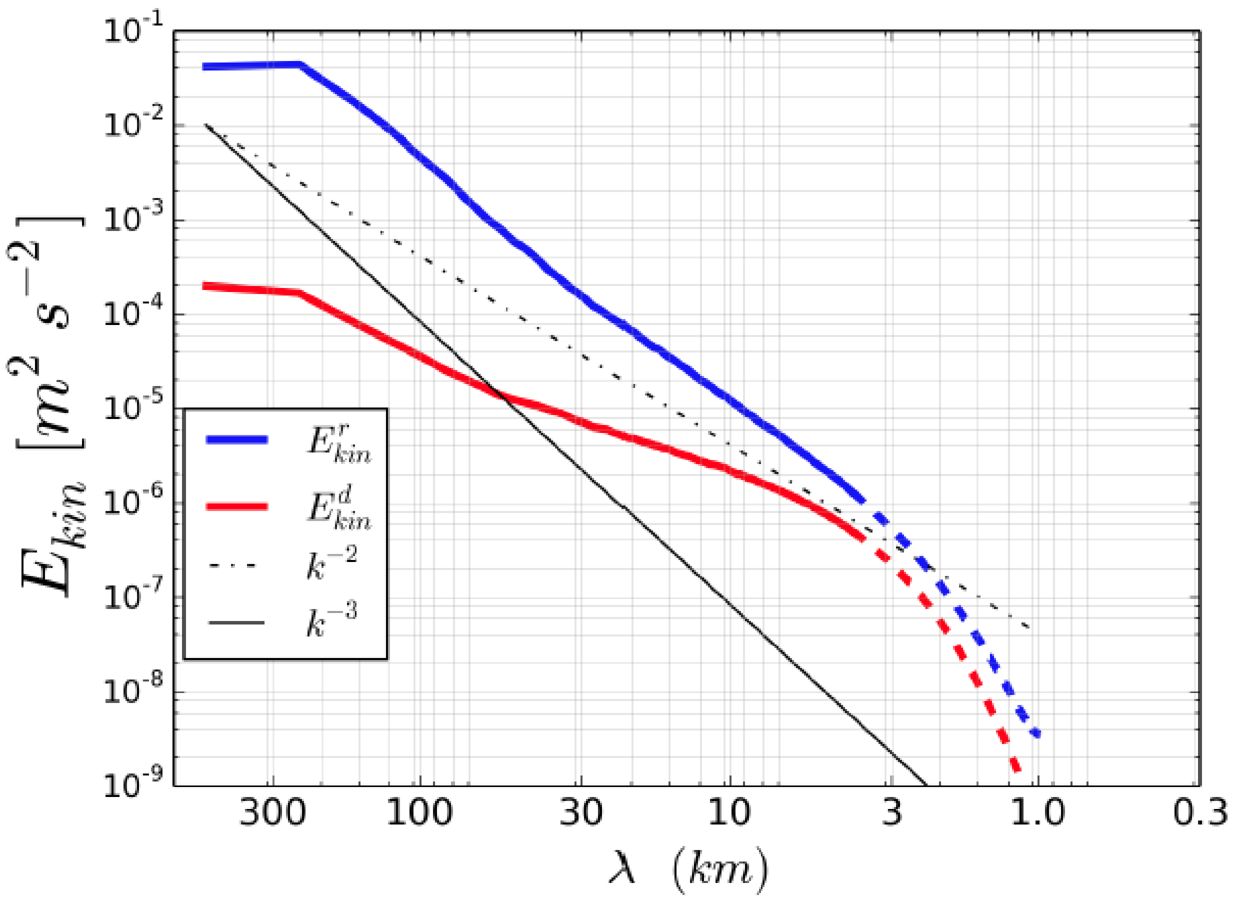


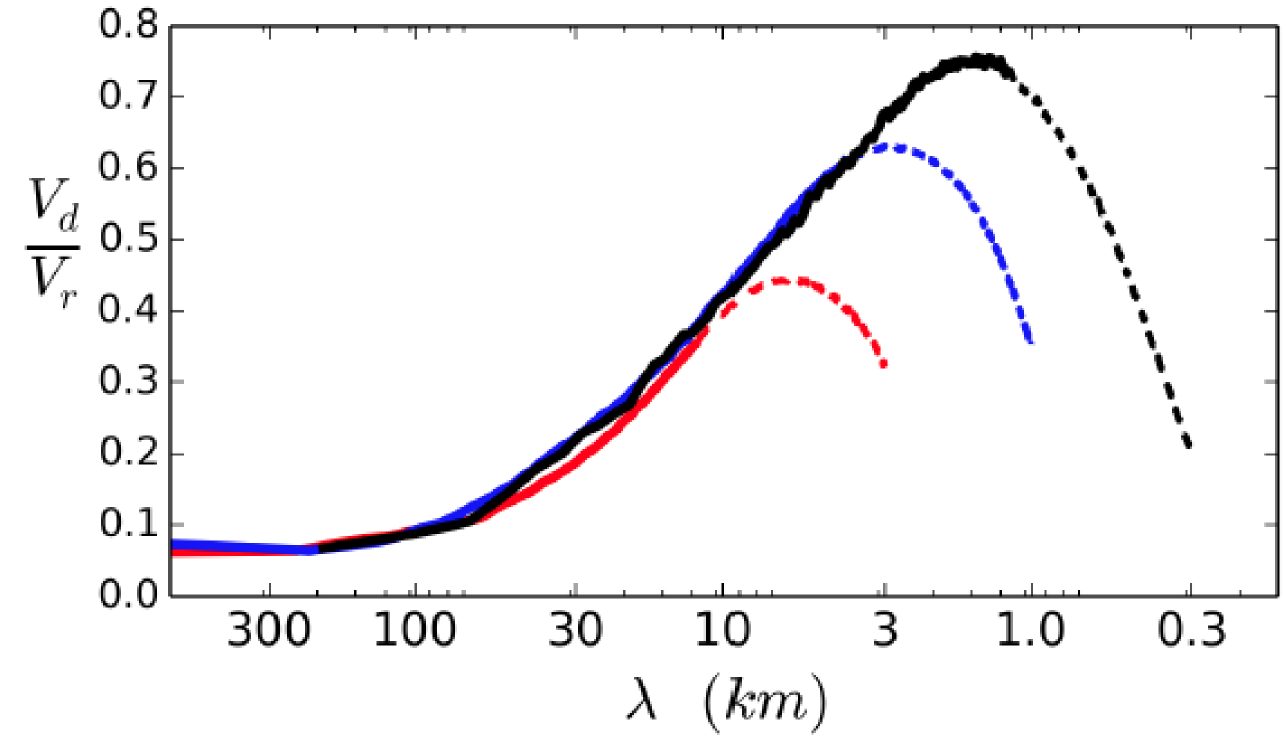


Surface **dense-filament frontogenesis** with secondary circulation and vorticity generation induced by a steady mesoscale deformation (strain) flow. $| \nabla_h \rho |$ and cyclonic vorticity (f ζ^z > 0) grow super-exponentially in time. This process is even stronger than "classical" density-step frontogenesis.

Helmholtz decomposition of horizontal flow at the surface in the Gulf Stream:

$$\mathbf{u}_h = \mathbf{u}_r + \mathbf{u}_d\,, \qquad \nabla \cdot \mathbf{u}_r = 0\,, \qquad \hat{\mathbf{z}} \cdot \nabla \times \mathbf{u}_d = 0\,.$$





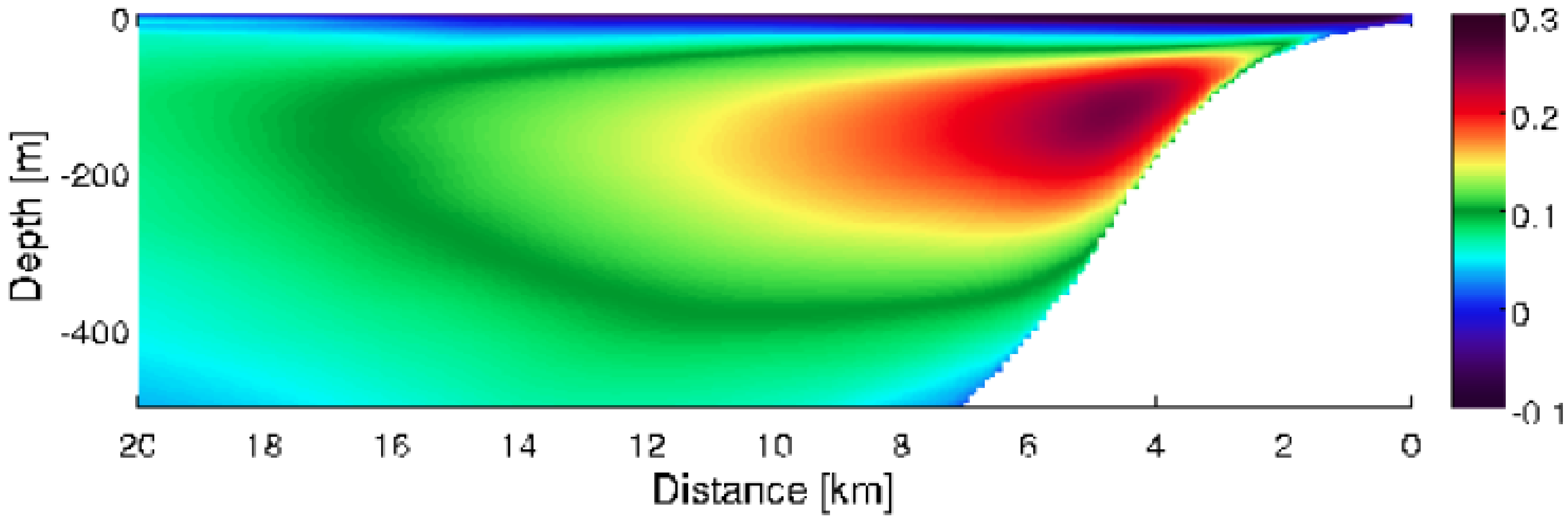
Azimuthally-averaged 2D wavenumber kinetic energy spectra in a simulation with dx = 0.5 km. Dashed lines indicate dissipation range.

Square-root ratio of divergent and rotational spectra for 3 solutions with dx = 1.5, 0.5, & 0.15 km. QG theory says this is O(Ro) and must be << 1.

=> QG behaviors are broken for λ smaller than about 30 km.

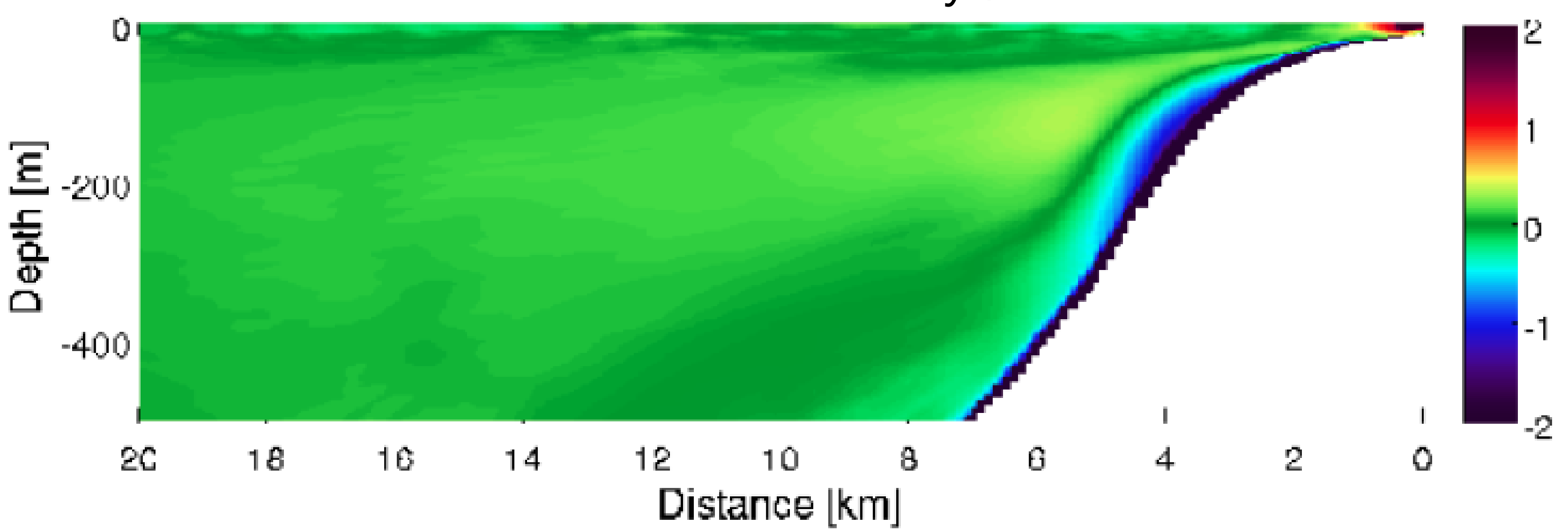
Bottom-boundary Generation of Vertical Vorticity in the California Undercurrent Upstream of a Monterey Bay Separation Point

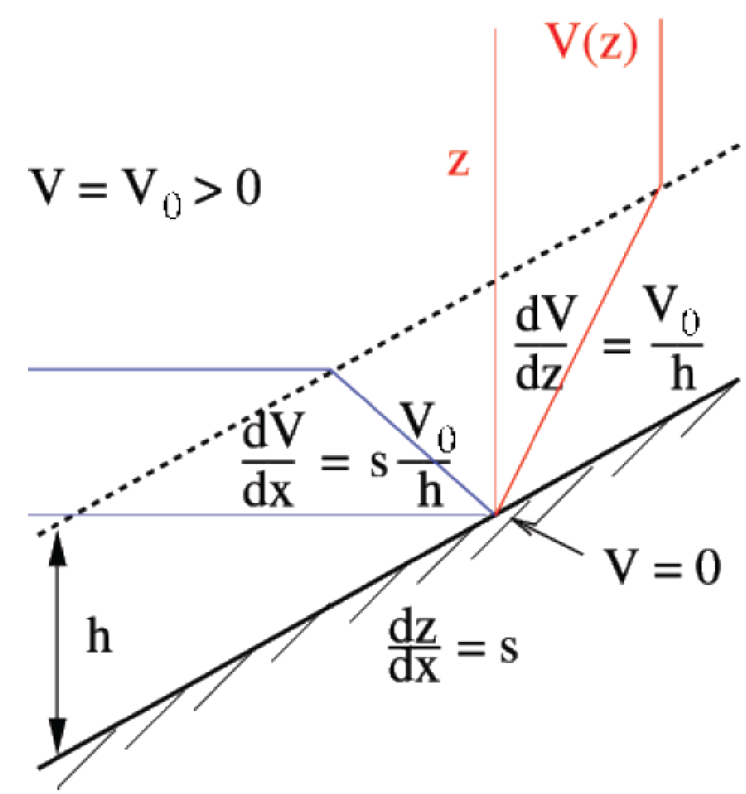
along-slope velocity [m/s]



generation mechanism in the turbulent bottom boundary layer:

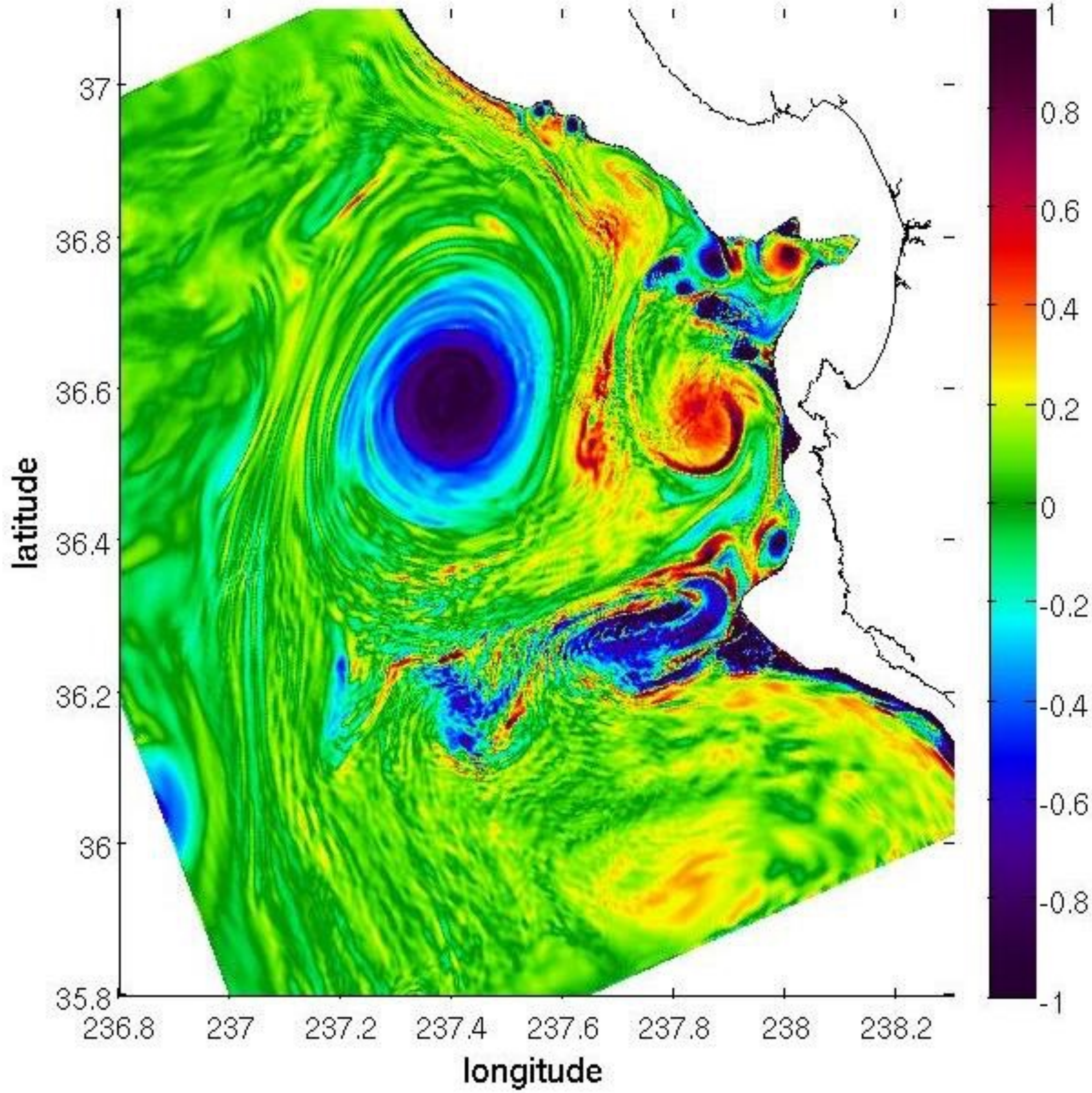
vertical vorticity / f





—> separation, wake instability, and formation of Submesoscale Coherent Vortices (CUDDIES)

(Molemaker et al., 2014)

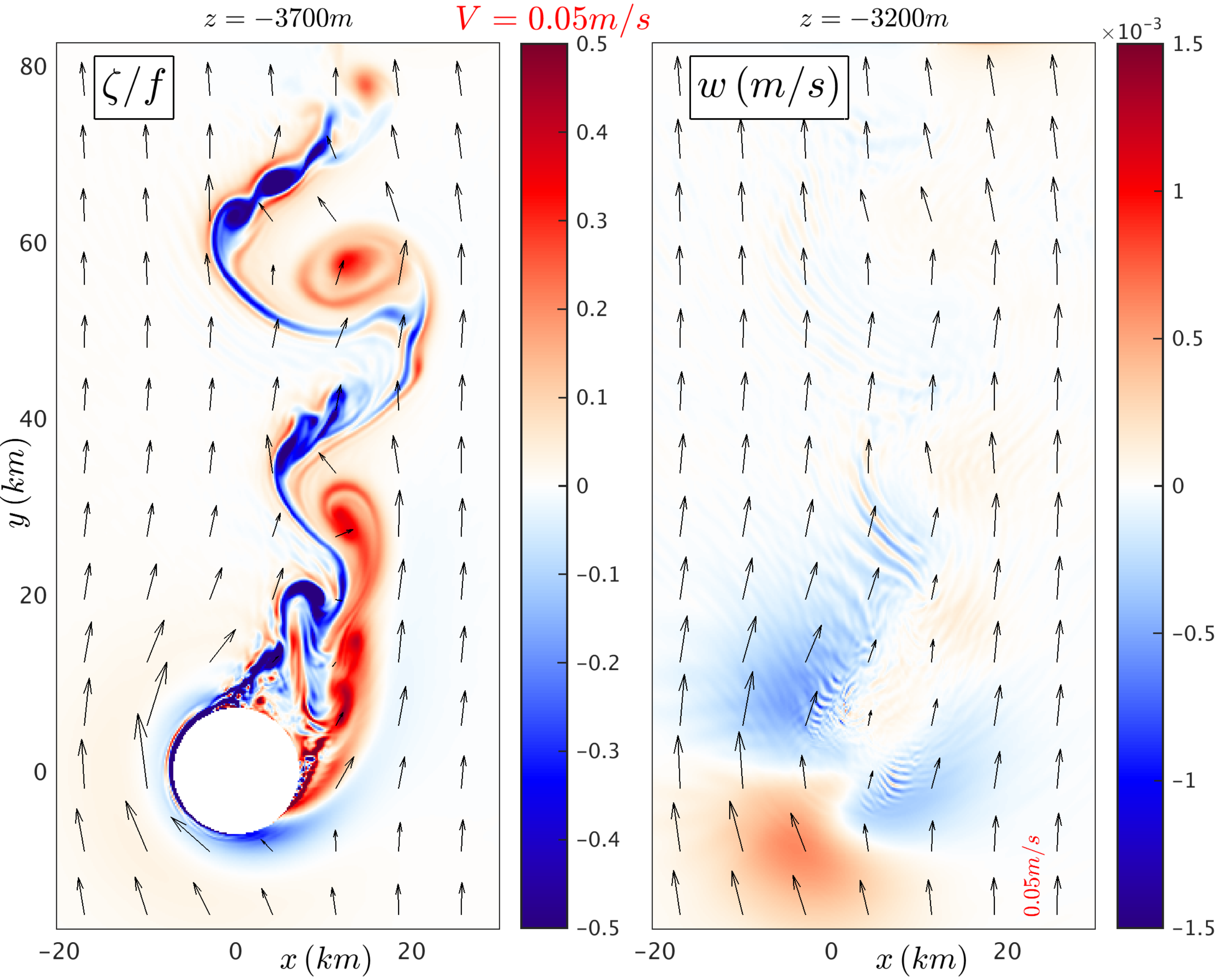


Snapshot of ζ^z / f at 250 m depth in Monterey Bay: the Undercurrent separates at Pt. Sur, goes centrifugally unstable, and eventually reorganizes into “Cuddies”: long-lived Submesoscale Coherent Vortices. Other boundary separation and submesoscale generation sites are also evident.

Uniform inflow past a stratified seamount: Submesoscale-vortical and IGW regimes.

[H = 4000 m, $h_{seamount}$ = 600 m, $D_{0.5}$ = 15 km, N/f = 7]

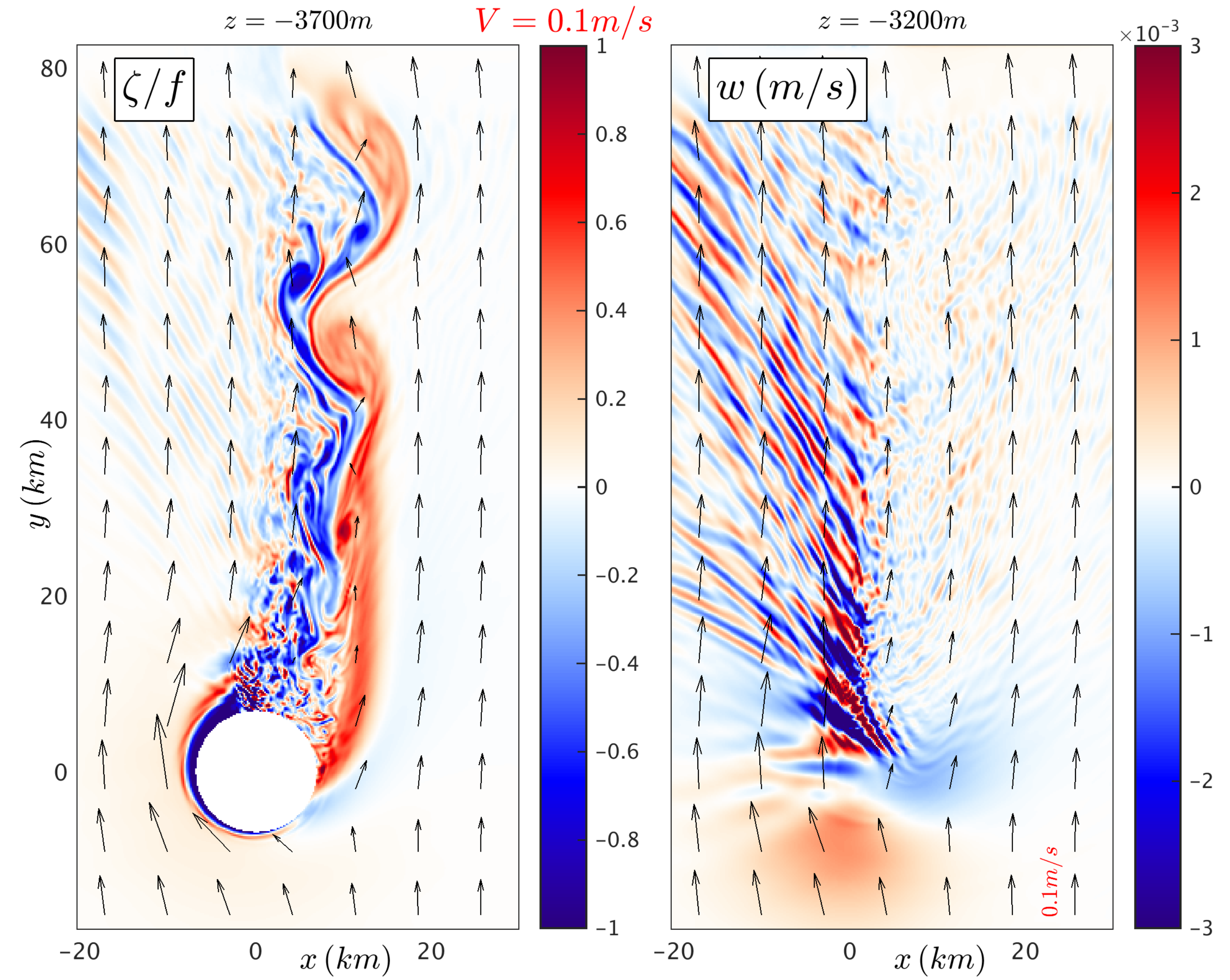
mid-mount just above



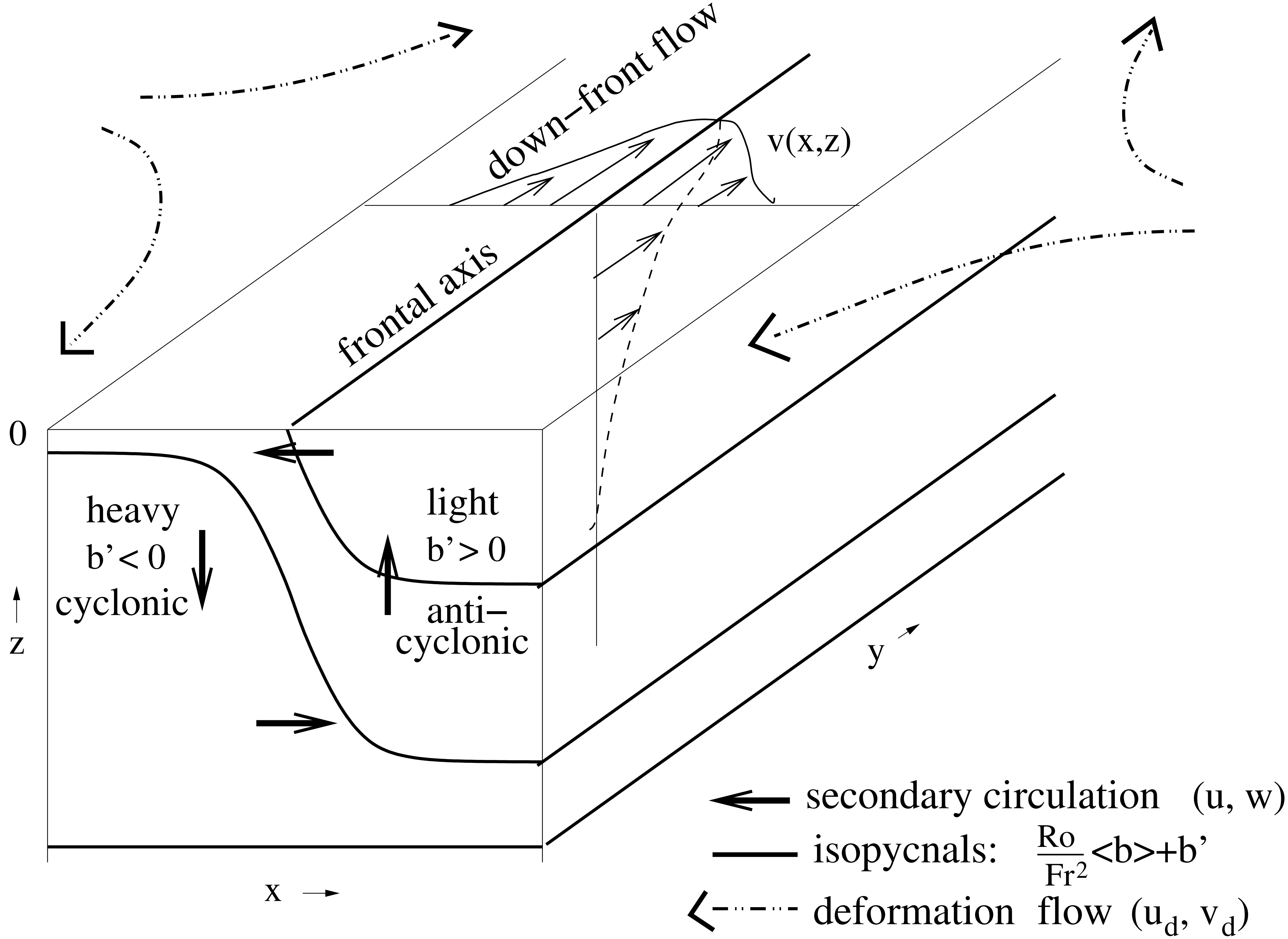
vortical regime

mixed wave & vortical regime

mid-mount just above

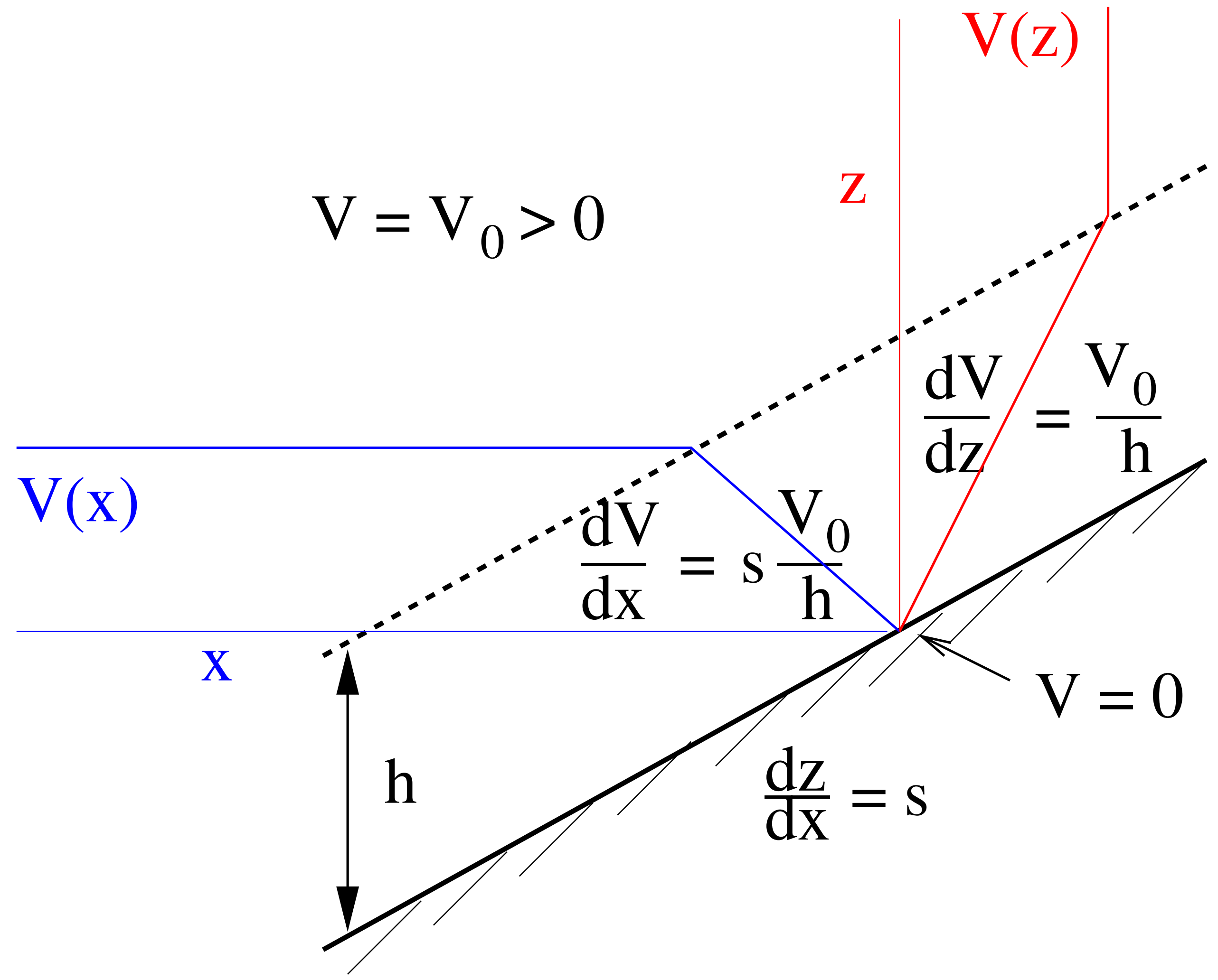


extra slides



Surface **frontogenesis** with secondary circulation and vorticity generation induced by a steady mesoscale deformation (strain) flow. $|\nabla_h \rho|$ and cyclonic vorticvity grow super-exponentially in time.

Vertical Vorticity Generation by Along-slope Bottom Flow



Along-slope current V + stratified $b(z)$ + Bottom Boundary Layer (BBL) $\Rightarrow$

- $b(z)$ weakly stratified in bottom layer
- $\zeta^z(x) = \partial_x v \sim Vs/h$, unlimited by f
- flow separation (macro- and mini-wakes)
- downstream shear instability (sometimes ageostrophic and centrifugal)
- anticyclonic SCV formation by “adjustment” around weakly stratified cores
- forward energy cascade $\rightarrow$ high mixing and dissipation in interior