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EDDY ROLES IN THE GENERAL CIRCULATION

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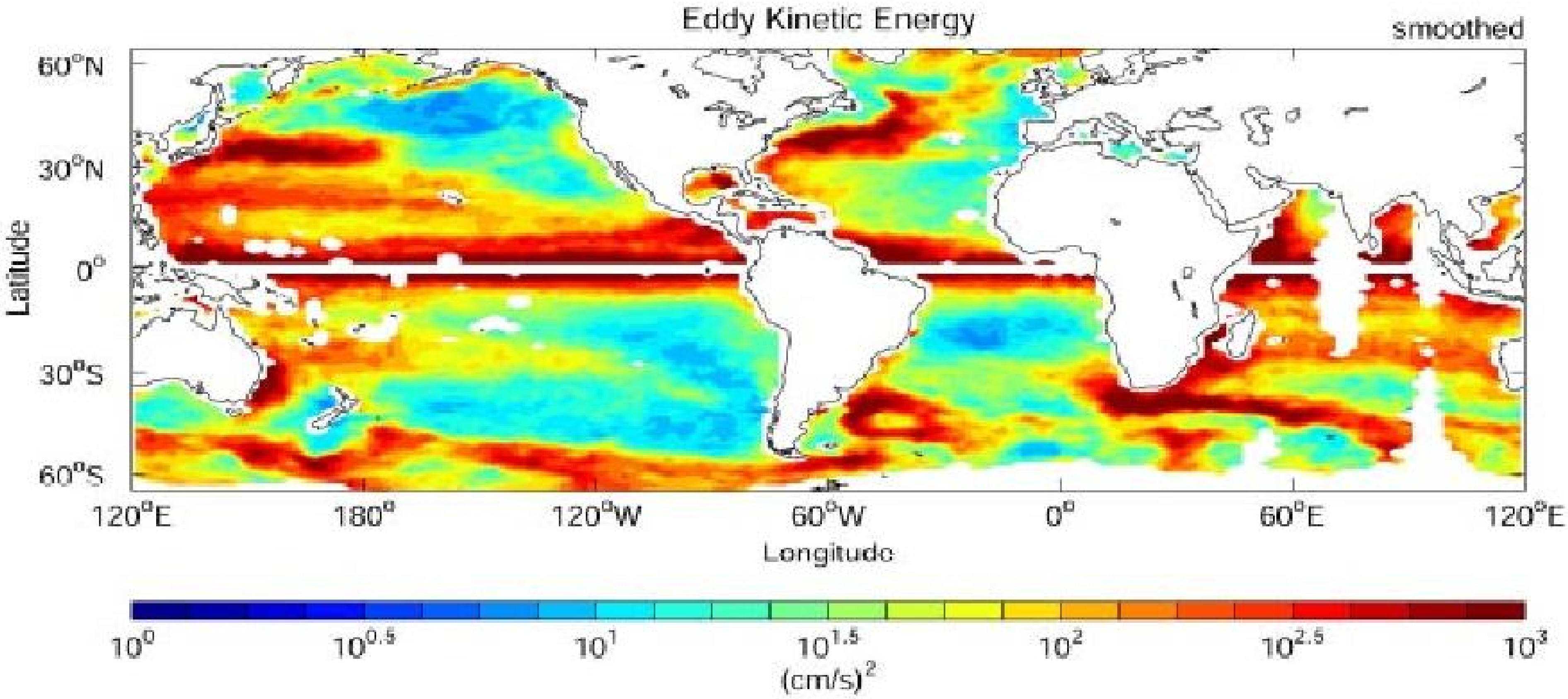

Surface geostrophic eddy kinetic energy estimated from the TOPEX/Poseidon-Jason1 tandem altimeter mission. Note the logarithmic scale. (Stammer, 2008)

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- Eddy Structure

$L \geq L_d = \frac{NH}{f}$; H for low vertical modes; $V \approx 0.1 - 1$ m s^{-1}; stronger in upper ocean

$Ro = \frac{V}{fL}$ and $Fr = \frac{V}{NH}$ small

- Eddy Dynamics

$\sim$ quasigeostrophic

strongly coupled to mean circulation; weakly coupled to surface forcing, inertia-gravity waves, and tides

- Eddy Modeling

dilemma: partially resolve with large, expensive grids or wholly parameterize with coarse, efficient grids

- Eddy Roles

criteria by which to judge representation of eddy effects in GCMs

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"Frictional" Maintenance of Strong Currents

boundary, Equatorial, Circumpolar, Azores, *etc.*

invocation of anisotropic eddy viscosity in both theory of currents and GCM practices

real processes are eddy instabilities:

- baroclinic instability of mean vertical shear
- barotropic instability of mean horizontal shear
- vertical shear instability in the Equatorial Undercurrent

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Material Dispersion and "Mixing"

mostly isopycnal in the quasi-adiabatic stratified interior

along-boundary and diapycnal in the turbulent boundary layers (especially the surface)

occasionally non-local by coherent vortex encapsulation ($e.g.,$ Meddies)

eddies mix potential vorticity along isopycnal surfaces, except where they don't

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Energy Cascades and Dissipation Routes

mean wind and buoyancy-flux work put energy into the general circulation; equilibration must occur by routes to dissipation

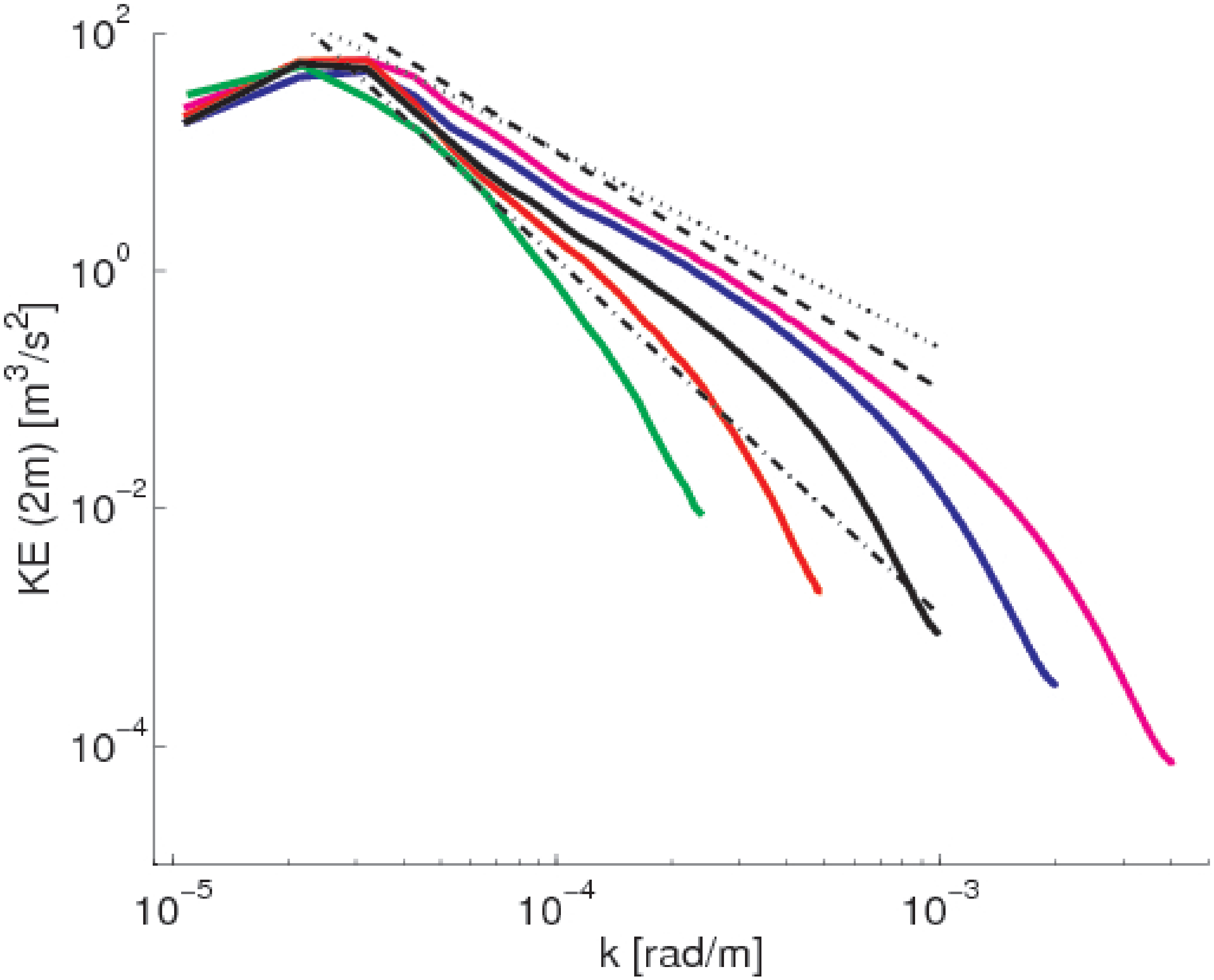
mean energy removal by eddy instabilities, but inverse energy cascade goes away from viscous dissipation of eddies

one dissipation route: bottom-boundary turbulent drag stress

tidal and internal-wave eddy viscosities are small

another route: forward energy cascade into the submesoscale through frontogenesis, topographic interactions, $etc.$., involving geostrophic, hydrostatic breakdown

Simulated Eastern Boundary Current: Horizontal Surface KE Spectrum



- convergence to $\sim k^{-2}$ (dashed) for Δx : 12 $\longrightarrow$ 0.75 km
- little mesoscale change with Δx in regional open-boundary configuration
- not forward enstrophy inertial-range of geostrophic turbulence $\sim k^{-3}$ (dot- dashed)
- not KE inertial-range $\sim k^{-5/3}$, neither forward 3D nor inverse QG or surface-QG cascades (dotted)

$\Rightarrow$ frontogenetic energization of submesoscale (Capet *et al.*, 2008)

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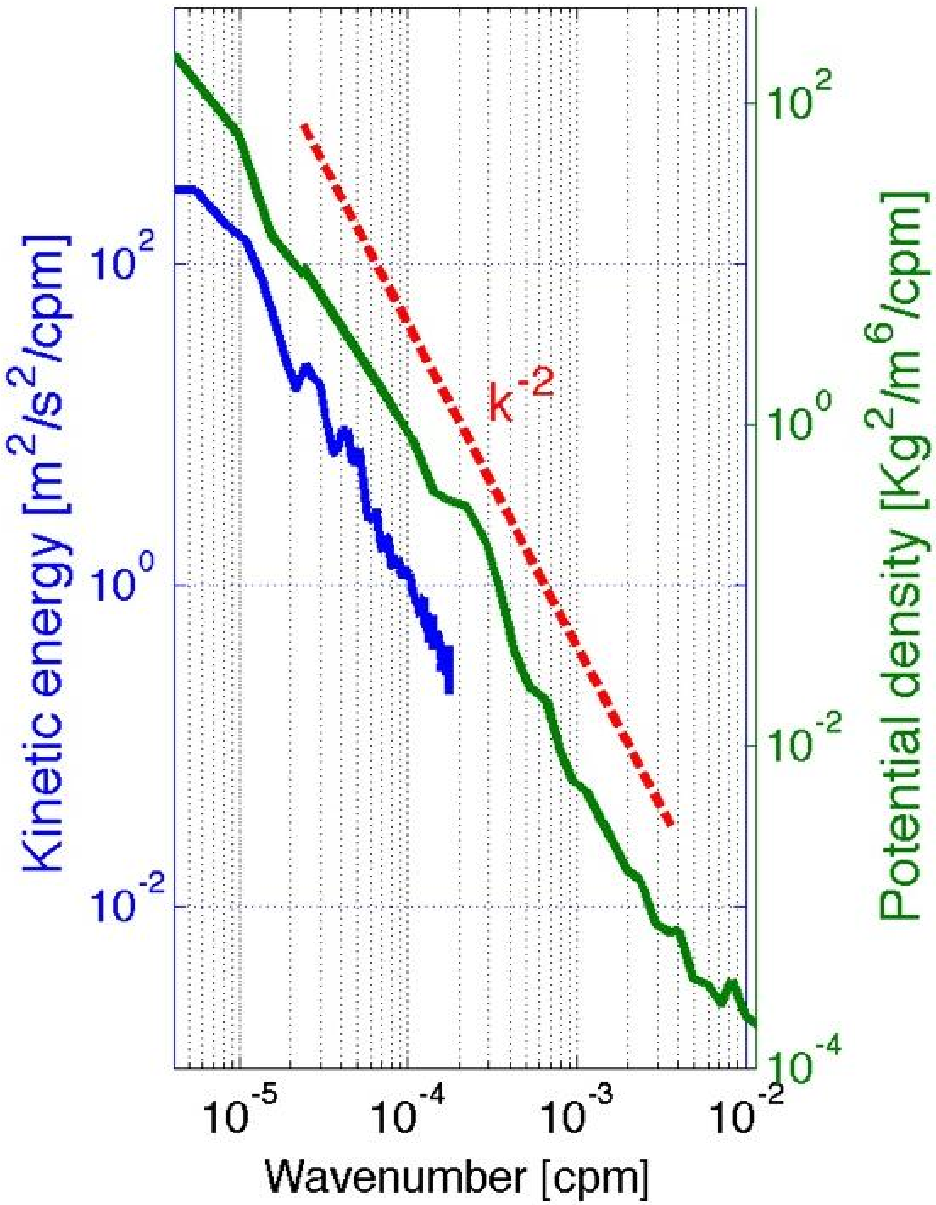
Measured Density and KE Spectra



Horizontal wavenumber spectrum for near-surface density measured from a towed SeaSoar and horizontal velocity from a shipboard ADCP in the subtropical Pacific. (Ferrari & Rudnick, 2000)

cf., submesoscale surface chlorophyll spectrum $\sim k^{-2}$ from satellite color. (Denman & Abbot, 1988.)

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Lagrangian Mean Advection

hypothesis: eddies quasi-adiabatically transport tracers and release APE in the stably stratified interior

eddy-induced advection (bolus velocity) by

$$\mathbf{v}^* \; = \; \nabla \times \mathbf{\Psi}^* , \qquad \Psi^* \; = \; - \frac{\langle \, \mathbf{v}' b' \, \rangle \times \nabla \langle \, b \, \rangle}{|\nabla \langle \, b \, \rangle|^2} \, .$$

with $b = -g\rho/\rho_0$ the buoyancy and $\langle \cdot \rangle$ an eddy average. For any tracer c, the eddy flux is

$$\langle \, \mathbf{v}' c' \, \rangle \; \equiv \; \mathbf{\Psi}^* \times \nabla \langle \, c \, \rangle + \mathbf{R}^* \, ,$$

where $\mathbf{R}^*$ is isopycnal mixing in the interior

a continuing challenge to parameterize $\mathbf{v}^*$ and $\mathbf{R}^*$, both in RANS mode (non-eddy) and LES mode (eddy-permitting)

an alternative view is that $\mathbf{v}^*$ should be based on eddy PV flux and mean PV gradients is problematic in several ways

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Eddy Density Restratification

baroclinic instability in particular, and baroclinic energy conversion (APE $\rightarrow$ KE) in general, $\Rightarrow \langle\, w'b' \,\rangle \,>\, 0$

$\Rightarrow$ quasi-adiabatic flattening of isopycnal surfaces increasing the vertical stratification

it happens many places in the pycnocline

it also happens in the upper ocean due to mixed-layer instability ($\partial_z v$ with weak N) and frontogenesis, working against boundary-layer vertical mixing

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Eddy Ventilation and Subduction

isopycnal eddy transport implies an exchange of material properties with the interior where mean isopycnal surfaces intersect the surface within a turbulent boundary layer

Eddy Stratification Control

hypothesis: mean stratification is set by surface heat and water fluxes convolved with isopycnal outcropping and interior topology ($cf.$, the ventilated thermocline)

the control by eddies occurs through influences on buoyancy transport: a combination of eddy-induced advection, restratification, and ventilation/subduction

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Eddy-induced Frontogenesis and Filamentogenesis

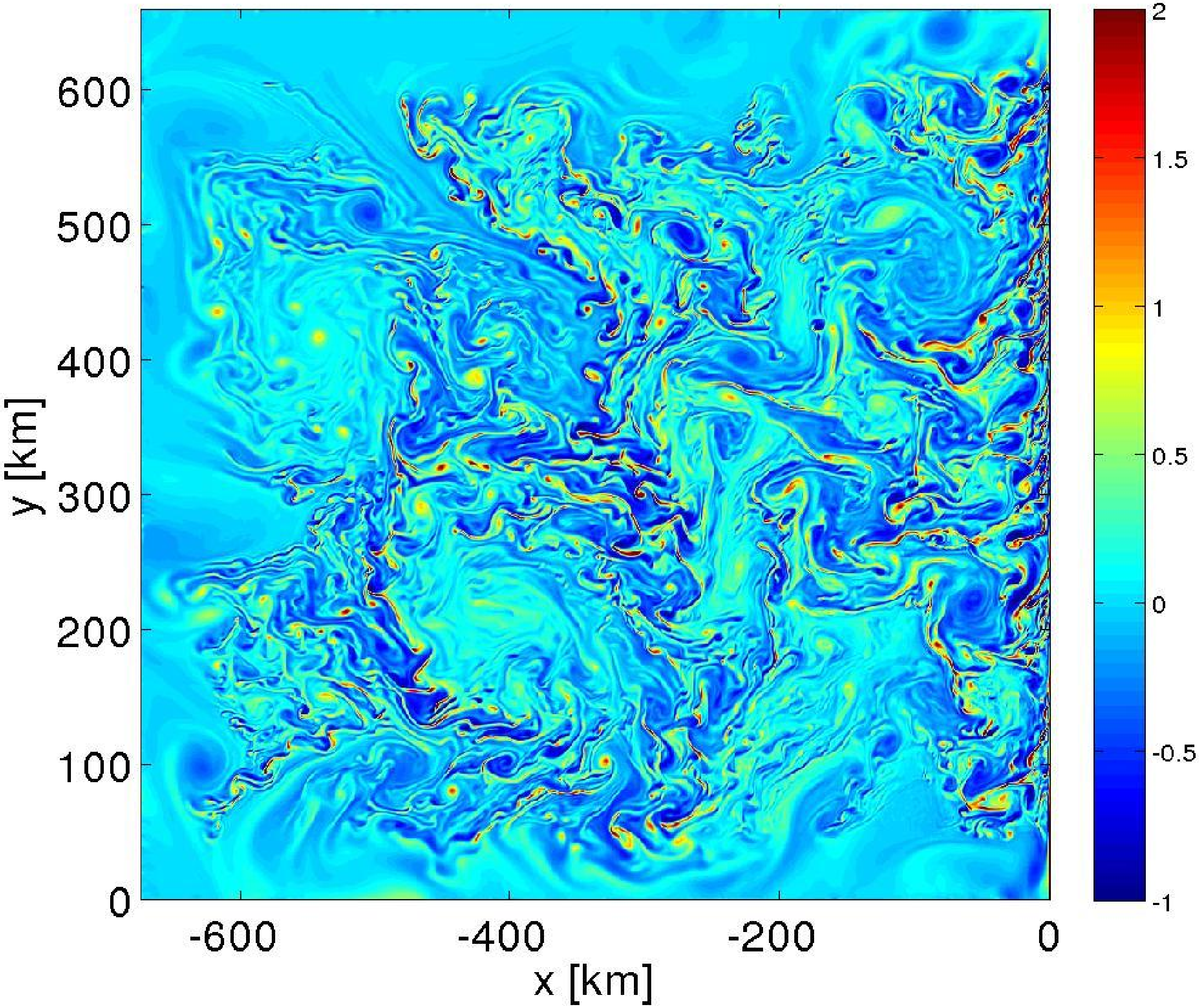
mesoscale strain rate (a.k.a. deformation flow, confluent flow) on eddy edges induces ageostrophic frontogenesis and filamentogenesis into the submesoscale, most strongly at the surface

filamentogenesis is analog of frontogenesis except for a buoyancy lateral extremum instead of monotonic lateral gradient

$\Rightarrow$ loss of balance; forward energy cascade (partly through submesoscale frontal instability); restratification; euphotic nutrient input; and material export to the interior

partly, but incompletely, represented in the surface quasigeostrophic approximation (SQG)

ω^z/f



Instantaneous surface vertical vorticity in a subtropical Eastern Boundary Current simulation. Submesoscales arise mainly by frontogenesis and frontal instability. (Capet *et al.*, 2008)

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Eddy Rectification

Reynolds stress from Rossby wave radiation forces a mean current: for a zonal eddy source on the β-plane, the mean flow is eastward in the source region and westward away from it.

in an eastward baroclinic zonal jet ($e.g.,$ ACC), up-gradient momentum flux accelerates the jet core — the opposite of eddy viscosity

transient, turbulent eddies force cyclonic flows along f/H contours ($e.g.,$ cyclonic basin-rim currents). A.k.a., the Neptune effect.

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Topographic Form Stress

time-mean eddies in a mean current over mesoscale topography provide a mean bottom stress that can be much bigger than the turbulent drag force, especially in the ACC and lateral boundary currents

form stress is not a direct energy sink, so it does not help in the mean energy balance except indirectly by altering mean and eddy currents and their viscous dissipation routes

form stress may also arise in association with gravity lee waves, a possibly important non-eddy sink of mean and eddy momentum and energy

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Biological Pumping and Quenching

suppling nutrients to oligotrophic plankton populations

eddy pumping is the reversible lifting of isopycnal surfaces into the euphotic zone where nutrients can be consumed, followed by nutrient recharge after subsidence through isopycnal eddy mixing

eddy quenching is where incompletely consumed nutrients are subducted along plunging isopycnals ($e.g.,$ offshore in the EBC)

near-surface w is much larger for submesoscale flows than for mesoscale, hence may often provide a more important eddy biological effect

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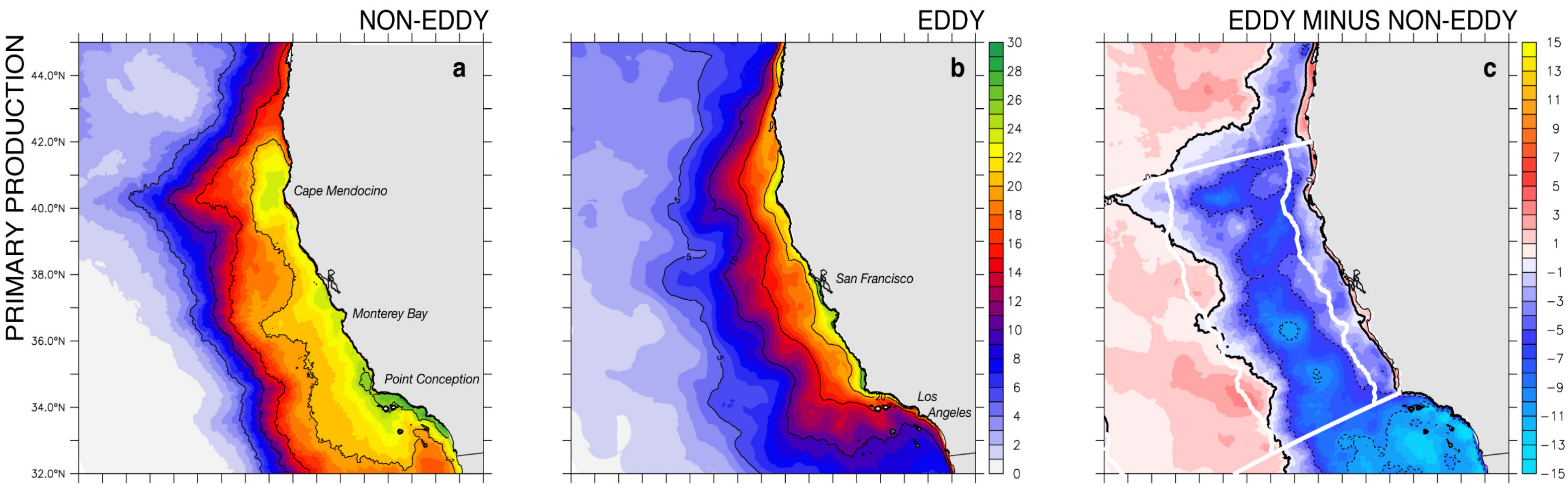
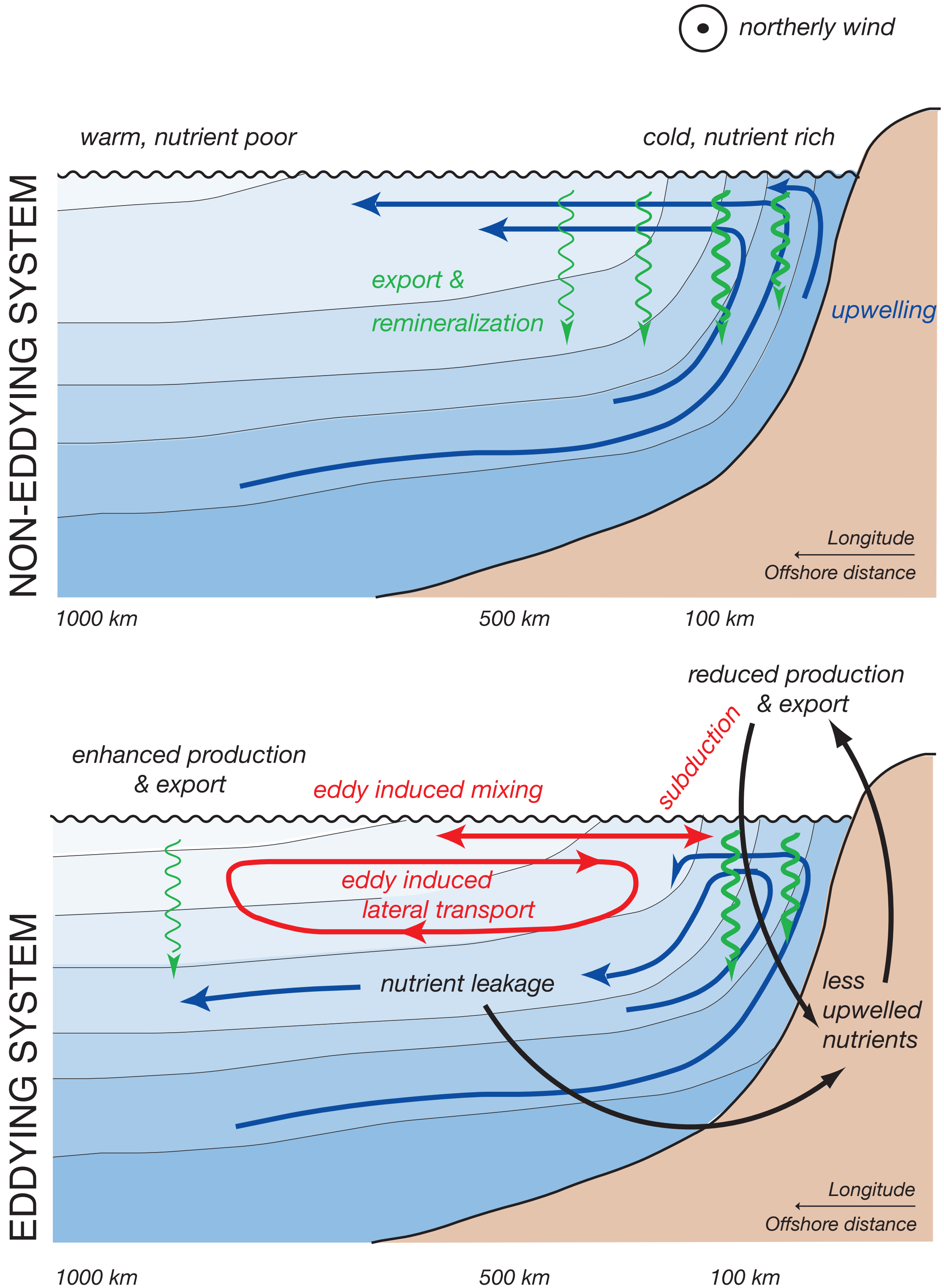


Eddy quenching: mean primary production [mol C m^{-2} yr^{-1}] in the California Current System, comparing a no-eddy case (with momentum advection suppressed) and an eddy-resolving case. (Gruber *et al.*, 2009)



Eddy transports leading to eddy quenching in an Eastern Boundary Current. (Gruber *et al.*, 2009)

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Generation of Intrinsic Climate Variability

spontaneous low-frequency variability of unstable wind gyres and ACC even with steady forcing through a broadening of the "eddy" spectrum to low frequencies and large scales

seen best in very high-resolution simulations (large eddy-viscous Re)

probably many other examples of broad-band intrinsic oceanic variability on climate-relevant scales: how well does it compete with intrinsic atmospheric variability?

Summary

Eddy processes and eddy fluxes have many roles in the oceanic general circulation and climate.

Evolution in oceanic modeling toward routinely including eddies through finer-scale grid resolution is a significant advance. But it needs supporting parameterization advances.

In spite of many theoretical and idealized computational demonstrations of eddy effects, as yet few strong tests have been performed with measurements, which are much needed.