Potential Vorticity Dynamics Near the Equator

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Potential vorticity and hydrodynamic stability

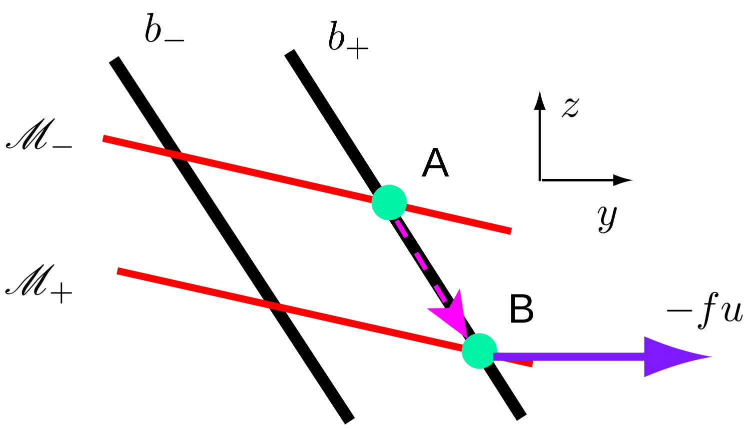
$$q = \boldsymbol{\omega}_a \cdot \nabla b$$

$$\boldsymbol{\omega}_a = f\hat{k} + \nabla \times \mathbf{u}; \quad b = -g\rho/\rho_o$$

- When $qf < 0$, the fluid is unstable to 2-D overturning motions termed gravitational, inertial, or symmetric instability.
- For a 2-D fluid, the PV is equal to the Jacobian of the buoyancy and absolute momentum $q = J(b, \mathscr{M}) = b_y \mathscr{M}_z - b_z \mathscr{M}_y$

$$\mathscr{M} = u - \int f dy$$

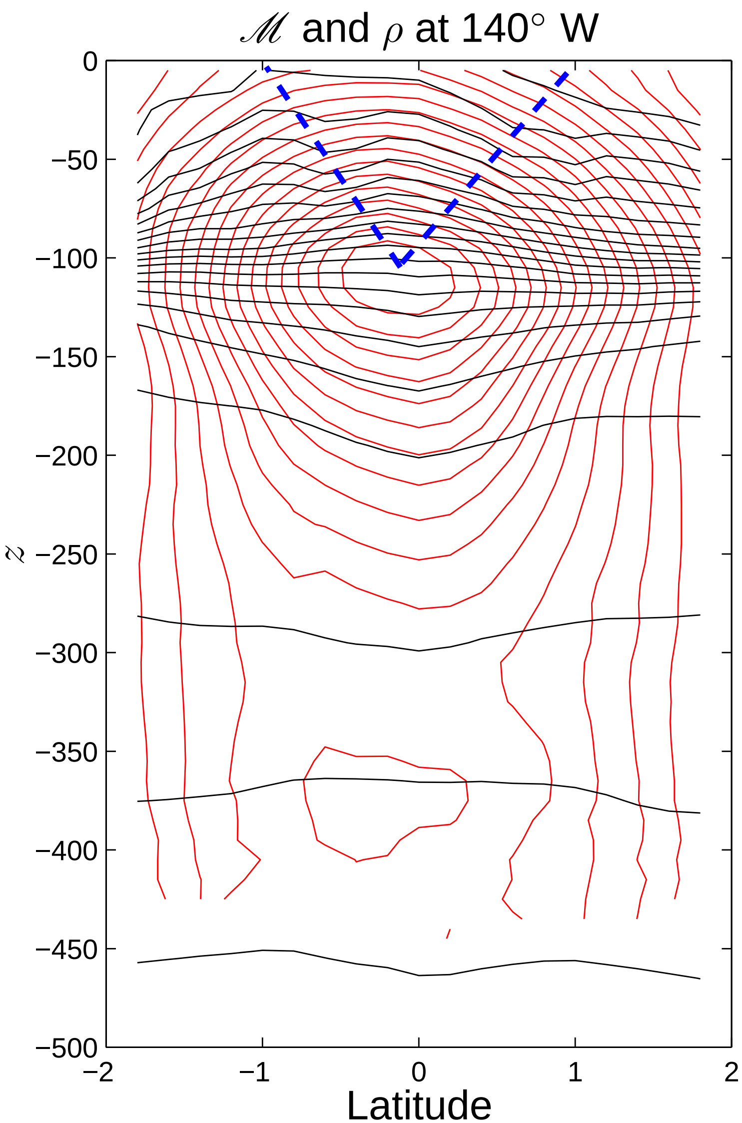
- Fluid unstable when isopycnals are steeper than $\mathscr{M}$-surfaces.



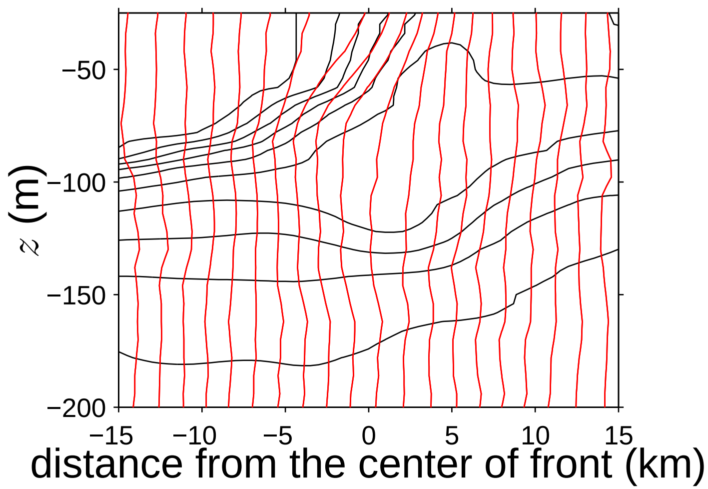
- Displace a fluid parcel along an isopycnal from A to B.
- Parcel conserves its buoyancy and absolute momentum and therefore reduces its zonal velocity.
- Coriolis force accelerates parcel to the north, away from A.

- When $\mathscr{M}$-surfaces are $\parallel$ to isopycnals, $q = 0$, and if the flow is in a thermal-wind balance, $Ri = 1$.

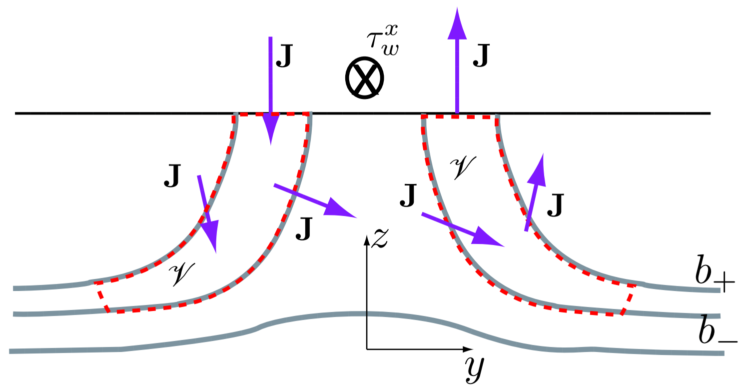
Observational evidence of stratified, low PV layers



- Johnson et al. (2002) mean CTD/ADCP sections show evidence of a wedge of fluid within $\pm 1°$ of the equator and above $z \approx -100$ m where $\mathscr{M}$-surfaces are nearly $\parallel$ to isopycnals.
- CTD/ADCP sections at the subpolar front of the Japan/East Sea taken during cold-air outbreaks reveal that $q < 0$ at the front.



Potential vorticity dynamics



- Flux form of PV equation

$$\frac{\partial q}{\partial t} = -\nabla \cdot \mathbf{J}$$

$$\mathbf{J} = \mathbf{u}q + \nabla b \times \mathbf{F} - \mathscr{D}\boldsymbol{\omega}_a$$

- Nonadvective PV flux associated with frictional forces $\mathbf{F}$ and diabatic processes $\mathscr{D} = Db/Dt$

- What PV flux will cause the PV averaged over $\mathscr{V}$ to go to zero?

$$\frac{\partial}{\partial t} \iiint_{\mathscr{V}} q dV \quad = \quad - \iint_{z=0} J_z dS$$

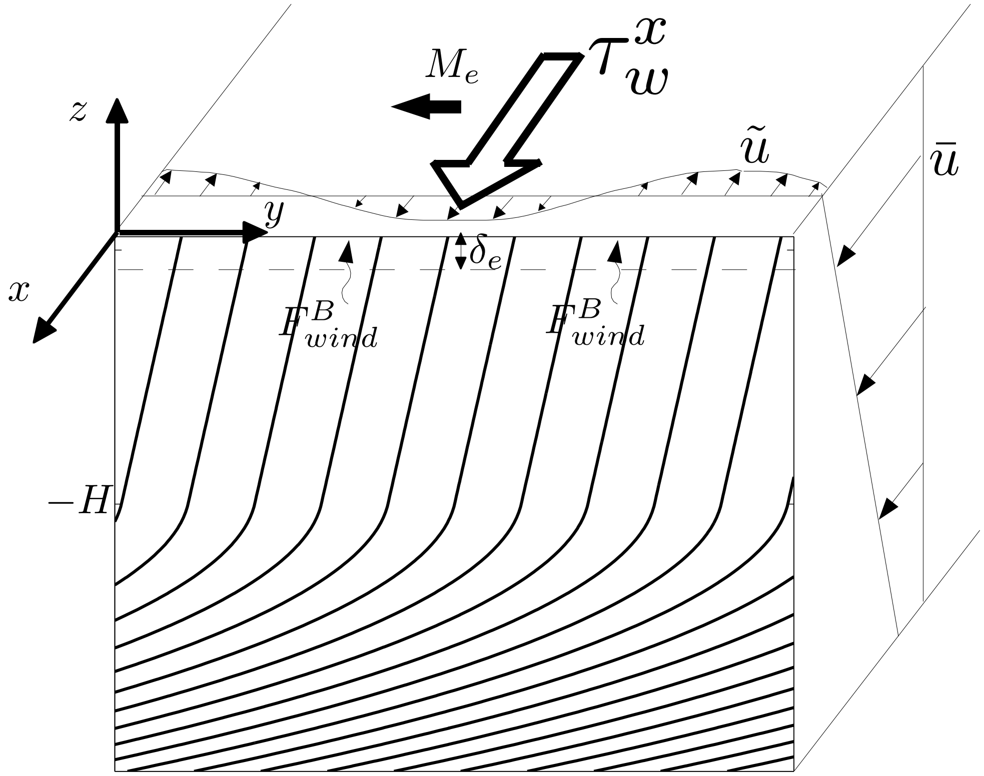
  - An upward (downward) surface PV flux north (south) of the equator.

- Surface $J_z^F = \nabla_h b \times \mathbf{F}$ is upward (downward south of the equator) when $\boldsymbol{\tau}_w \cdot \partial \mathbf{u}_g / \partial z > 0$ (“down-front” wind) $\rightarrow$ westward wind-stress.

PV destruction by winds at a midlatitude front

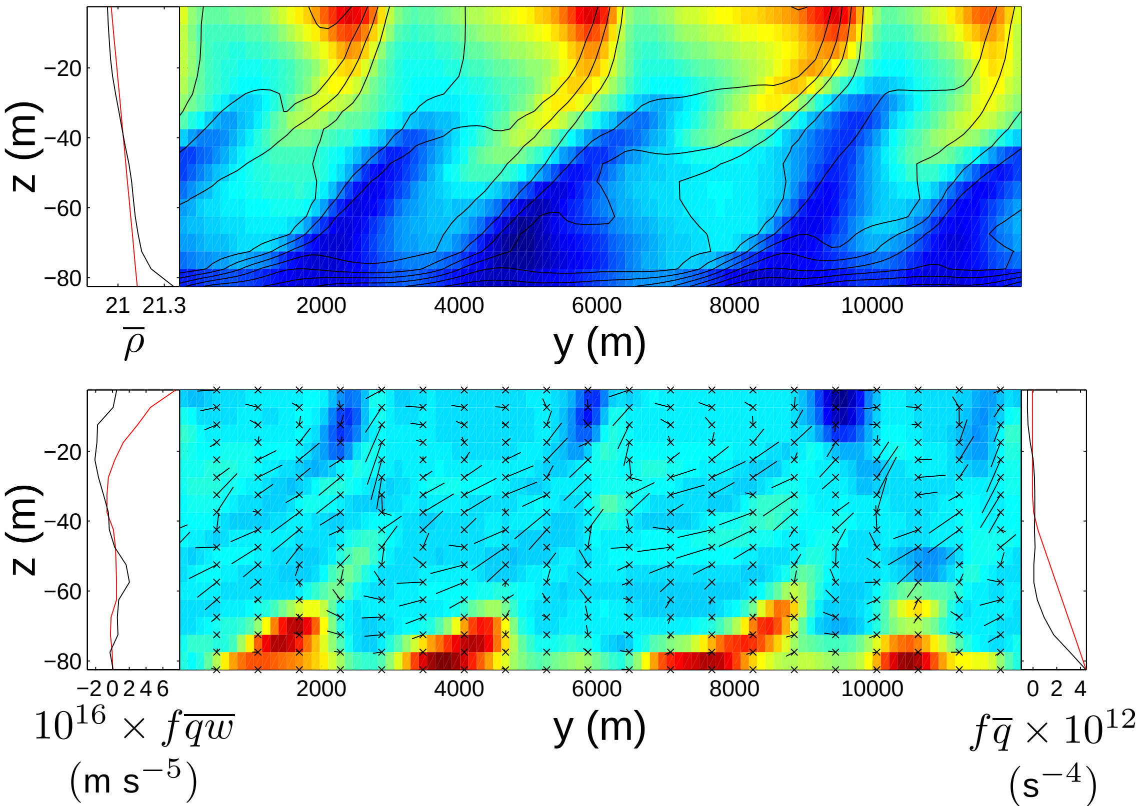
- Force a baroclinic zone with a spatially-uniform down-front wind-stress.
- Mixed layer with constant N^2_{ml}, $S^2 = f\frac{\partial \bar{u}}{\partial z} = -\frac{\partial \bar{b}}{\partial y}$, and potential vorticity

$$q = fN^2_{ml} - S^4/f \approx 0$$



- Studied the evolution of the $q \approx 0$ layer using high resolution, hydrostatic numerical simulations utilizing a KPP mixing scheme modified to parameterize Ekman-driven convection.

2-D hydrostatic numerical experiments using ROMS



- For down-front winds, the vertical component of the PV flux at the surface $-F^x \partial b/\partial y > 0 \rightarrow$ extracts PV from the fluid.
- The flux is transmitted through the $q \approx 0$ “mixed”-layer by the ageostrophic secondary circulation (ASC), becoming an advective flux $\overline{wq} > 0$.
- Advective flux extracts PV from the pycnocline, thus deepening the $q \approx 0$ layer. ASC may be termed “forced symmetric instability.”

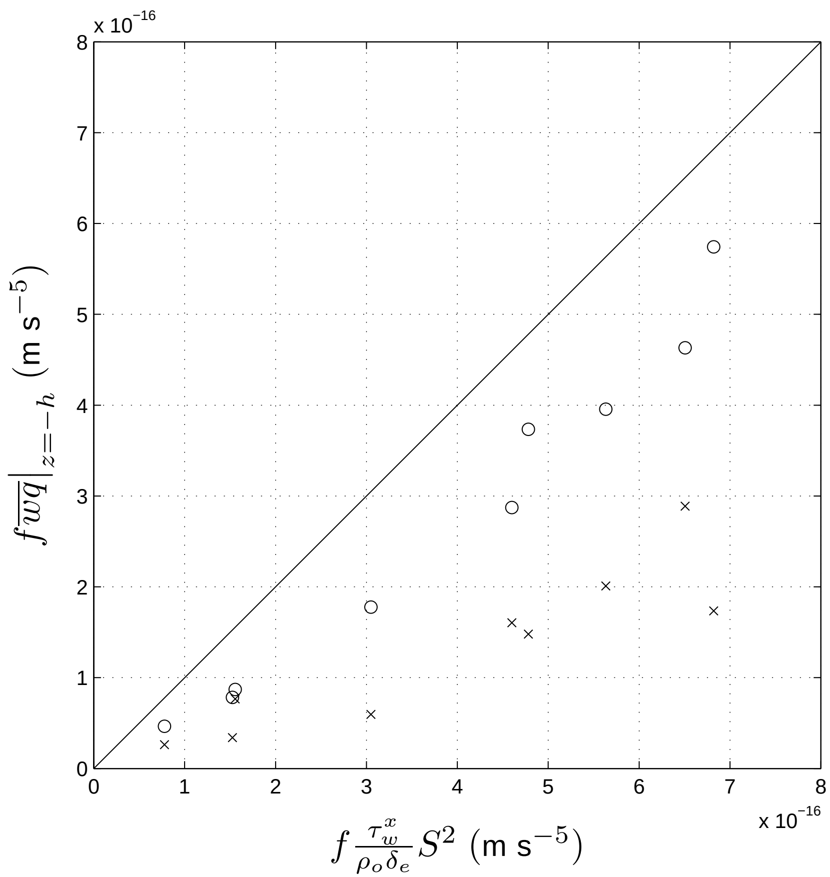
Scaling for the potential vorticity flux

- Scaling for surface PV flux

$$-F^x\frac{\partial b}{\partial y} \sim \frac{\tau_w^x}{\rho_o\delta_e}S^2$$

$$S^2 = -\frac{\partial \bar{b}}{\partial y}$$

- Advective PV flux $\overline{wq}$ at the base of the "mixed"-layer scales with the surface PV flux.



- Implication: for a coarse-grid model that can resolve the baroclinic zone and S^2, an estimate for $\overline{wq}\big|_{z=-h}$ can be made and used as a nonlocal flux to determine the rate of deepening of the $q \approx 0$ layer.

Conclusions and proposed numerical experiments

- The similarity in the near-surface PV and PV fluxes driven by atmospheric forcing near the equator and at midlatitude fronts motivates performing numerical experiments designed to study PV reduction by “forced symmetric instability.”
  - High-resolution, 2-D numerical experiments initialized with an idealized version of the near equatorial flow and forced by westward winds and buoyancy forcing with diurnal variability.
  - If “forced symmetric instability” is prominent, develop parameterizations for the fluxes of PV and other tracers associated with the ageostrophic flow.
  - Utilize these parameterizations in coarser resolution 3-D experiments.

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