More than a length scale:
Air-sea interaction at submesoscale fronts

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Submesoscales are dynamically unique

- Mesoscale: ~100 km
- Submesoscale: ~5 km
- Small-scale mixing: ~50 m
Submesoscales are dynamically unique

Rossby number: \[ Ro \sim \frac{U}{fL} \]

Richardson number: \[ Ri \sim \frac{N^2}{U^2} \]

- \( U \): velocity scale
- \( f \): Coriolis frequency
- \( L \): horizontal length scale
- \( N^2 \): vertical buoyancy gradient
Submesoscales are dynamically unique

Planetary rotation, nonlinearity, and stratification are all important

Rossby number: \( Ro \sim \frac{U}{fL} \)

Richardson number: \( Ri \sim \frac{N^2}{U_z^2} \)

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Ro ≪ 1, Ri ≫ 1
Ro ~ 1, Ri ~ 1
Ro ≫ 1, Ri < 1
What are the mechanisms of submesoscale air-sea interaction?

Physical mechanisms of *mesoscale* air-sea interaction also active at *submesoscale*
What are the mechanisms of submesoscale air-sea interaction?

LES suggests strong response of ABL (including winds) to submesoscale fronts

To what extent does this hold for realistic submesoscale turbulence? Always in a large Rossby number regime \( \frac{U_a}{fL_{SST}} \gg 1 \)

Heat fluxes also generate a direct flux of eddy potential energy (see poster by Igor Uchoa!)
What are the mechanisms of submesoscale air-sea interaction?

\[ \tau = \rho_a c_d |U_a - u_o| (U_a - u_o) \]

\[ \tau' = \tau - \rho_a c_d |U_a| U_a \]

Surface currents also introduce a current feedback on stress (CFB)

Definition is entirely local, mechanism is robust at all scales
Current feedback introduces small-scale variability in stress

Re-entrant channel
$\Delta x = \Delta y = 500 \text{ m}$
Mild wind towards NE ($7 \text{ m s}^{-1}$)
Surface buoyancy loss ($25 \text{ W m}^{-2}$)
Spun-up for 360 days at lower res.
Current feedback introduces small-scale variability in stress

Re-entrant channel
\( \Delta x = \Delta y = 500 \text{ m} \)

Moderate wind towards NE (7 ms\(^{-1}\))

Surface buoyancy loss (25 Wm\(^{-2}\))

Spun-up for 360 days at lower res.
Stress anomalies oppose the surface currents

Anti-correlation between currents and stress important for wind-work, eddy energetics.

eg. Renault et al. 2018
Anti-correlation between currents and stress important for wind-work, eddy energetics. 

*eg. Renault et al. 2018*

Correlation with buoyancy gradient will affect the Ekman buoyancy flux at fronts!
Current feedback modifies the Ekman buoyancy flux

\[ EBF = \frac{\tau \times \hat{k}}{\rho_0 f} \cdot \nabla_h b \]

Ekman transport advects buoyancy at fronts:

Observed values equivalent to \(O(10,000 \text{ Wm}^{-2})\) surface heat fluxes!

Also generates a flux of potential vorticity.

D’Asaro et al. 2011
Current feedback modifies the Ekman buoyancy flux

Ekman transport advects buoyancy at fronts:

$$EBF = \frac{\tau \times \hat{k}}{\rho_0f} \cdot \nabla_h b$$

Can be expanded as a mean and CFB component:

$$EBF = \frac{\bar{\tau} \times \hat{k}}{\rho_0f} \cdot \nabla_h b + \frac{\tau' \times \hat{k}}{\rho_0f} \cdot \nabla_h b$$

$$EBF = EBF_{\bar{\tau}} + EBF_{\tau'}$$

D’Asaro et al. 2011
Submesoscale symmetric instability

Background thermal wind flow

Turbulent kinetic energy

EBF

destroys/injects PV

sets the rate of energy extraction (geostrophic shear production)

Chor, Wenegrat, and Taylor, 2022 JPO
A forward cascade of energy to turbulence

Background thermal wind flow

Geostrophic shear production

Turbulent kinetic energy

Dissipation ($\epsilon$) and mixing ($\epsilon_\rho$)

Secondary Kelvin-Helmholtz instabilities

Inertial time = 0.0

Inertial time = 5.0

Chor, Wenegrat, and Taylor, 2022 JPO
Significant modification to Ekman buoyancy flux

Ratio of current feedback to mean EBF:

\[
\frac{EBF_{\tau'}}{EBF_{\bar{\tau}}} \sim \frac{U_o}{U_a \cos \psi}
\]

where \(U_o\) scales the surface currents, \(U_a\) scales the wind speed, and \(\psi\) is the angle between the wind and the surface thermal wind shear.

Large contribution when:

- Surface velocities are large
- Winds are weak
- Winds are misaligned with fronts (eg. Wenegrat et al. 2018 JPO)
Current feedback acts as buoyancy & PV source

- Ekman heat flux $[\text{W m}^{-2}]$
- Change in mean PV $[\text{s}^{-3}]$

- 50% decrease in mean EBF
- 50% increase in PV injection

*simulations without buoyancy flux
A potential pathway for modifying energetics

- Background kinetic energy
- Eddy potential energy
- Eddy kinetic energy
- Geostrophic shear production
- Buoyancy production
- Secondary instabilities
- 3D Turbulence
- Dissipation ($\epsilon$)
- Mixing

Symmetric instability

3D Turbulence

Dissipation

Baroclinic instability
A potential pathway for modifying energetics

**Background kinetic energy**

**Eddy potential energy**

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**Eddy kinetic energy**

Secondary instabilities

3D Turbulence

Dissipation ($\epsilon$)

Mixing

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'**Eddy killing**' effect on mixed-layer KE:

$$\frac{\tau' \cdot u_o}{\rho_o} \sim - \left( \frac{u_*^2}{U_a} \right) U_o^2$$

- **Symmetric instability**
- **Geostrophic shear production**
- **Buoyancy production**
- **Baroclinic instability**

Thomas and Taylor 2010

Geostrophic shear production
A potential pathway for modifying energetics

Current feedback effect on EBF-

\[ \overline{GSP} \tau' \sim - \left( \frac{u_*^2}{U_a} \right) U_o \Delta U_g \]

\( \Delta U_g \) is the change in geostrophic velocity across the mixed-layer depth.

‘Eddy killing’ effect on mixed-layer KE:

\[ \frac{\tau' \cdot u_o}{\rho_o} \sim - \left( \frac{u_*^2}{U_a} \right) U_o^2 \]

\( \frac{\tau' \cdot u_o}{\rho_o} \) represents the change in geostrophic velocity across the mixed-layer depth.
More than a length scale: submesoscale air-sea interaction

- Submesoscale is a **dynamical regime**, may promote the importance of alternate air-sea interaction mechanisms

- The current feedback on stress acts as a source of **Ekman buoyancy flux**, reduces PV destruction by winds

- Modifies the **geostrophic shear production**, effects on energetics may be comparable to the surface wind-work (‘eddy-killing’)

Wenegrat, J., 2023: The surface current feedback on stress modifies the Ekman buoyancy flux. In review for JPO.
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- **Open challenges**: model resolution, cross-scale effects (direct and indirect changes), shared parameter dependencies for many submesoscale processes...

Wenegrat, J., 2023: The surface current feedback on stress modifies the Ekman buoyancy flux. *In review for JPO.*
Extras
Current feedback modifies the Ekman buoyancy flux

Perturbation Ekman buoyancy flux:

\[ EBF_{\tau'} \approx - \frac{3}{2} \frac{\rho_a c_d}{\rho_o f} |U_a| |u_o| |\nabla h b| \]

Suggests the current feedback acts to generate a source of buoyancy and PV to the mixed-layer
Current feedback weakens submesoscales

Vorticity

Divergence

Strain
Cross-scale effects of air-sea interaction

- Air-sea interaction modifies all scales.
- Many submesoscale processes share parameter dependencies (eg. MLI, EBF, SI, TTW)
- Indirect effects of air-sea interaction may be as important as direct effects.
Current feedback acts as buoyancy & PV source

Ekman heat flux in W m$^{-2}$

Change in mean PV in z$^{-3}$

Days

50% decrease in mean EBF

15% decrease in PV destruction

*simulations without buoyancy flux

(Includes diabatic contributions)