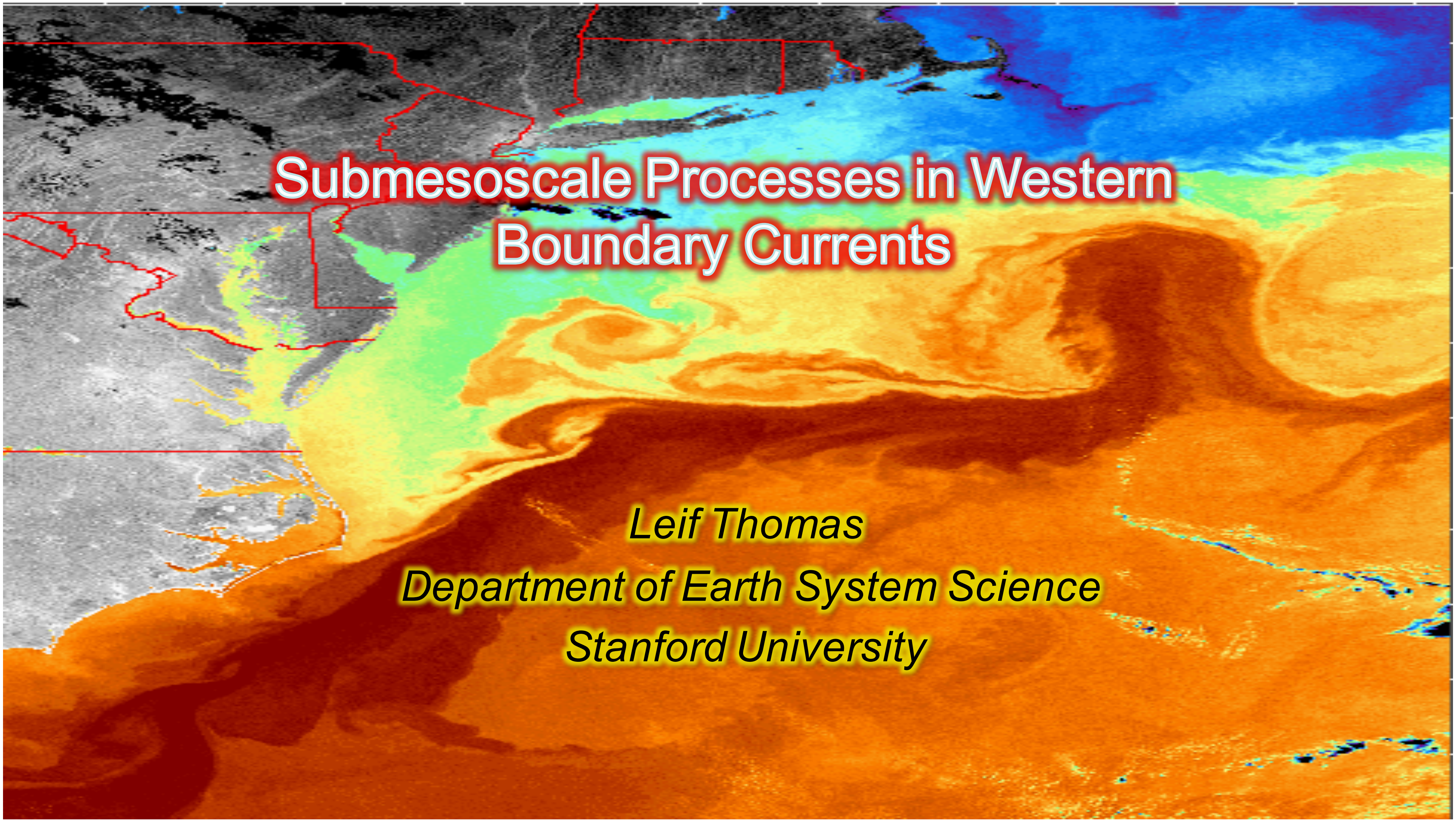

Submesoscale Processes in Western Boundary Currents

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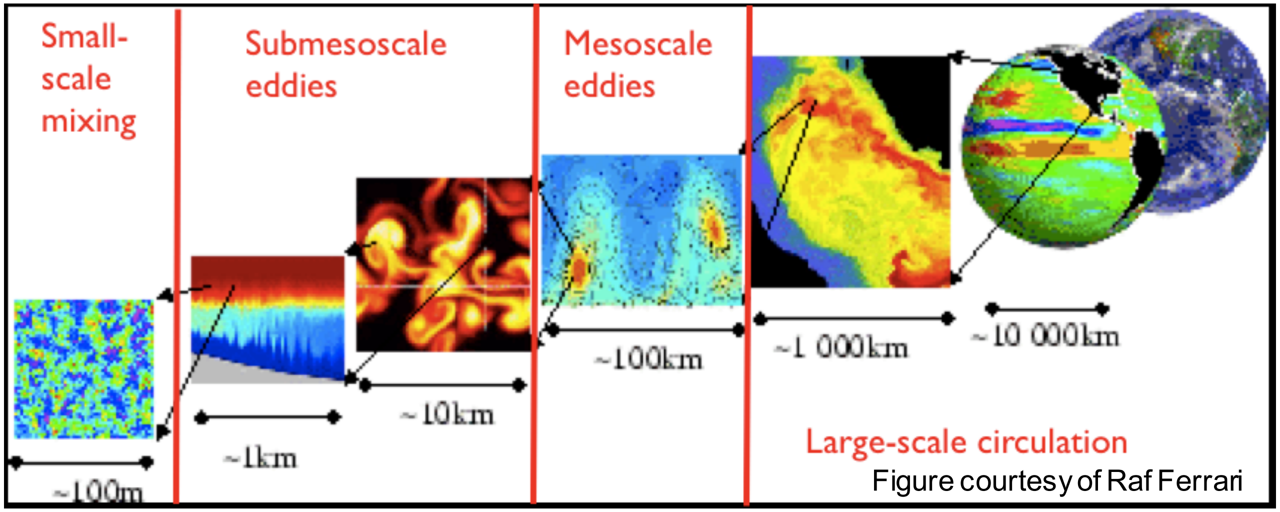
Definition of the submesoscale



•Descriptive definition: flows with lateral length scales between 100 m and 10 km

•Dynamical definition: geostrophic flows characterized by order one Rossby and Richardson numbers

$$Ro_g = \frac{\zeta_g}{f} = \frac{1}{f}\left(\frac{\partial v_g}{\partial x} - \frac{\partial u_g}{\partial y}\right)$$

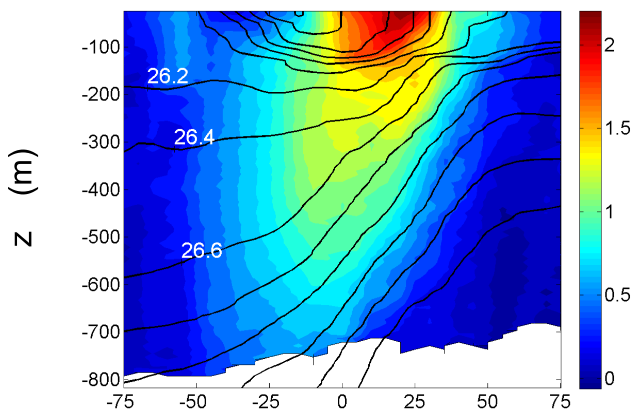
$$Ri_b = \frac{N^2}{|\partial \vec{u}_g / \partial z|^2}$$

Thomas et al (2008); McWilliams (2016)

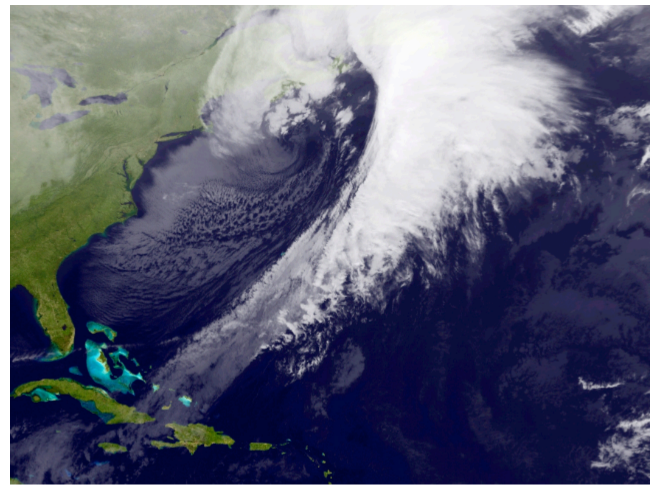
Where and when do submesoscale flows form?

- Where: **fronts**
  - Frontal currents provide an energy source for submesoscale motions and strongly constrain their dynamics.

Down-stream velocity (m/s) and Density (kg/m^3)

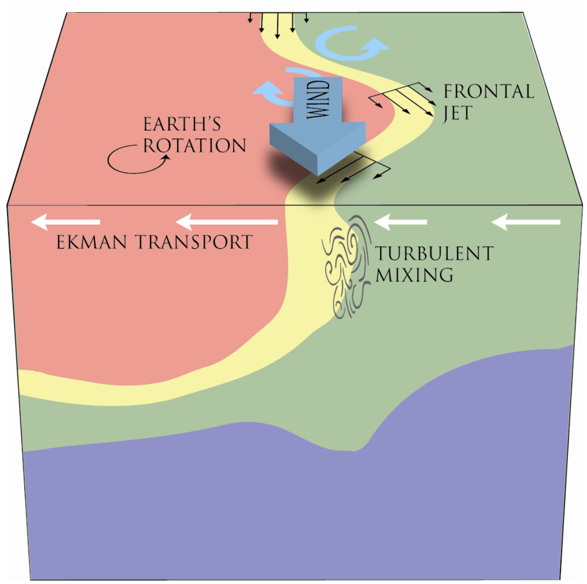


Cross-stream distance (km)



- When: under **destabilizing atmospheric forcing**
  - Ocean loses heat to the atmosphere.
    →The submesoscale is energized in the winter
    Sasaki et al 2014; Callies et al 2015
  - Winds are directed down-front.

Down-front winds



- When the wind is *down-front* it has a component *along* the frontal jet and
  - Ekman flow advects denser water over light, mixing ensues, and the stratification is reduced..

Thomas and Taylor (2010)

Impacts of submesoscale processes on biogeochemistry in WBCs

Figure from Palter et al (2011)

$$P^* = PO_4^{3-} - \frac{NO_3^-}{16}$$

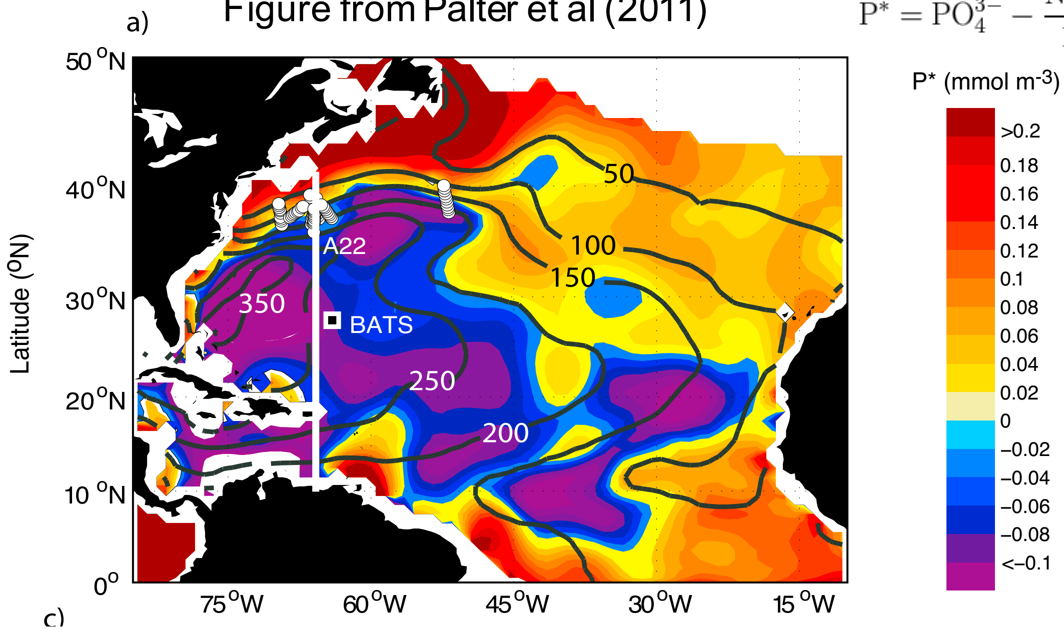
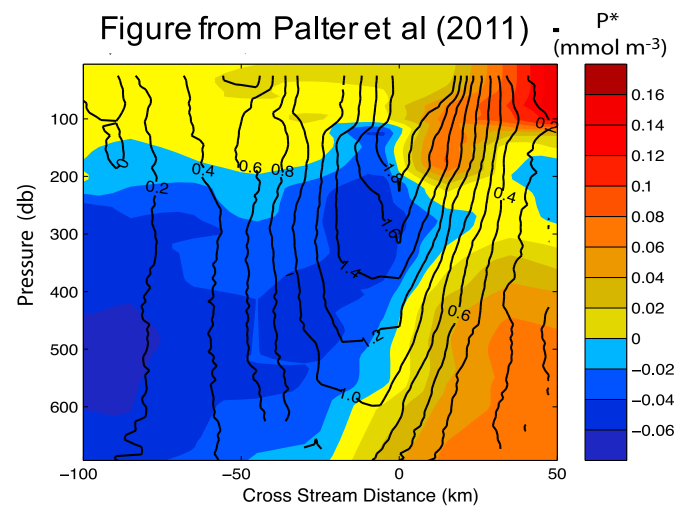
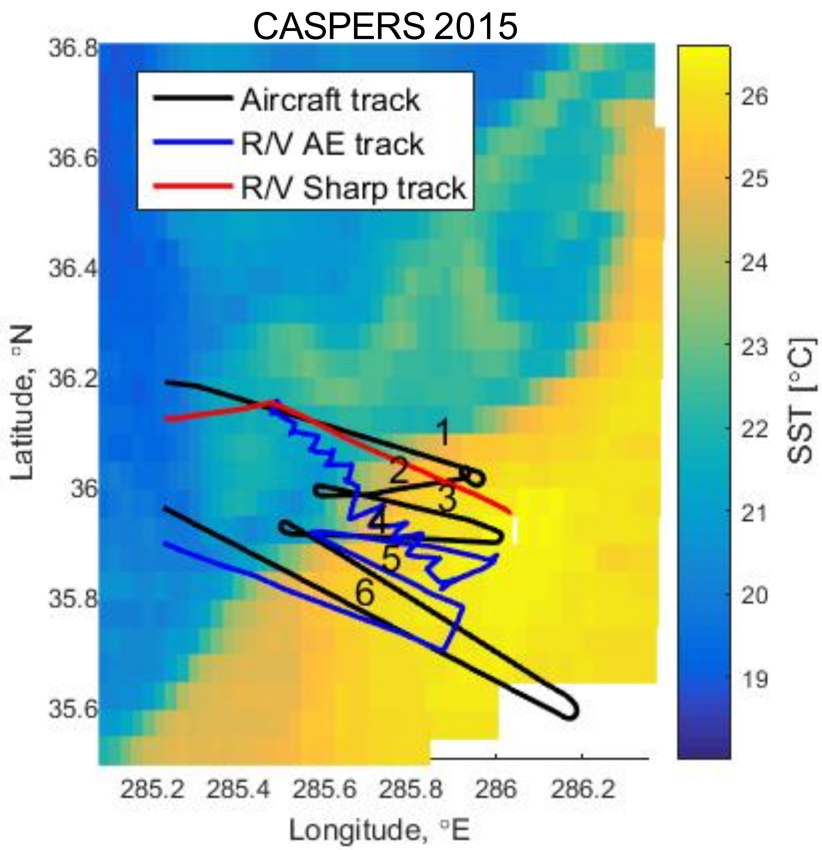


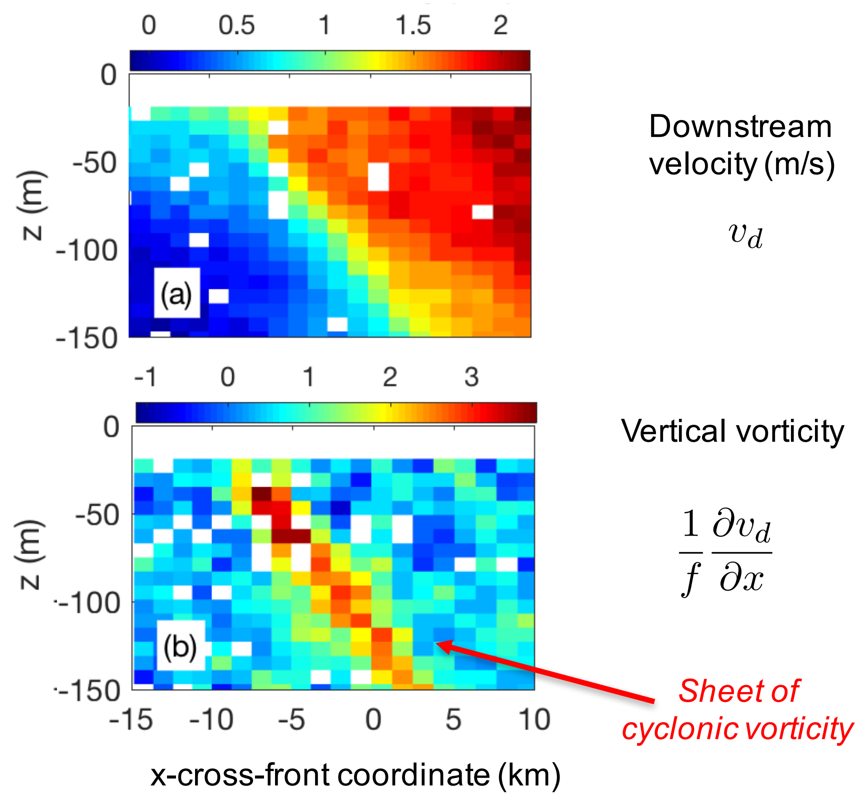
Figure from Palter et al (2011)



- Submesoscale processes tend to be intensified at gyre boundaries where gradients in biogeochemical tracers are strongest. They are effective at:
  - → Lateral mixing across the gyres
  - → Vertical exchange between the ocean surface/bottom and interior

Intense lateral shear at the gyre boundary

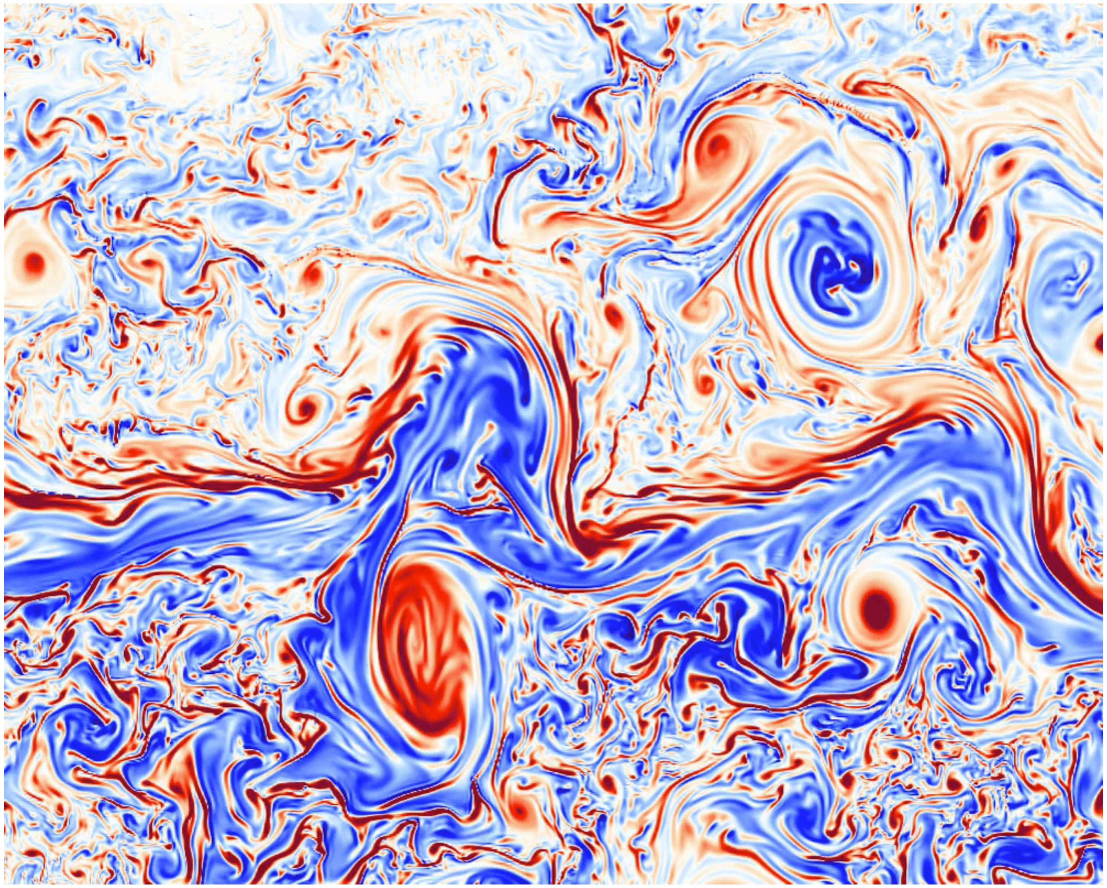




- The downstream velocity in a WBC drops precipitously at the gyre boundary, generating intense lateral shear.

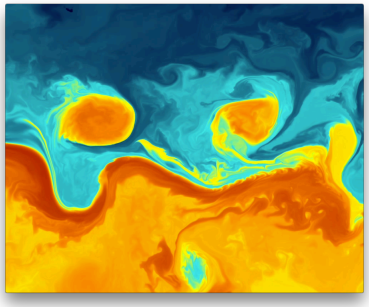
Savelyev et al (2017)

Lateral shear instabilities at the gyre boundary



Surface vorticity field from a high resolution (500 m) simulation of the Gulf Stream.

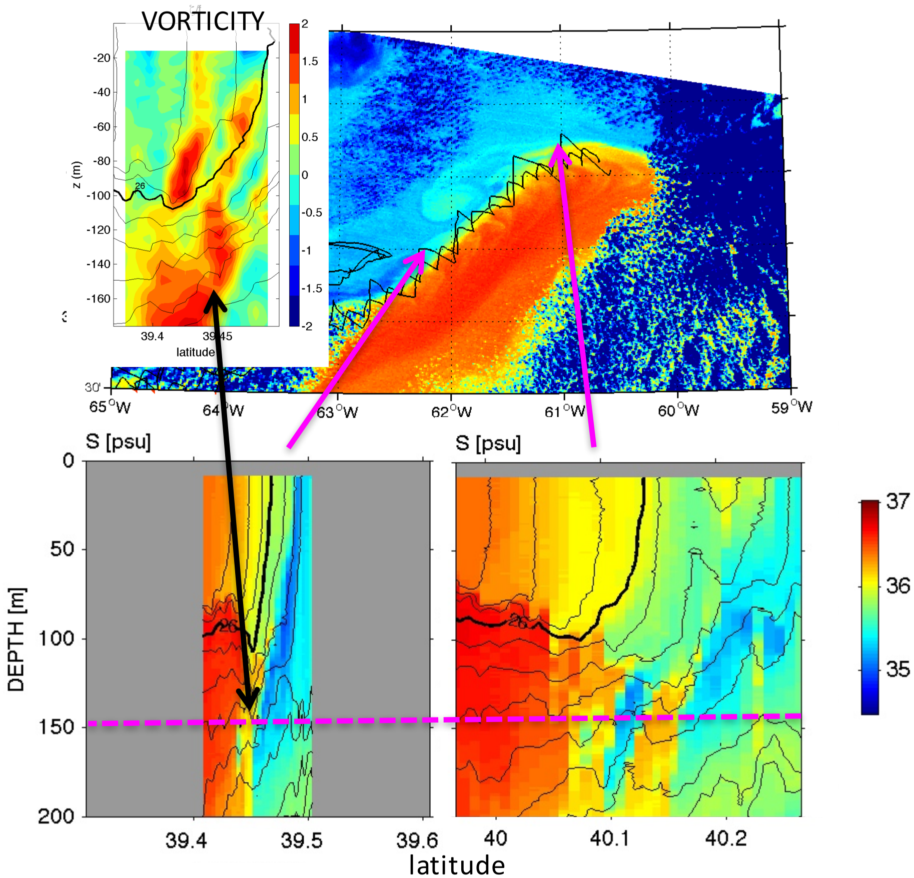
Gula et al (2015)

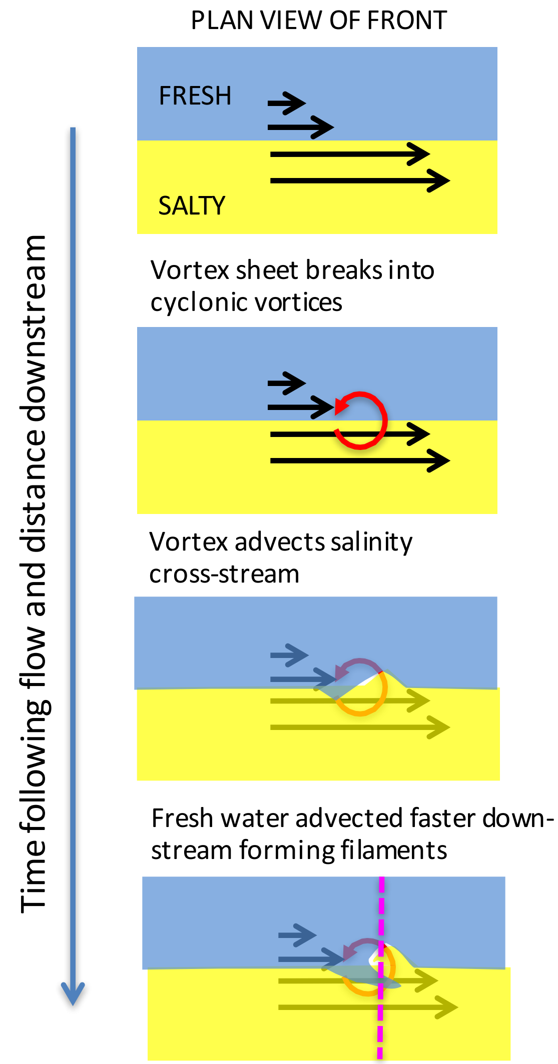


Surface temperature

Animation courtesy of Jonathan Gula http://stockage.univ-brest.fr/~gula/movies.html

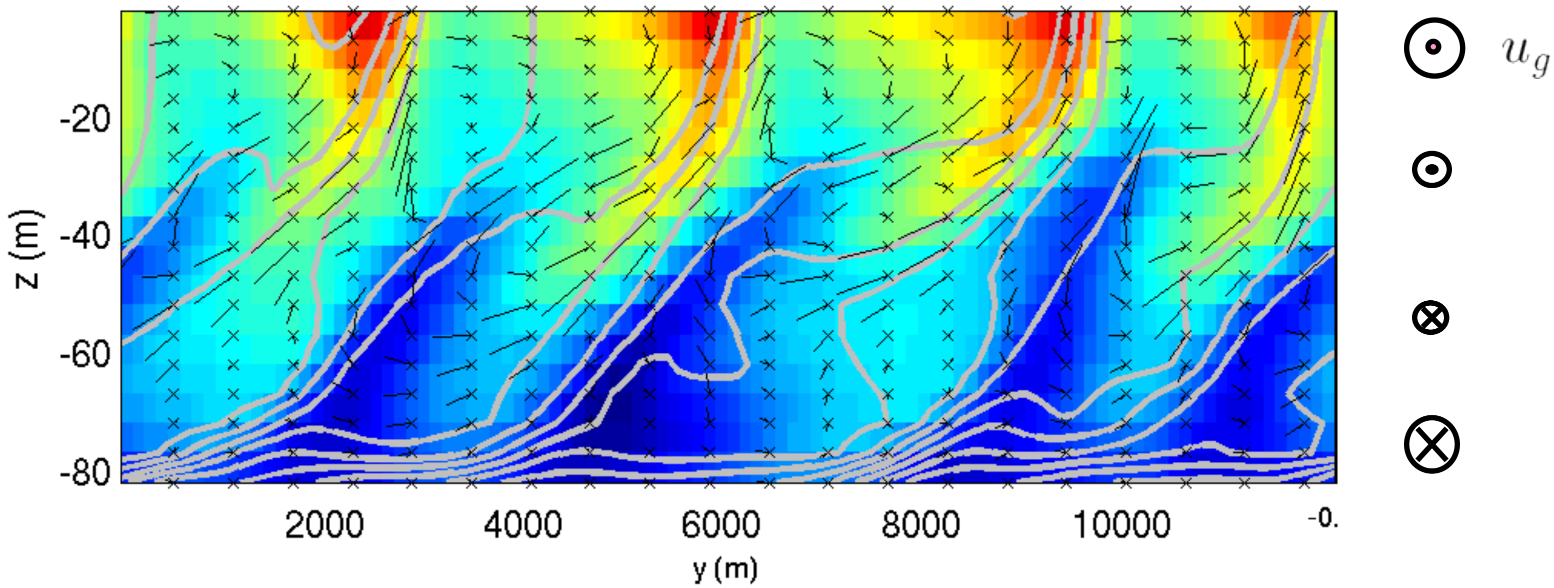
Lateral mixing by shear instabilities





- Lateral stirring by shear instabilities mixes tracers across the gyre boundary with an inferred diffusivity of order 100 m^2/s. Klymak et al (2016)

Vertical shear at the gyre boundary and symmetric instability



•Symmetric instability (SI) is an overturning instability that forms at fronts with strong vertical shear, weak stratification, and low Richardson numbers.

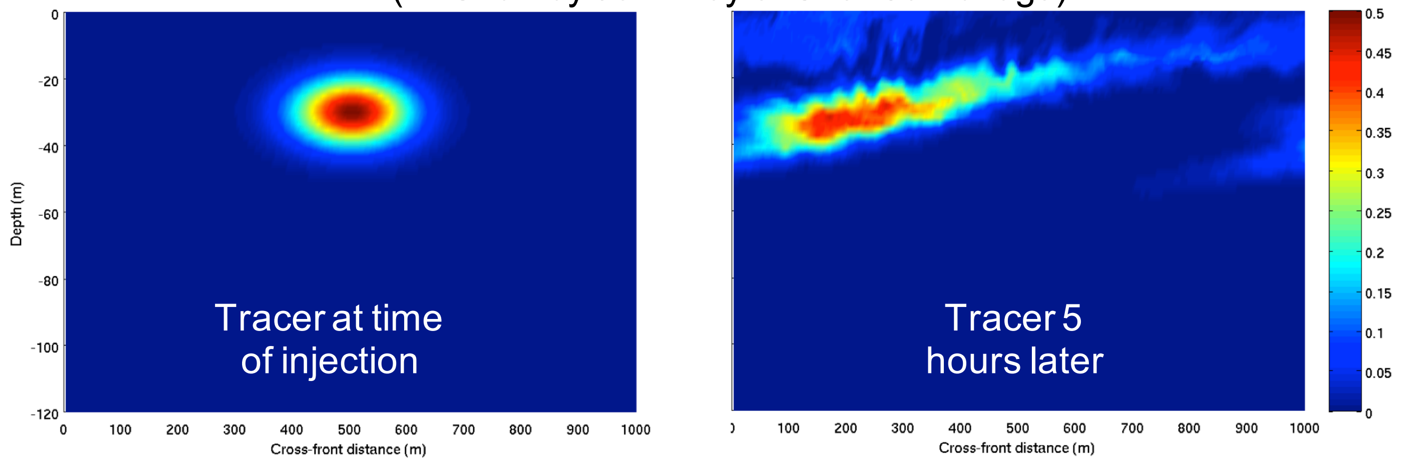
•SI is characterized by overturning cells that run along the tilted isopycnals of a front.

•It forms when the winds are down-front and/or when a front is being cooled.

Thomas and Taylor (2010); Taylor and Ferrari (2010); Thomas et al (2013)

Lateral dispersal of tracers by SI

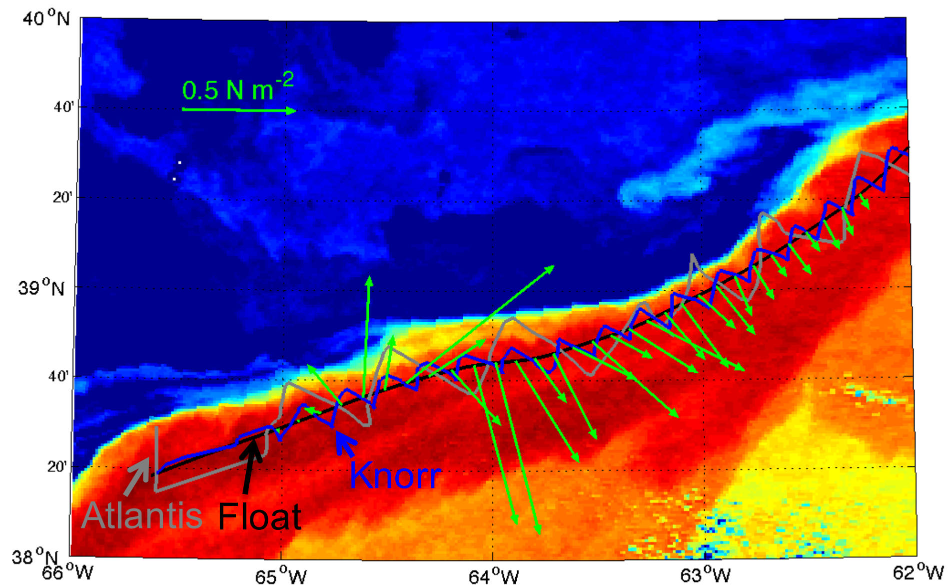
Numerical simulation of the dispersal of a tracer by symmetric instability
(LES run by John Taylor U. of Cambridge)



- The slanted overturning motions of SI are able to mix tracers laterally along density surfaces.

Visit Jacob Wenegrat's poster to learn more!

LatMix 2012 field campaign: SI-drift II

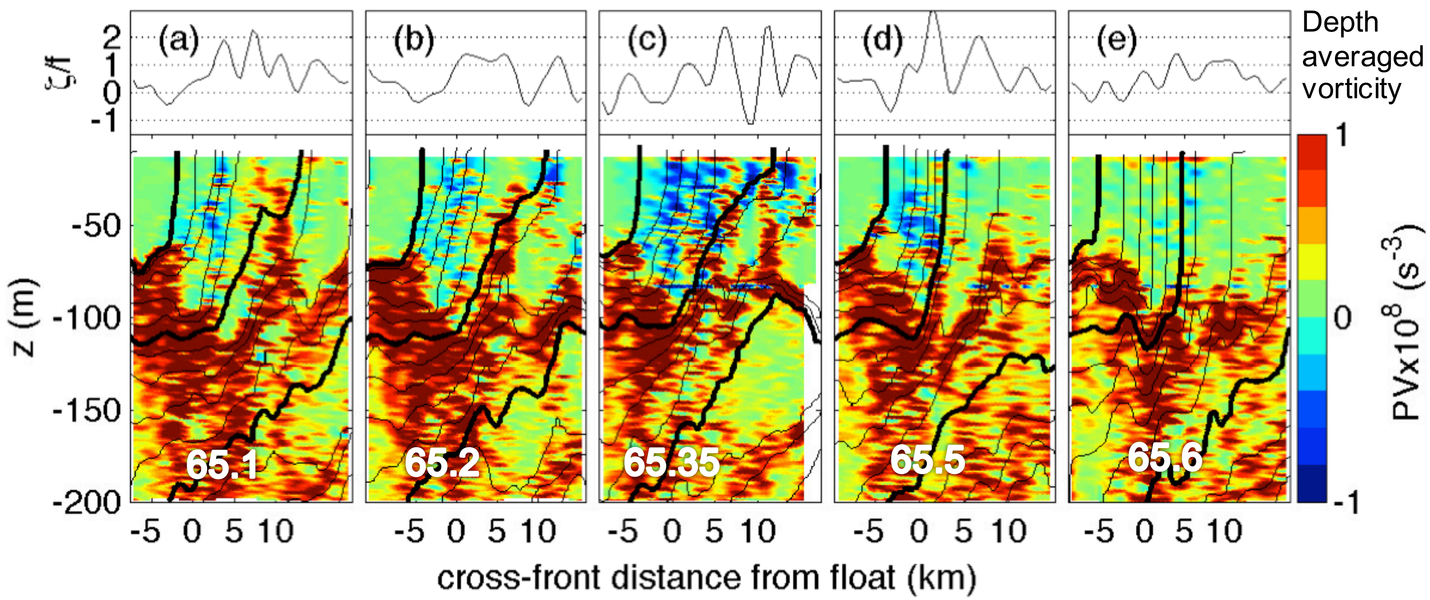


March 5-8

- Storm passed during the drift, max winds had a significant down–front component → should trigger SI.
- Miles Sundermeyer released fluorescein dye near the float and its dispersal was tracked with a fluorometer on a Triaxus.

Thomas et al (2016)

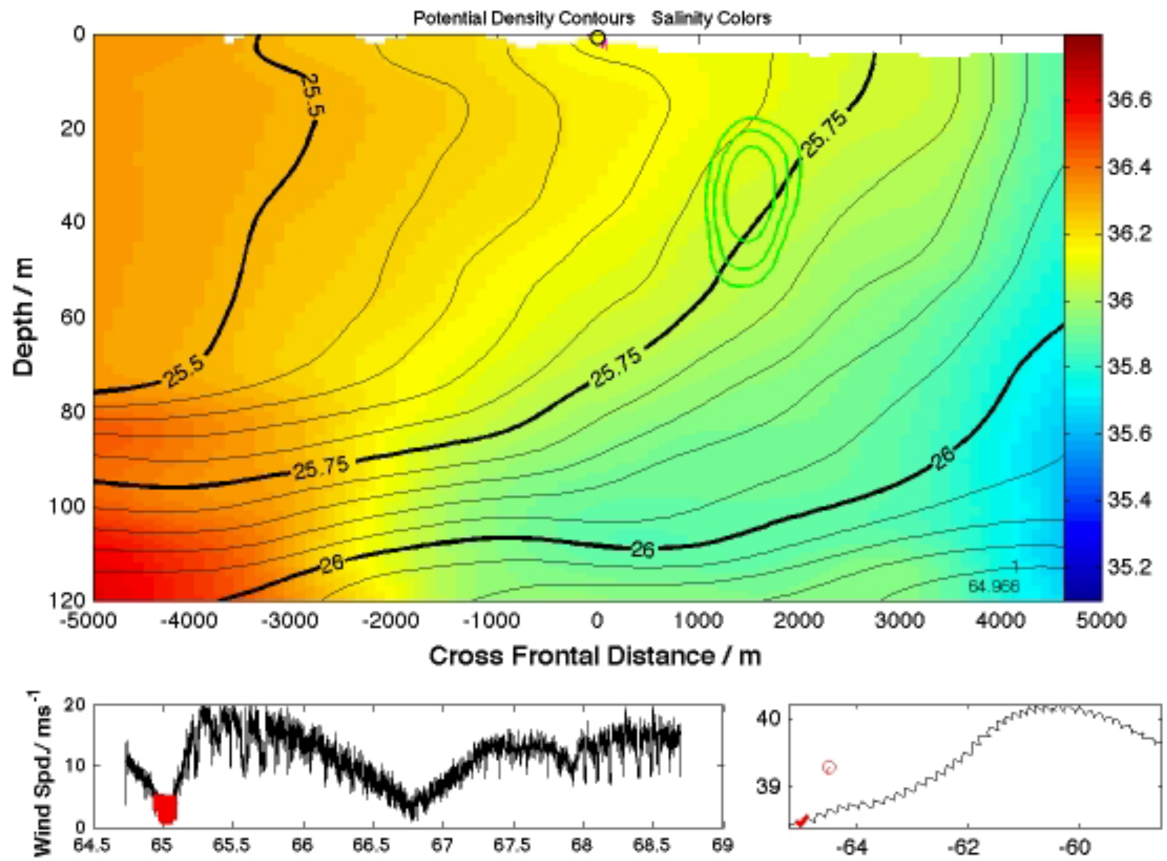
Telltale signs of symmetric instability



- The stratification in the boundary layer is stable and the potential vorticity is negative.
  - ➔The flow is unstable to symmetric instability.

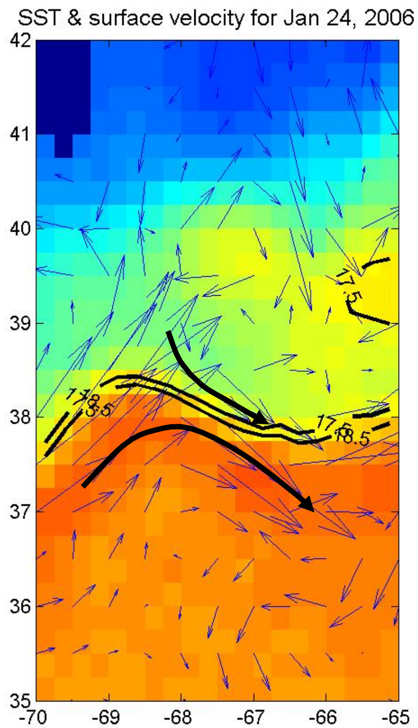
Observed dispersal of dye

Animation courtesy of Eric D'Asaro



- Dye spreads to width of front (5km) in ~0.5 day → lateral diffusivity ~100 m^2/s

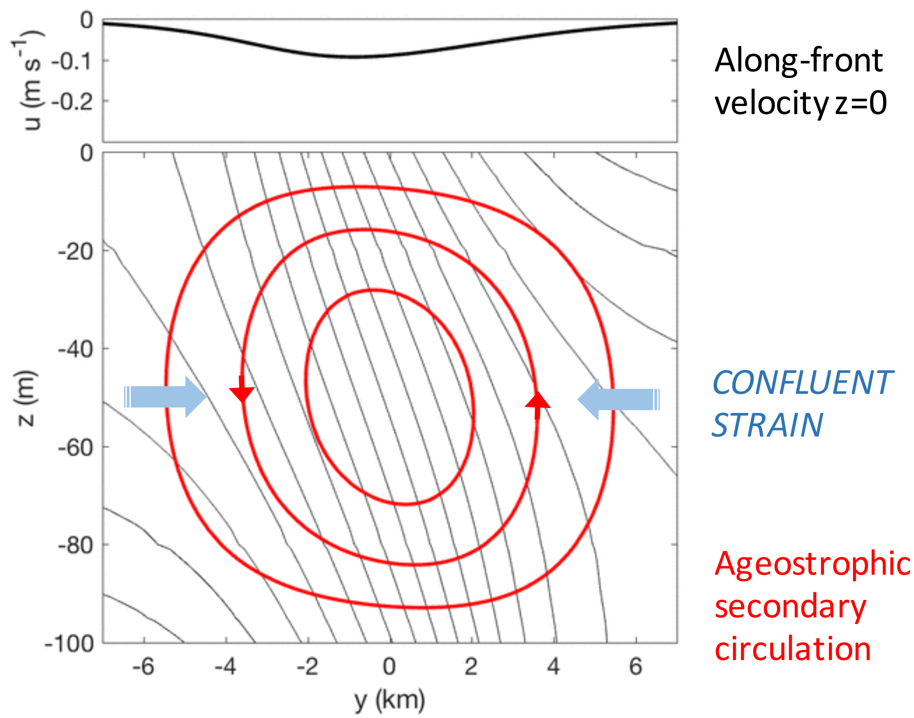
Frontal vertical circulations driven by confluent strain



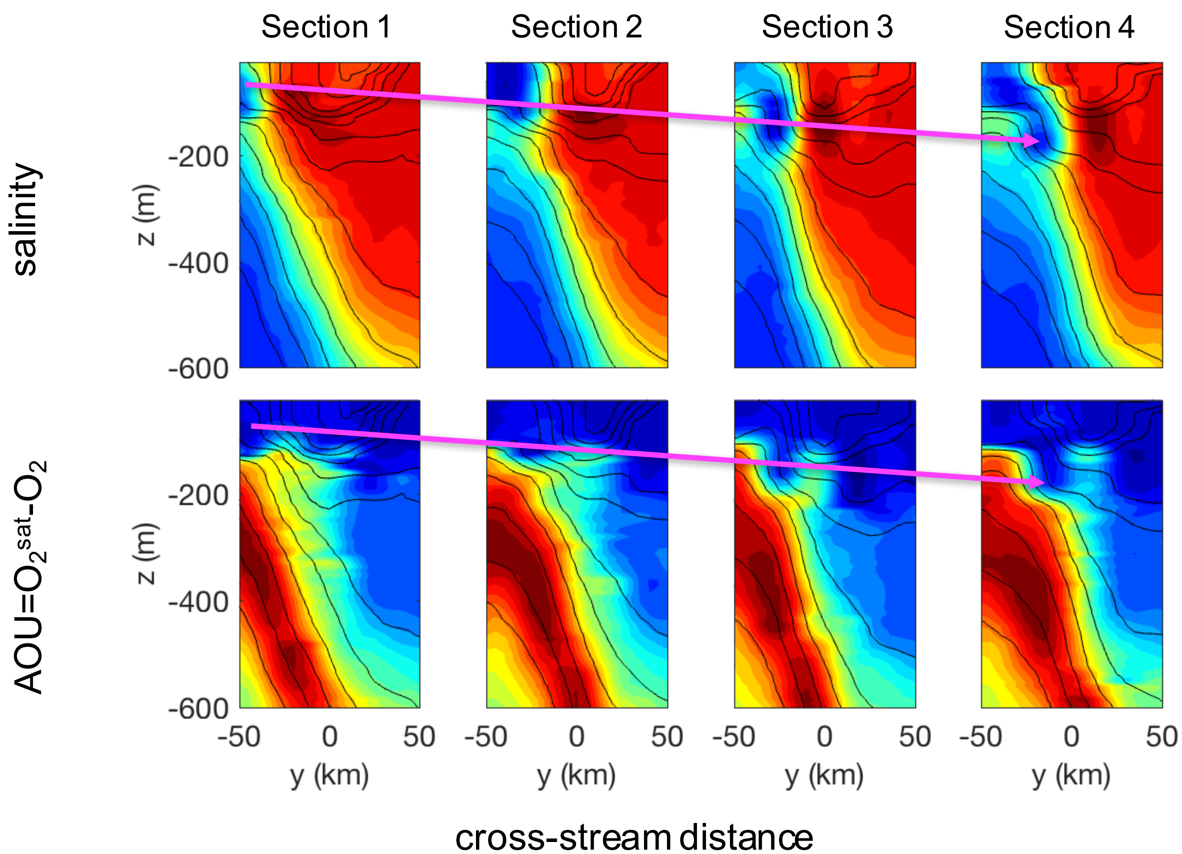
Frontal meandering and eddies can generate confluent strain

Hoskins (1982); Rudnick (1996); Thomas et al (2010)

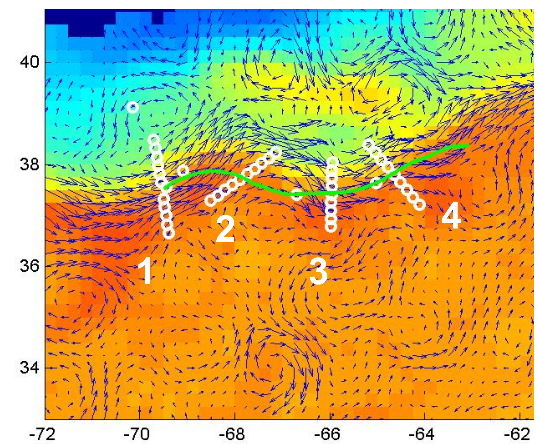
- Density fronts are intensified by confluent strain through a process known as frontogenesis.
- This generates an ageostrophic circulation with strong vertical velocities.



Evidence of vertical exchange at the North Wall of the Gulf Stream



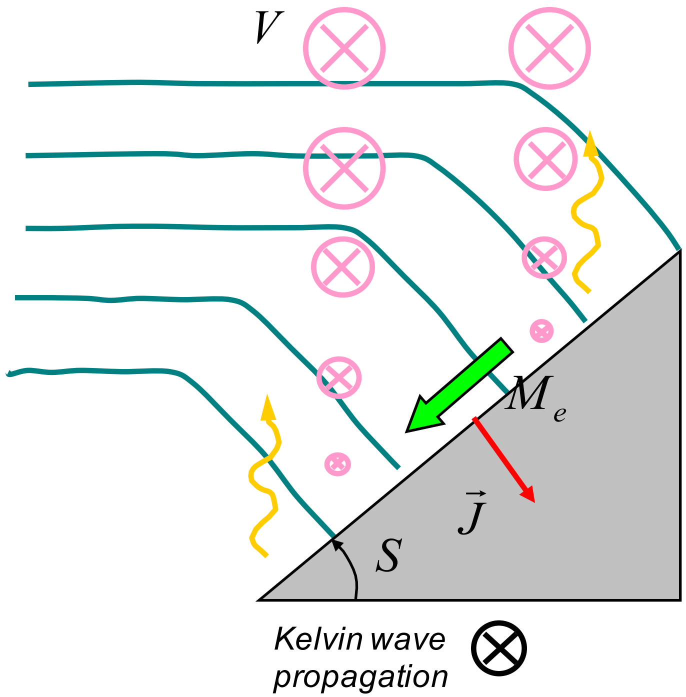
CLIMODE 2006



- Sections of salinity and AOU made following a spar buoy moving with the Gulf Stream reveal the subduction of a freshwater intrusion from the surface.
- Vertical velocities inferred from the strain and density fields were 10-40 m/day, similar to the observed rate of subduction of the intrusion.

Thomas and Joyce (2010)

Submesoscale instabilities in the bottom boundary layer



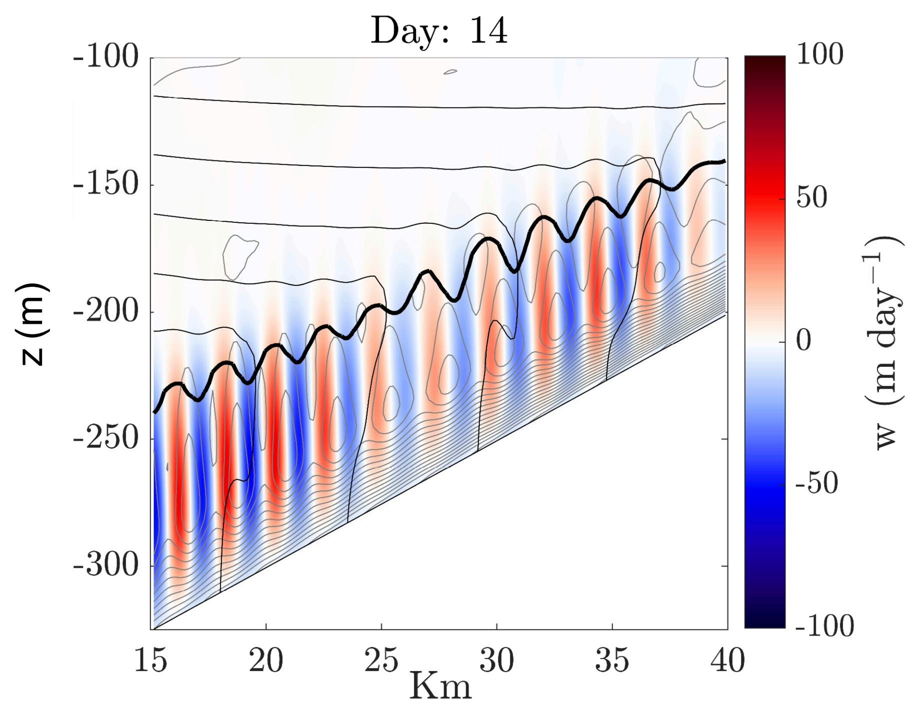


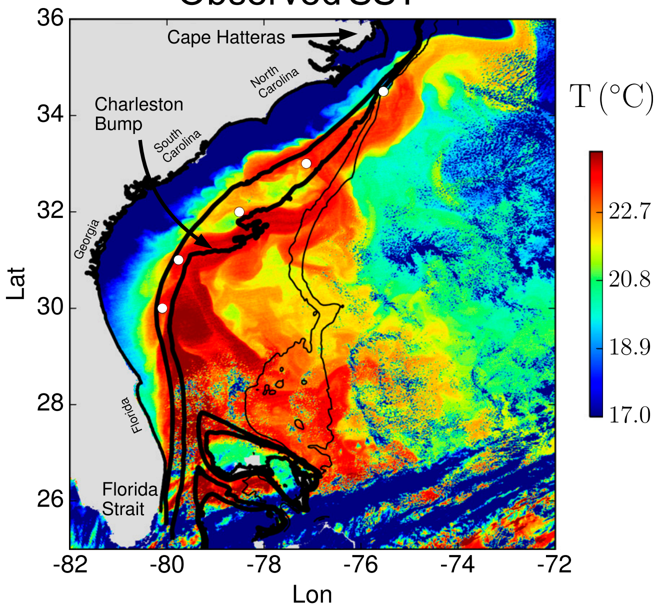
Figure courtesy of Jacob Wenegrat

- The deceleration of WBCs by bottom friction on the continental margins can generate a bottom boundary layer (BBL) with strong shear and weak stratification that could be unstable to submesoscale instabilities.
- These instabilities could flux biogeochemical tracers such as iron from the BBL into the ocean interior.

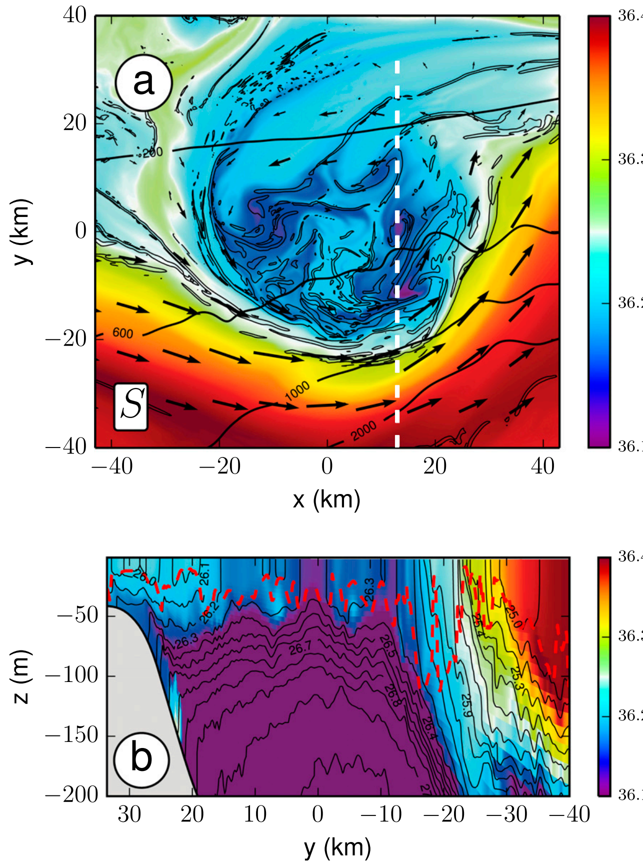
Benthuysen and Thomas (2012); McWilliams (2016)

Thick bottom boundary layers and mixing near the Gulf Stream

Observed SST

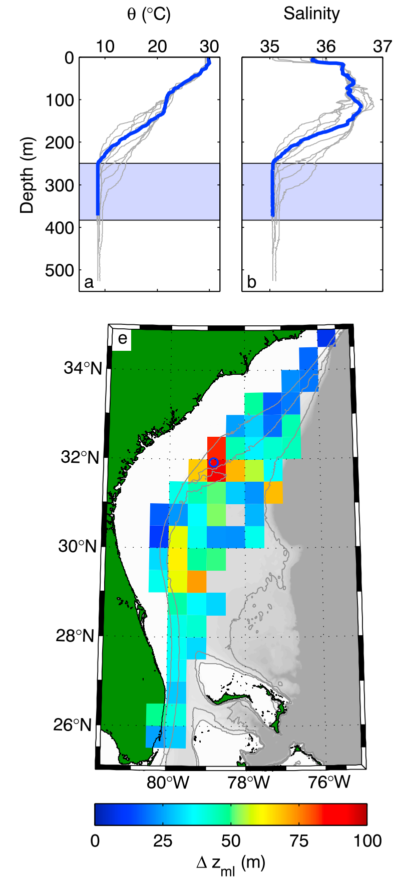


ROMS simulation



Gula et al JPO (2016)

Glider observations



Todd GRL (2017)

- Simulations reveal that cyclonic eddies shed in the lee of the Charleston Bump generate thick BBLs on the slope with water entrained from the shelf and mixed in the vertical.
- Thick BBLs have been observed in this region with gliders.

Conclusions

- Submesoscale instabilities are intensified at the gyre boundaries where the lateral and vertical shear in WBCs are strong and the Rossby and Richardson number is order one.

- Horizontal gradients in physical and biogeochemical tracers are largest at the gyre boundaries and can be mixed by submesoscale lateral shear instabilities and symmetric instability with effective horizontal diffusivities of order 100 m^2/s.

- Vertical velocities of 10-100 m/day are ubiquitous at the front that marks the gyre boundary and are typically generated by confluent strain associated with meanders and eddies. These vertical circulations drive subduction and ventilate the thermocline.

- WBCs decelerated by bottom friction on continental margins can develop thick bottom boundary layers prone to submesoscale instabilities. These instabilities could flux shelf water, potentially enhanced in iron, out of the bottom boundary layer, into the WBC.