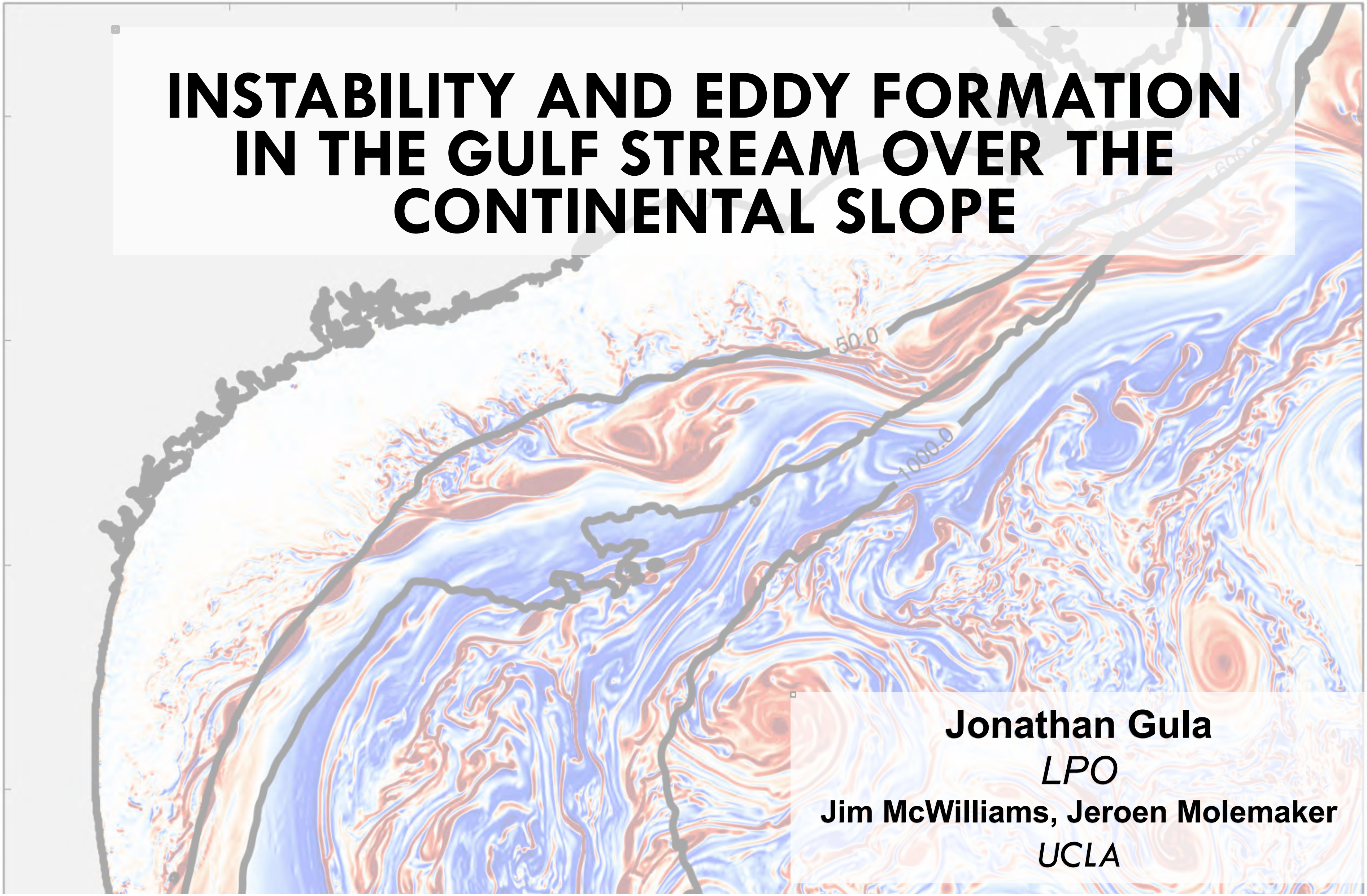
INSTABILITY AND EDDY FORMATION IN THE GULF STREAM OVER THE CONTINENTAL SLOPE



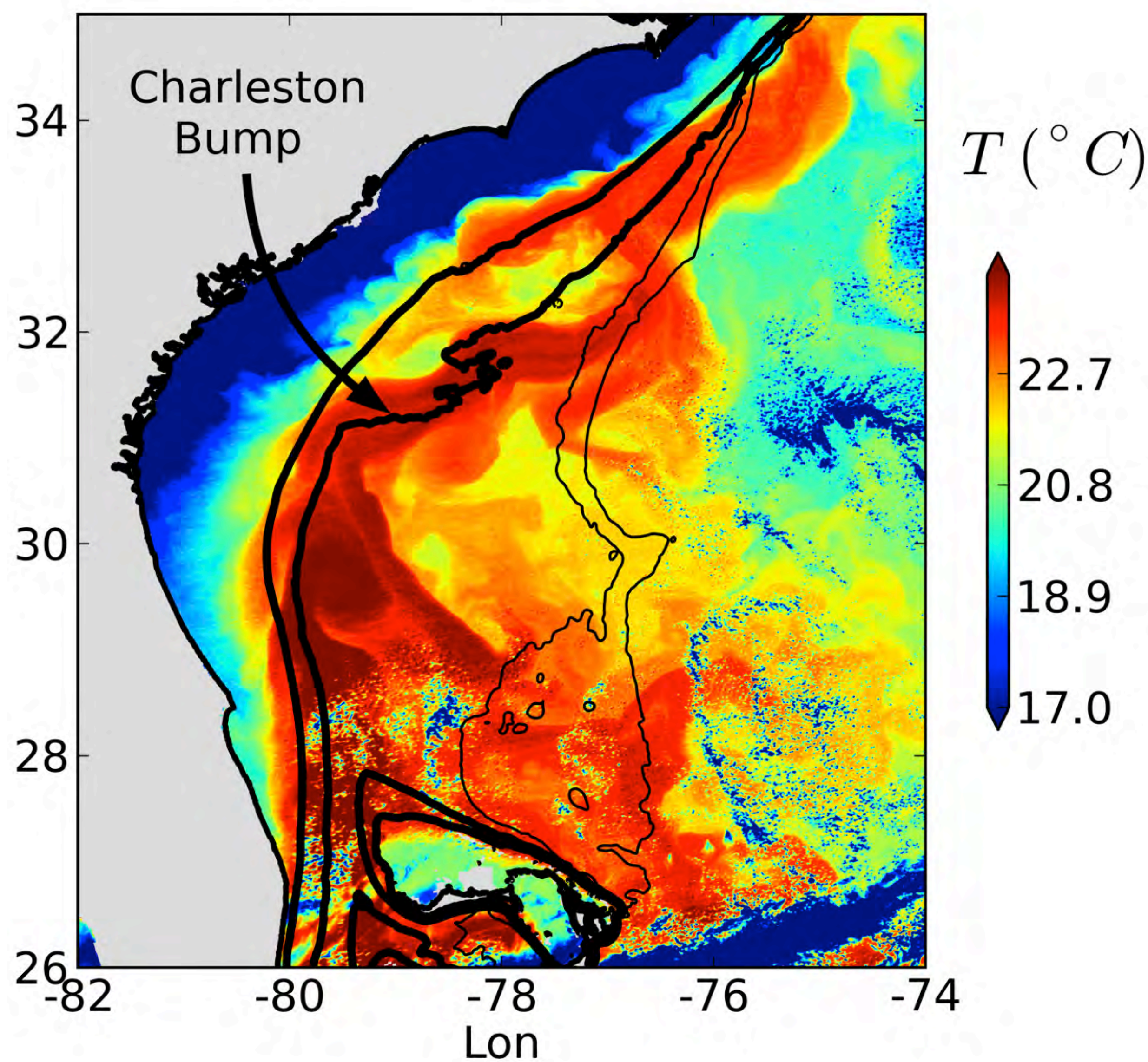
Jonathan Gula
LPO
Jim McWilliams, Jeroen Molemaker
UCLA

July, 6th 2015

SYNBIOS Workshop, Paris, France

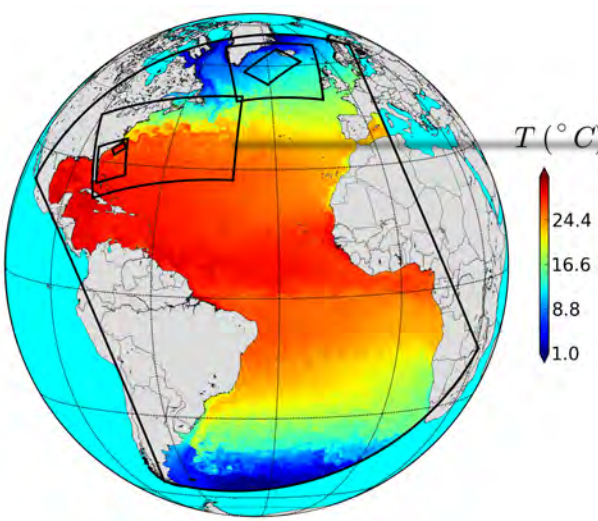
Observed Gulf Stream

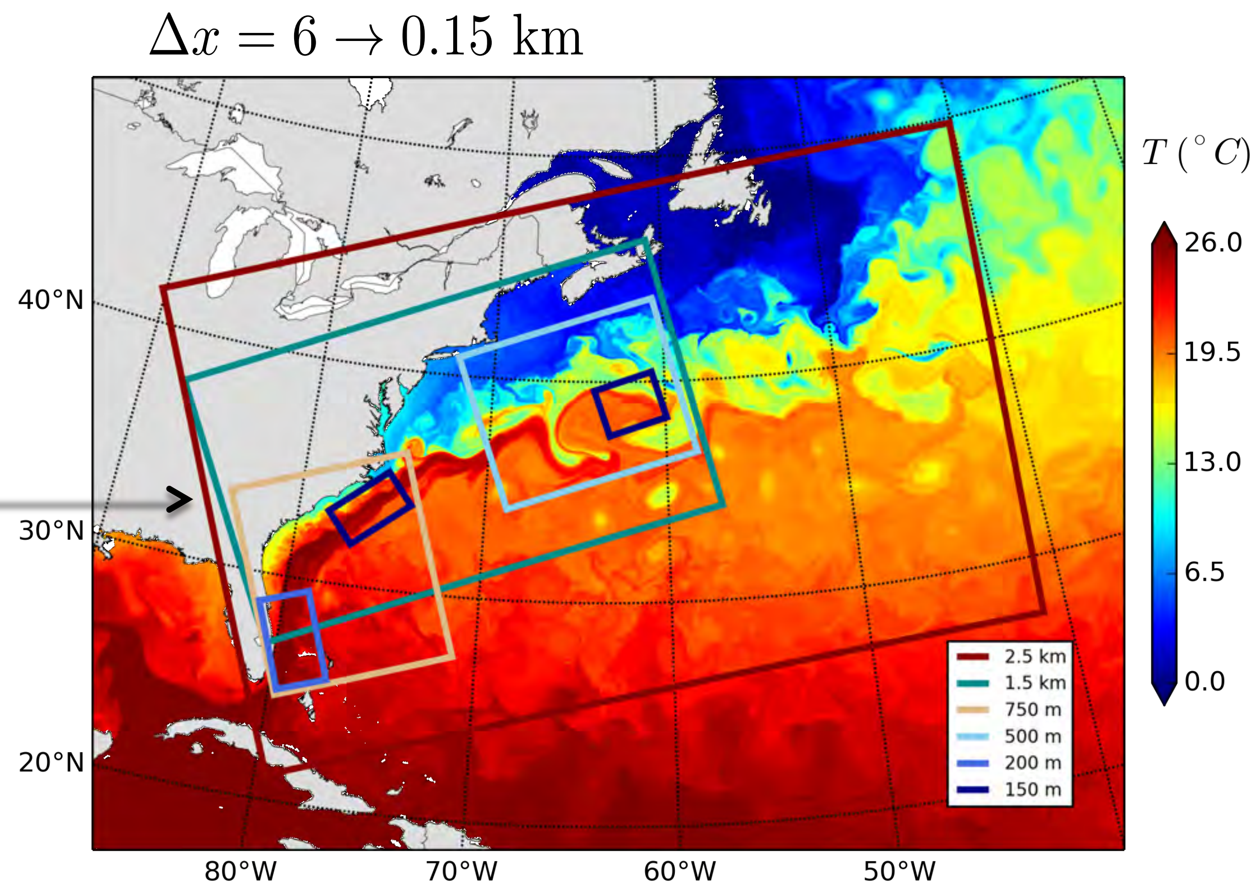
MODIS SST [02/04/10]:



Numerical simulation of the Gulf Stream

ROMS is a free-surface, terrain-following, primitive equations ocean model.





A portion of the Atlantic domain showing mean SST and several (1-way) nested grids: Forced by repeating "typical" year with QuikSCAT and SODA at open boundaries.

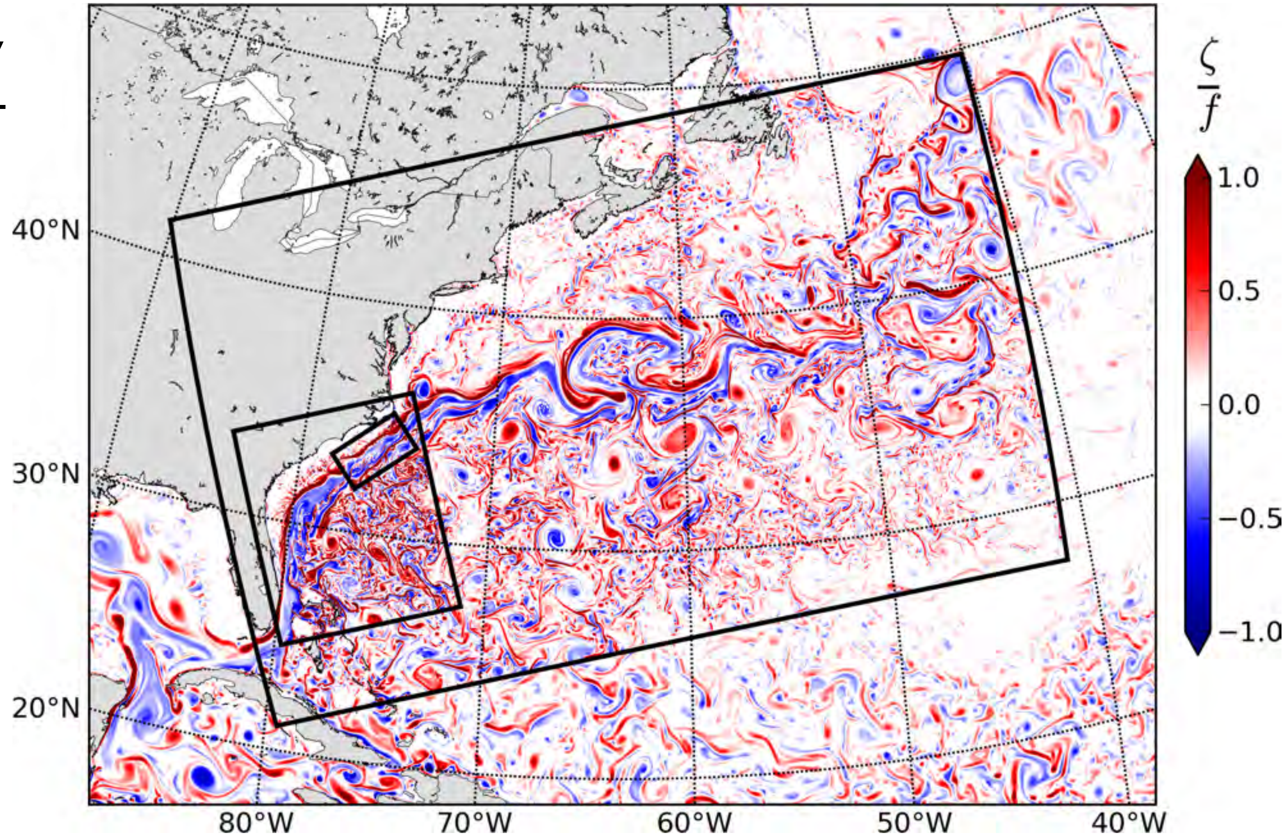
Numerical simulation of the Gulf Stream

Mean and mesoscale variability have been validated against in-situ measurements and satellite observations.

[GS dynamics along the southeastern U.S. Seaboard, Gula et al., JPO, 2015]

[Submesoscale dynamics of a GS Frontal Eddy off the South Atlantic Bight., Gula et al., in revision for JPO]

[North Atlantic Barotropic Vorticity Balances and the Gulf Stream Separation in Numerical Models, Schoonover et al., in prep]



Statistics of submesoscale dynamics validated against in-situ measurements

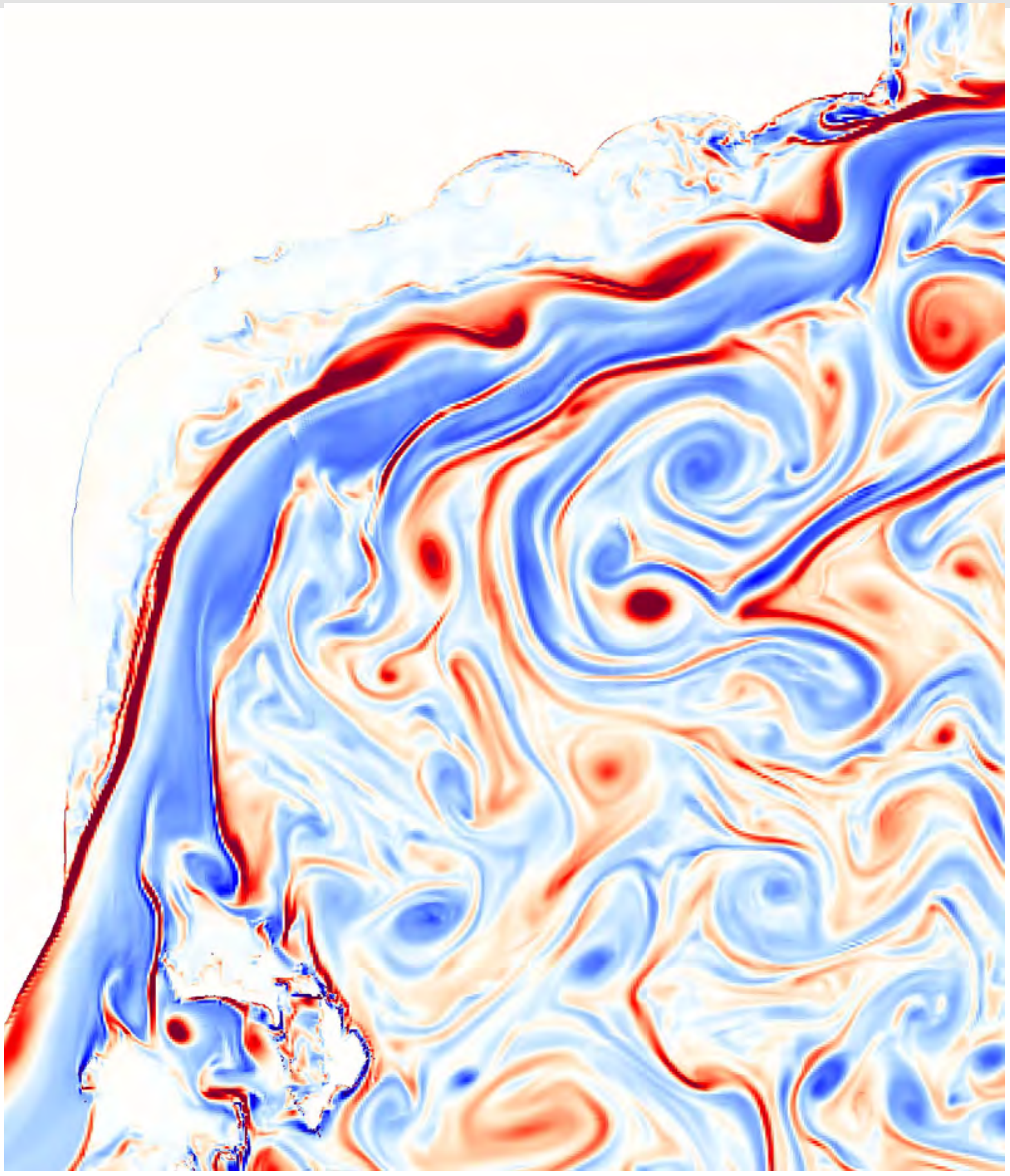
[Statistics of vertical vorticity, divergence, and strain in a developed submesoscale turbulence field, Shcherbina et al., GRL, 2013]

Gulf Stream along the continental slope

Surface relative vorticity $(\pm f)$

1 year of ROMS Simulation

$$\Delta x = 750\,\mathrm{m}$$



Gulf Stream along the continental slope

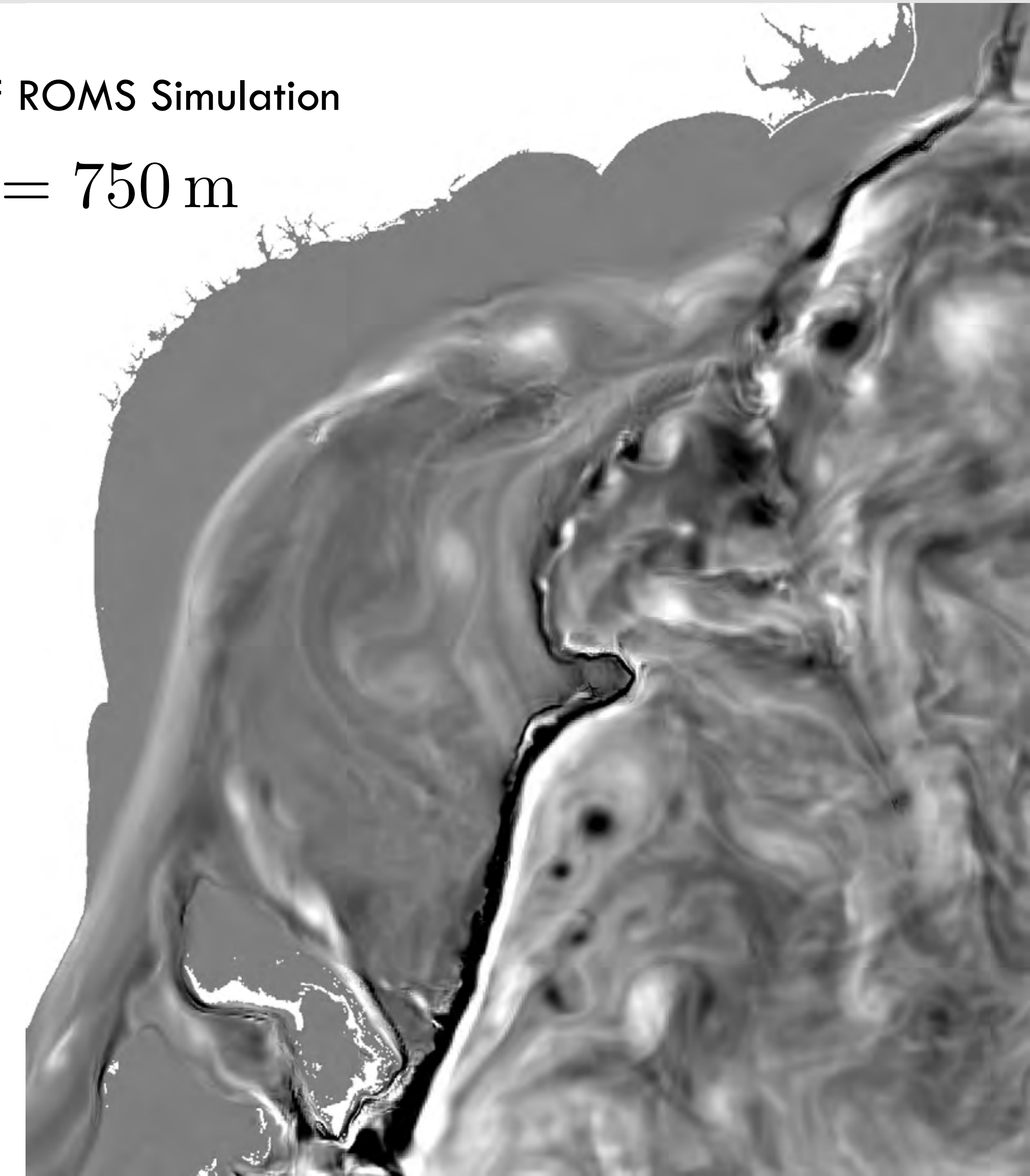
Barotropic vorticity :

$$\Omega = \frac{\partial \overline{v}}{\partial x} - \frac{\partial \overline{u}}{\partial y}$$

$$\overline{u} = \int_{-h}^{\zeta} u \, dz,$$

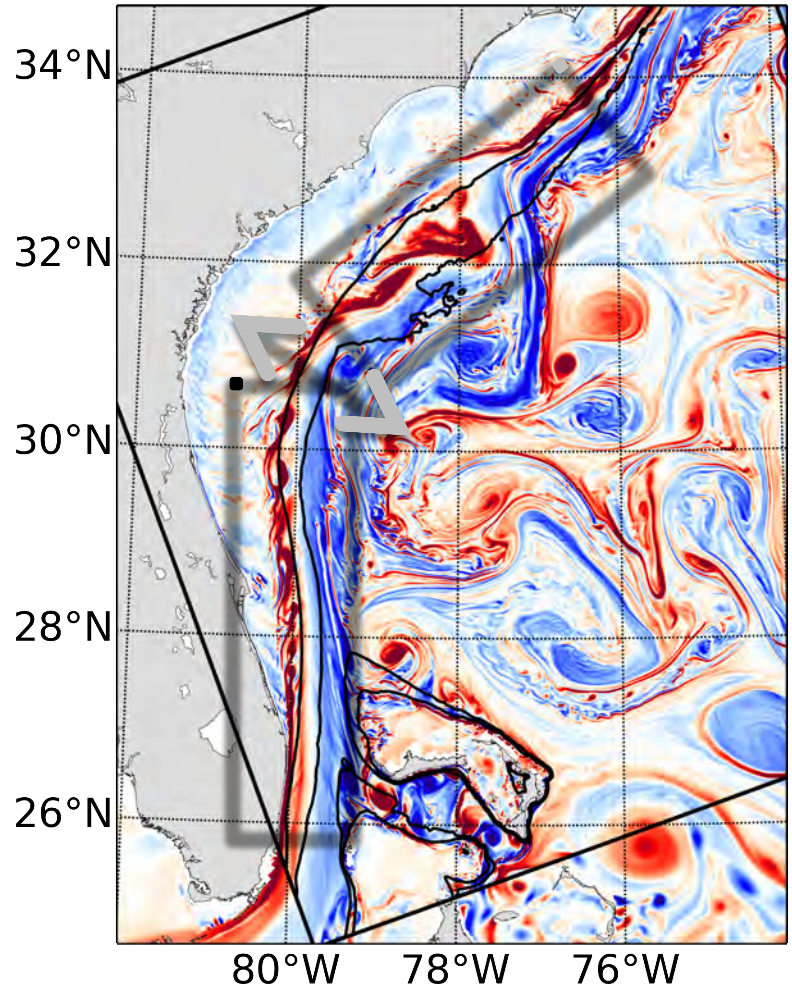
1 year of ROMS Simulation

$$\Delta x = 750\,\mathrm{m}$$



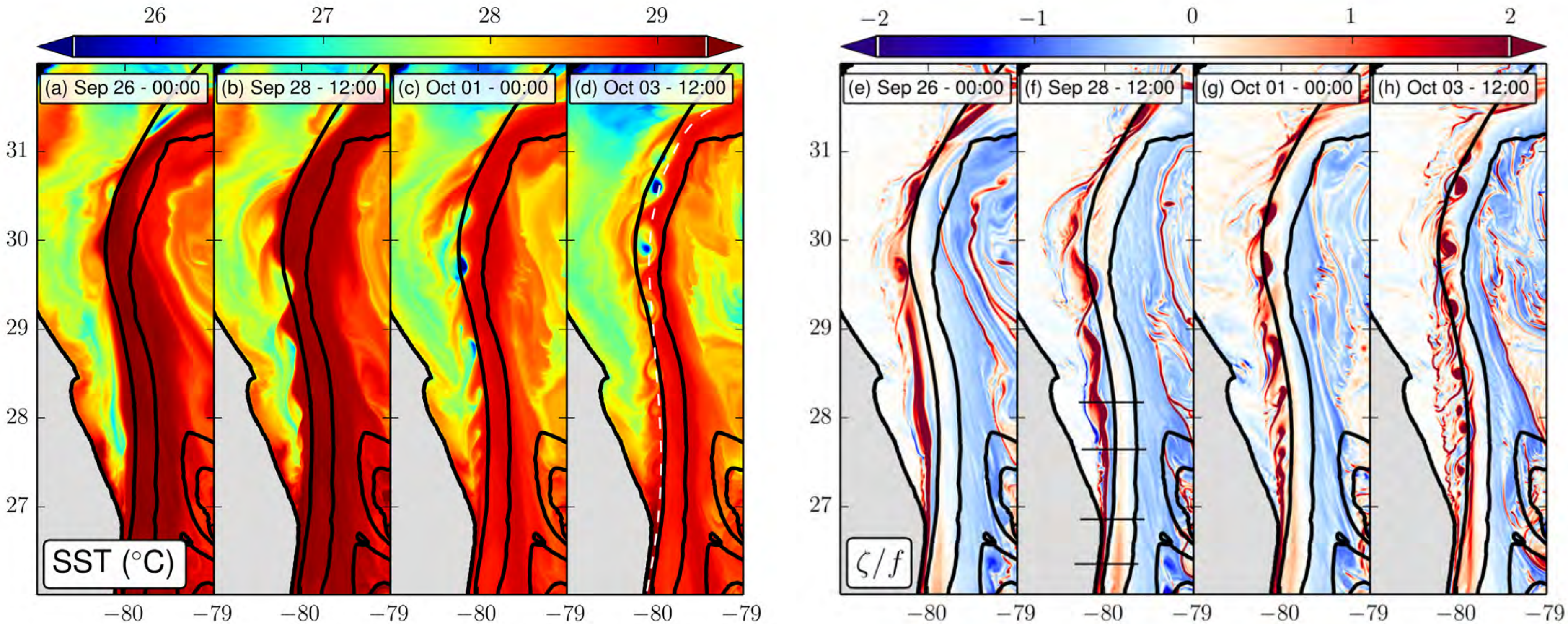
Gulf Stream along the continental slope

1. Submesoscale instability and vortex street formation
2. Frontal eddy generation
3. Impact for cross-shelf exchanges



Submesoscale instability

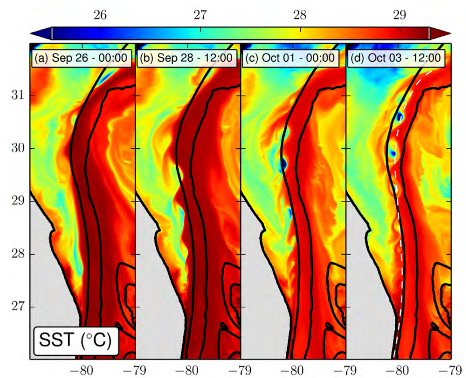
ROMS $\Delta x = 750\,\mathrm{m}$

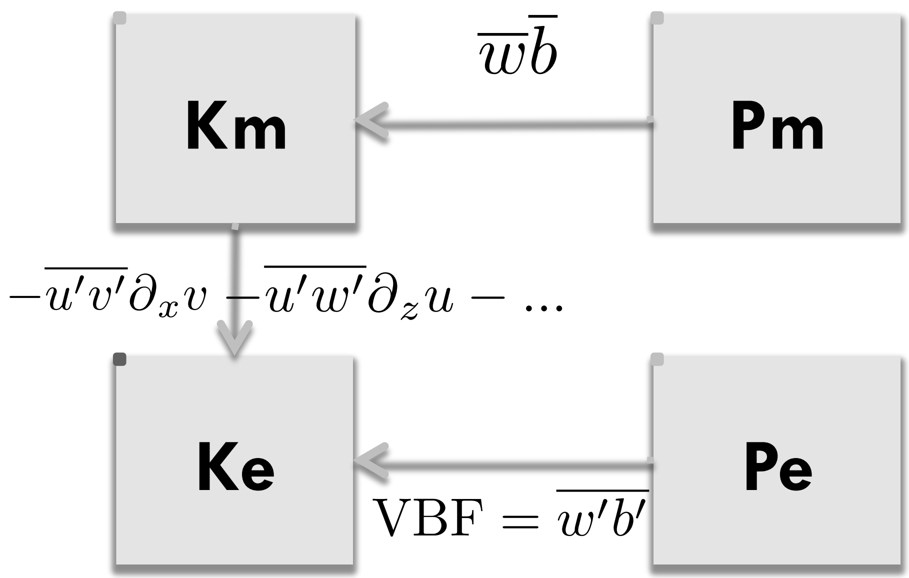


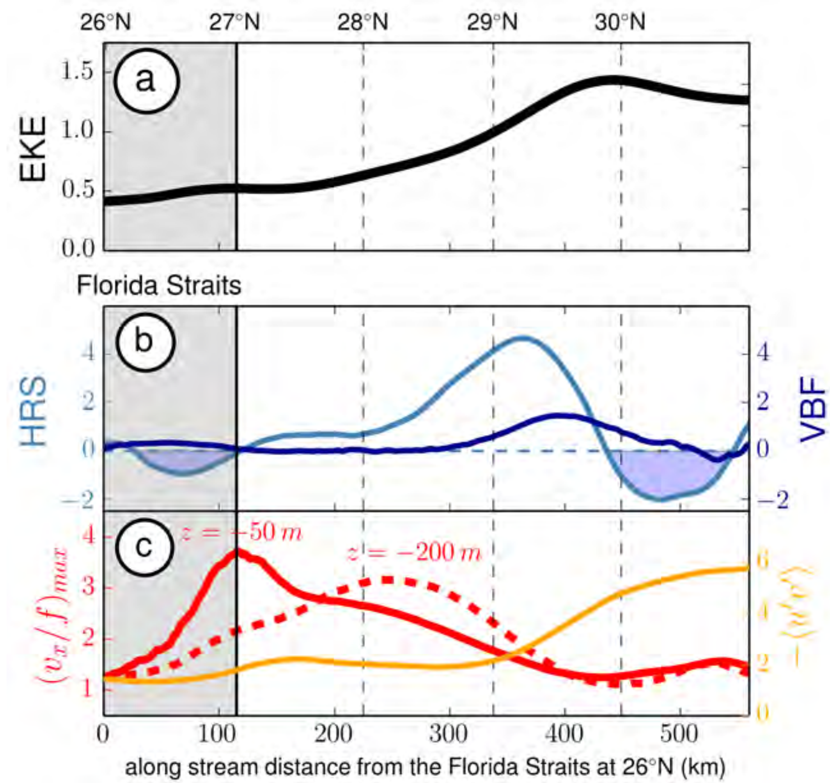
Sequence of SST and relative vorticity showing instability and vortex street formation

Topographic vorticity generation, submesoscale instability and vortex street formation in the Gulf Stream [Gula, Molemaker & McWIlliams, GRL, 2015]

Source of eddy kinetic energy





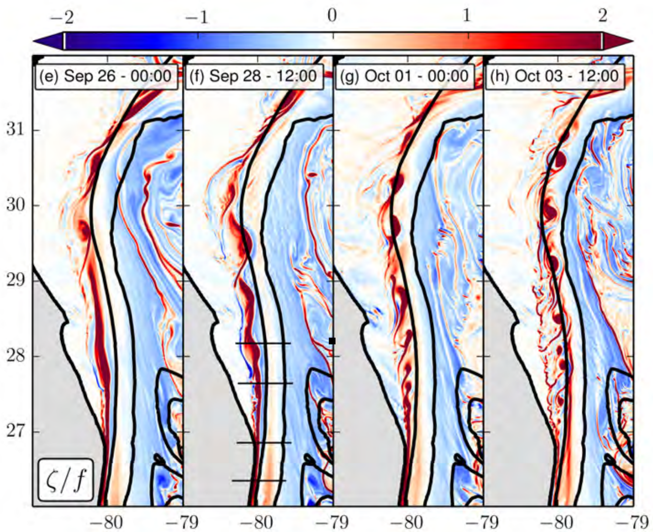


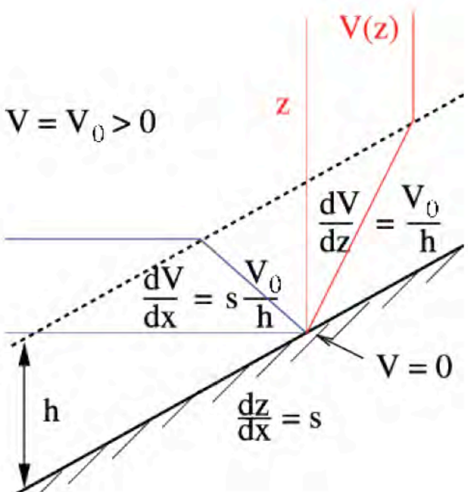
[Perturbation relative to the time mean]

Model showing **barotropic instability** is the main source of eddy kinetic energy

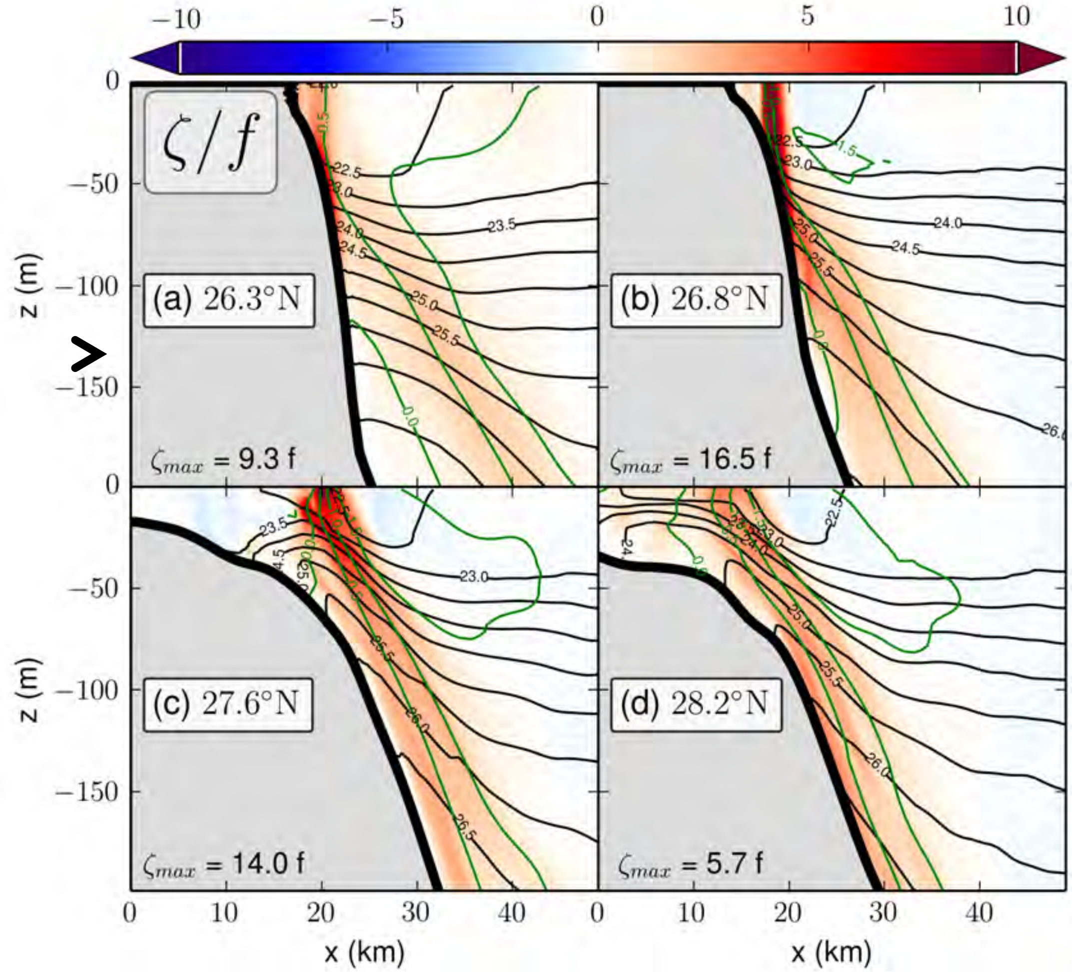
$$\mathrm{HRS} = -\overline{u'v'}\partial_x \overline{v} > 0$$

Topographic vorticity generation



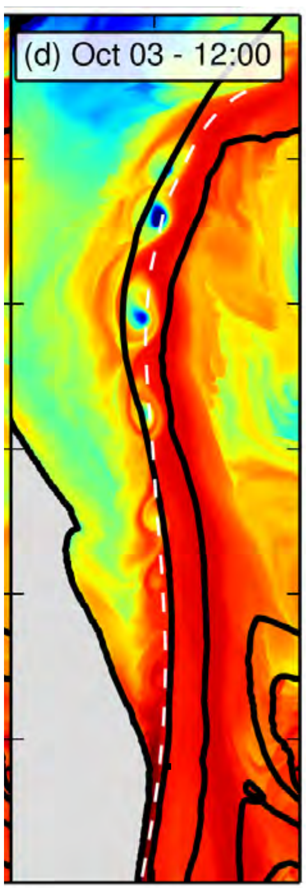


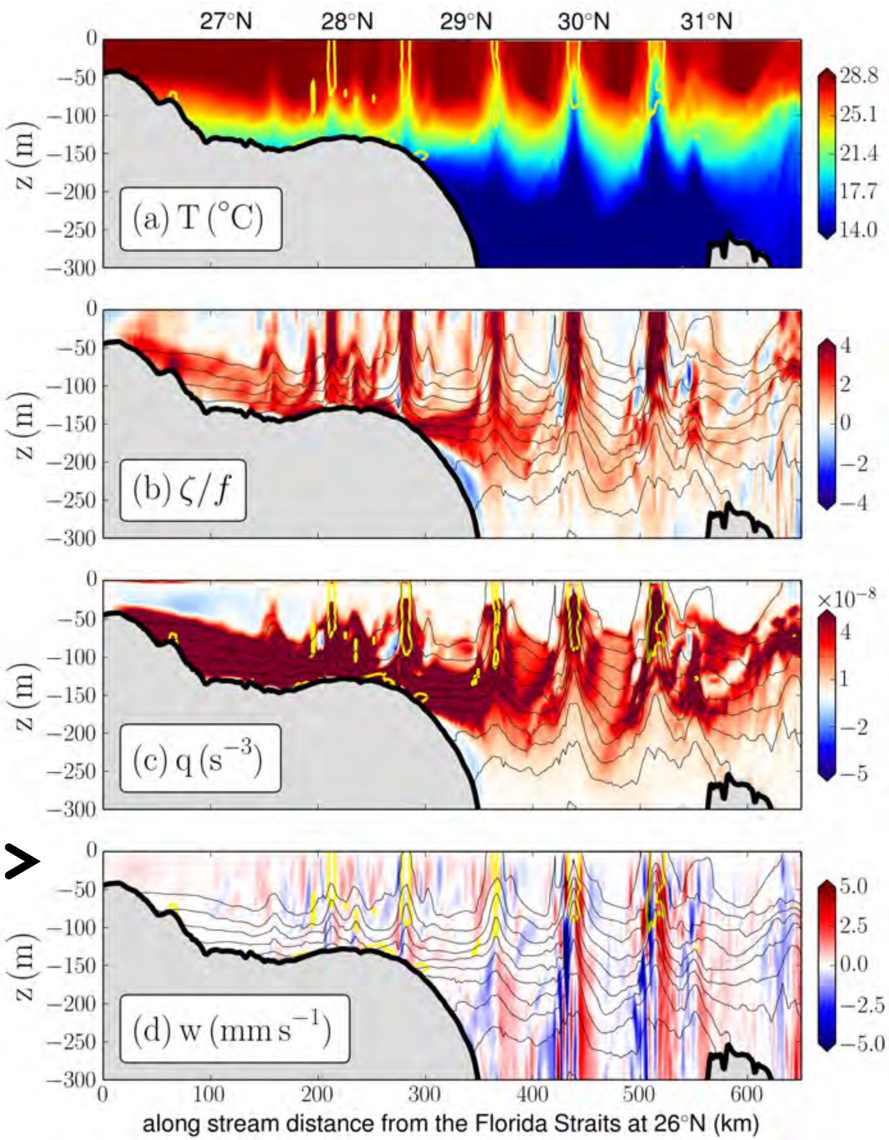
[Molemaker et al., 2015]



Cyclonic vorticity generation by bottom drag on the slope.

Formation of submesoscale vortices



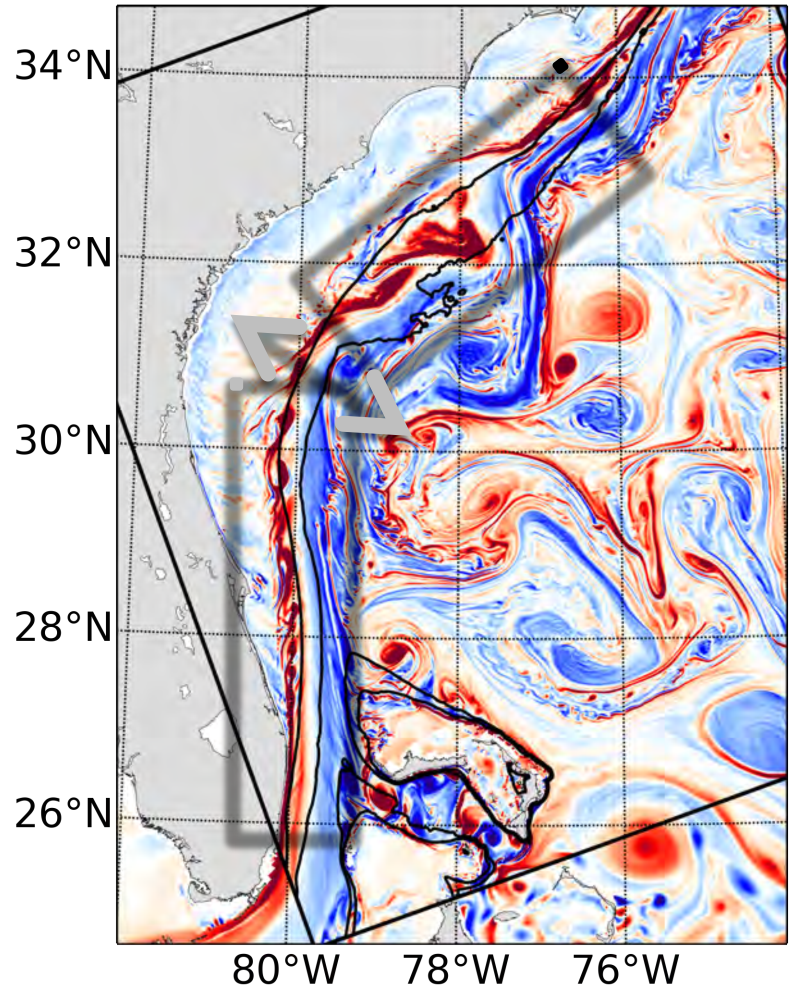


The vortices expand as they propagate northward along the shelf, where they generate large vertical displacements and cross-shelf exchanges.

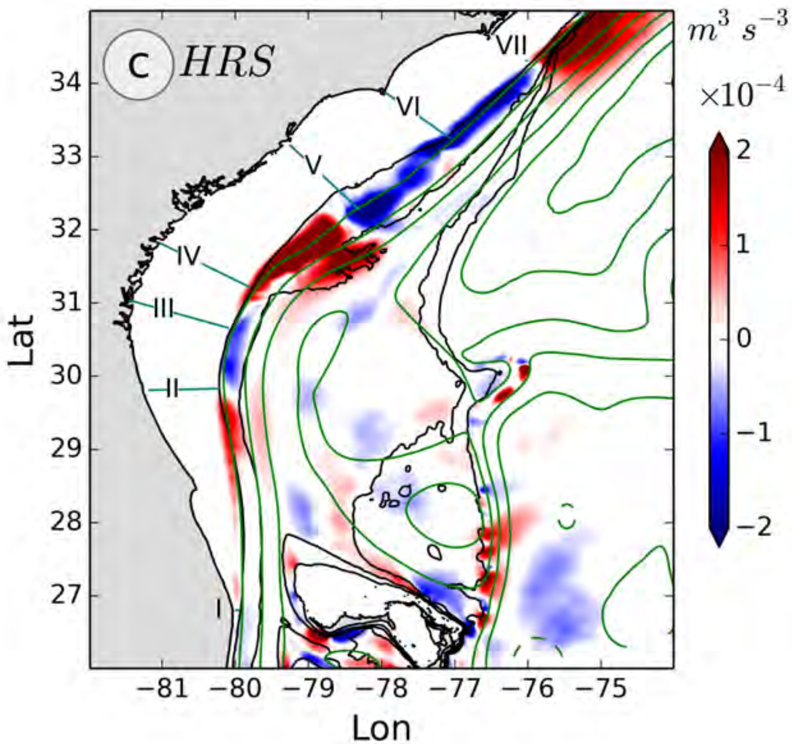
The vortices later feed into meanders at Charleston Bump.

Gulf Stream along the continental slope

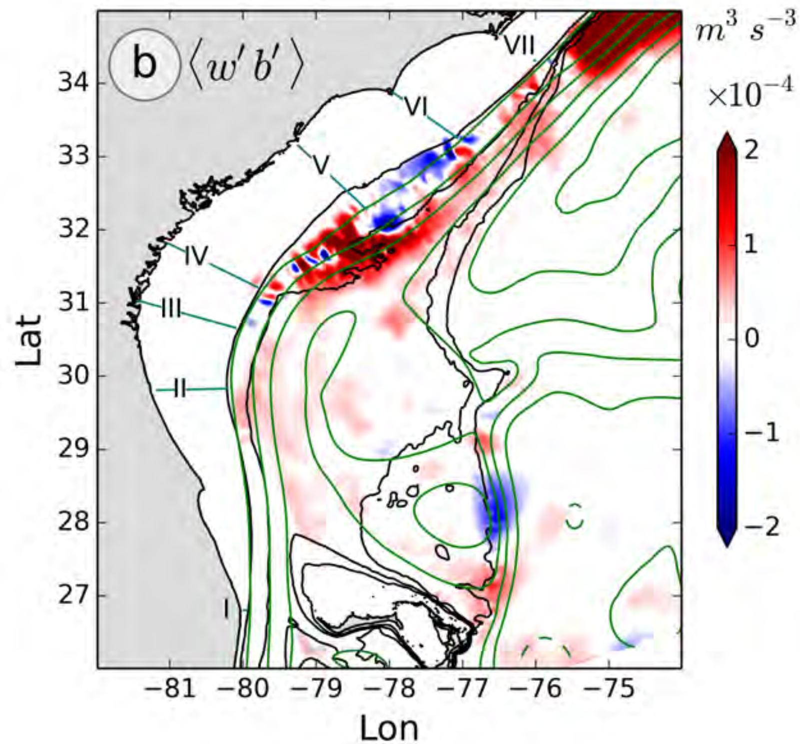
1. Submesoscale instability and vortex street formation
2. Frontal eddy generation
3. Impact for cross-shelf exchanges



Source of eddy kinetic energy



Conversion from mean kinetic to eddy kinetic energy (Barotropic instability)

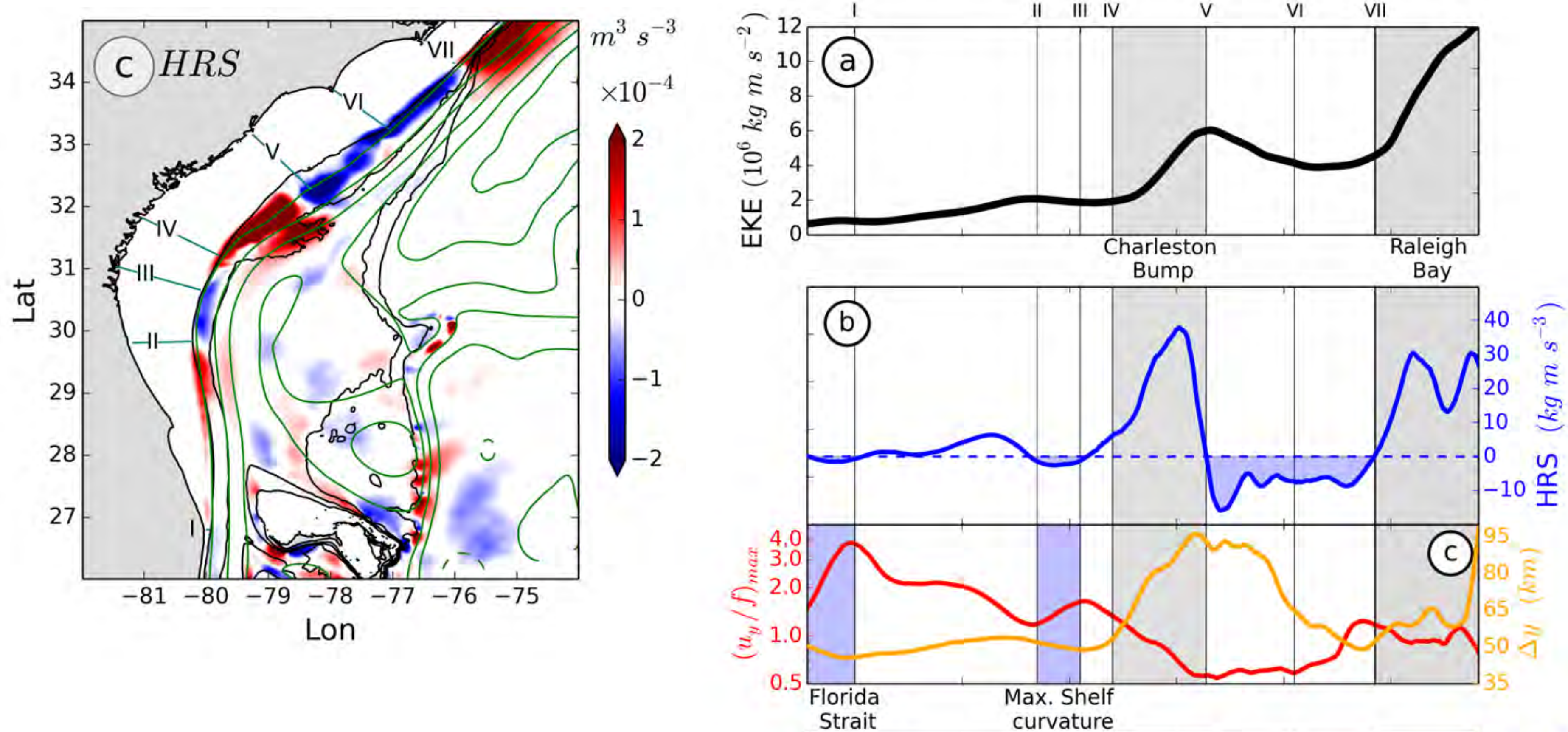


Conversion from eddy potential to eddy kinetic energy (Baroclinic instability)

Mixed barotropic-baroclinic conversion at the Bump

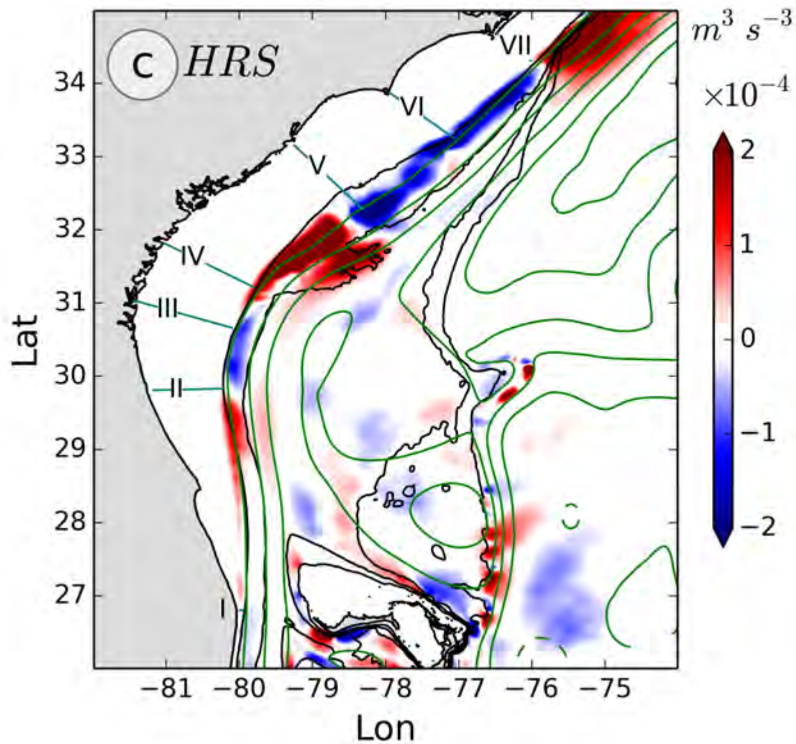
[GS dynamics along the southeastern U.S. Seaboard, Gula, Molemaker & McWIlliams, JPO, 2015]

Source of eddy kinetic energy

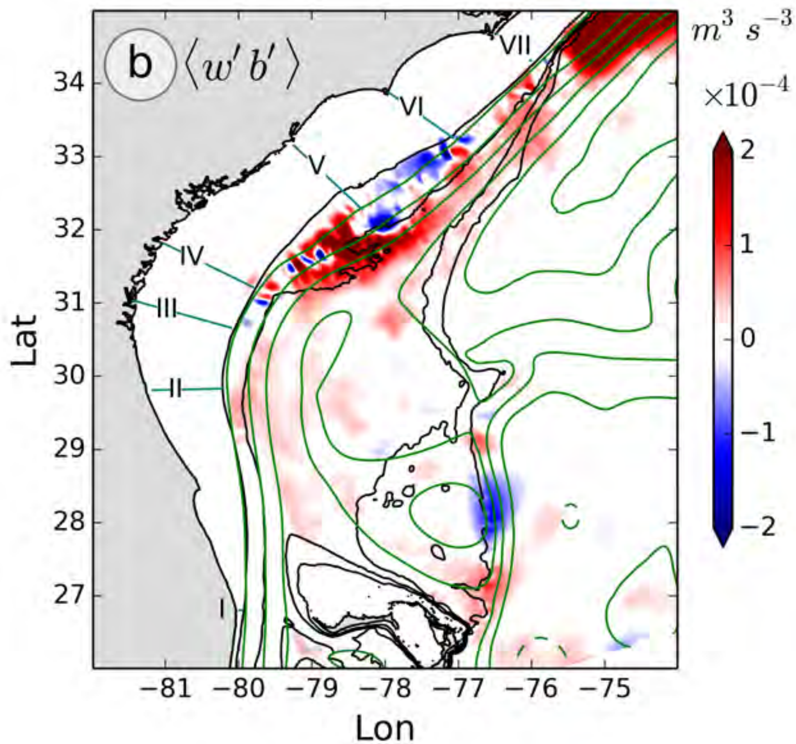


Conversion from mean kinetic to eddy kinetic energy (Barotropic instability)

Source of eddy kinetic energy



Conversion from mean kinetic to eddy kinetic energy (Barotropic instability)



Conversion from eddy potential to eddy kinetic energy (Baroclinic instability)

Mixed barotropic-baroclinic conversion at the Bump

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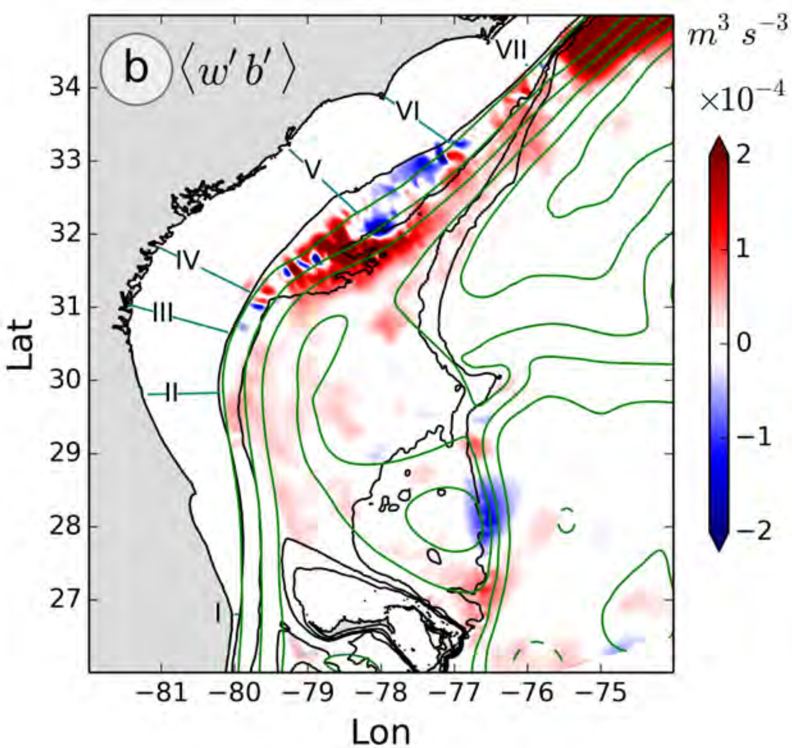
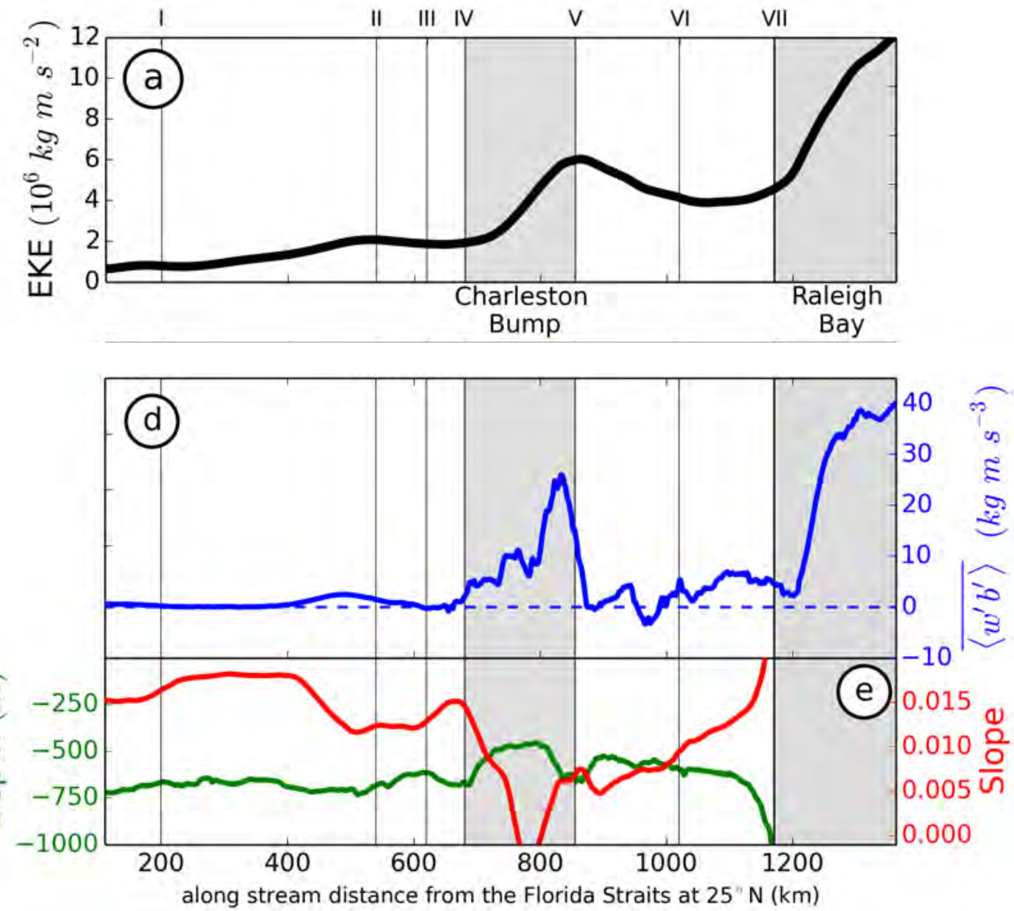
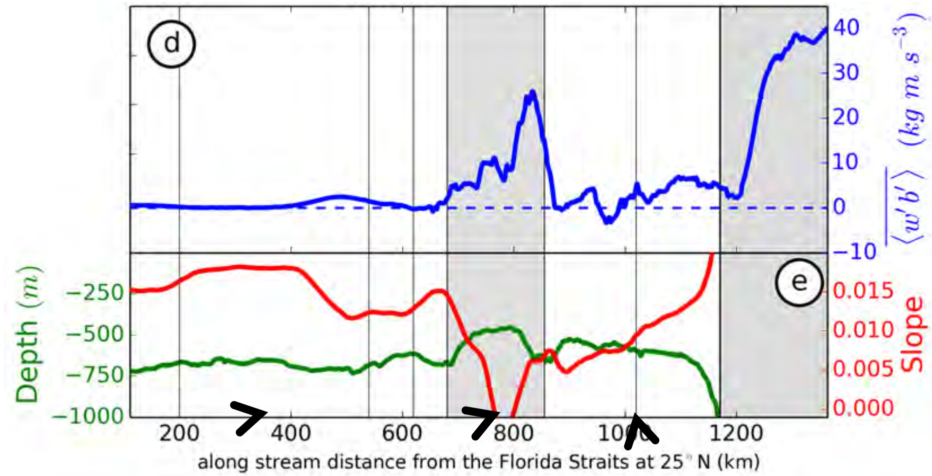


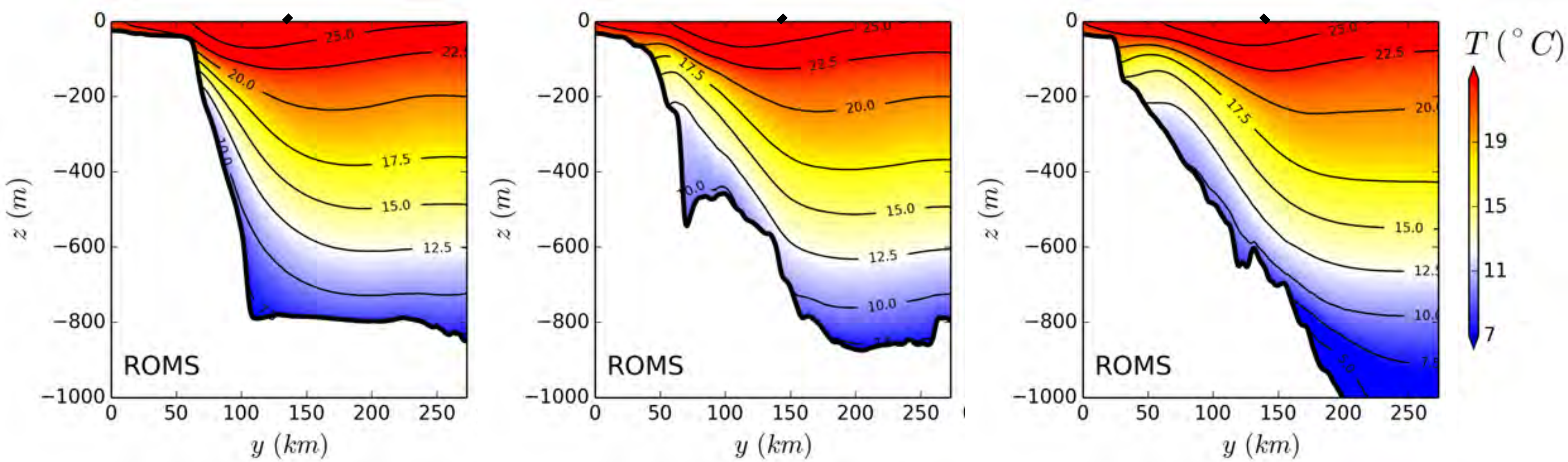


Conversion from eddy potential to eddy kinetic energy (Baroclinic instability)

Control of the topographic slope

Stabilization of the baroclinic instability by the slope



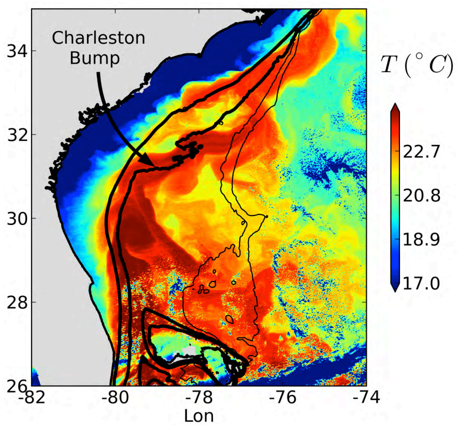


Stable $\mathrm{To} \geq 1$ Unstable $\mathrm{To} = 0$ Stable $\mathrm{To} \geq 1$

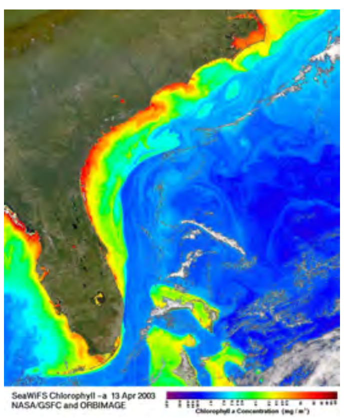
To = ratio between the shelf slope and the isopycnal slope

Formation of a frontal eddy

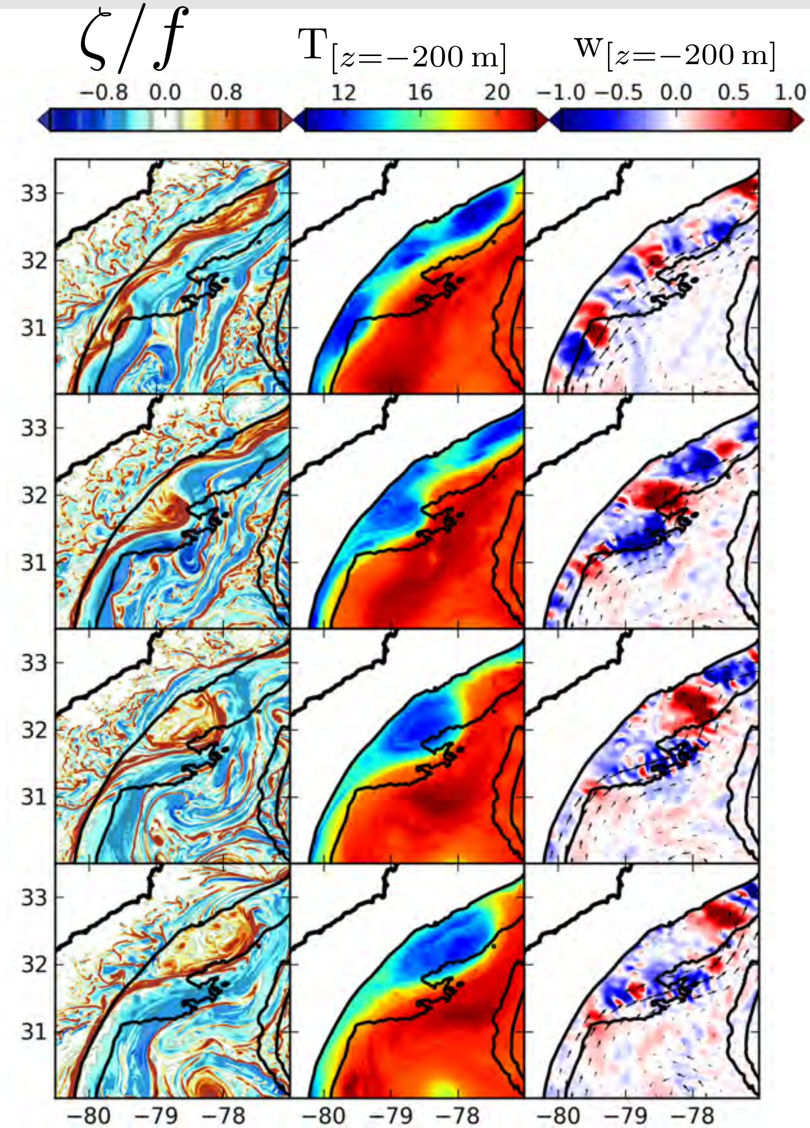
The **Charleston Bump** is a region of strong amplification for meanders and frontal eddies through mixed barotropic/baroclinic energy conversion.



Observed SST of the Gulf Stream on March 15, 2013. Data from MODIS-AQUA.



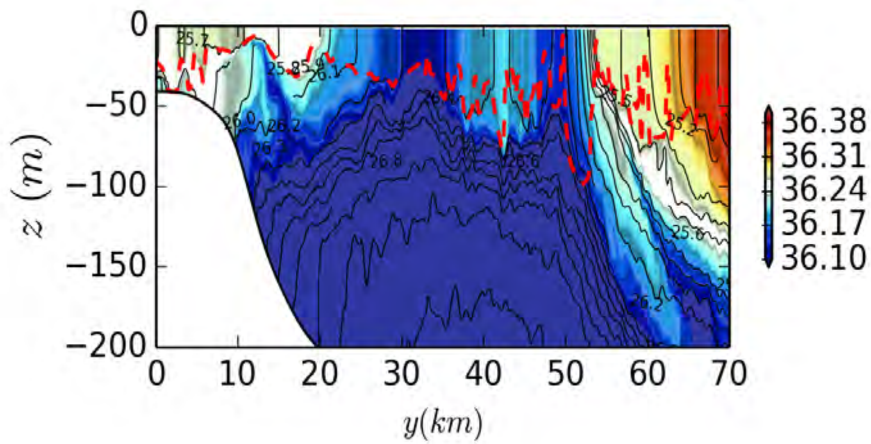
SeaWiFS chl a on April 13, 2003



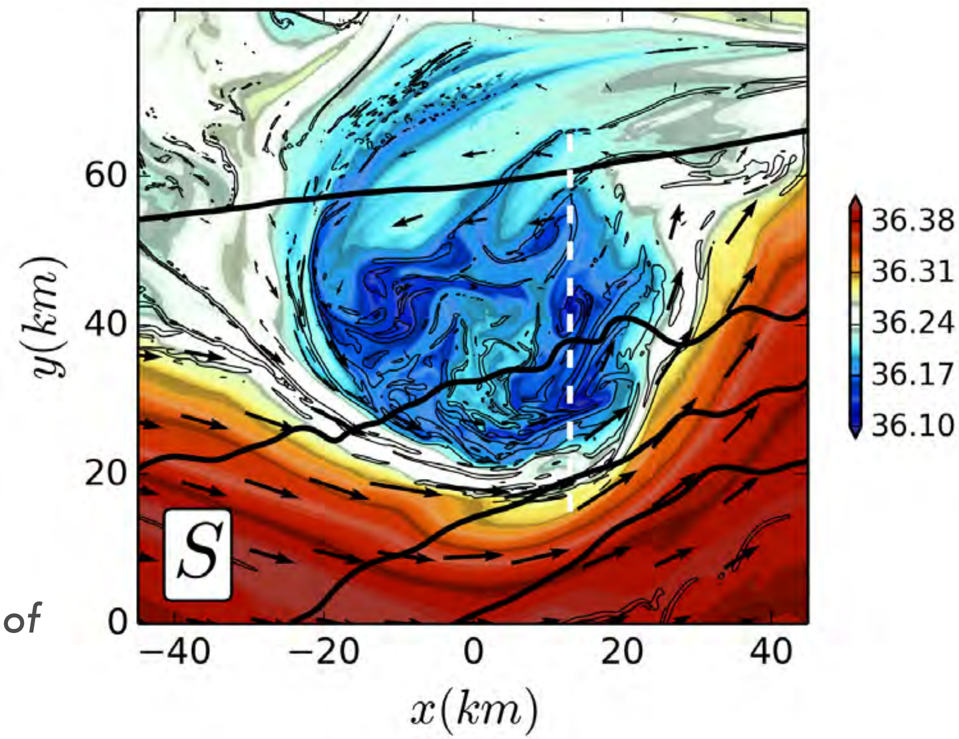
[Submesoscale dynamics of a GS Frontal Eddy off the South Atlantic Bight, Gula, Molemaker & McWIlliams, in rev for JPO,]

Structure of a frontal eddy

ROMS $\Delta x = 150\text{m}$



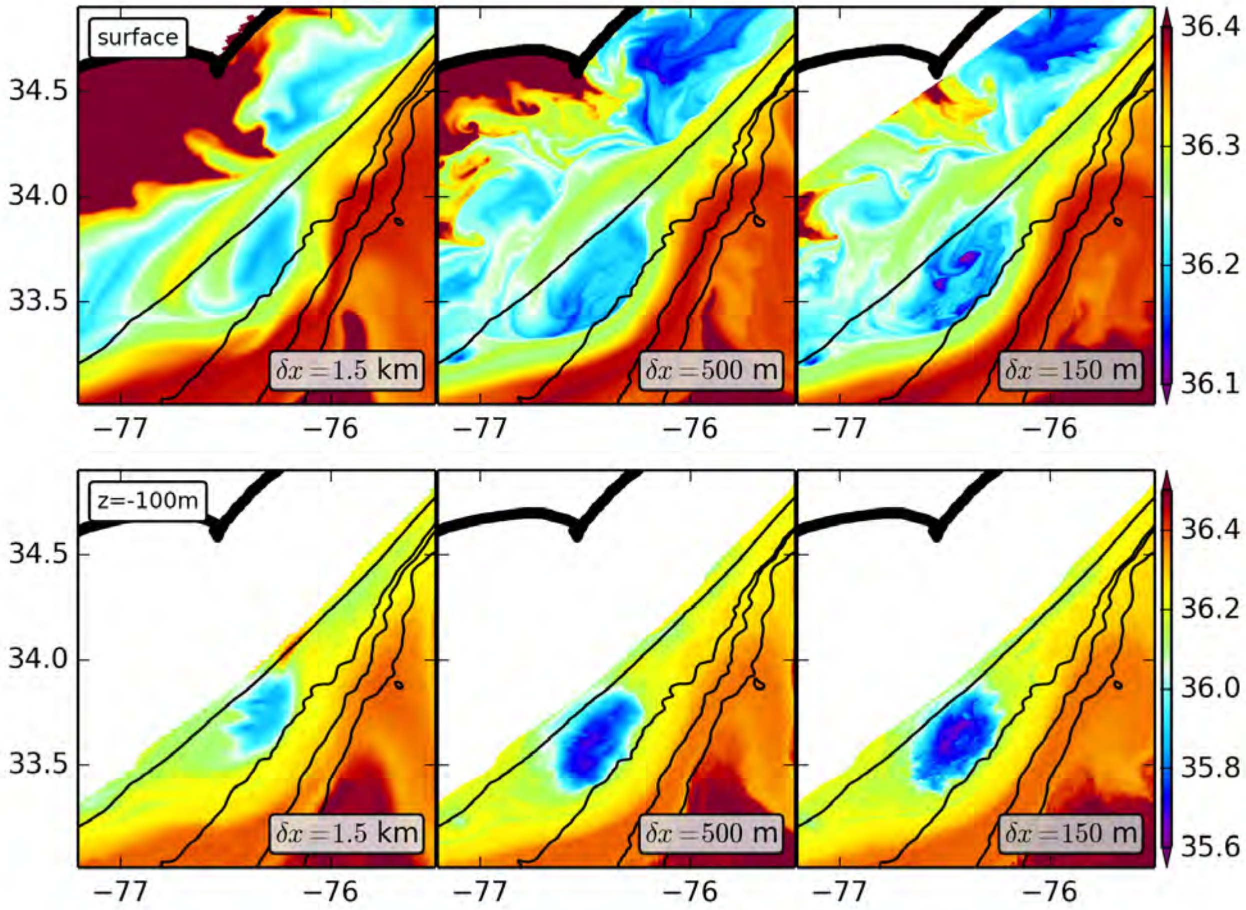
Horizontal (left) and vertical (right) sections of salinity for a frontal eddy (dx=150 m)



Frontal eddies are formed in the troughs of northward propagating meanders and consist of **deeply upwelled cold domes.** They are often associated with shallow warm filaments, known as "shingles", which form at the surface.

[Submesoscale dynamics of a GS Frontal Eddy off the South Atlantic Bight, Gula, Molemaker & McWIlliams, in rev for JPO,]

Influence of the submesoscale



Salinity at surface (top) and at z=-100m (bottom) for a frontal eddy in simulations with increasing resolutions

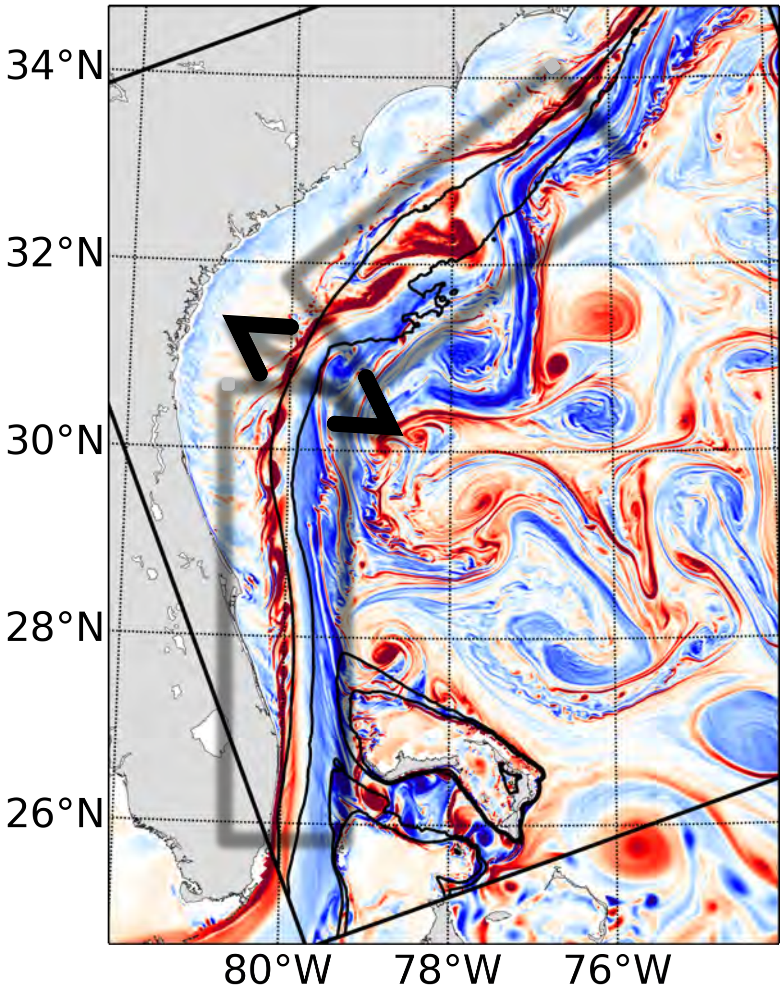
The upwelling in the cold core of the eddy is more intense when the resolution increases. At very high resolutions there are additional submesoscale patterns and localized regions of intense upwelling bringing cold and fresh water from the upwelled cold of the eddy inside the surface mixed-layer.

Gulf Stream along the continental slope

1. Submesoscale instability and vortex street formation

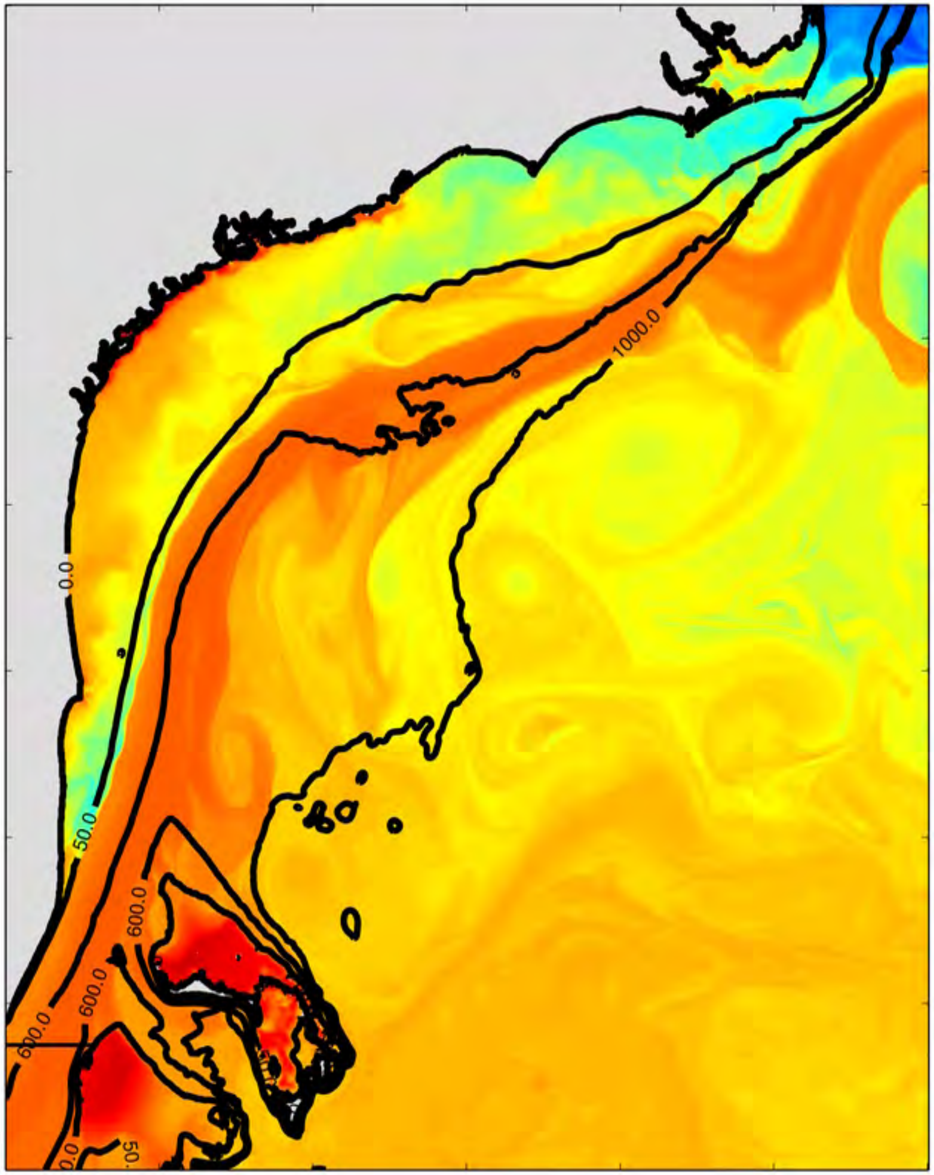
2. Frontal eddy generation

3. Impact for cross-shelf exchanges



Gulf Stream intrusions on the shelf

Continuous release of Lagrangian particles in the core of the Stream

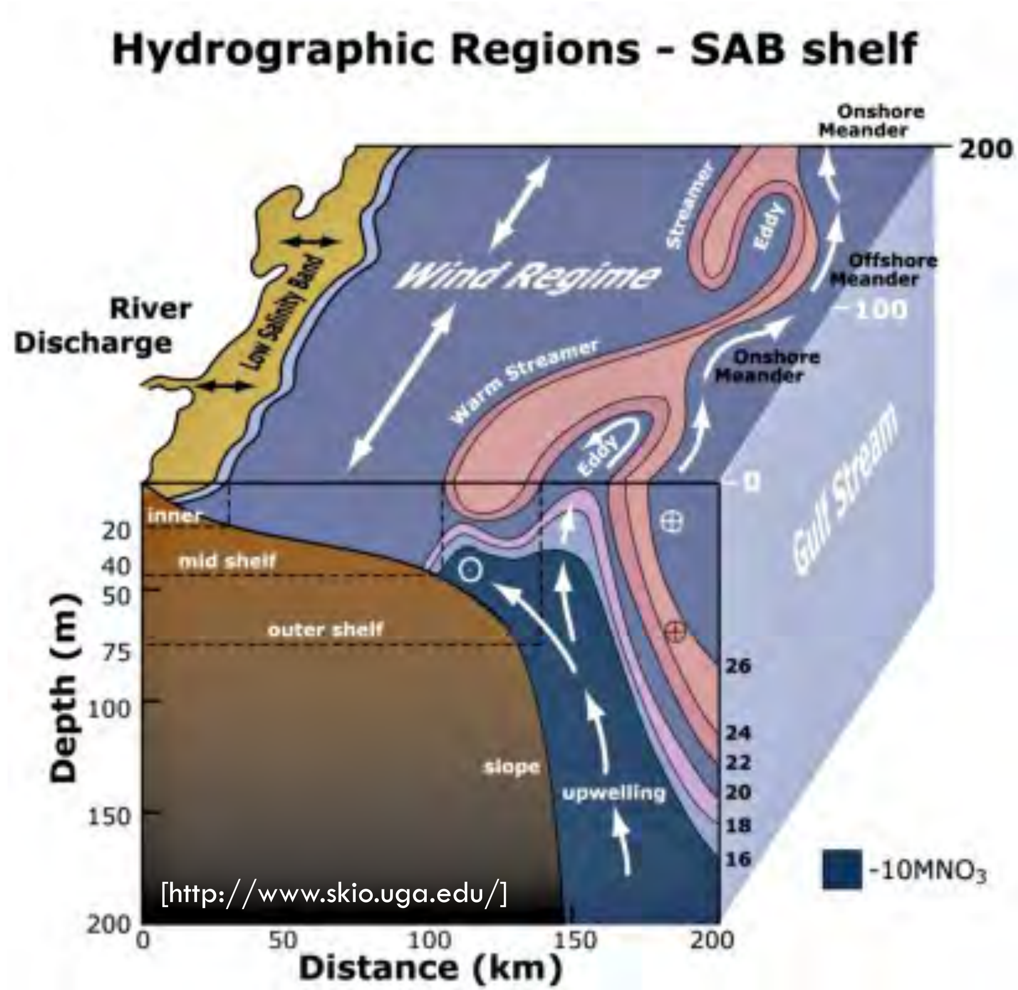


Gulf Stream intrusions on the shelf

Frontal eddies propagate northward along the shelf, bringing cold, nutrient-rich waters onto the outer shelf.

The extent to which the eddies intrude onto the shelf is dependent on atmospheric conditions and seasonal variations in the shelf hydrography.

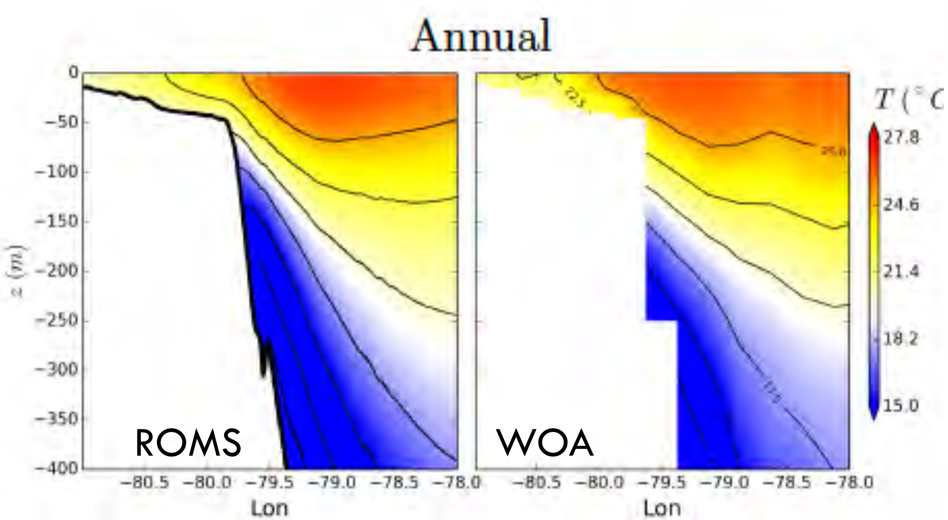
[e.g. Lee et al, 91, Castelao, 11]

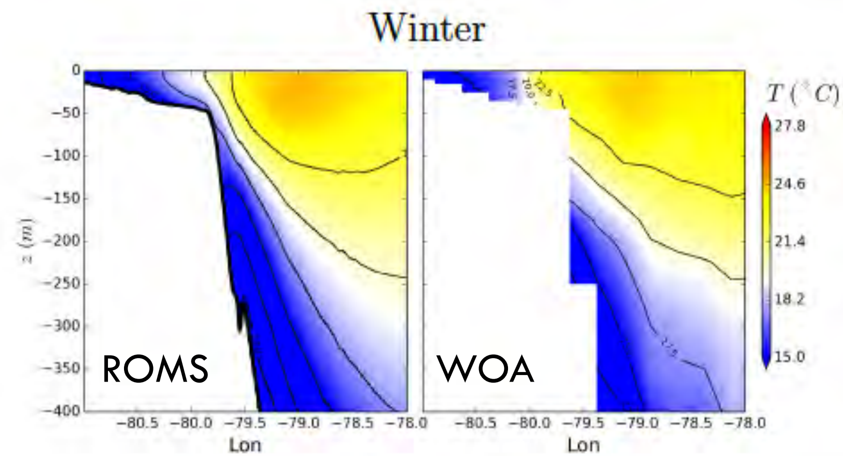


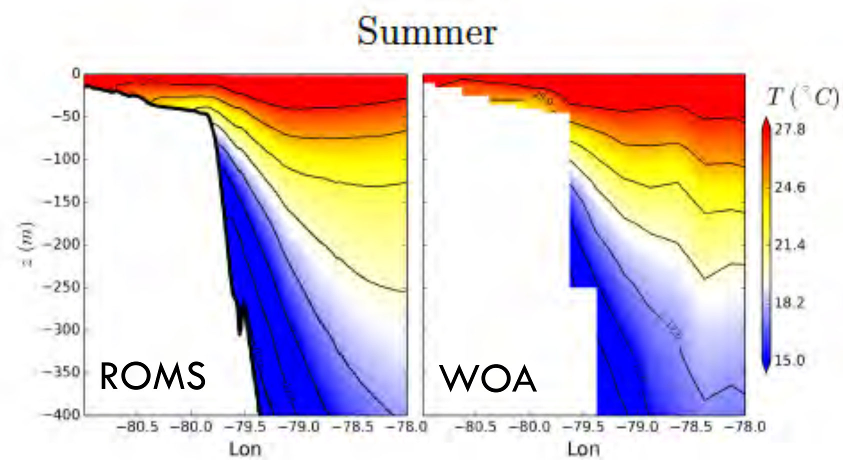
[http://www.skio.uga.edu/]

Seasonal Stratification over the shelf

Vertical section of temperature at 31.5N from model and obs.





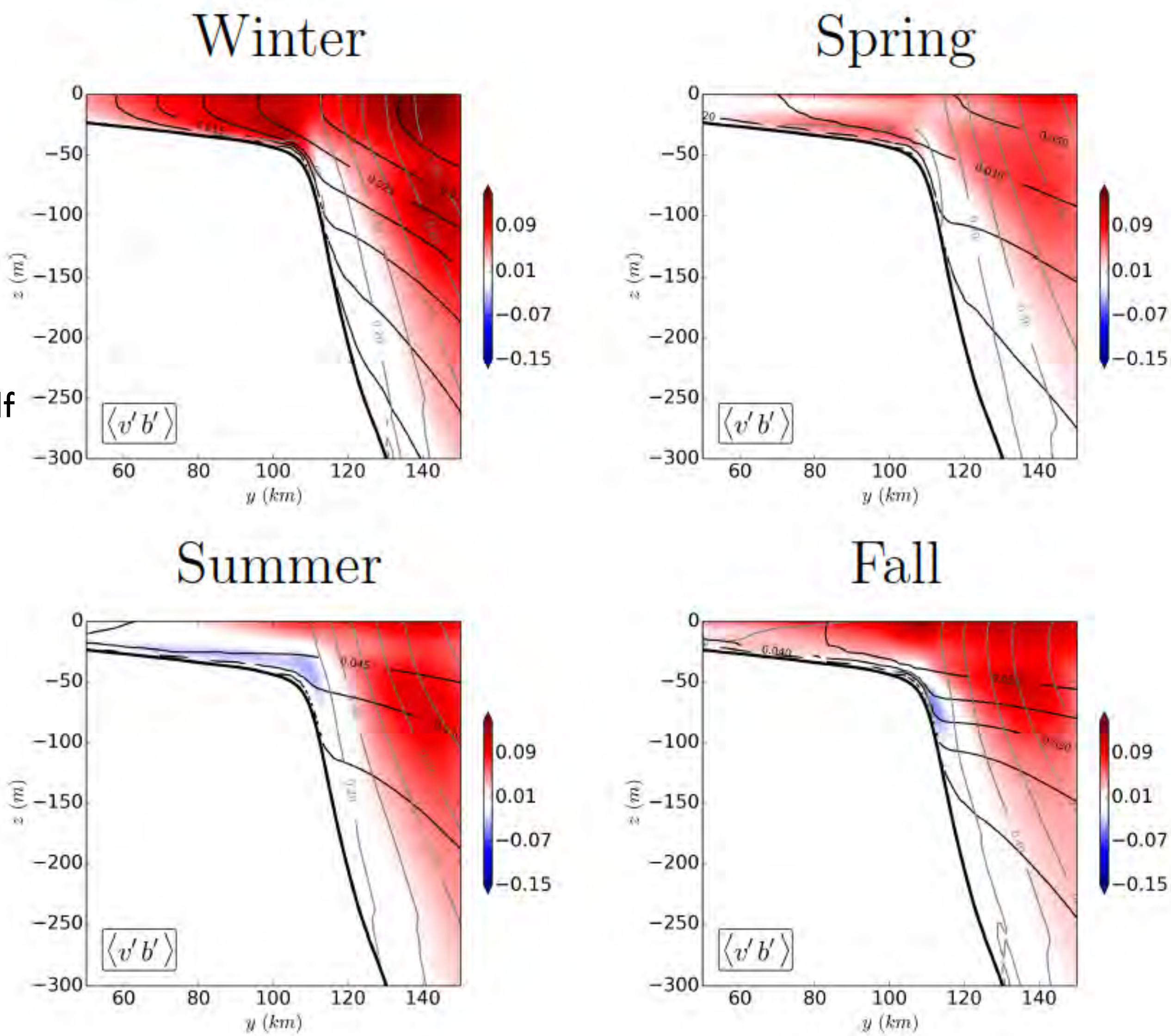


Cross-shelf exchanges over the slope

Eddy buoyancy fluxes
(along shelf averaged)

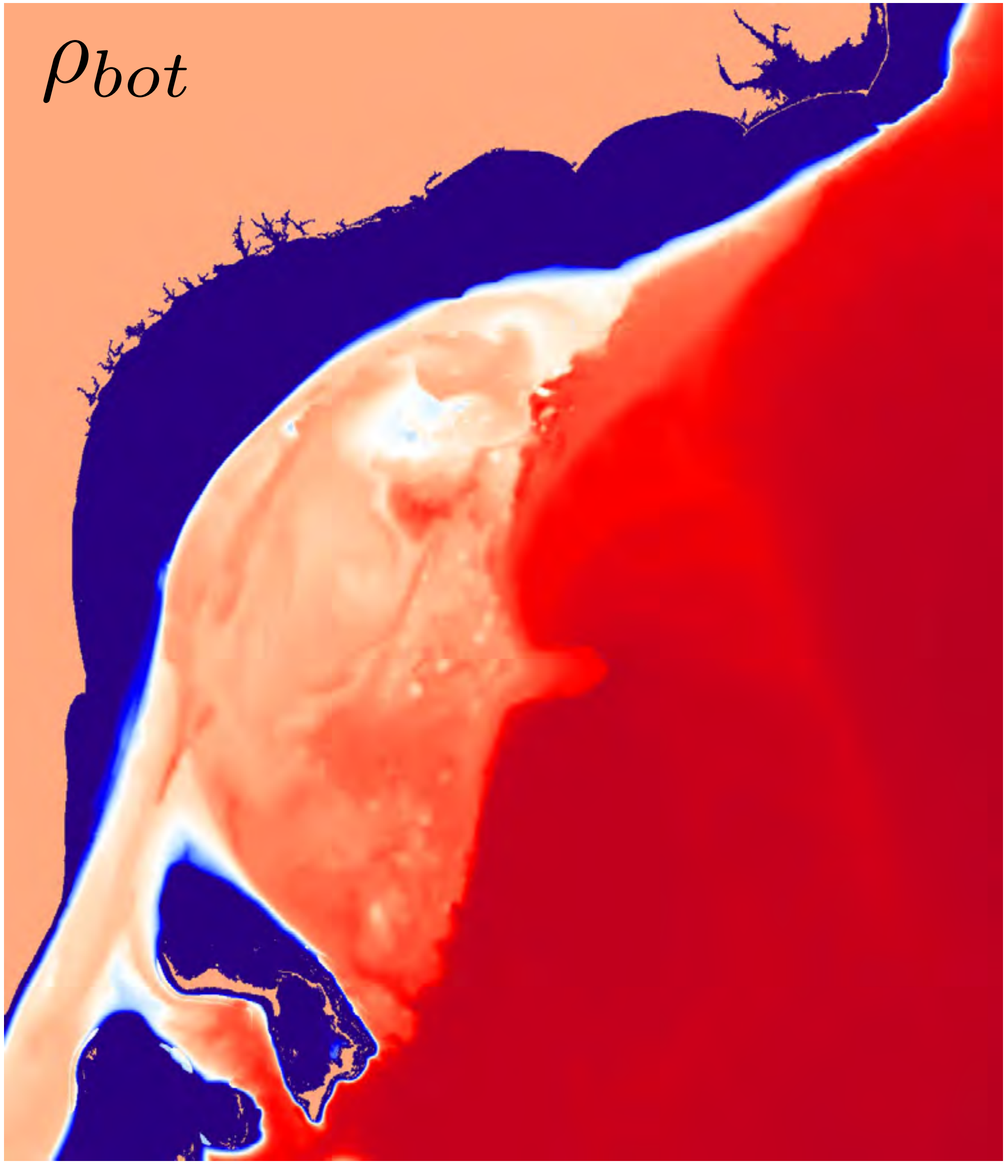
Positive fluxes = from the Gulf Stream to the shelf onto the shelf

Strong seasonal variations



Cross-shelf exchanges of dense water

Bottom density
(one year animation starting in June)

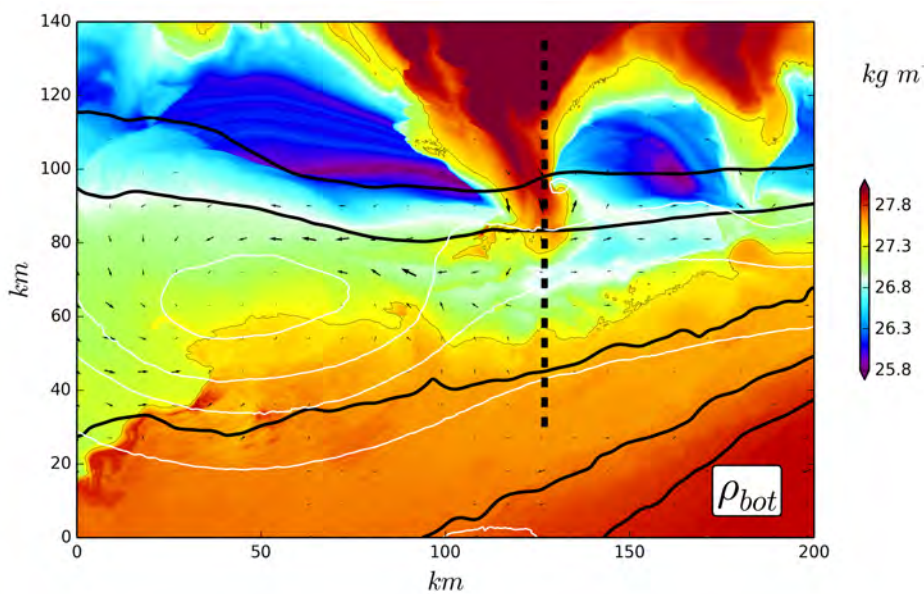


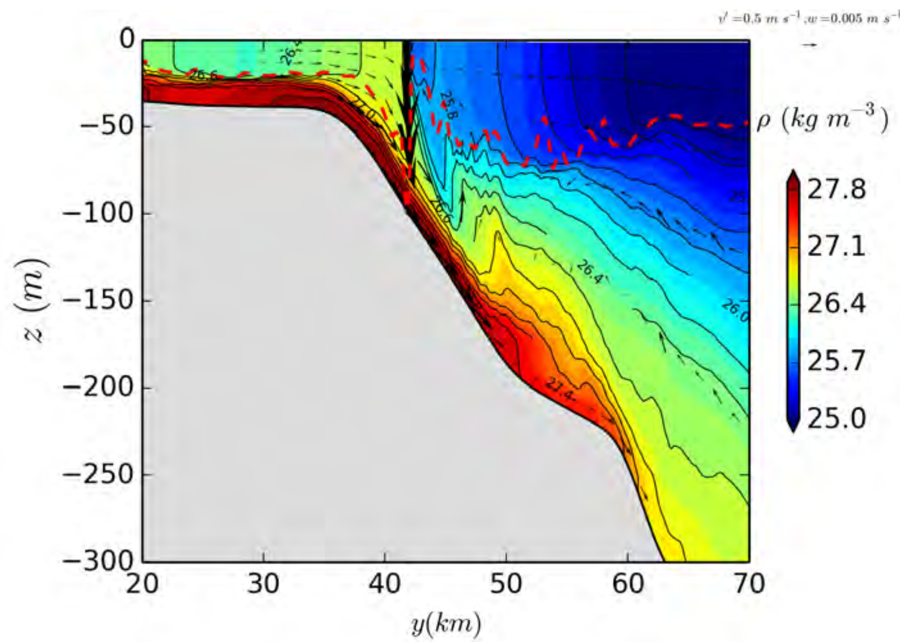
Dense water upwelled on the shelf, mostly in summer (upwelling favorable winds + shelf stratification + more GS transport)

Dense water formed on the shelf in winter descending down the continental slope: "*Cascading of dense shelf waters*"

Cascading of dense shelf waters

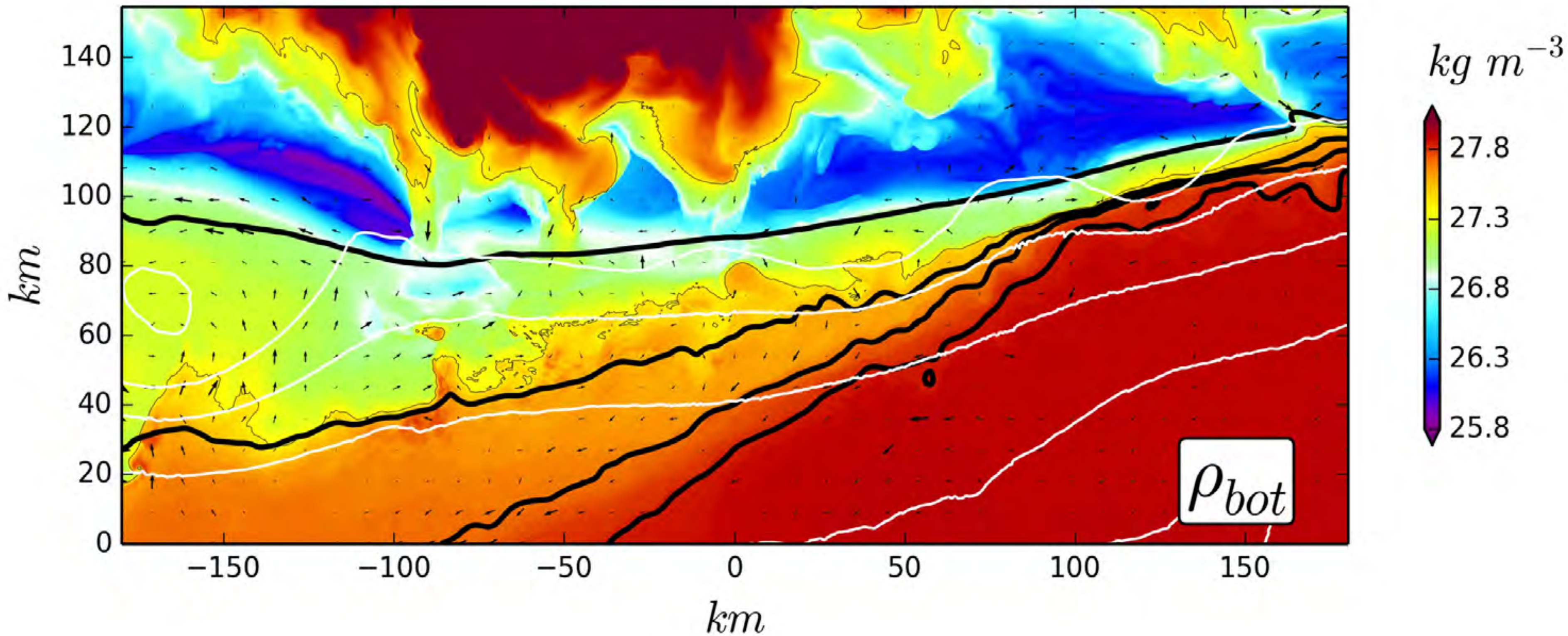
ROMS $\Delta x = 150\mathrm{m}$





Density at bottom (colors), topography (black contours), bottom velocity (arrows) and free surface (white contours).

Cascading of dense shelf waters



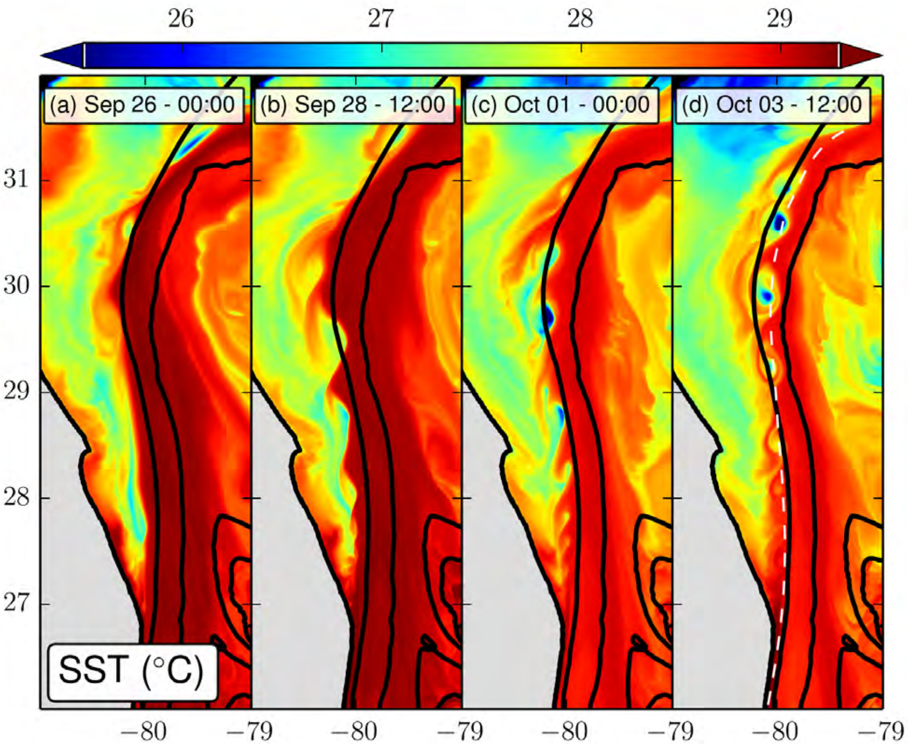
Density at bottom (colors), topography (black contours), bottom velocity (arrows) and free surface (white contours).

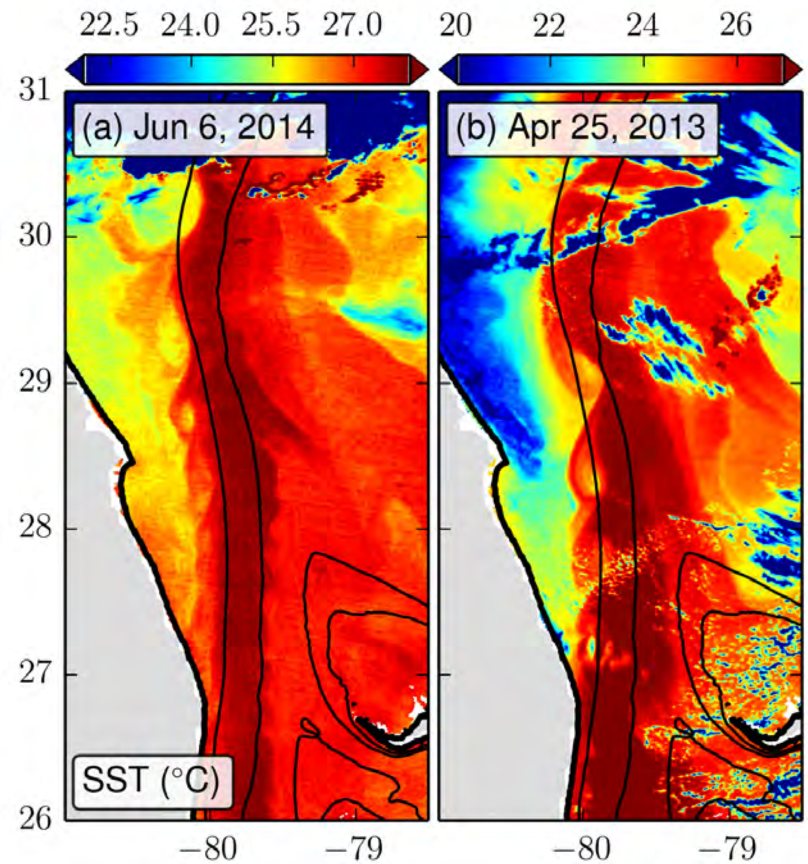
Conclusions

- Eddy-mean interactions modulations controlled by topographic slope width and curvature
  - The baroclinic instability is stabilized by the slope everywhere except past the bump.
  - Eddy growth by Reynolds stress and downstream development of the eddies (= oceanic storm tracks)
  - Frontal eddies generated by mixed barotropic/baroclinic instability process at the Bump
- Eddies are the main source of variability along the South Atlantic Bight and drive cross-shelf exchanges by generating surface and bottom intrusions onto the shelf.
- Strong seasonal variations depending on shelf stratification.
  - Eddy induced upwelling stronger in summer
  - Cascading of dense shelf waters during winter and fall.

Submesoscale instability

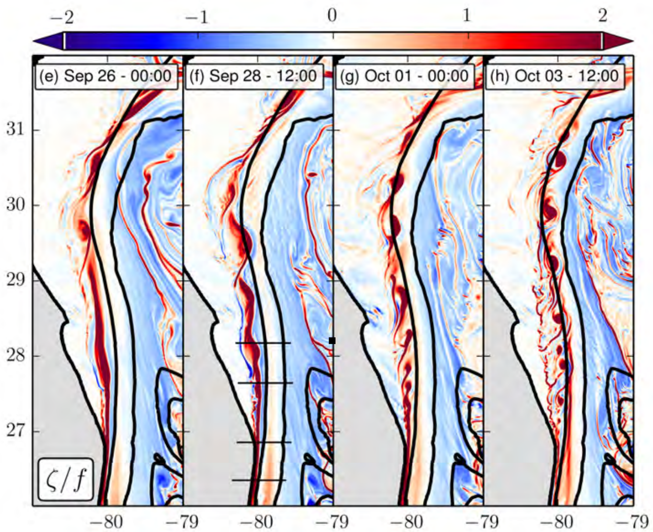
ROMS $\Delta x = 750\,\mathrm{m}$





Observed SST showing cyclones on shoreward flank of Gulf Stream downstream from Florida Straits

Horizontal shear instability



[Perturbation relative to the along-front mean]

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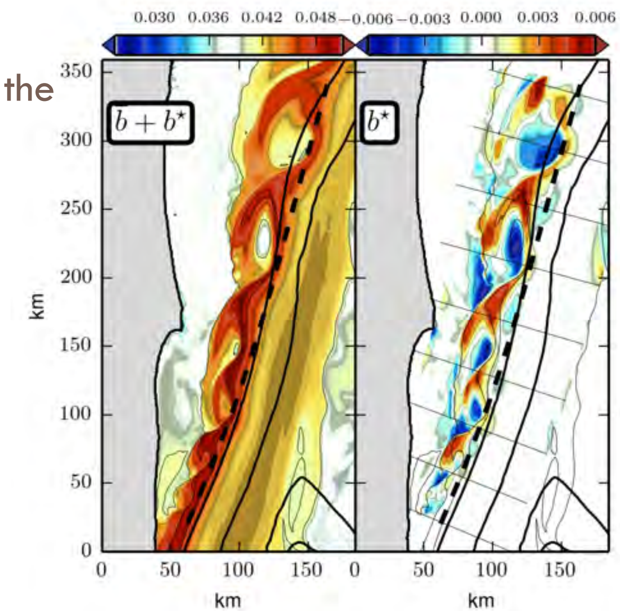
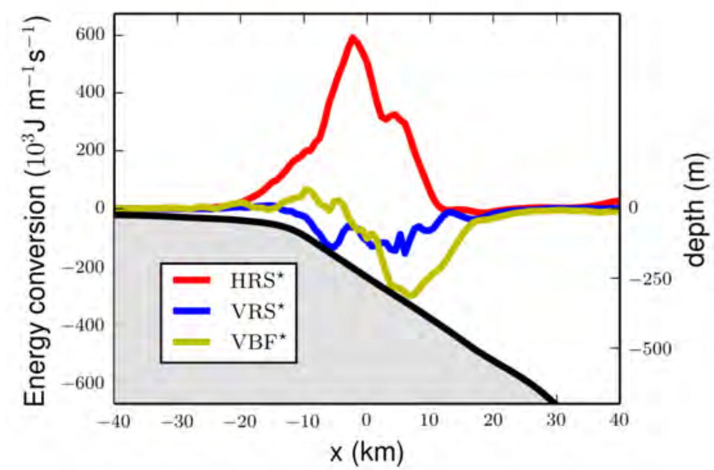
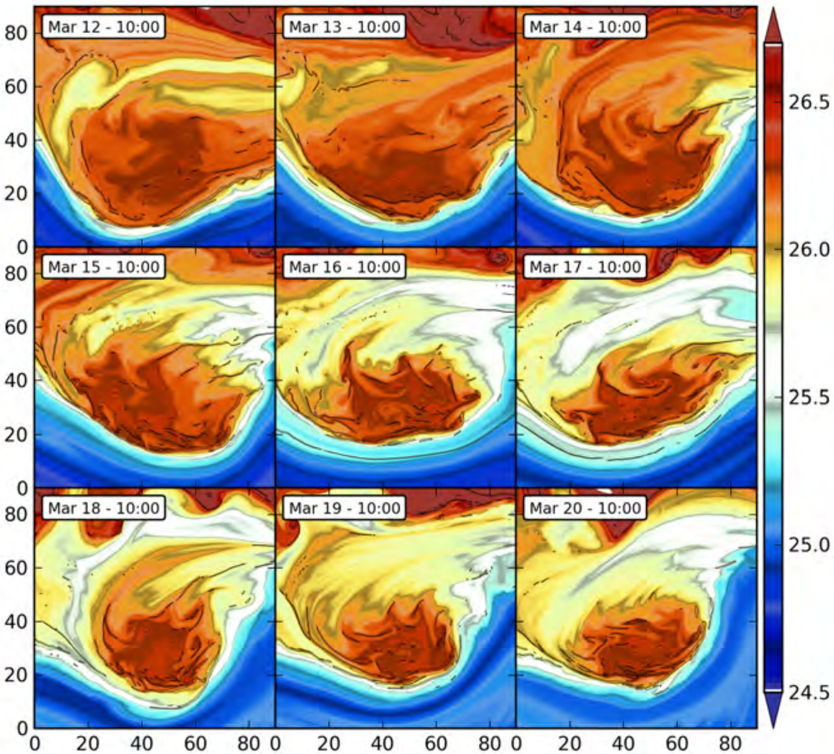


Energy source for the instability?

$$\mathrm{HRS}^* = -\langle u^* v^* \rangle \partial_x \langle v \rangle > 0$$



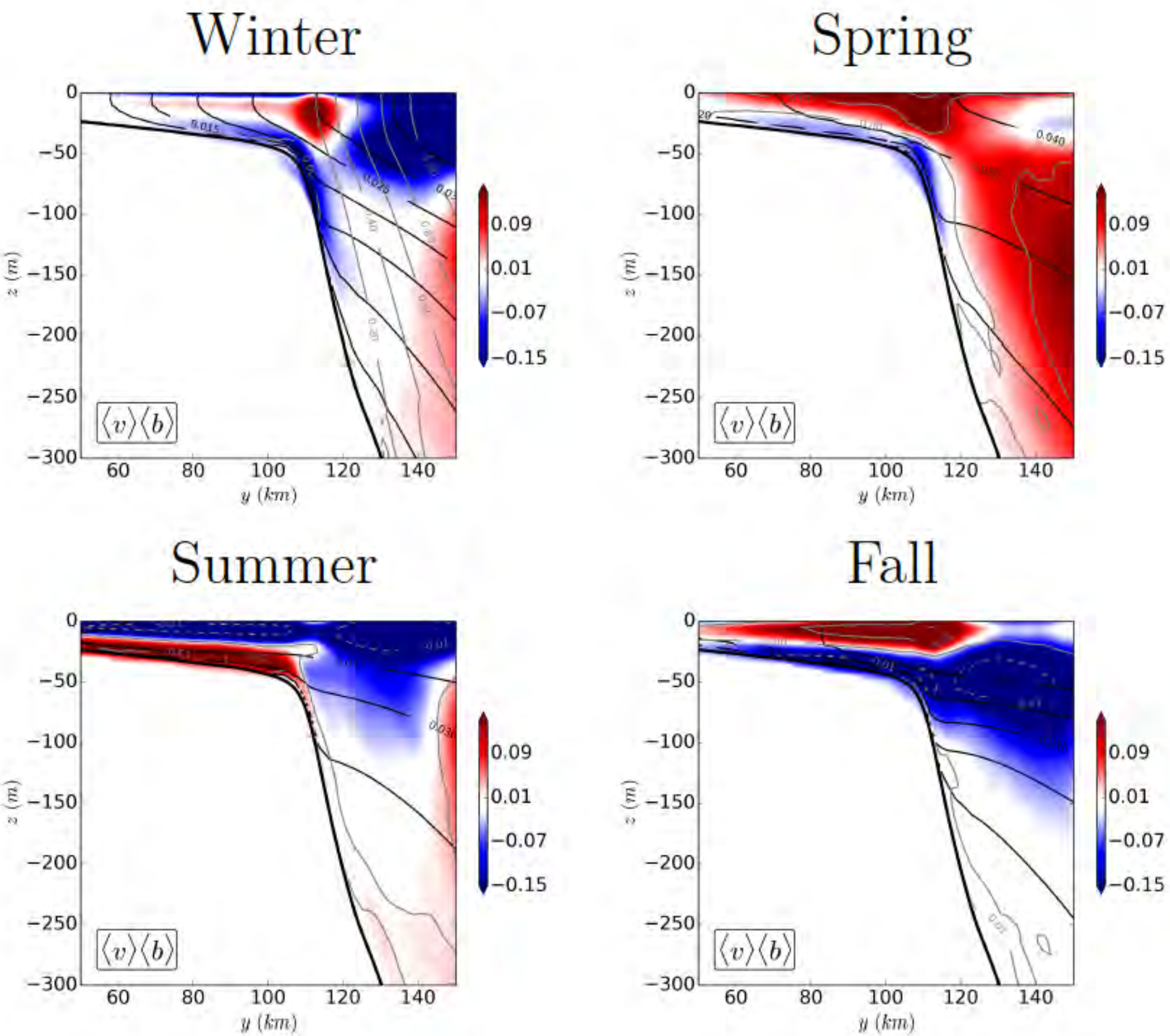
Submesoscale instability in the frontal eddy



Surface density (colors) and vorticity (black contours)

- The strong straining acts to sharpen the velocity gradient on the upstream face of the trough.
- The strain weakens in the trough and the sharp front becomes unstable on the downstream.
- The small-scale meandering perturbations ultimately evolve into rolled-up vortices that are advected back into the frontal eddy

Cross-shelf exchanges over the slope



Observed Gulf Stream

MODIS SST + MERIS GLITTER [02/04/10]: