When the Stream meets the Bump…

NHOM-Brest: Workshop on Non-Hydrostatic Ocean Modeling
Bridging the gap between sub-mesoscales and boundary layer turbulence
15-17 Oct 2018, Brest (France)

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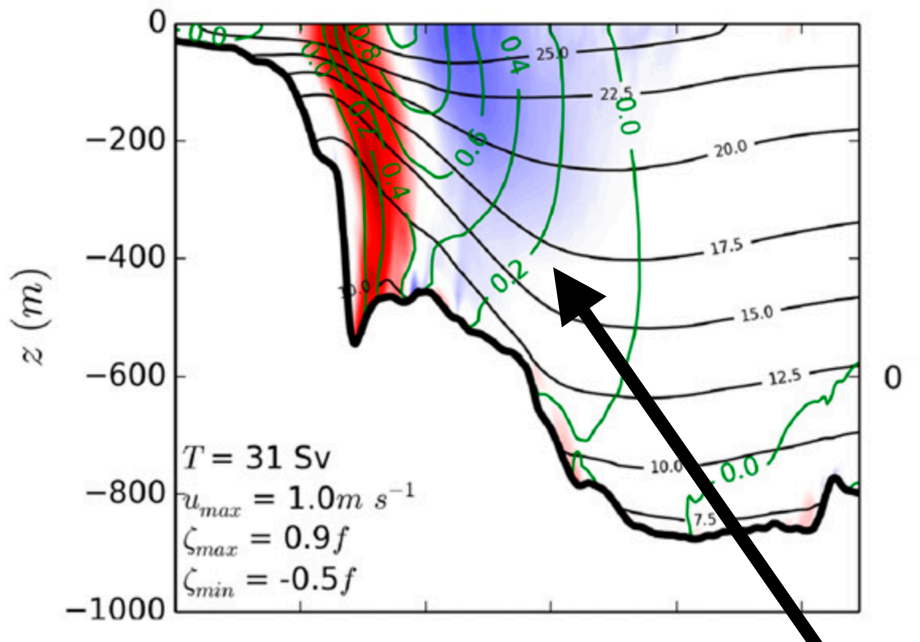
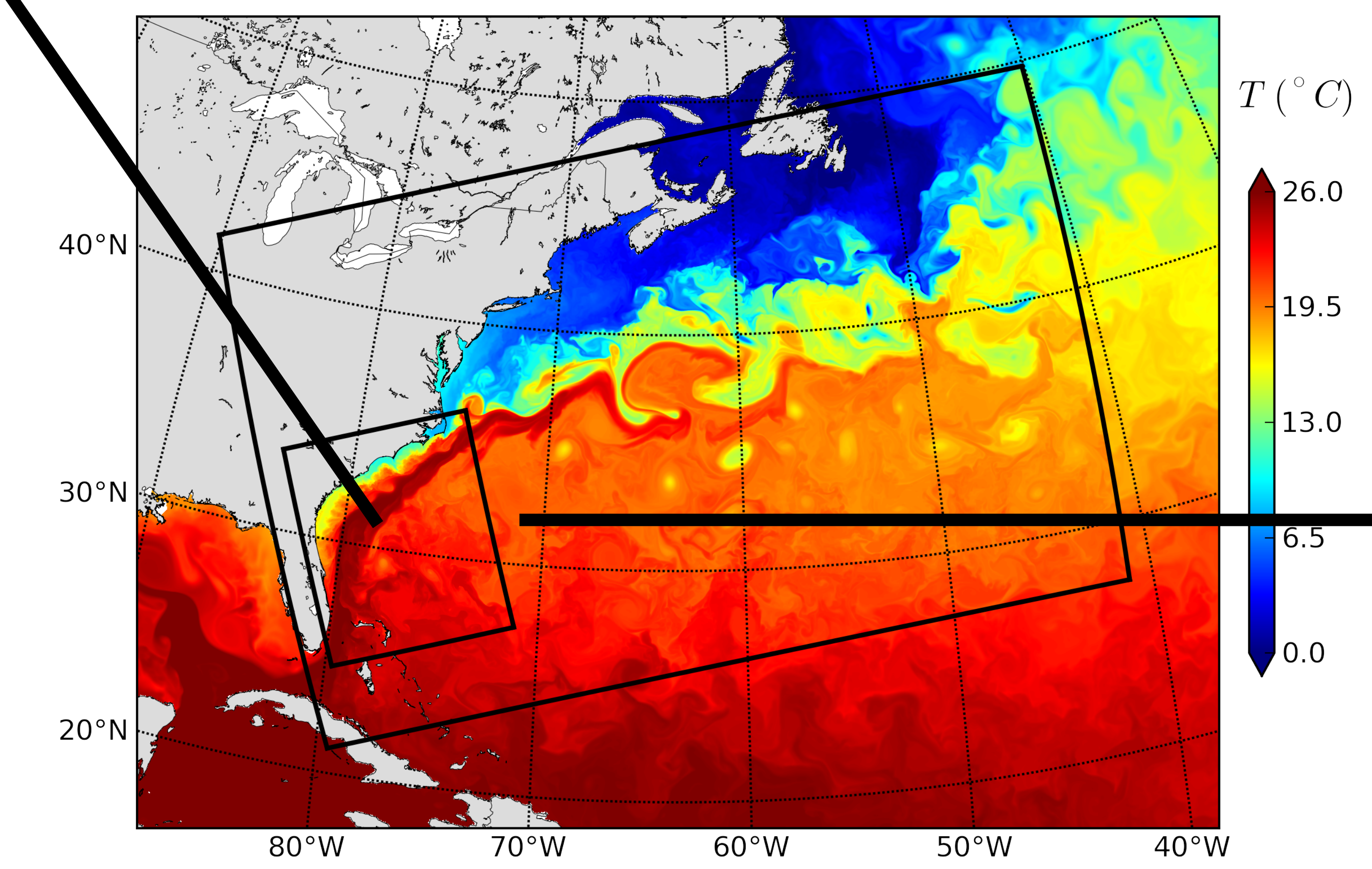
Tanya Blacic (MSU) & Robert Todd (WHOI)

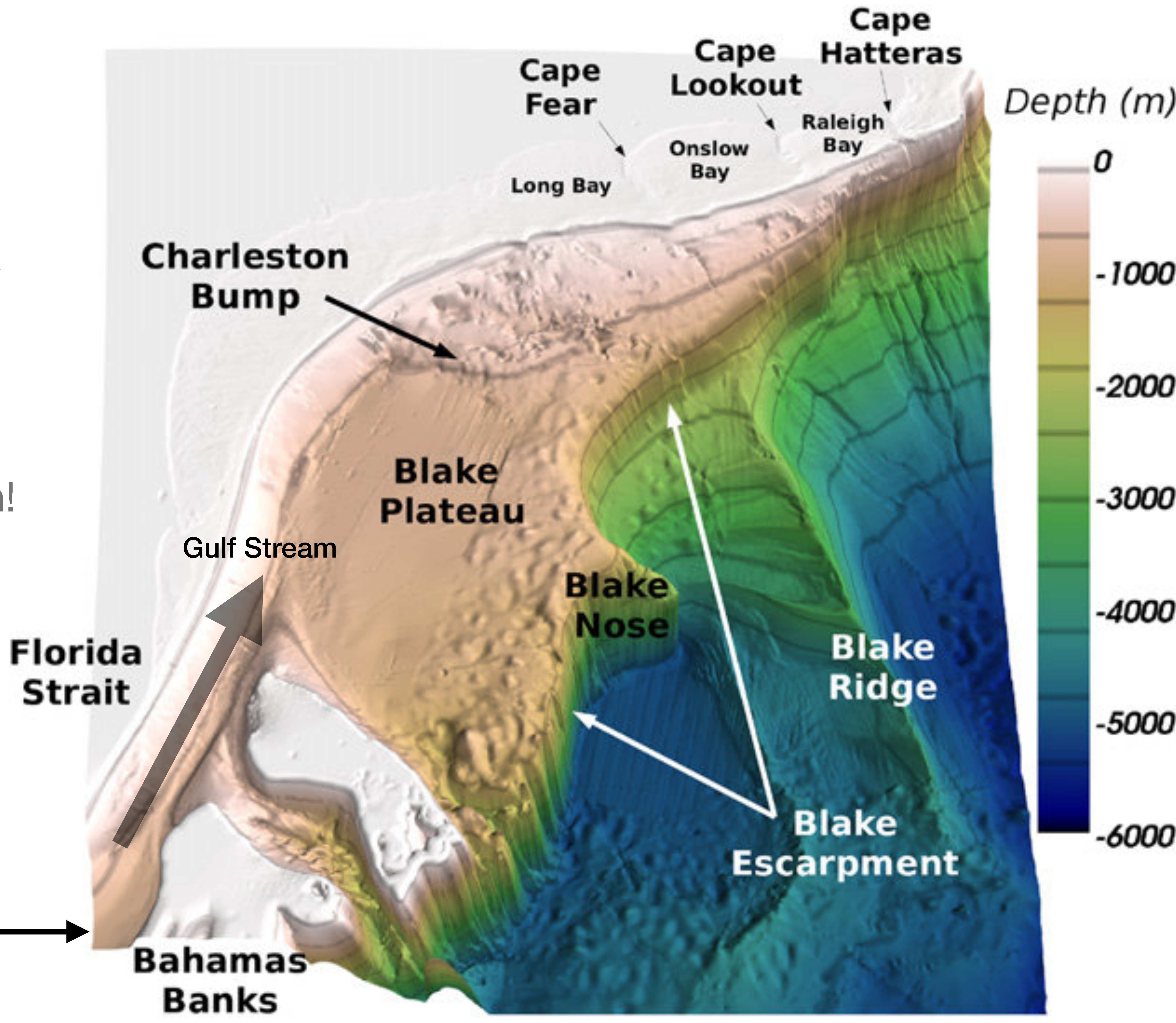
What is the Charleston Bump?

- The Charleston Bump is a prominent topographic feature along the U.S, eastern seaboard (100 km x 200 km)



Right on the Gulf Stream path!





Generation of frontal eddies

- Mesoscale frontal eddies are commonly observed in the lee of the Bump
- It is a region of strong amplification for meanders and frontal eddies through mixed barotropic/baroclinic energy conversion.
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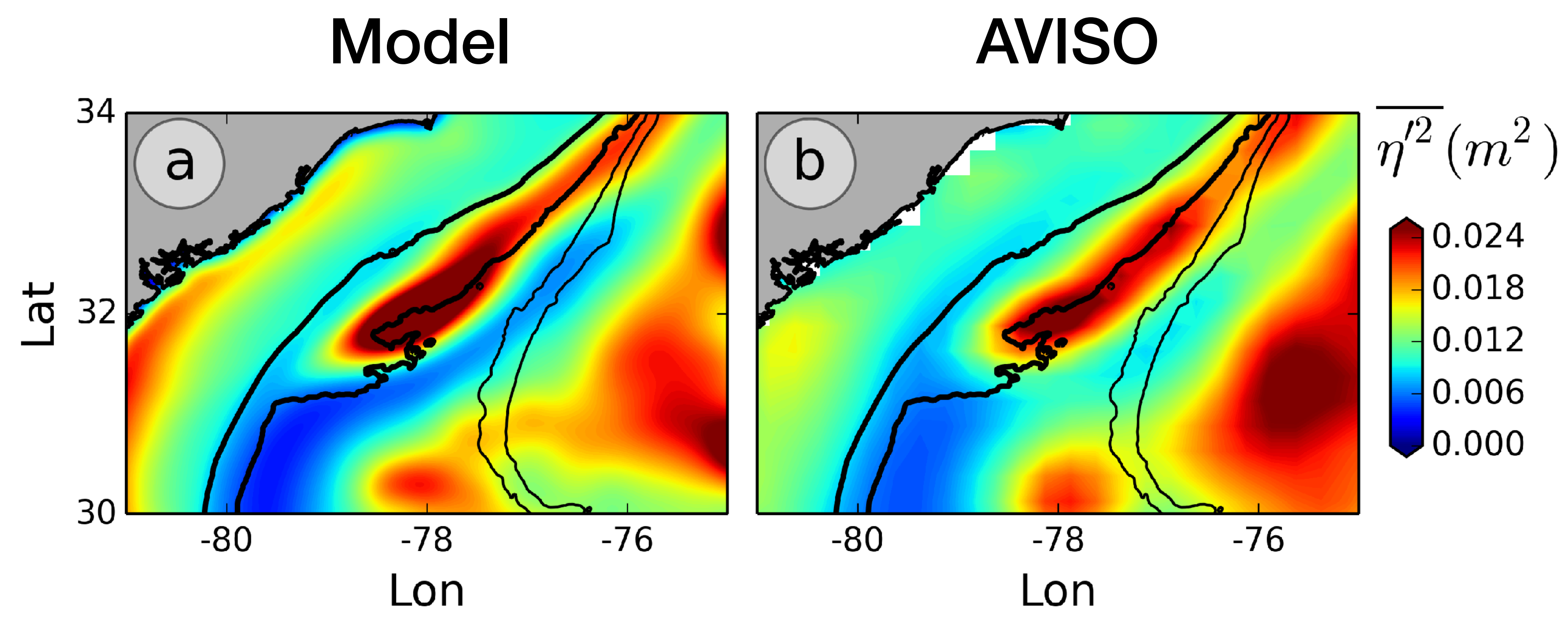
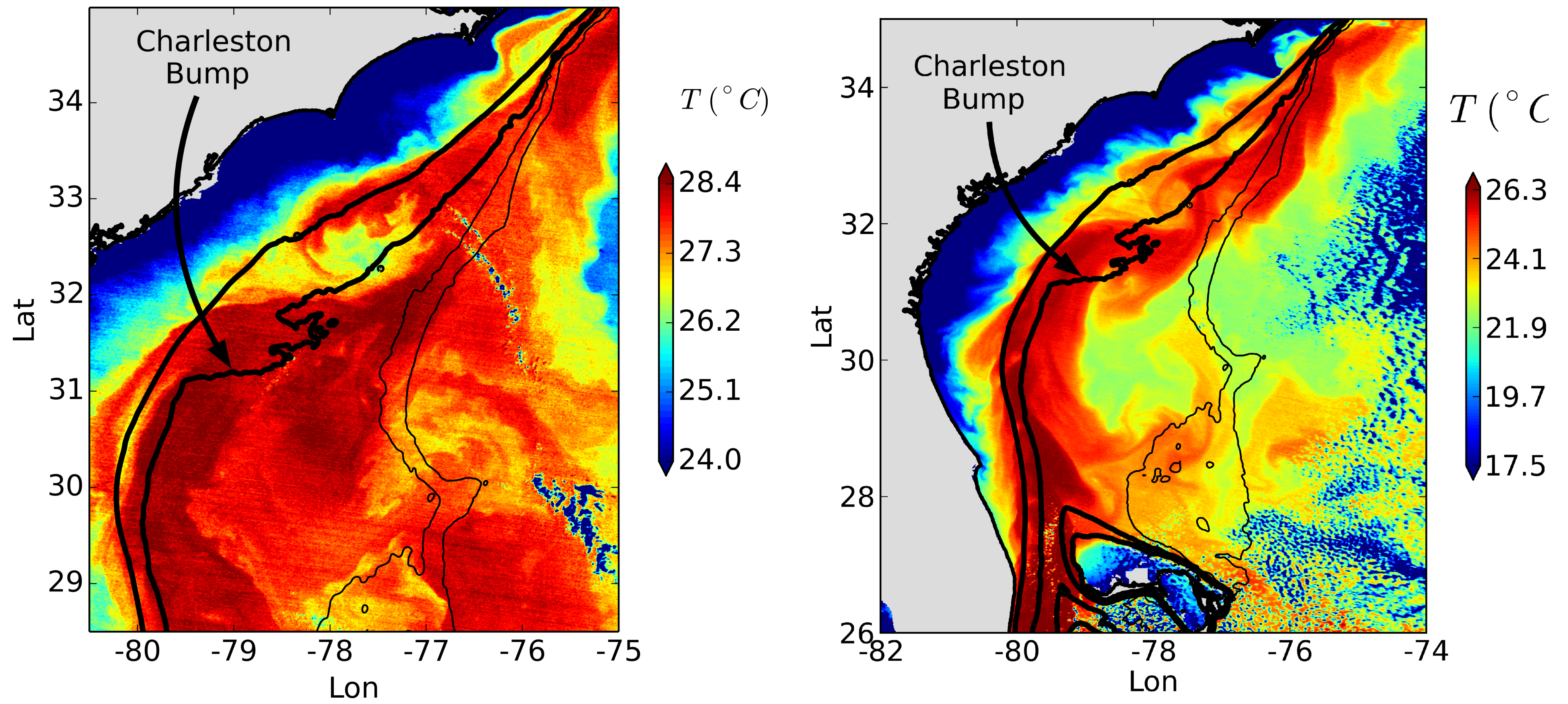
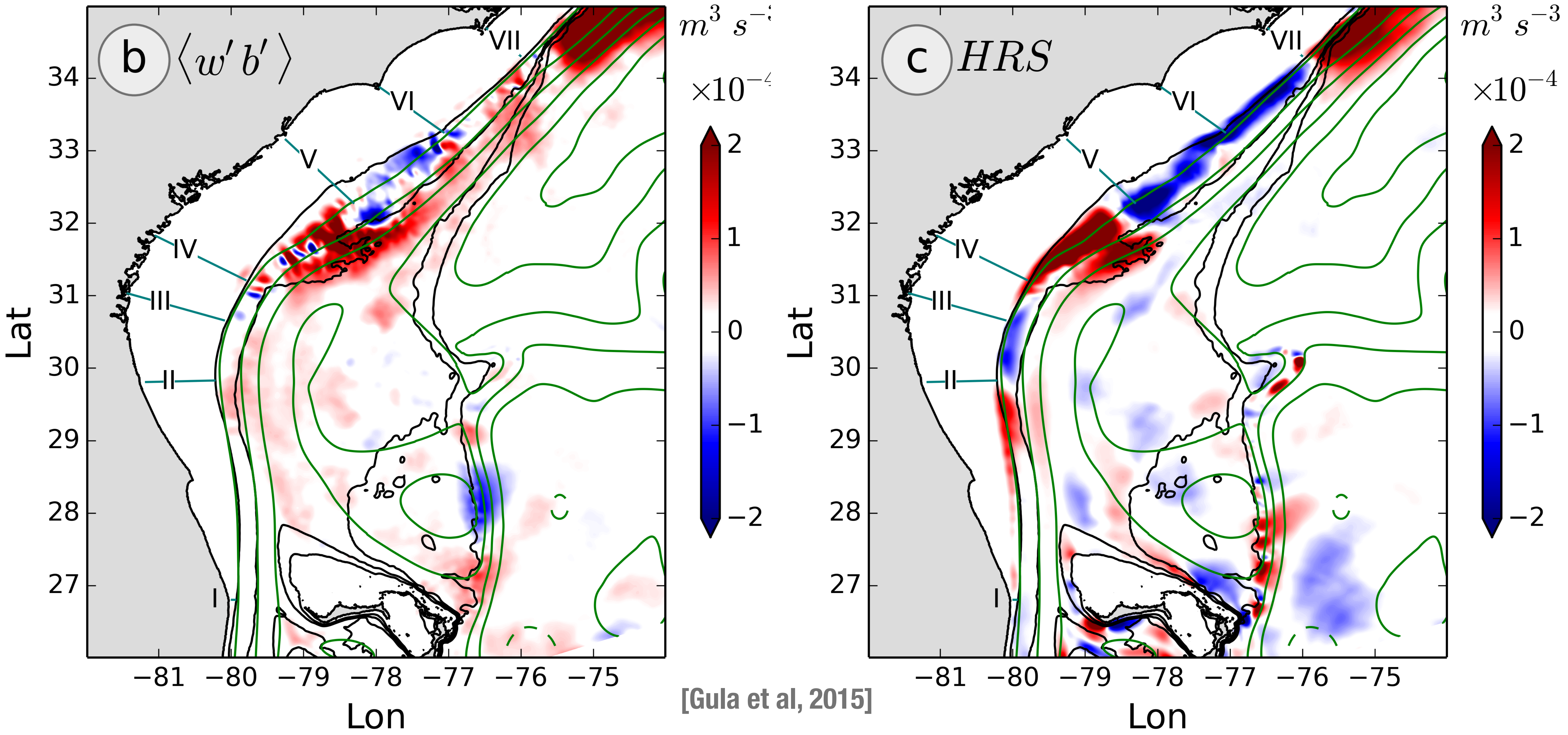


SSH variability from model and AVISO



Observed Sea Surface Temperature (SST) of the Gulf Stream. Data from MODIS-AQUA.



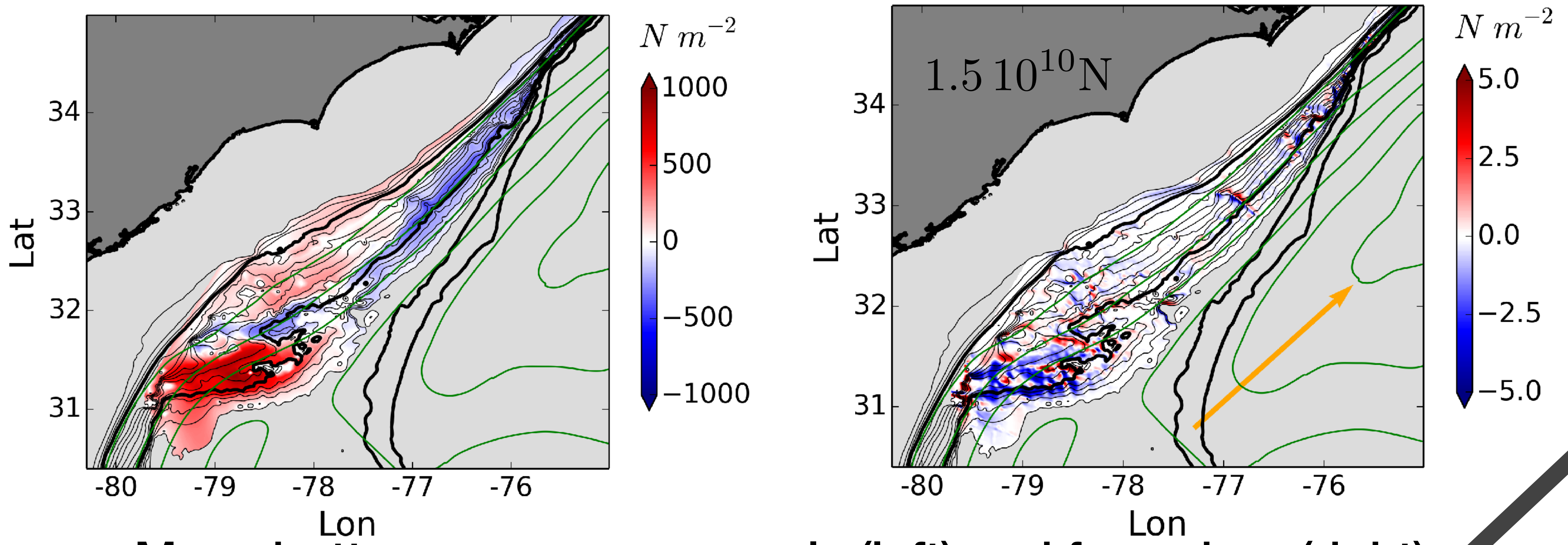
[Gula et al, 2015]

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

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

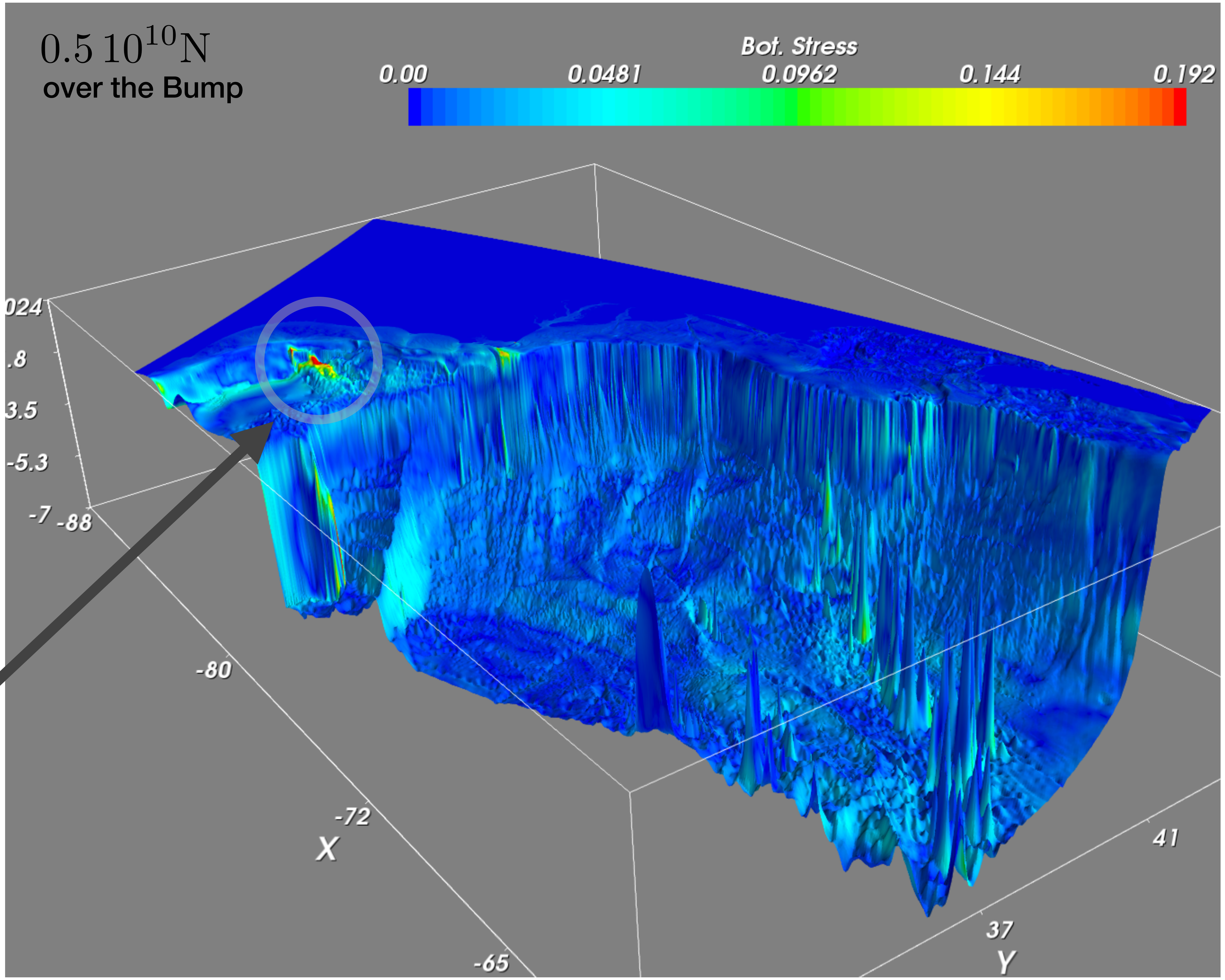
Flow topography interactions

- Significant local pressure anomalies and topographic form drag exerted by the Bump that retard the mean flow and steer the mean current pathway seaward.



Mean bottom pressure anomaly (left) and form drag (right) from a ROMS dx=750 m simulation

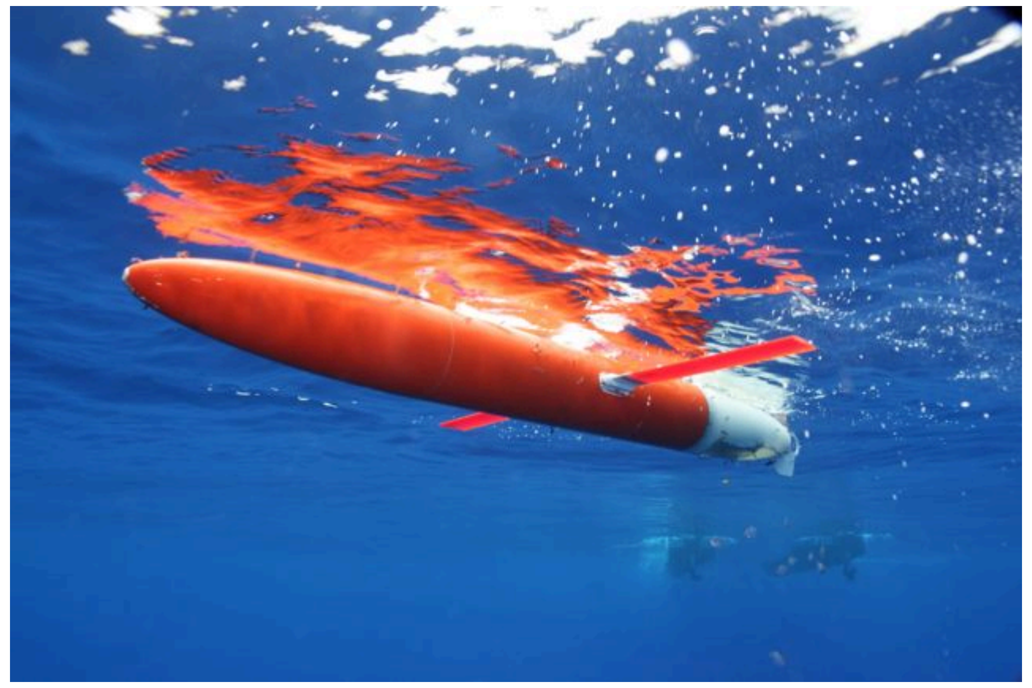
- Hot spot for the viscous drag

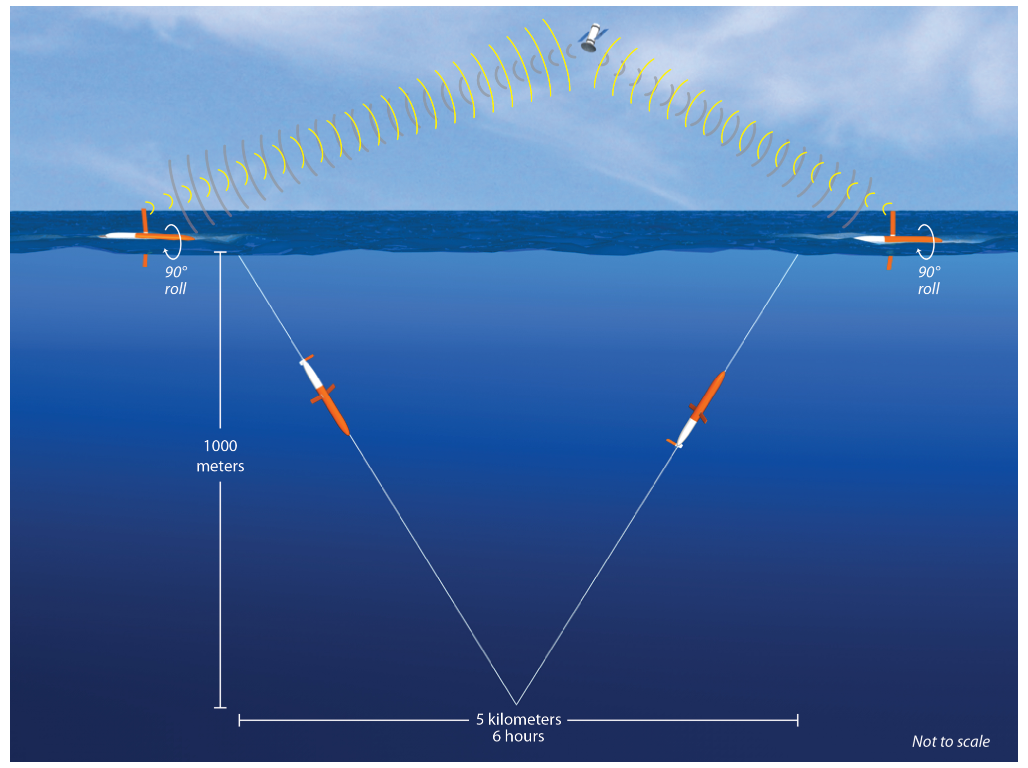


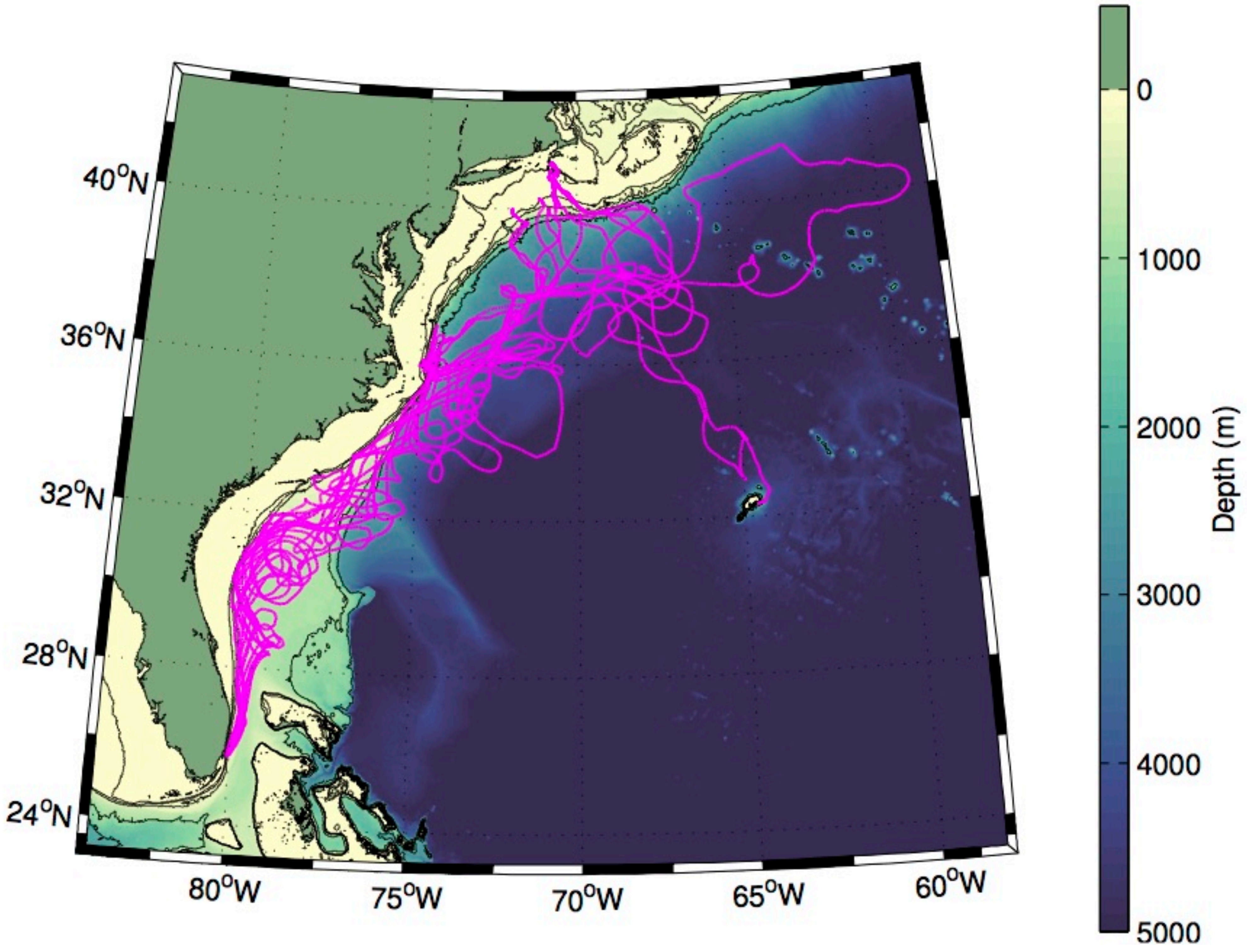
Amplitude of viscous bottom stress in a ROMS dx=750 m simulation

Bottom boundary layer

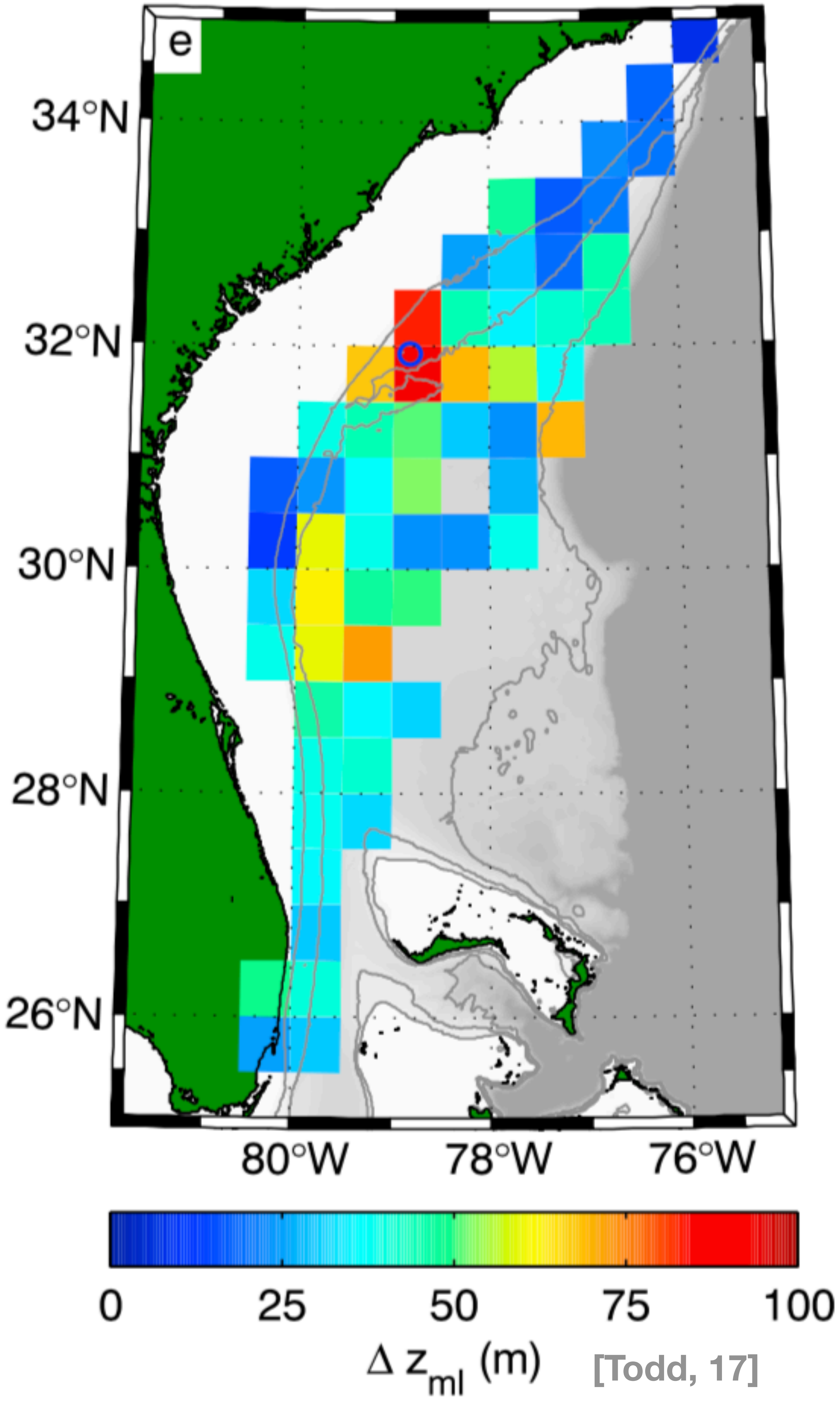
- Thick O(100 m) bottom mixed layers are generated in the lee of topography, likely due to enhanced turbulence generated by O(1) m s-1 near-bottom flows.







Glider Data [Todd & Owens, 16]
publicly available: https://spraydata.ucsd.edu/projects/GS



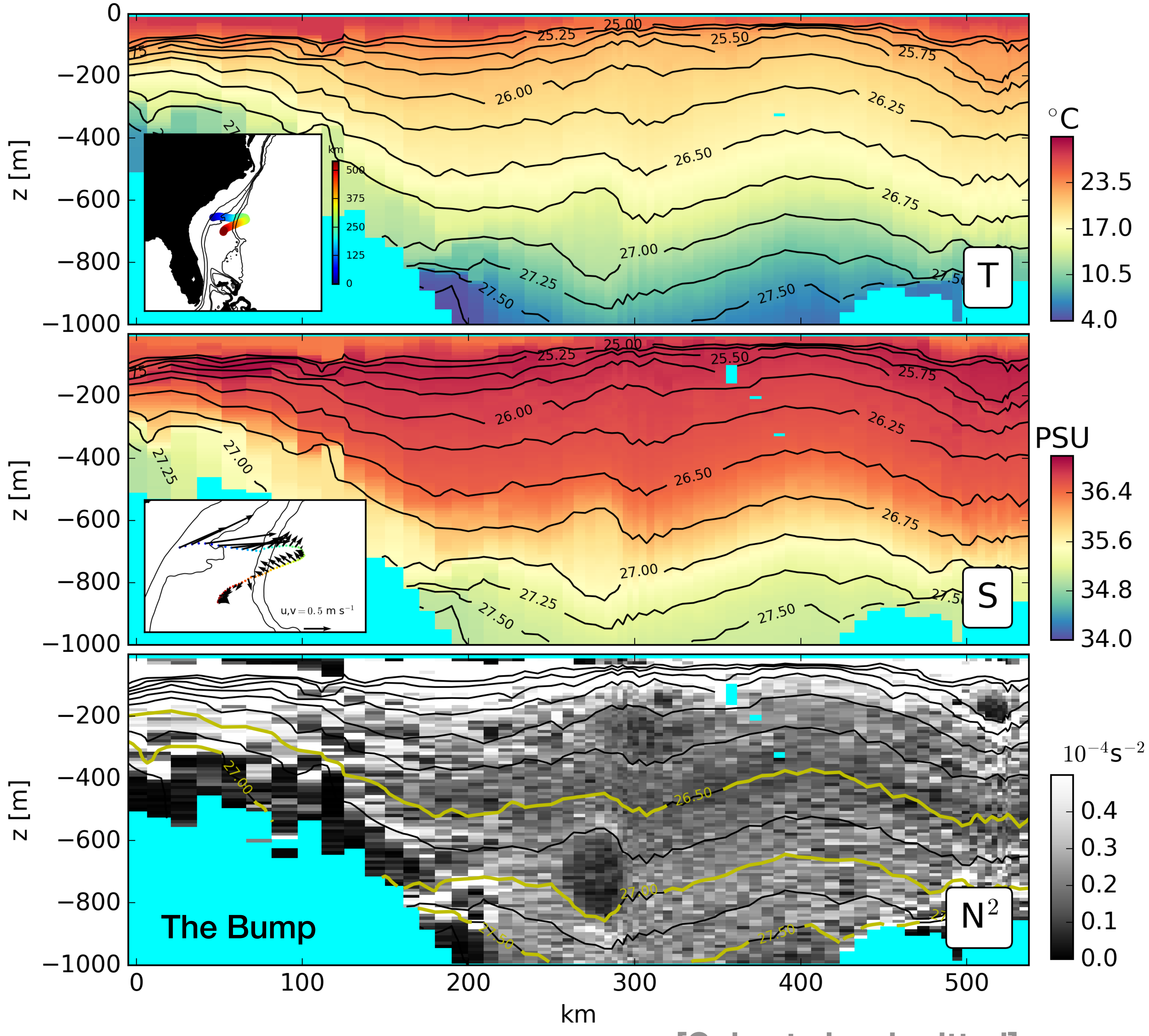
[Todd, 17]

Generation of submesoscale coherent vortices (SCVs)

- Submesoscale lenses of well-mixed water are observed in glider sections of the Gulf Stream in the lee of the Bump

Part 1 of this talk

Glider data



[Gula et al, submitted]

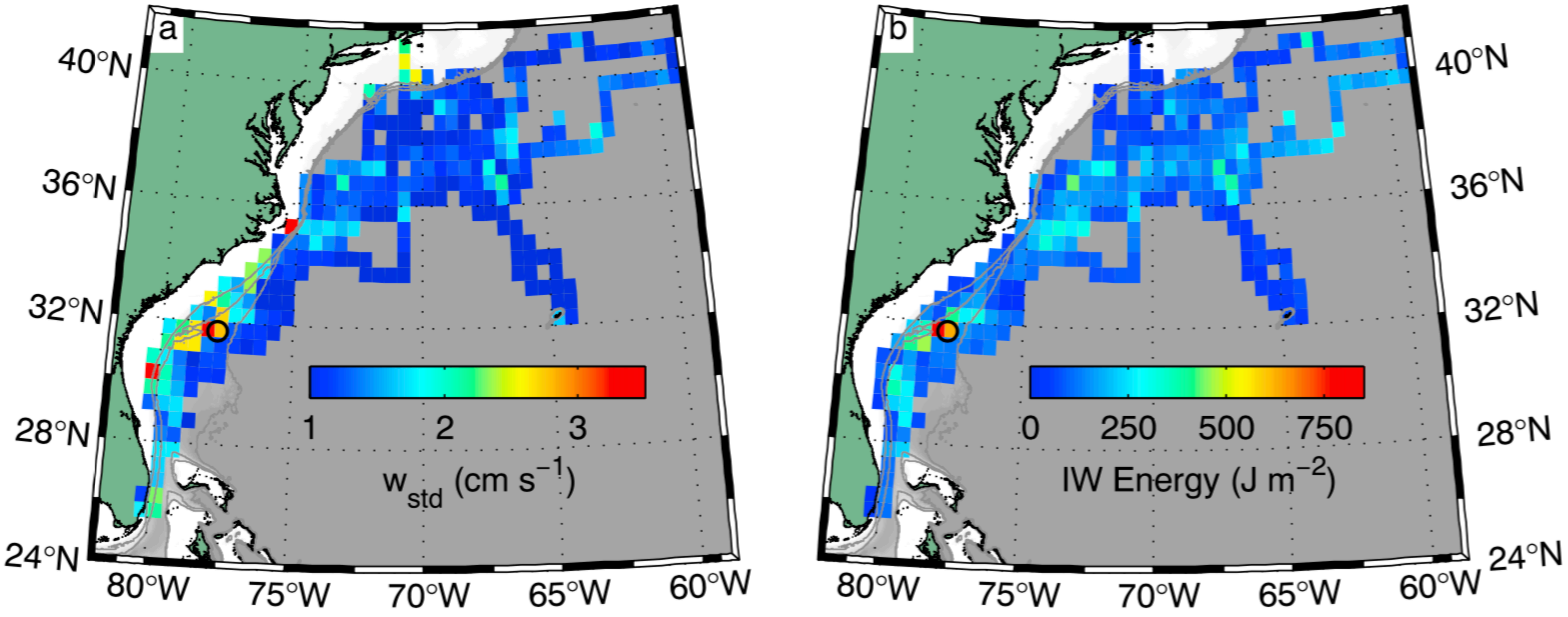
Strong internal wave activity

Strong internal wave activity

- Internal waves with vertical velocities exceeding 0.1 m s^{-1} are found over the Charleston Bump.

Part 2 of this talk

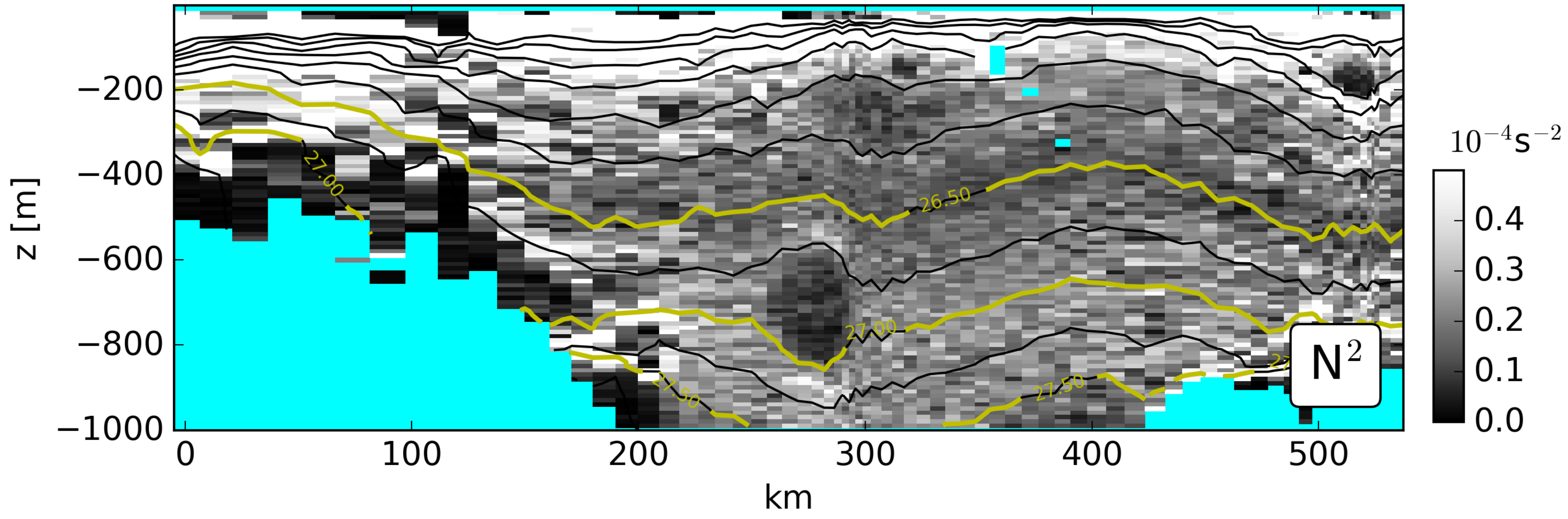
Glider data



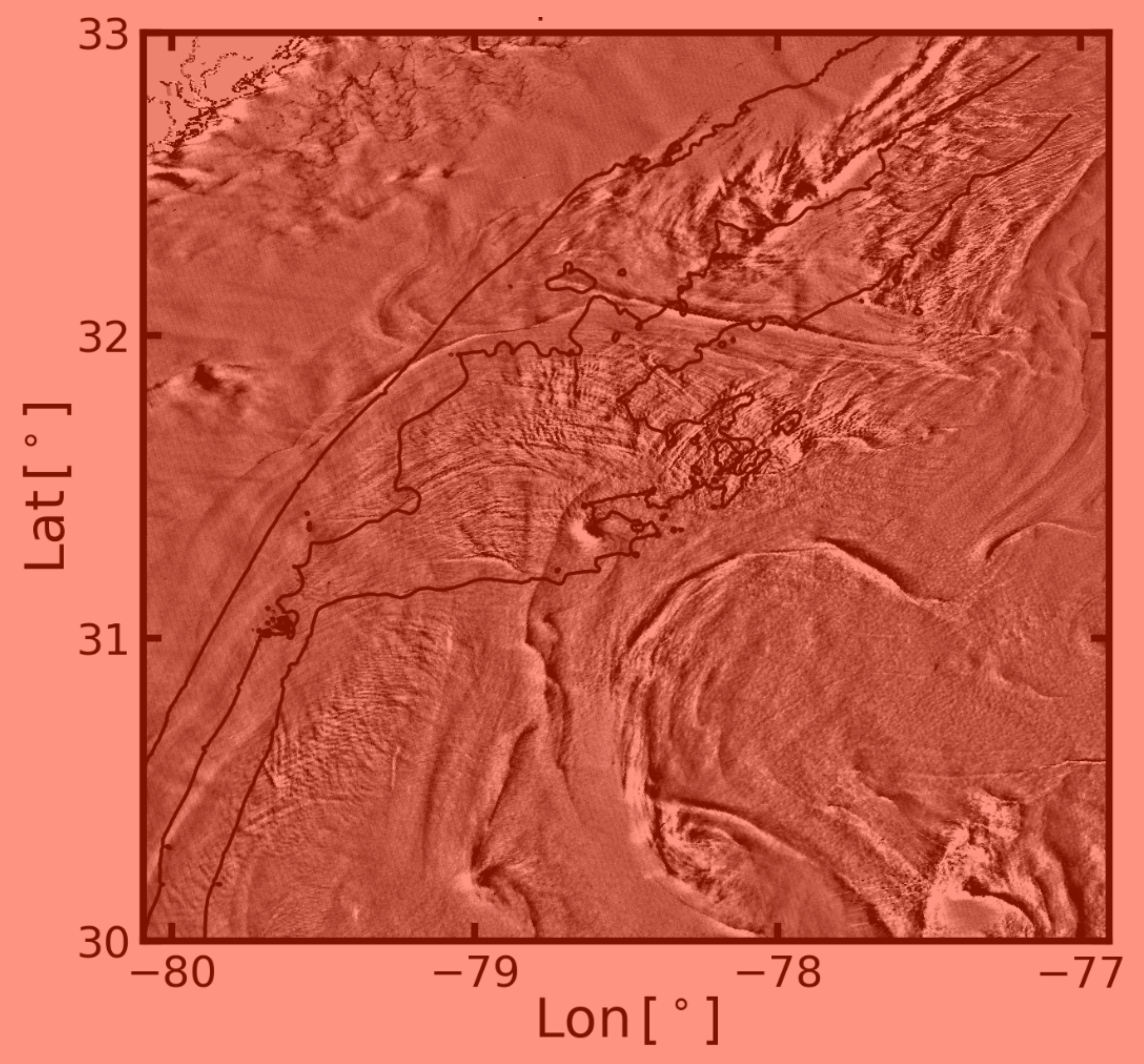
(a) Standard deviations of vertical velocities from individual glider dives averaged in 0.5◦ × 0.5◦ boxes. (b) Vertically integrated internal wave energy [Todd, 17]

OUTLINE

1. Generation of Submesoscale coherent vortices in the lee of the Bump

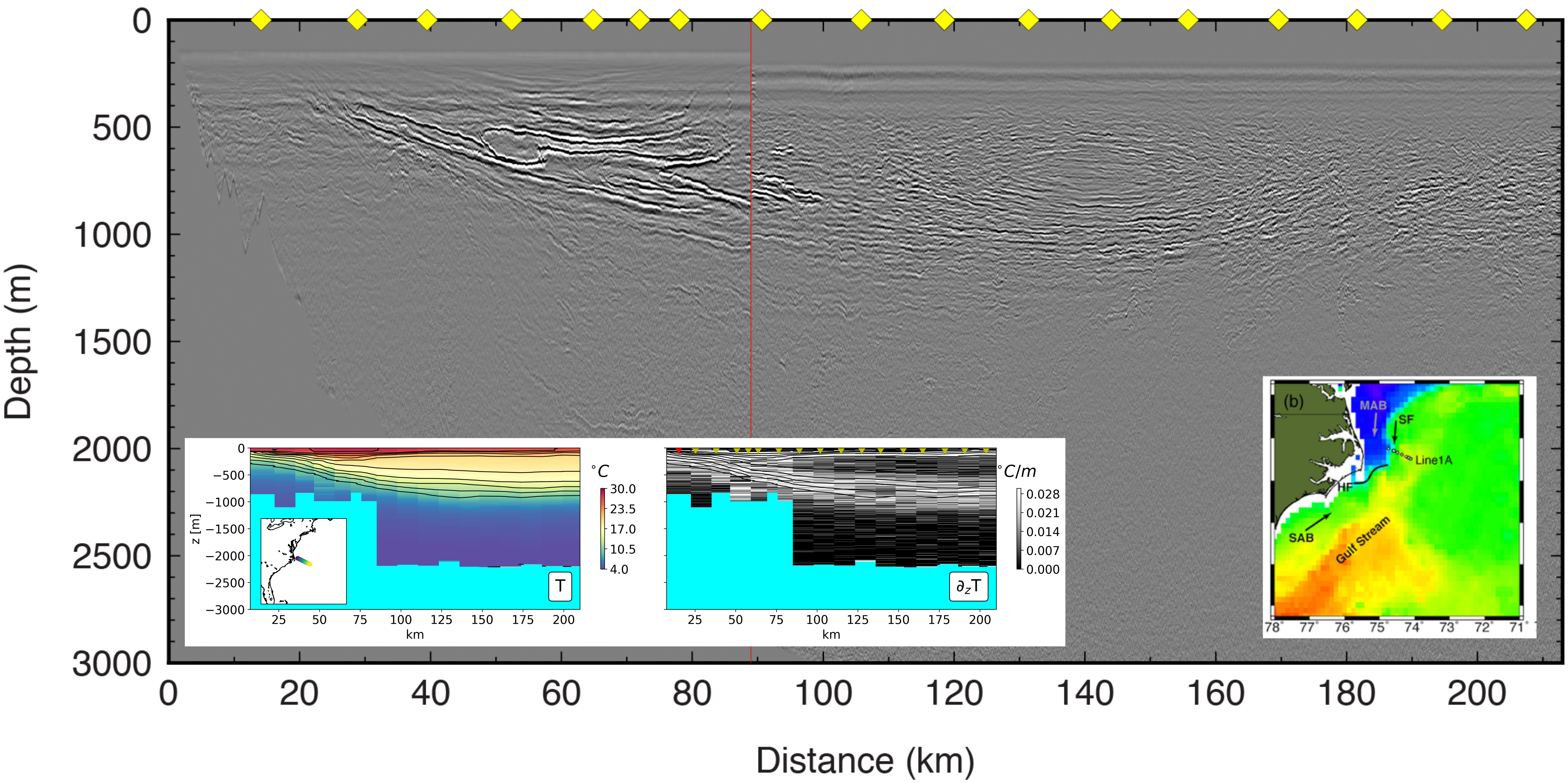


2. Generation of Lee waves over the Charleston Bump



Observations of SCVs in the Gulf Stream

Seismic Data from the Eastern North America Margin Community Seismic Experiment in Sep. 2014



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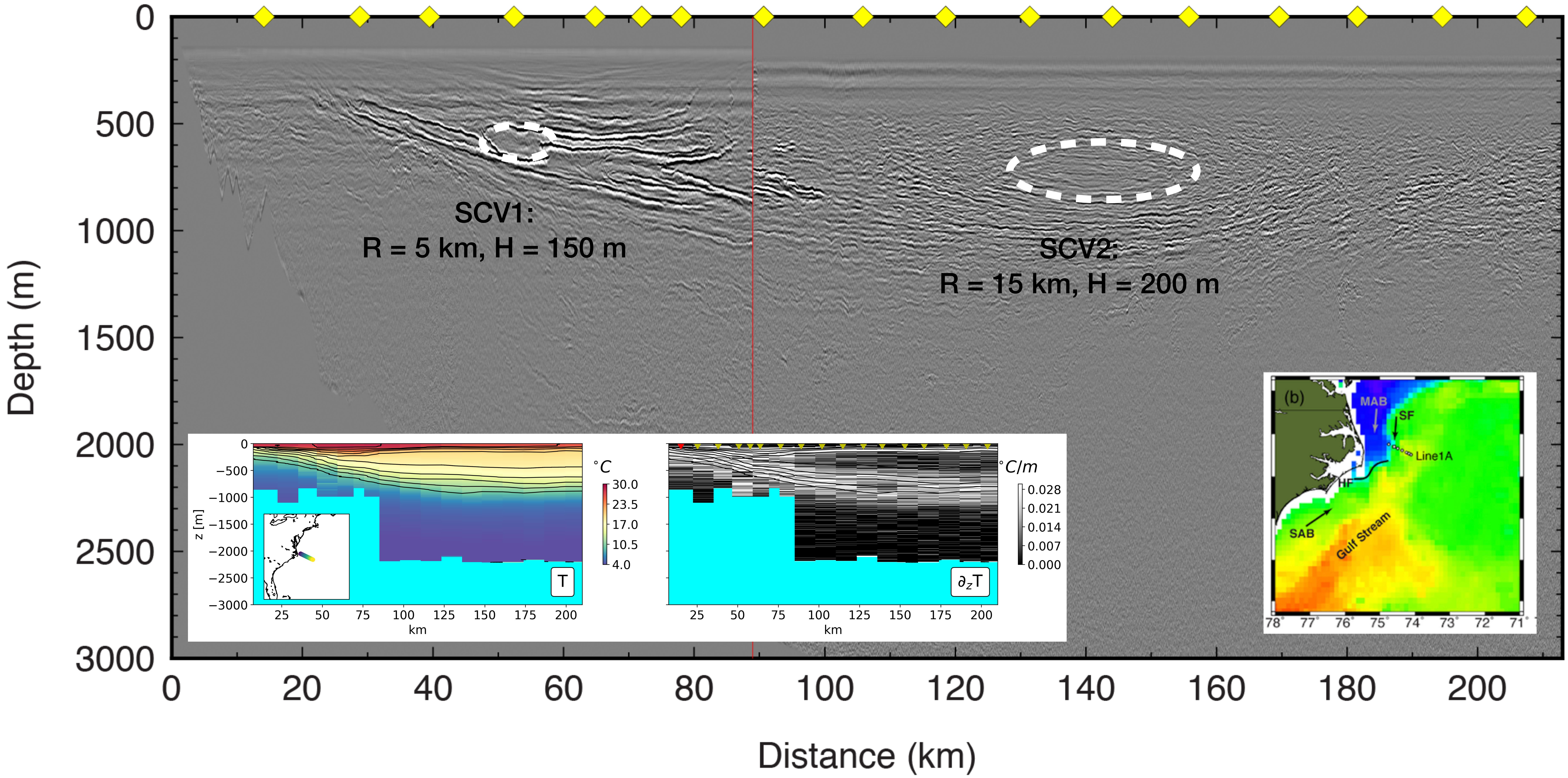


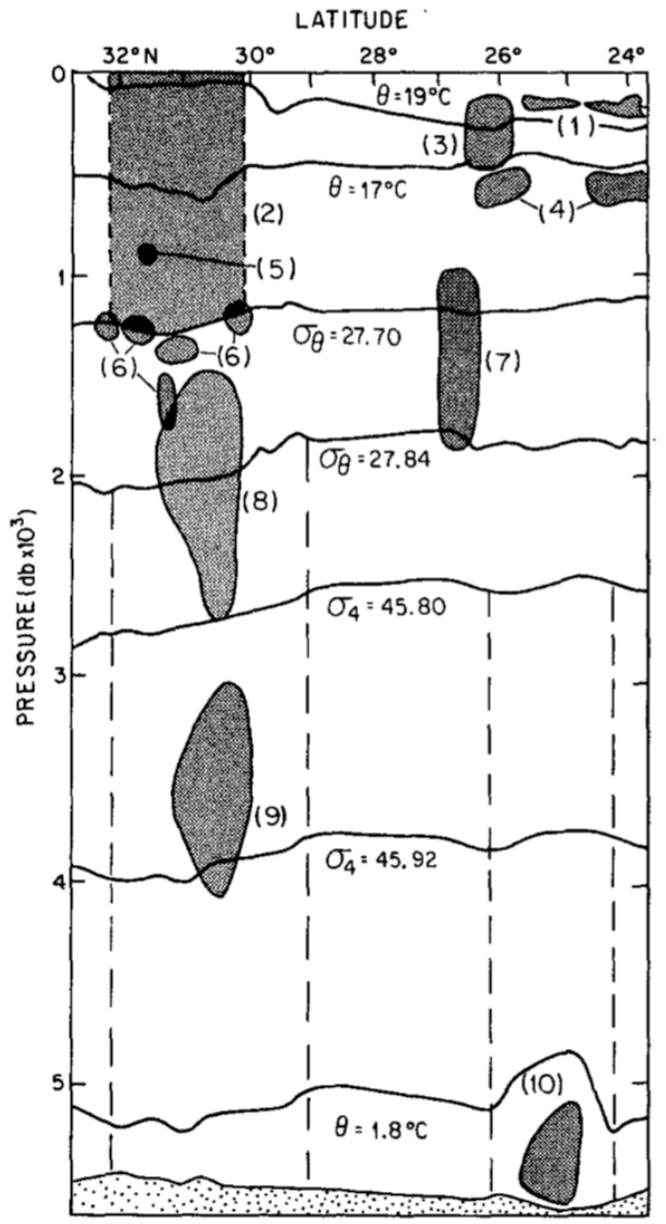
Observations of SCVs in the Subtropical gyre

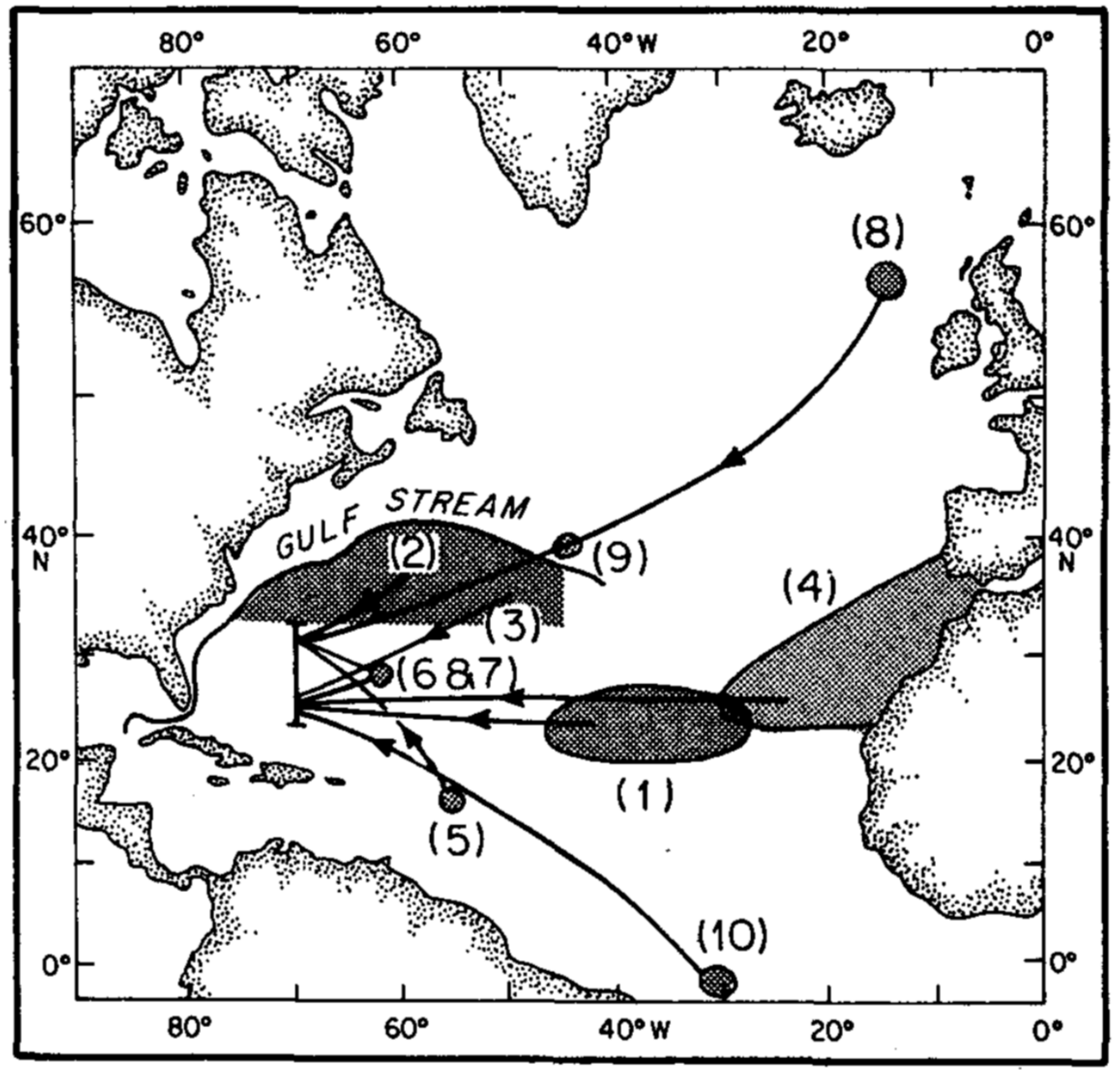
Historical observations

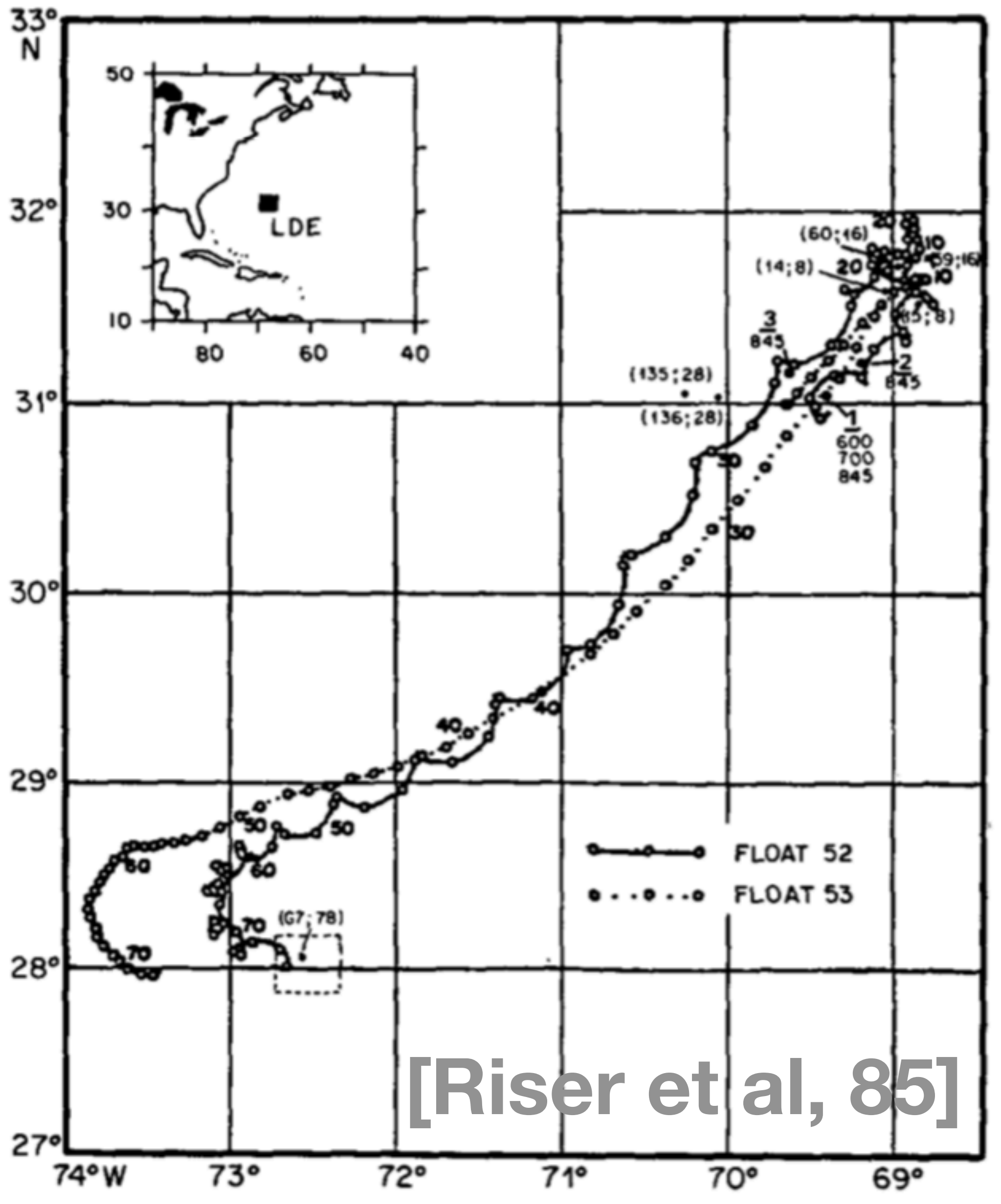
- A number of moorings and hydrographic sections in the Sargasso Sea highlighted presence of SCVs **[Dugan et al, 82, McWilliams, 85, Lindstrom & Taft, 85, McDowell, 86, Bane et al, 89, Kostianoy & Belkin, 89, etc.]**. About 1 SCV per 100 km.'

- Several SCVs with very similar properties than the one observed in seismic data **[e.g. Riser et al, 86]**.

- Origins of SCVs can be tracked using water-mass properties and oxygen **[e.g. Ebbesmeyer et al, 86]**





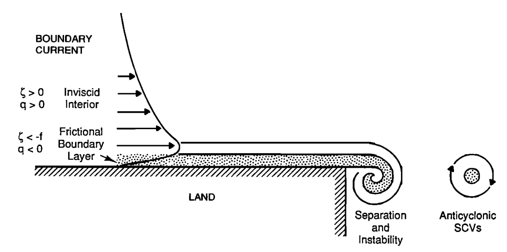


[Riser et al, 85]

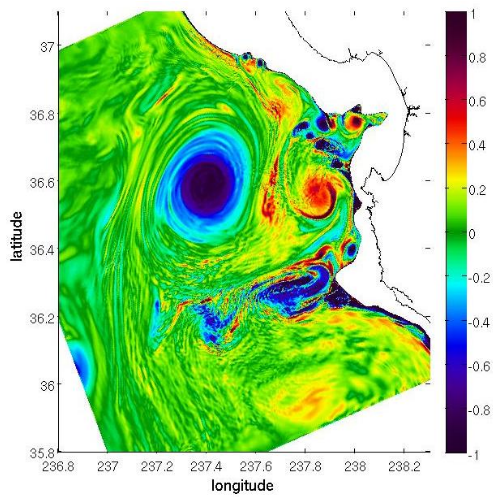
Generation mechanisms of SCVs in the Subtropical gyre

- Surface diabatic effects (deep convection): **Labrador Sea, Greenland Sea, Mediterranean Sea**
- Frictional effects (wind over fronts): Everywhere
- Diabatic effects at the bottom (hydrothermal forcings): **Juan de Fuca Ridge**
- Boundary Current instabilities/Frictional effects along topography: **Mediterranean outflow, Red Sea, Persian Gulf, Beaufort Gyre, California Undercurrent, Peru-Chile Undercurrent, West African upwelling, DWBC, etc.**

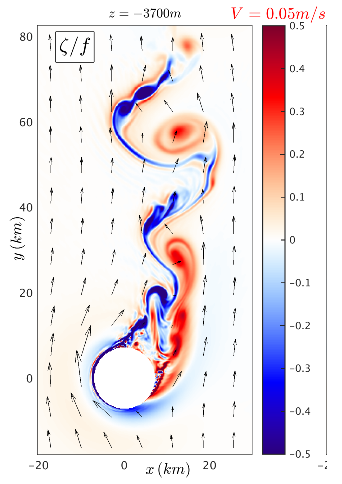
[D'Asaro, 88]



[Molemaker et al, 2015]



[Srinivasan et al, 2018]



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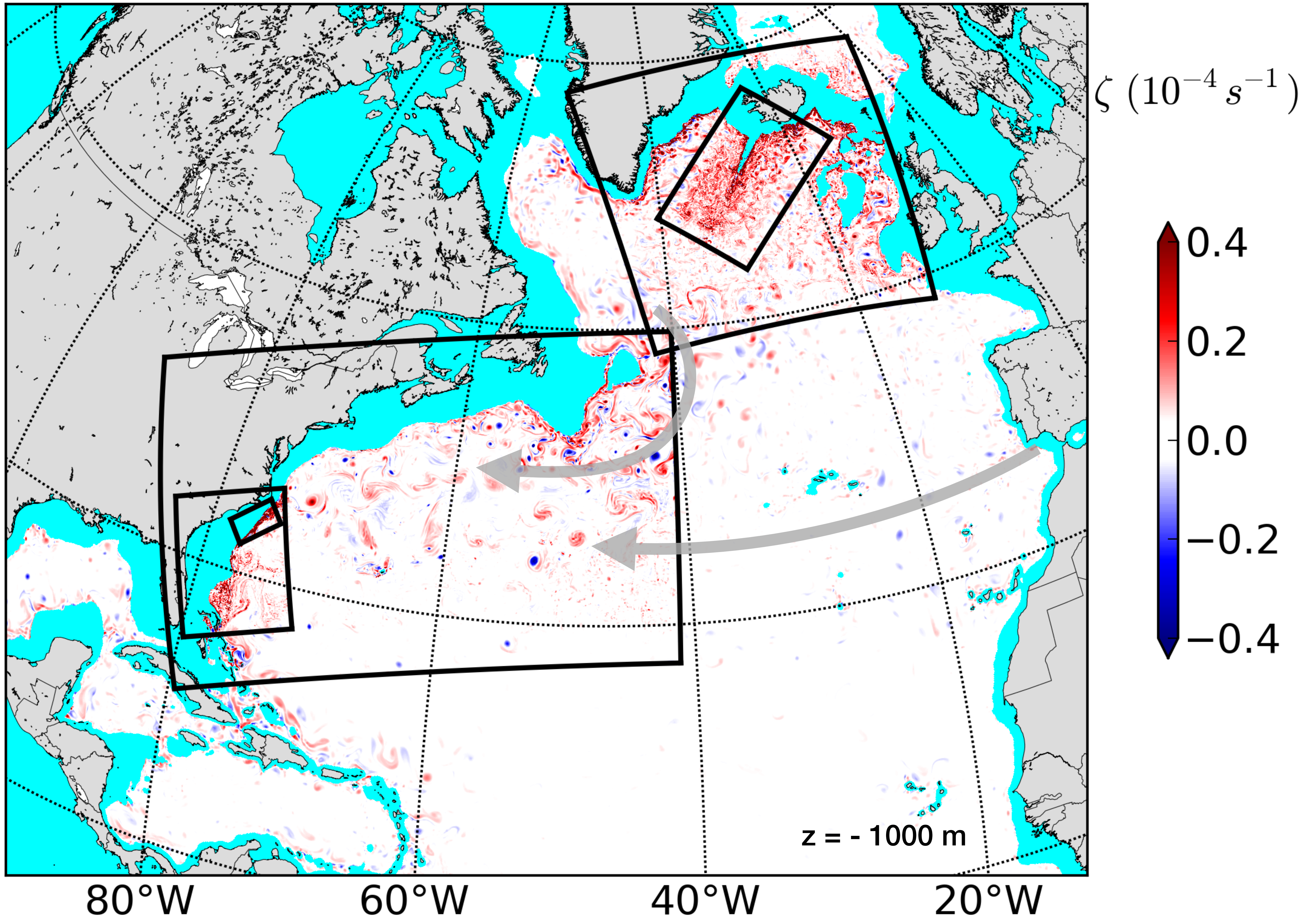
SCV1 and SCV2 do not match Labrador or Med sea water. How are they generated? Local processes?

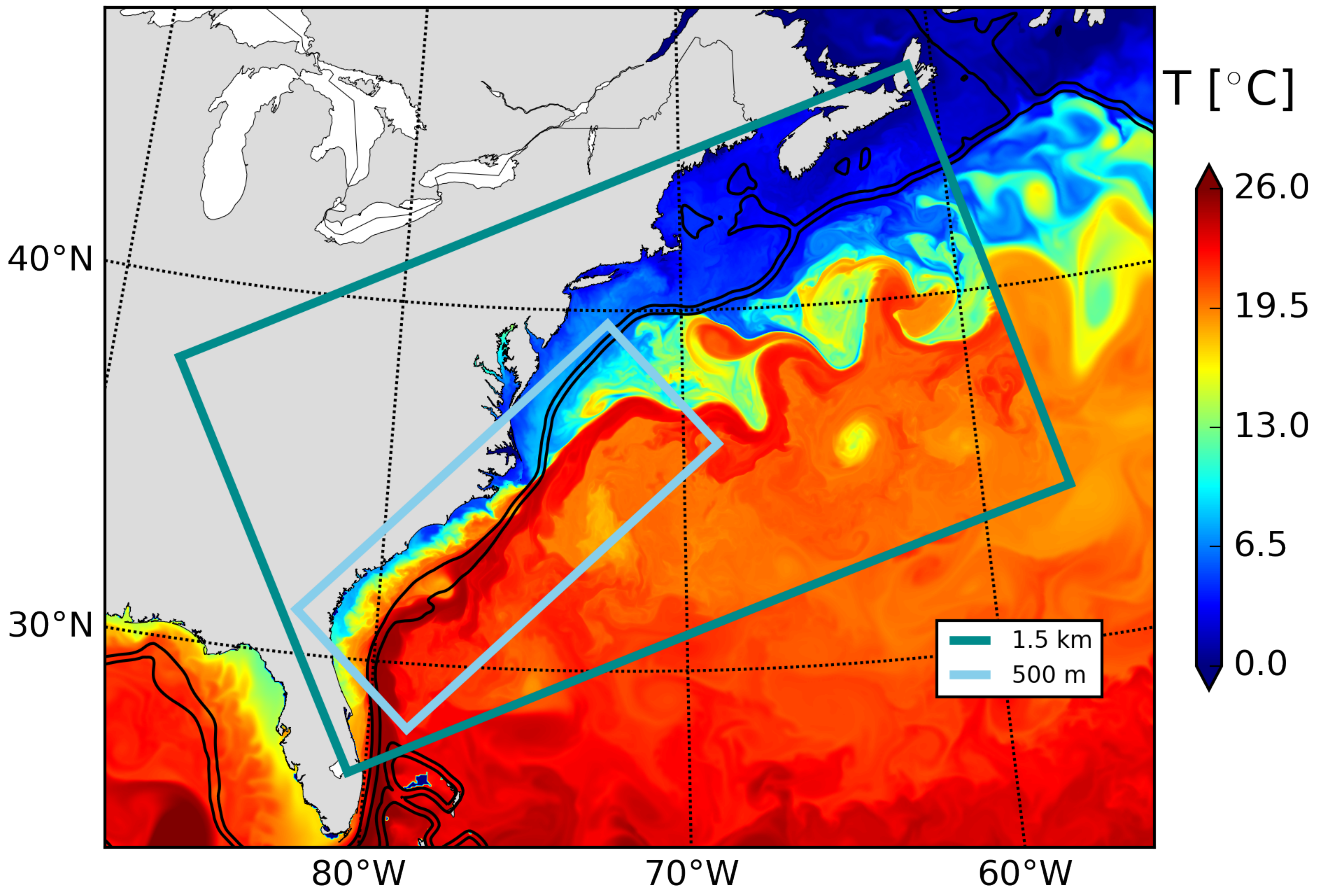


Realistic modelling with ROMS/CROCO

- Successive down-scale nested grids with the ROMS/CROCO model, from Atlantic (dx = 6 km) to local subdomains (dx = 500 m, 100 lev.).

- Nx x Ny x Nz = 2800 x 1600 x 100

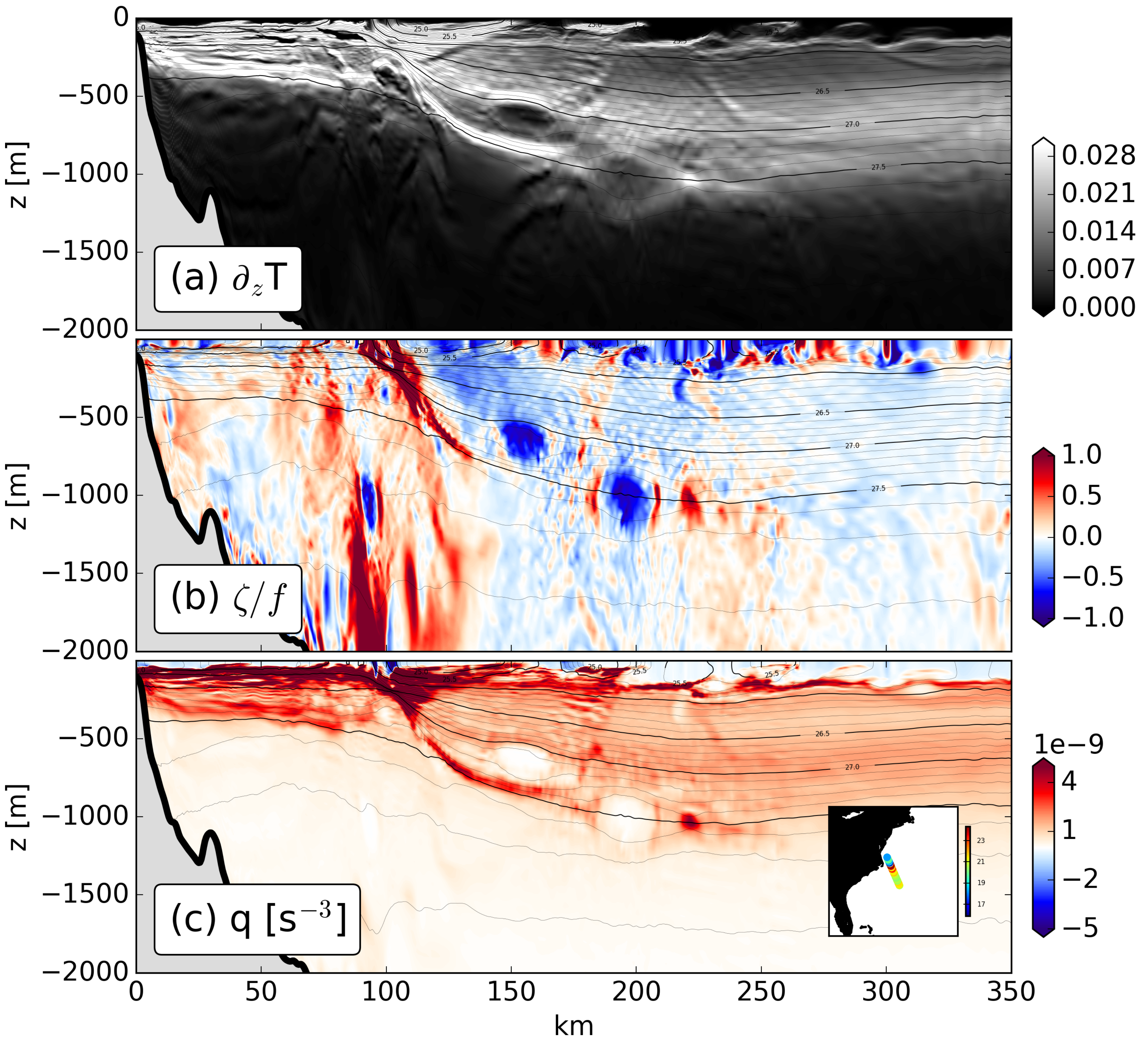
- Climatological forcings (daily winds, no tides)



SCV's in the Gulf Stream

Model (dx = 500 m)

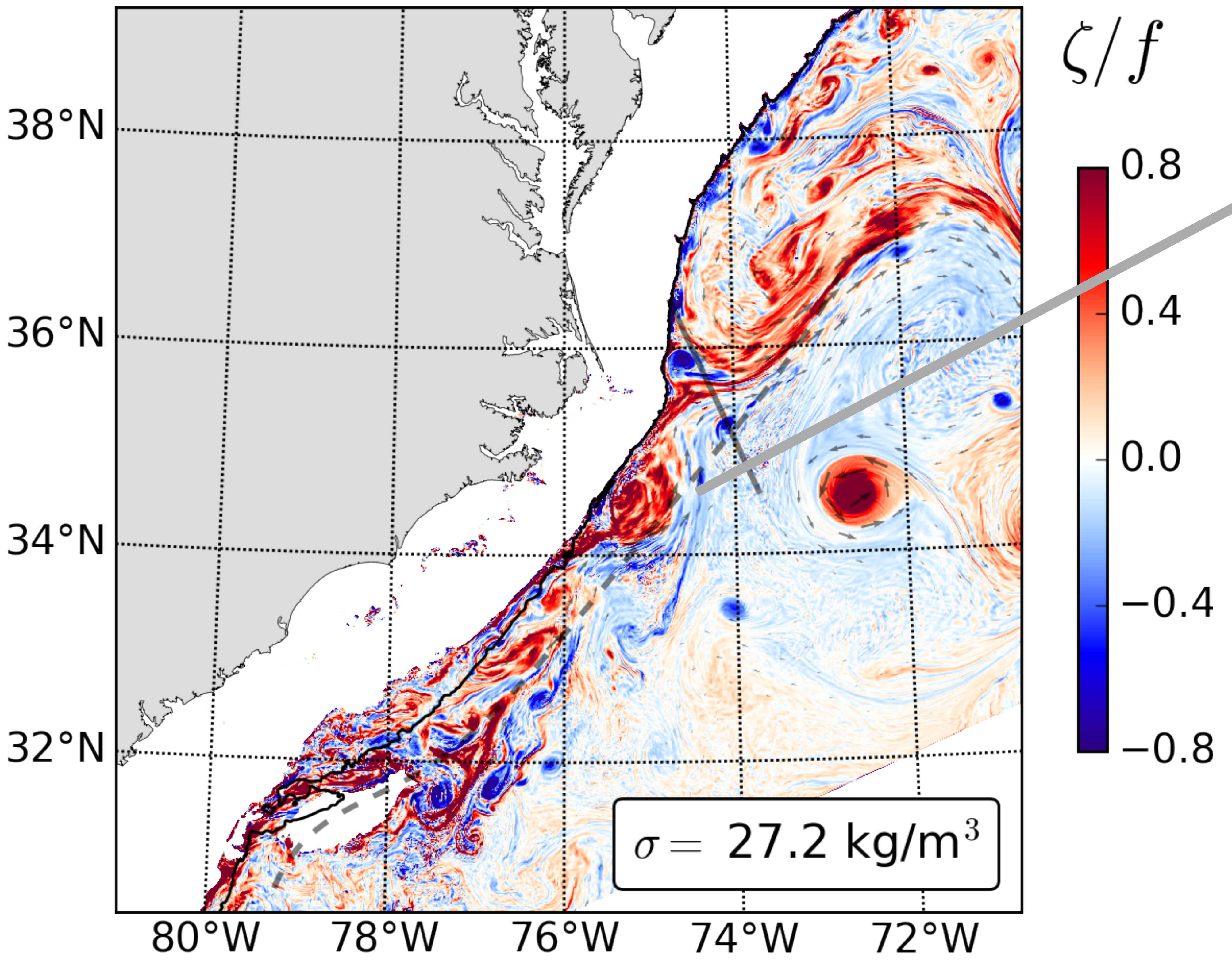
- The model typically exhibit a few SCVs at the location of the seismic data. They are located at similar depths and have similar radius and thickness.

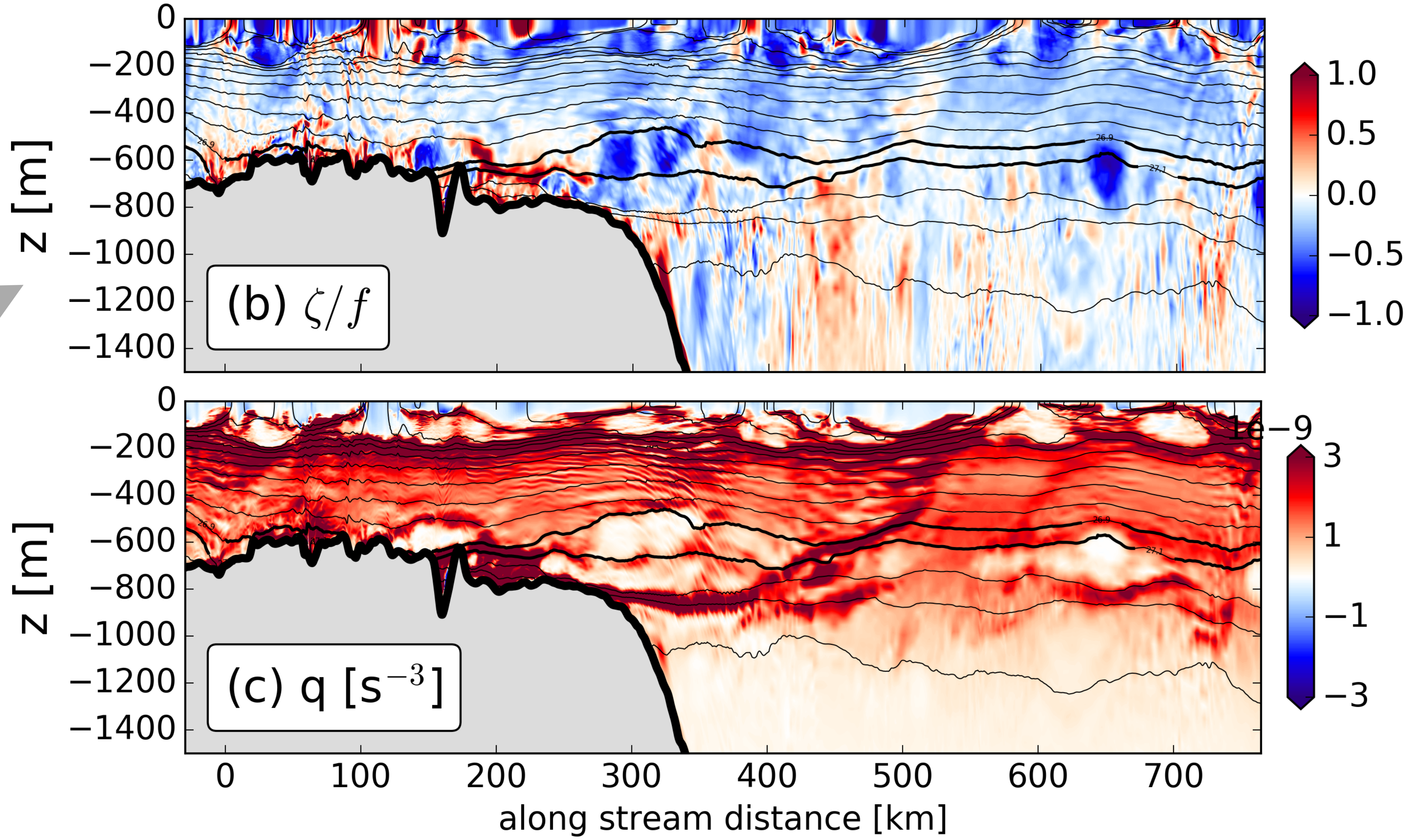


SCV’s in the Gulf Stream

Model

- The SCVs originate from the Charleston Bump, where there is a strong generation of vorticity due to frictional effects

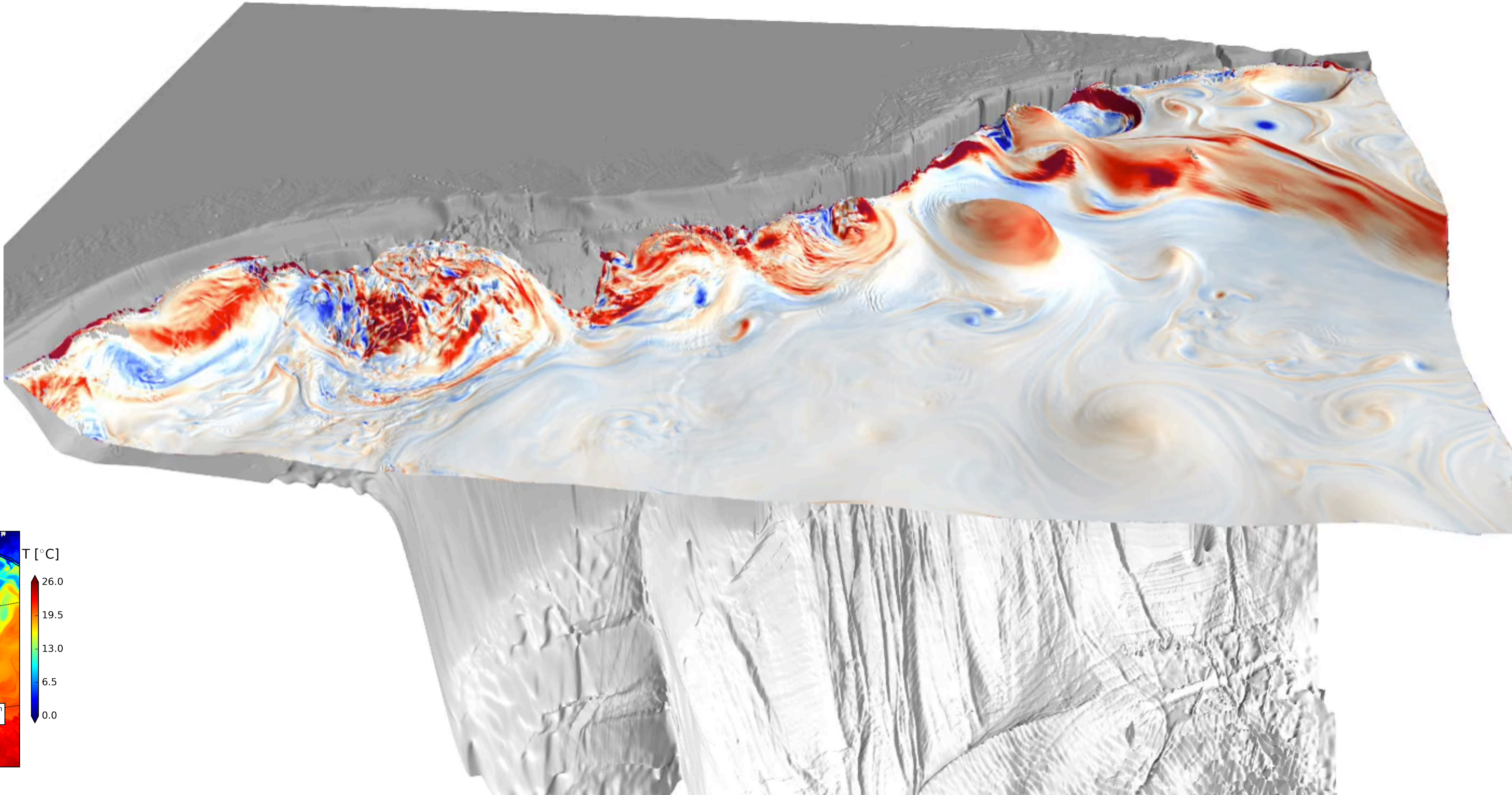


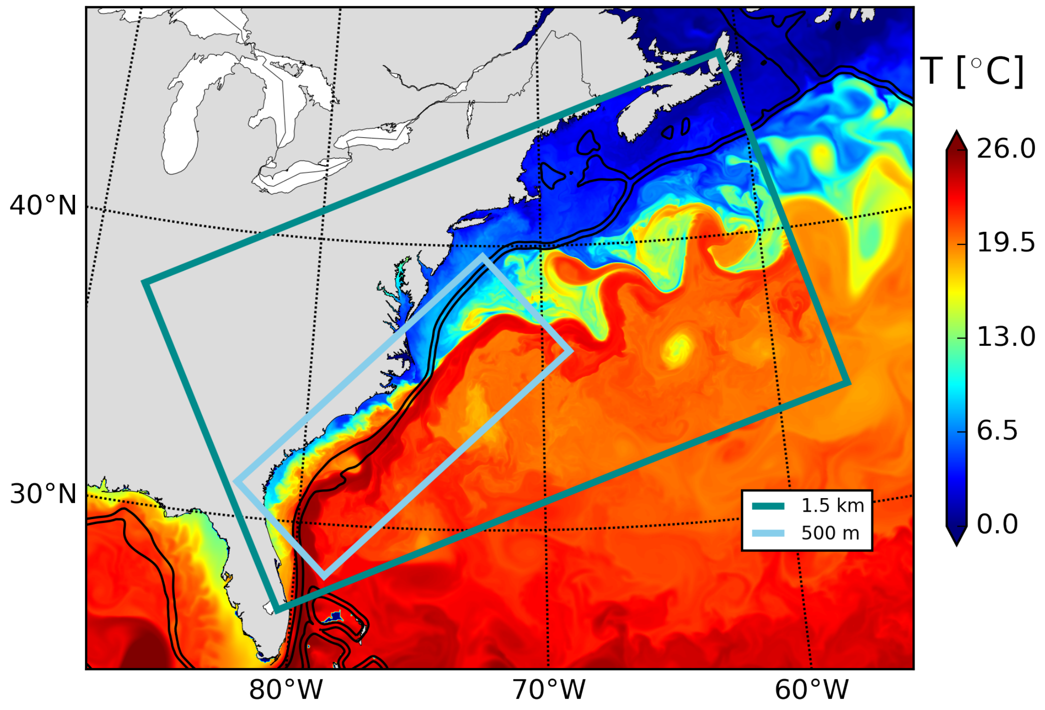


SCV’s in the Gulf Stream

Relative vorticity on the isopycnal .

$$\sigma = 27\,\mathrm{kg\,m^{-3}}$$



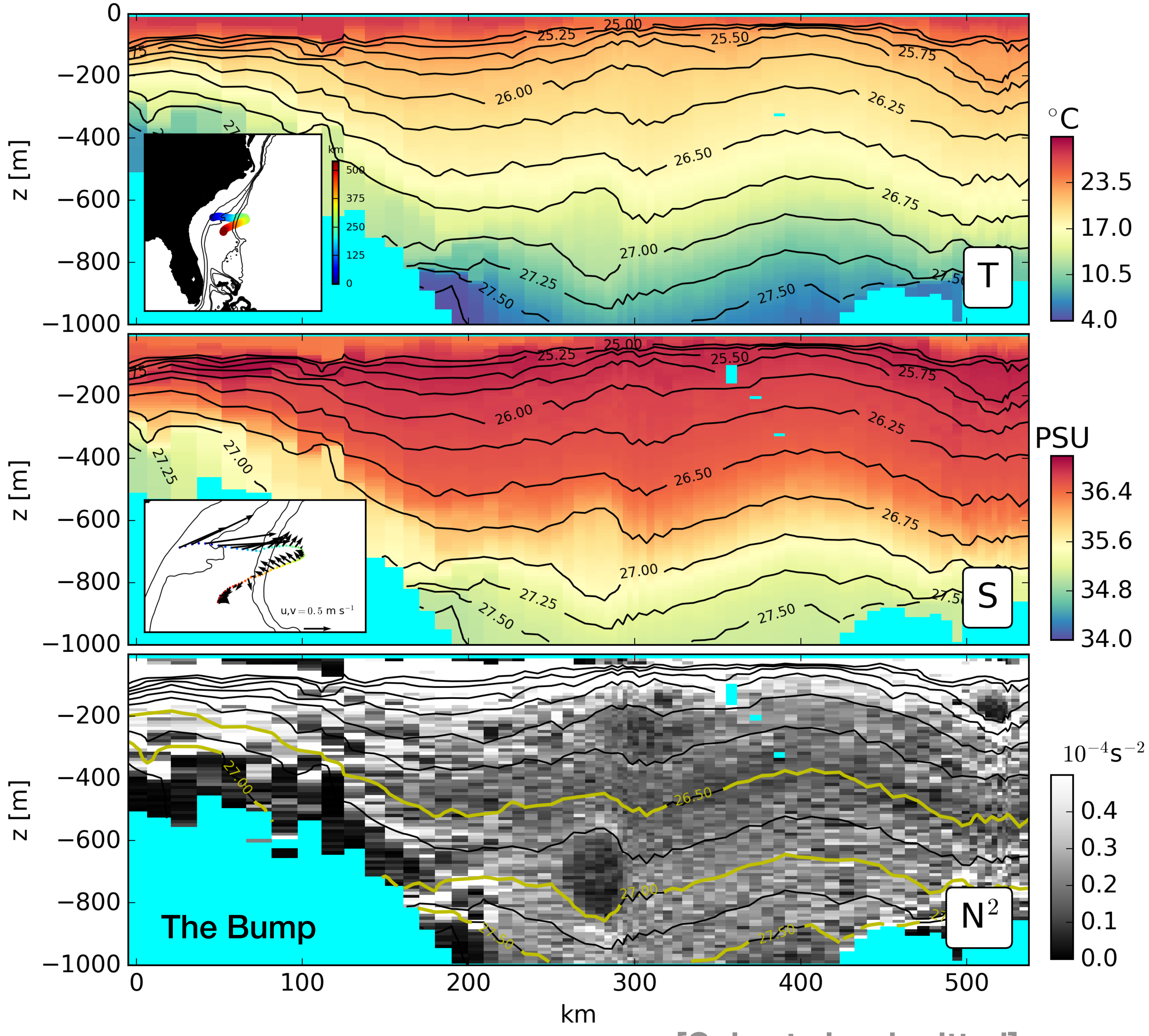


Generation of submesoscale coherent vortices (SCVs)

- Anticyclonic submesoscale lenses of well-mixed water are observed in glider sections of the Gulf Stream in the lee of the Bump

- Generation process is confirmed by Glider measurements.

Glider data



[Gula et al, submitted]

Bottom flux of PV

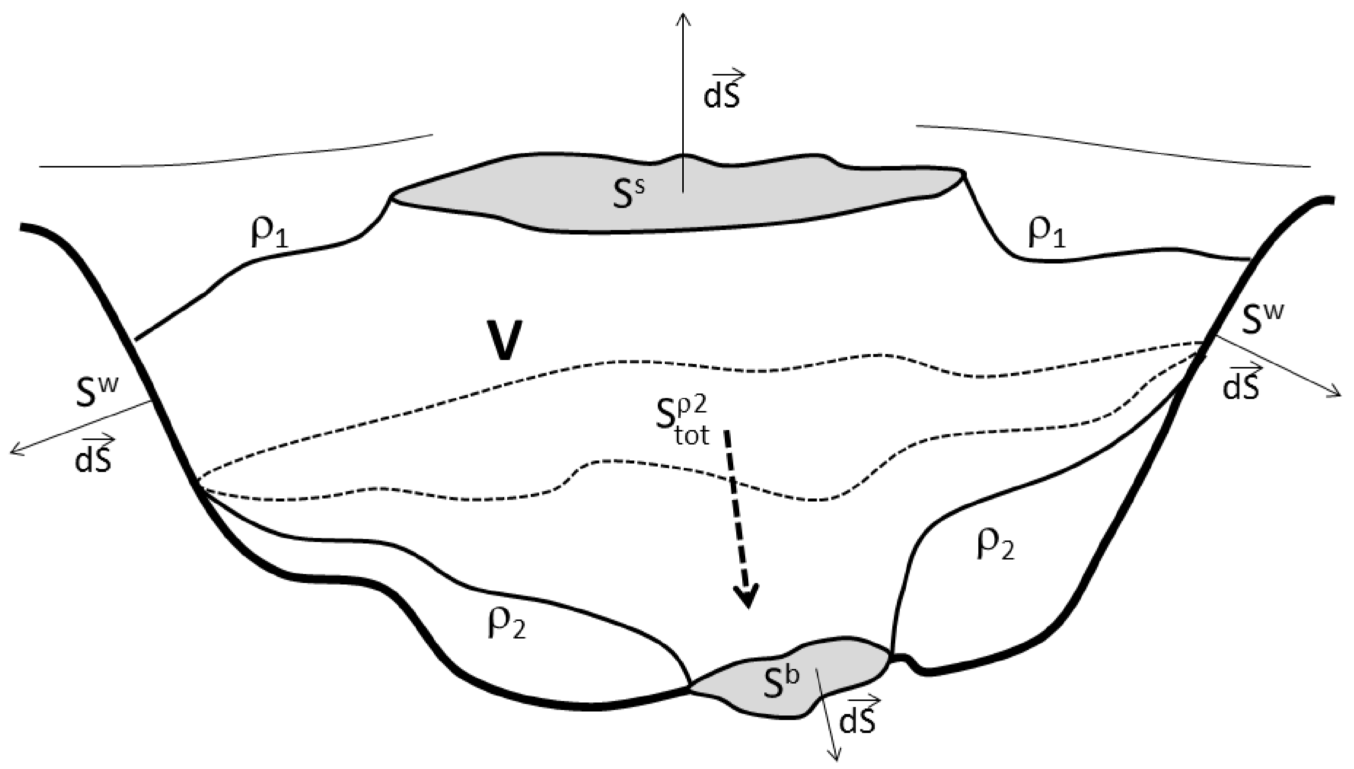
- The mechanisms of SCV formation must account for the creation of the low PV anomalies in their cores. They need to provide a source of low PV in a spatially intermittent fashion.

- PV is defined as. $q = \omega_{\mathbf{a}} \cdot \nabla b$ with $\omega_{\mathbf{a}} = f\mathbf{z} + \nabla \times \mathbf{u}$ and $b = -g\frac{\rho}{\rho_0}$

- PV fluxes can be written: $$\frac{\partial q}{\partial t} + \nabla \cdot [\underbrace{q\mathbf{u}}_{\mathrm{J_A}} - \underbrace{\omega_{\mathbf{a}} \frac{Db}{Dt}}_{\mathrm{J_D}} + \underbrace{\nabla b \times \mathbf{F}}_{\mathrm{J_F}}] = 0,$$

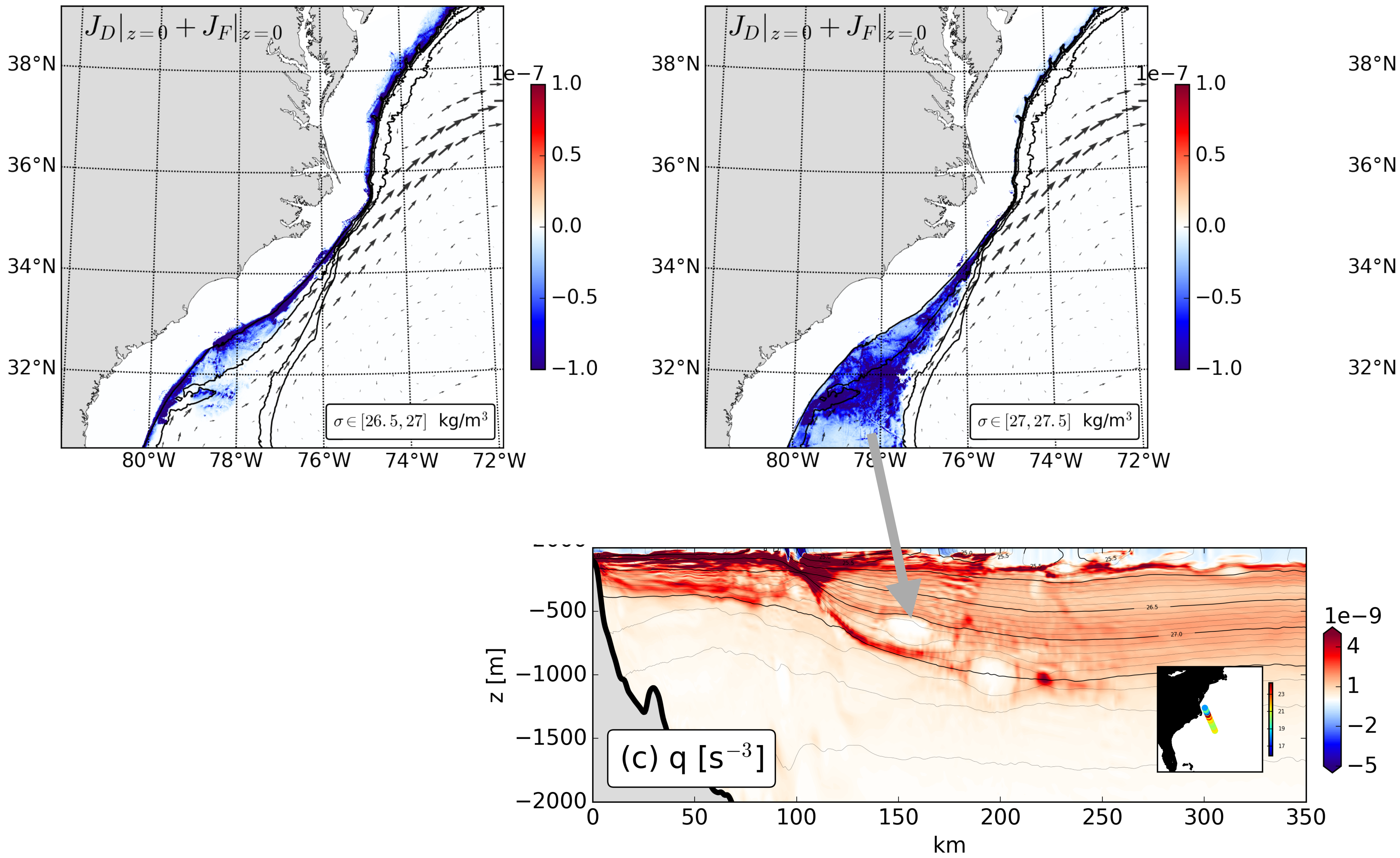
- For a volume of water between 2 isopycnals, the potential vorticity impermeability theorem [Haynes & McIntyre, 87, Haynes & McIntyre, 90], states that PV changes can only be due to frictional or diabatic effects in outcropping regions:

$$\frac{\partial}{\partial t}\int q dV = -\int (J_D|_{z=0} + J_F|_{z=0}) dA,$$



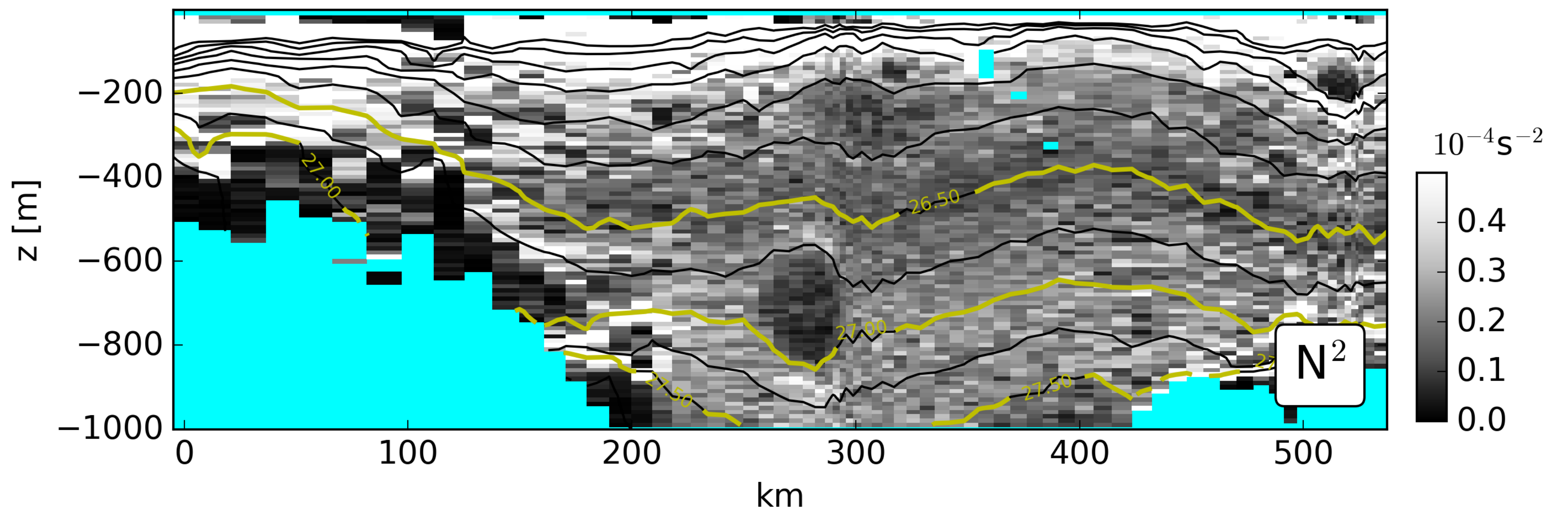
Bottom flux of PV

- Injection of negative PV within different isopycnal ranges:



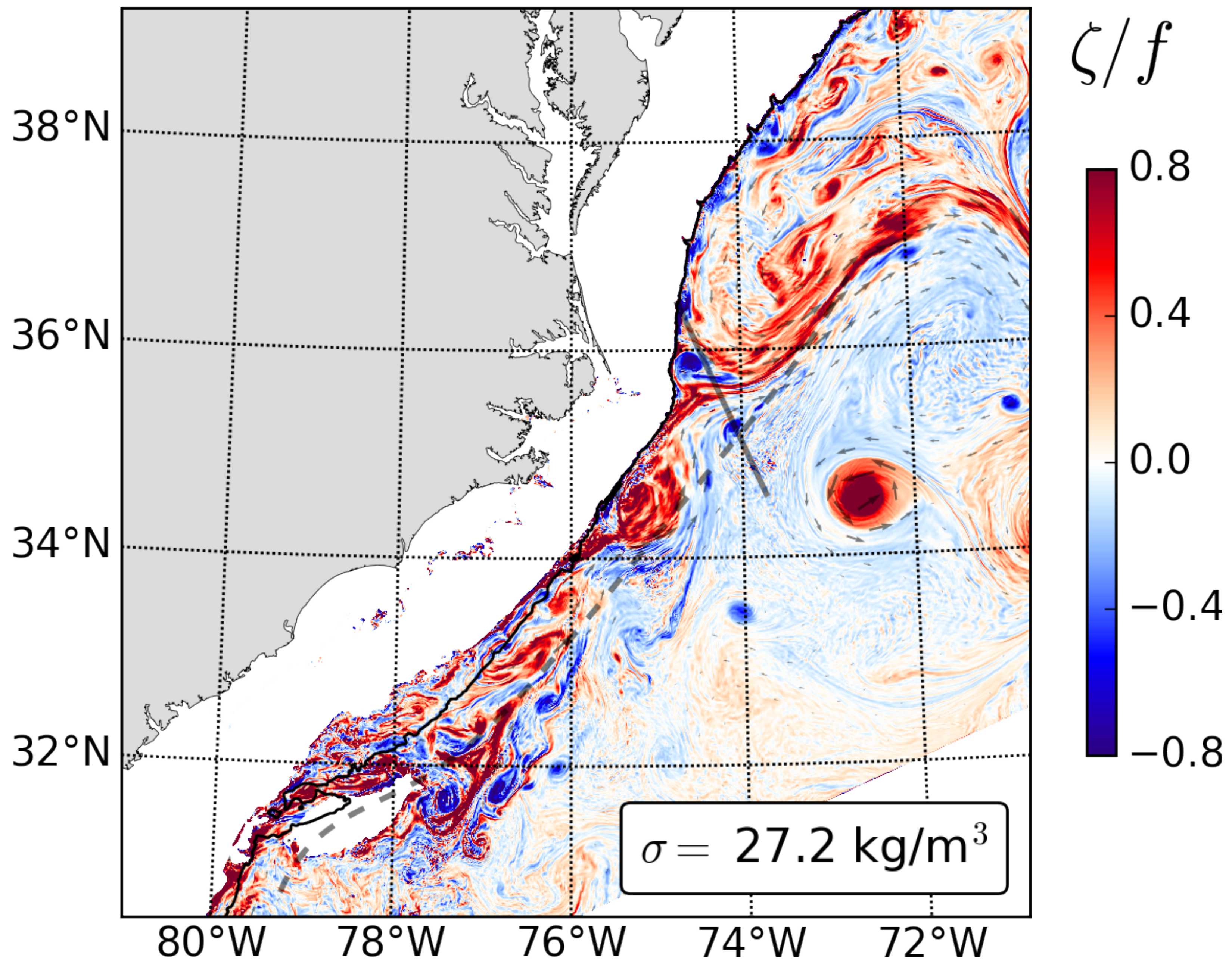
Partial Summary

1. Submesoscale lenses of well-mixed water are observed in seismic reflection images and glider sections of the Gulf Stream



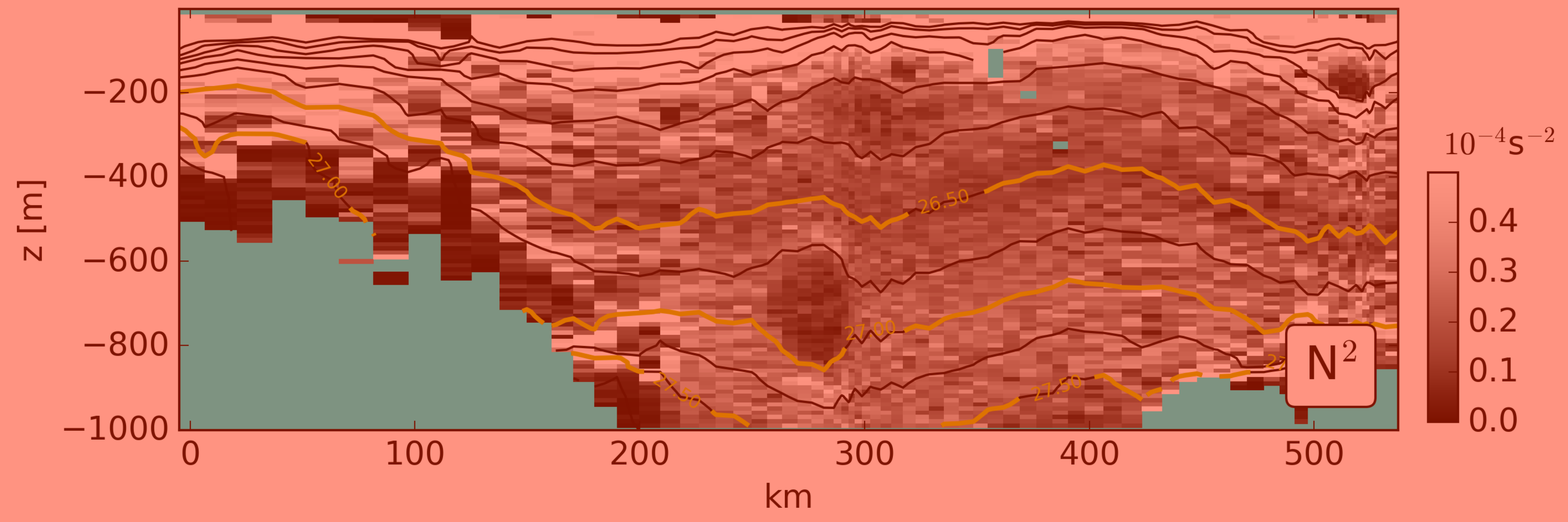
2. They are reproduced by a submesoscale resolving realistic simulation and identified as anticyclonic submesoscale coherent vortices

3. Submesoscale coherent vortices are generated by flow topography interactions in the lee of the Charleston Bump

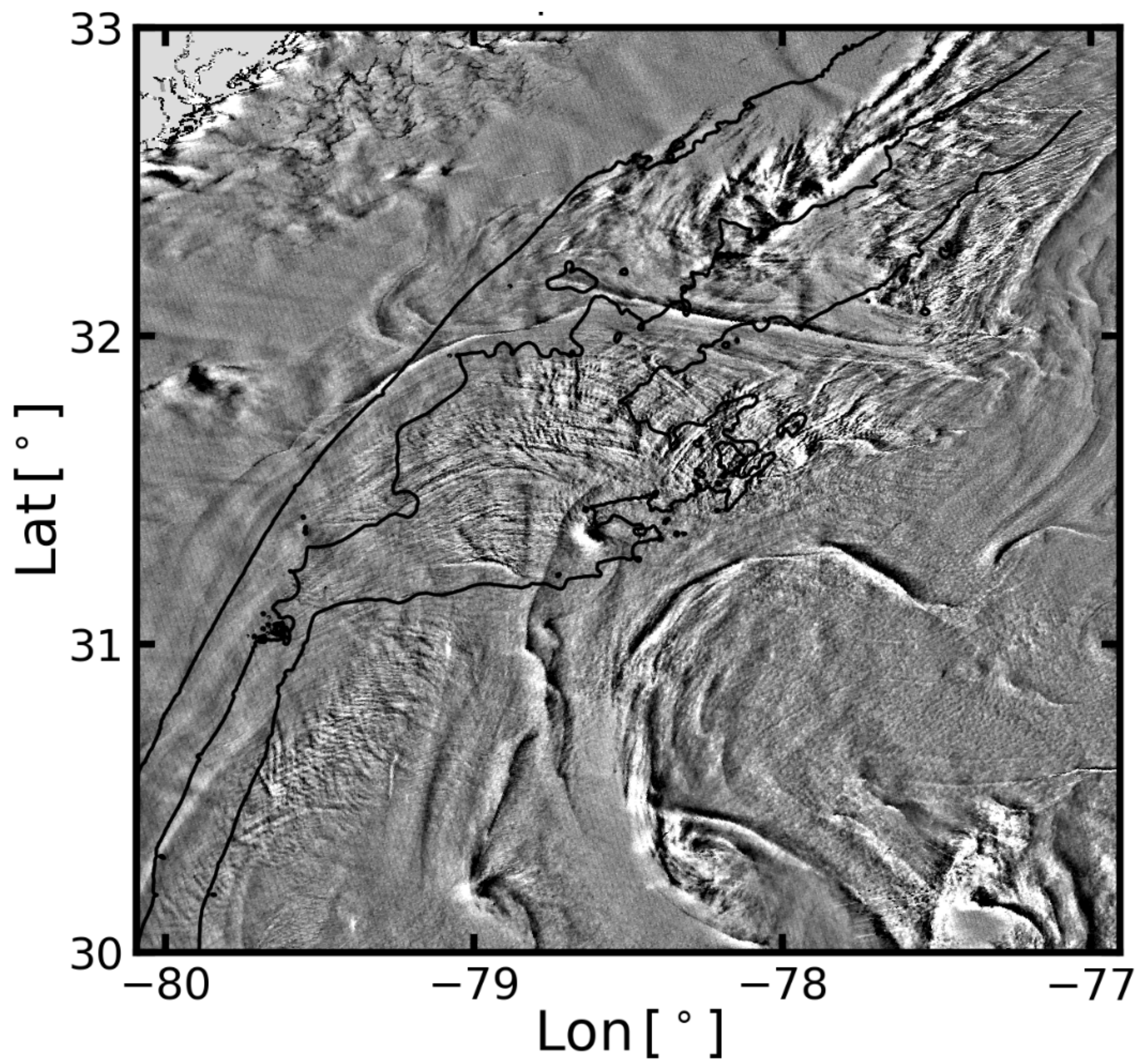


OUTLINE

1. Generation of Submesoscale coherent vortices in the lee of the Bump

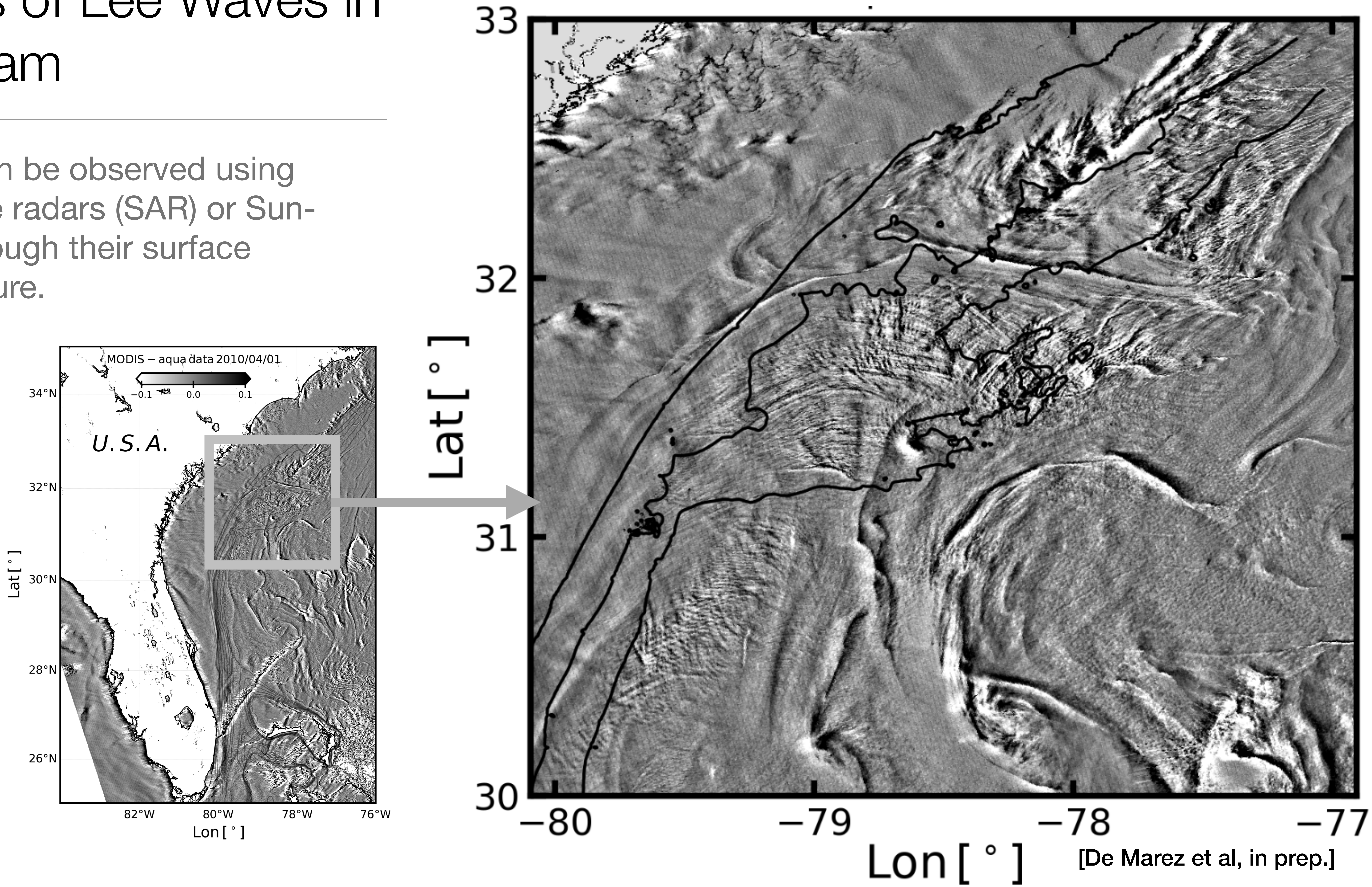


2. Generation of Lee waves over the Charleston Bump



Observations of Lee Waves in the Gulf Stream

- Internal waves can be observed using synthetic aperture radars (SAR) or Sun-glitter images through their surface roughness signature.



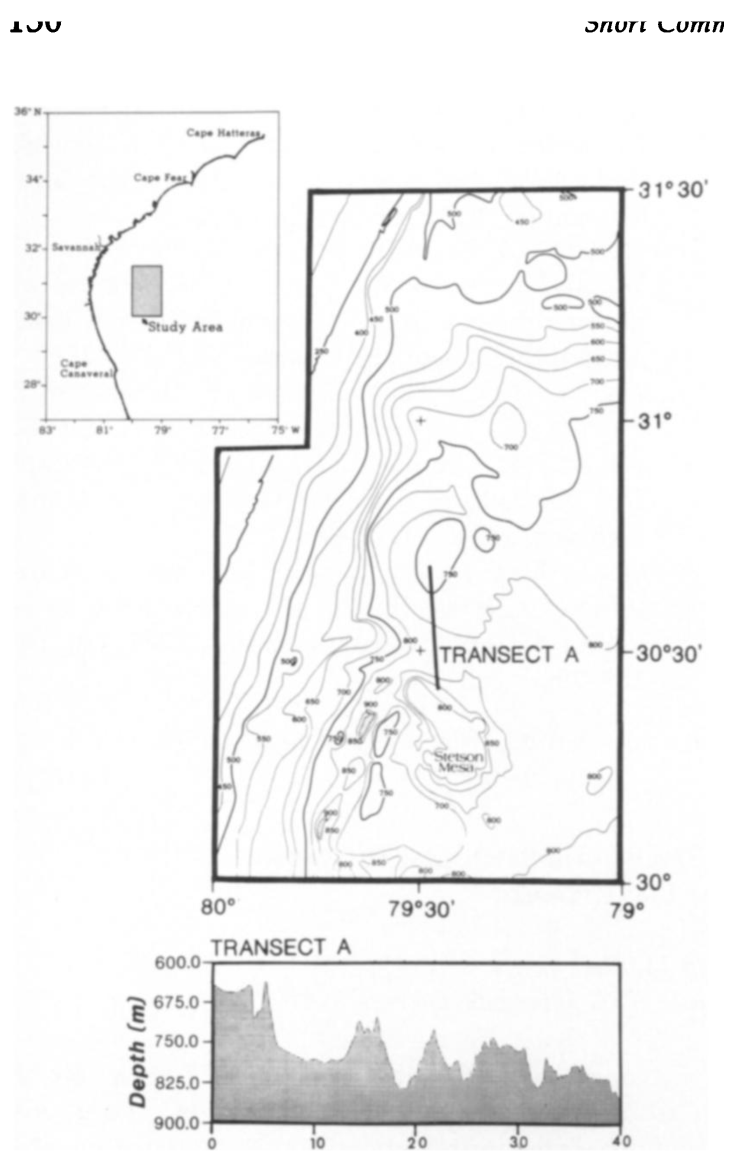
[De Marez et al, in prep.]

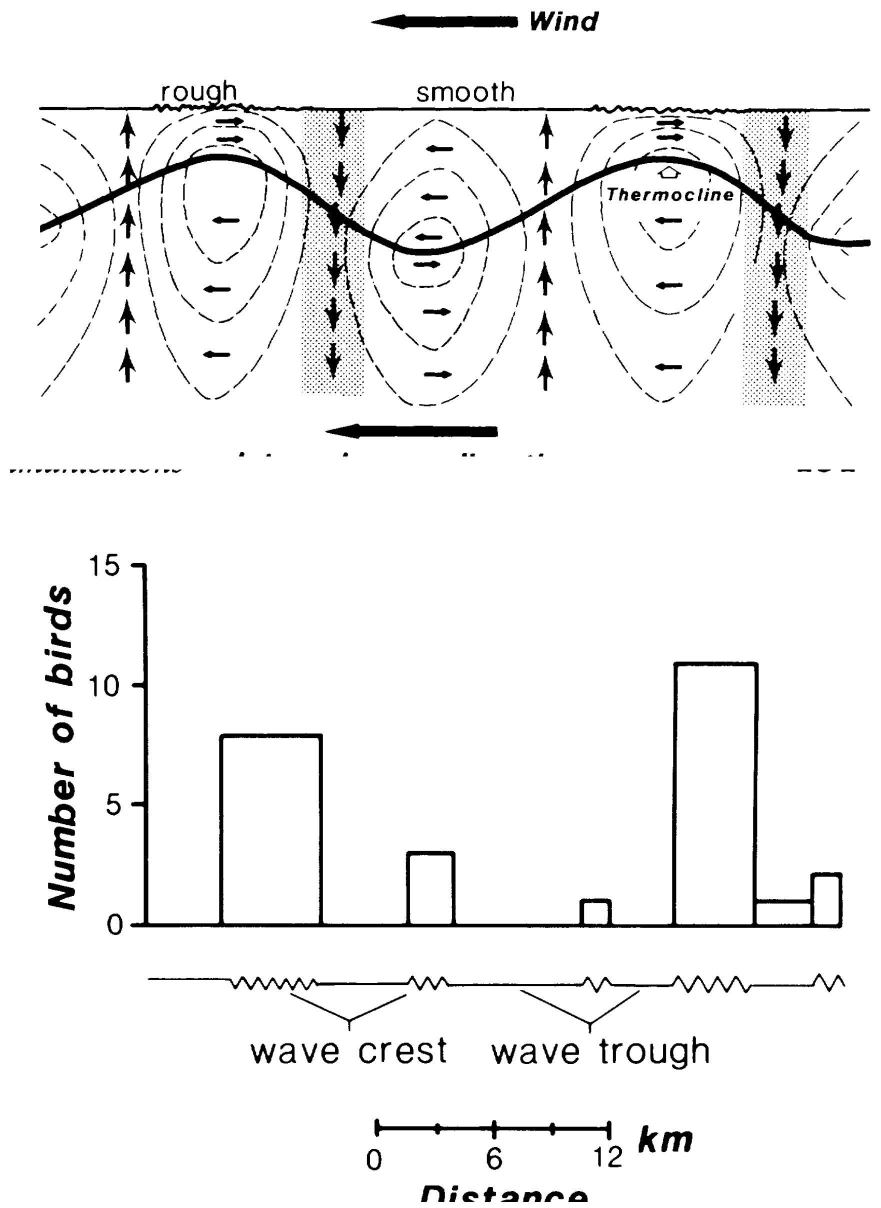
Observations of Lee Waves in the Gulf Stream

- They were also previously inferred from patchiness in sea-birds distribution:

The American Ornithologists' Union

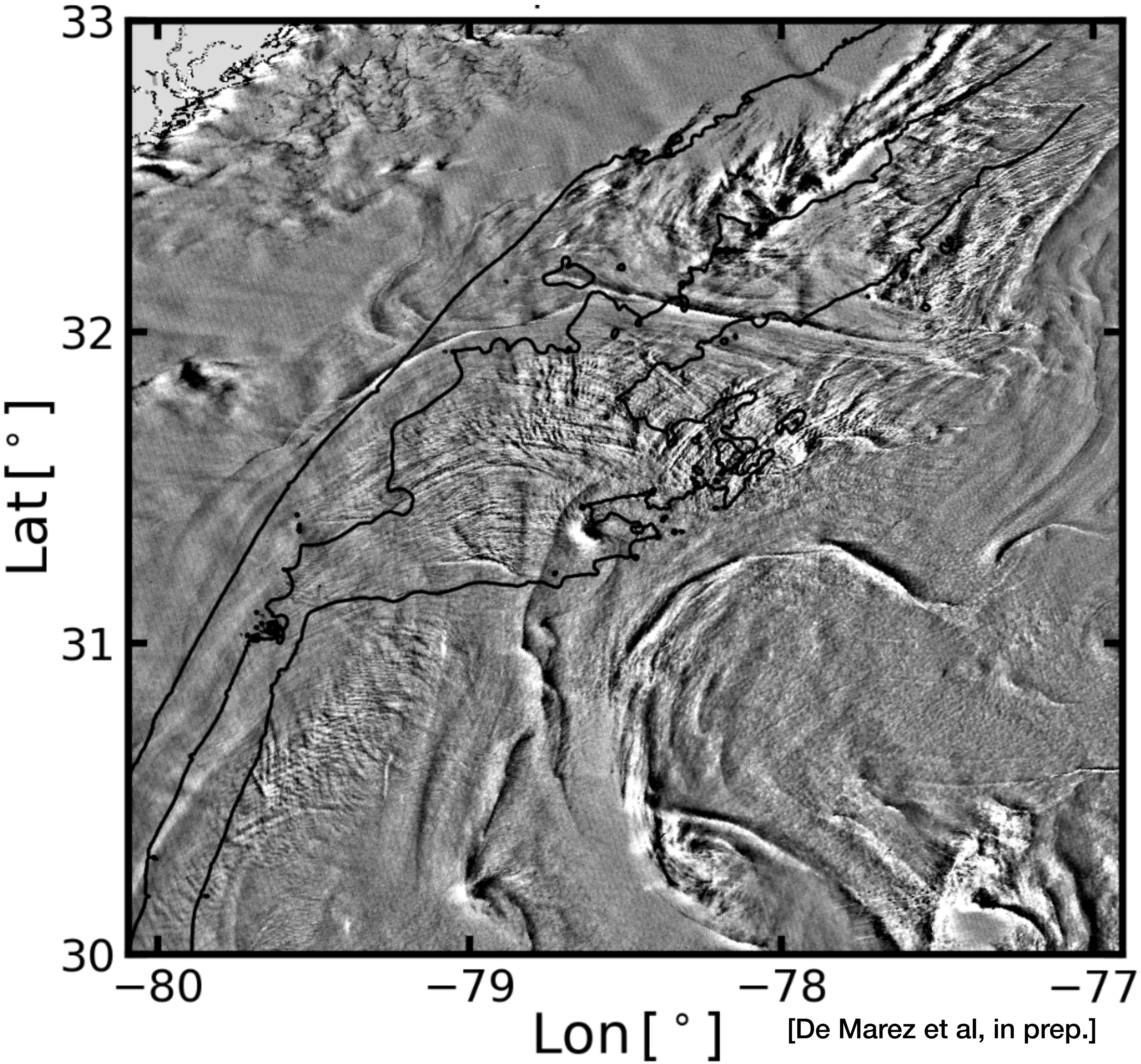
Haney, 1986: “Ocean Internal Waves as Sources of Small-Scale Patchiness in Seabird Distribution on the Blake Plateau“.





Questions about Lee Waves

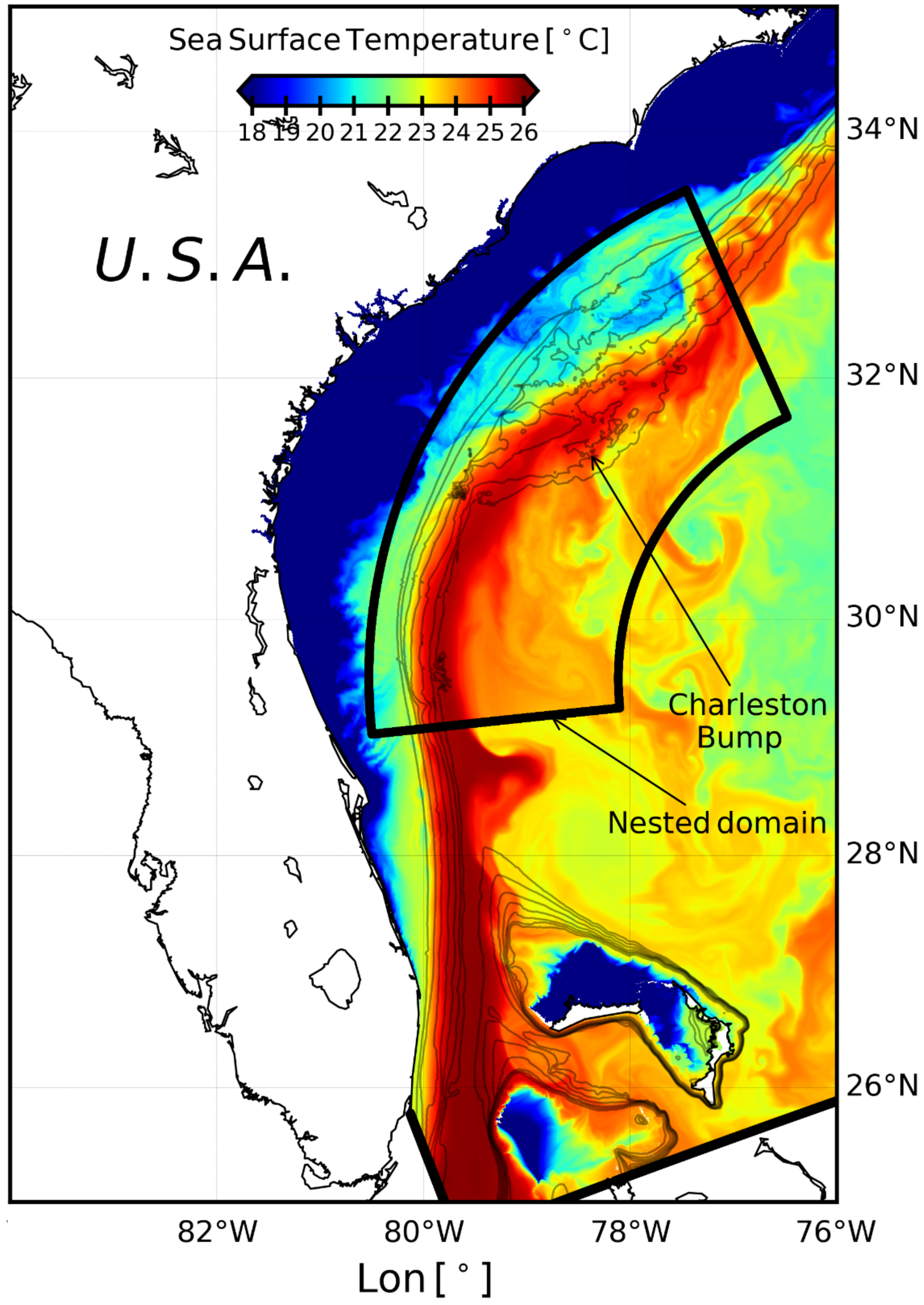
- Formally identify the internal waves signature, are all of these signatures of Lee waves?
- Characterize Lee waves dynamics. Are they linear, hydrostatic?
- Do they impact energy dissipation and mixing?

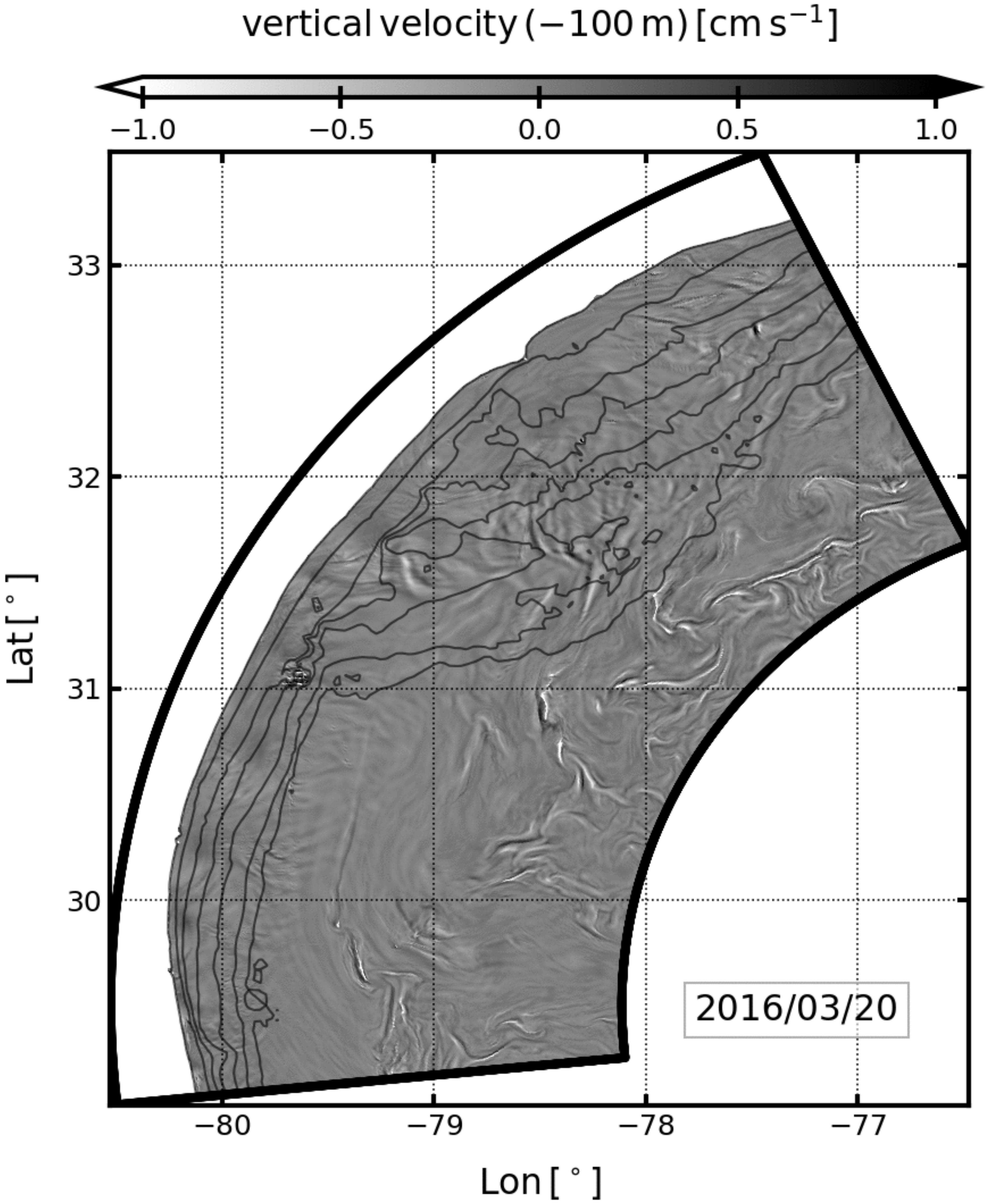


[De Marez et al, in prep.]

Simulation of the Gulf Stream

- We performed a ROMS/ CROCO nest **dx = 200 m,**
- Nx x Ny x Nz = 1024 x 2048 x 128
- Climatological forcings (monthly winds, no tides)
-





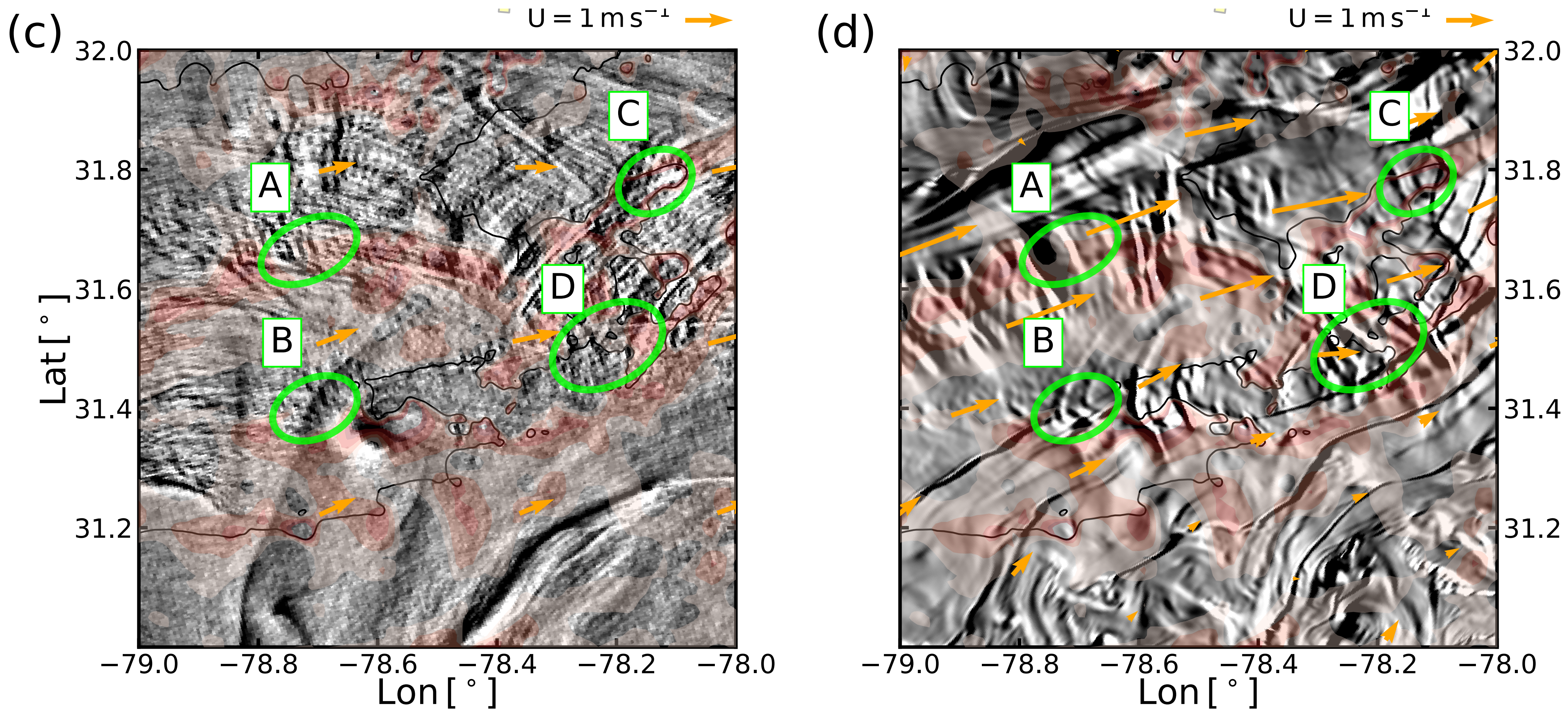
Lee Waves in the Gulf Stream

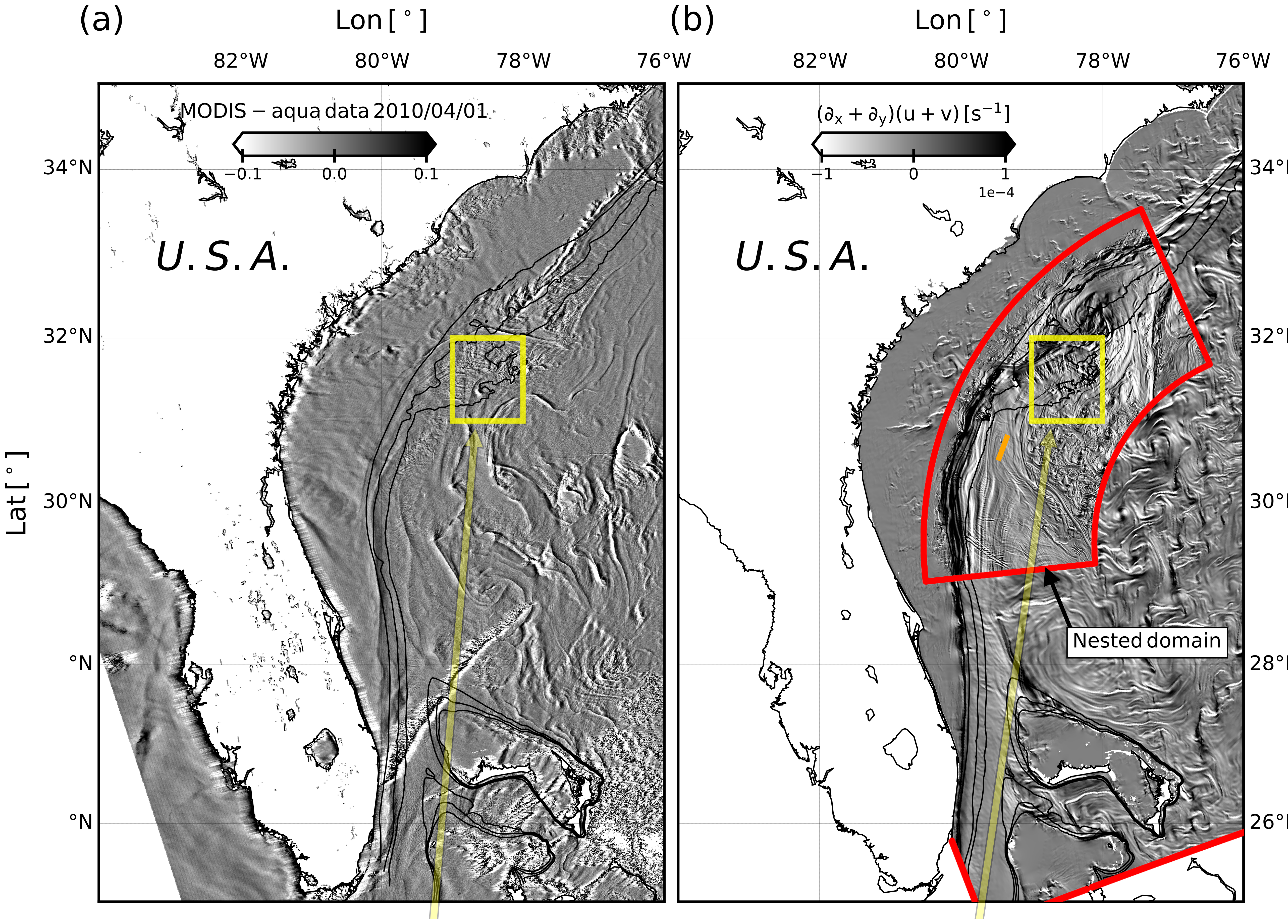
The surface roughness can be interpreted as:

$$\text{roughness} \sim \alpha\partial_x u + \beta\partial_y u + \gamma\partial_x v + \delta\partial_y v,$$

where the coefficients α, β, γ and δ are functions of (1) the wind direction and (2) the position of the measuring device with respect to the position of the sun. So we compute, as a first approximation:

$$\left(\partial_x + \partial_y\right)\left(u + v\right)$$

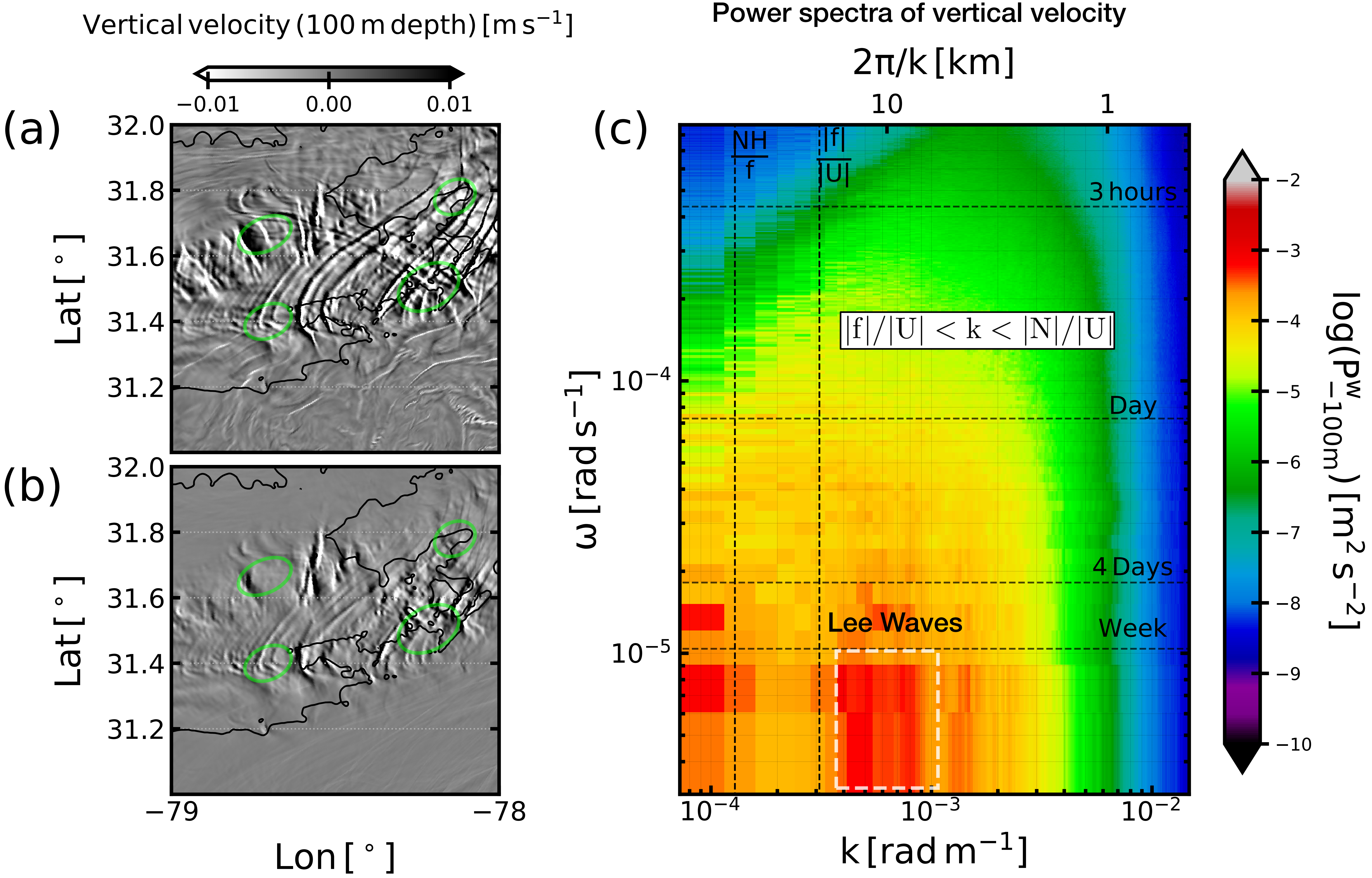




Qualitatively similar wave patterns in the simulation — *Point to point comparison limited by accuracy of topographic data (here SRTM30)!*

Lee Waves in the Gulf Stream

- We can isolate patterns related to Lee Waves by looking at time-low passed vertical velocities below the thermocline:



Lee Waves in the Gulf Stream

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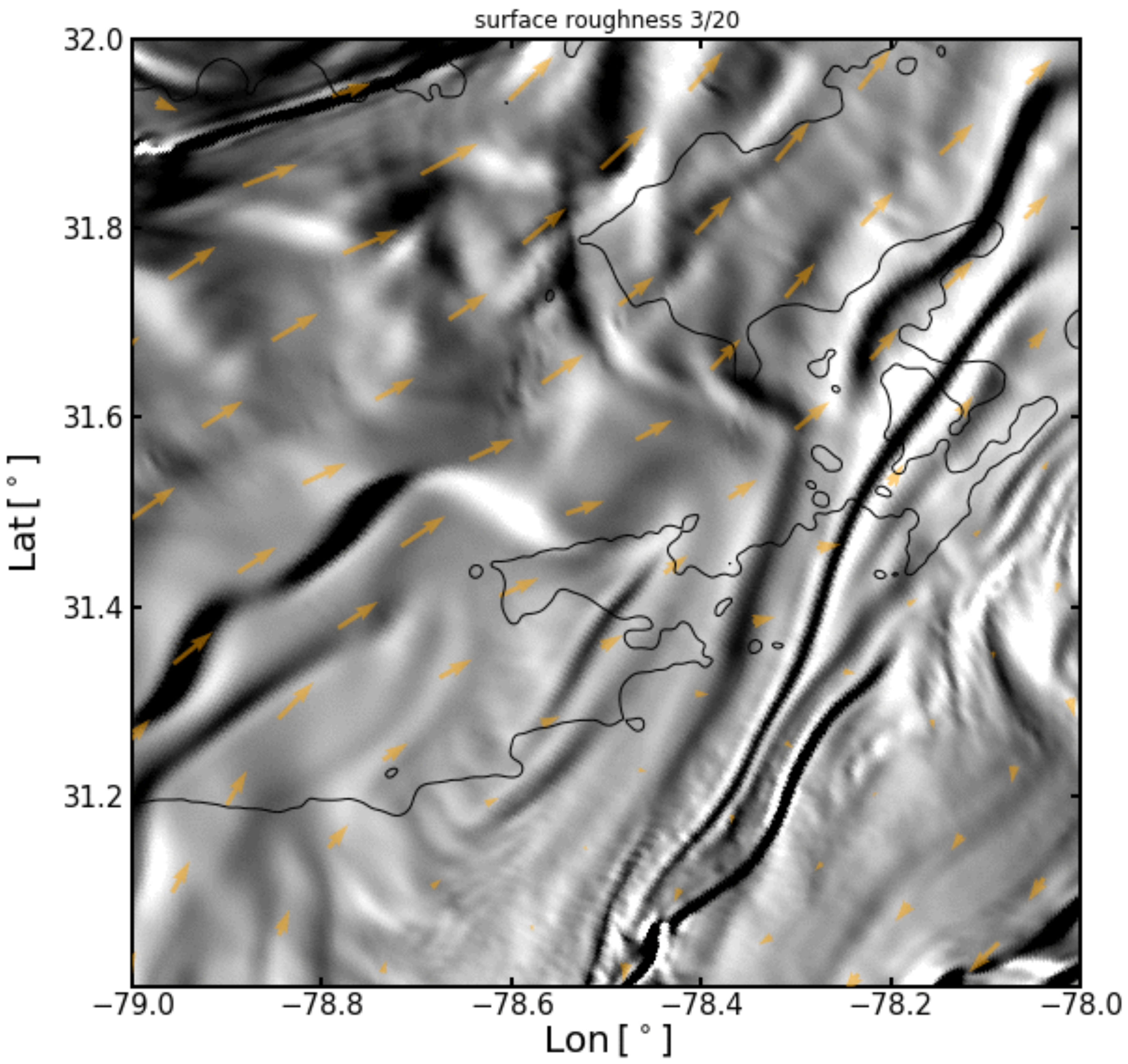
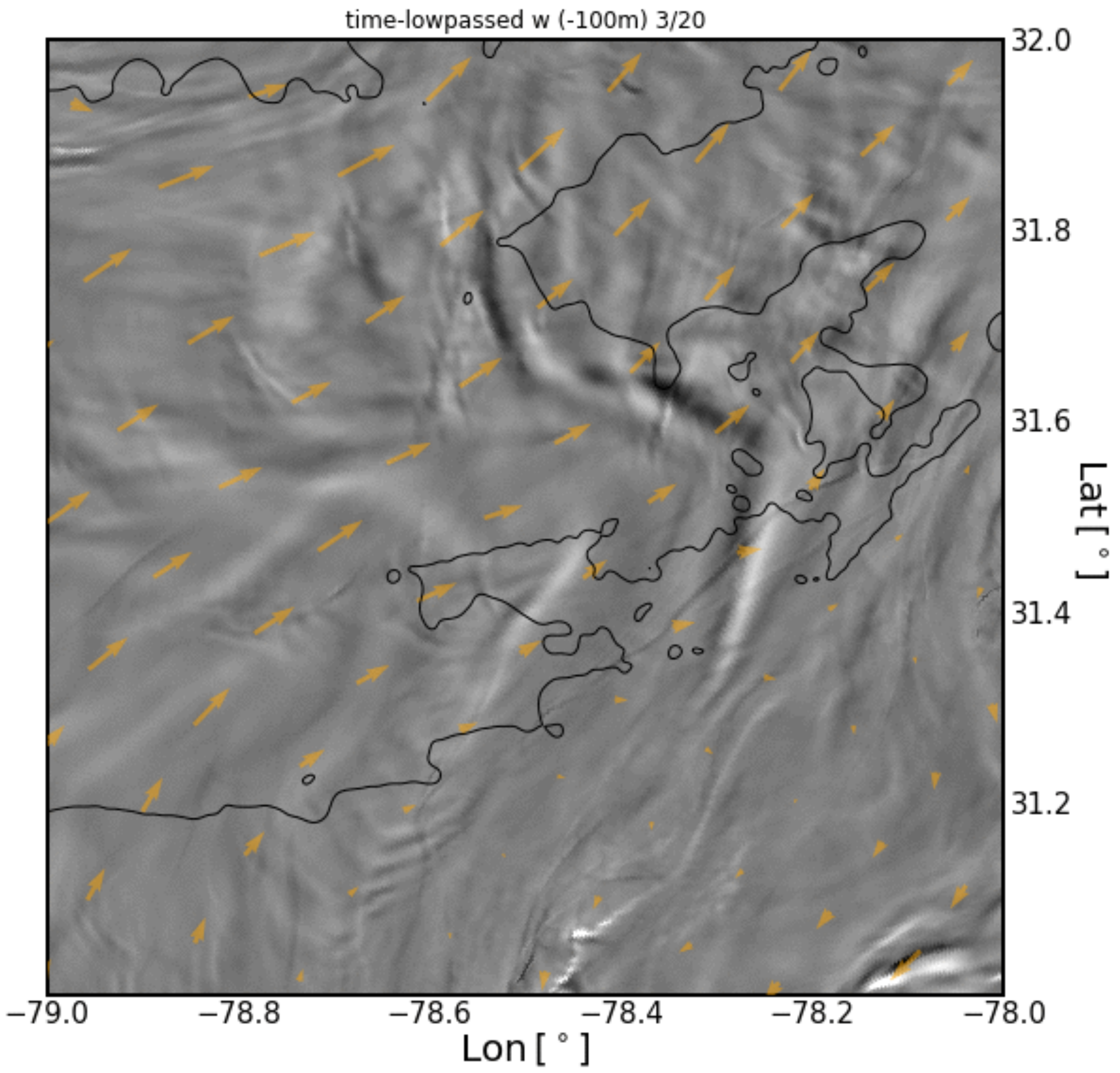




Comparison of Lee Waves with linear theory

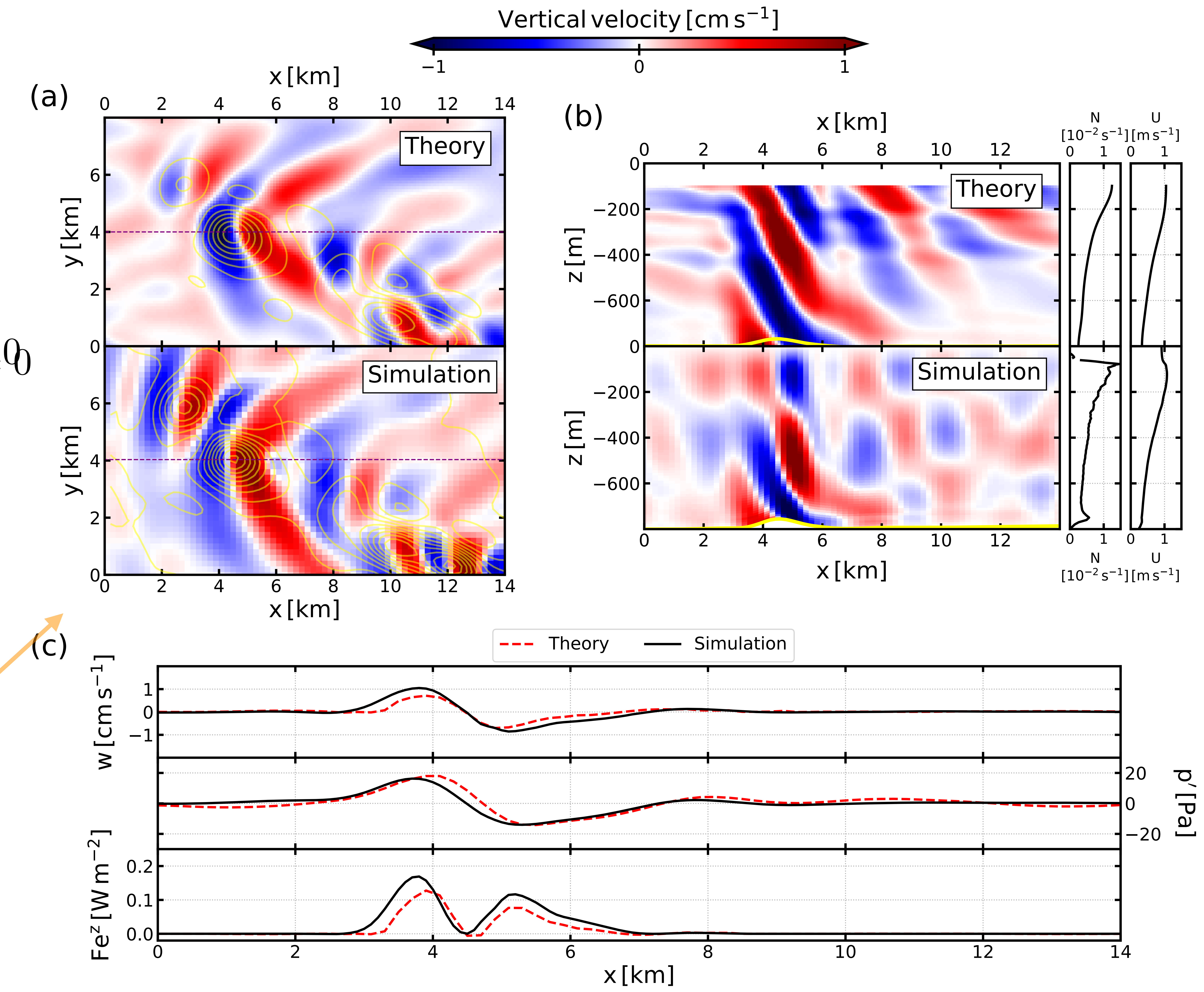
3D theoretical prediction of hydrostatic lee waves is obtained by numerically solving:

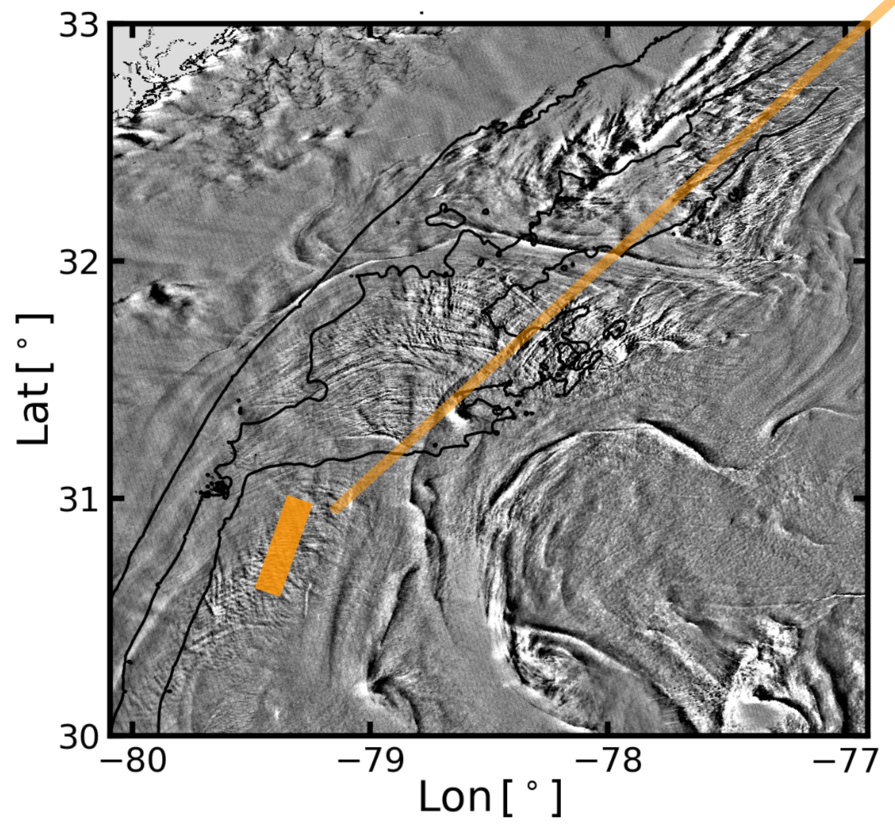
$$\partial_{zz}\tilde{\eta}(\mathrm{k},\mathrm{m},\mathrm{z}) + \mathrm{n}^2\tilde{\eta}(\mathrm{k},\mathrm{m},\mathrm{z}) = 0$$

under the WKBJ approximation with the dispersion relation:

$$\mathrm{n}^2(\mathrm{k},\mathrm{m},\mathrm{z}) = \mathrm{k}^{-2}(\mathrm{k}^2+\mathrm{m}^2)\left(\frac{\mathrm{N}^2}{\mathrm{U}^2} + \frac{\partial_{zz}\mathrm{U}}{\mathrm{U}}\right)$$

and radiation condition at the top of the domain and a Dirichlet condition at the bottom.





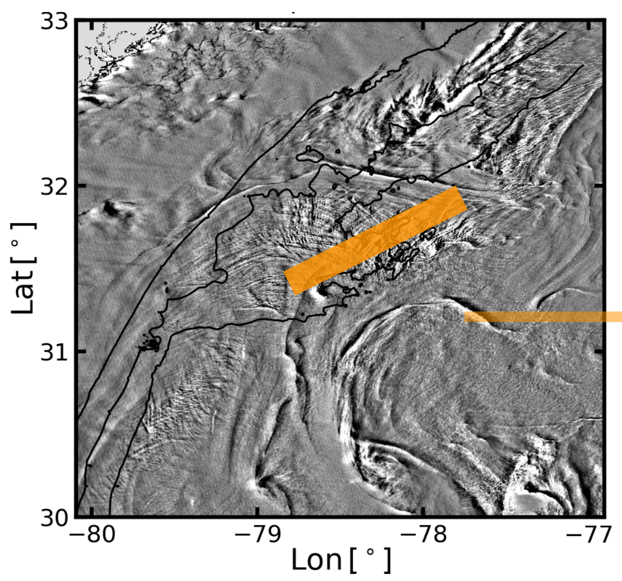
Comparison of Lee Waves with linear theory

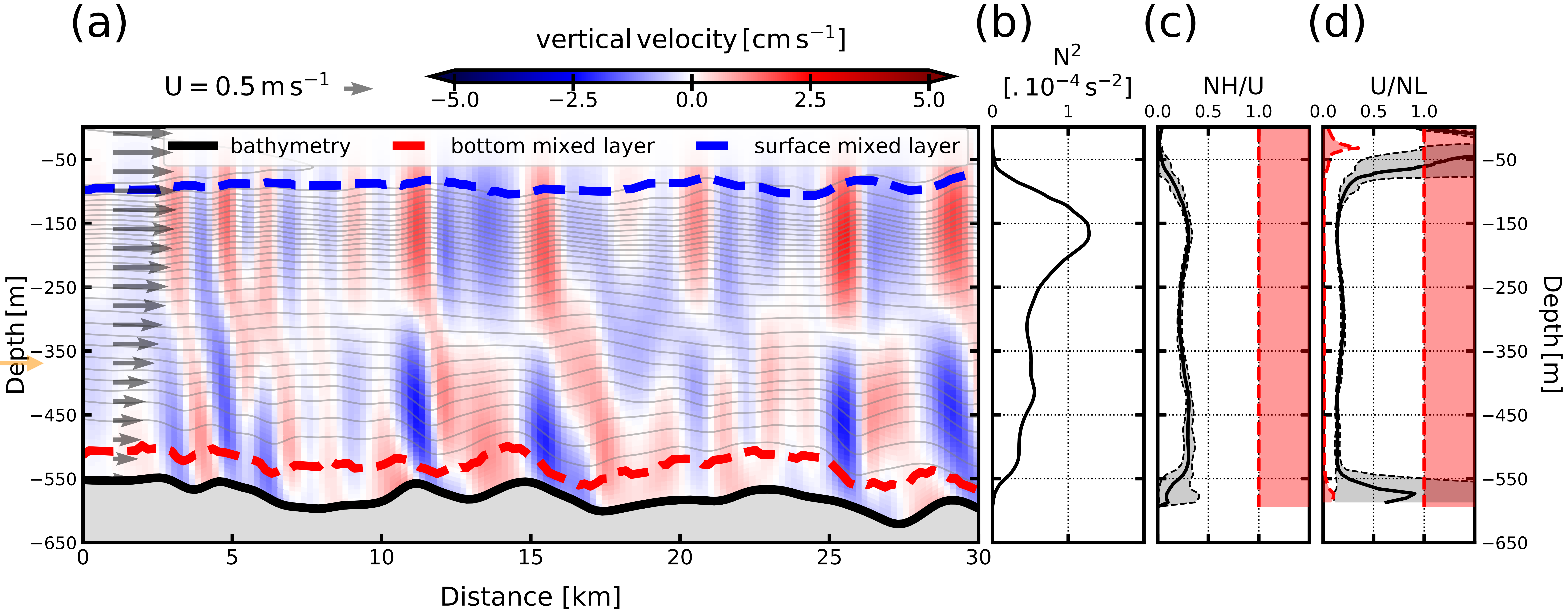
Condition for a hydrostatic flow: $$\varepsilon = \frac{\mathrm{U}}{\mathrm{NL}} \ll 1 \rightarrow \mathrm{Hydrostatic}$$

And for linear waves:
[Mayer and Fringer, 2017]

$$\mathrm{Fr_{lee}} = \frac{\mathrm{NH}}{\mathrm{U}} = \frac{\text{vertical velocity within the lee wave}}{\text{group velocity of the lee wave}}.$$

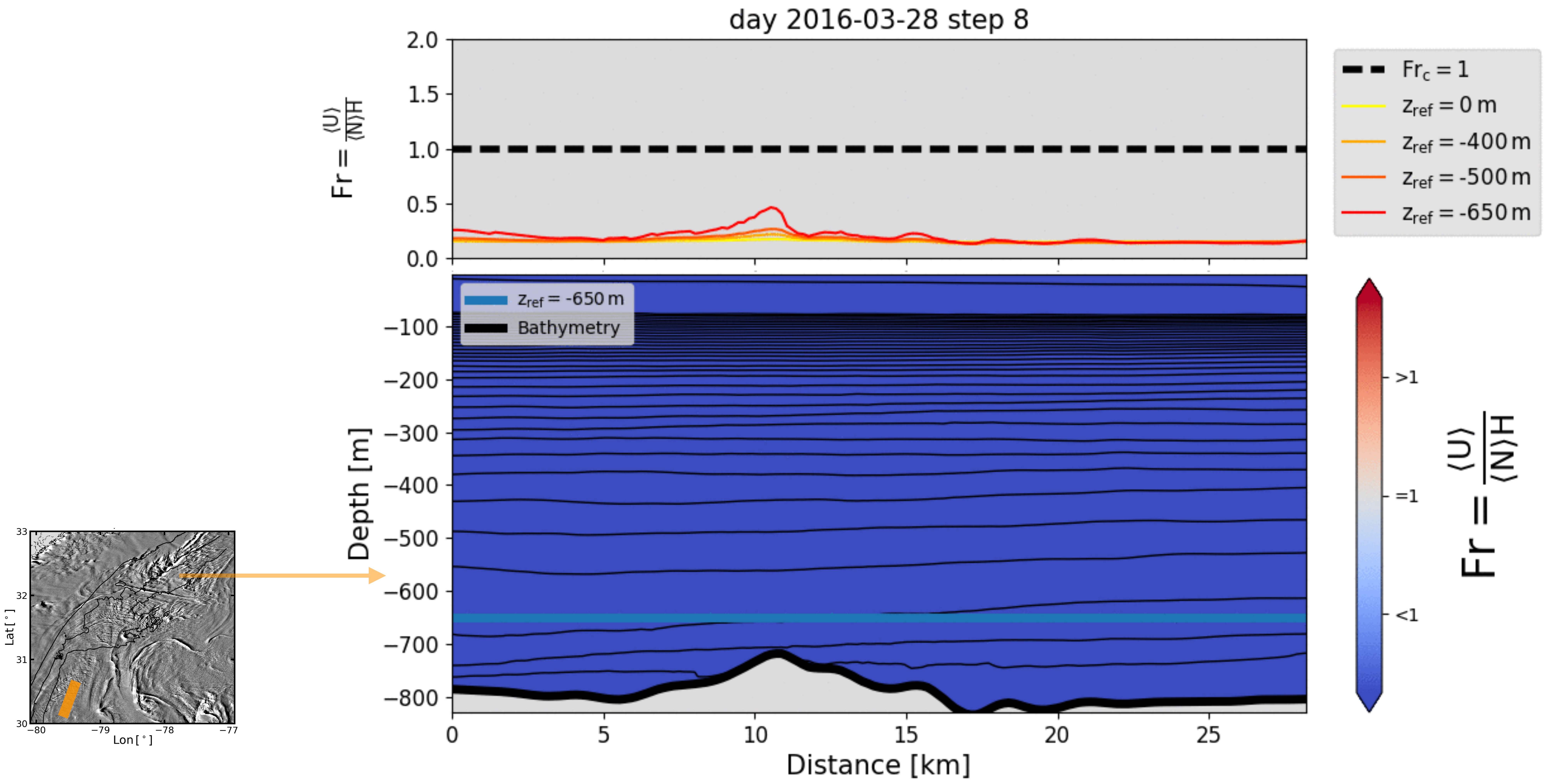
$$\mathrm{Fr_{lee}} < 1 \rightarrow \text{linear propagation of the waves}$$
$$\mathrm{Fr_{lee}} \gtrsim 1 \rightarrow \text{non} - \text{linearity of the waves.}$$





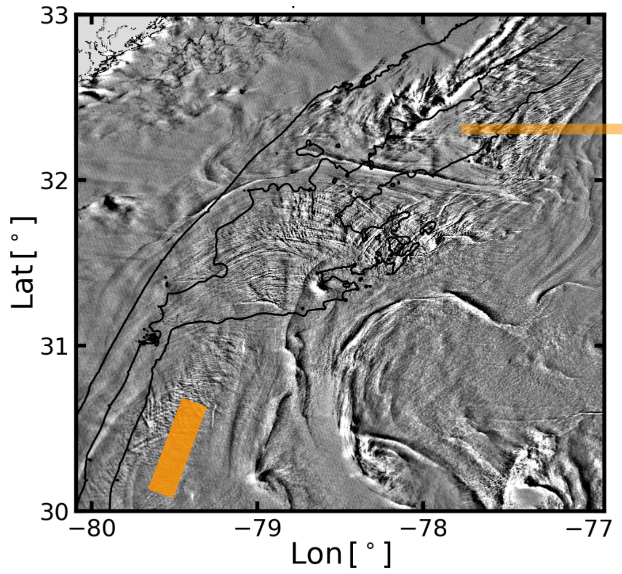
Non-linearities at the bottom

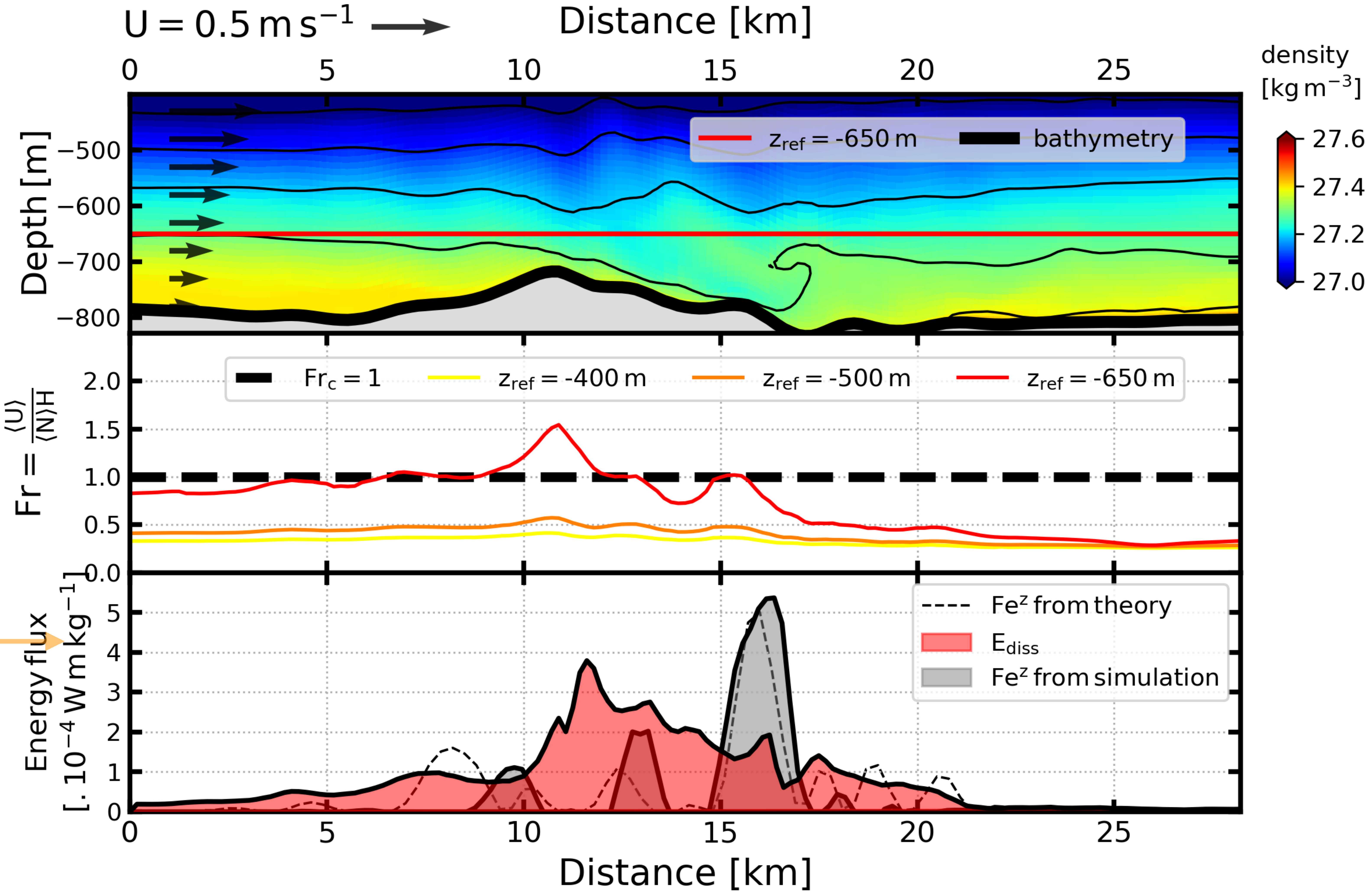
Examples of hydraulic jumps:



Non-linearities at the bottom

Examples of hydraulic jumps:





Energy dissipation due to Lee Waves

A significant amount of energy (O(1) GW) is being dissipated in the interior of the fluid by the lee waves, including at locations where these waves may exhibit nonlinearities.

The lee wave energy flux ($\mathrm{Fe^z = p'w}$) computed using analytical formulation of Nikurashin and Ferrari (2011):

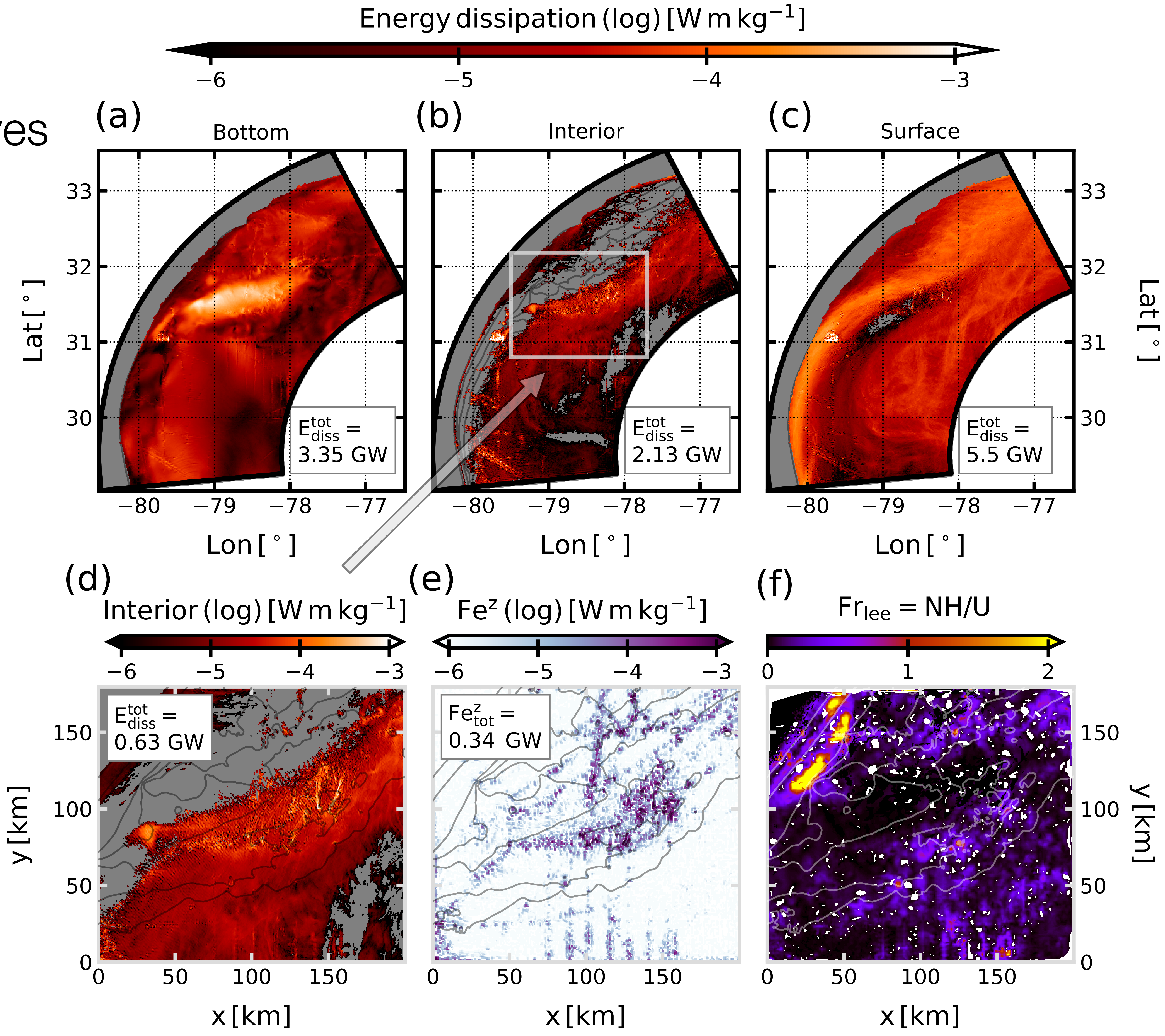
$$E = \frac{\rho_0|\mathbf{U}|}{2\pi}\int_{|f|/|\mathbf{U}|}^{N/|\mathbf{U}|} P_*(k)\sqrt{N^2-|\mathbf{U}|^2k^2}\sqrt{|\mathbf{U}|^2k^2-f^2}\,dk,$$

yields a total conversion of O(0.3)GW.

The wave drag can be computed as:

$$\mathrm{Form\,Drag} = \rho_0\sqrt{\mathrm{(u'w)^2+(v'w)^2}}$$

It amounts to O(1) GN and represents about 20% of the form drag exerted by the whole Charleston Bump.



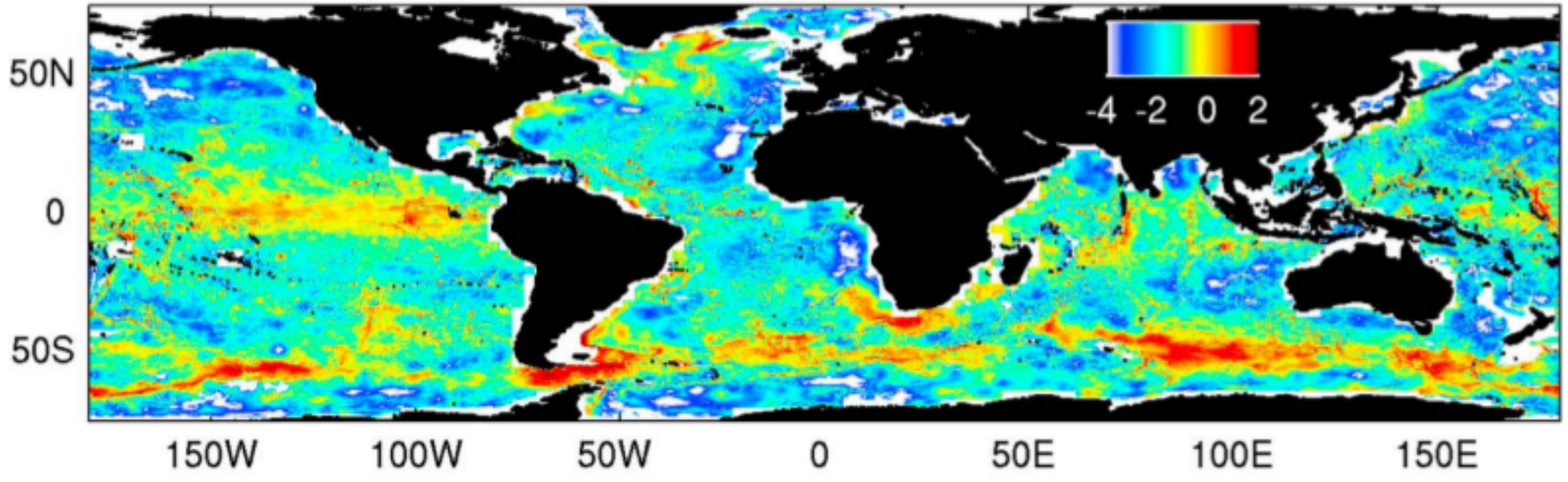
Another Summary

1. Signature of lee waves are observed over the Gulf Stream in satellite sun-glitter images and reproduced using a realistic simulation.

2. Linear theory accurately reflects the generation properties of lee waves over most of the domain.

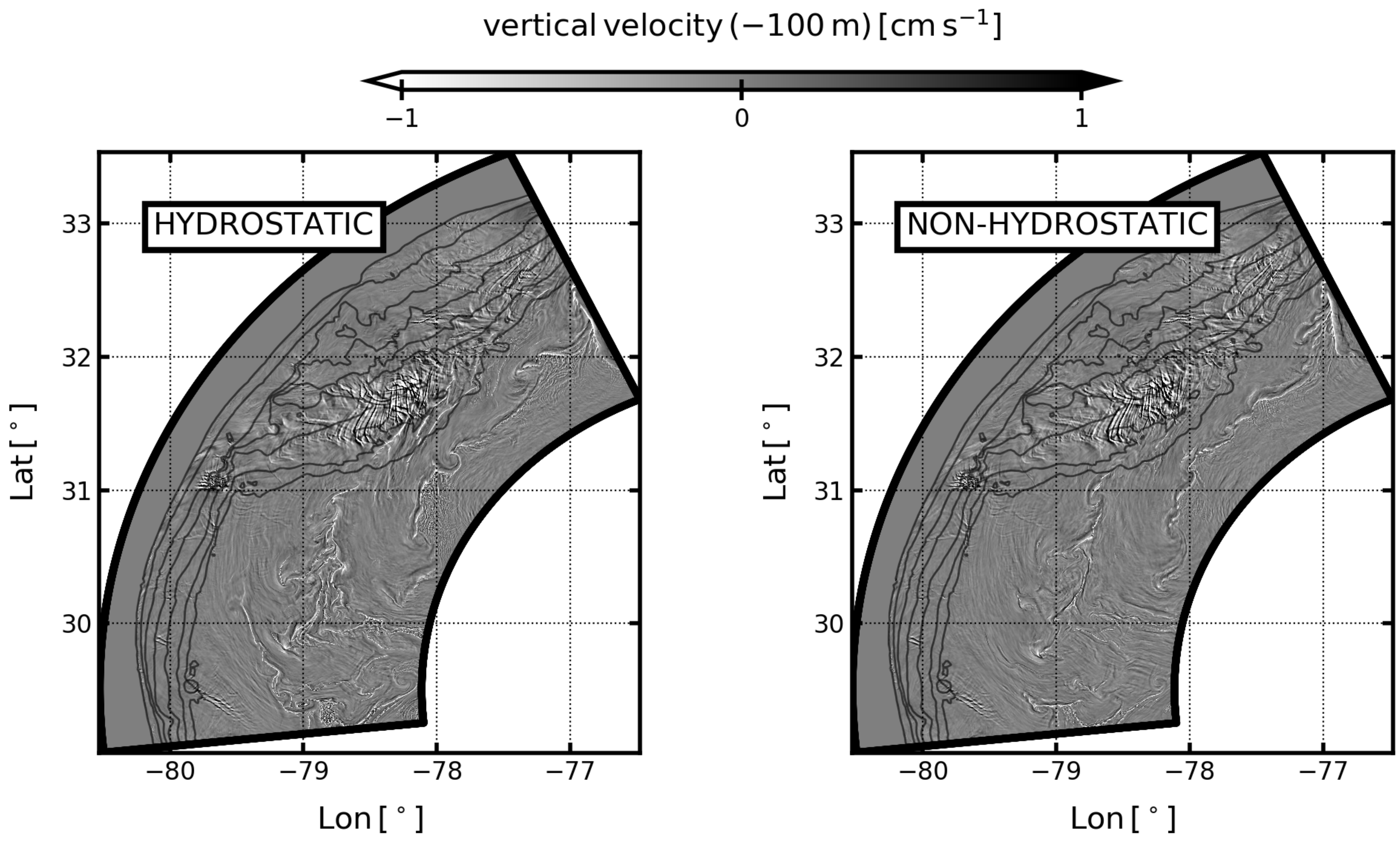
3. The breaking of lee waves above the Charleston Bump provides a significant mechanism for the dissipation of energy : O(1 GW)

Total energy dissipated by lee waves: 0,2TW - 0.8TW



Energy flux into internal lee waves in log10 (mW m^{-2}) [Nikurashin & Ferrari, 2011]

Some extras: Differences with the non-hydrostatic code?



- Identical simulation with:

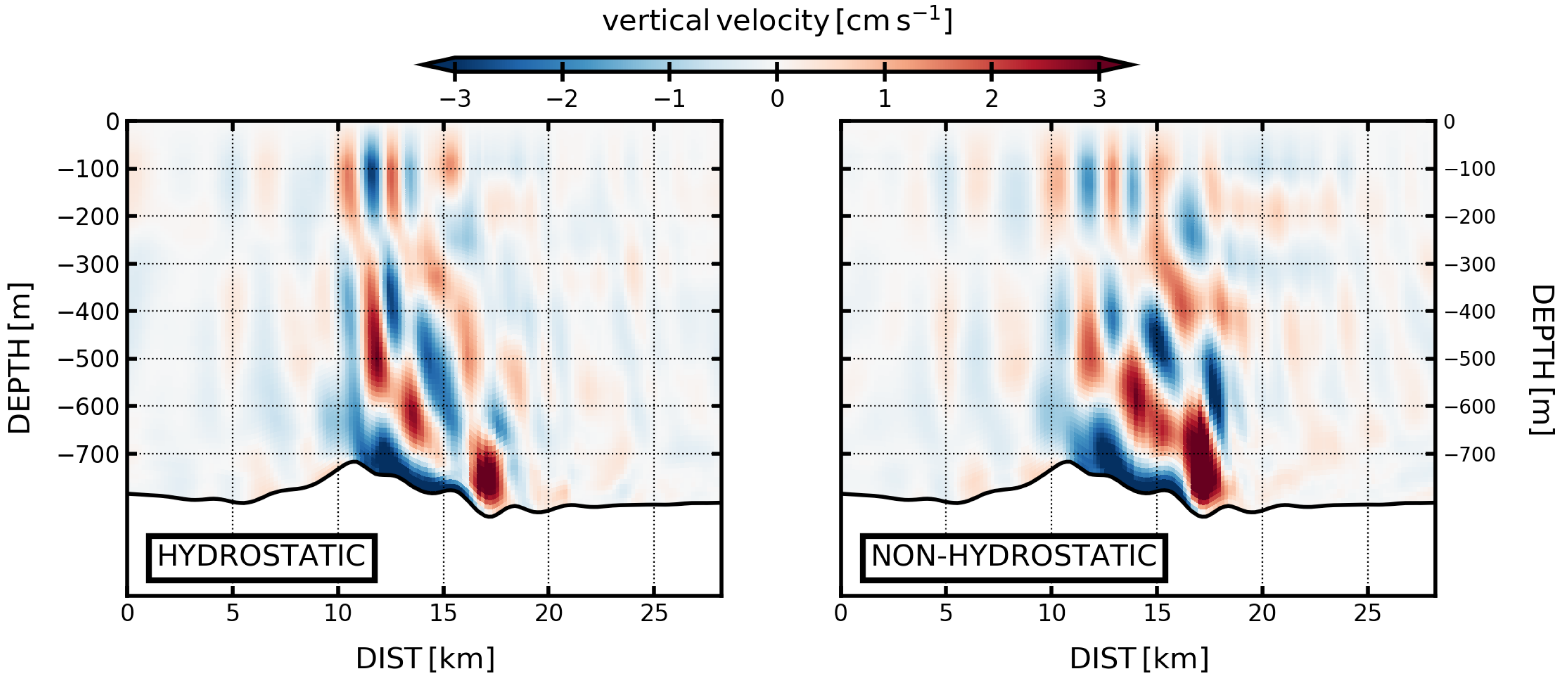
define NHMG

define NONTRAD_COR

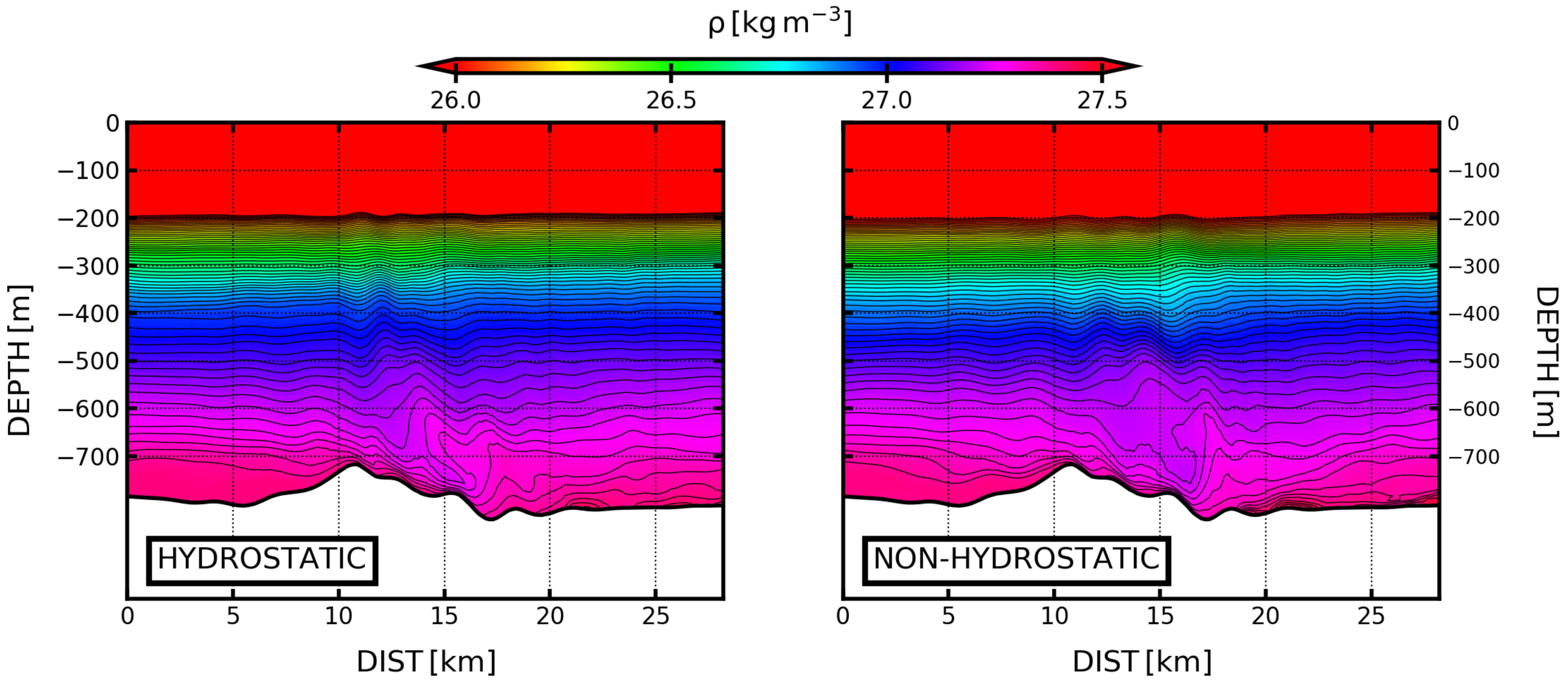
- Identical time-step

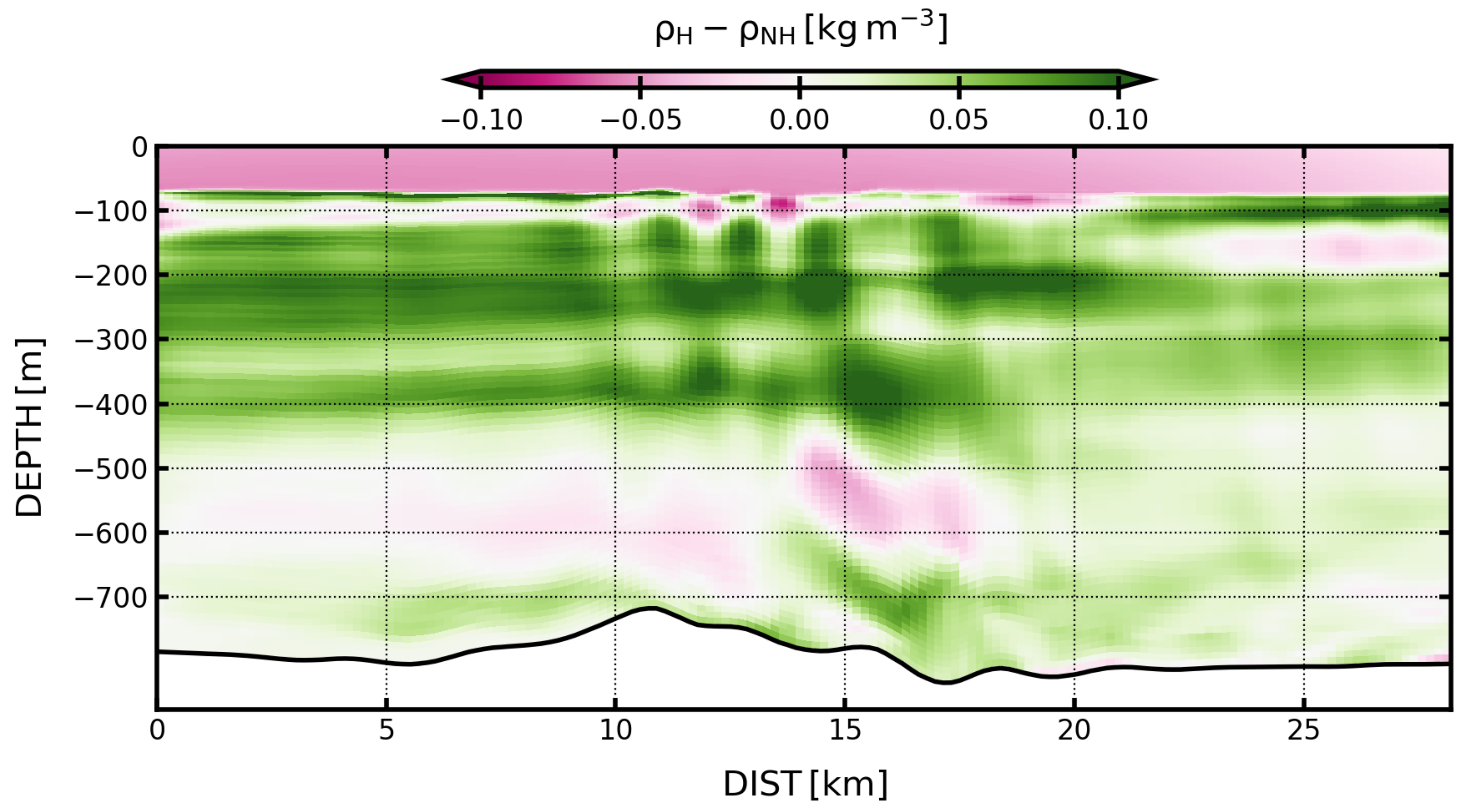
- Overhead = 215 %

Some extras: Differences with the non-hydrostatic code?



Some extras: Differences with the non-hydrostatic code?

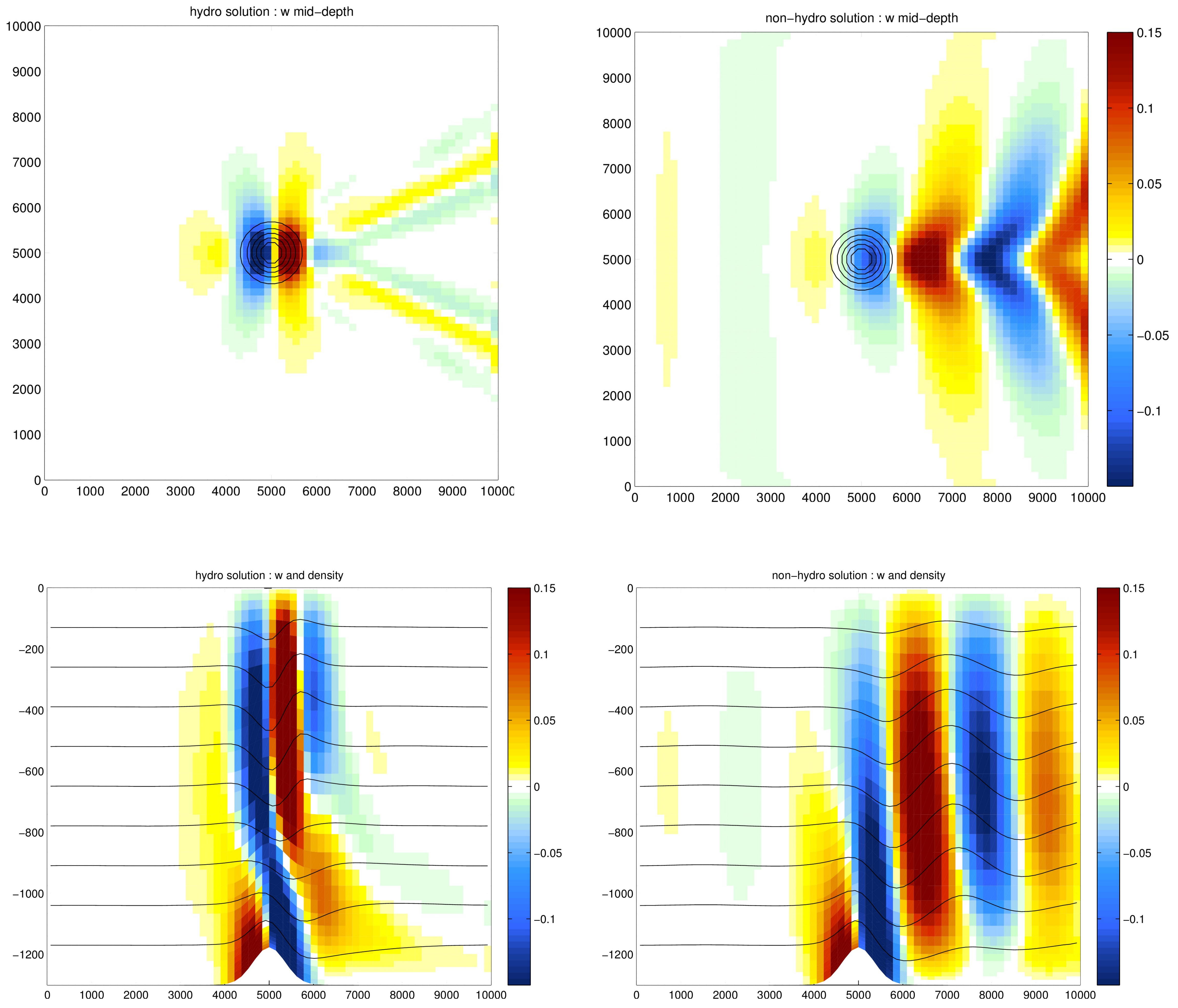




Thanks for your attention

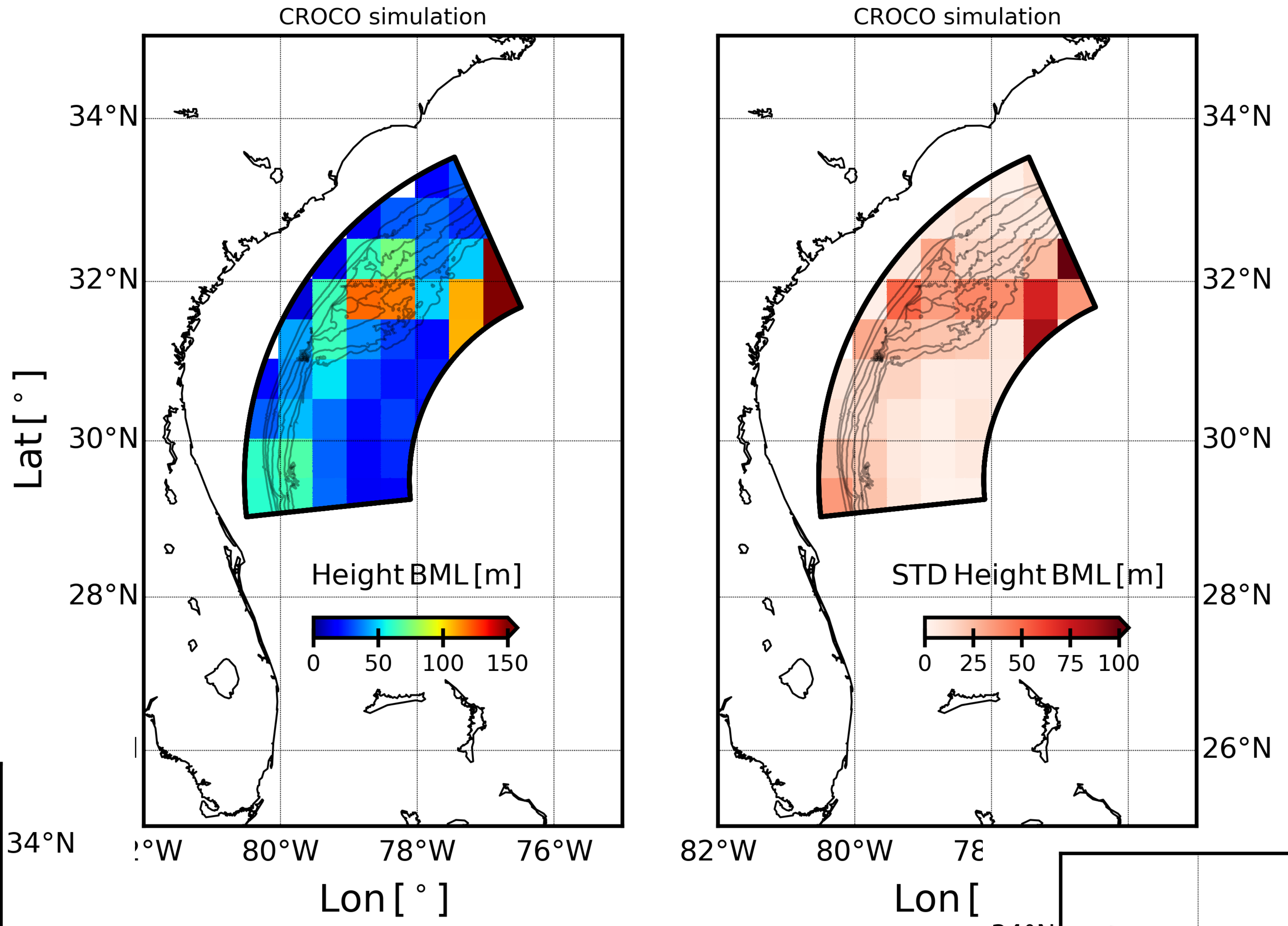
Some extras: Differences with the non-hydrostatic code?

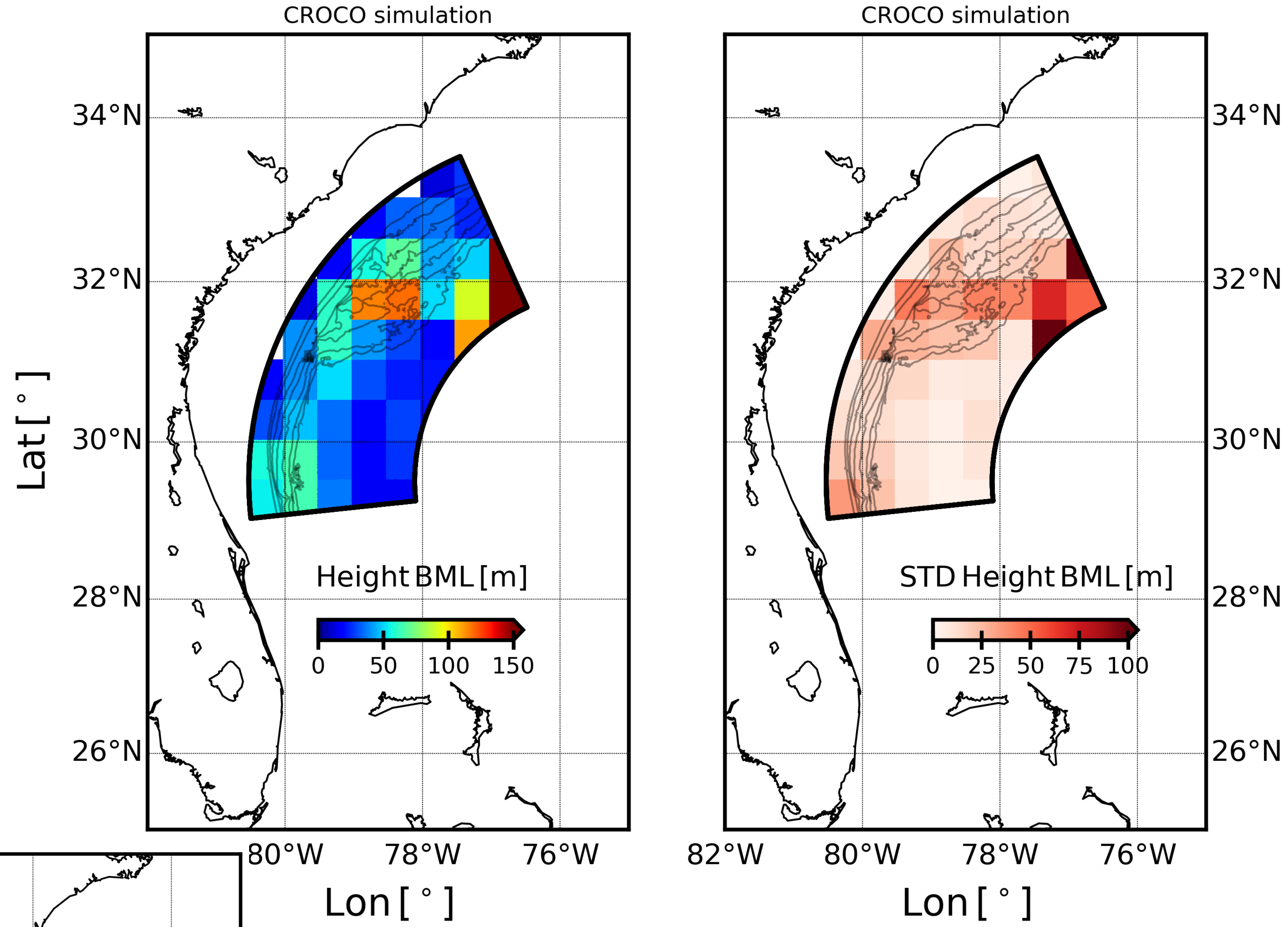
- With U~1.2 m s^{-1} and N~3e-3 s^{-1},
- U/N~400 m and L~500 m
-



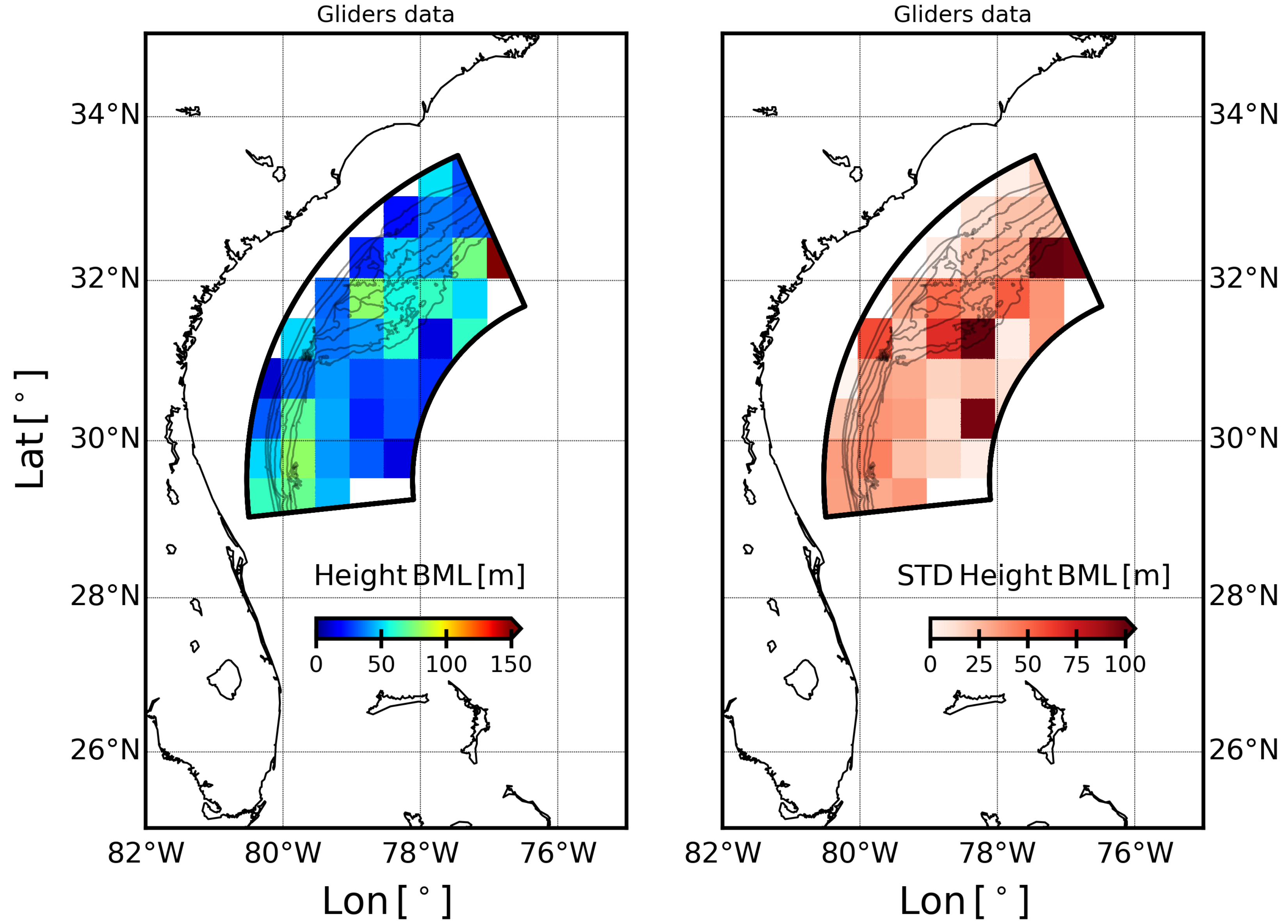
From N. Ducousso

Some extras: Differences with the non-hydrostatic code?



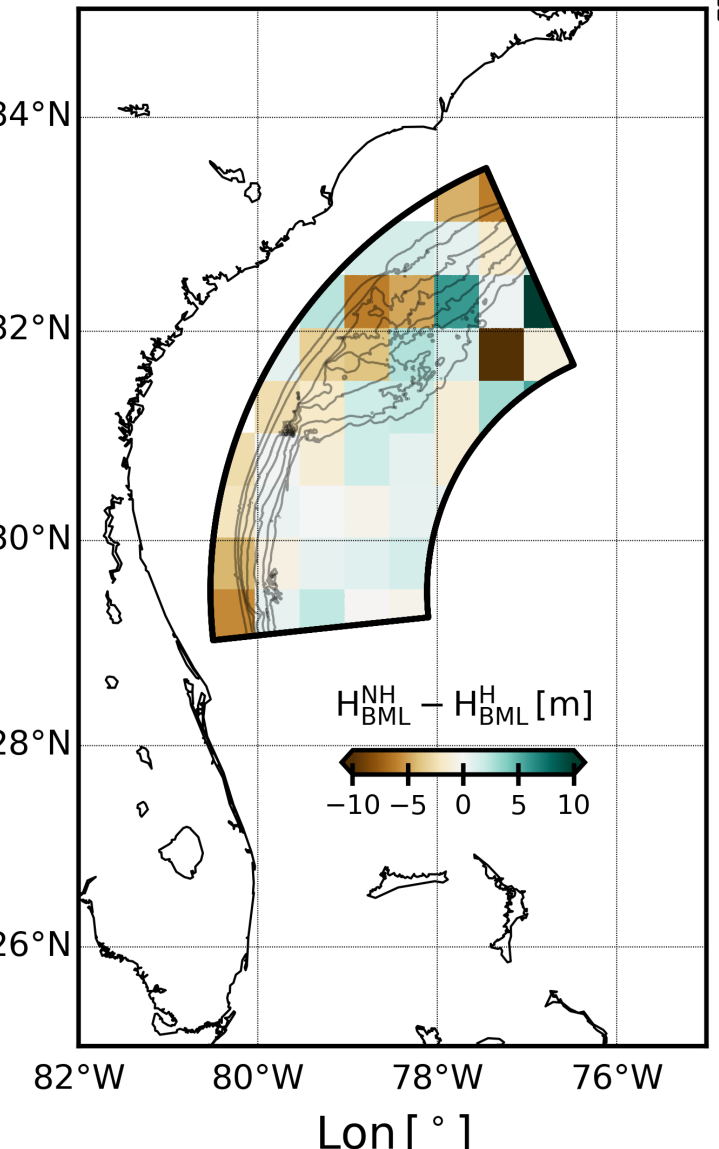


Gliders



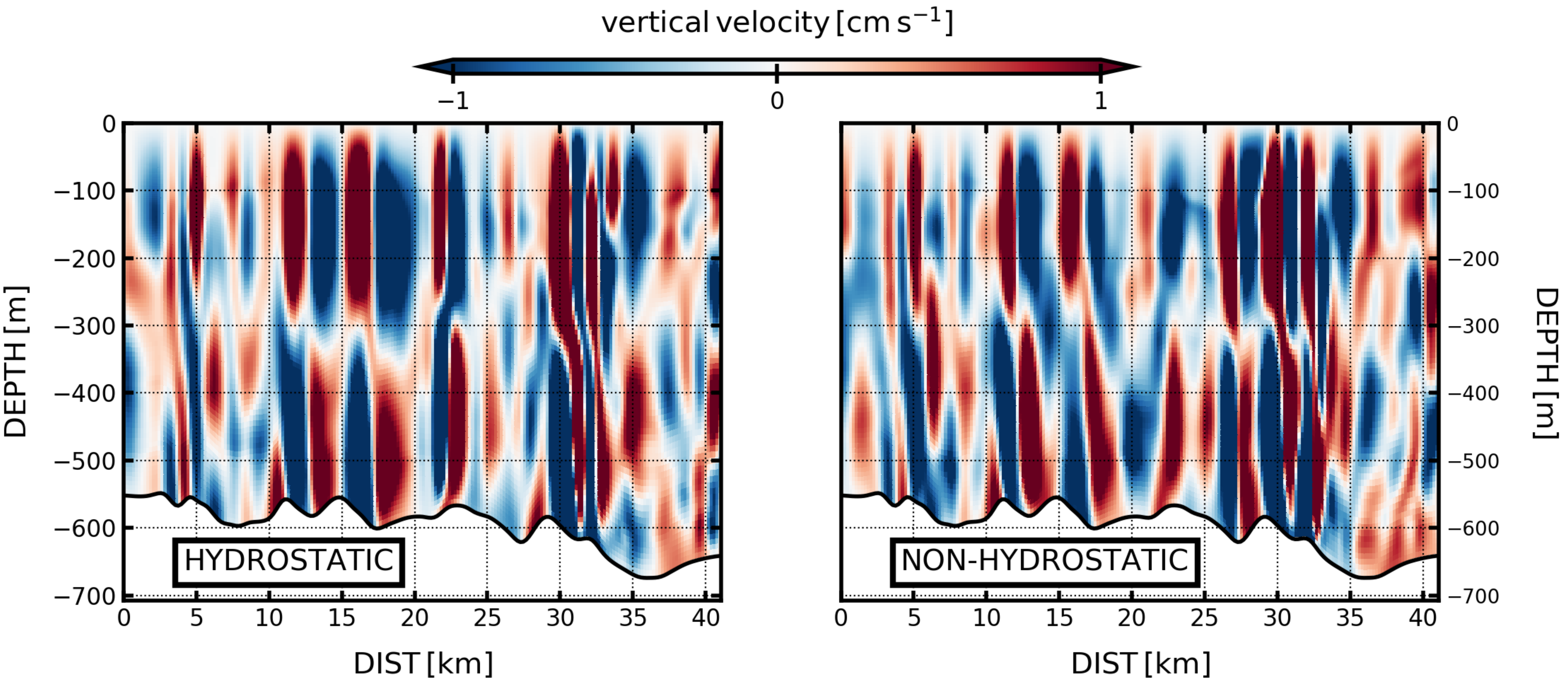
Hydrostatic Code

Non-Hydrostatic Code



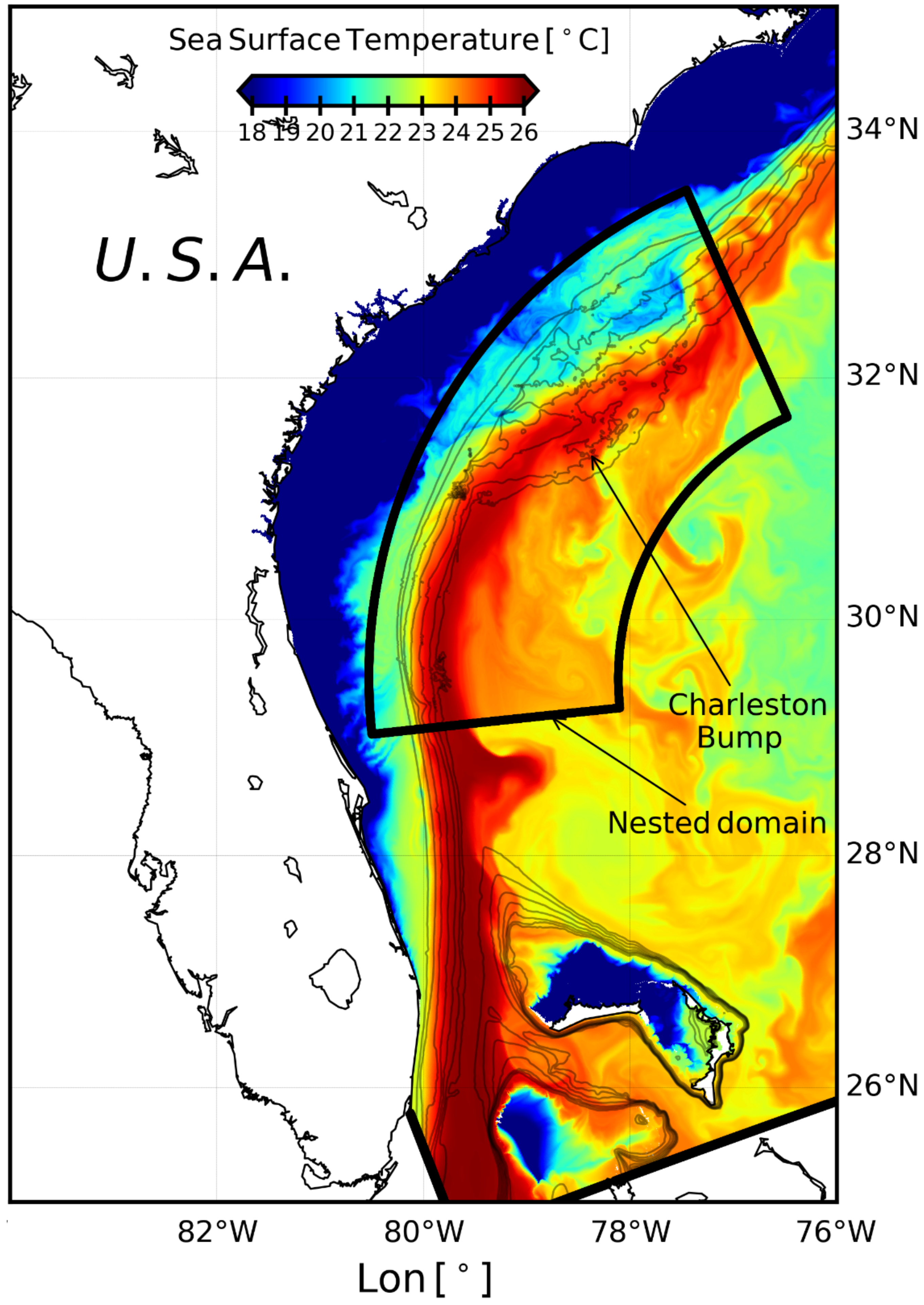
NH - H

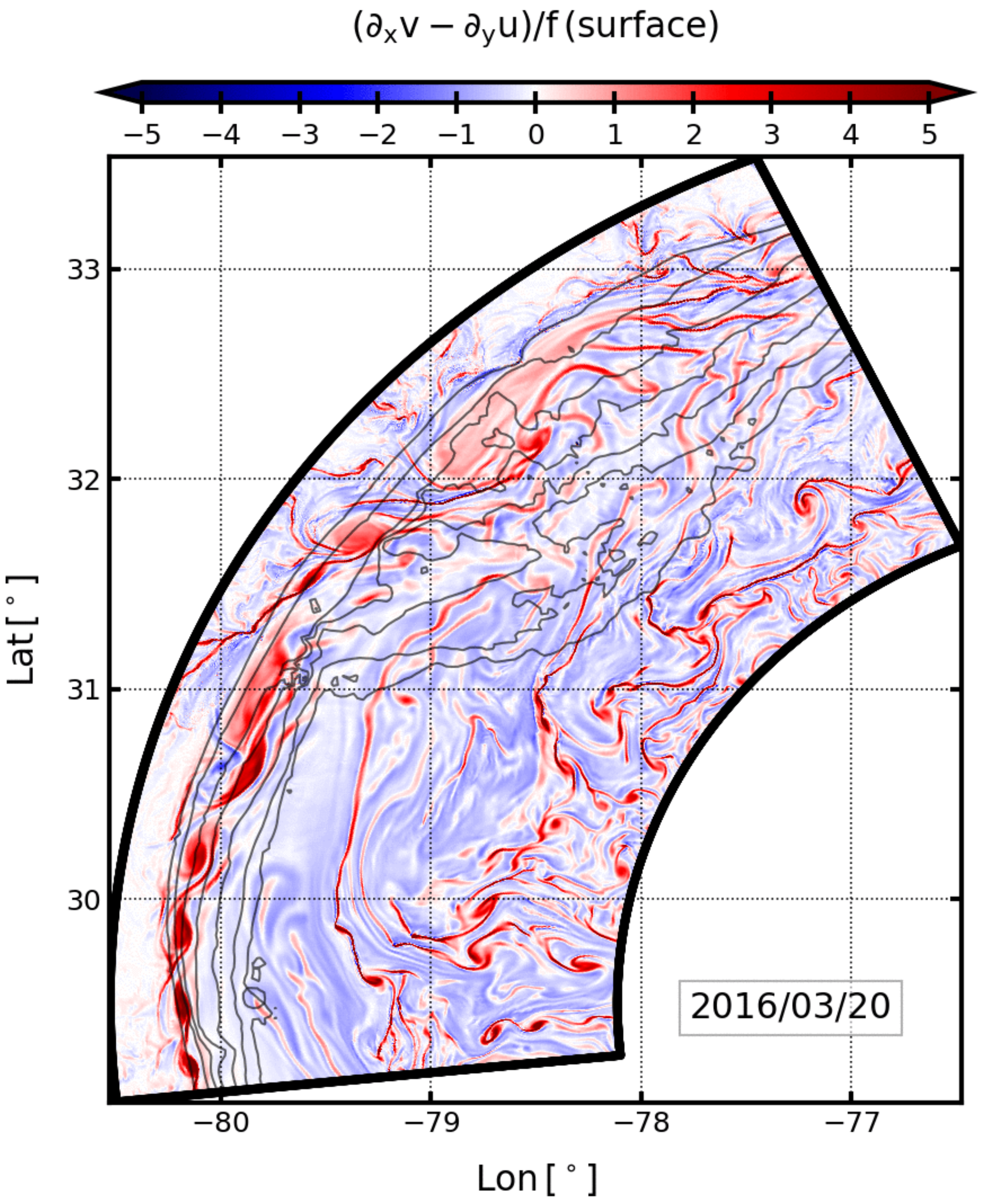
Some extras: Differences with the non-hydrostatic code?



Simulation of the Gulf Stream

- We performed a ROMS/CROCO nest **dx = 200 m, 128 lev.**
- Climatological forcings (monthly winds, no tides)





Impact for biology and fisheries

- The frontal eddies have strong implications for the biological production in the South Atlantic Bight. The upwelling pumps nutrient-rich bottom waters toward the surface, resulting in high levels of ocean productivity.

- The Bump provides a unique habitat for pelagic and demersal fishes, nursery habitats for early life history stages, and a “stepping stone” in the migratory route of several highly migratory pelagic fishes.