Dynamics of Gulf Stream Separation from the Coast and its Pathway to the East

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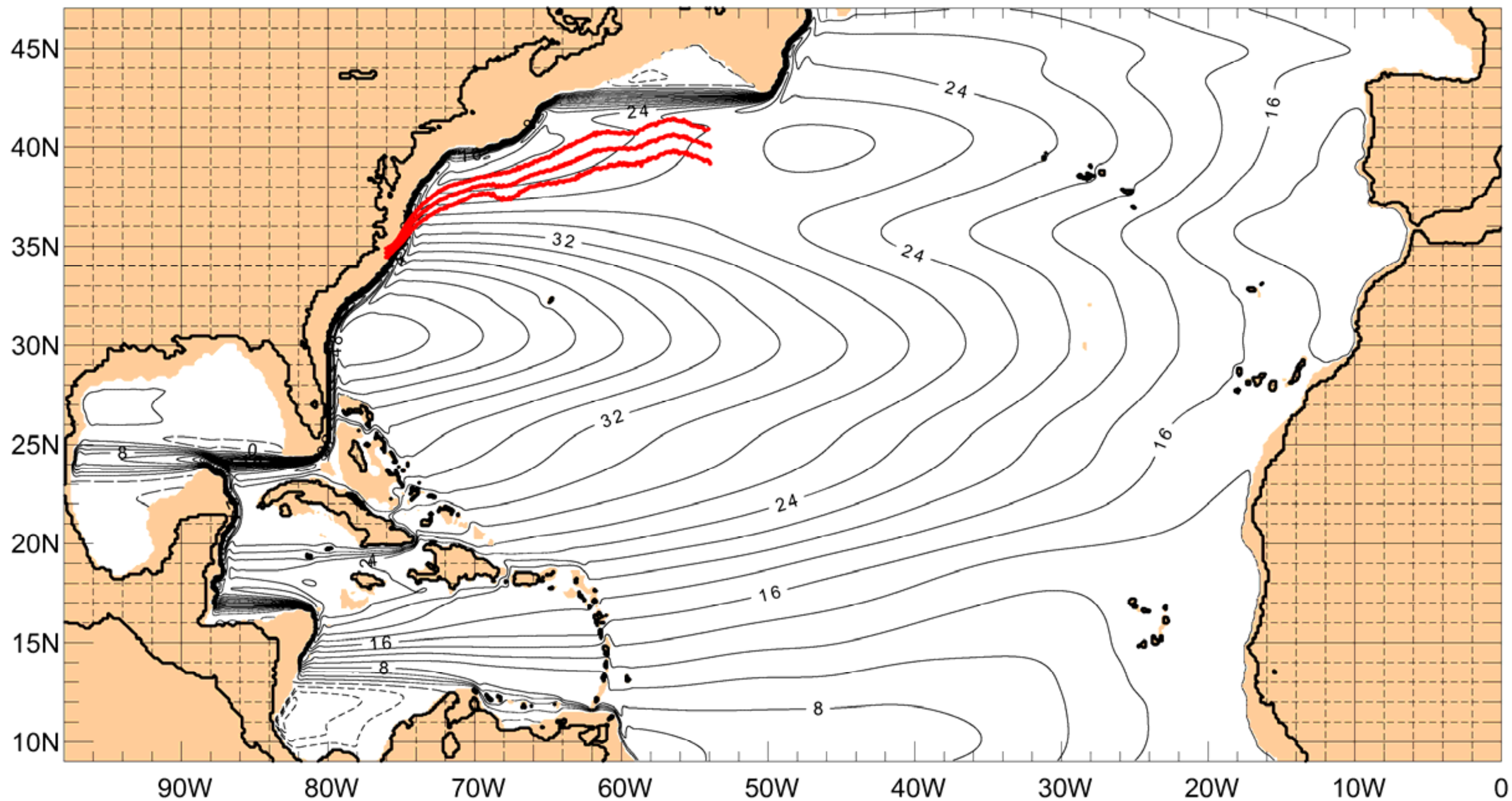
Mass Transport Streamfunction from a 1/16° 1.5 layer linear simulation forced by the smoothed Hellerman-Rosenstein wind stess climatology plus the northward upper ocean flow of the meridional overturning circulation

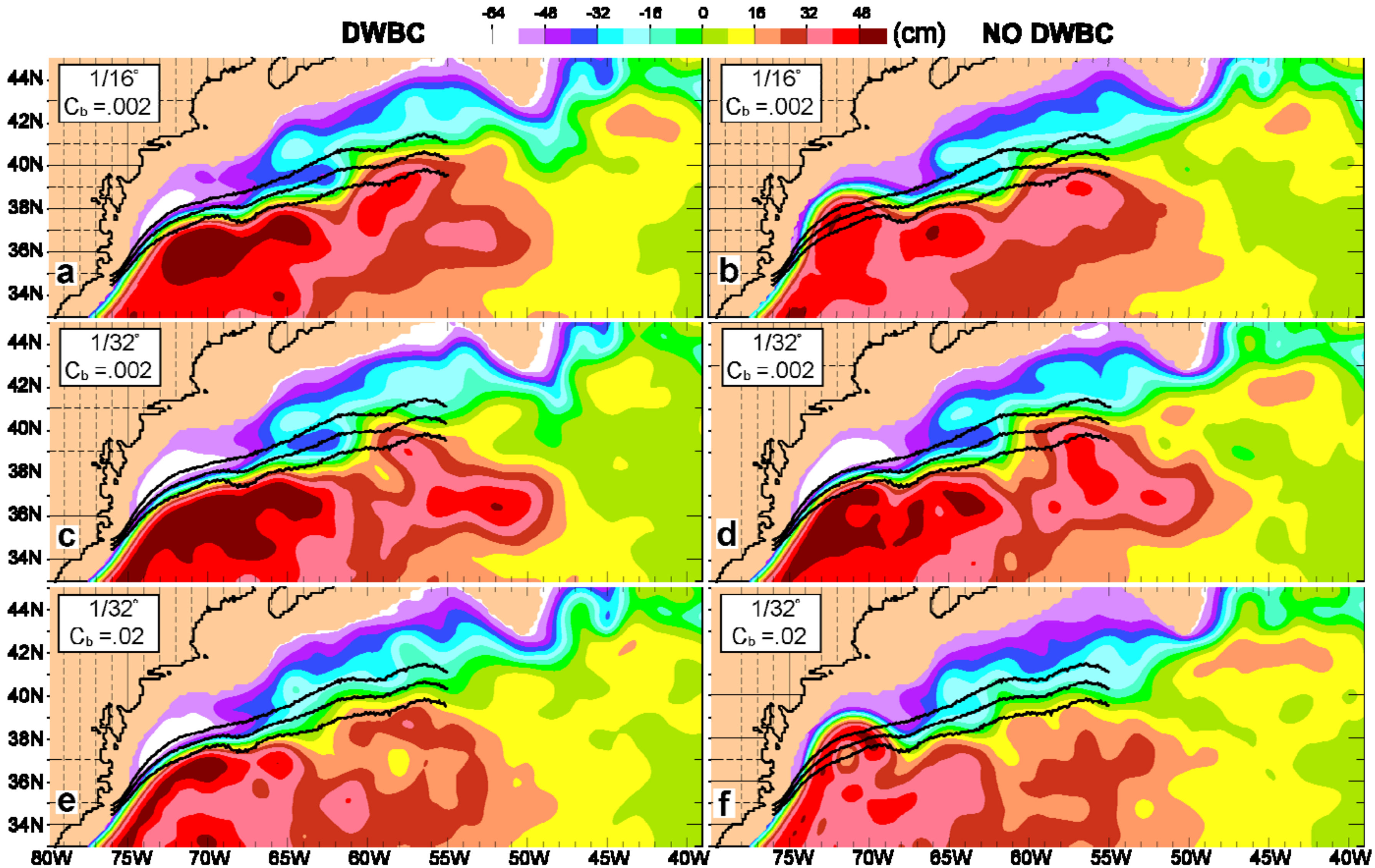


Sverdrup (1947) interior flow with Munk (1950) western boundary layers

Observed mean IR north wall pathway (1982-1996) +/- 1 std. dev. by Cornillon and Sirkes (from Hurlburt and Hogan, 2008, DAO)

Model domain used for 5-layer nonlinear hydrodynamic simulations by the NRL Layered Ocean Model (NLOM) in Hurlburt and Hogan (2000, DAO; 2008, DAO)

Gulf Stream Separation from the Coast
Roles of the DWBC and the Eddy-Driven Abyssal Circulation



From Hurlburt and Hogan (2008, DAO)

Mean sea surface height forced by Hellerman and Rosenstein (1983) wind stress and meridional overturning northward upper ocean flow. Observed mean IR north wall pathway (1982-1996) by Cornillon and Sirkes

Abyssal Current Steering of Upper Ocean Current Pathways

In a two-layer model, the continuity equation for layer 1 is

$$\frac{\partial h_1}{\partial t} + h_1 \nabla \cdot \vec{v}_1 + \vec{v}_1 \cdot \nabla h_1 = 0 \qquad (1)$$

The advective term in (1) can be related to the layer 2 velocity by

$$\vec{v}_{1g} \cdot \nabla h_1 = \vec{v}_{2g} \cdot \nabla h_1 \qquad (2)$$

$$\hat{k} \times f\left(\vec{v}_{1g} - \vec{v}_{2g}\right) = -g' \nabla h_1 \qquad (3)$$

Since $\quad \left|\vec{v}_1\right| >> \left|\vec{v}_2\right| \qquad (4)$

∇h_1 is a good measure of $\vec{v}_1$.

From this, we see that abyssal currents affect the advection of upper layer thickness gradients and therefore the pathways of upper layer currents.

(Hurlburt and Thompson, 1980, JPO; Hurlburt et al., 1996, JGR-O; 2008, DAO)

Application of the 2-layer Theory for Abyssal Current Advection of Upper Ocean Current Pathways to Models with Higher Vertical Resolution

Applies when all of the following are satisfied:

a) The flow is nearly geostrophically balanced

b) The barotropic and first baroclinic modes are dominant

c) The topography does not intrude significantly into the stratified ocean

The interpretation in terms of surface currents applies when $\left|\vec{\mathbf{V}}_{\text{near sfc}}\right| \gg \left|\vec{\mathbf{V}}_{\text{abyssal}}\right|$

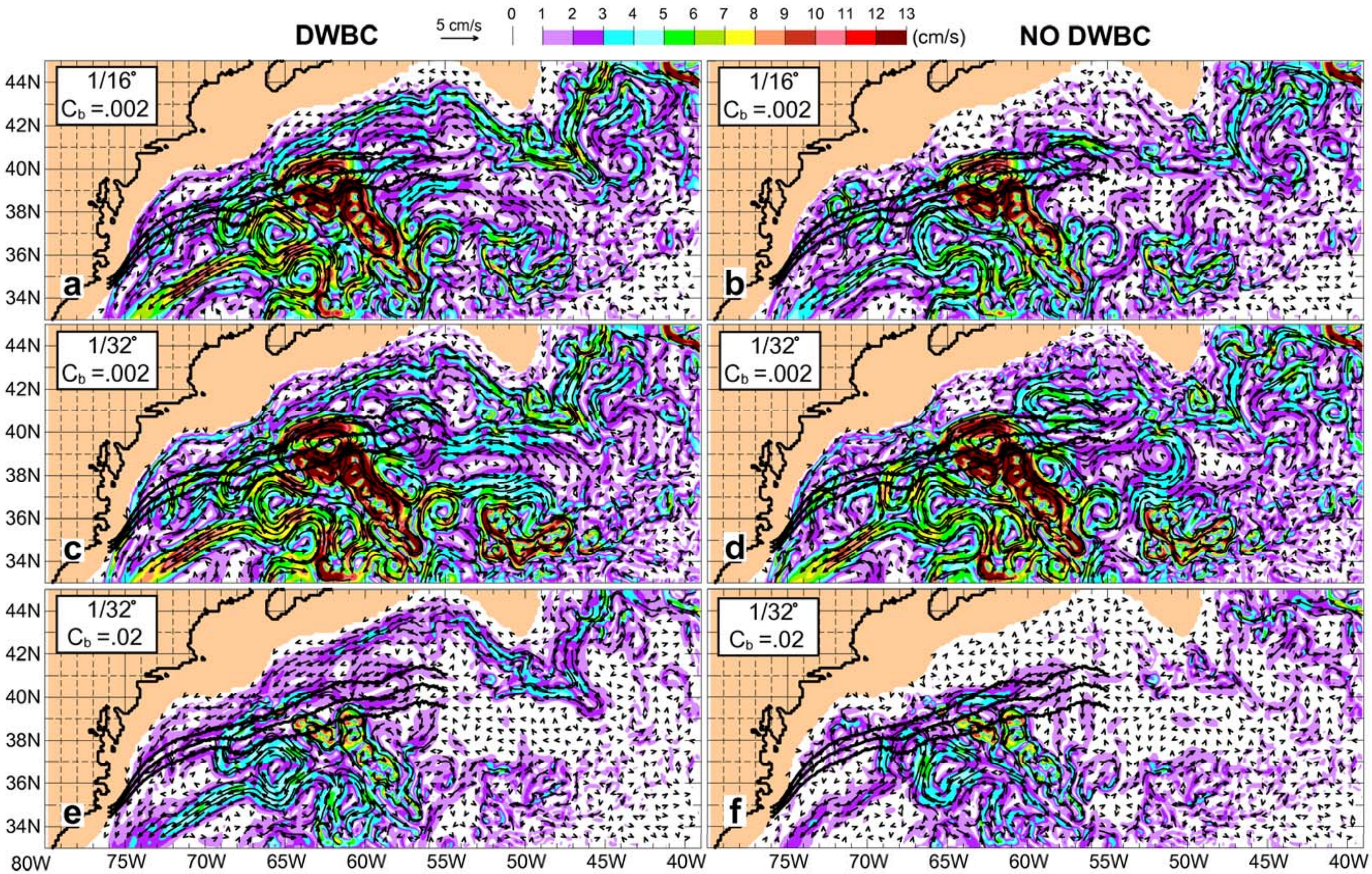
Notes:

1) The theory does not apply at low latitudes because of a) and b)

2) Abyssal current advection of upper ocean current pathways is strengthened when the currents intersect at large angles, but often the end result of this advection is near barotropy

Hurlburt et al. (2008, DAO)

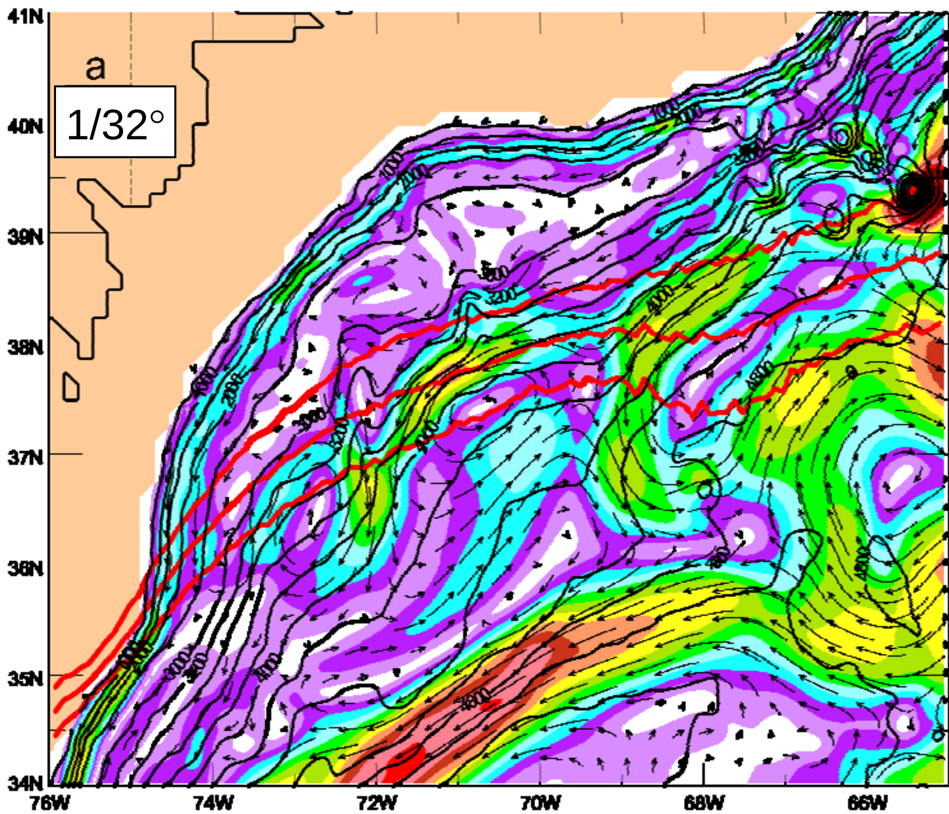
Simulated mean abyssal currents in the Gulf Stream region

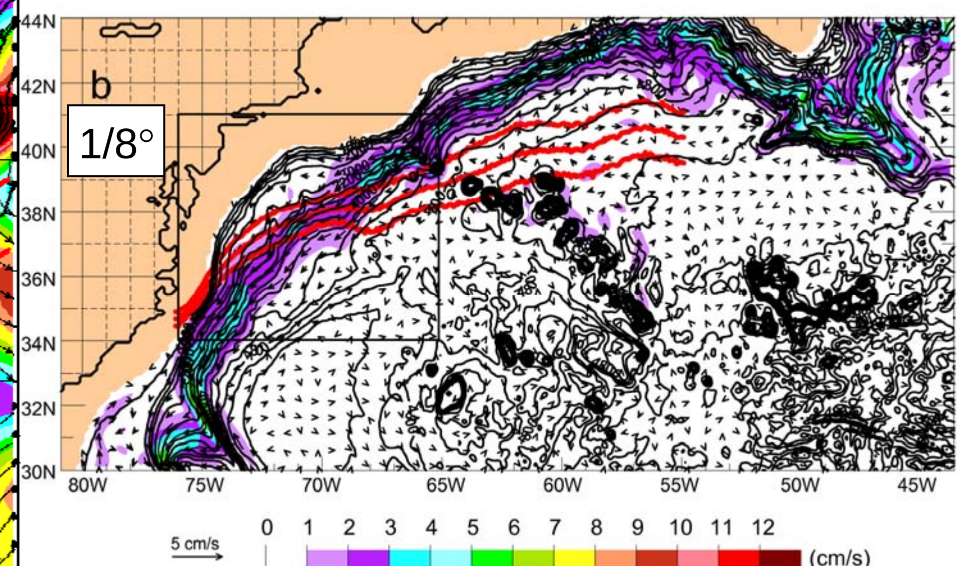


Model layer 5 with the Cornillon-Sirkes mean Gulf Stream IR northwall frontal pathway overlaid (—). DWBC is most easily seen paralleling the northern boundary north of 41°N, 65°W-51°W (left panels vs right panels). From Hurlburt and Hogan (2008, DAO)

Mean abyssal currents from 1/32° eddy-resolving and 1/8° eddy-permitting simulations in the Gulf Stream region

Zoom of 1/32° simulation with
CB=.002 and a DWBC



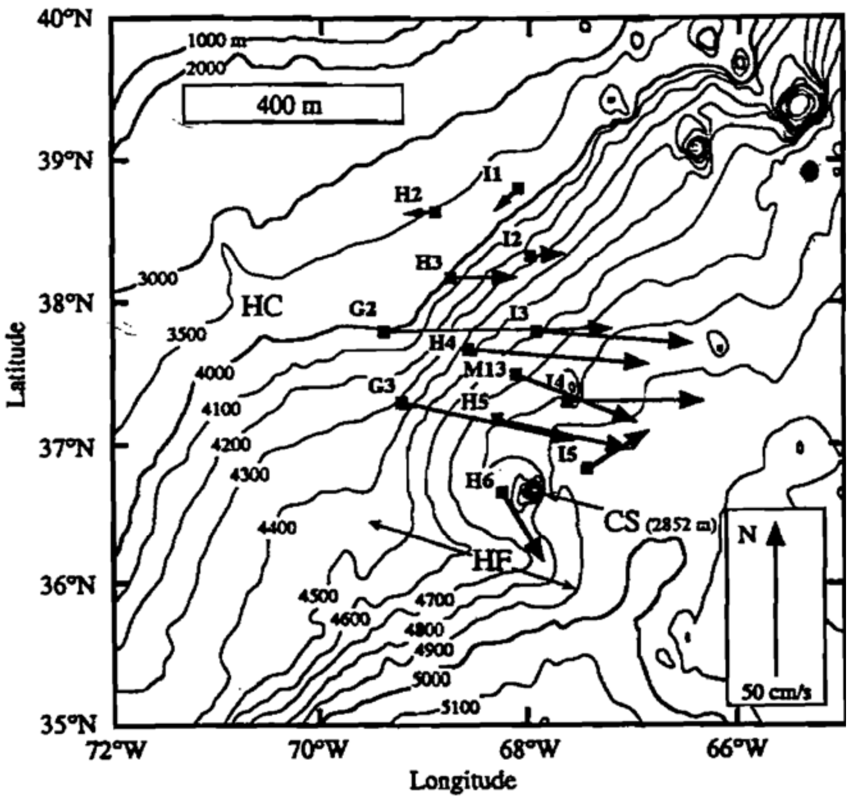


Box outlines zoom region used in left panel
Abyssal layer = model layer 5

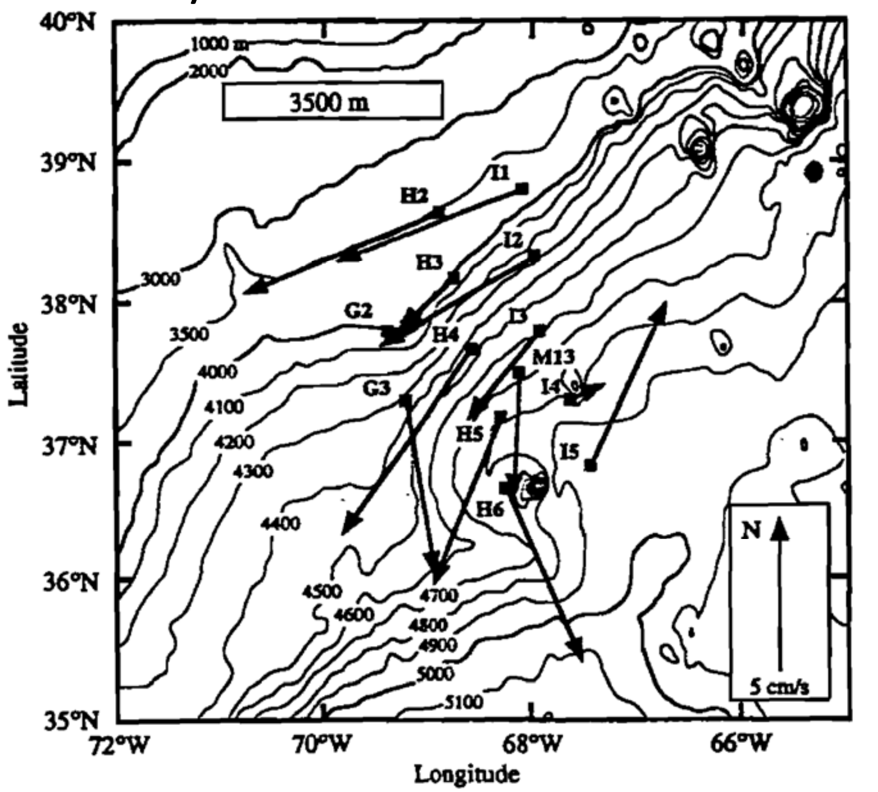
Overlaid on full amplitude uncompressed depth contours
Cornillon-Sirkes mean Gulf Stream IR northwall frontal pathway (—)
From Hurlburt and Hogan (2008, DAO)

26-month mean currents observed by a current meter array in the Gulf Stream region near 68°W

Gulf Stream

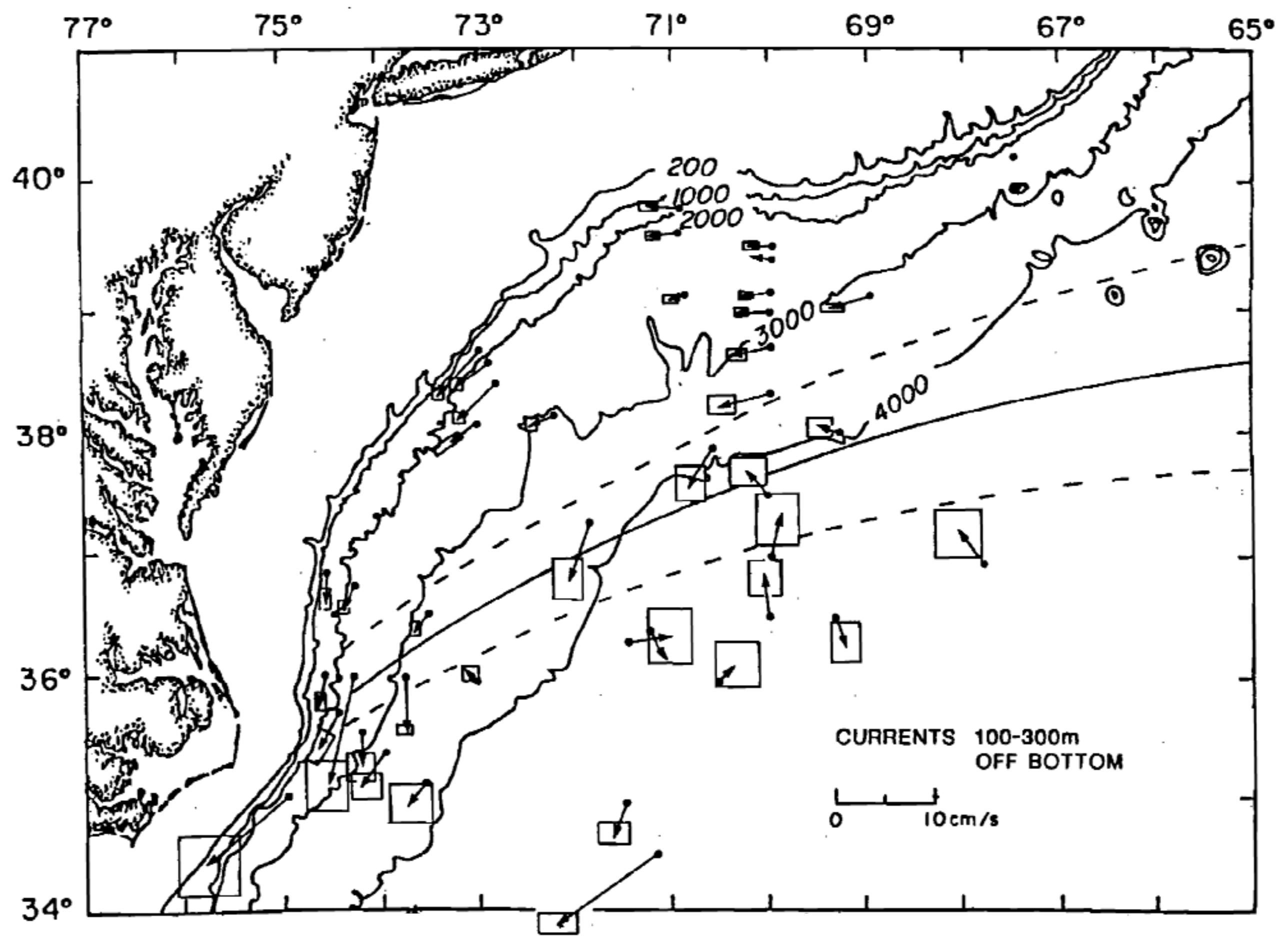


Abyssal currents



From Johns et al. (1995, JGR-O)

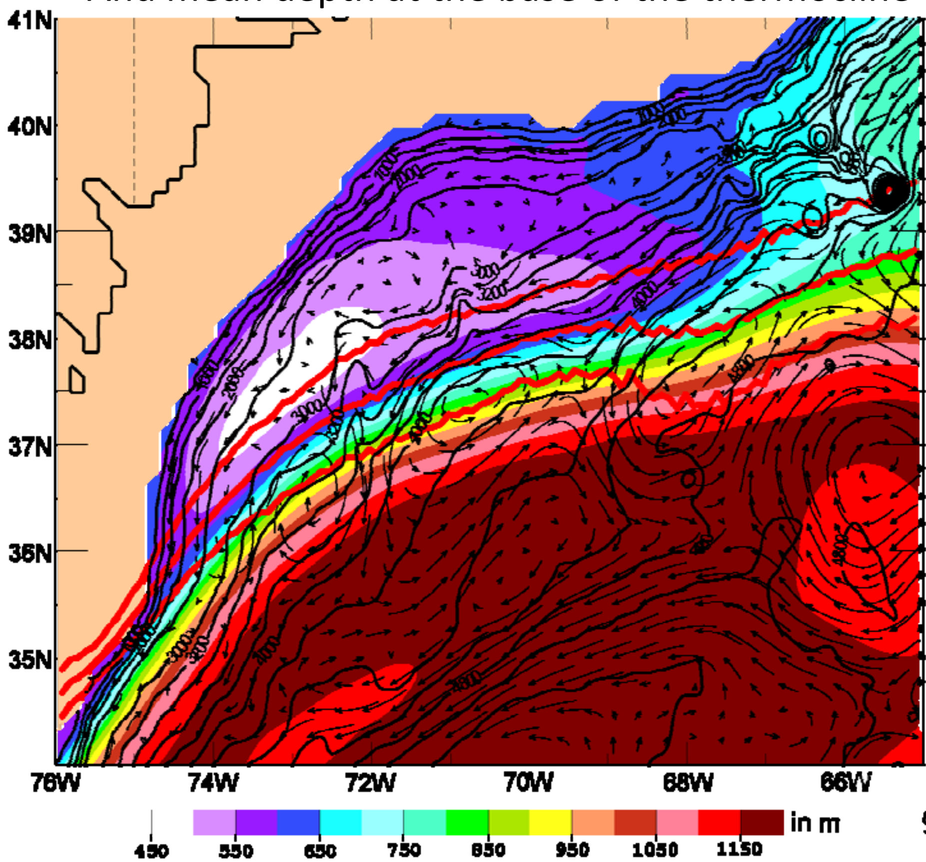
Mean current meter velocities 100-300 m off the bottom from historical measurements



The measurement record lengths vary from 4 mo. to 2 yrs, and the box associated with each vector gives the uncertainty of the mean, typically 1-2 cm/s.
From Pickart and Watts (1990, JMR).

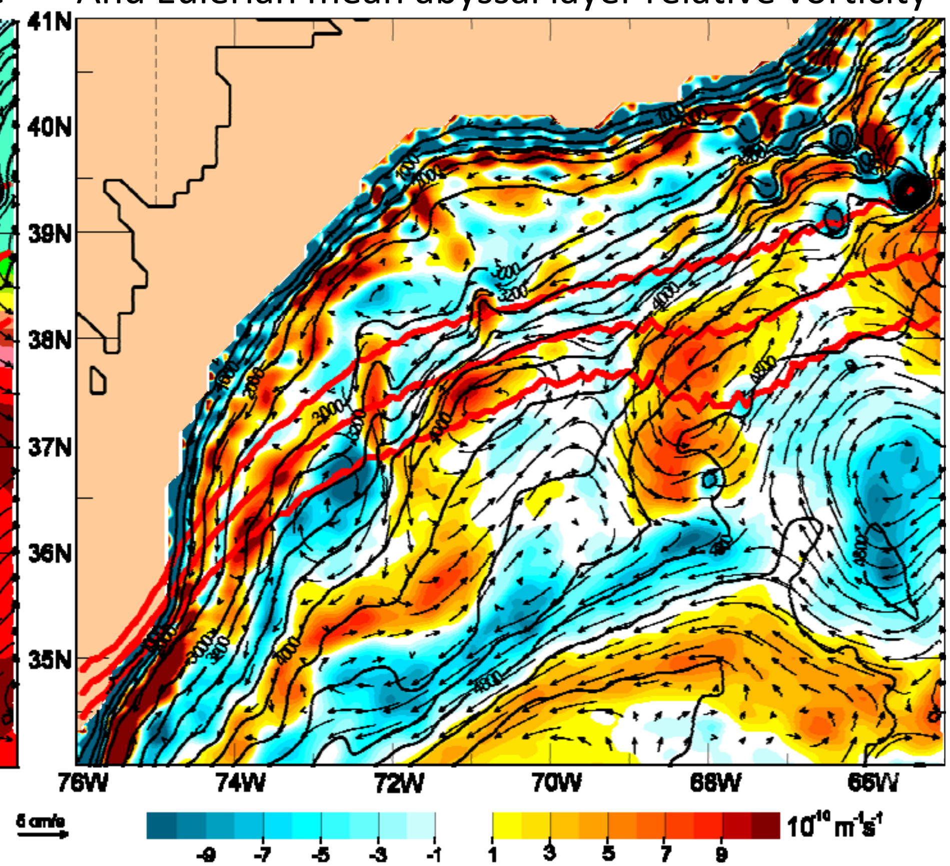
Mean abyssal currents (arrows) from 1/32° simulation with CB=.002 and a DWBC overlaid on full amplitude, uncompressed topographic contours

And mean depth at the base of the thermocline



Mean depth of the model interface between layers 4 and 5

And Eulerian mean abyssal layer relative vorticity

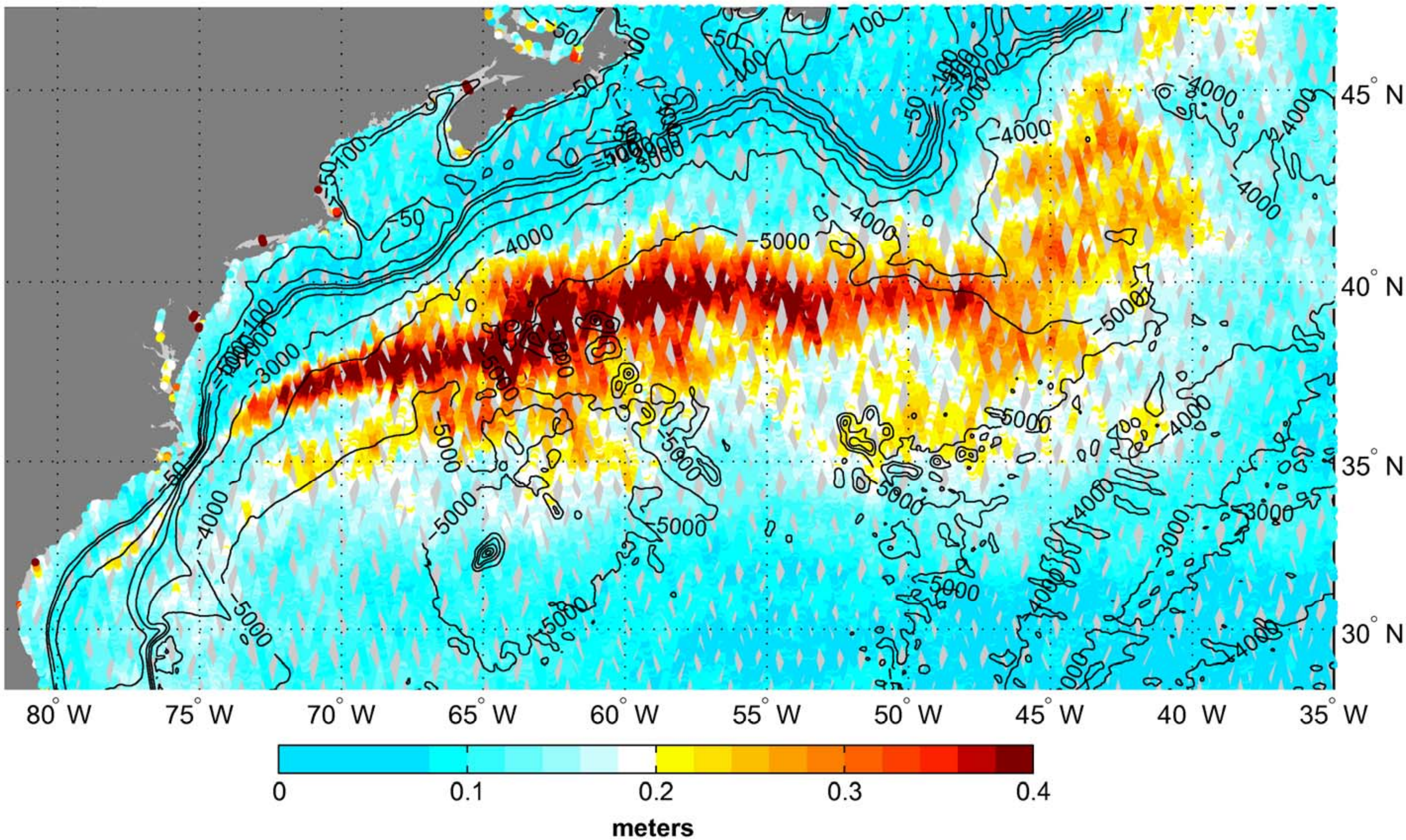


Abyssal layer = model layer 5

Cornillon and Sirkes mean Gulf Stream IR northwall frontal pathway (—)

From Hurlburt and Hogan (2008; DAO)

Quasi-contemporaneous along-track SSH variability from satellite altimeter data in 4 orbits in the Gulf Stream region



Overlaid on topographic contours
From Hurlburt and Hogan (2008, DAO), provided by Gregg Jacobs (NRL)

Constant Absolute Vorticity (CAV) trajectories in a 1.5 layer reduced gravity model

Assumptions

- Frictionless steady free jet
- Streamline at the core of the current following contours of constant SSH and layer thickness
- The preceding requires geostrophic balance so that conservation of potential vorticity becomes conservation of absolute vorticity along a streamline at the core of the current

Calculated from

$$\cos\alpha = \cos\alpha_0 + \frac{1}{2} y^2/r^2 - \frac{y}{\gamma_0}$$

- An integrated form of the differential equation that assumes, v_c, at the core of the current = constant.

- $r = (v_c/\beta)^{\frac{1}{2}}$, γ = trajectory radius of curvature

- α = current angle wrt positive x-axis on a β-plane

- y = distance of the trajectory from the x-axis

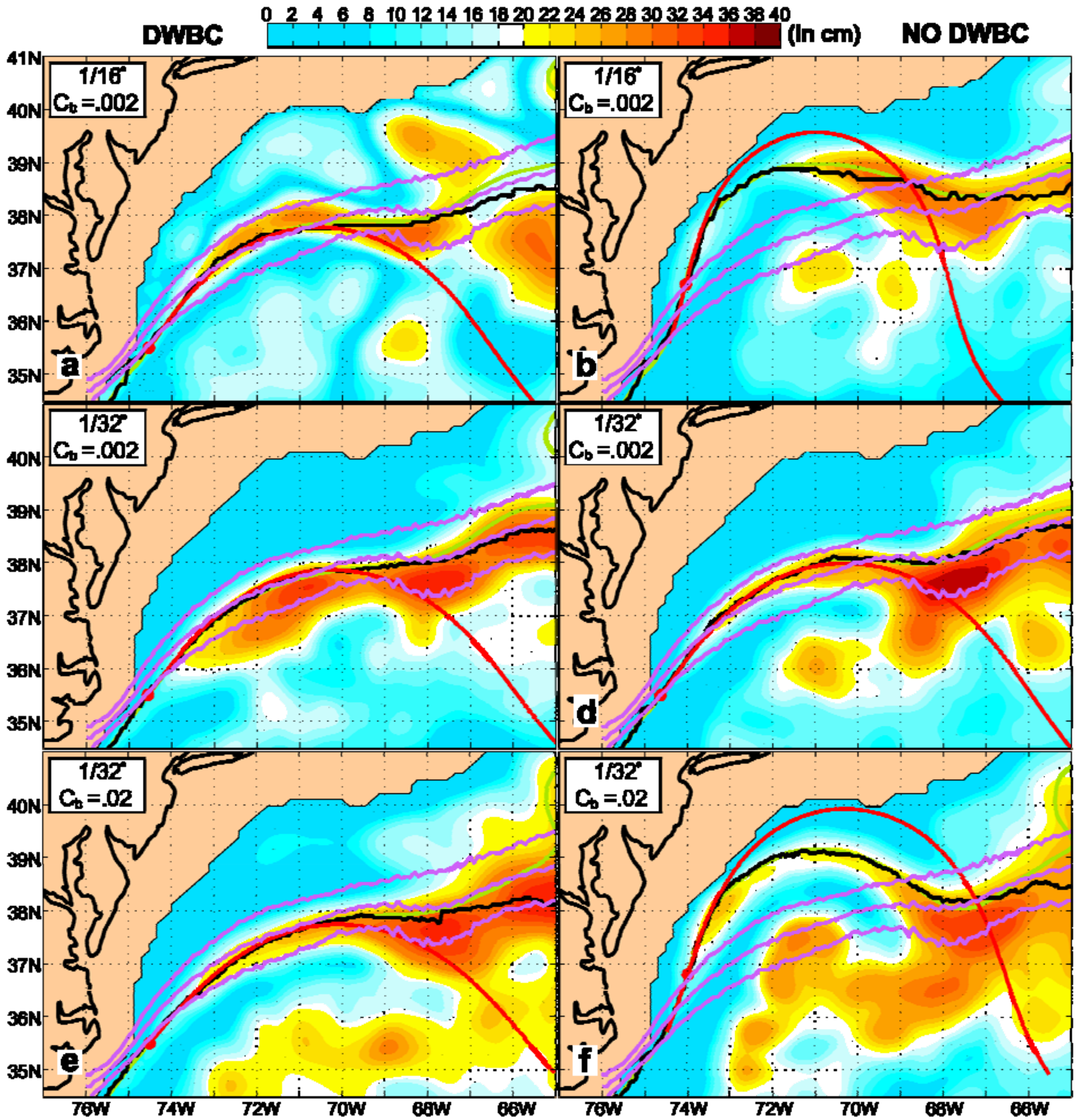
- Subscript$_0$ = values at origin (taken to be an inflection point where $\gamma \rightarrow \infty$)

Amplitude of the trajectory wrt the inflection points

$$b = 2r \sin\frac{1}{2}\alpha_0$$

Original CAV trajectory reference: C.-G. Rossby (1940, QJRMS)

CAV trajectories (—) vs. model mean Gulf Stream velocity axis (—) and mean SSH contour nearest the axis (—)



Overlaid on model mean SSH variability and the Cornillon-Sirkes mean Gulf Stream IR northwall frontal pathway (—) From Hurlburt and Hogan (2008, DAO)

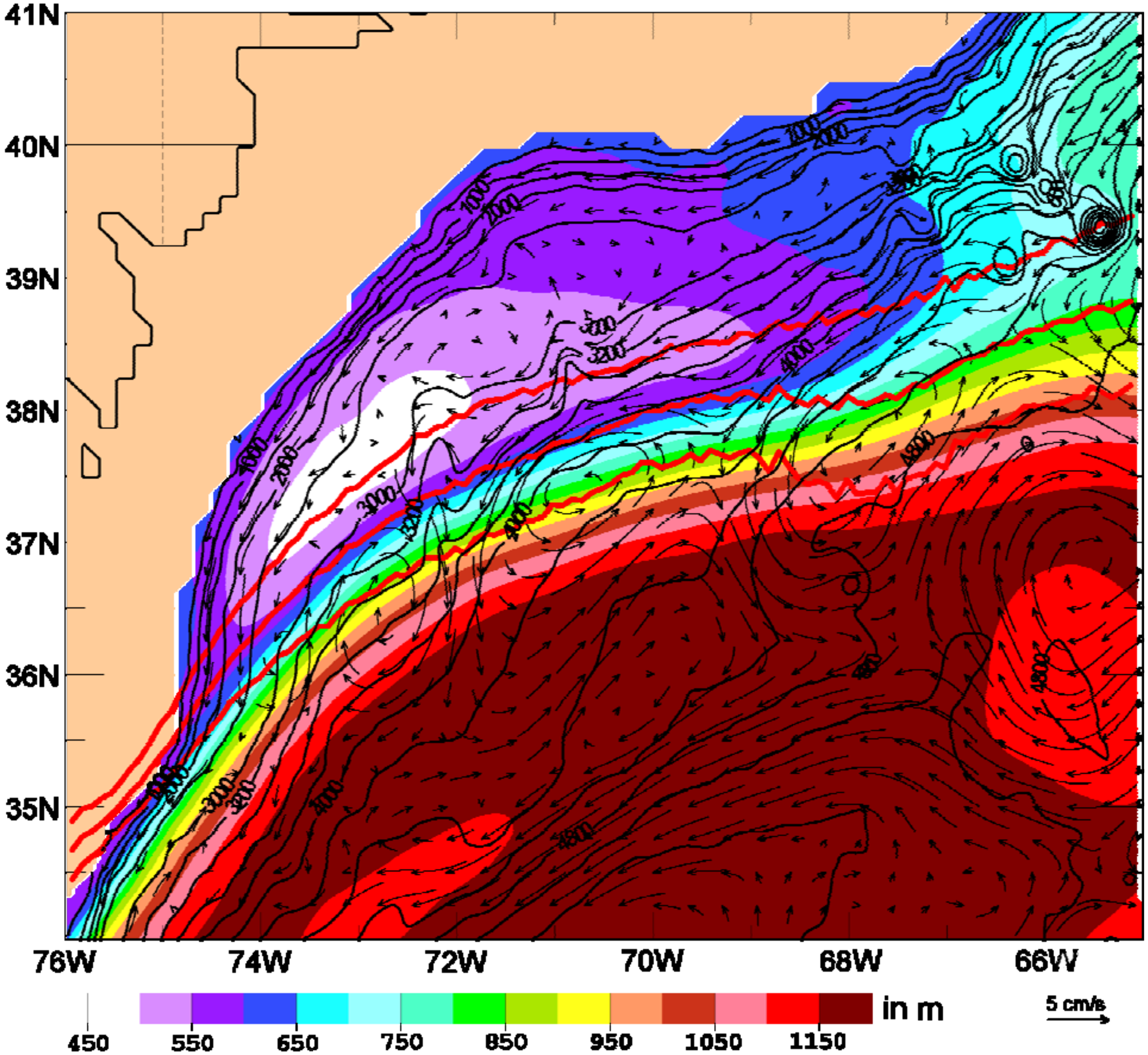
Gulf Stream Dynamics Summary and Conclusions (p. 1)

Two-part dynamical explanation of Gulf Stream separation and its mean pathway to the east

1. An eddy-driven abyssal current, topography, and a Gulf Stream feedback mechanism constrain the latitude of the Gulf Stream at ~68½ºW.

- An eddy-driven abyssal current advects the Gulf Stream pathway southward
- To conserve potential vorticity, the abyssal current crosses to deeper depths while passing under the Gulf Stream (Hogg and Stommel, 1985)
- Due to the topographic configuration, the passage to deeper depths requires curvature to the east and generation of positive relative vorticity
- Once the abyssal current becomes parallel to the Gulf Stream, further southward advection of the Gulf Stream is halted
- The local latitude of the Gulf Stream is determined by the northernmost latitude where the abyssal current can become parallel to the Gulf Stream
- Thus, the resulting local Gulf Stream latitude is not very sensitive to the strength of the abyssal current once it is sufficient to perform the advective task
- Constraint of the Gulf Stream latitude near 68½ºW is not a sufficient explanation of the Gulf Stream pathway between the western boundary and 69ºW

Mean abyssal currents (arrows) from 1/32° simulation with CB=.002 and a DWBC overlaid on full amplitude, uncompressed topographic contours and mean depth of the base of the thermocline



Mean depth of the model interface between layers 4 and 5

Cornillon and Sirkes mean Gulf Stream IR northwall frontal pathway (—)

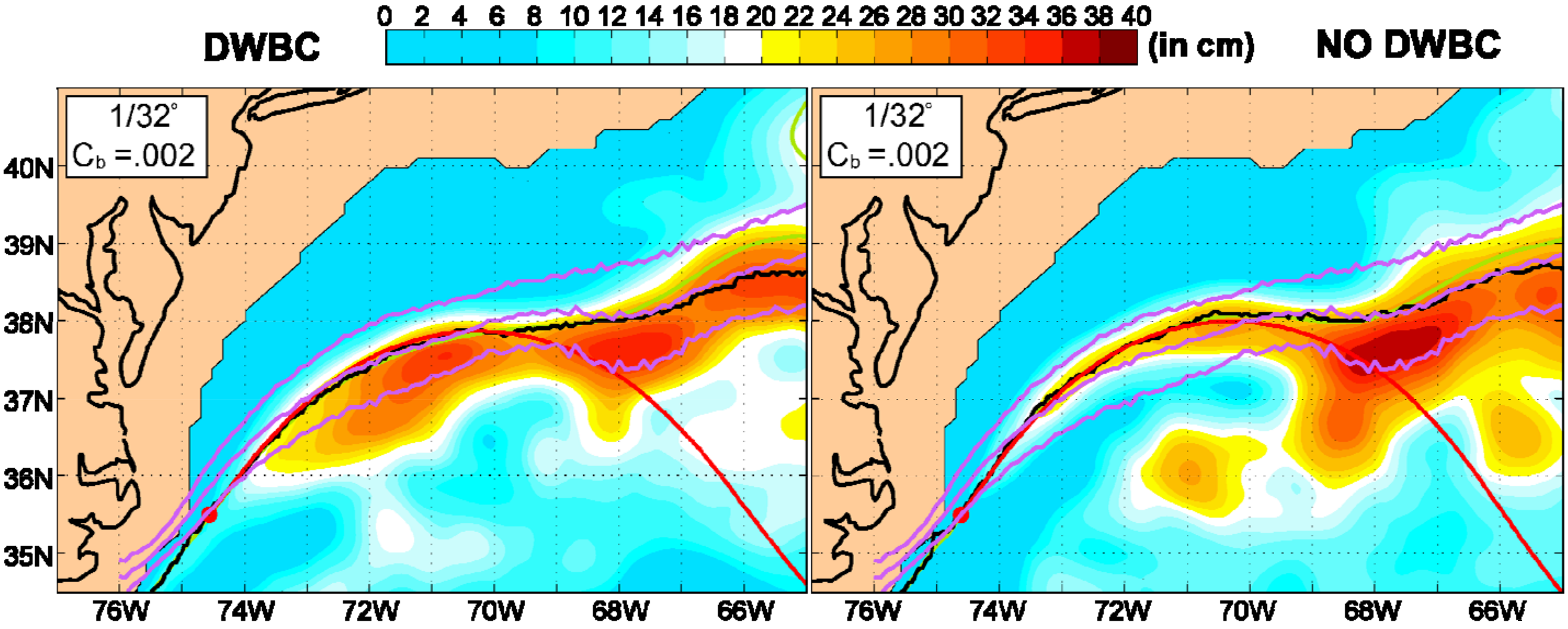
From Hurlburt and Hogan (2008; DAO)

Gulf Stream Dynamics Summary and Conclusions (p. 2)

Two-part dynamical explanation of Gulf Stream separation and its mean pathway to the east

2. The mean Gulf Stream pathway closely follows a CAV trajectory between its separation from the western boundary and ~70ºW.

- The CAV trajectory depends on
  - the angle (wrt latitude) of current separation as largely determined by the angle of the shelfbreak prior to separation
  - the speed at the core of the current
  - an inflection point located where current separation occurs



Gulf Stream Dynamics Summary and Conclusions (p. 3)

Part 1 and Part 2 in concert

- Neither Part 1 nor Part 2 of the explanation alone is sufficient
- Gulf Stream simulations with realistic speeds at the core of the current are not sufficiently inertial (a) to overcome the linear solution demand for an overshoot pathway and (b) to obtain realistic separation without assistance from the abyssal current near 68½ºW
- The eddy-driven abyssal circulation is necessary and sufficient to obtain the key abyssal current, which was not simulated without it
- The DWBC is neither necessary nor sufficient, but did augment the key abyssal current and did assist the eddy-driven abyssal circulation in effecting separation when the latter was not sufficiently strong by itself
- The impact of the DWBC on Gulf Stream separation was resolution dependent: required at 1/16º but not at 1/32º
- The dynamical explanation is robust. As long as the speed at the core of the current was consistent with observations and the key abyssal current was sufficiently strong, the simulated Gulf Stream separation and its pathway to the east were in close agreement with observations despite differences in model resolution, bottom friction, strength of the abyssal circulation, and presence or absence of a DWBC

The explanation is consistent with a wide range of observational evidence in the upper and abyssal ocean