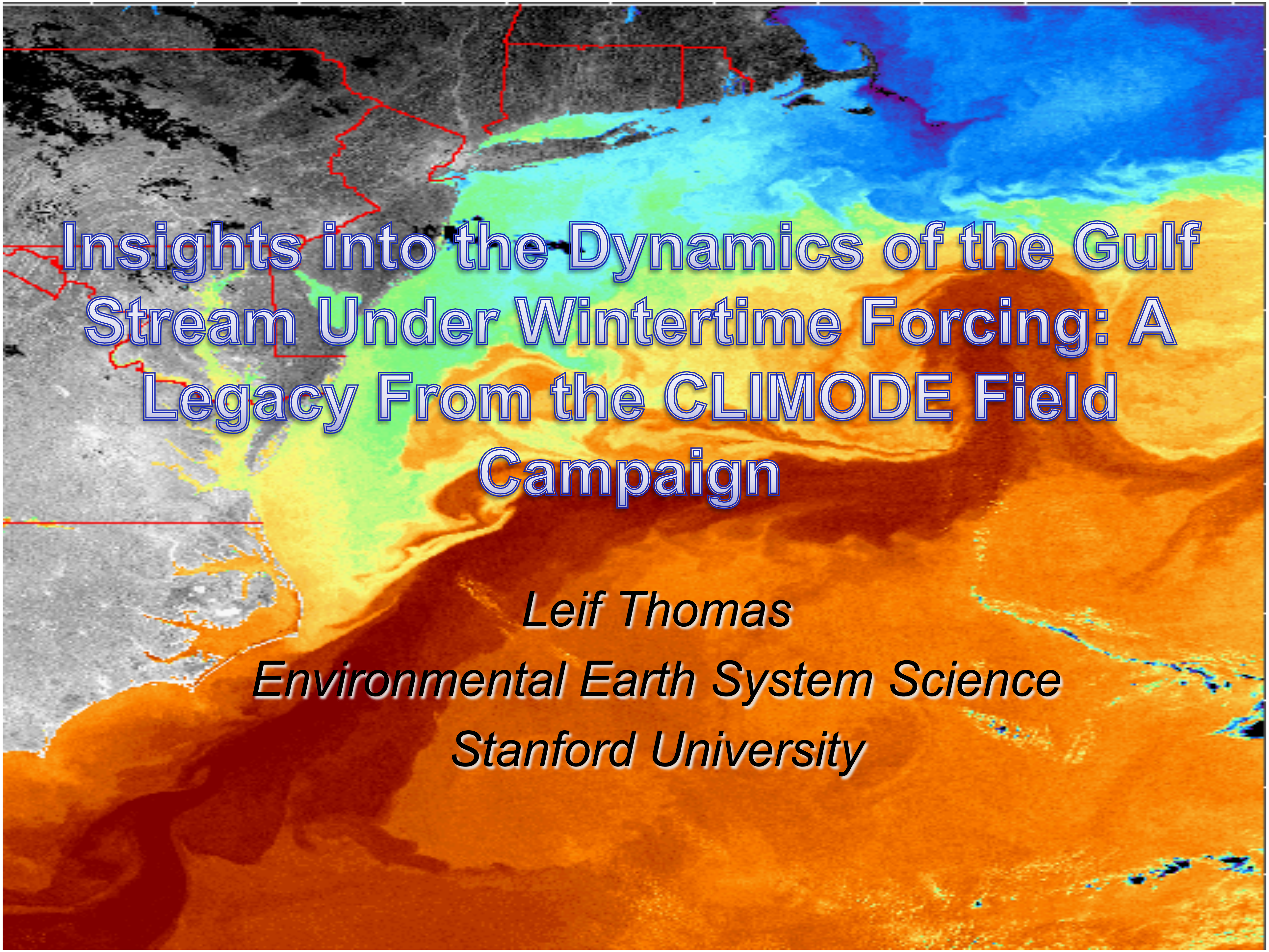

# Insights into the Dynamics of the Gulf Stream Under Wintertime Forcing: A Legacy From the CLIMODE Field Campaign

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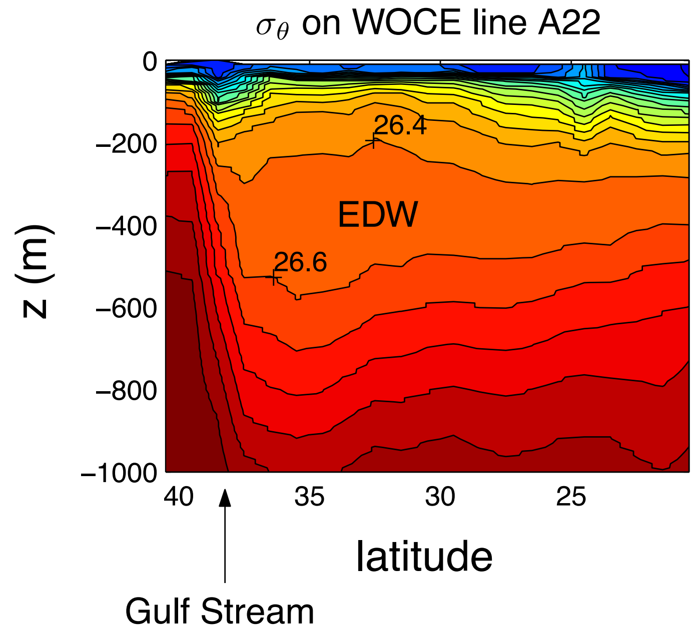
CLIvar MOde water Dynamics Experiment

*www.climode.org*

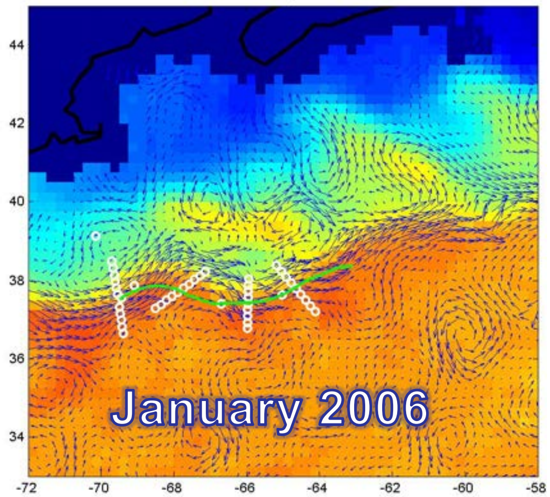


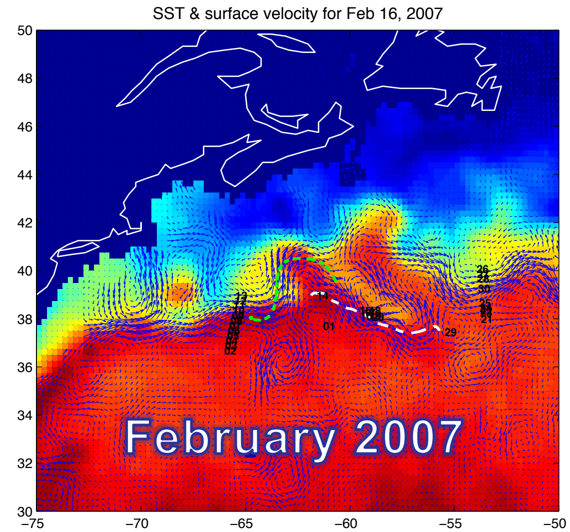

- CLIMODE was a process study (2005 - 2009) of the formation, subduction, & dispersal of Eighteen Degree Water (EDW).

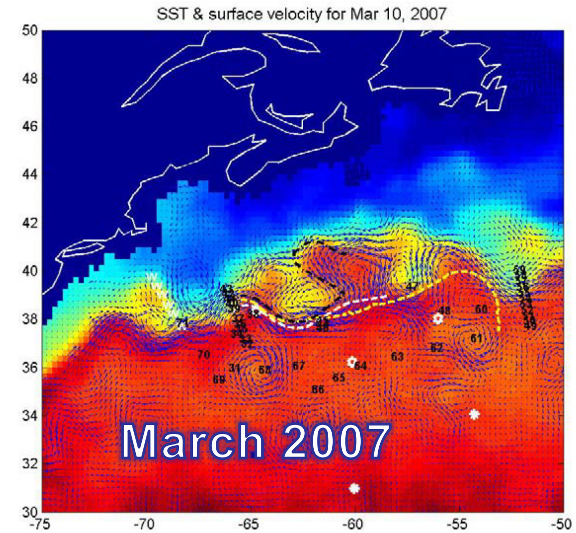
- The scientific goals of CLIMODE were focused in four areas:
  - *Air-sea interaction* (Kelly, Edson, Weller, Samelson, Skyllingstad, Bates)
  - *Eddies, mixing, and frontal dynamics* (Joyce, Gregg, Toole, Lumpkin)
  - *Subduction and circulation* (Fratantoni, Talley, Straneo)
  - *Modeling* (Marshall, Dewar, Ferrari/CPT-EMILIE)

# Wintertime frontal surveys

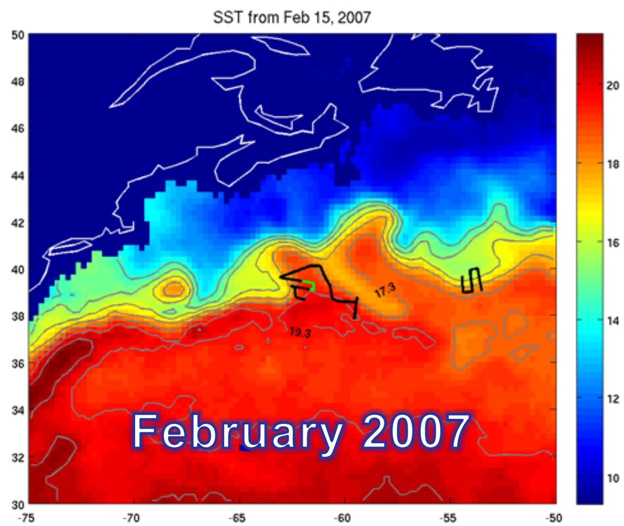
- CTD/ADCP surveys

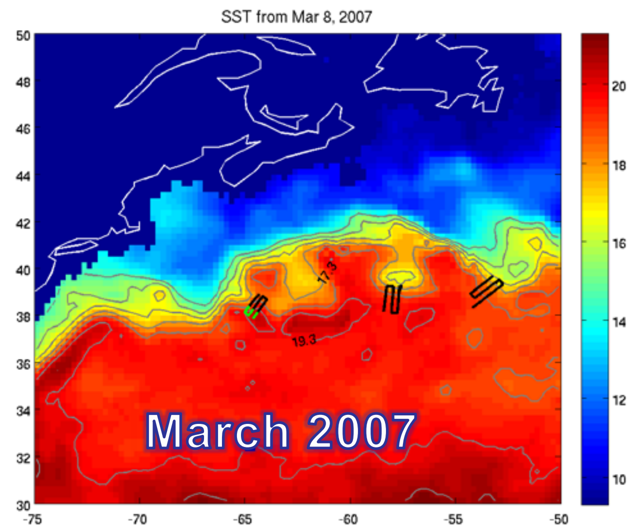


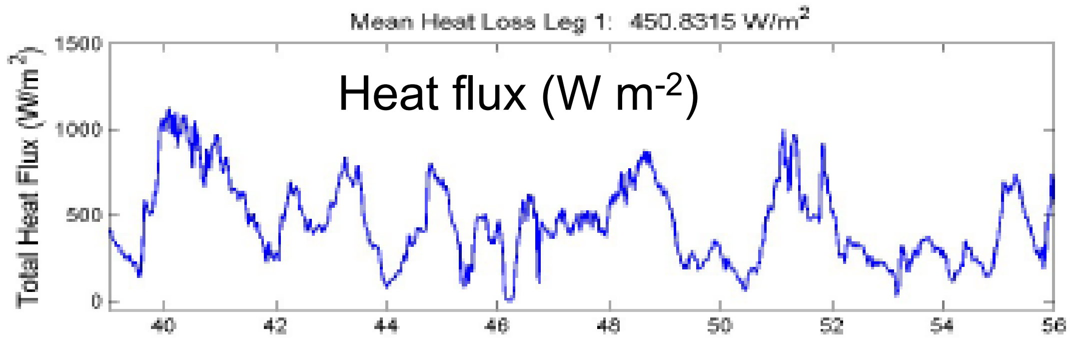

- SeaSoar/ADCP surveys



# Atmospheric forcing of the Gulf Stream during cold air outbreaks


Photo by A. Pluedemann (WHOI)



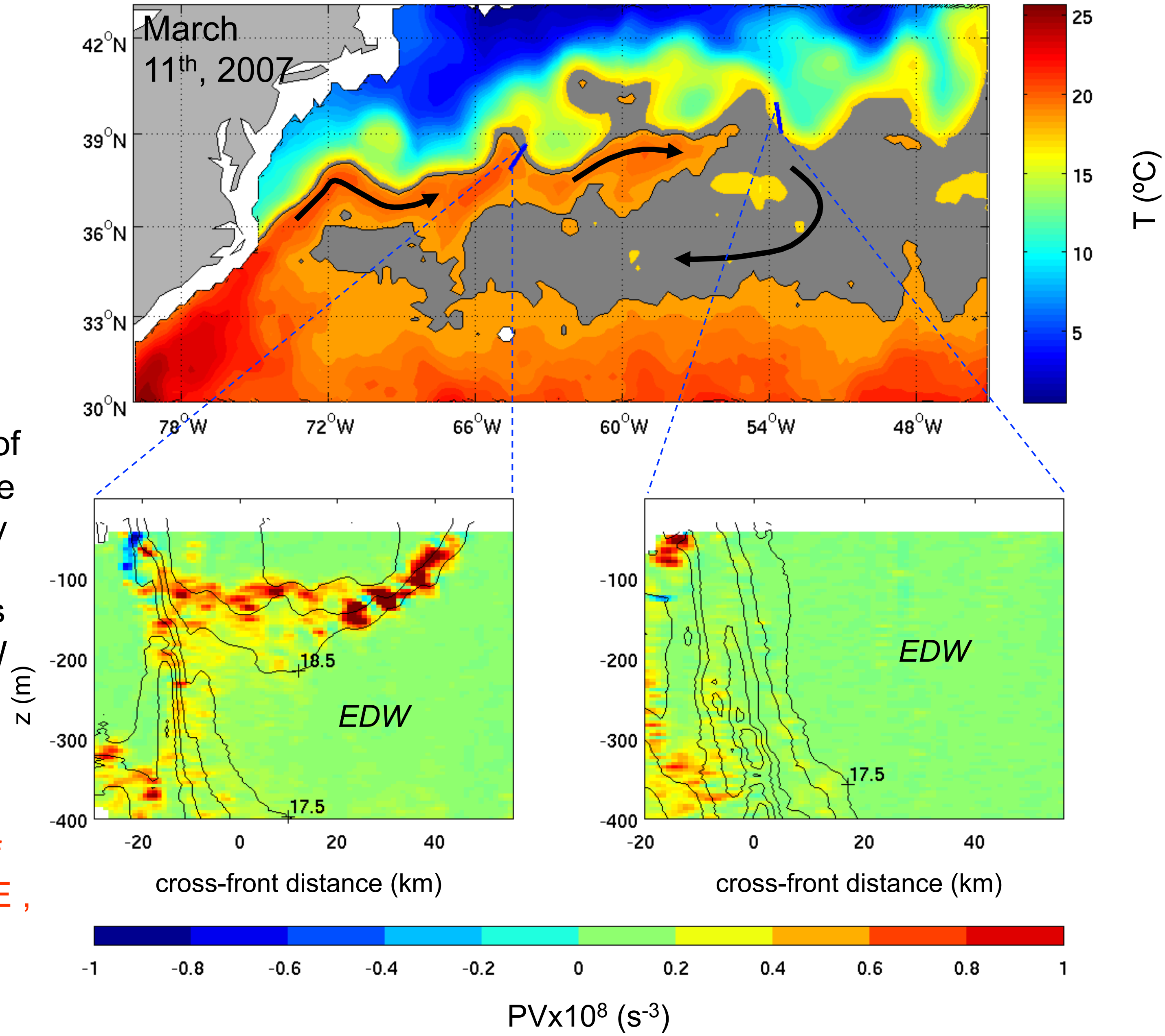

year day 2007

- The large air sea temperature and low humidity of the air resulted in heat fluxes of 1000 W $m^{-2}$.
- The front was also forced by strong winds with wind-stress values from 0.1-1 N $m^{-2}$.

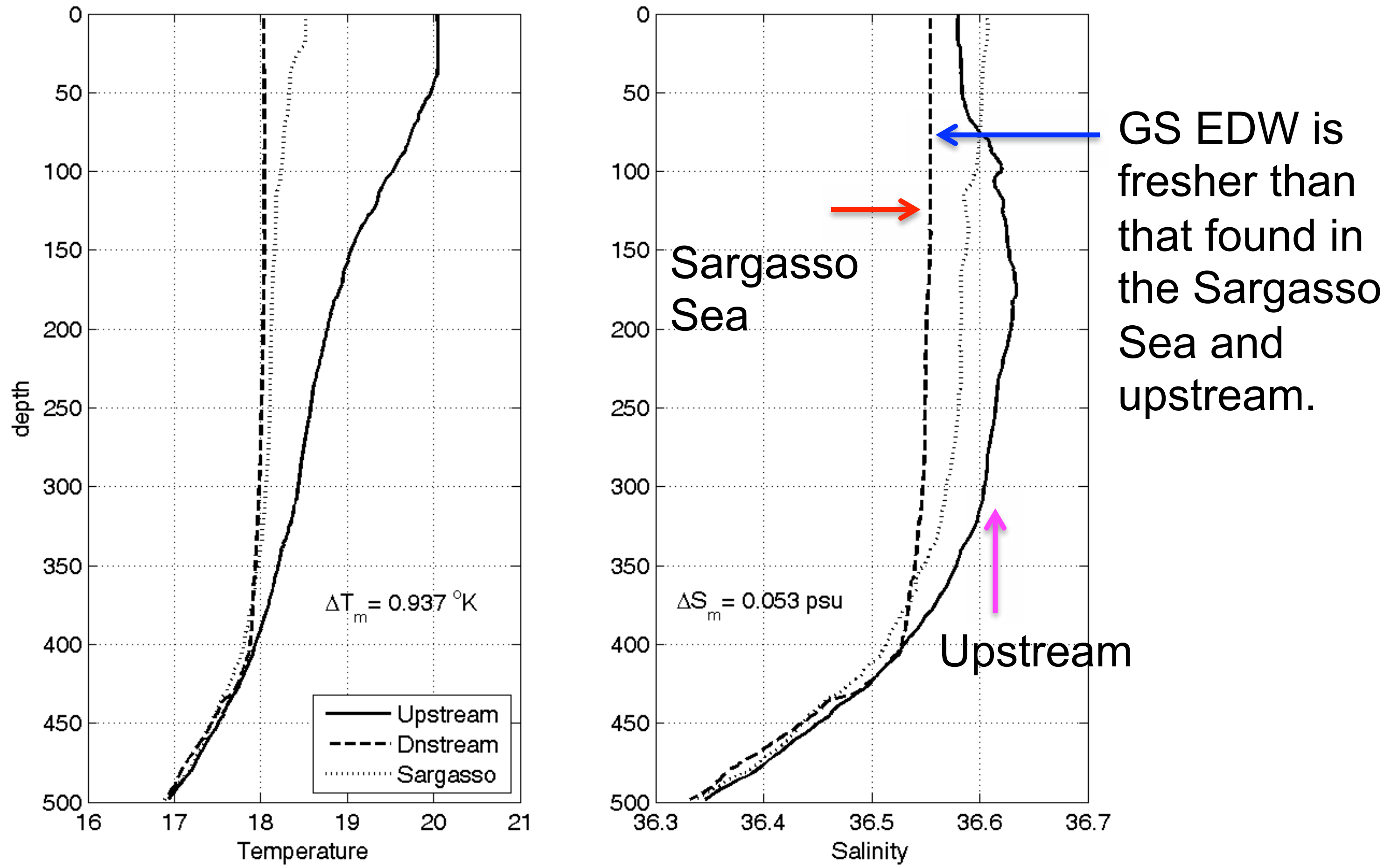
# Gulf Stream source of EDW

- The easternmost sections in the Gulf Stream were characterized by a weakly-stratified, recently-ventilated watermass with properties similar to EDW.
- A substantial portion of new EDW entering the Sargasso Sea is likely generated within the Gulf Stream and adds to the fraction of EDW formed locally.

Joyce, Thomas, Dewar, Girton, 2012. EDW formation within the Gulf Stream during CLIMODE , DSR II, accepted



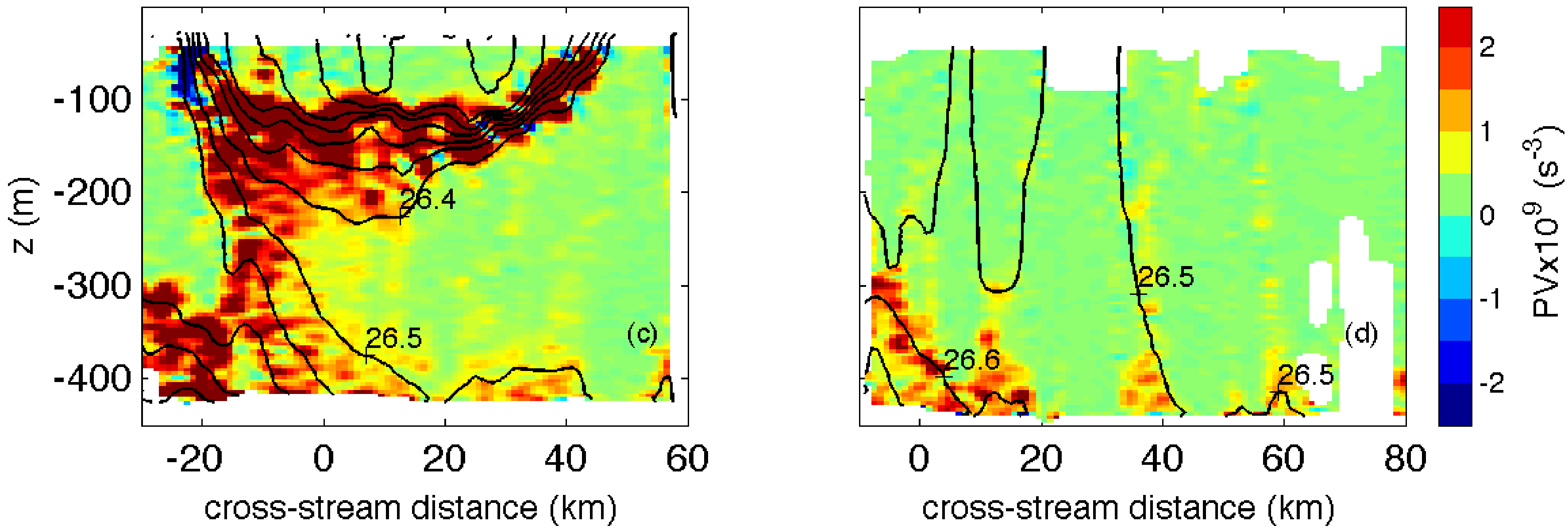
# T-S properties of EDW formed in the Gulf Stream




*Joyce et al DSR II (2012)*

- The Gulf Stream waters that form EDW become fresher as they move downstream.
- This freshening cannot be explained by air-sea fluxes.
- A lateral diffusivity of ~100 $m^2$ s yielding a fresh water flux across the North Wall could explain the freshening.
- Submesoscale processes such as mixed layer eddies and symmetric instability could accomplish this lateral mixing.

# Observational evidence of symmetric instability



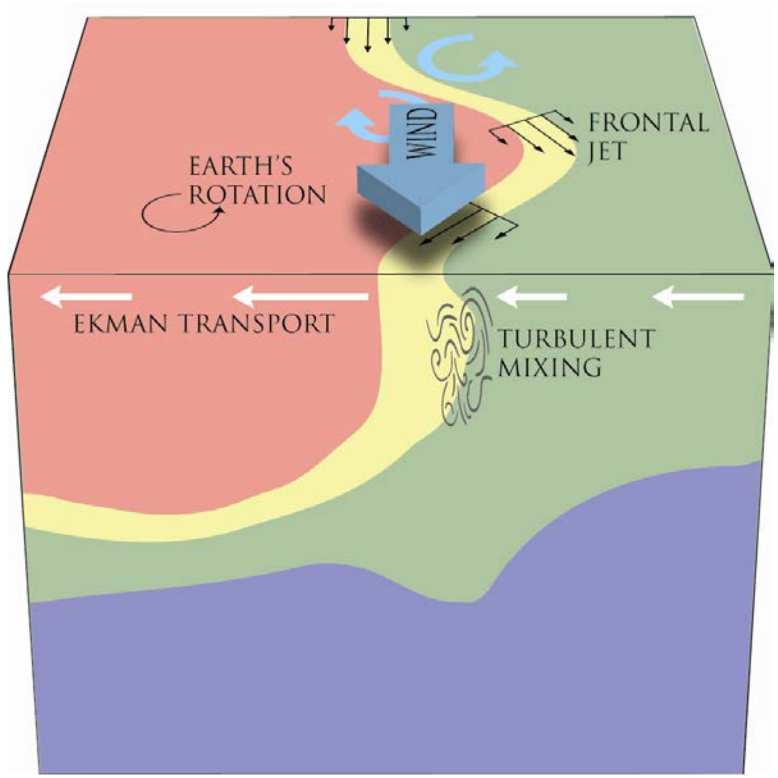

•A geostrophic flow is symmetrically unstable when its potential vorticity is negative

$$q = \boldsymbol{\omega}_a \cdot \nabla b = \underbrace{(f+\zeta)N^2}_{q_{vert}} + \underbrace{\boldsymbol{\omega}_h \cdot \nabla_h b}_{q_{bc}}$$

•AND when the negative PV is associated with the vertical shear/horizontal density gradient, not the stratification or vertical vorticity. These conditions are met when the Richardson number of the geostrophic is low.

•The CLIMODE observations revealed several examples of negative PV in the Gulf Stream.

# Reduction of the potential vorticity by down-front winds




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

$\mathbf{M}_e$ Ekman transport

EKMAN BUOYANCY FLUX $\mathbf{M}_e \cdot \nabla_h b$

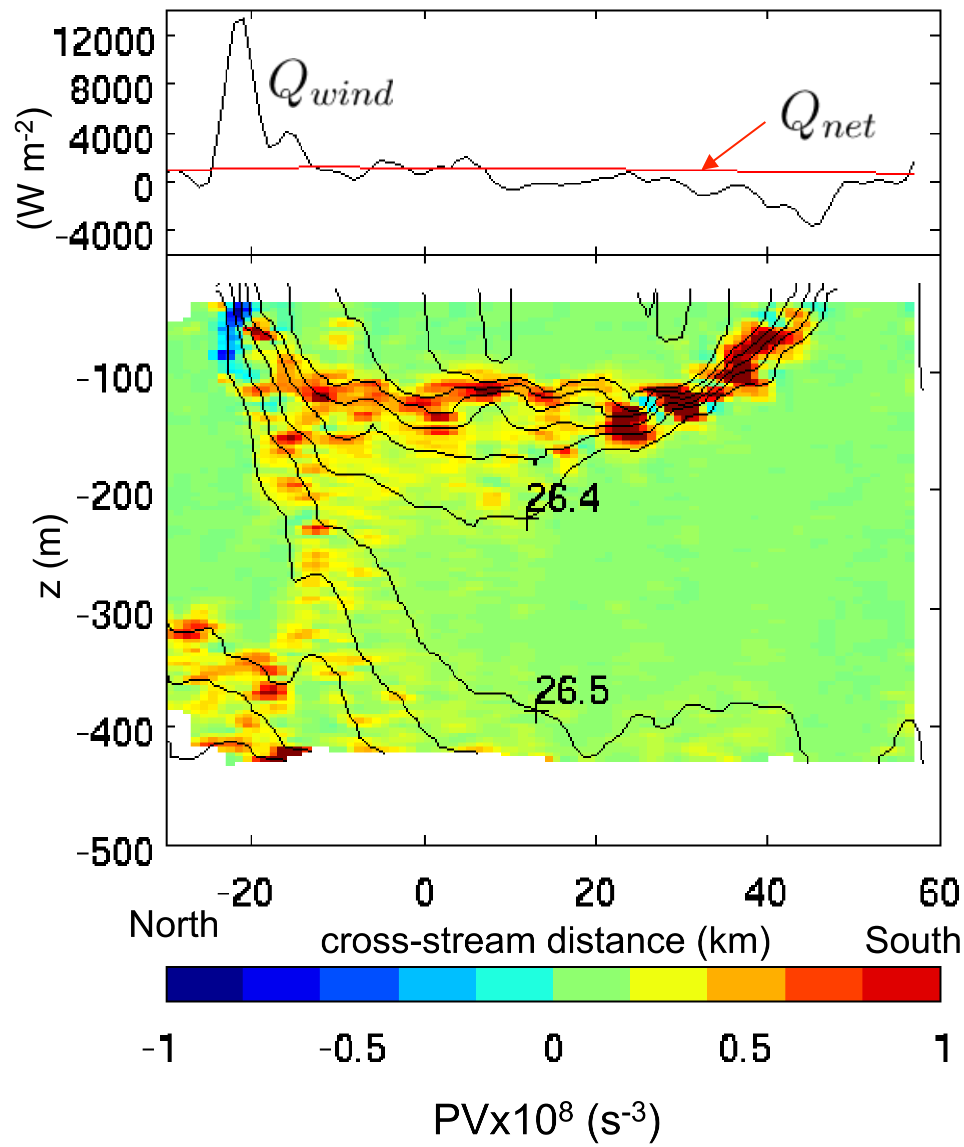
$$b = -\frac{g}{\rho_o}\rho$$

Thomas and Taylor *GRL* (2010)

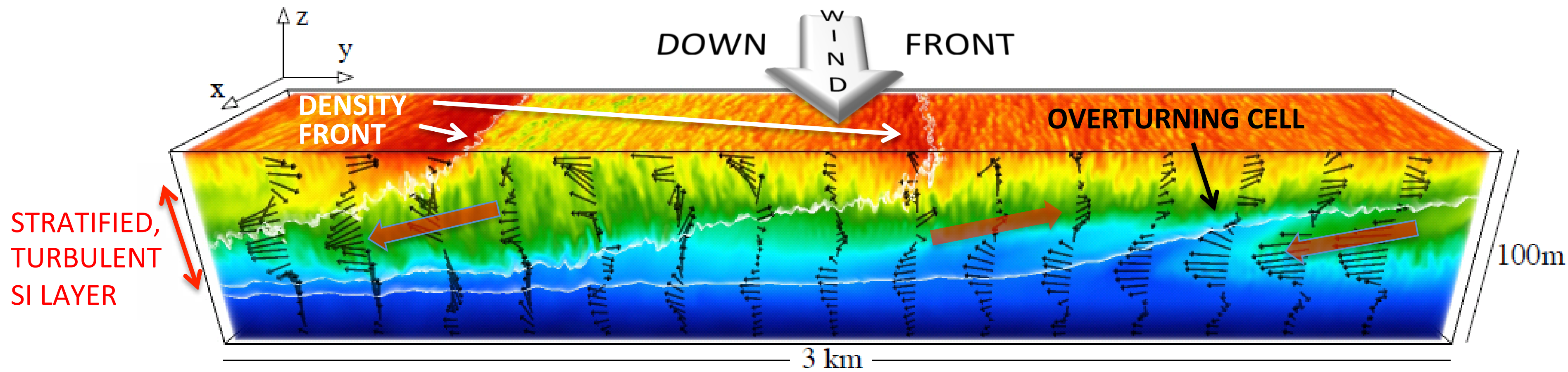
# Evidence of wind-driven PV reduction at the Gulf Stream

$$Q_{wind} = \left(\frac{\rho c_p}{\alpha g}\right) \mathbf{M}_e \cdot \nabla_h b$$

- The Ekman buoyancy flux can be expressed in units of a heat flux.
- The Ekman buoyancy flux peaks at a value equivalent >12000 W m$^{-2}$ of heat loss at the frontal outcrop on the north wall.
- The net heat loss was ~1000 W m$^{-2}$.
- The PV is negative at the front beneath the maximum in the Ekman buoyancy flux.



# Symmetric Instability – a new form of upper ocean turbulence




•Symmetric instability is an overturning instability that extracts KE from the geostrophic flow by driving a down-gradient momentum flux. The rate at which SI does this is:

*GEOSTROPHIC SHEAR PRODUCTION*

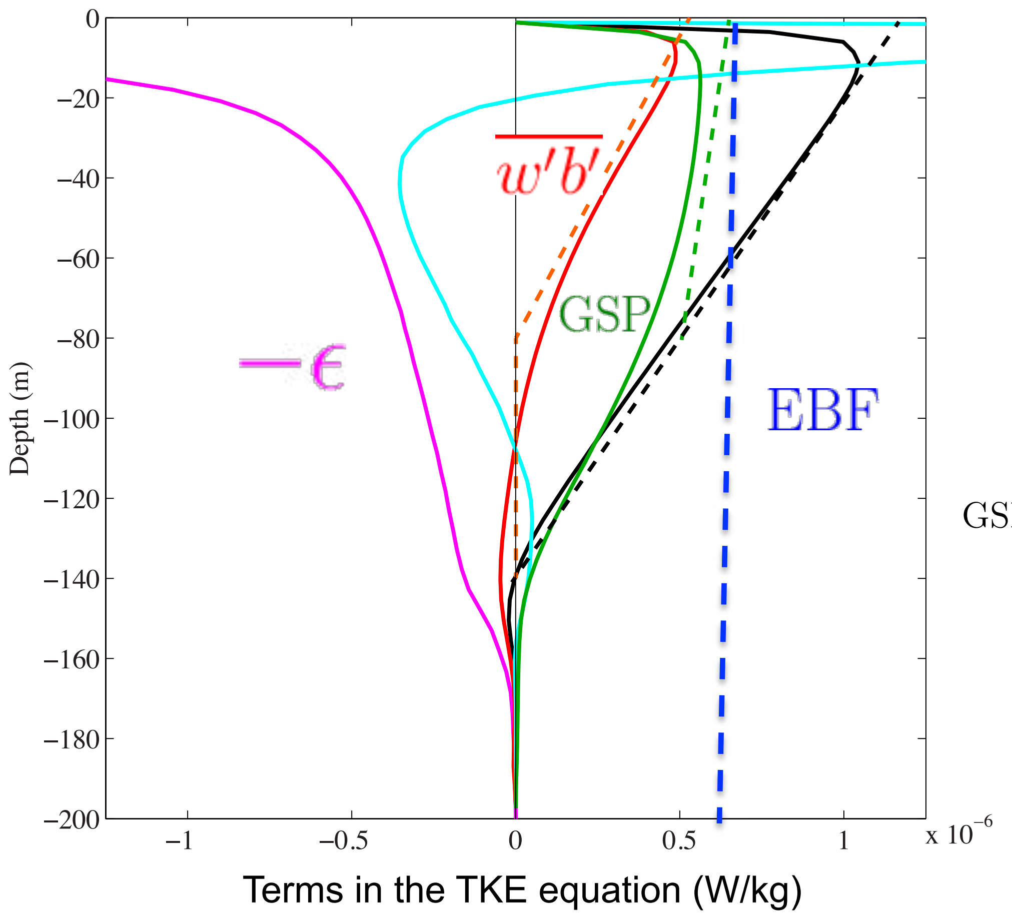
$$\mathrm{GSP} = -\overline{\mathbf{u}'w'} \cdot \frac{\partial \overline{\mathbf{u}}_g}{\partial z}.$$

•Theoretical scalings suggest that the GSP scales with the EBF

$$\boxed{\mathrm{GSP} \sim \mathrm{EBF}}$$

•John Taylor (DAMPT) ran a large eddy simulation configured with flow and forcing parameters based on the CLIMODE surveys to test this scaling in this setting.

# Shear production associated with wind-forced symmetric instability: LES results and parameterization




Thomas, L. N., J. R. Taylor, R. Ferrari, and T. M. Joyce, 2012. Symmetric instability in the Gulf Stream, DSR II, accepted

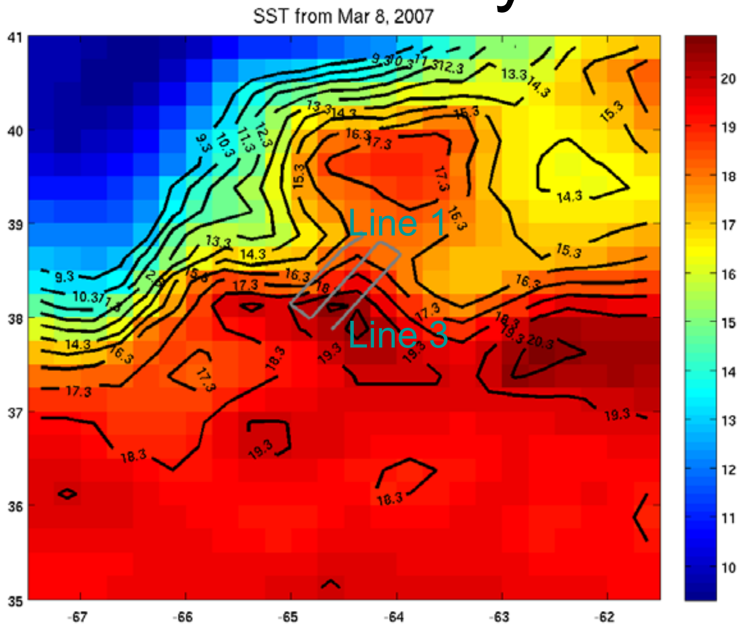
•The geostrophic shear production peaks at a value near the Ekman buoyancy flux and decays with depth consistent with the following parameterization:

$$\mathrm{GSP} \approx \begin{cases} (\mathrm{EBF} + B_o)\left(\frac{z+H}{H}\right) - B_o\left(\frac{z+h}{h}\right) & z > -h \\ (\mathrm{EBF} + B_o)\left(\frac{z+H}{H}\right) & -H < z < -h \\ 0 & z < -H \end{cases}$$

•The dissipation of KE mirrors the shear production.

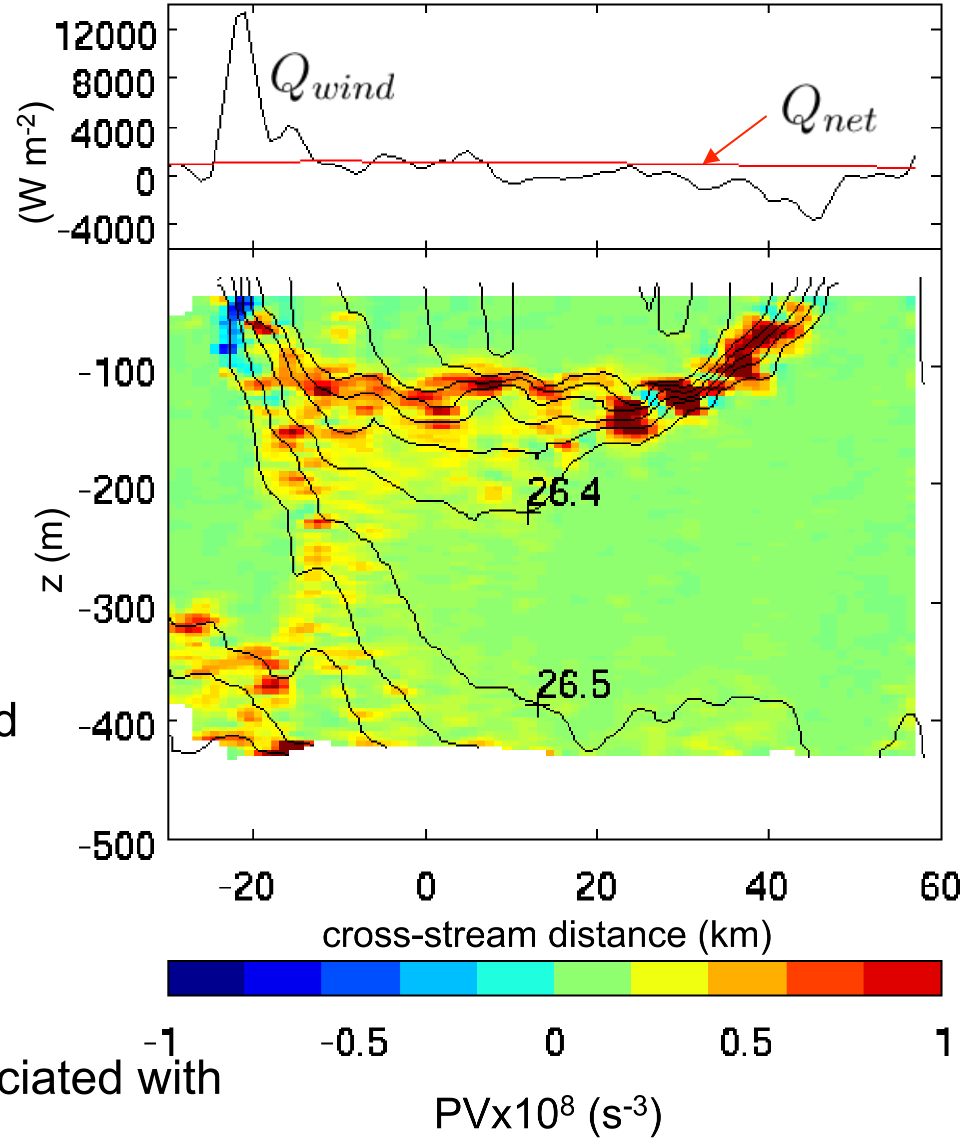
→Energy extracted from the geostrophic flow is dissipated by friction at a rate proportional to the EBF.

# Evidence of symmetric instability in the Gulf Stream




•The parameterization for the GSP/ dissipation was evaluated using the hydrographic and meteorological data and averaged over the area of the survey:

$$\overline{\rho_o \int \mathrm{GSP} dz}^{xy} \approx 30 \text{ mW m}^{-2}$$




- Comparable to the net dissipation associated with IGW breaking in the Southern Ocean.

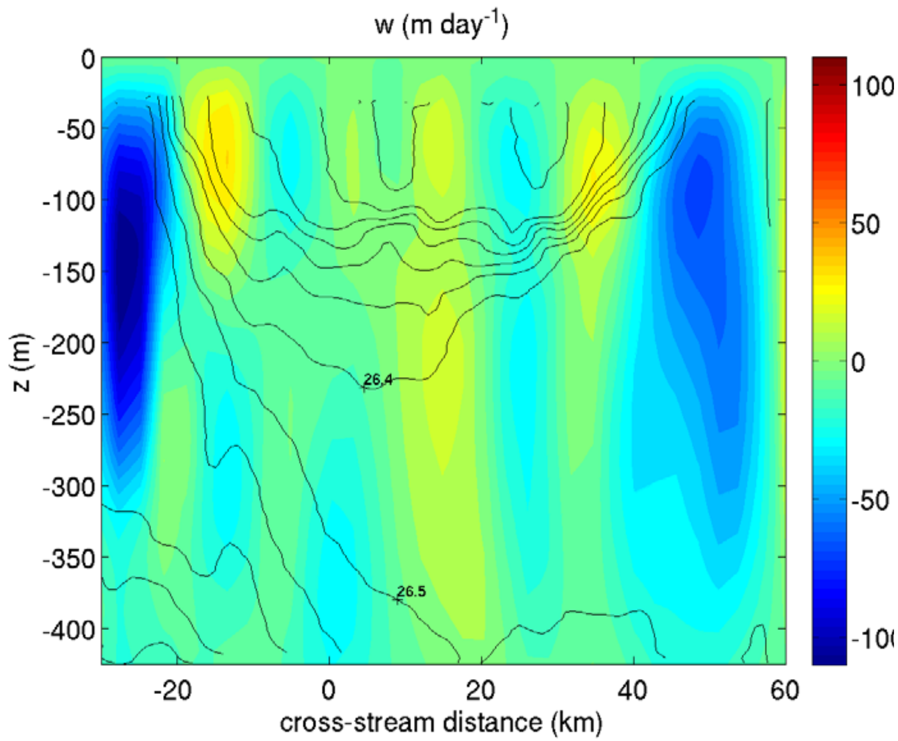
Thomas et al, 2012. Symmetric instability in the Gulf Stream, DSR II, accepted

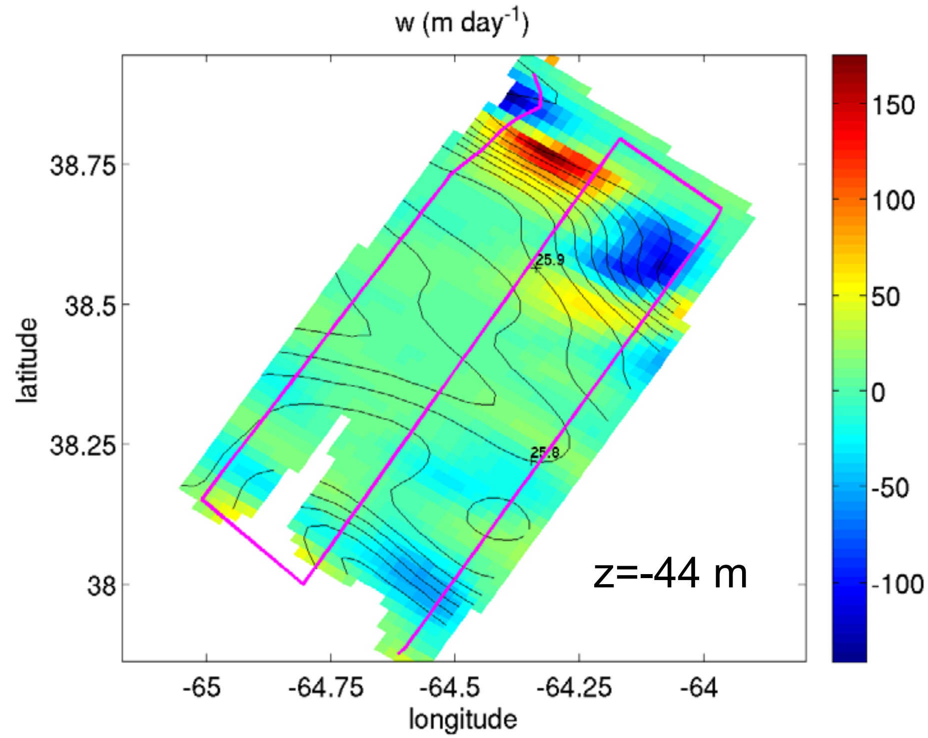
# Release of APE by baroclinic instability

•Baroclinic instability releases available potential energy at a rate equal to the buoyancy flux:

$$I = \overline{w'b'}^{xy}$$

•To estimate the buoyancy flux, the vertical circulation was inferred using solutions to the omega equation, and was thermally direct, releasing APE.




•Integrated over the SBL, the net buoyancy flux is 23 mW m$^{-2}$, comparable to the GSP.

# Conclusions

- The CLIMODE field campaign has revealed a new energy pathway for the circulation that is active at ocean fronts under wintertime forcing:

Buoyancy loss and down-front winds

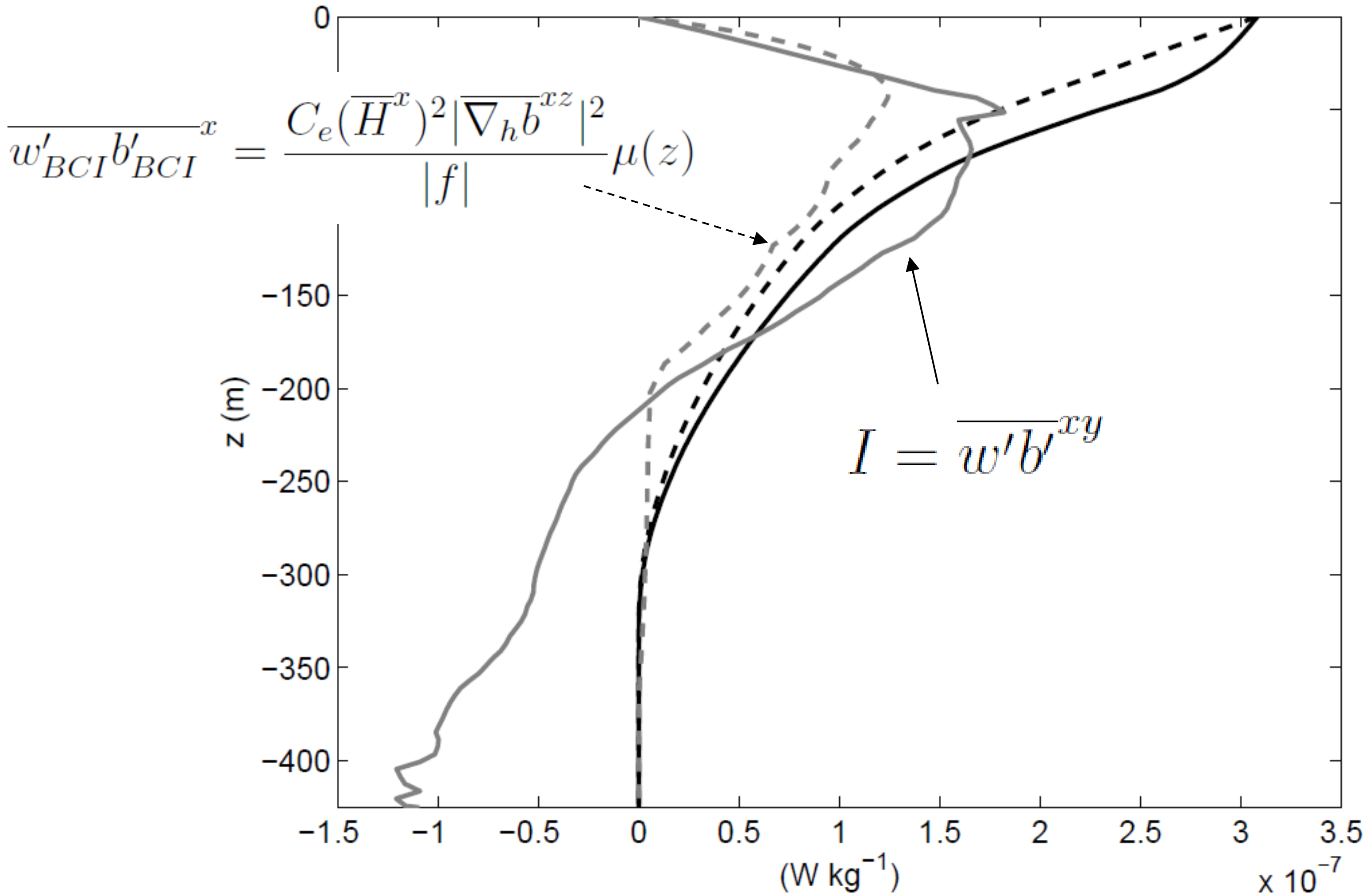
*APE of front* $\xrightarrow{w'b'}$ *Mixed layer eddies* $\xrightarrow{\text{GSP}}$ *Symmetric instability* $\xrightarrow[\text{cascade}]{\text{forward}}$ *Small-scale turbulence and dissipation*

- The observations also suggest that a significant fraction of the EDW that is found in the Sargasso Sea forms nonlocally in the Gulf Stream and is anomalously fresh owing to lateral mixing across the North Wall.

- These results represent a small fraction of the analysis that has been performed on the CLIMODE observations and simulations. A complete list of publications can be found at: *http://www.climode.org/Data/Publications/publ.htm*

- A second phase of analysis has been funded by NSF to study:
  - Evolution and Fate of EDW in the North Atlantic Subtropical Gyre (Kwon, Fratantoni, Straneo, Park)
  - Dynamics of EDW from CLIMODE Observations and its Climate Implications (Dong and Ortner)
  - Examining a New Paradigm for Eighteen Degree Water Formation (Joyce, Thomas, Dewar, Girton).

# Estimate of the release of APE




•Above 200m, within the SBL, the inferred buoyancy flux has a similar structure and magnitude to the parameterization of Fox-Kemper et al 2008.

•Integrated over the SBL, the net buoyancy flux is 23 mW m$^{-2}$, comparable to the GSP.