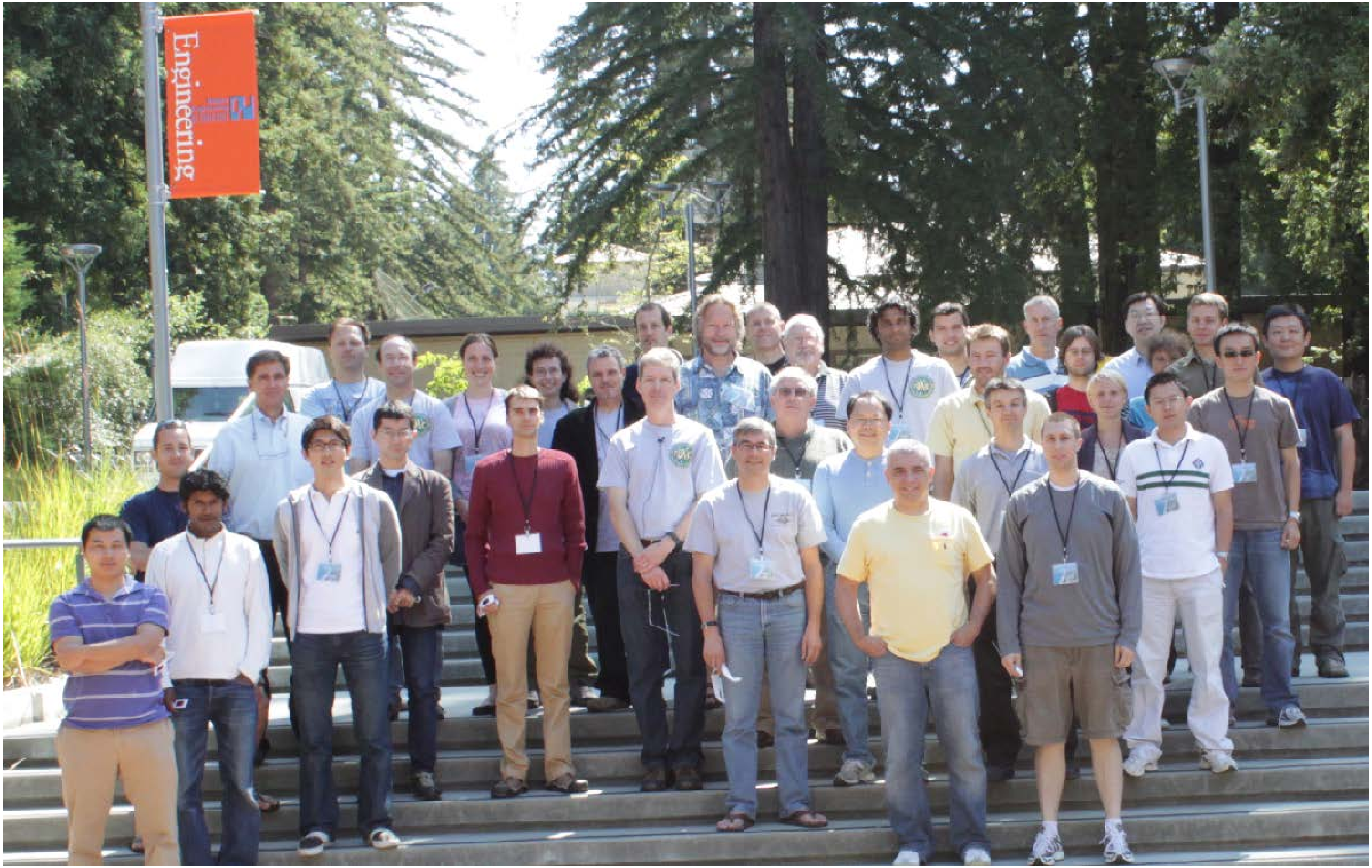

Workshop on the ROMS 4D-Var Data Assimilation Systems for Advanced ROMS Users:

Date: July 12, 2010

Place: The Simularium, Baskin School of Engineering, University of California Santa Cruz


Engineering

- **Chen, K., R. He, B. Powell, G. Gawarkiewicz, A. M. Moore, and H. G. Arango.** (**2014**): Data assimilative modeling investigation on Gulf Stream Warm Core Ring interaction with continental shelf and slope circulation, *Journal of Geophysical Research: Oceans,* doi: 10.1002/2014JC009898.

- **Li, Y., R. He, K. Chen, and D. McGillicuddy** (**2015**): Variational data assimilative modeling of the Gulf of Maine in spring and summer 2010, *Journal of Geophysical Research: Oceans*, doi: 10.1002/2014JC010492.

- **Zeng, X. and R. He (2016):** Gulf Stream variability and a triggering mechanism of its large meander in the South Atlantic Bight, *Journal of Geophysical Research - Oceans*, doi: 10.1002/2016JC12077

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Gulf Stream Variability and a Triggering Mechanism of Its Large Meander in the South Atlantic Bight

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North Carolina State University, U.S.A.

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(1706-1790)

Benjamin Franklin

- Politician
- Physicist
- Inventor
- Publisher

- Writer of declaration of Independence
- First Post Master of U.S.
- 1st U.S. Ambassador to France

Benjamin Franklin published the first map of the Gulf Stream in 1769

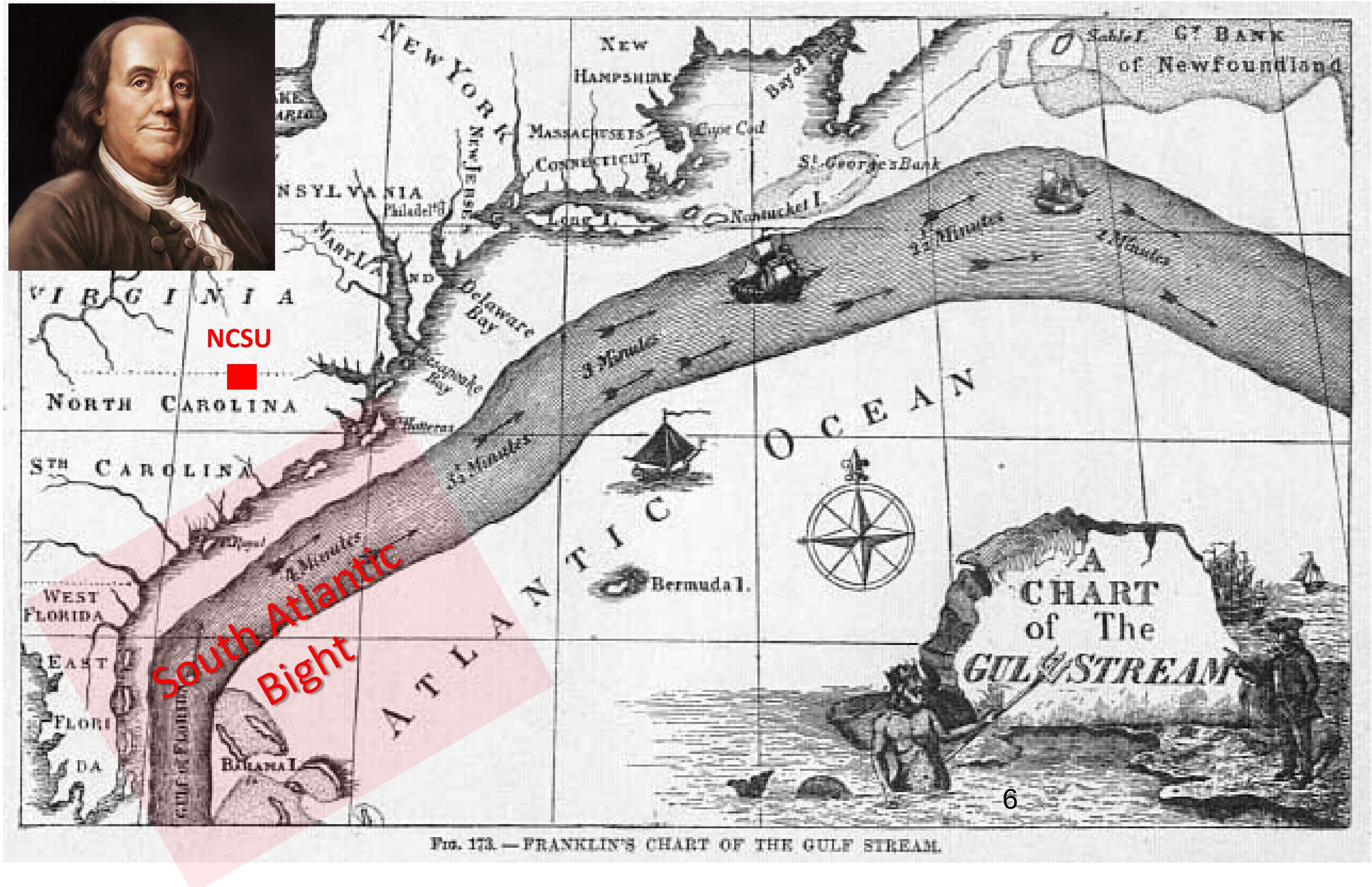


Fig. 173. — FRANKLIN'S CHART OF THE GULF STREAM.

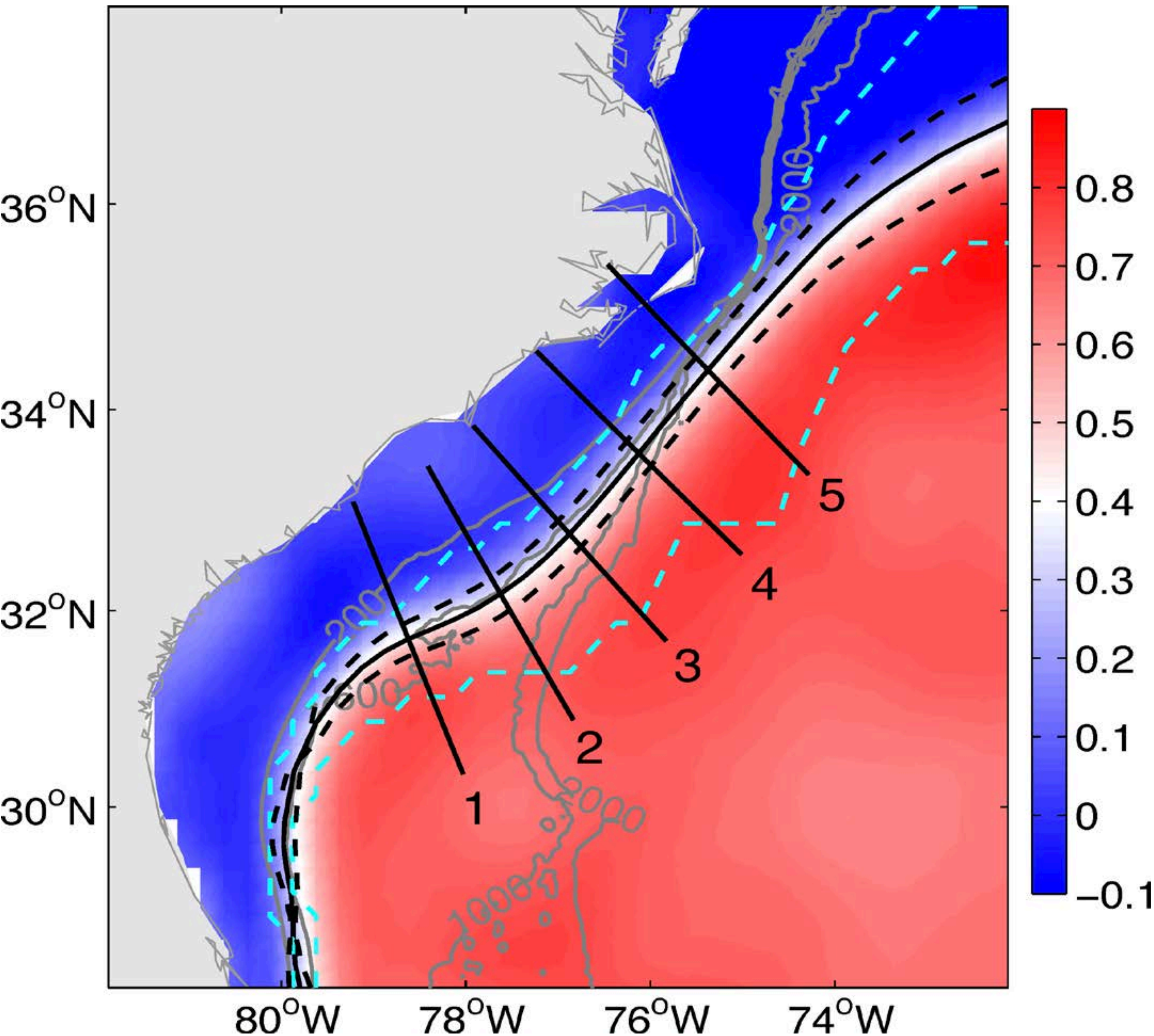
What is the GS variability in SAB?

data & method

- Daily Sea Surface Height (SSH) field over 13 years (2003-2015) from AVISO.

- We tracked the Gulf Stream (GS) front in the South-Atlantic Bight (SAB) based on the maximum SSH gradient, and computed daily nearest cross-shore distance between GS and coastline

Mean SSH (unit: m) during 2003-2015

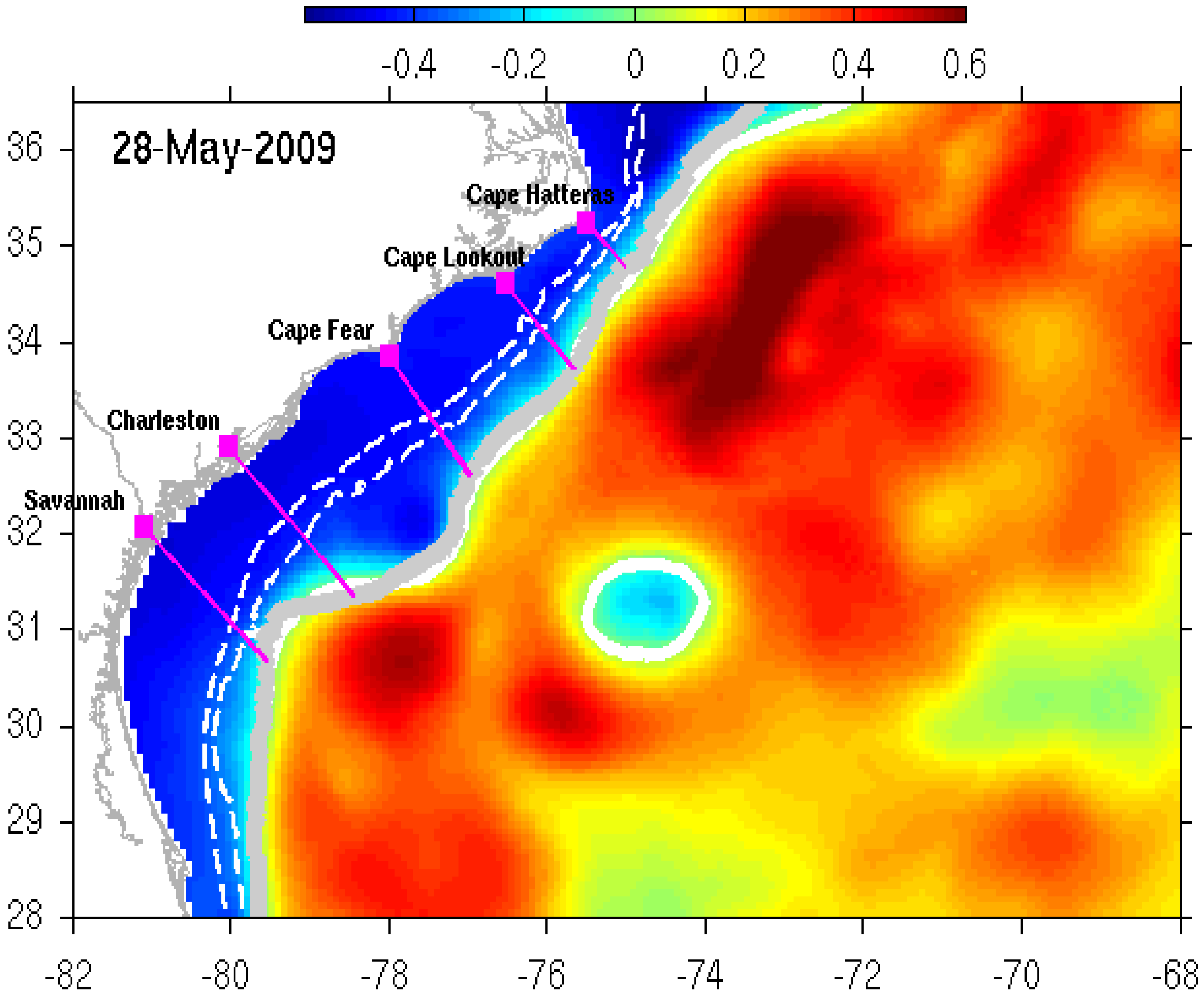


- Black solid line: **Mean GS front** at the largest SSH gradient.

- Gray dashed lines: **Mean GS+STD; Mean GS-STD**.

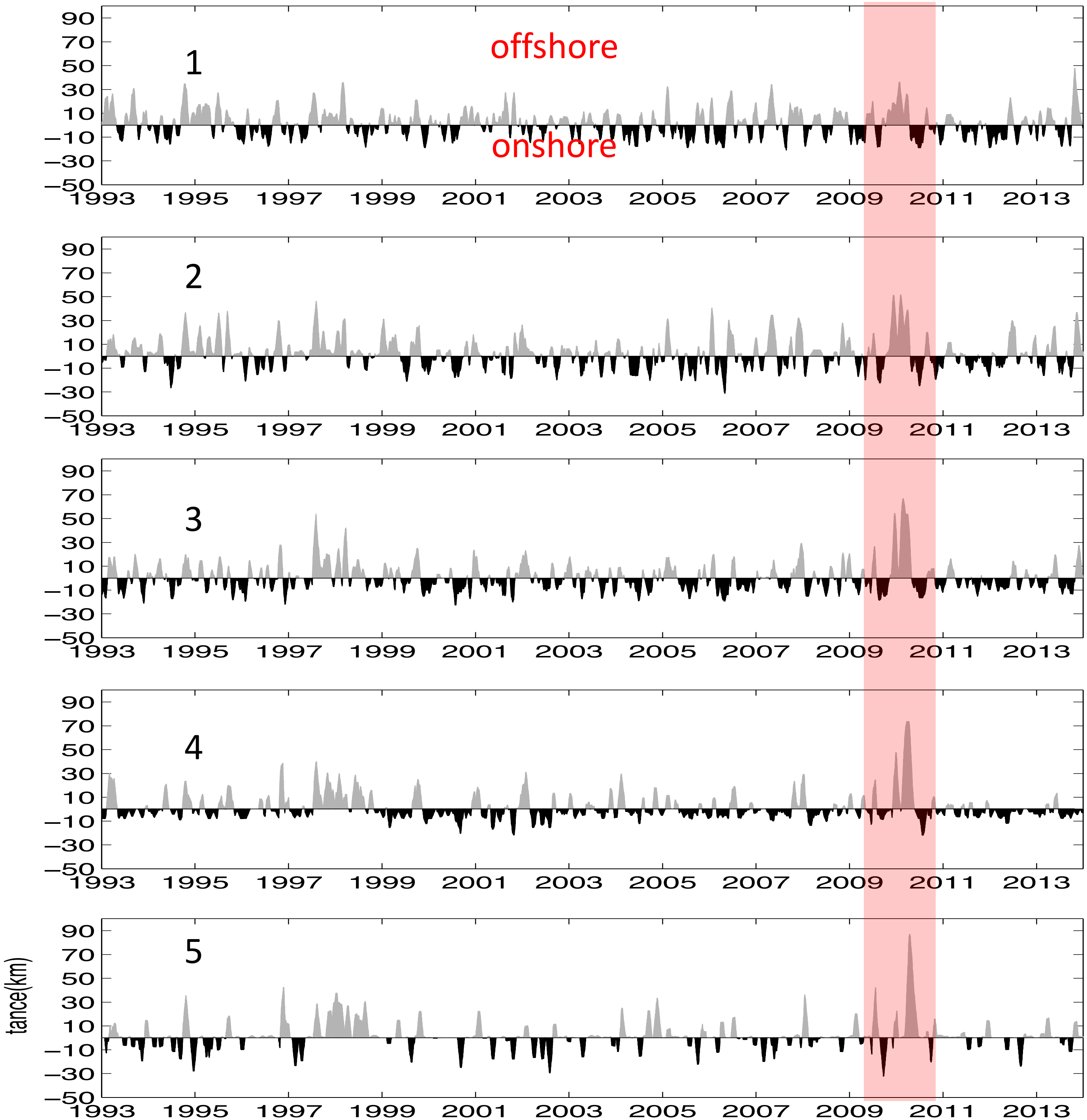
- Cyan dashed line: **Envelop of GS**

Daily position of GS and cross-shelf distance

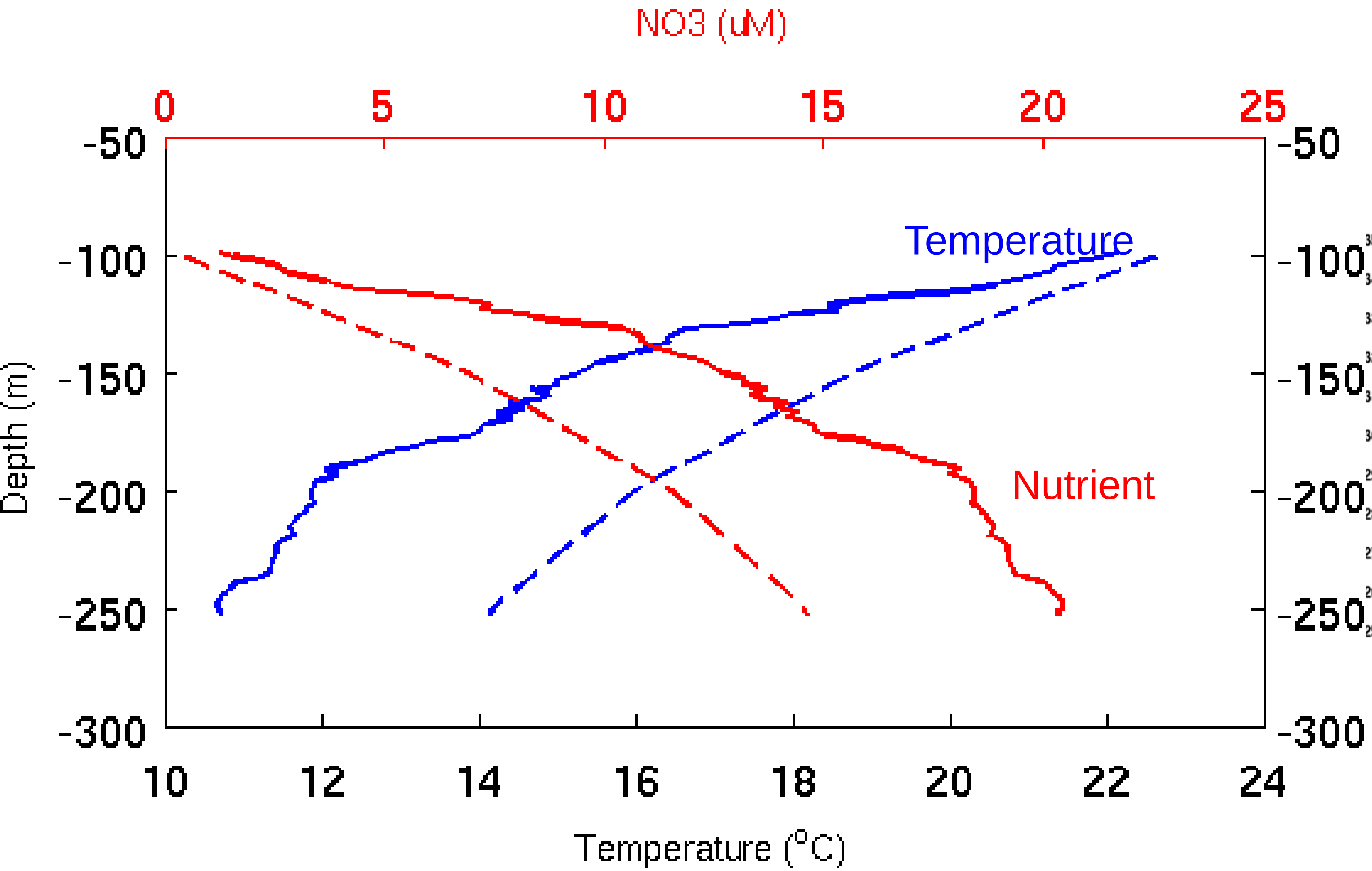


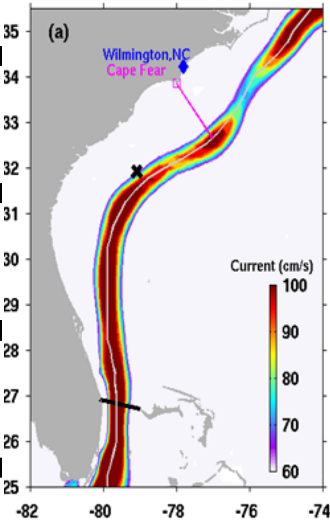
Pink: Cross-shelf distance of GS to the 5 coastal sites.

Gray: GS locations based on maximum SSH gradient.


offshore
onshore
1
2
3
4
5
tance(km)
90
70
50
30
10
−10
−30
−50
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013

Comparisons between observed temperature and nutrient profiles in **Nov 2009 (solid)** and their respective long term means (dashed, from NODC)





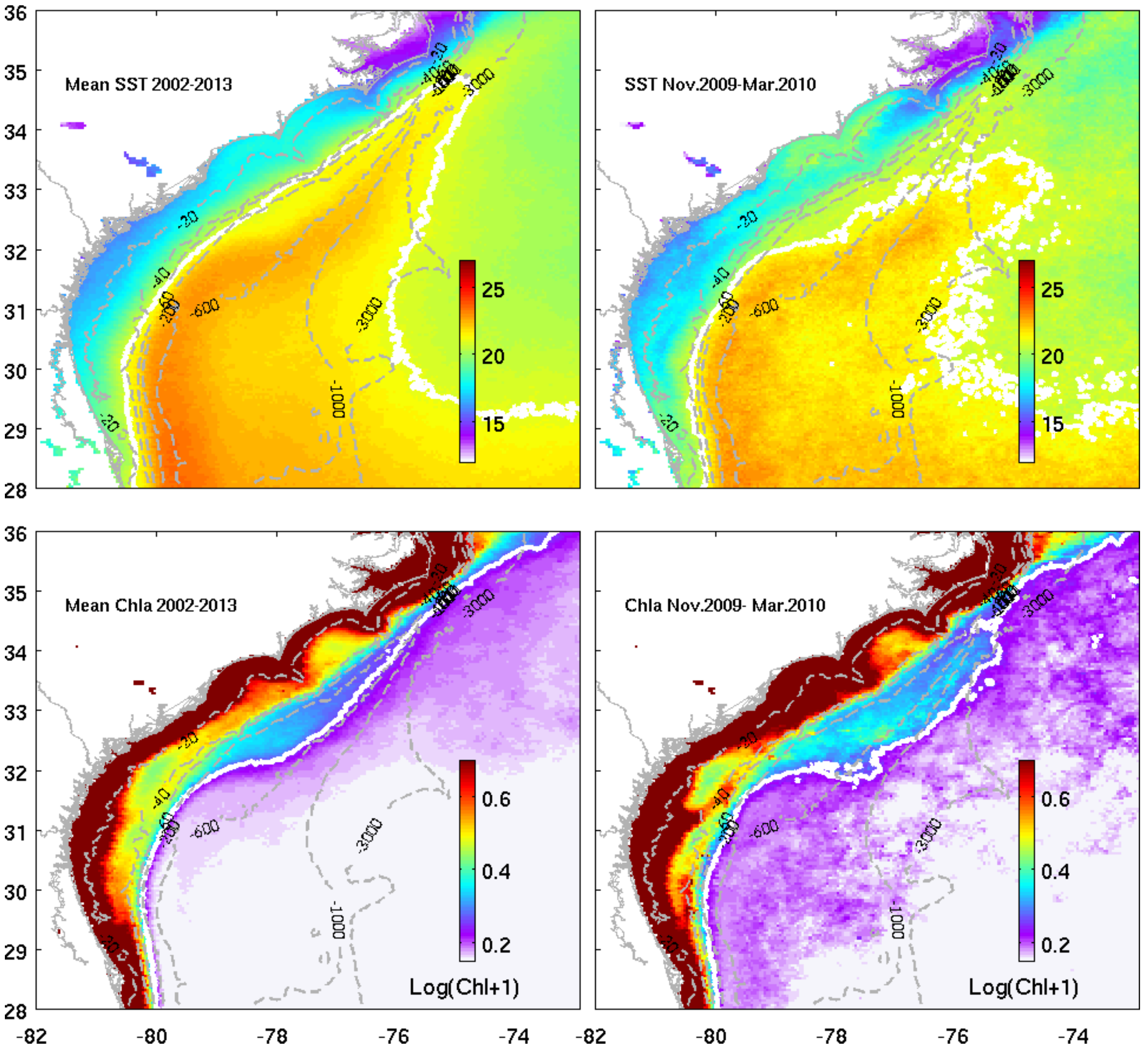
Comparisons of SST & ocean color

Long term Mean

SST

Nov 2009-Mar 2010 Mean

SST



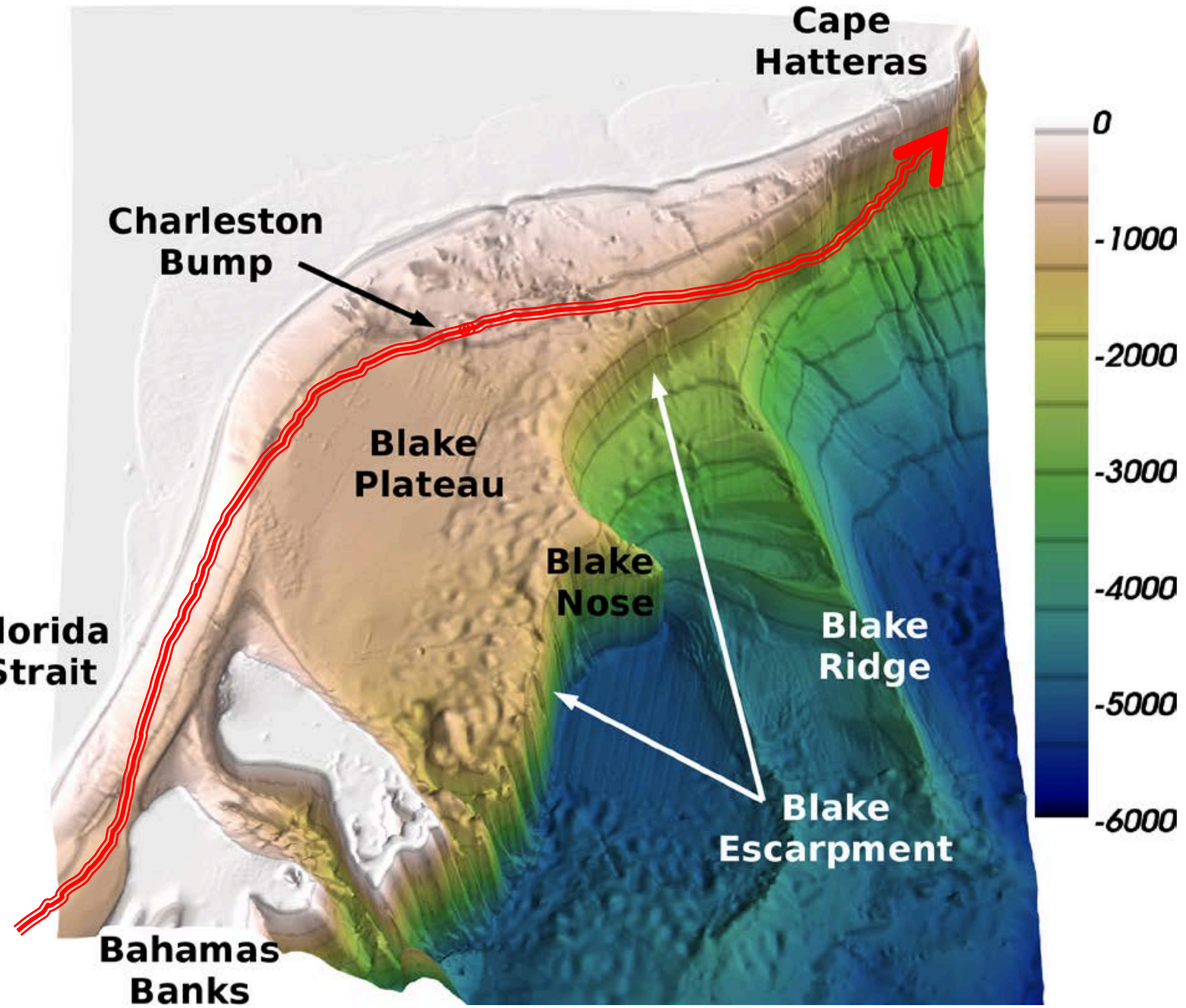
Chl-a

Chl-a

Question:

What is the triggering mechanism for this large GS meander in Nov 2009?

- ❑GS Instability induced by bathymetric feature (e.g., Bane & Dewar, 1988)
- ❑Upstream GS transport
- ❑Open ocean impact



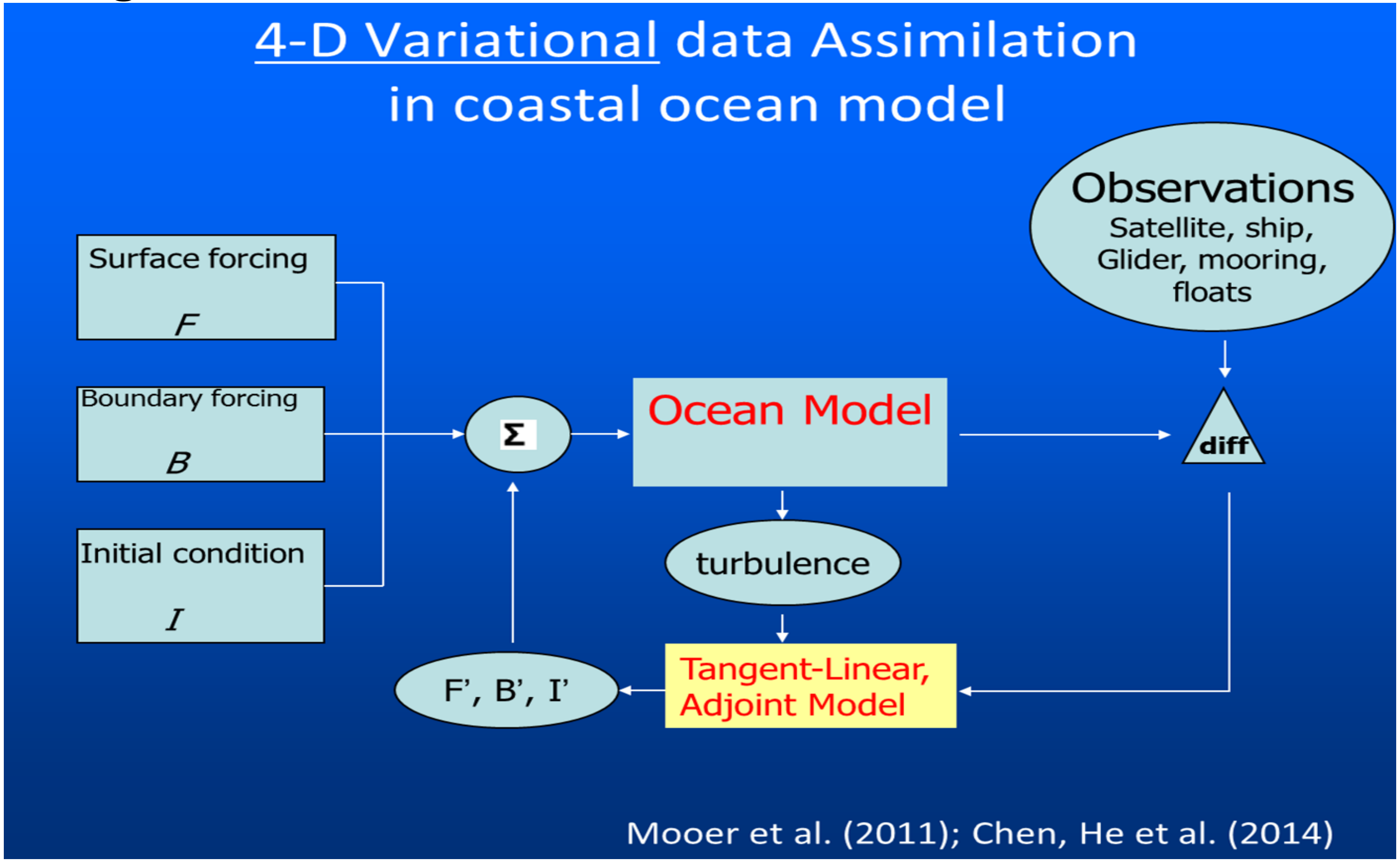
Model analysis

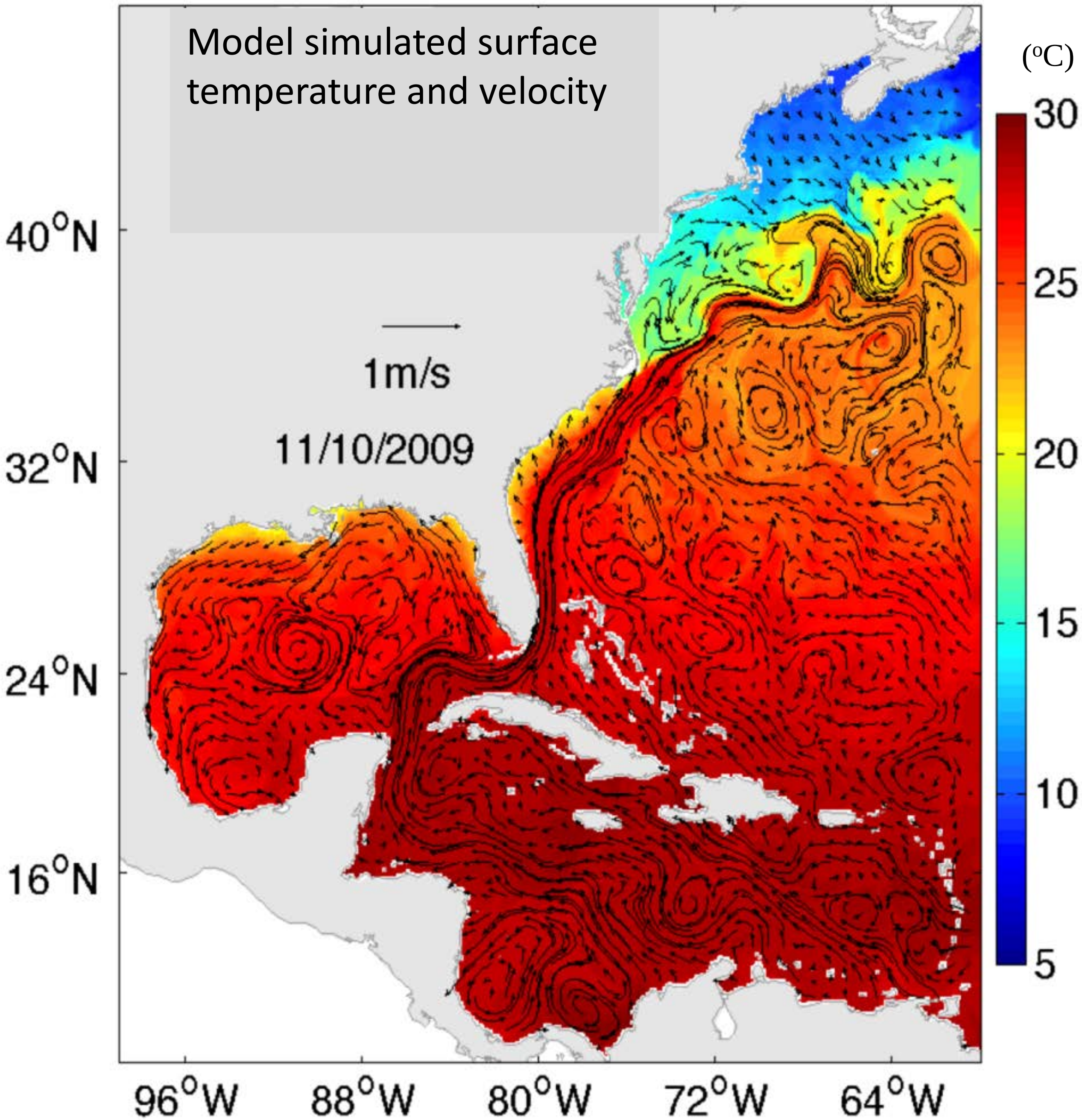
- ROMS (Regional Ocean Modeling System) forward model

  ocean state estimate in November 2009

- Backward in time adjoint sensitivity analysis

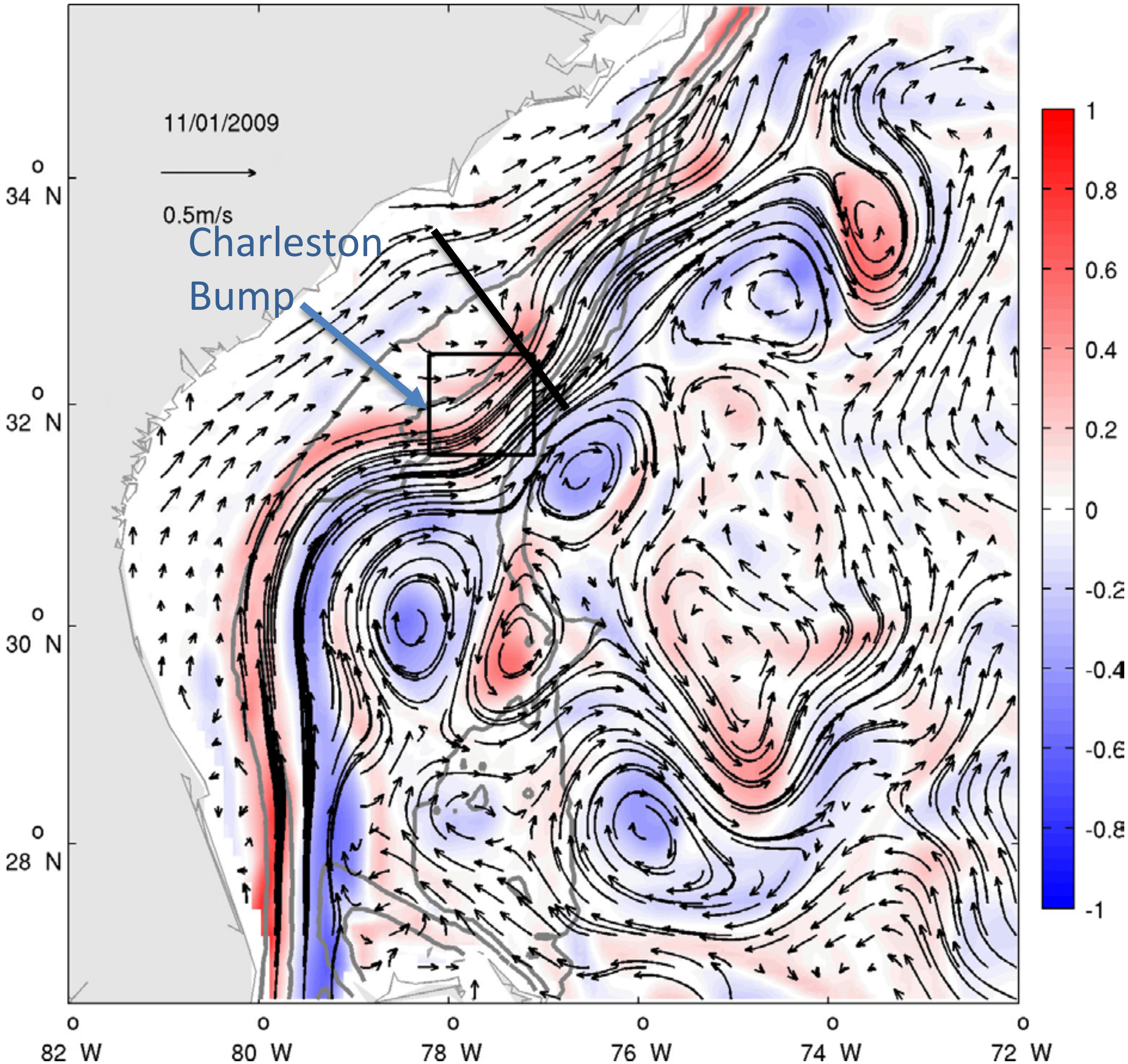
  diagnostics backward in time to understand processes triggering the large meander





- ~7 km horizontally
- 36 vertical layers
- Forcing: ECMWF 3-hourly
- Open boundary: HYCOM
- Initial condition: HYCOM

Simulated Surface Velocity and Relative Vorticity (color-shading)



- Relative vorticity is normalized by f
- Gray lines are 200, 600, 1000, and 2000 m isobaths
- GS variation inside the black box is selected for adjoint sensitivity analysis

Adjoint sensitivity analysis
using ROMS backward-in-time, tangent-linear adjoint model

An ocean model: $y = m(x)$

A scalar measure of a target process (e.g., the GS offshore meander)

$$J = J(y)$$

The result of input perturbations: $\Delta J = J(x + x') - J(x)$

A first order Taylor approximation to ΔJ

$$J' = \sum_i \frac{\partial J}{\partial x_i} x'_i$$

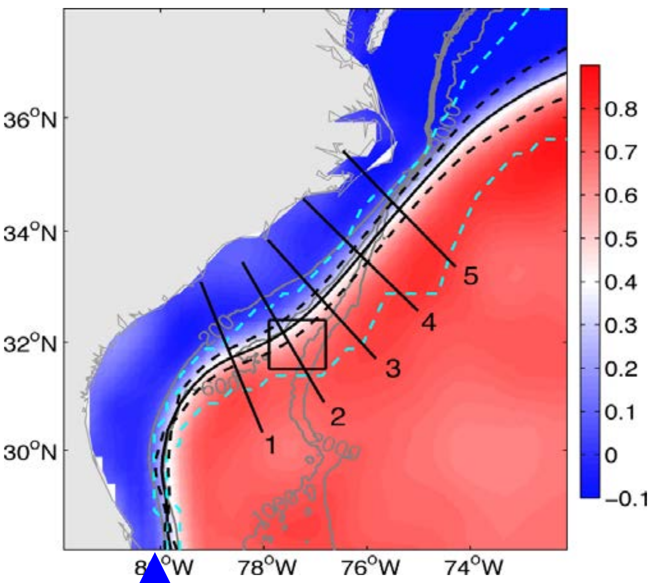
Adjoint sensitivity of *J* to a state variable x_i

~ f (x, y, z, t)

(Errico 1997; Moore et al., 2011; Chen, He et al., 2014)

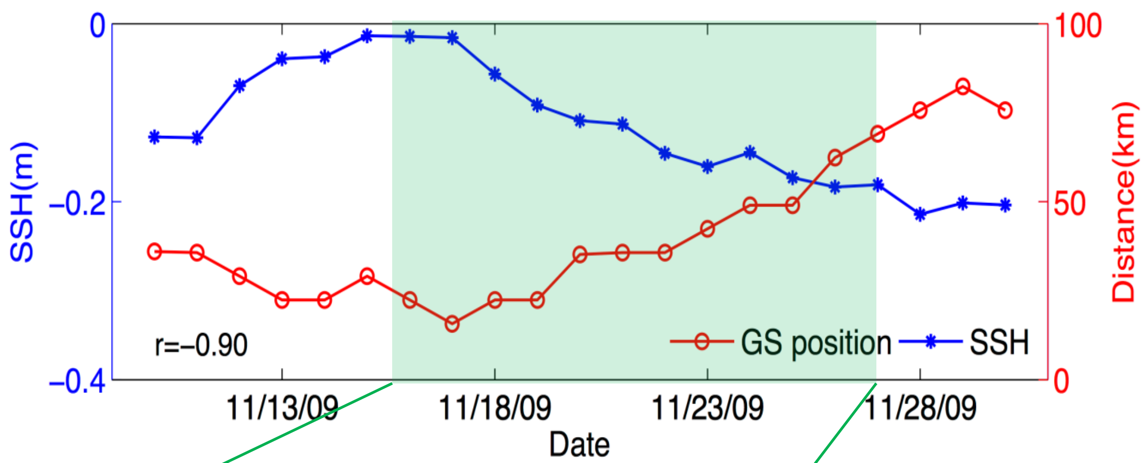
Index function $J = -< SSH >= -\frac{1}{(t_2 - t_1)A}\int_{t_1}^{t_2}\int_A \eta dAdt$

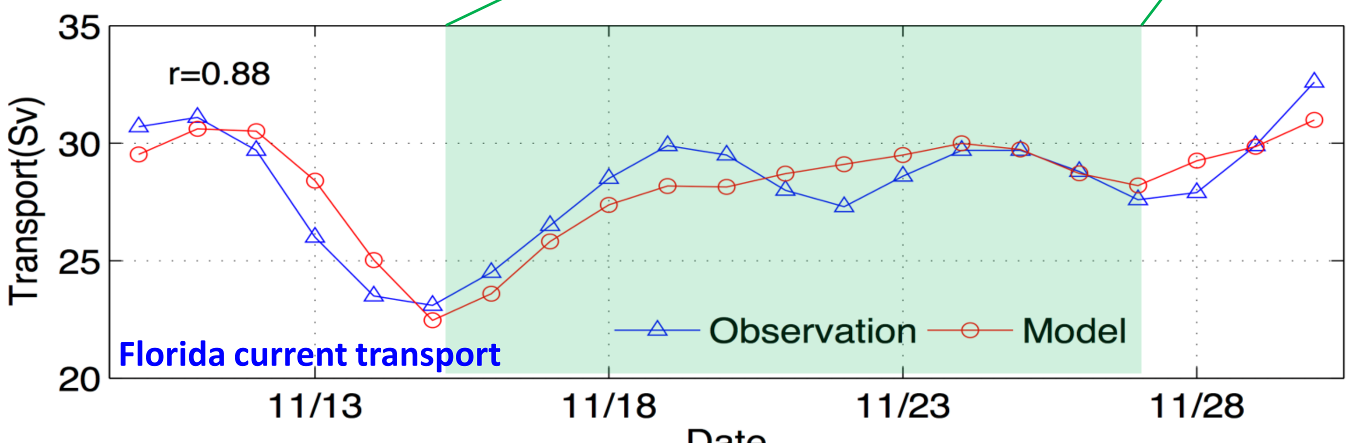
i.e., using the accumulative sea level perturbation as the scalar to quantify GS offshore meander



25% upstream Florida Current Transport increase

Daily mean SSH in the black box and GS position simulated by the model

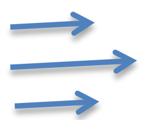




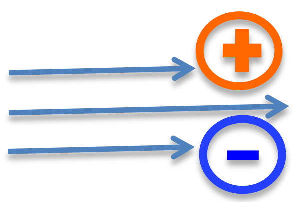
Adjoint sensitivity of *J* to ocean transport (ubar, vbar): backward in time

- flow perturbations on/off shelf
- Generation of **cyclonic velocity Perturbation** around the Charleston Bump

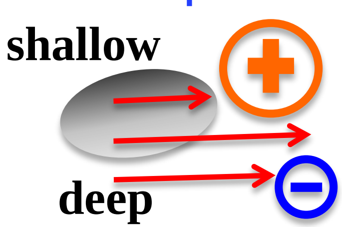
Gulf Stream Jet (normal)



Increased transport without Bump

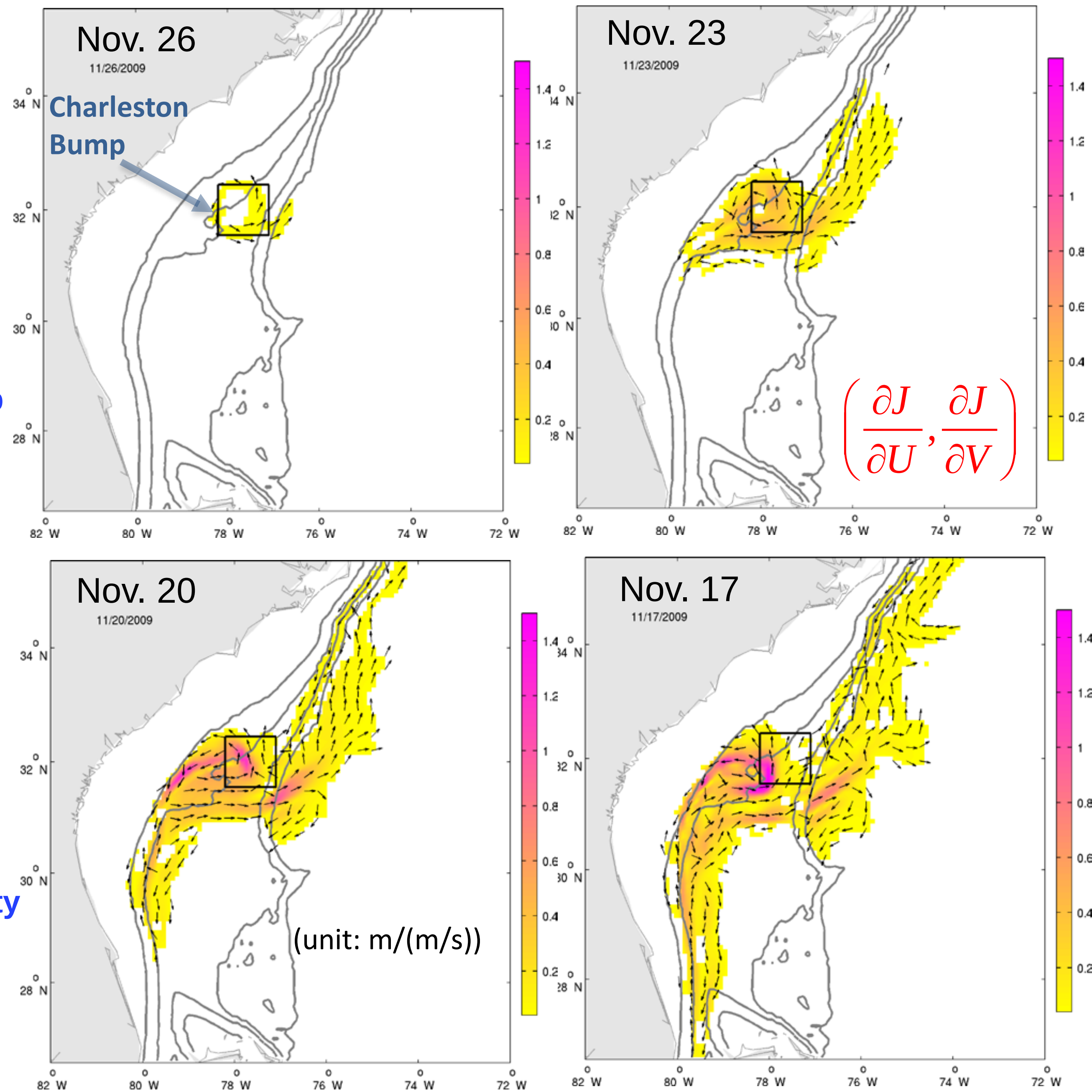


Increased transport with Bump



Conservation of potential vorticity

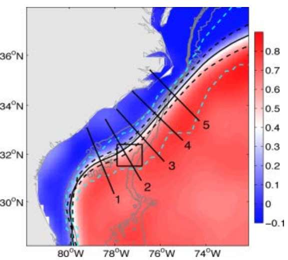
$$\underset{\text{(constant)}}{PV} = \frac{f + \zeta \uparrow}{h \uparrow}$$



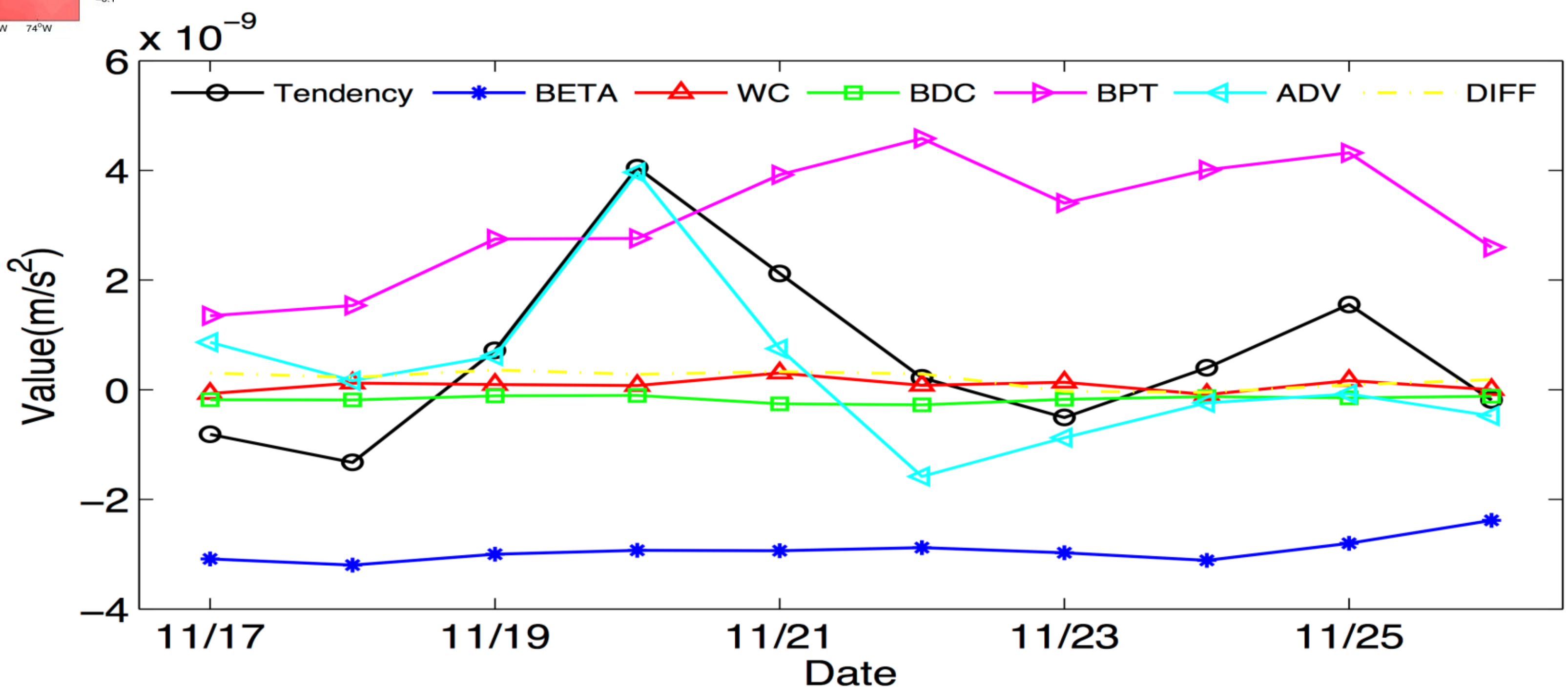
Vorticity budget analysis

$$\underbrace{\frac{\partial\Omega}{\partial t}}_{\text{Tendency}} = \underbrace{-\nabla\cdot(f\bar{\mathbf{u}})}_{\text{BETA}} + \underbrace{\frac{\mathbf{J}(P_b,h)}{\rho_0}}_{\text{BPT}} + \underbrace{\mathbf{k}\cdot\nabla\times\frac{\boldsymbol{\tau}^{wind}}{\rho_0}}_{\text{WC}} \underbrace{-\mathbf{k}\cdot\nabla\times\frac{\boldsymbol{\tau}^{bottom}}{\rho_0}}_{\text{BDC}} + \underbrace{D_\Sigma}_{\text{DIFF}} \underbrace{-A_\Sigma}_{\text{ADV}}$$

Planet. Vort. Adv. **Bot. Pres. Torque** **Wind Curl** **Bot. Drag Curl** **Horiz. Diff.** **NL Adv.**



Sub-regional vorticity budget

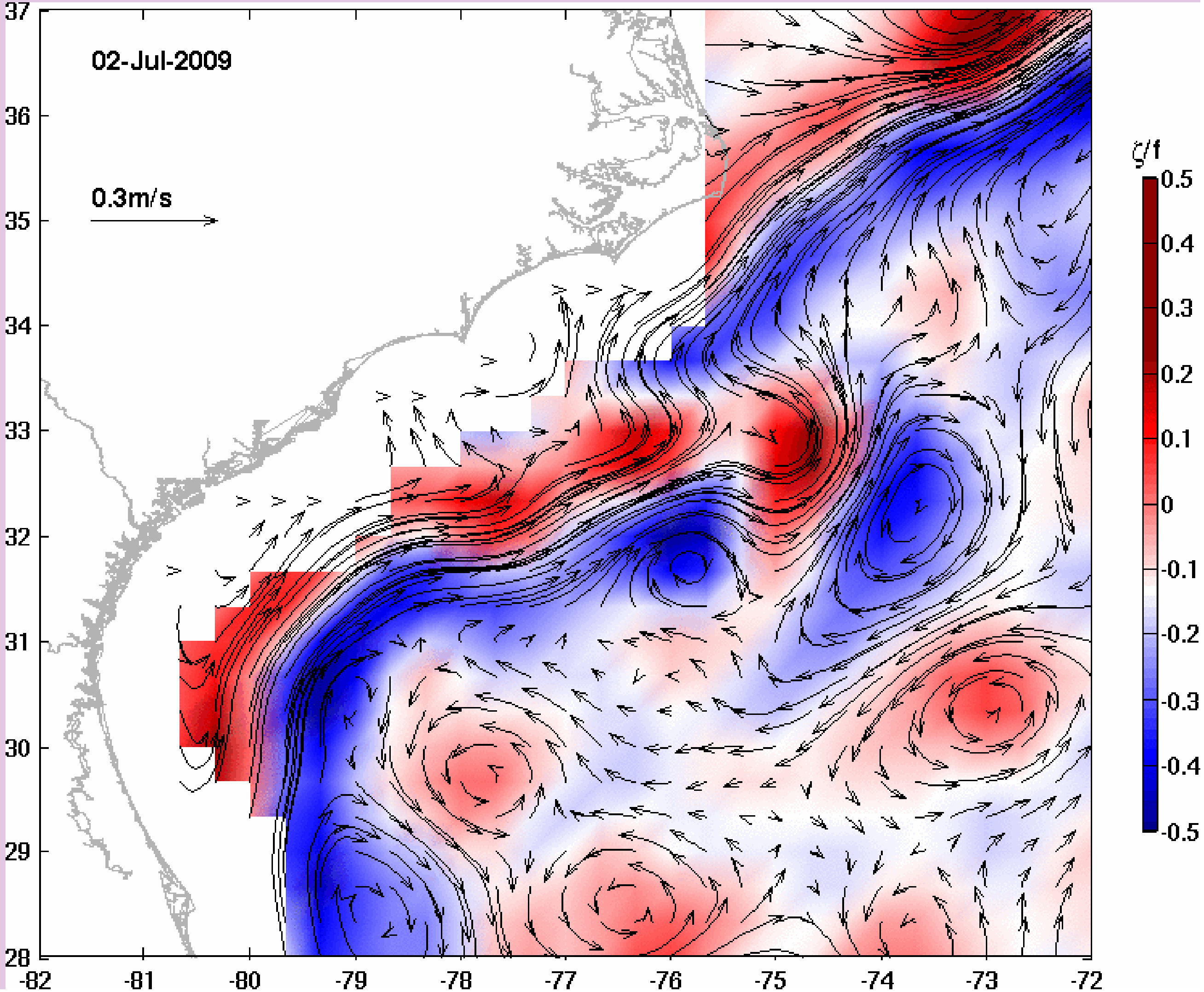


Triggering mechanism (Nov 2009):

- GS Instability induced by bathymetric feature
- stronger upstream GS transport

Maintaining mechanism (Nov 2009-Apr 2010):

- Open ocean impact



Gulf Stream reconstruction based on Altimetry SSH & surface wind fields

Open ocean mesoscale eddies
(positive vorticity injection into GS)

Potential vorticity Conservation:

$$\frac{f+\varsigma}{H} = \text{const}$$

ς: increase
H: increase

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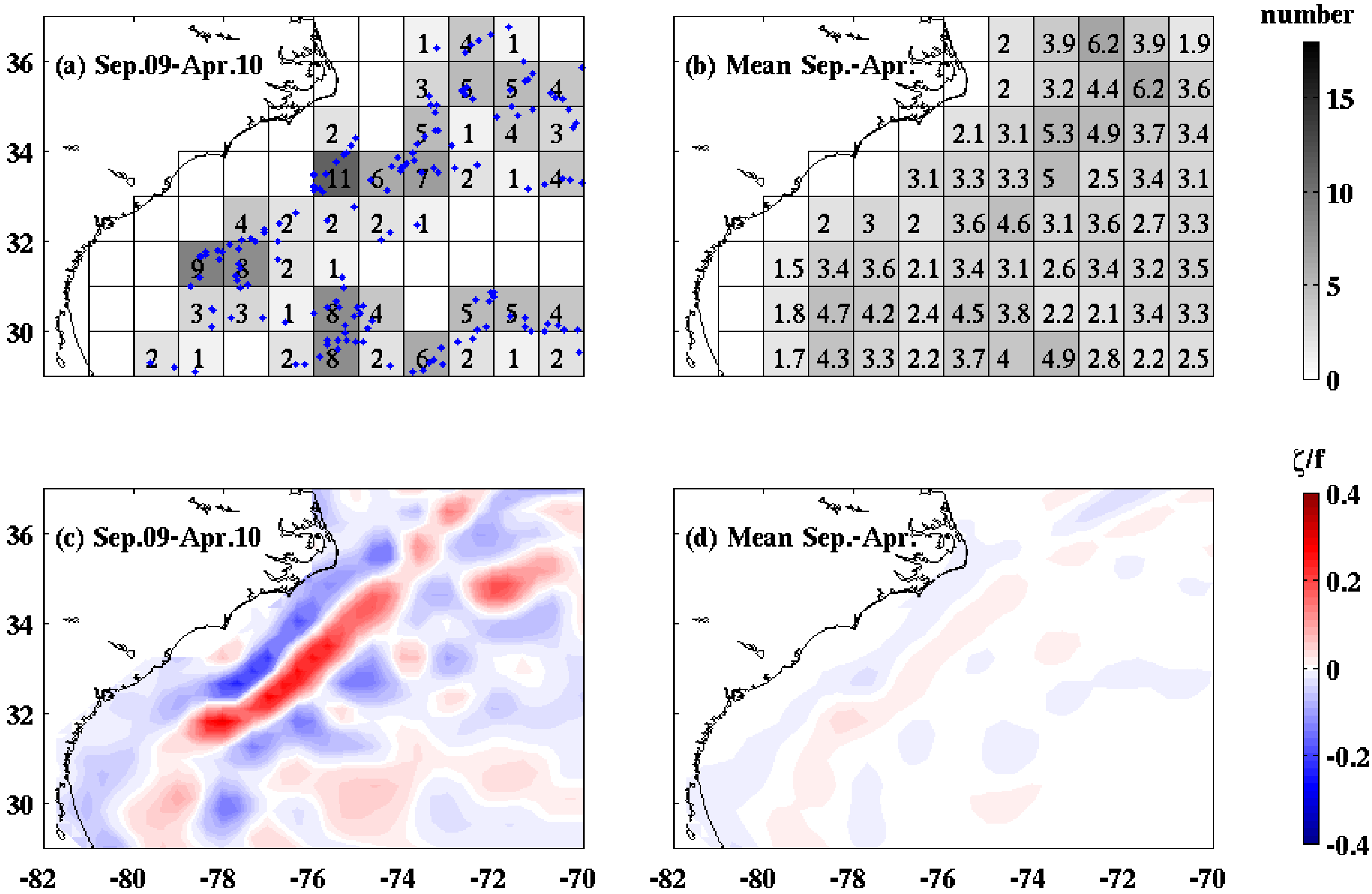
More numbers of cyclonic eddies in Nov 2009 – Apr 2010 than the mean



Summary

- Weak and strong meander (deflection) patterns of Gulf Stream (GS) path in the South Atlantic Bight (SAB) were confirmed by analyses of the long-term satellite observations.
- Adjoint sensitivity analysis shows the large offshore GS meander in Sept 2009-Apr 2010 was **triggered** by the combined effect of an increase of upstream Florida Current transport, and its strong interaction with shelf topography near the Charleston Bump.
- More than normal open ocean cyclonic eddies occurred during the same time and helped to **maintain** such offshore displacement by injecting positive vorticity into the GS.
- Stronger GS upwelling was induced, transporting more cold and nutrient rich deep-ocean water onshore and stimulating a larger marine productivity in the southeastern U.S. coastal ocean.

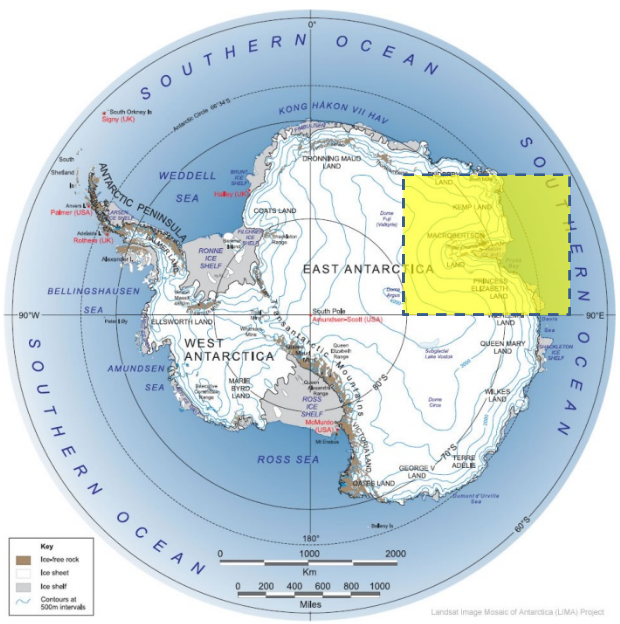
Collaborative Research: Contribution of Prydz Bay Shelf Water to Antarctic Bottom Water Formation

COLUMBIA UNIVERSITY

NSF

NC STATE UNIVERSITY

Project period: 2015-2018



Scientific Questions:

(Q1) What are the mechanisms that control CDW intrusions and its synoptic, seasonal and interannual variations?

(Q2) What are the spatial/temporal variations in the distributions of dense shelf water formed in the Prydz Bay shelf region?

(Q3) What are the dynamic processes controlling the export and fate of the dense shelf water formed in the Prydz Bay shelf region?

COAWST

Coupled Ocean– Atmosphere – Wave – Sediment Transport Modeling System to investigate variability of coastal environments.

Warner, J., B. Armstrong, R. He, and J. Zambon (2010), Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system, *Ocean Modelling*, v35, 3, 30-244

Xue, Z., R. He, J. P. Liu, and J. Warner (2012), Modeling transport and deposition of the Mekong River sediment, *Continental Shelf Research*, doi: 10.1016/j.csr.2012.02.010

Olabarrieta, M., J. Warner, B. Armstrong, J. Zambon, and R. He (2012), Ocean-atmosphere dynamics during Hurricane Ida and Nor'Ida: An application of the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system, *Ocean Modelling*, 43-44, 112-137

Nelson, J. and R. He, (2012), Effect of the Gulf Stream on winter extratropical cyclone outbreaks, *Atmosphere Research Letters*, doi: 10.1002/asl.400

Xue, Z., R. He, K. Fennel, W. J. Cai, S. Lohrenz, and C. Hopkinson (2013), Modeling ocean circulation and biogeochemical variability in the Gulf of Mexico, *Biogeosciences*, 10, 7219-7234, doi: 10.5194/bg-10-7219-2013

Zambon, J. B., R. He, and J. C. Warner (2014) Tropical to extratropical: Marine environmental changes associated with Superstorm Sandy prior to its landfall, *Geophysical Research Letters*, doi: 10.1002/ 2014GL061357.

Zambon, J. B., R. He, and J. C. Warner (2014) Investigation of Hurricane Ivan using the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Model, *Ocean Dynamics*, 64(11), pp. 1535-1554, doi: 10.1007/s10236-014-0777-7.

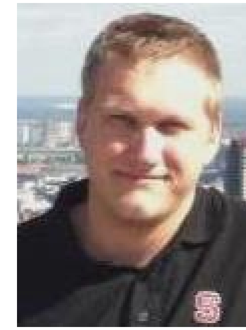
Nelson, J., R. He, J. C. Warner, and J. Bane. (2014) Air-sea interactions during strong winter extratropical storms, *Ocean Dynamics*, doi: 10.1007/s10236-014-0745-2

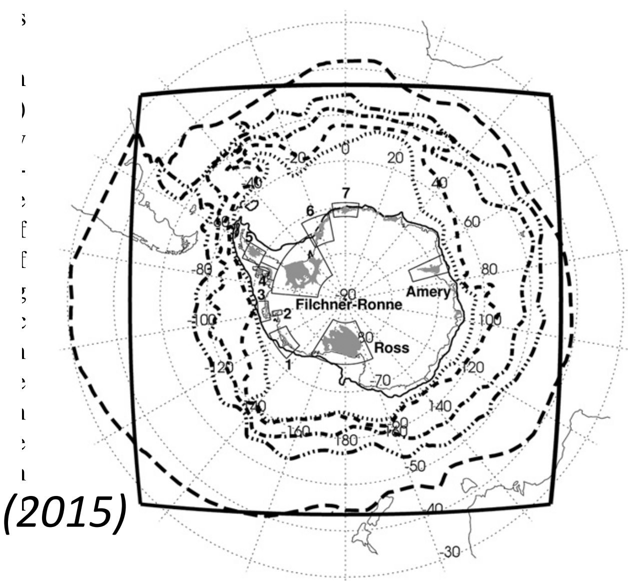
Xue, Z., J. Zambon, Z. Yao, Y. Liu, and R. He (2015) An integrated ocean circulation, wave, atmosphere, and marine ecosystem prediction system for the South Atlantic Bight and Gulf of Mexico, *Journal of Operational Oceanography*, doi:10.1080/1755876X.2015.1014667.

Xue, Z., R. He, K. Fennel, W.J. Cai, S. Lohrenz, W.J. Huang, H. Tian, W. Ren, and Z. Zang (2016) Modeling pCO_2 variability in the Gulf of Mexico, *Biogeosciences*, 13, 4359-4377, doi: 10.5194/bg-13-4359-2016.

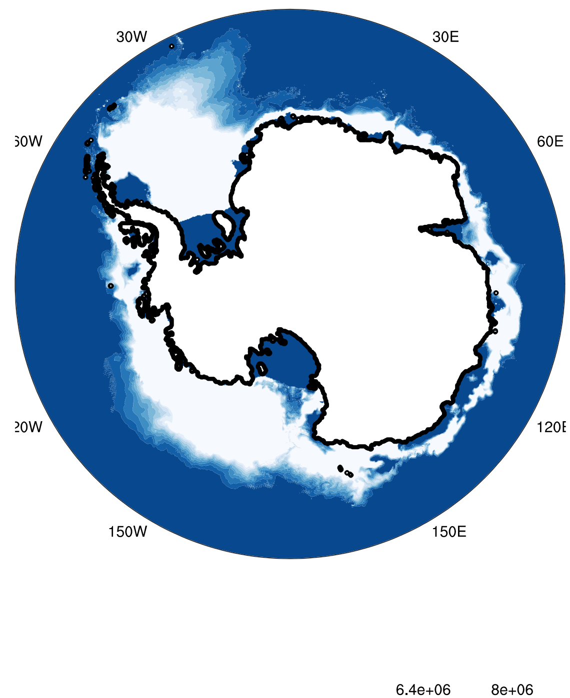
Antarctic COAWST

- NCSU – Ruoying He, Jeff Willison
- ODU – Mike Dinniman, John Klinck
- UTAS- Ben Galton-Fenzi, Dave Gwyther
- UAF- Kate Hedstrom
- OSU – Dave Bromwich, L. Bai



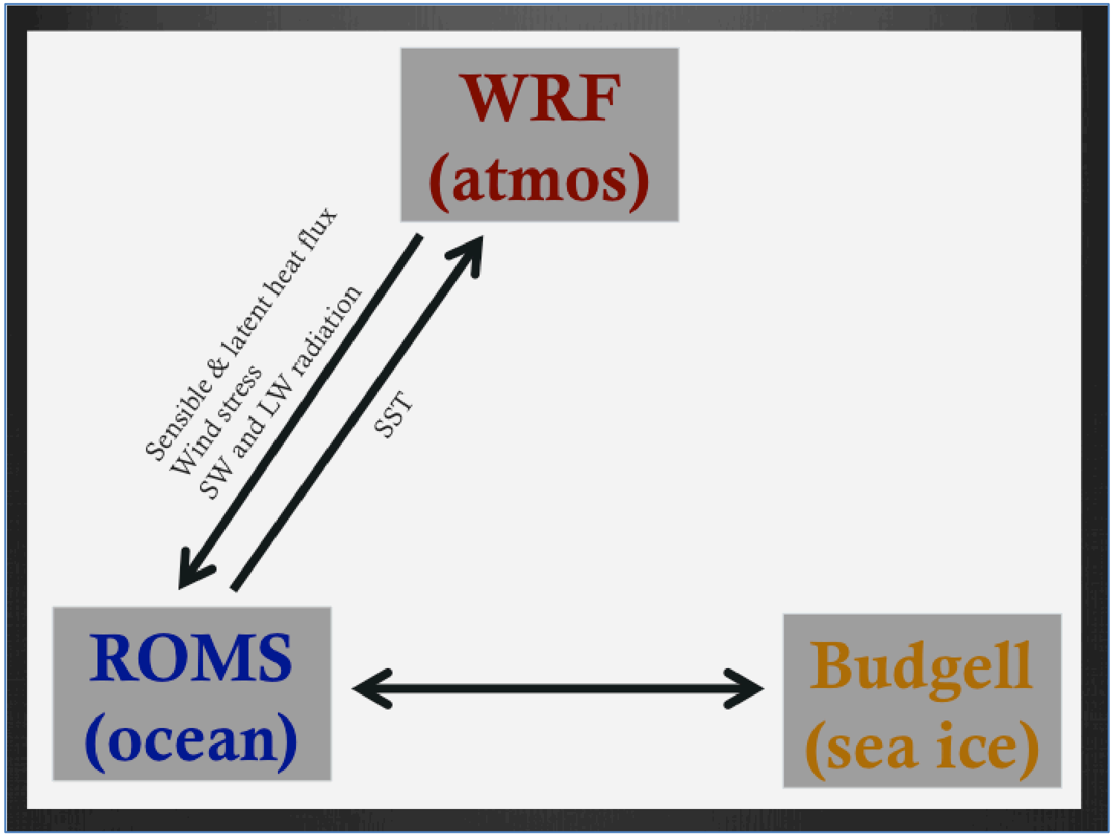


Dinniman et al. (2015)



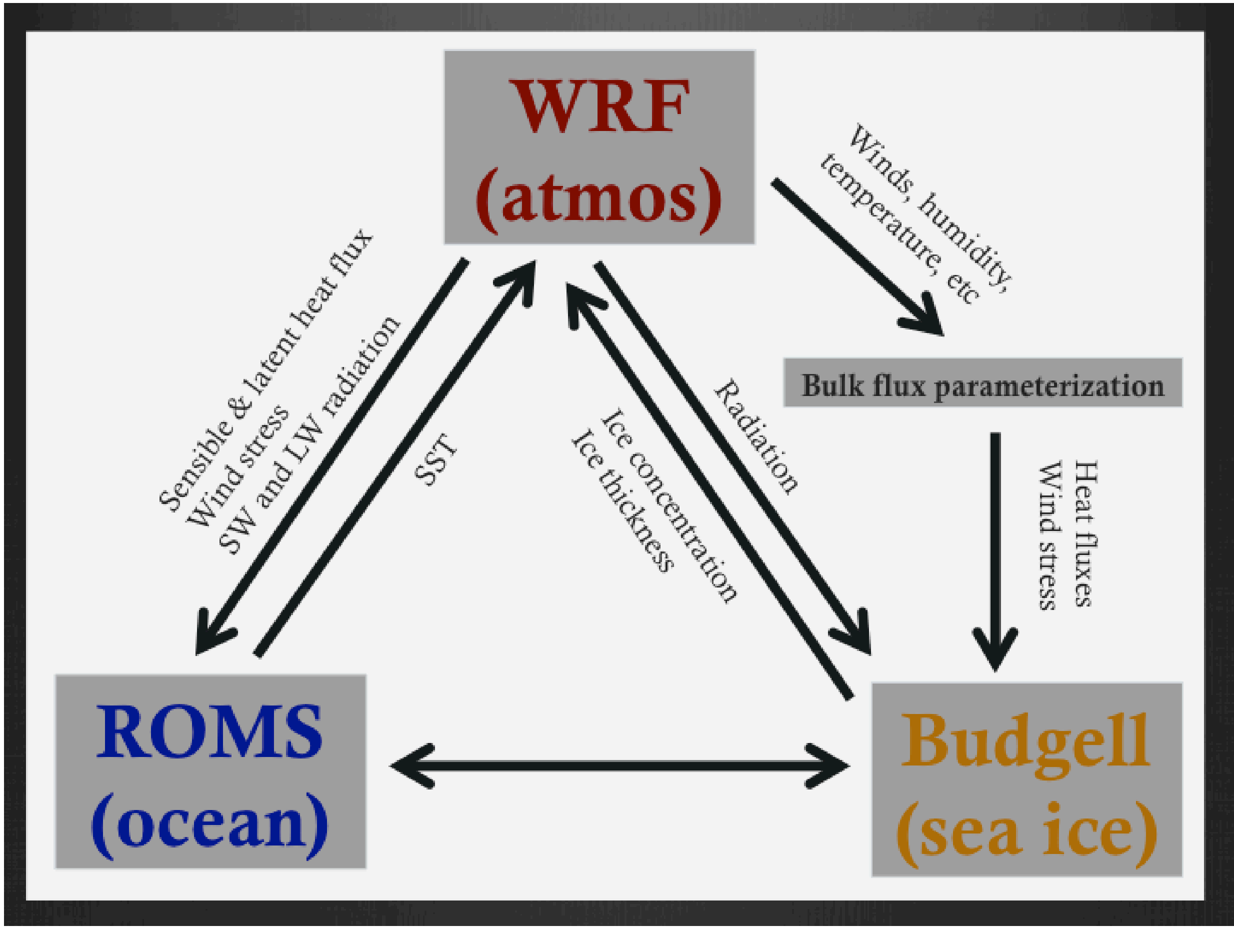
COAWST out of the box

No communication between atmosphere and sea ice models



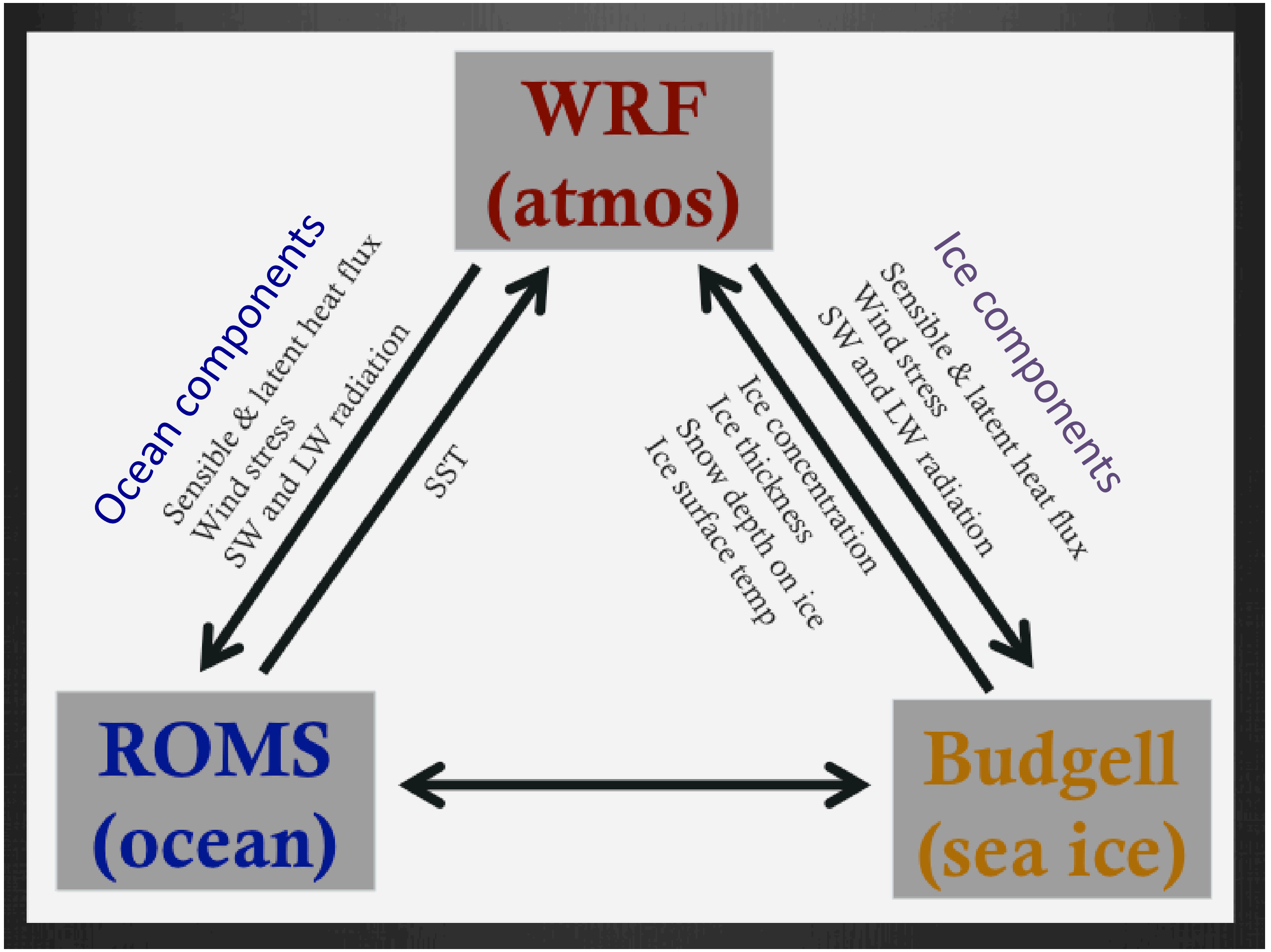
Version 1 coupling

Use atmospheric fields to parameterize fluxes.



Version 2 coupling

Appropriate atmospheric fields <u>passed directly</u> to ice model.



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Ocean Observing and Modeling Group

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- coastal circulation dynamics, modeling, and data assimilation
- coastal marine ecosystem dynamics and modeling
- Antarctic ice shelf and sea ice dynamics and modeling
- three-dimensional modeling of the Gulf of Mexico circulation and biogeochemistry

Applicants must hold a PhD degree in physical oceanography, ocean engineering, marine ecosystems, or a related science. The successful candidate must have the ability to work well independently and as part of a team, and have strong communication skills, both verbal and written. Preferred candidates will have experience with advanced ocean modeling, mathematical, and computational skills. Candidates should be motivated to drive new developments in ocean circulation modeling, marine ecosystems simulations, and/or data assimilation. Demonstrated proficiency in running complex model codes on high-performance computers, performing statistical analyses, and scientific programming (e.g., Fortran) and scripting (Perl, Python, NCL, Matlab) is greatly appreciated. The successful candidate will publish scientific articles and contribute to writing new funding proposals. Participation in short ocean cruises is a possibility.

Applications are currently being accepted for these funded positions. Details and application materials may be found on NCSU's employment site. Click on Search Jobs (or Quick Search: Post Doc), then search for keyword 00105109. You may also contact Professor He directly at **rhe [at] ncsu [dot] edu** and send your CV.