NC STATE UNIVERSITY

# Daily to Decadal Ecological Forecasting along North American Coastlines: *Gulf of Mexico and Southeast U.S.*


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In collaboration with (in alphabetical order)

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# Outline

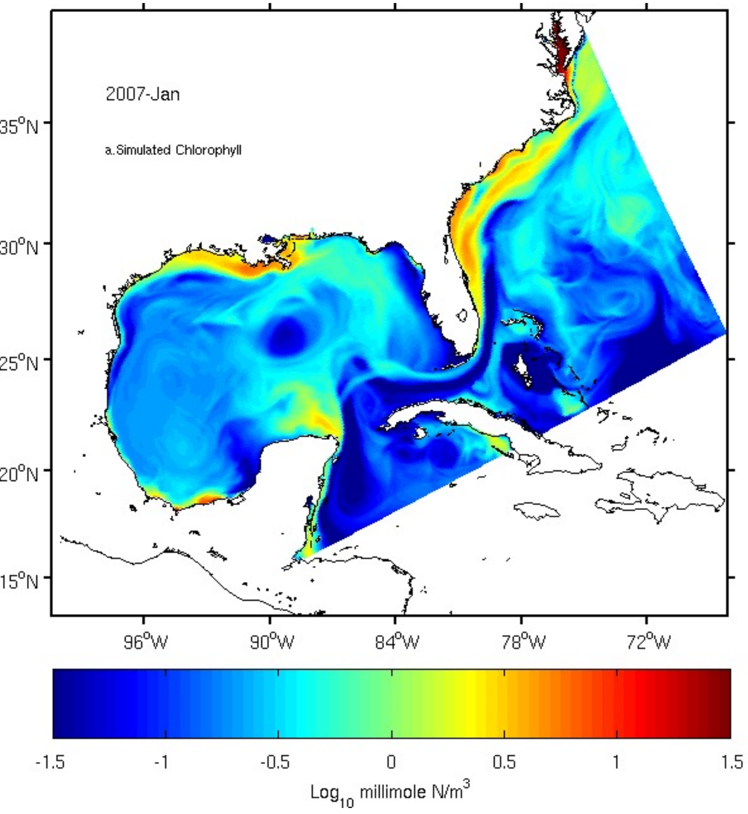
- ❑ Review
- ❑ Key driver 1: Storms
- ❑ Key driver 2: the Loop Current
- ❑ Key driver 3: the Gulf Stream
- ❑ New research focuses
- ❑ Summary

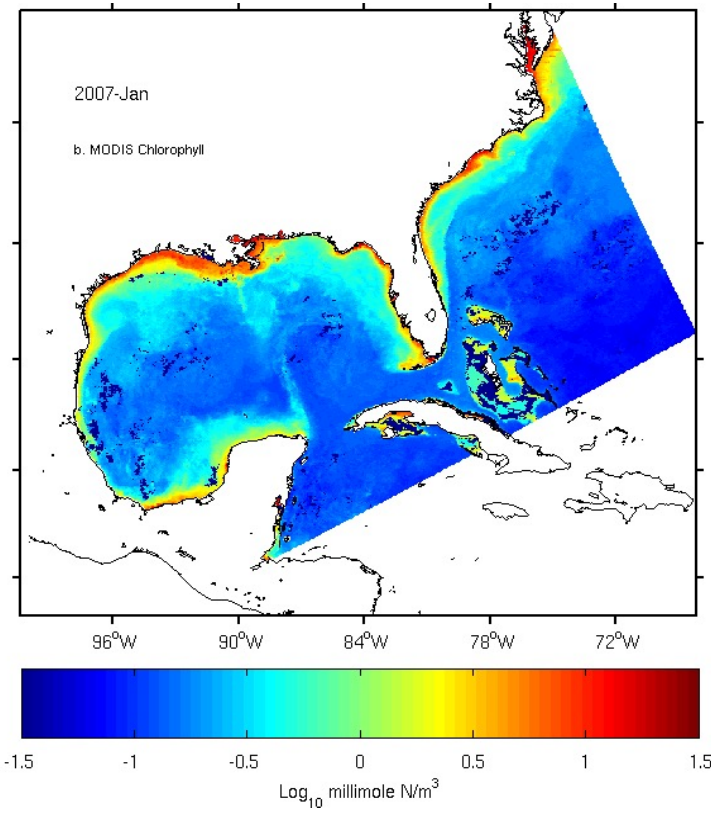
# Several major Physical-Biogeochemical (BGC) Model studies conducted in the GoM and southeast U.S.

| References | Highlights |
|---|---|
| **Fennel, K.**, Hetland, R., Feng, Y., and DiMarco, S. (**2011**): A coupled physical-biological model of the Northern Gulf of Mexico shelf: model description, validation and analysis of phytoplankton variability, Biogeosciences, 8, 1881–1899, https://doi.org/10.5194/bg-8-1881-2011. | examined phytoplankton dynamics on the Louisiana and Texas continental shelf, concluding that loss terms (e.g., grazing) rather than growth rates dictated accumulation rates of phytoplankton biomass. |
| **Xue, Z.**, He, R., Fennel, K., Cai, W.-J., Lohrenz, S., and Hopkinson, C.(**2013**): Modeling ocean circulation and biogeochemical variability in the Gulf of Mexico, Biogeosciences, 10, 7219–7234, https://doi.org/10.5194/bg-10-7219-2013. | conducted the first gulf-wide study to investigate broad seasonal biogeochemical variability and to constrain a shelf nitrogen budget. |
| **Gomez, F. A.**, Lee, S.-K., Liu, Y., Hernandez Jr., F. J., Muller-Karger, F. E., and Lamkin, J. T. (**2018**): Seasonal patterns in phyto-plankton biomass across the northern and deep Gulf of Mex-ico: a numerical model study, Biogeosciences, 15, 3561–3576,https://doi.org/10.5194/bg-15-3561-2018. | implemented a biogeochemical model with multiple phytoplankton and zooplankton functional types to gain a more detailed understanding of nutrient limitation and phytoplankton dynamics in the GoM |
| **Damien, P.**, Pasqueron de Fommervault, O., Sheinbaum, J.,Jouanno, J., Camacho-Ibar, V. F., and Duteil, O. (**2018**): Partitioning of the Open Waters of the Gulf of Mexico Based on the Seasonal and Interannual Variability of Chlorophyll Concentration, J. Geophys. Res.-Oceans, 123, 2592–2614, https://doi.org/10.1002/2017JC013456. | examined phytoplankton seasonality and biogeography in the oligotrophic Gulf of Mexico, and validated a PBM based on a unique subsurface autonomous glider dataset. |
| **Shropshire, T. A.**, Morey, S. L., Chassignet, E. P., Bozec, A., Coles, V. J., Landry, M. R., Swalethorp, R., Zapfe, G., and Stukel, M. R. (**2020**): Quantifying spatiotemporal variability in zooplankton dynamics in the Gulf of Mexico with a physical–biogeochemical model, Biogeosciences, 17, 3385–3407, https://doi.org/10.5194/bg-17-3385-2020. | configured a coupled physical-BGC model for the GoM to estimate zooplankton abundance and analyze size-structure zooplankton community dynamics. |

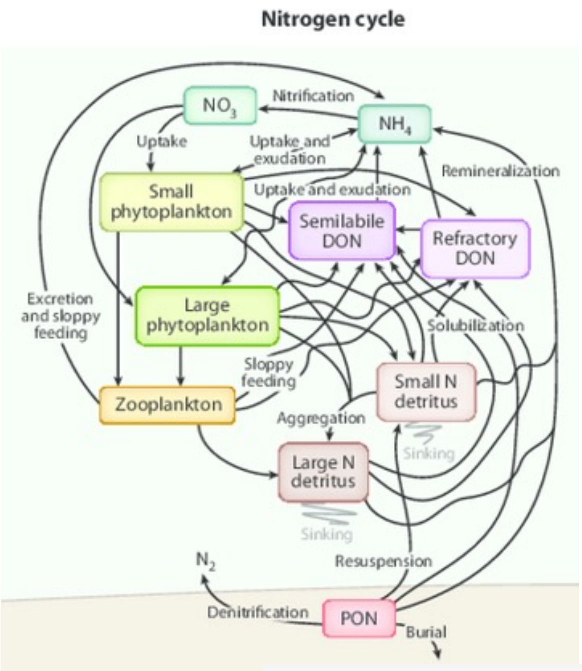
# SAB-GOM Fennel Model

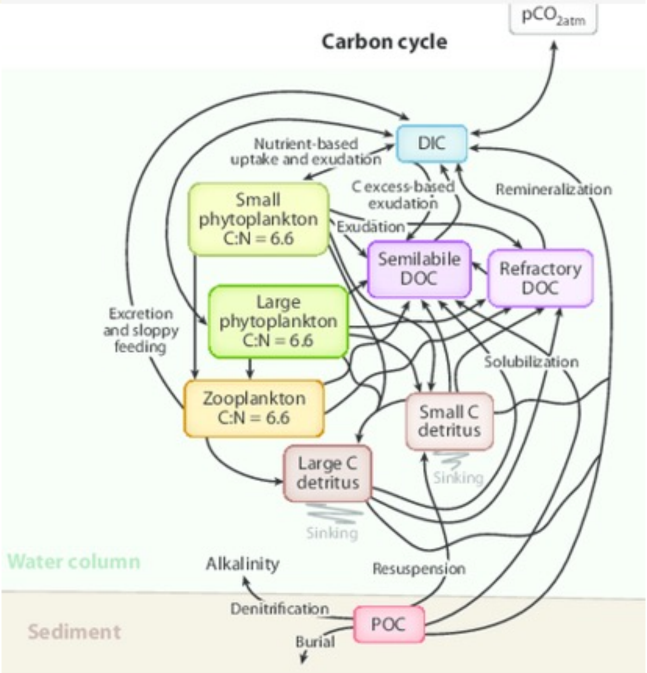
- The spatial resolution is 5 km
- extends from 2004 to 2017
- Based on SABGOM ROMS hydrodynamics




(Xue, He, Fennel et at., 2013)

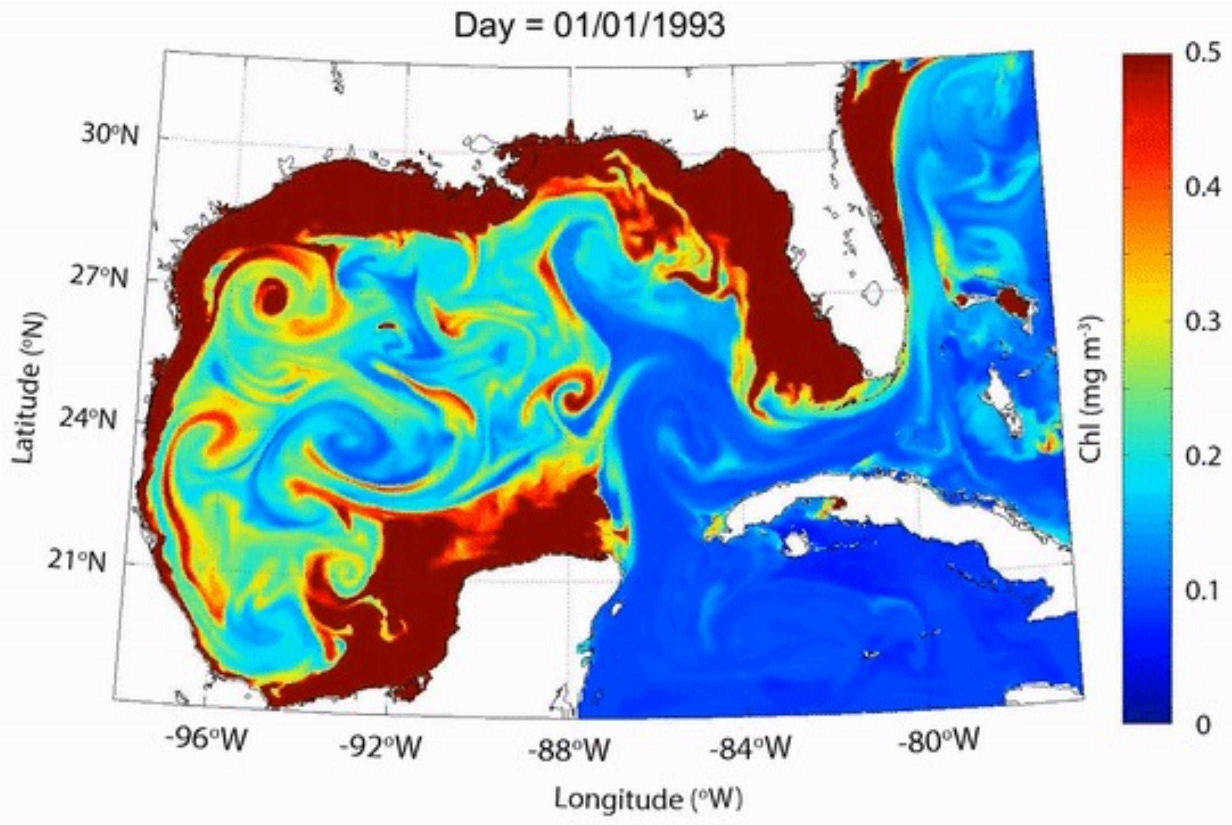


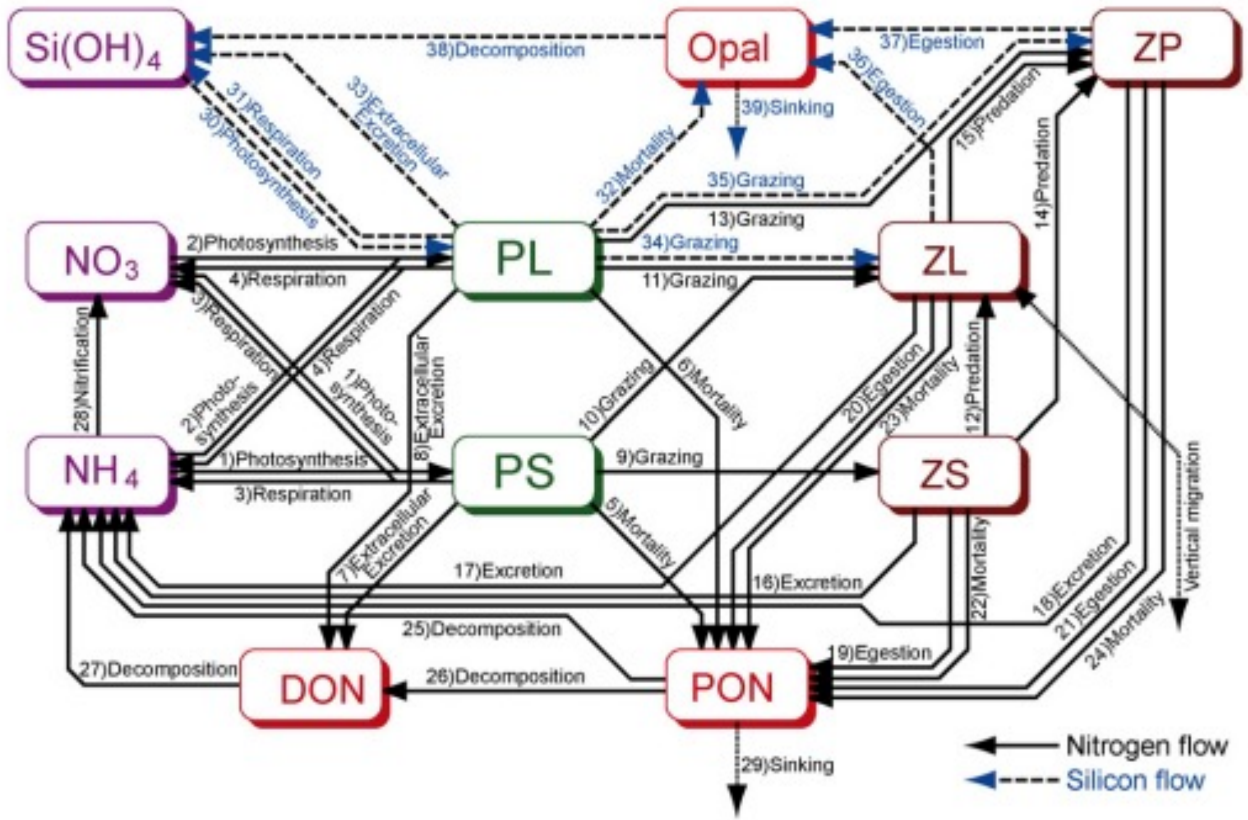

(Hoffmann et at., 2011)

# GOM NEMURO Model

- The spatial resolution is 1/25th degree
- extends from 1993-2012
- Based on GoM HYCOM hydrodynamics



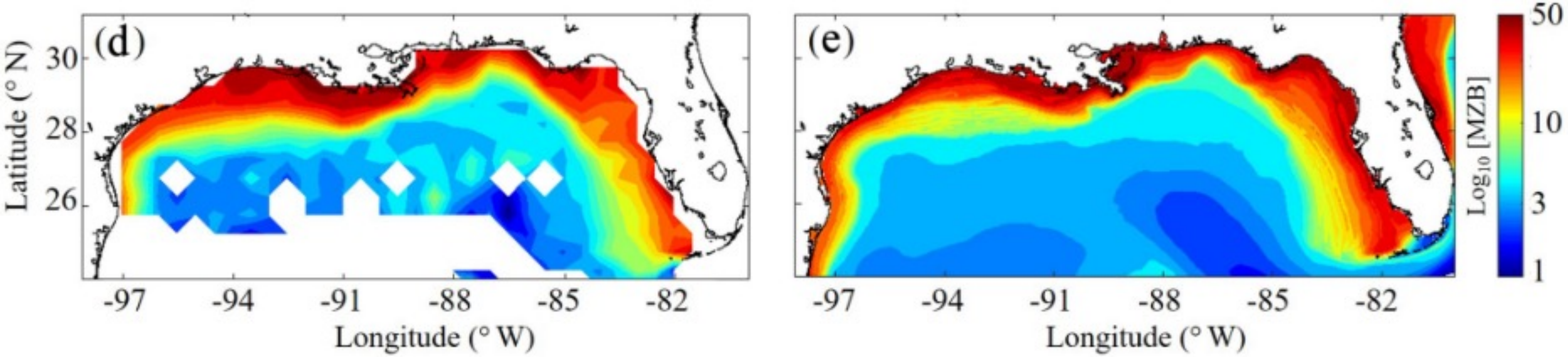

Shropshire et al. (2020)




Kishi et al., (2007)

# Climatological meso-zooplankton biomass

SEAMAP Observations | Model simulation

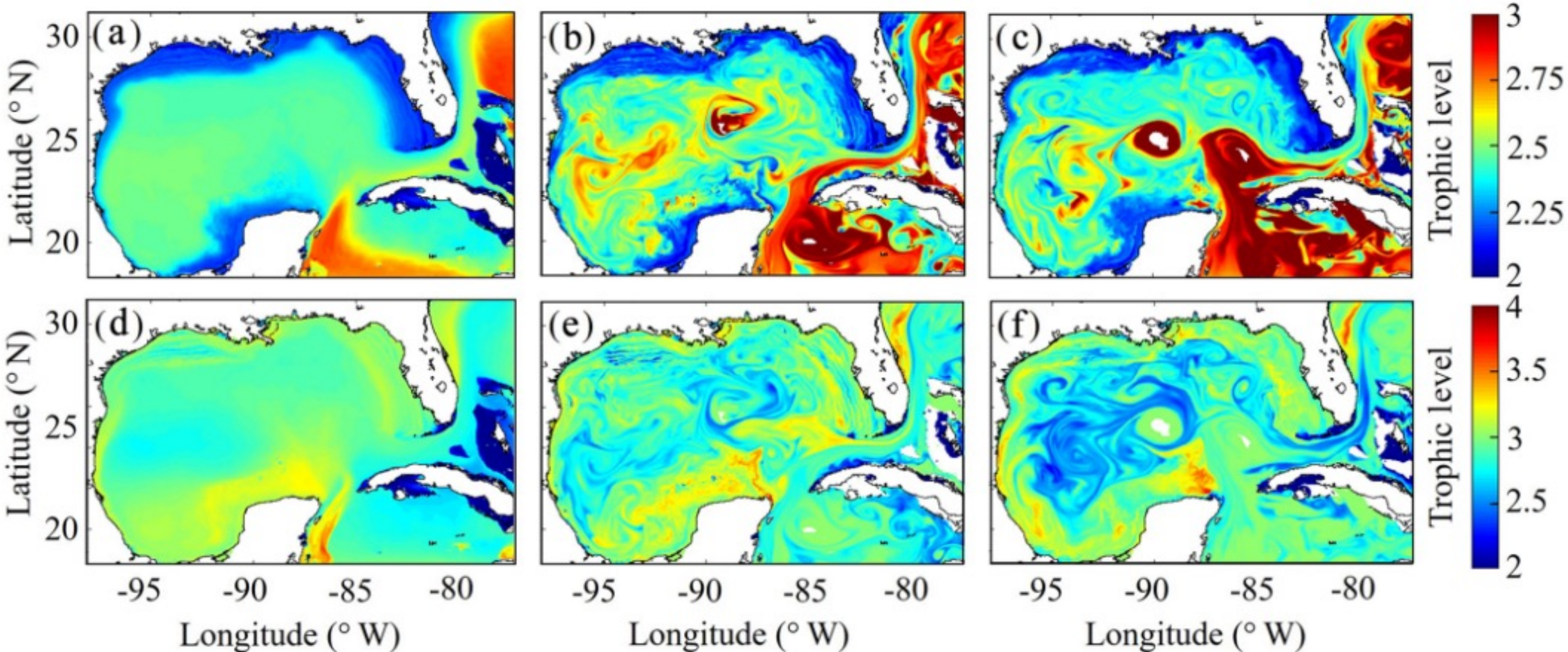



Shropshire et al. (2020)

Annual Mean | Feb, 4 2012 | Aug 2, 2011

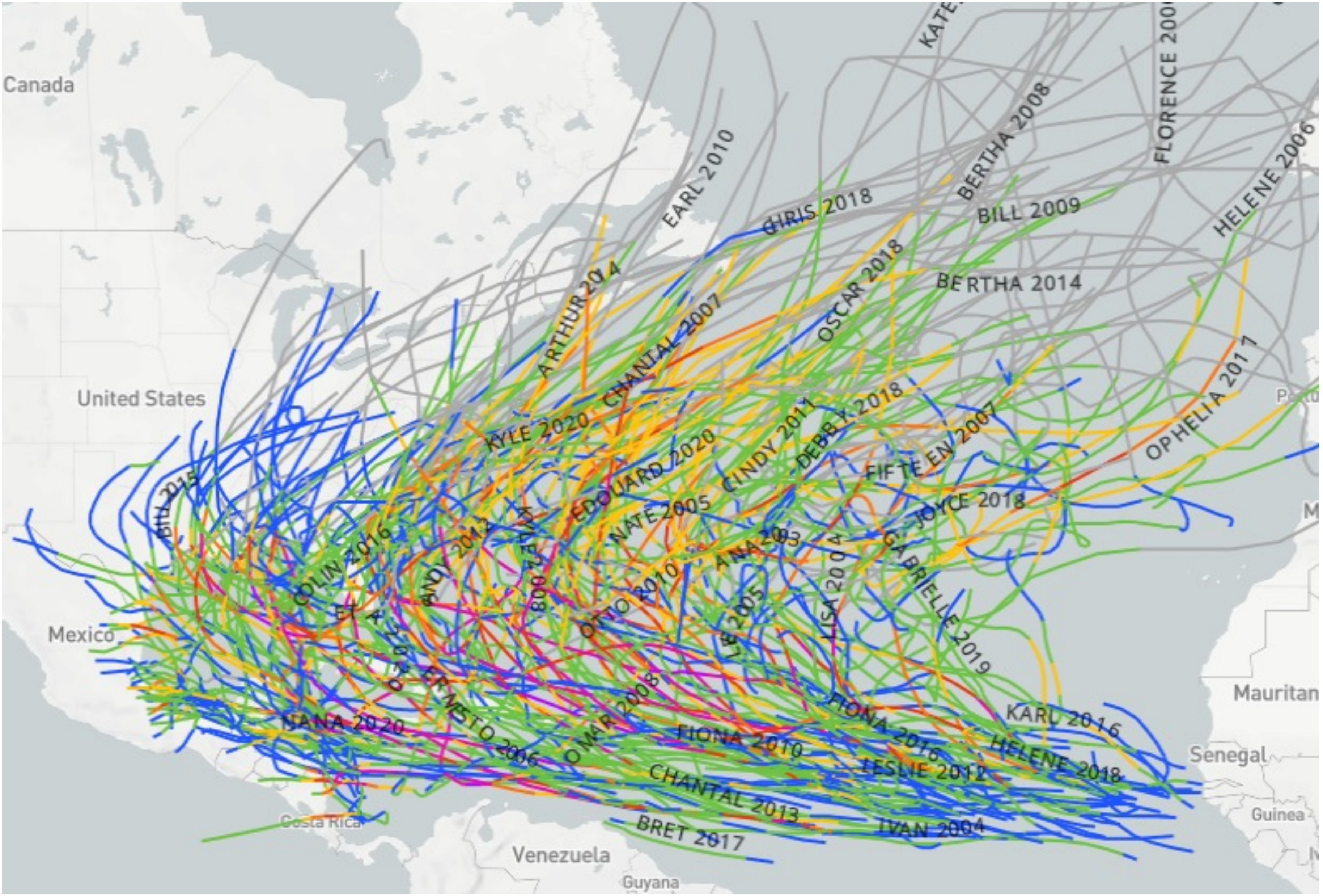
Large Zooplankton

Predatory Zooplankton



- Many progresses have been made in developing BGC/marine ecological models that have encouraging seasonal and mesoscale skills.

- The predictability of marine ecosystem and marine resources are dependent upon how well we can understand and predict their physical drivers.




# 2003-2020

321 matching storms

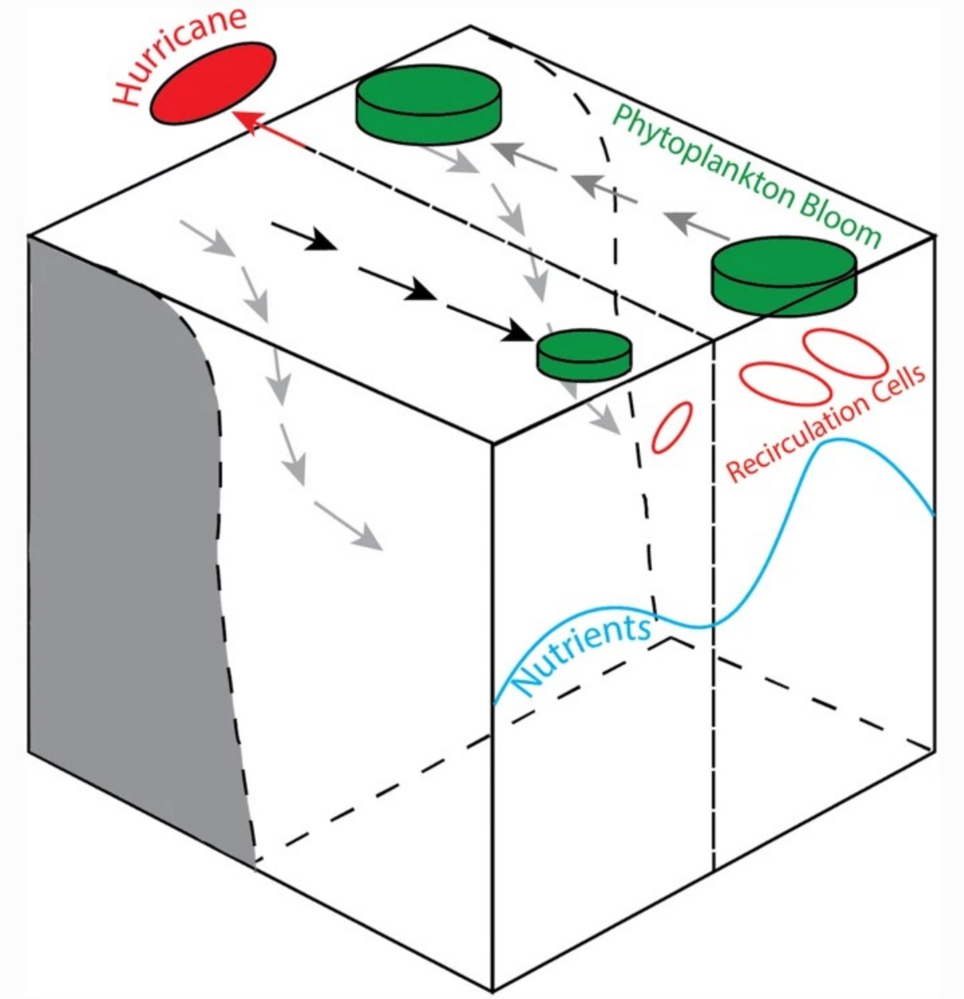
**Storm Categories**

The categories shown are based on the Saffir-Simpson Hurricane Wind Scale.

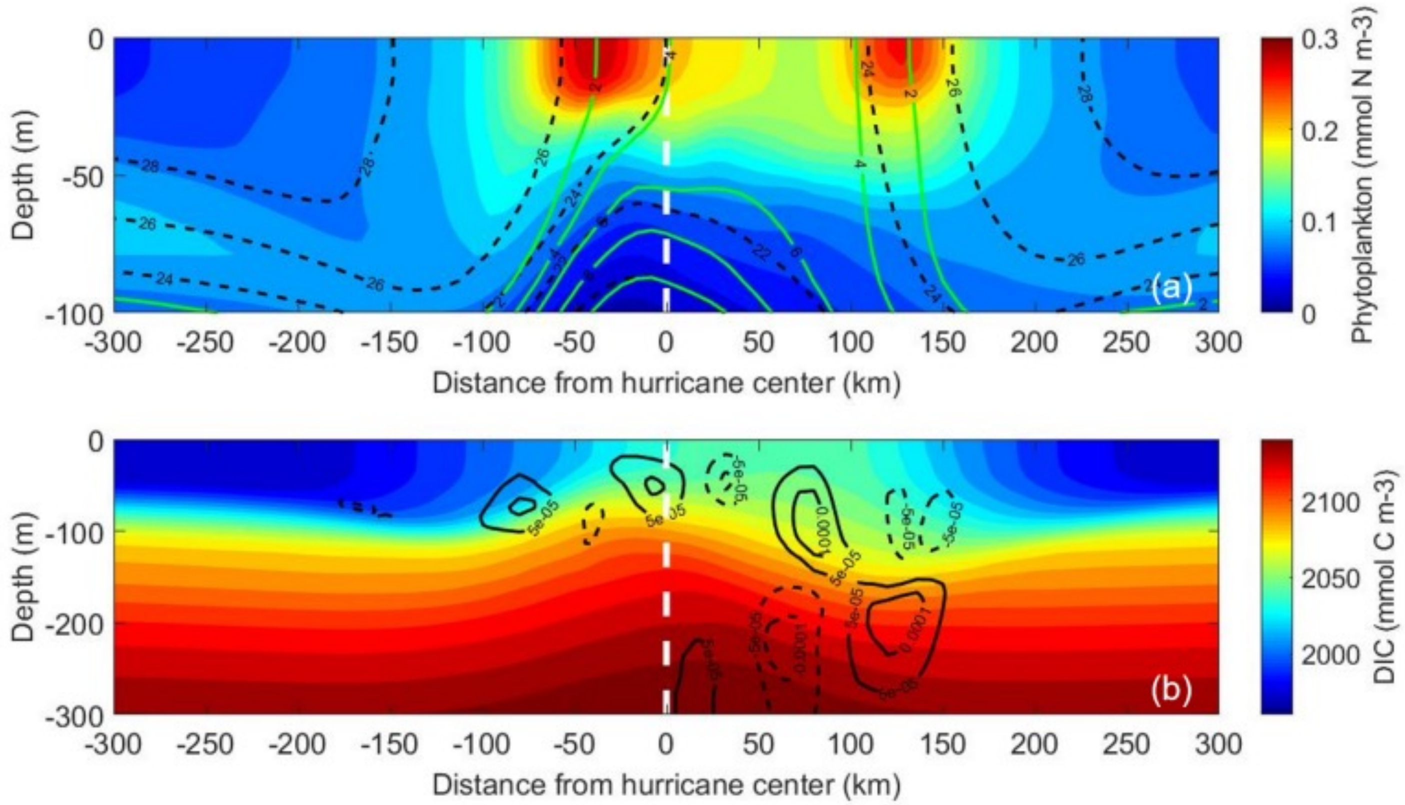
- Category 5
- Category 4
- Category 3
- Category 2
- Category 1
- Tropical Storm
- Tropical Depression

coast.noaa.gov

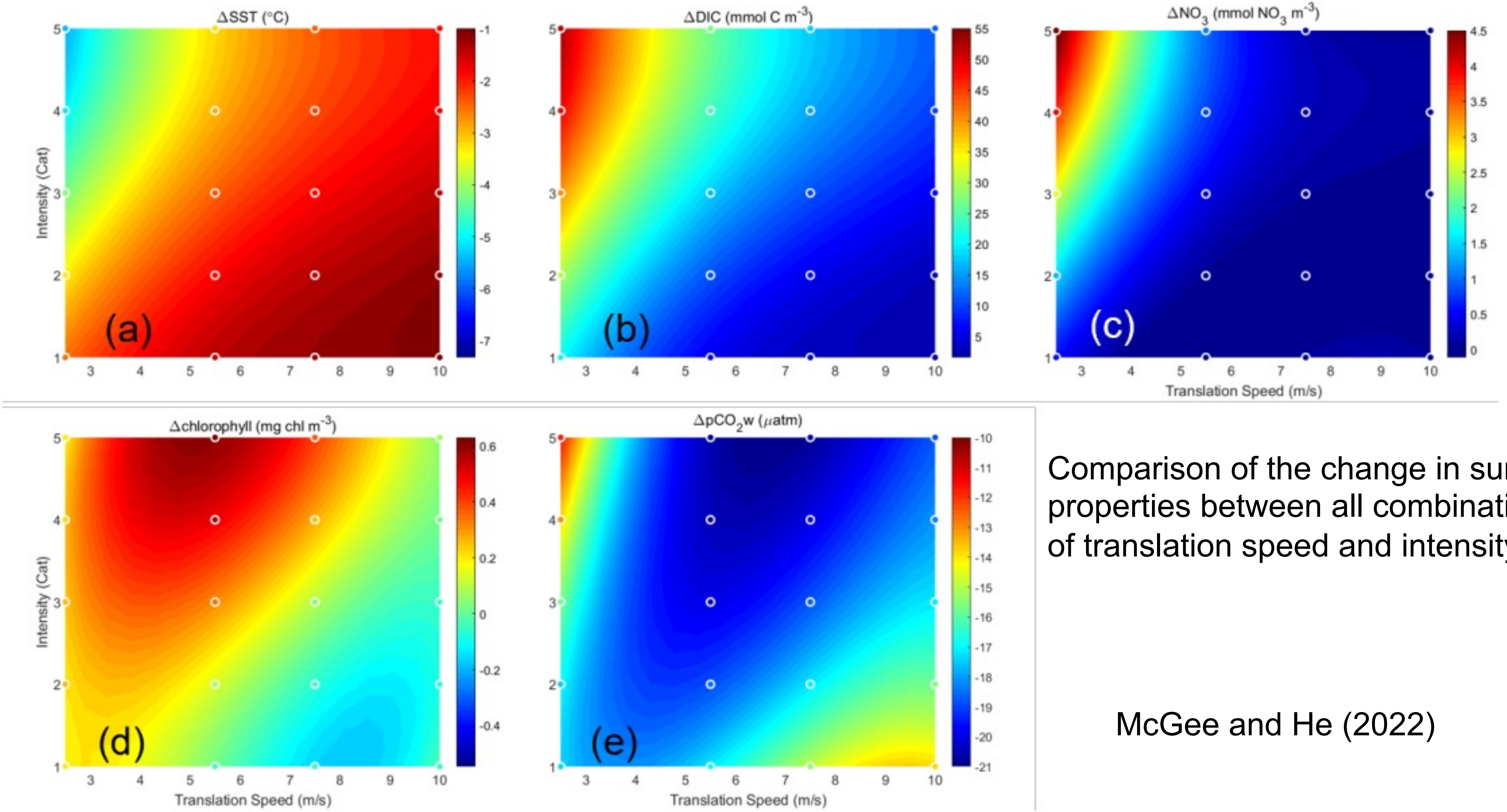
# "Right-hand" bias of SST, Chl-a, DIC, and air-sea pCO2 fluxes




McGee and He (2018)

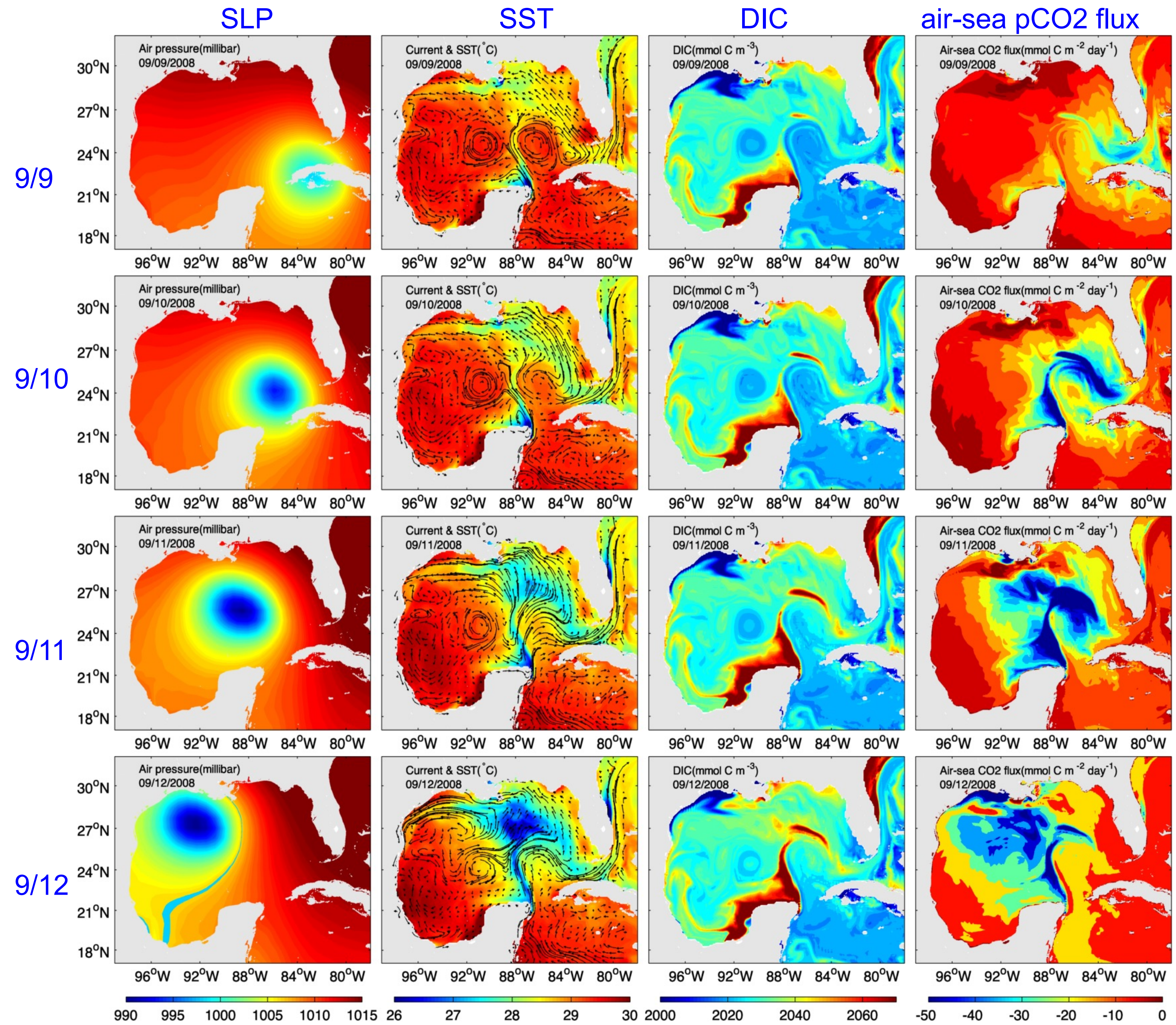



McGee and He (2022)

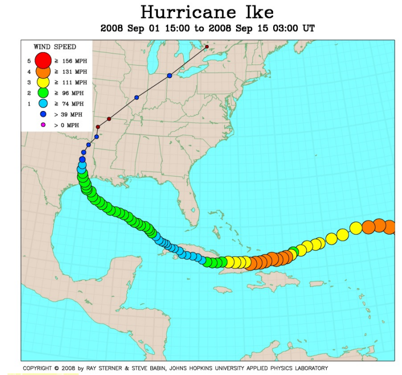



Comparison of the change in surface properties between all combinations of translation speed and intensity.

McGee and He (2022)




## Hurricane Ike: 9/1 -9/15, 2008

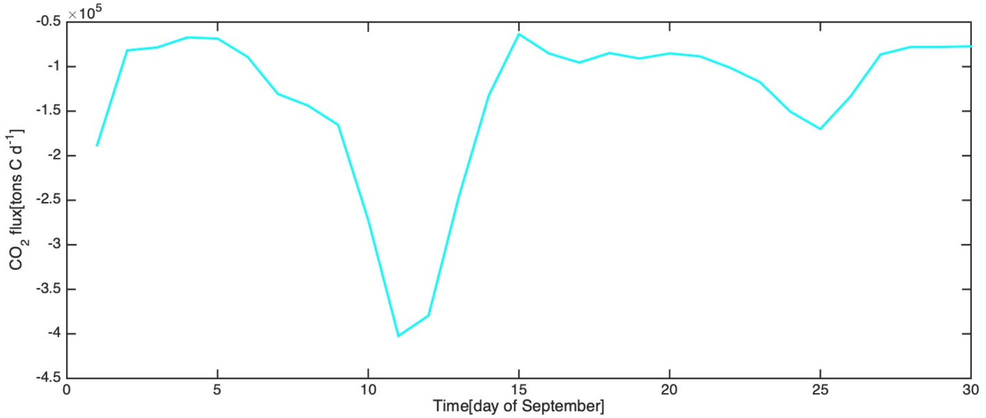



$$\Delta pCO_2 = pCO_{2\,a} - pCO_{2\,w}$$

$$CO2\ flux = k \ x\ s\ x\ \Delta pCO_2$$

$$F = \int_0^A CO_2Flux\ da$$

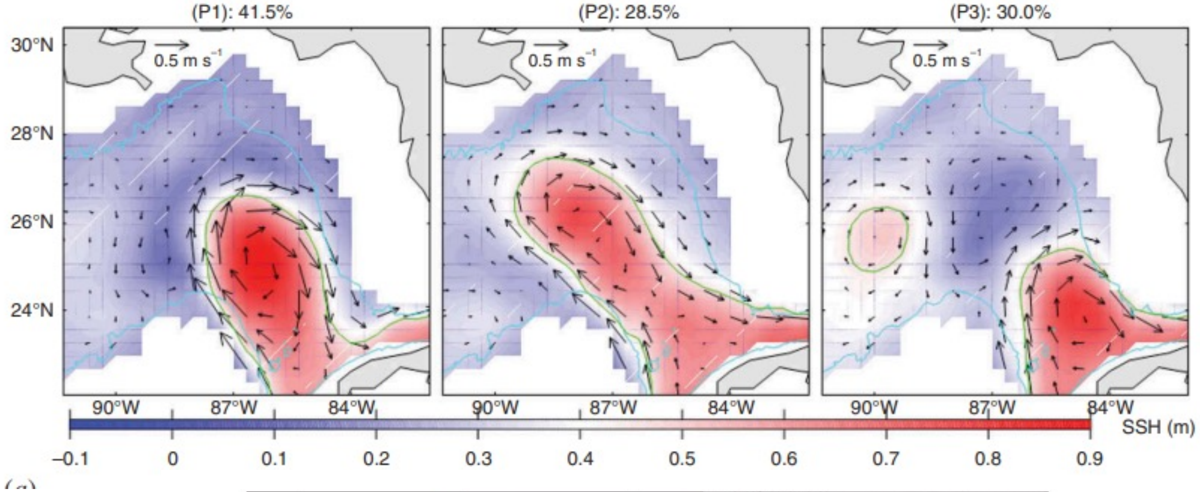
*a* is the area of Gulf of Mexico

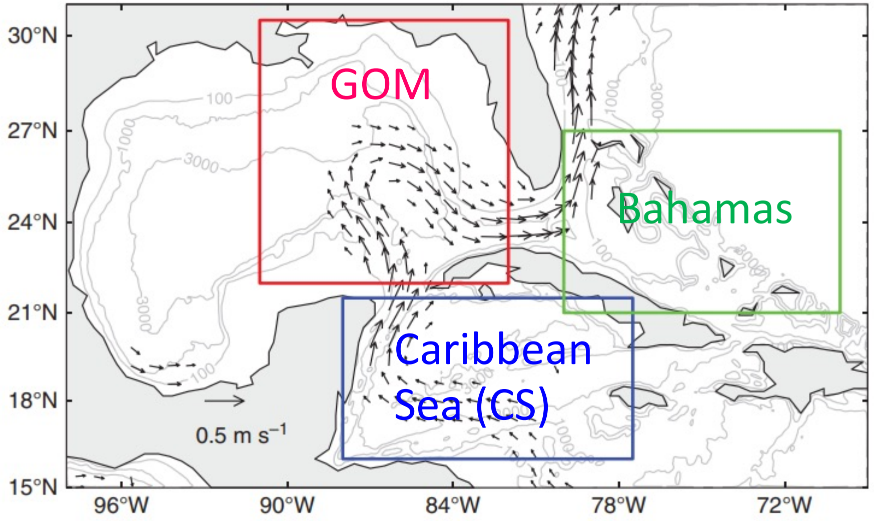



Zong and He (submitted)

"The position, strength, and structure of the Loop Current System (LCS) has major implications for hurricane intensity, marine ecosystems, oil and gas operations, the fishing industry, tourism, and the Gulf region's economy."        NAS Study report (2018)

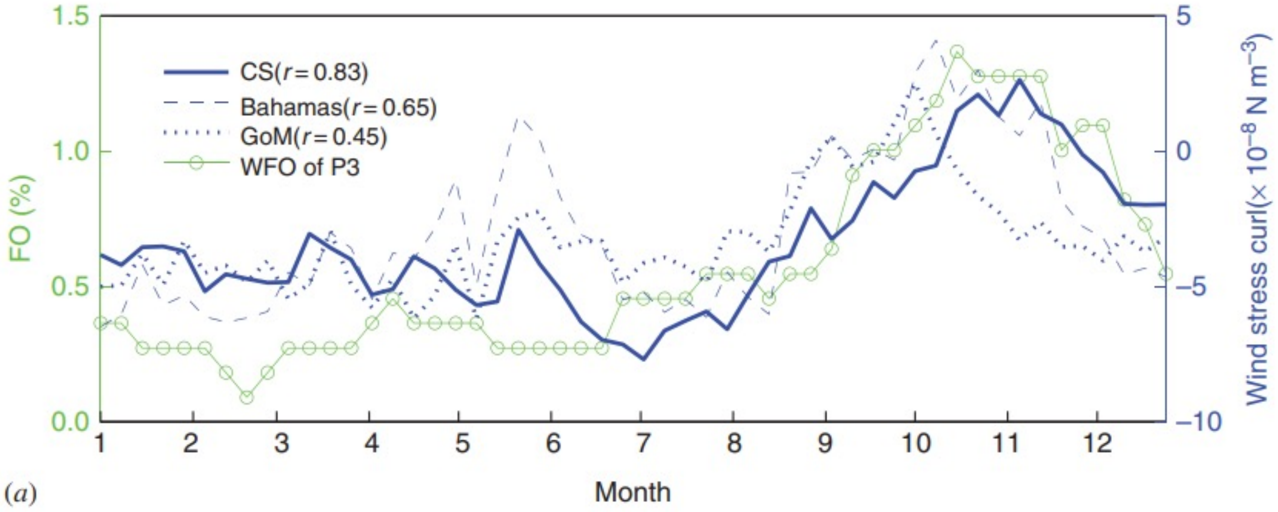
Normal        Extension        Retraction/Separation



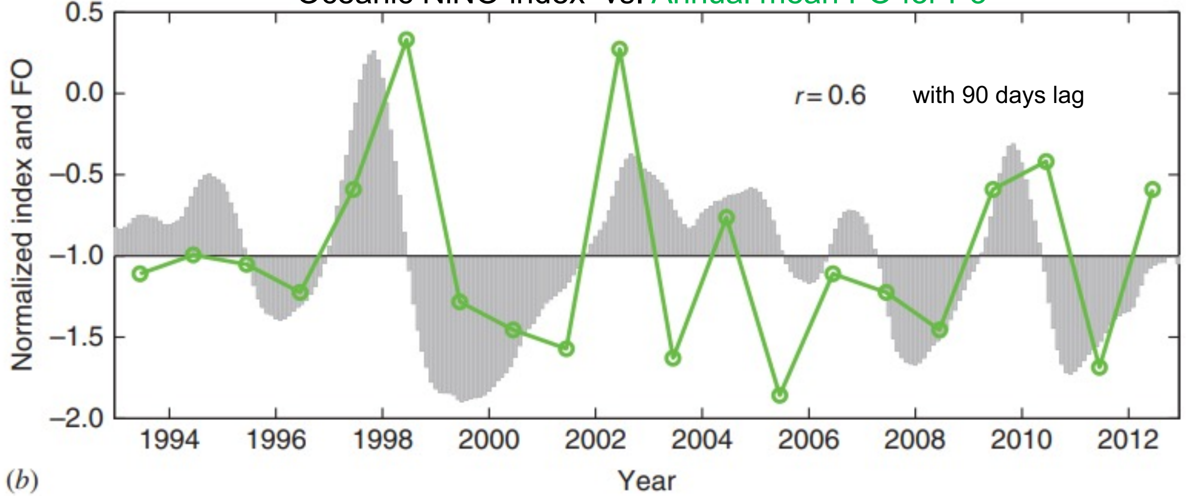




Zeng et al. (2015)

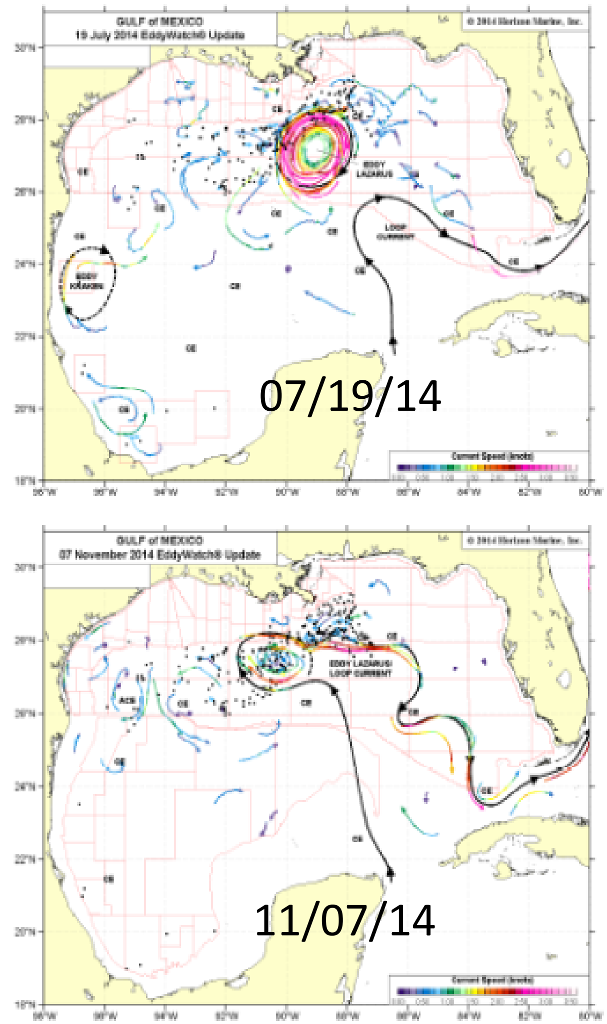
P3 Frequency of Occurrence (FO) vs. Wind Stress Curls




Oceanic NiNO index vs. Annual mean FO for P3

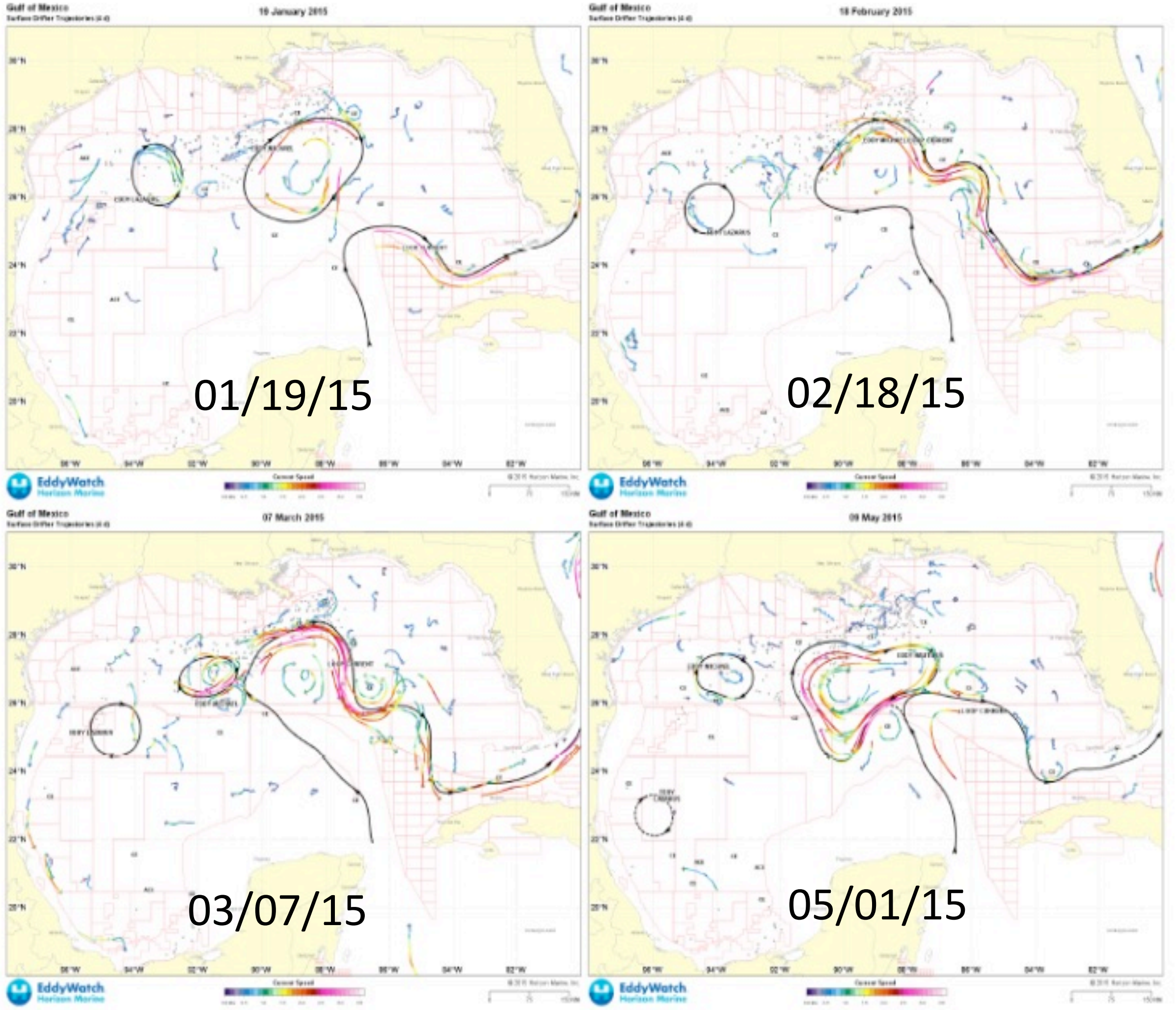


# Loop Current “Hyperactivity” (2014-2015): forecasting “nightmare”

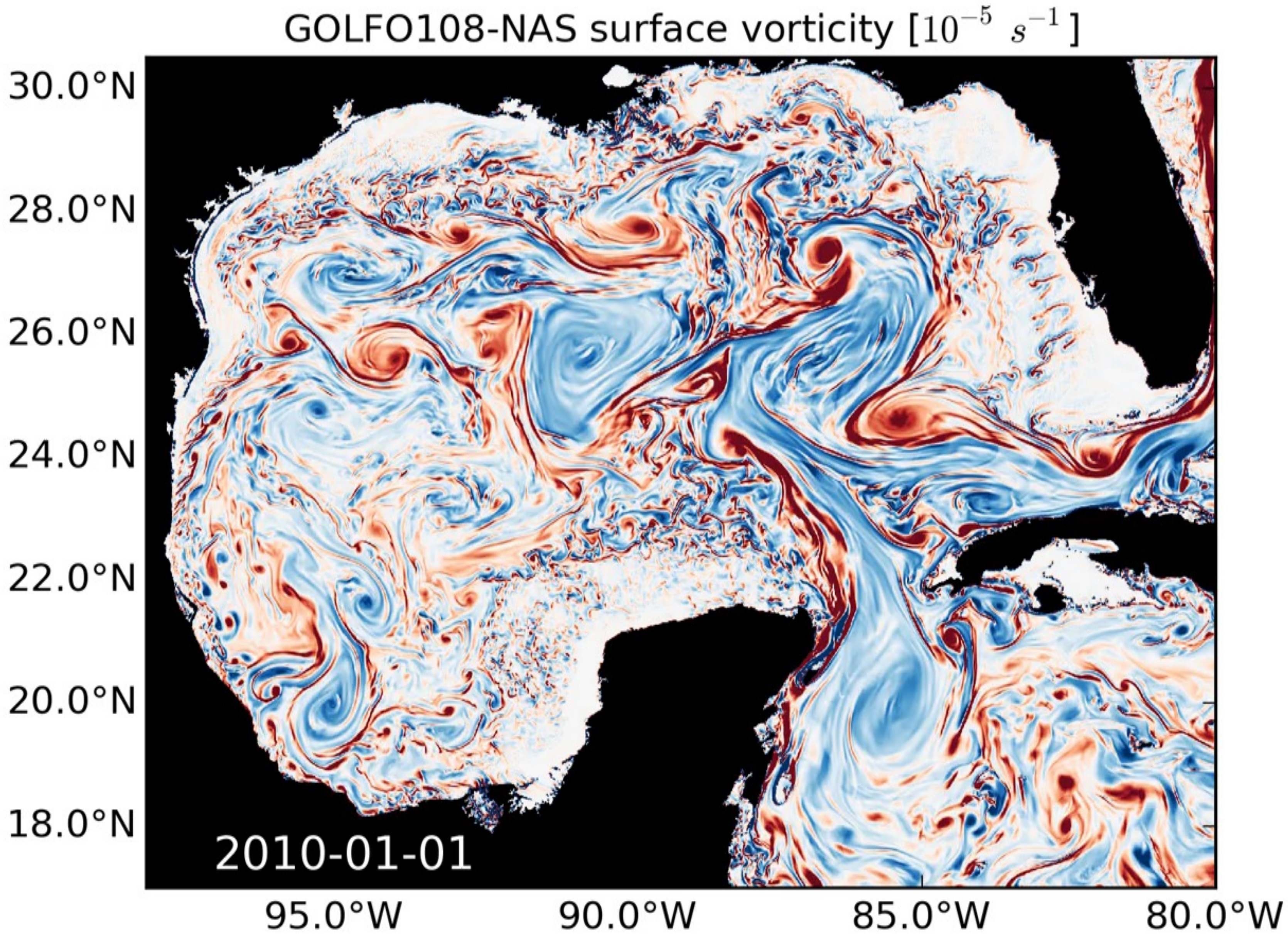



Sharma et al. (2016)

Eddy Lazarus on 19 July, 29 September, 07 November, and 01 December 2014.




Eddy Michael on 19 January, 18 February, 07 March, and 01 May 2015.



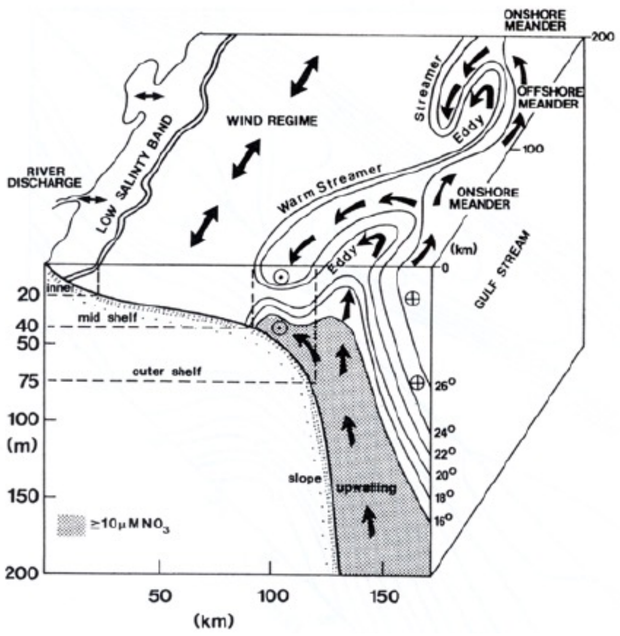

# 1-km NEMO model simulation of surface ocean vorticity

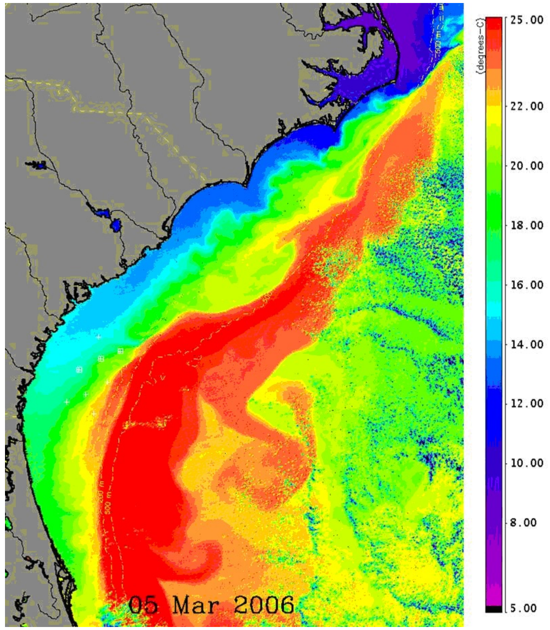
Movie courtesy: Julien Jouanno

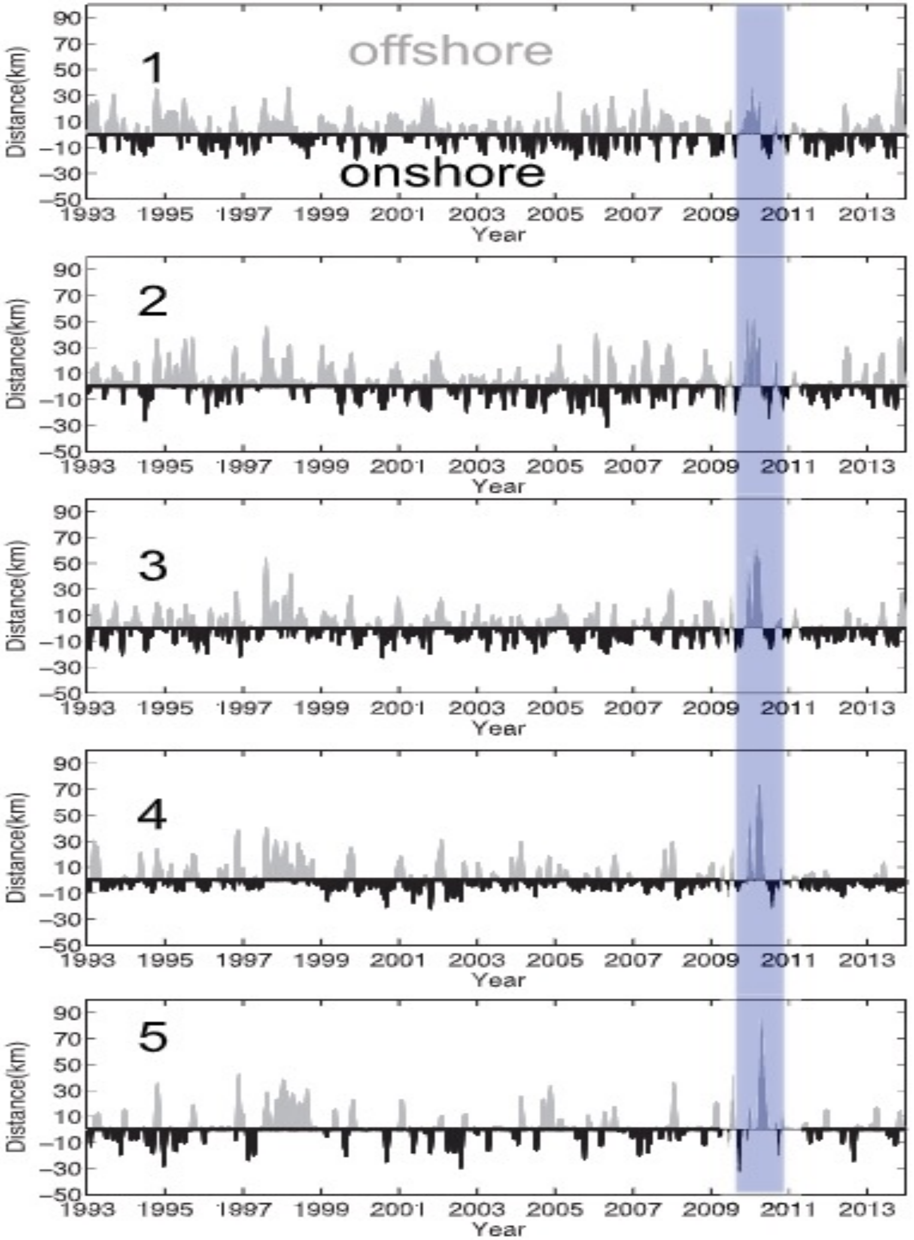
McWilliams (2016)
Mahadevan (2016)
McGillicuddy(2016)

# GS meanders and Offshore Distance

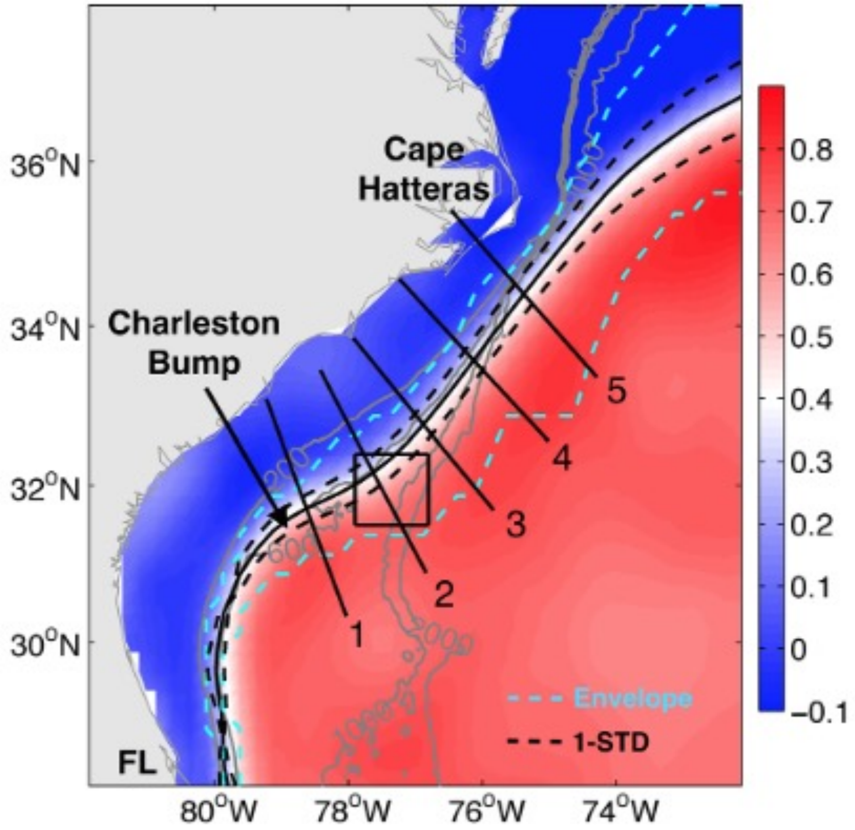
*Lee et al.(1991), JGR*



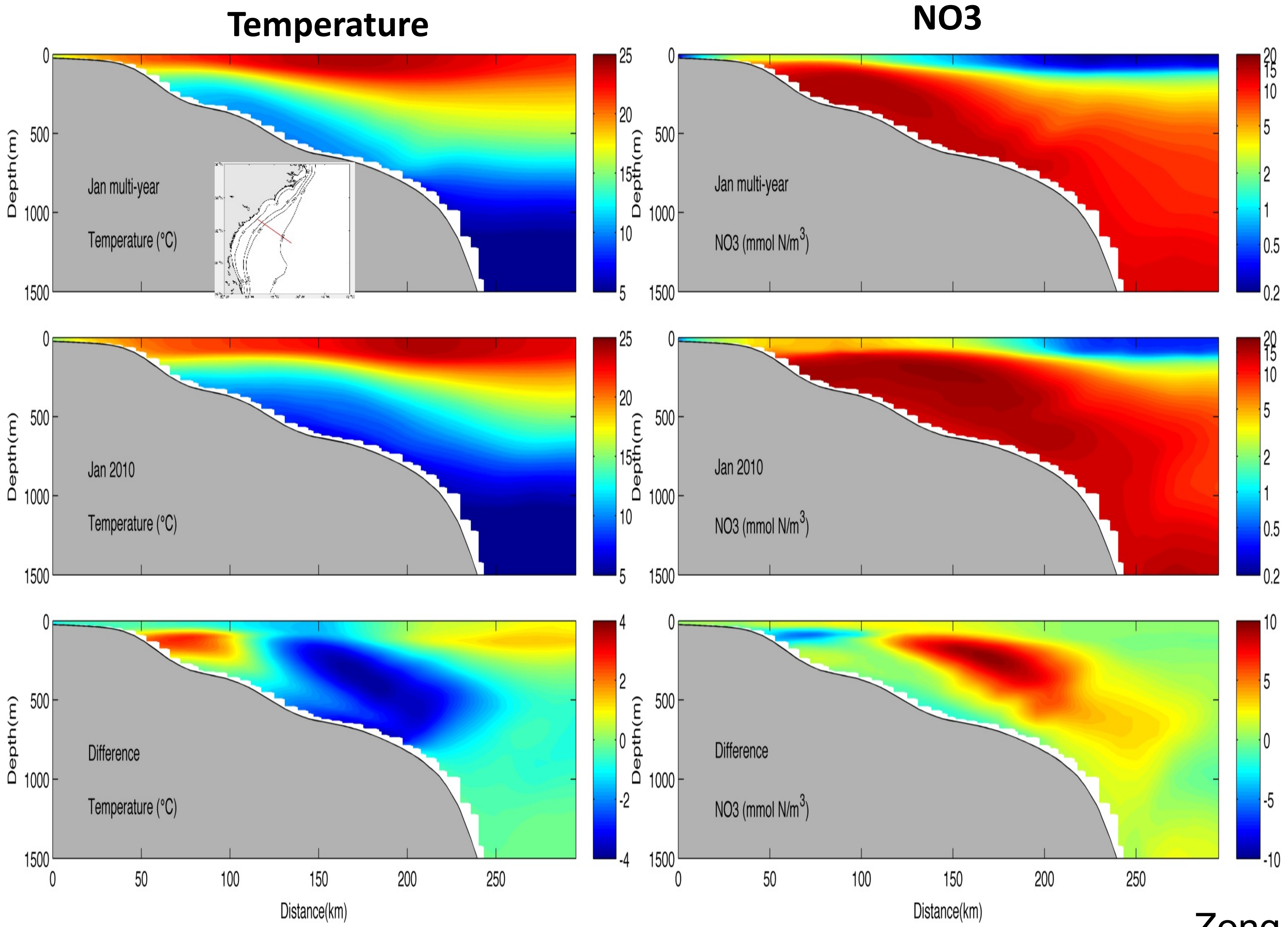




1993-2013 Mean SSH (color shading)
Mean GS position, STD, and Envelop



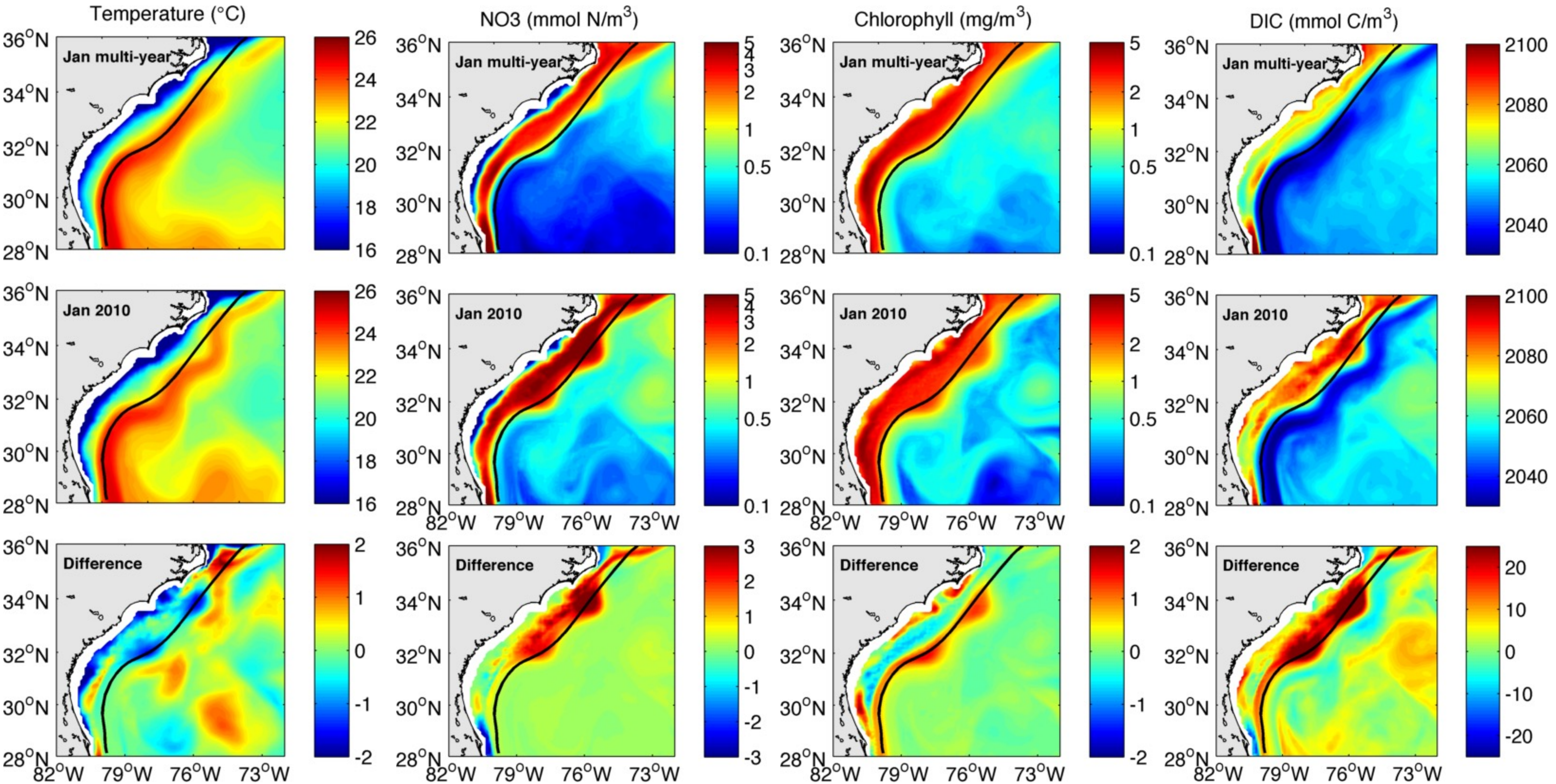

Zeng and He (2016)

# Coupled Physical-BGC Model simulation for the largest GS offshore meander occurred in November 2009 to April 2010




Zong and He (submitted)

# Subsurface (20 m) distribution of SST, NO3, Chl-a, and DIC



# Some key predictability questions to be addressed:

1) Are the Loop Current Eddy separation (LCES) and Gulf Stream meanders (GSM) predictable?

2) How are LCES and GSM affected by winds and other large scale air-sea processes?

3) How do LCES and GSM vary on the daily to decadal time scale?

4) How do the LCES and GSM initiate?

5) How do multiscale physical-BGC processes interact? downscaling (mesoscale → submeso scale) and upper-scaling (submesoscale → mesosccale)

6) How well can models reproduce the timings, strengthes, and durations of LCES and GSM, and the biogeochemical variability associated with them?

# Ways to improve our understanding

(1) Generate long term (decadal-scale) ocean reanalysis:
- require data assimilation to keep the model on track

(2) Develop new evaluations and improvements in ocean forecasting methodology:
- multi-model ensembles for inter-comparisons and uncertainty quantification

(3) Better integrate model and models beyond just validation:
- Observing System Simulation Experiments (OSSEs) can be used to provide a reference for observational design criteria, instrument locations, and sampling intervals for the field campaign

# Ensemble Data Assimilation Ocean Reanalysis (1993-2021)

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{B}\mathbf{H}^T \left[\mathbf{H}\mathbf{B}\mathbf{H}^T + \mathbf{R}\right]^{-1} \left[\mathbf{y} - \mathcal{H}(\overline{\mathbf{x}^f})\right],$$

$$\mathbf{B} \equiv \mathbf{A}\mathbf{A}^T \left[(\mathbf{m}-1)\right]^{-1},$$

"Kalman Gain"

$\mathbf{x}^a$ and $\mathbf{x}^f$ are DA analysis and model forecast state variables, respectively $\mathbf{x}(\eta, T, S, U, V, \bar{u}, \bar{v})$

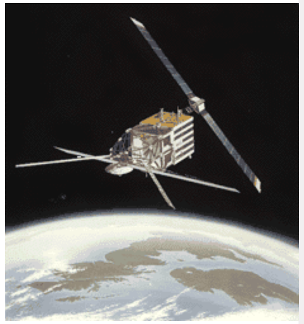
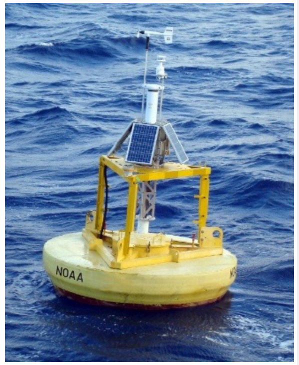
**y**: observations ($\eta$, $T$ , $S$, $U$ , $V$);

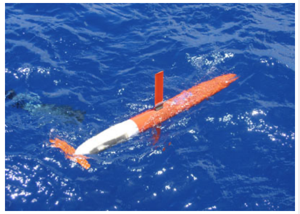
**H**: the observation sampling operator;

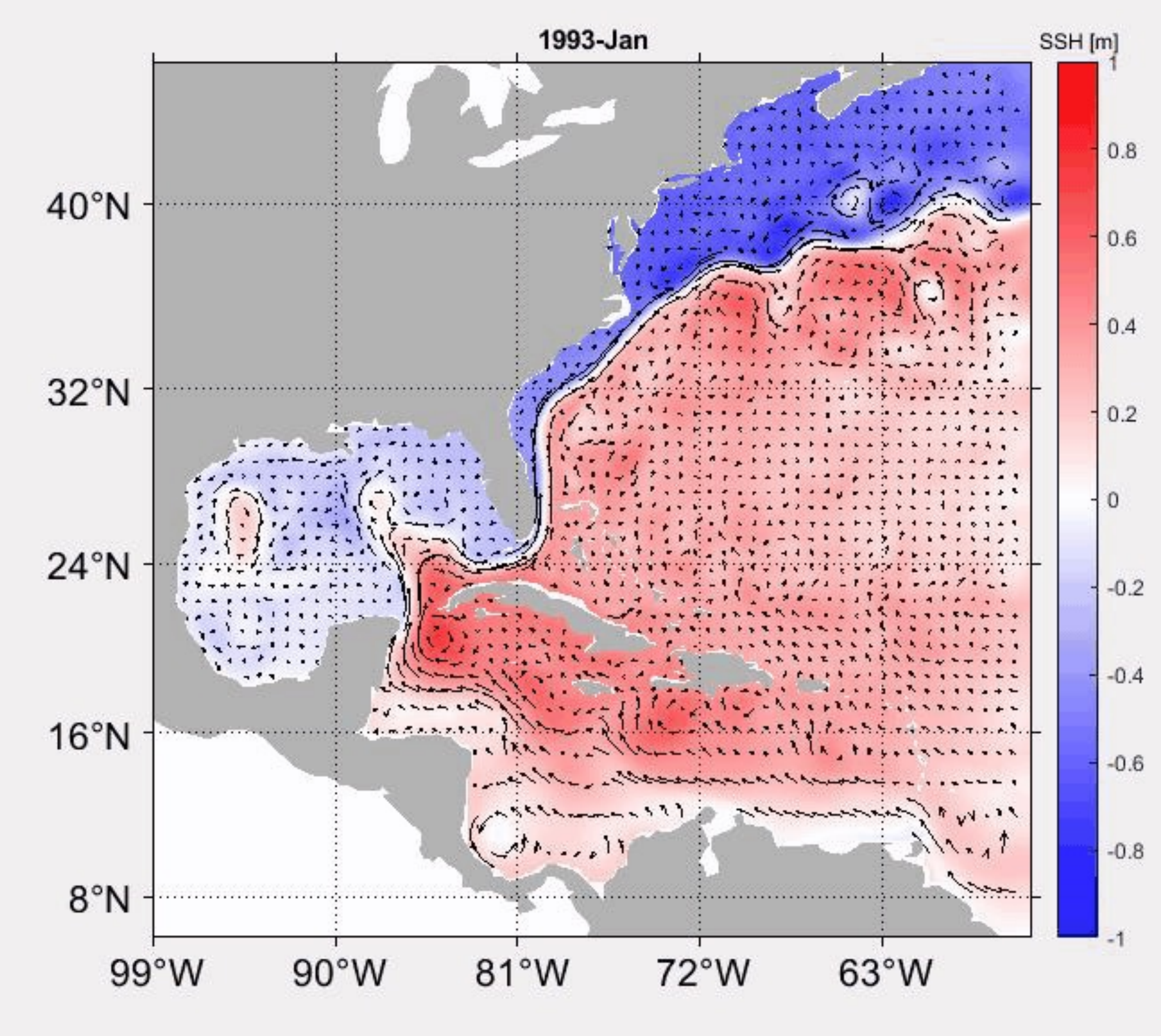
**B**: background error covariance;
**A**: ensemble anomalies
155 ensemble members running with perturbed initial conditions → **B**

**R**: observation error covariance

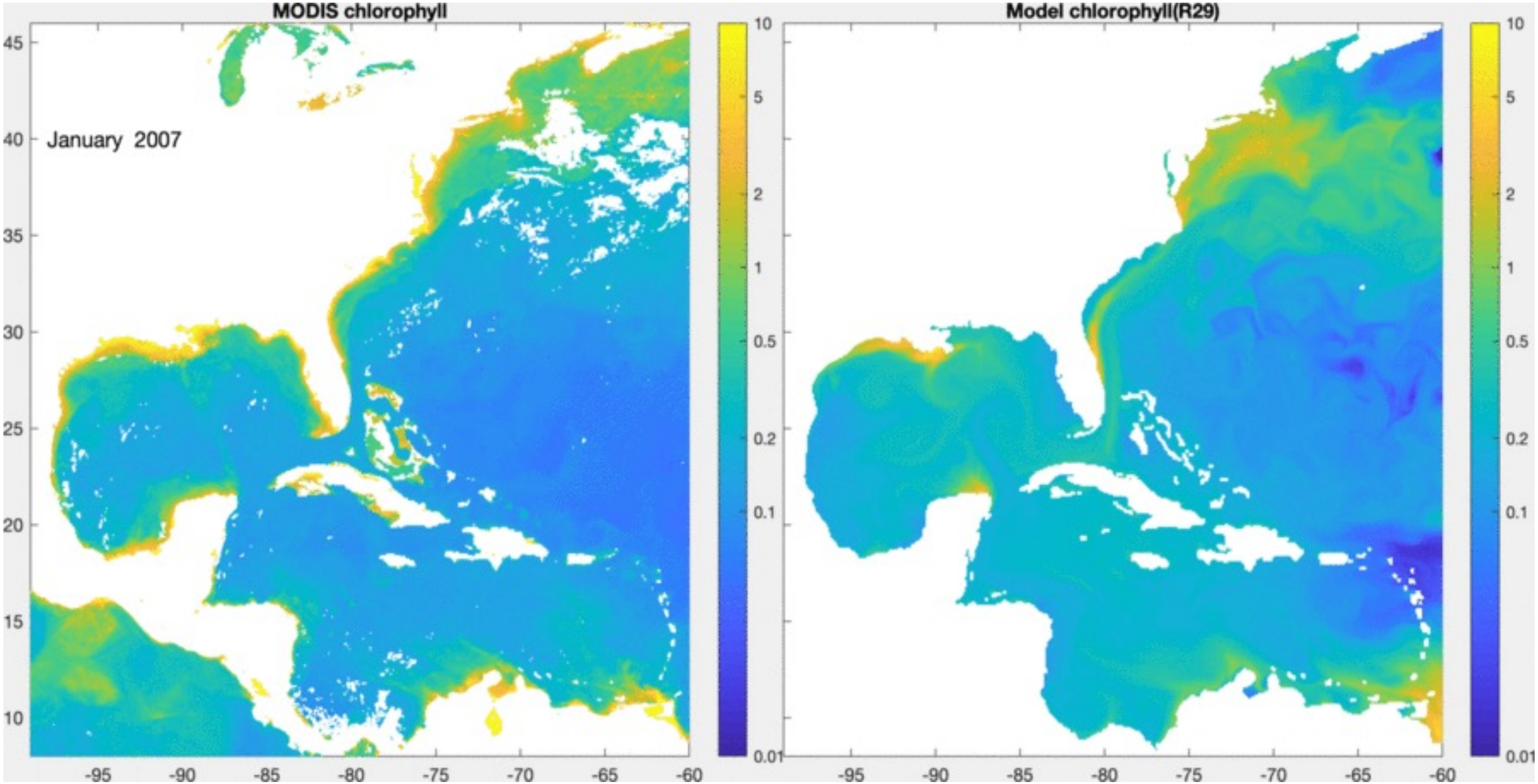
He et al. (in prep)



# Comparison between observed and modeled monthly surface Chl-a field ($mg/m^3$)



- Hurricanes play a major role in US. southeast-GOM ecological forecasting. Improved hurricane forecast, and better understanding of how hurricanes interact with the ocean's nutrient and carbon cycling will help us predict regional ecological processes.

- Broad spectrum histogram shows the Loop Current eddy shedding has a weak seasonal signal: maximum in fall, and minimum in spring. Natural shedding of the Loop Current eddy depend on internal, nonlinear physics, modulated/perturbed by interannual variations of the large-scale wind forcing.

- Shelfbreak upwelling and across-shelf transport associated with the Gulf Stream meanders are the dominant processes leading to large interannual variability in U.S. southeast marine ecosystem.

Q1: Are there large scale sources of predictability for the U.S. southeast and GOM that could advance coastal circulation and ecological forecasting?

Yes, large scale wind fields, NAO, AMO, etc.

Q2: Which ocean observations are most useful for testing processes relevant to coastal dynamics and ecological forecasting?

It depends on the processes under study. OSSE can be a good way to quantify that.

Q3: How could (and should) we leverage high resolution coastal models to better parameterize coastal processes in global climate models?

Examine both downscaling (global → coastal) and upper-scaling (coastal → global) and quantify (meso and submeso scales) interactions.


# Thank you!

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919-513-0249