Atmospheric and Oceanic Drivers of Marine Heatwaves in the Northwest Atlantic Coastal Ocean

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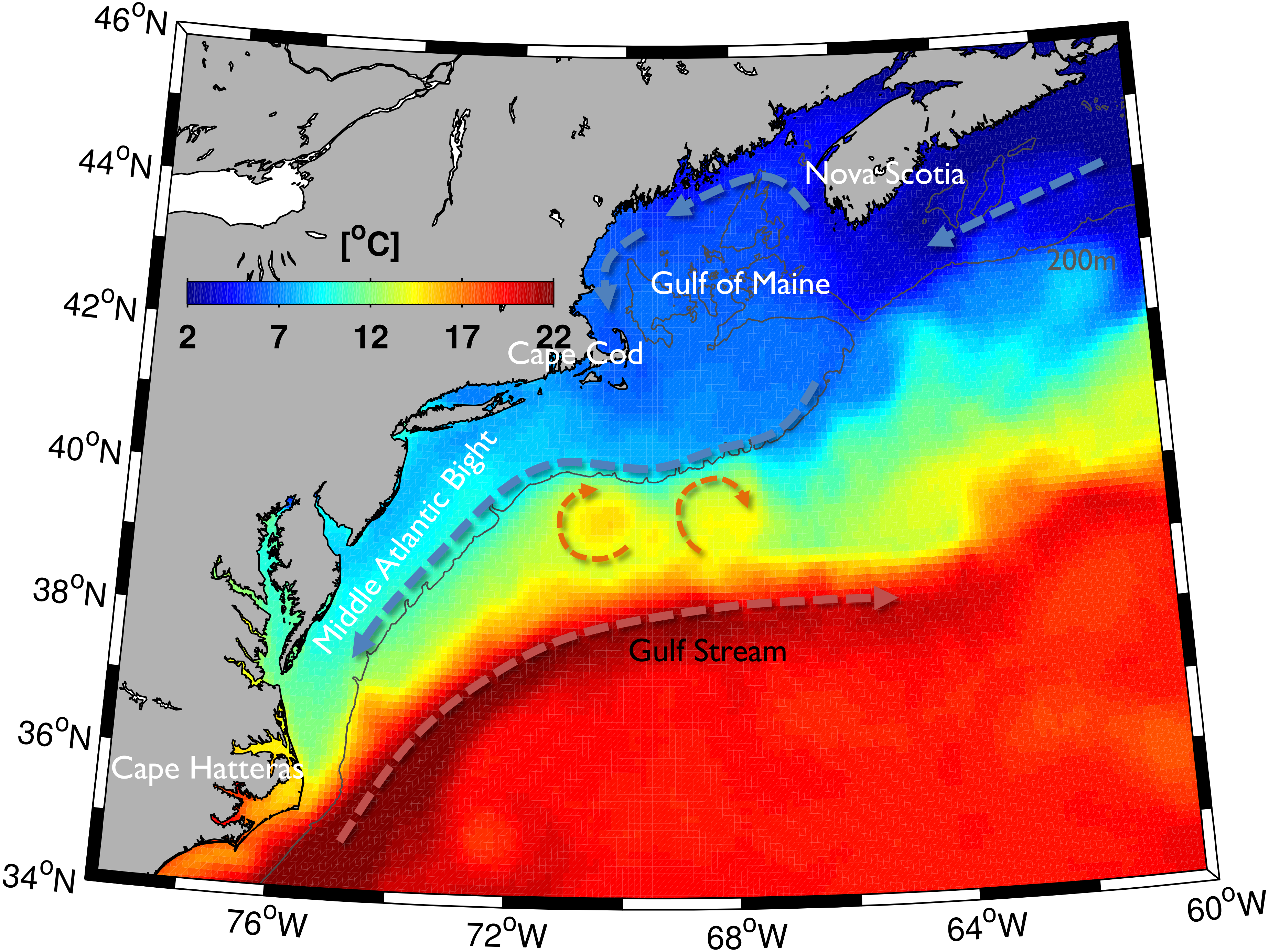
US CLIVAR Summit 2023

Oceanographic Setting



SST in March 2012, NOAA blended product

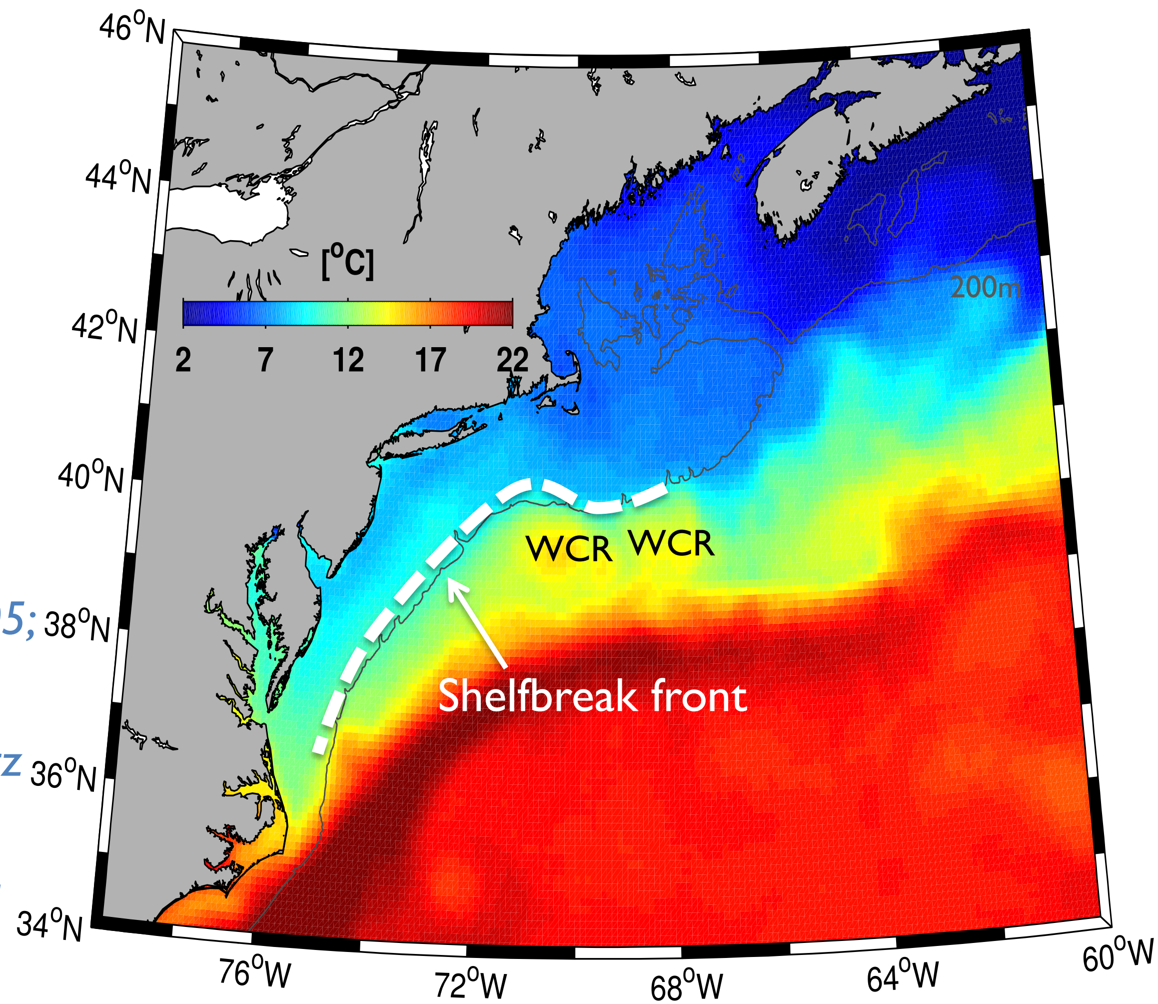
Oceanographic Setting

Water Properties:

- Cold fresh shelf water
- Warm salty slope water
- Separated by a front that is dynamically trapped at the shelf break *(Gawarkiewicz and Chapman 1992; Chapman and Lentz 1994; Chapman 2000)*

Shelf-Slope Exchange:

- Wind forcing *(Lentz et. al. 2003)*
- Frontal Instability *(Lozier and Reed 2005; Zhang and Gawarkiewicz 2015)*
- Salty Intrusion *(Lentz 2003; Gawarkiewicz et al., 2022)*
- Bottom Ekman transport *(Brink and Lentz 2010ab; Brink 2012; Benthuysen et. al. 2015)*
- Warm Core Rings (WCR) *(Lee and Brink 2010; Chen et. al. 2014; Zhang and Gawarkiewicz 2015)*

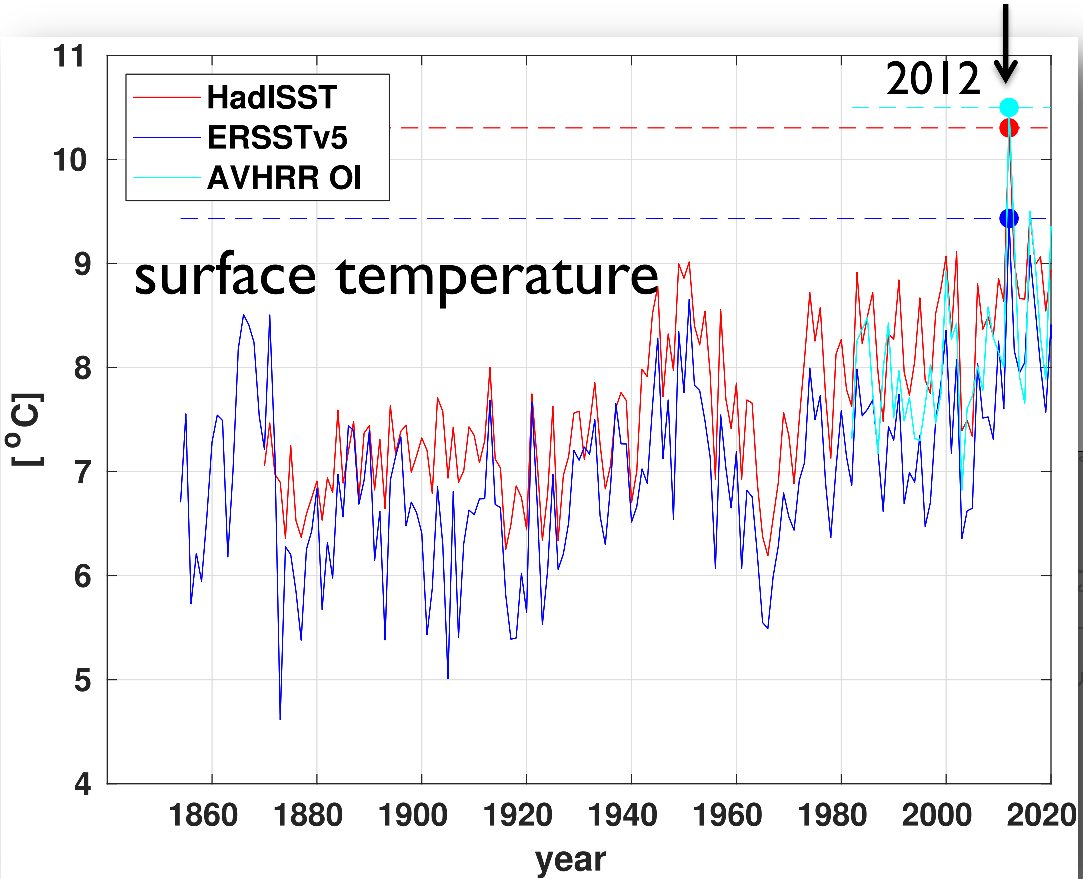


SST in March 2012, NOAA blended product

Outline

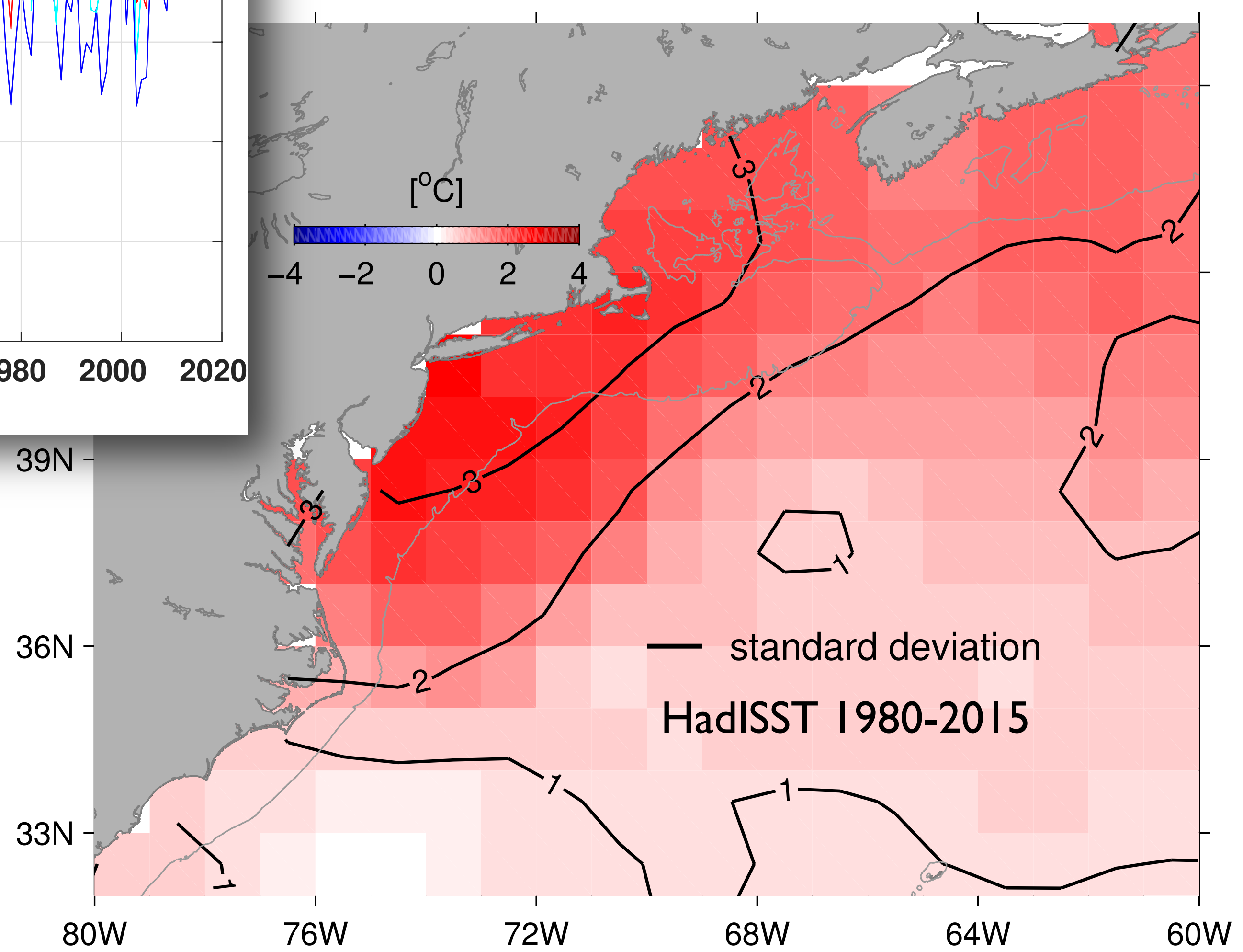
1. An Unprecedented Extreme Event in 2012
   - *Local Heat Balance: Observations and modeling*
2. An Advective, Subsurface Marine Heatwave in 2017
   - *Preconditioning associated with cyclonic eddies*
   - *Upwelling wind and local bathymetry*
3. Summary

The Extreme Warm Anomaly in 2012: Jan-Jun SST

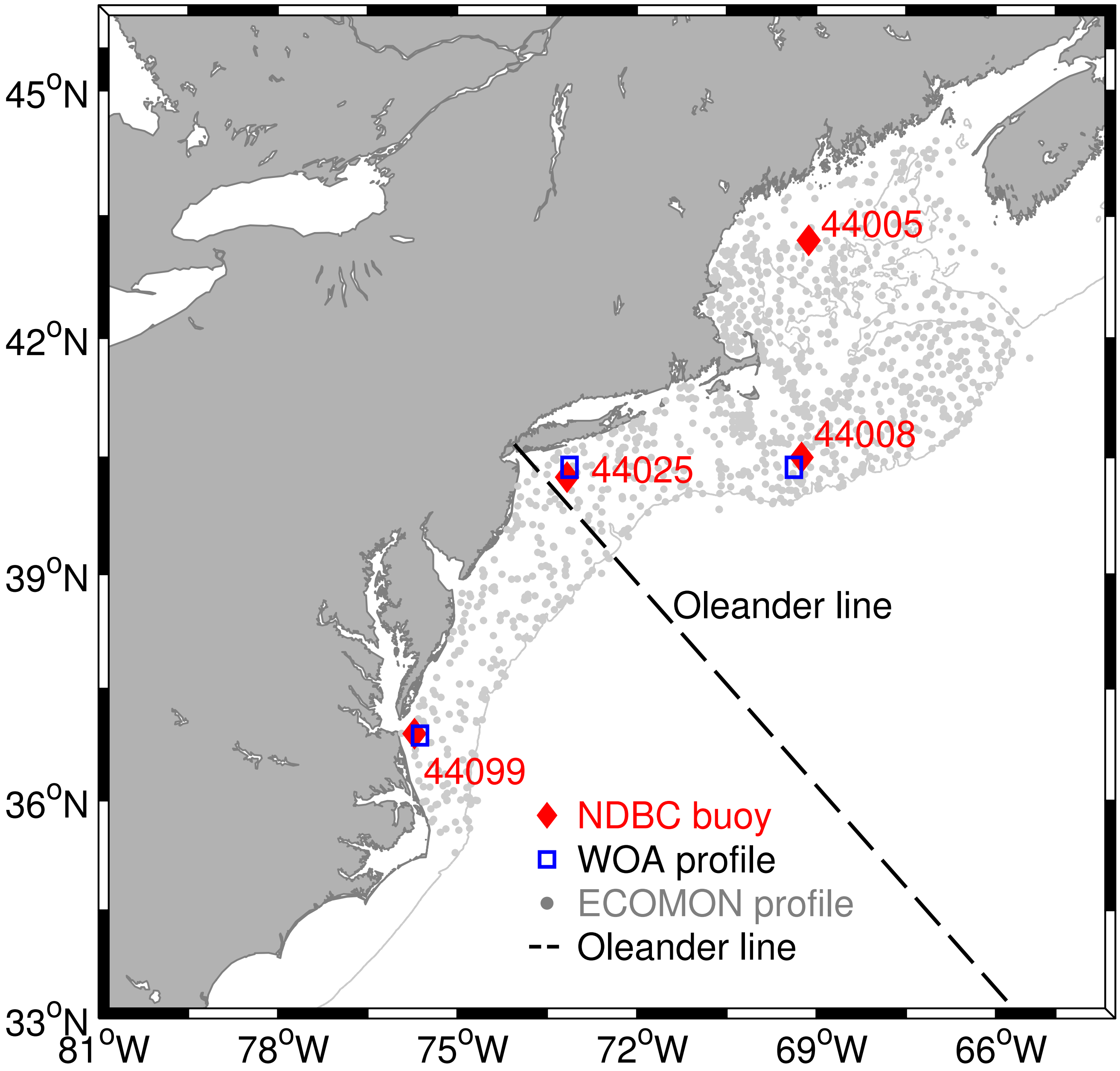


Highest on record based on 3 SST products

Exceeding 3 STDs in the MAB and GoM



Observations in 2012: in situ, remote sensing, reanalysis



NDBC buoys:
Surface Temperature

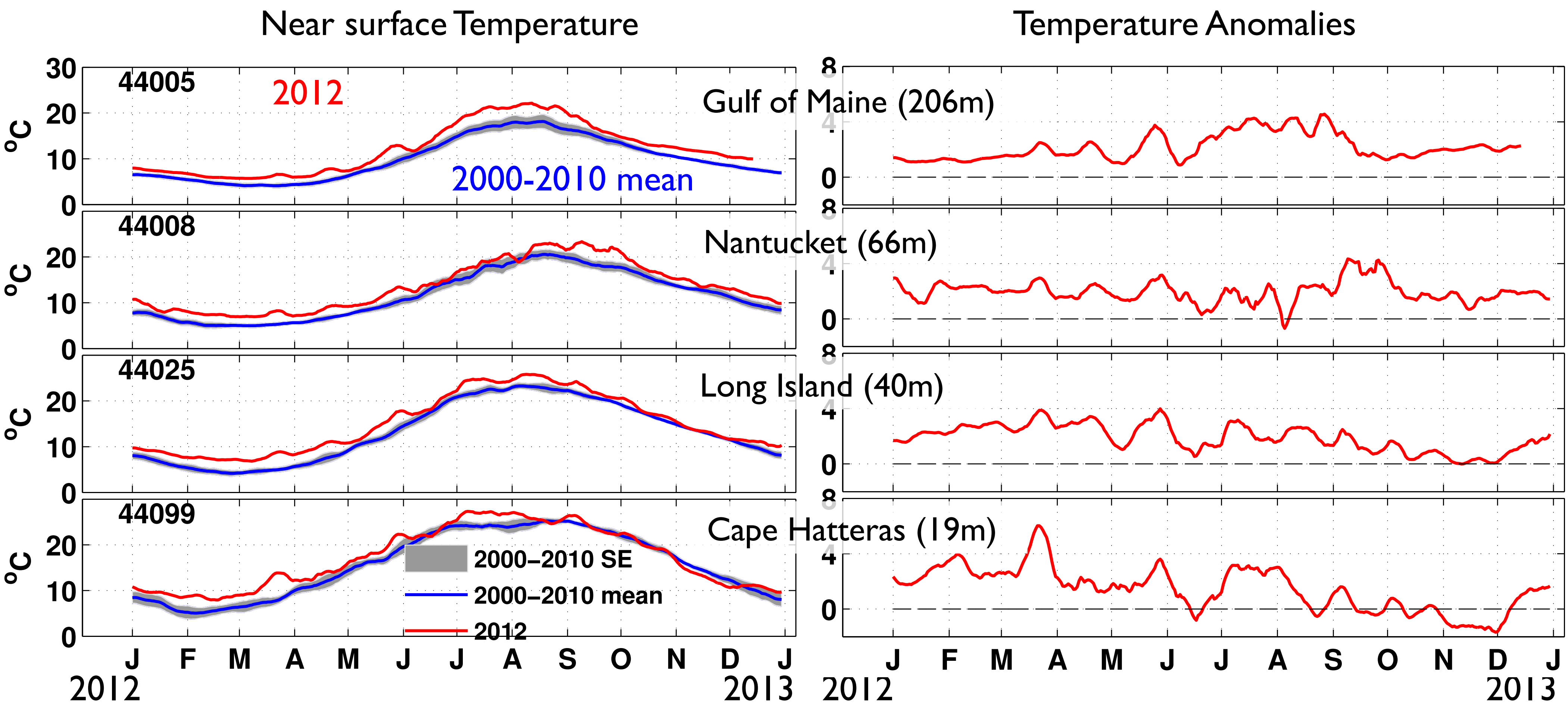
Oleander line:
XBT Profiles

NEFSC ECOMON survey:
Temperature/Salinity

World Ocean Atlas (WOA):
Temperature/Salinity

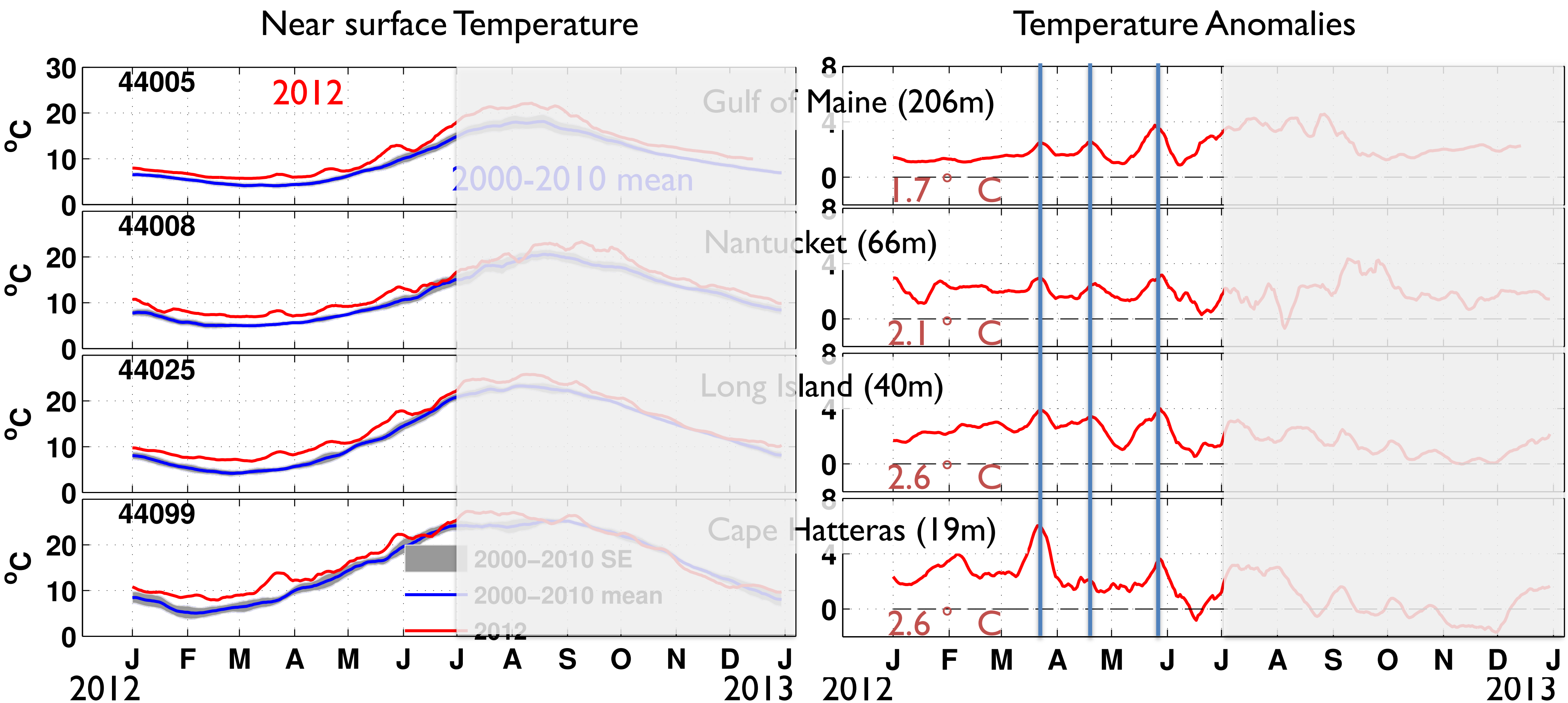
NCEP NARR:
Air-Sea Heat flux,
Vector Wind

NDBC Buoy Temperature: 2012 vs 2000-2010 mean



- 2012 temperature was above average most of the time
- Consistent shelf-wide warm anomaly in the first half of 2012
- 6-month anomaly: 1.7-2.6° C, maximum (6° C) in March near Cape Hatteras
- In-phase variation of temperature anomalies

NDBC Buoy Temperature: 2012 vs 2000-2010 mean



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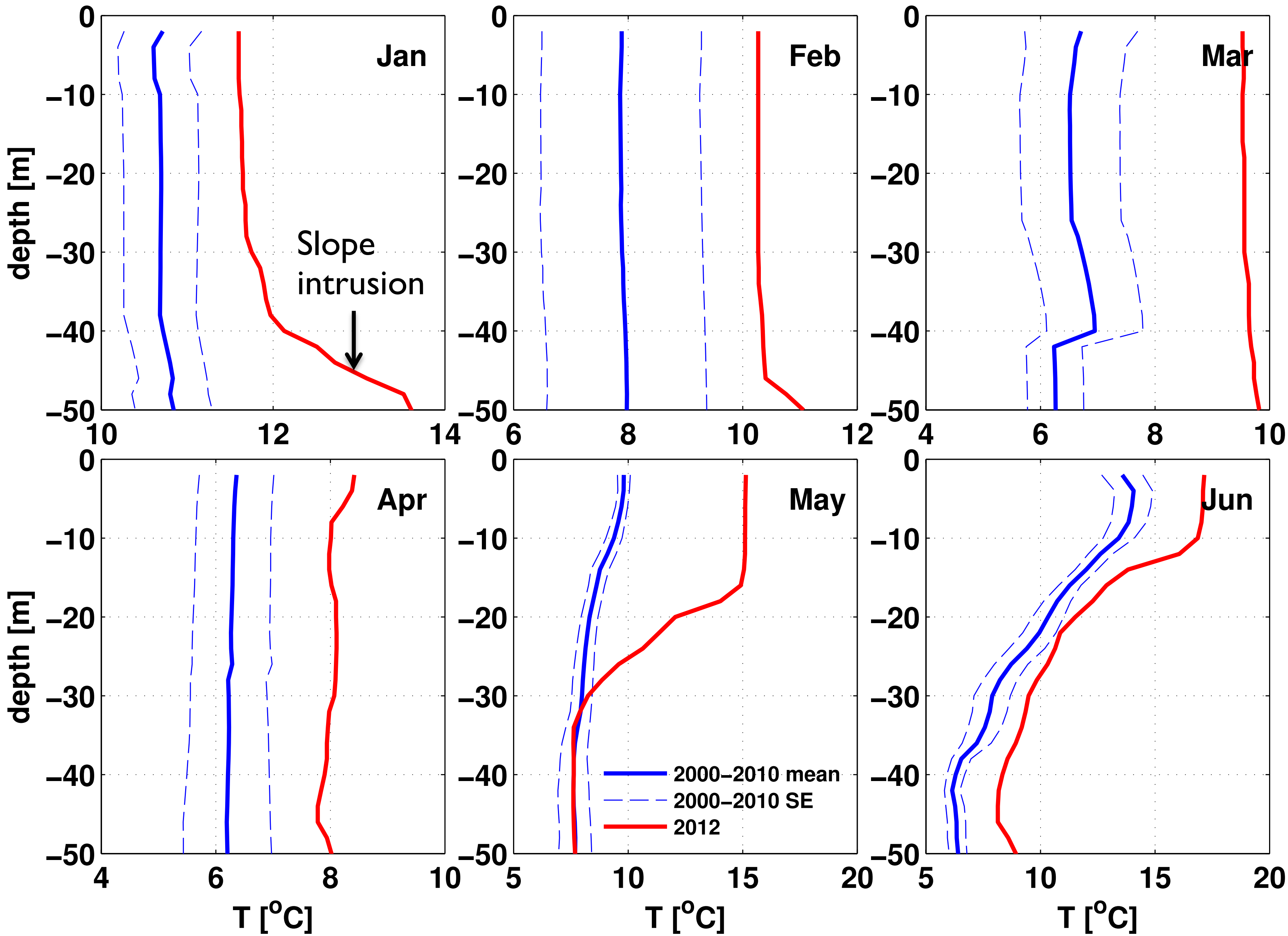
Monthly XBT Profiles near NJ Shelf Break: mean vs 2012



XBT profiles from MV Oleander

Temperature Budget Diagnostics: 1-D Balance

Temperature Balance:

$$\frac{\partial T}{\partial t} = \frac{Q}{\rho_o c_p H} - \frac{1}{H}\int_{-H}^{0} \mathbf{u} \bullet \nabla T' dz$$

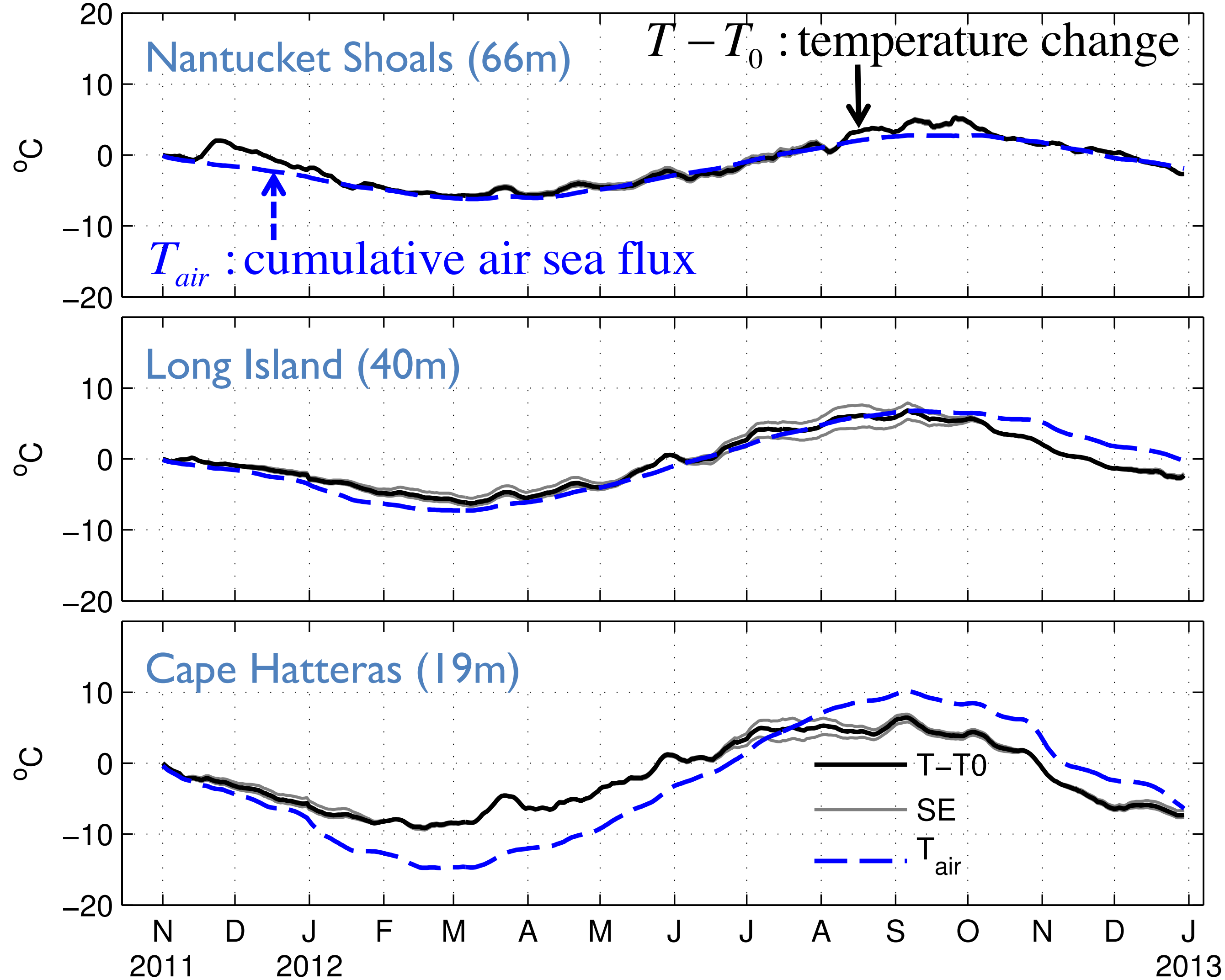
Temporal integration:

$$T - T_0 = T_{air} - T_{adv}$$

where:

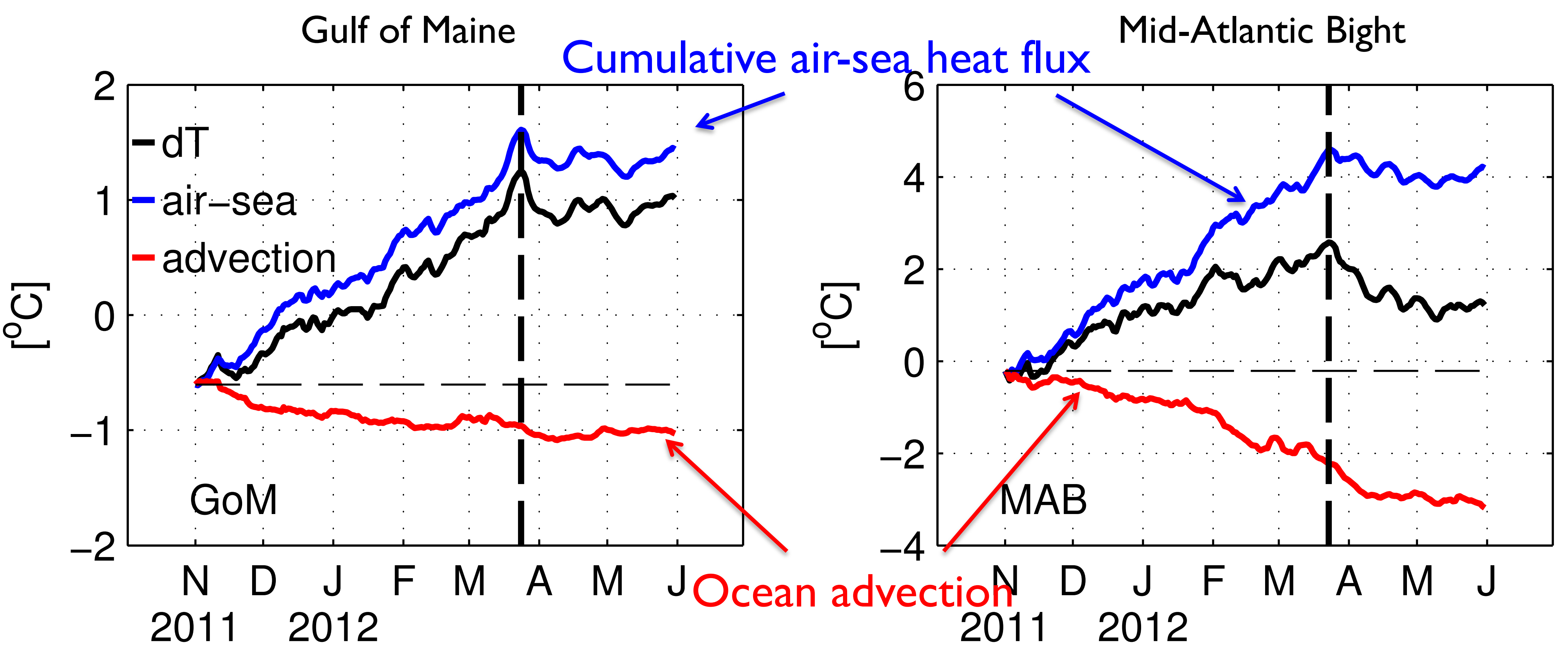
$$T_{air} = \int_0^t \frac{Q}{\rho_o c_p H} dt'$$

$$T_{adv} = \int_0^t \left(\frac{1}{H} \int_{-H}^{0} \mathbf{u} \bullet \nabla T' dz \right) dt'$$



- Air-sea heat flux largely controlled the temperature change over the MAB shelf
- Availability of observations prevents the quantification of advective flux and budget closure

Temperature Anomaly (2012 vs 2004-2013) Budget



- Temperature was not above average in late 2011
- Increasing anomaly predominantly controlled by the air-sea flux
- Ocean advection was cooling the entire region

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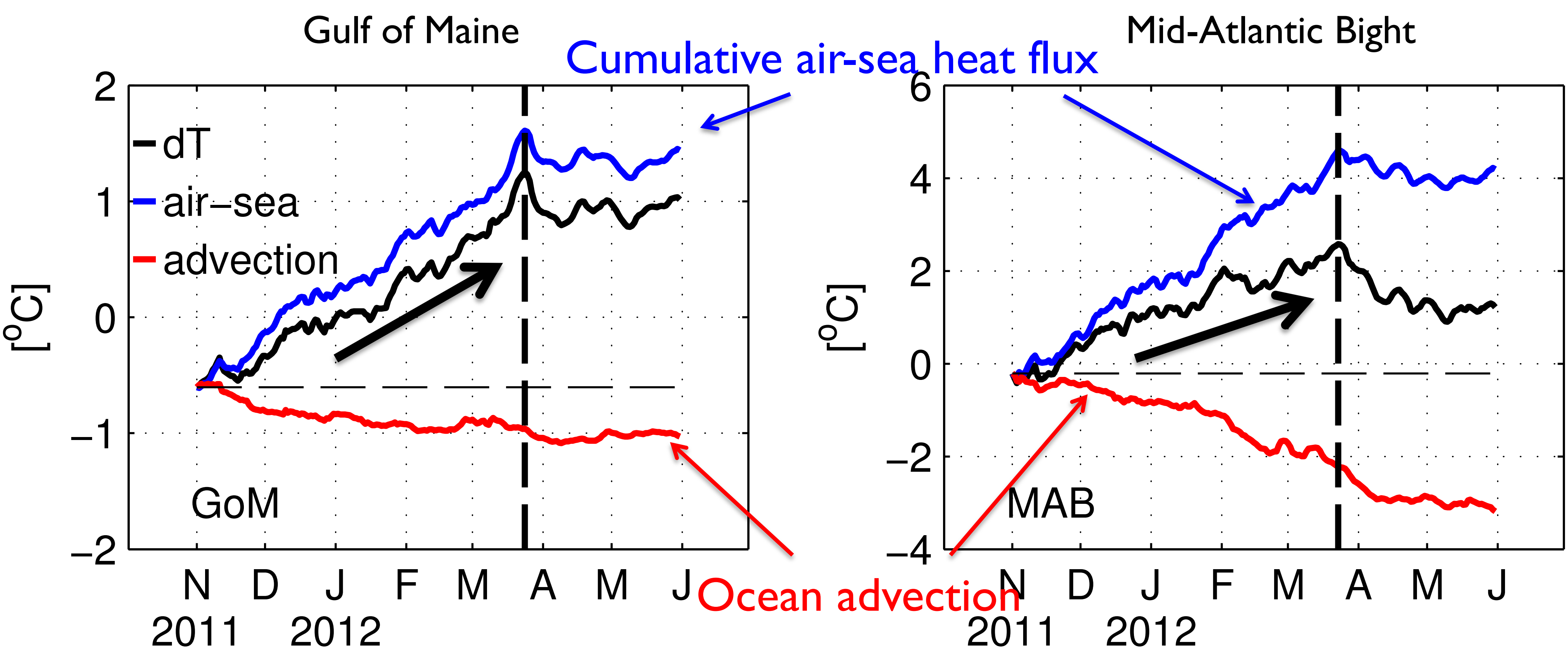

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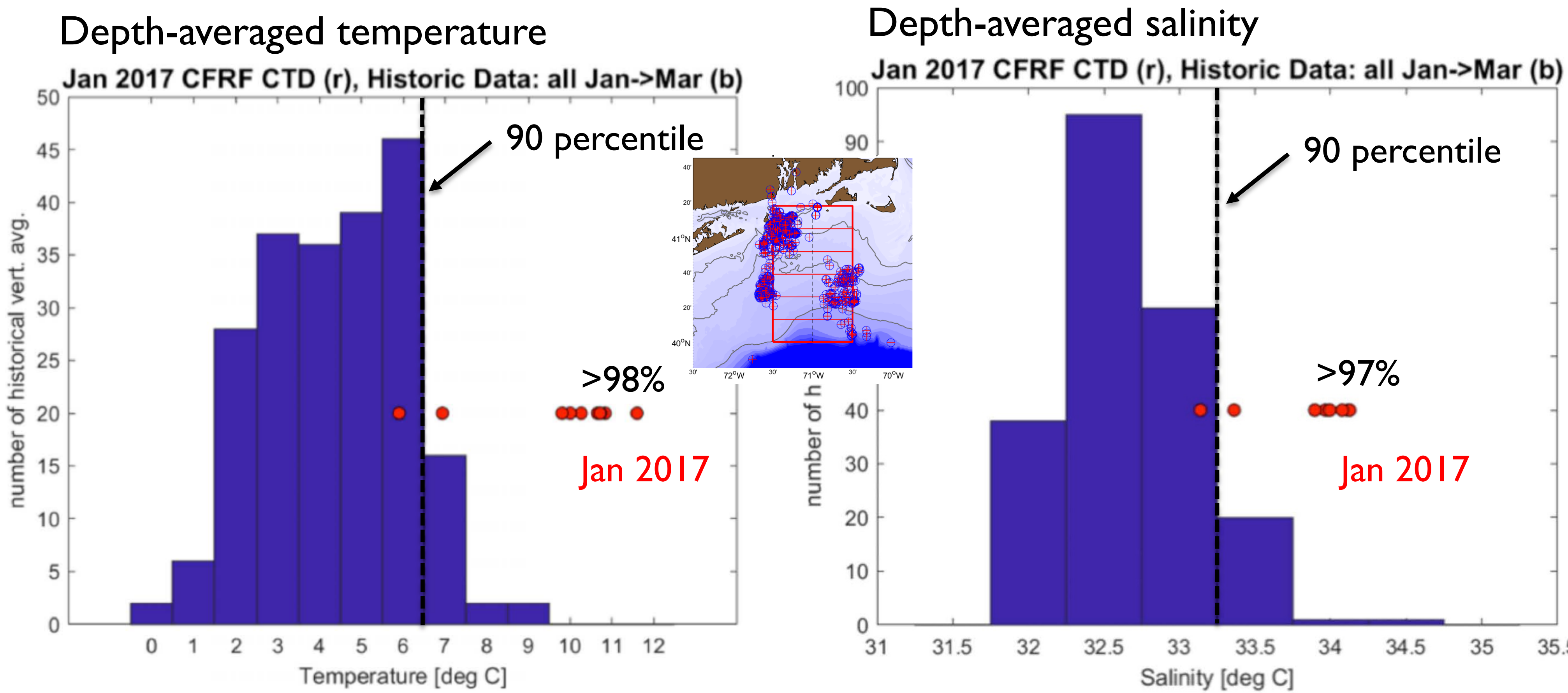
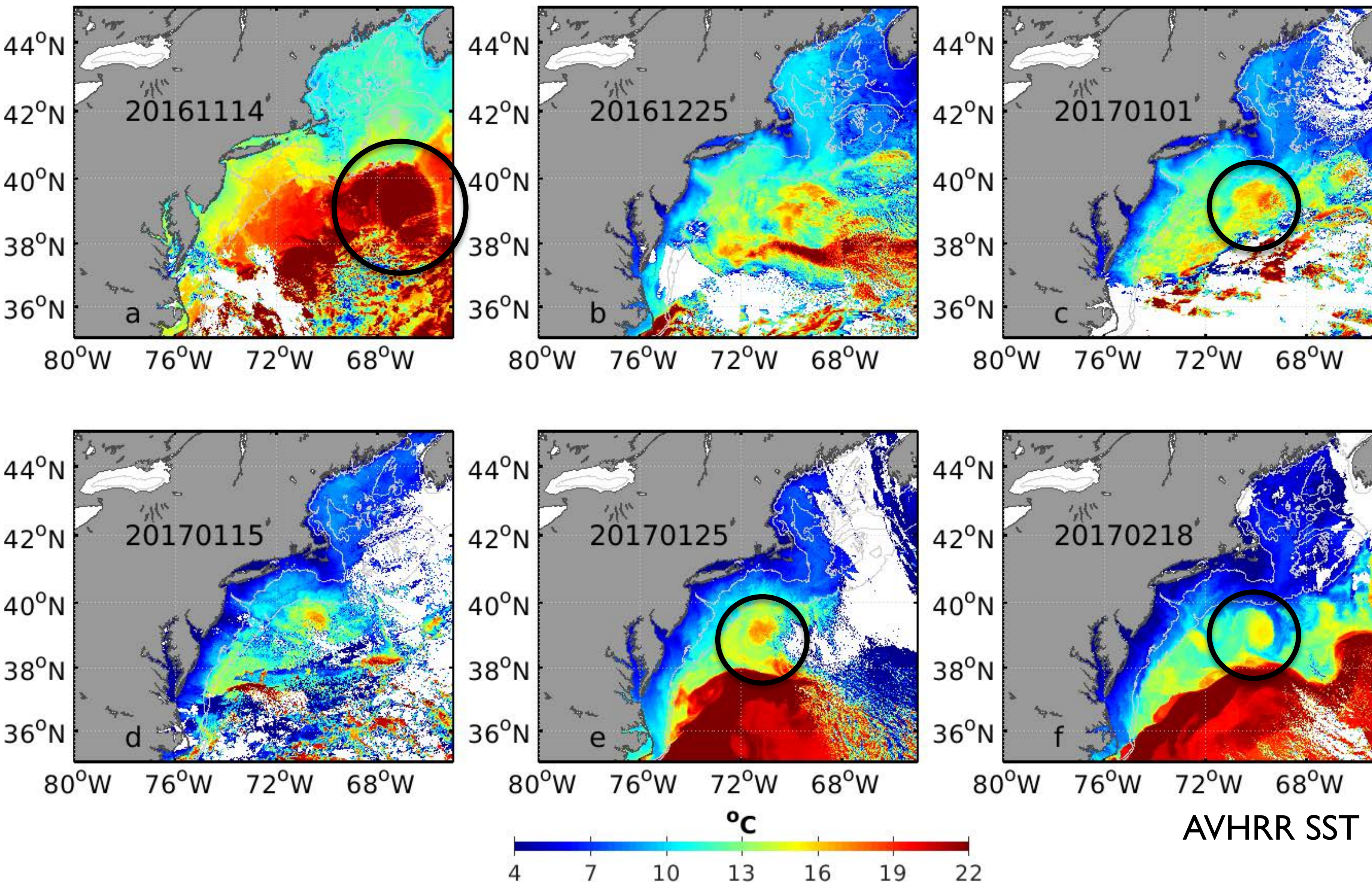
A subsurface, advective heatwave in 2017



Gawarkiewicz et al., 2019

- First discovered by commercial fishing industry: unusual catch of Gulf Stream species near Block Island
- Anomalously high temperature and salinity: >4 °C and >1, above 90%
- Compound extreme event: strong indication of offshore origin

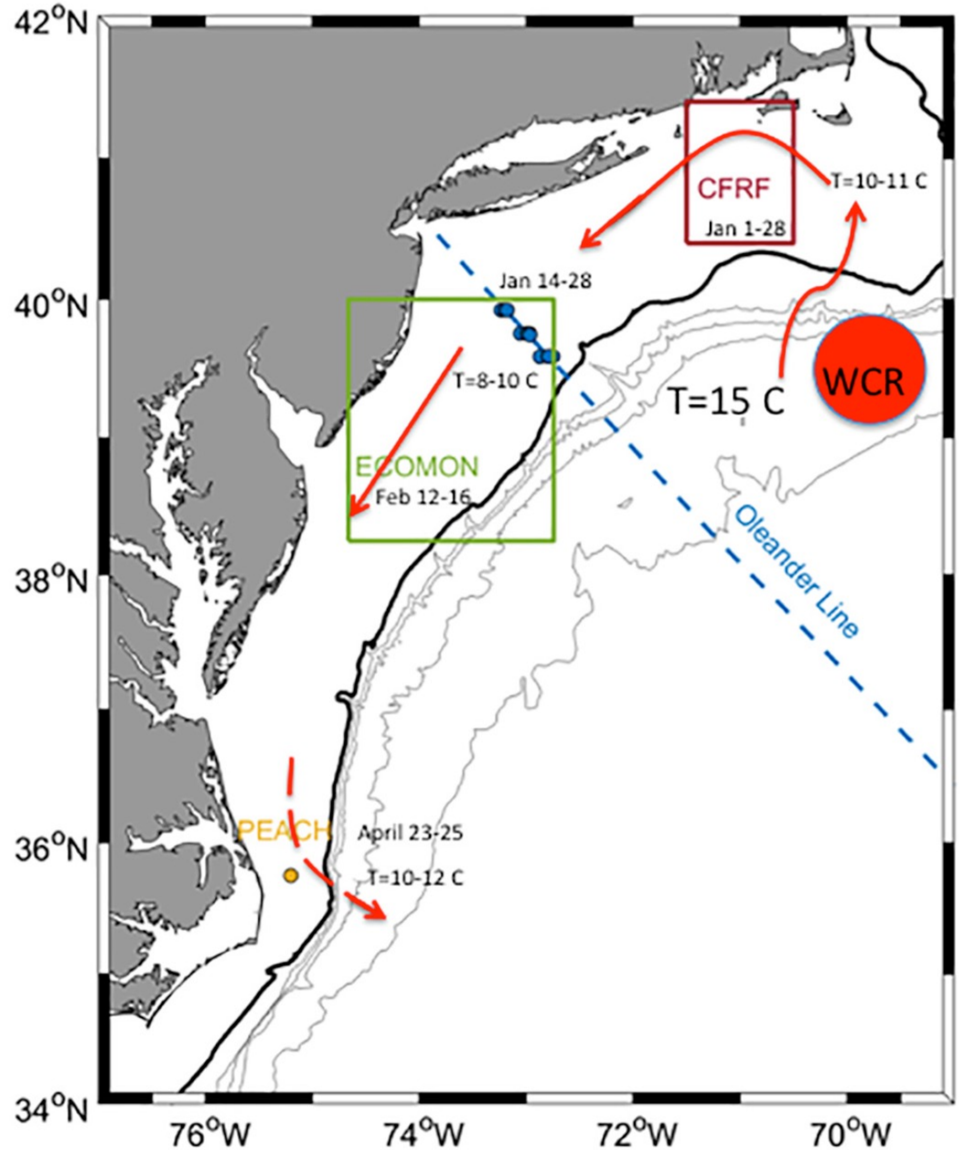
The (indirect) evidence of Gulf Stream intrusion



AVHRR SST images

Series of Gulf Stream Warm Core Rings: Nov 2016, Jan 2017, and Feb 2017

The hypothesis



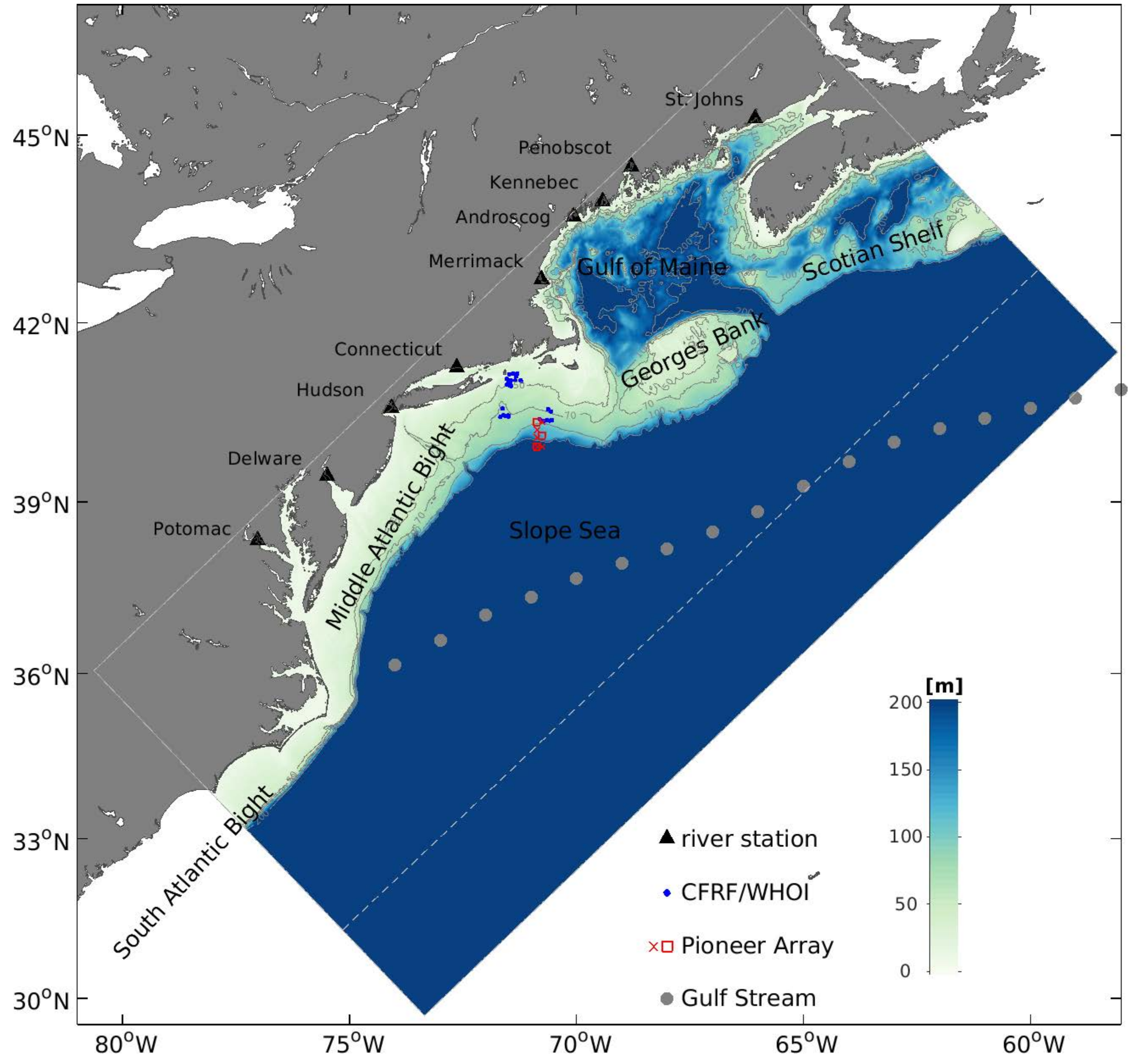
Gawarkiewicz et al., 2019

- Gulf Stream Warm Core Rings bring warm/salty water onto the shelf
- Anomalous water mass rides on the mean along-shelf flow and exits the shelf in April

However, …

1. A thorough proof using existing data is not possible
2. Whether not WCRs are indeed important?
3. What is the exact working mechanism?
4. What about other factors, e.g., atmospheric forcing?

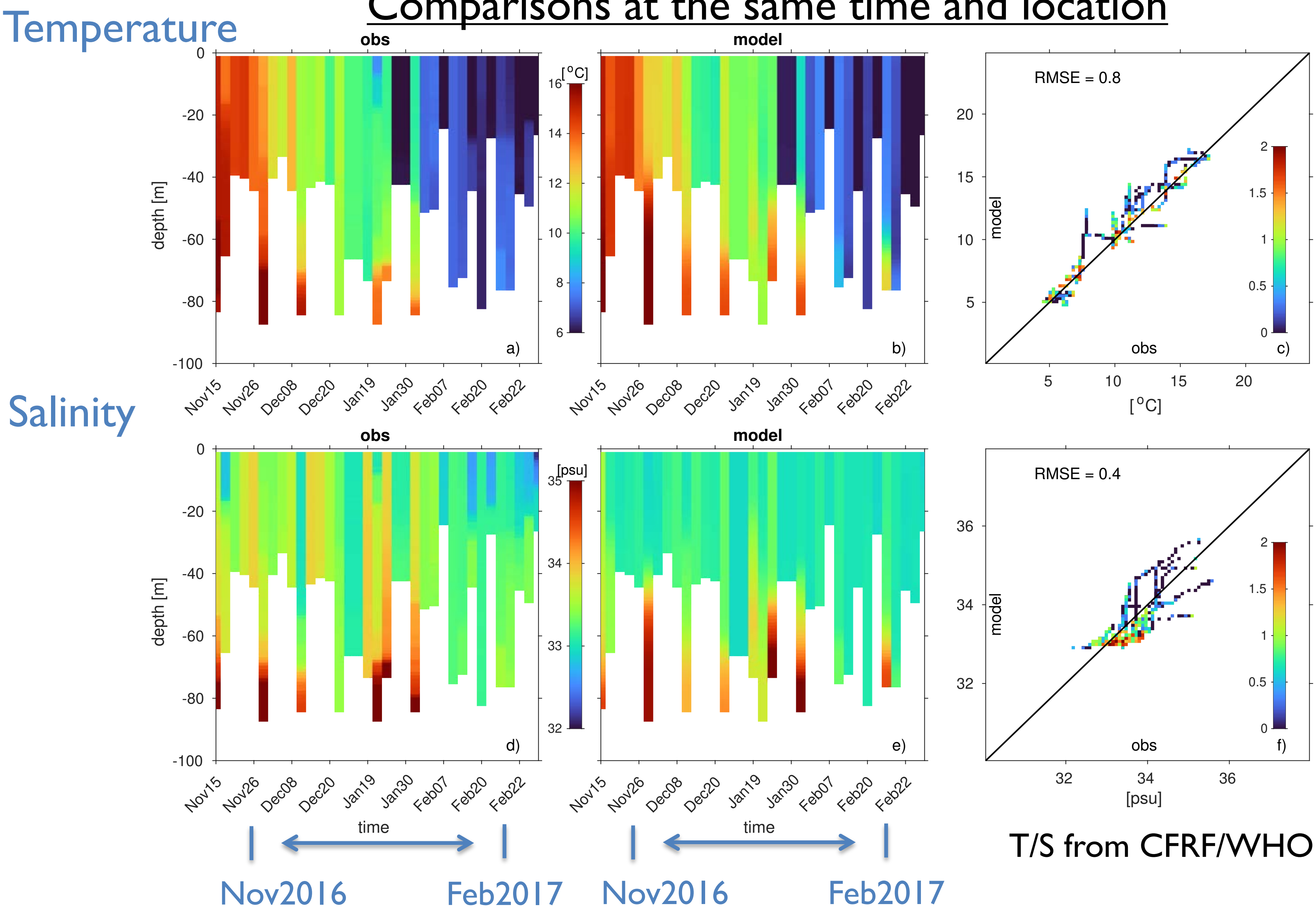
Realistic Numerical Modeling



- Regional Ocean Modeling System (ROMS)
- 1 km horizontal resolution
- 40 terrain-following layers
- 9 major rivers, M2 tide
- 3 hourly atmospheric forcing from ERA5
- Downscaled from global HYCOM/NCODA

Model Skill Assessment: Comparison of 4-D T/S Structure

Comparisons at the same time and location



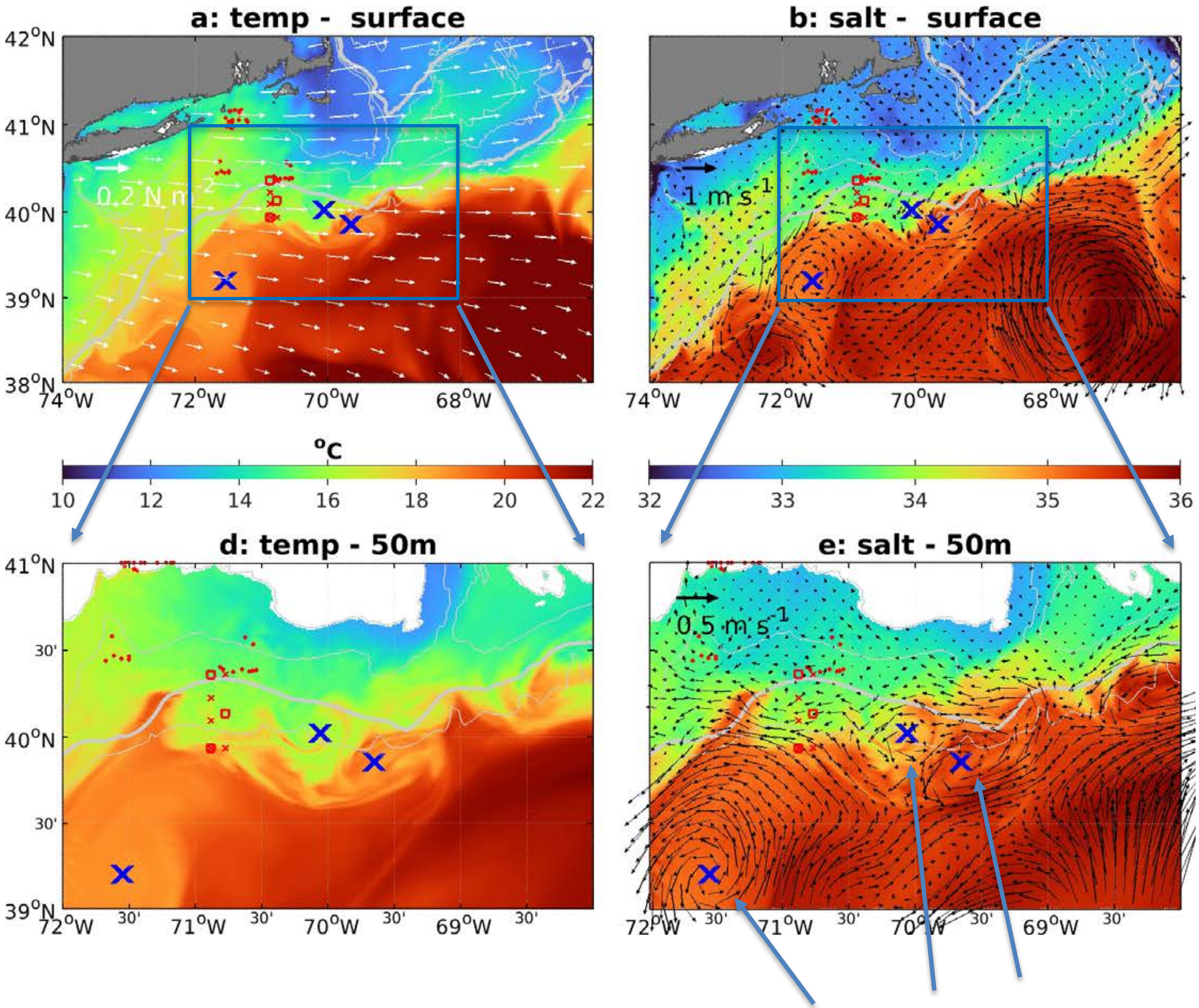
T/S from CFRF/WHOI CTD data

Cross-shelf bottom intrusion

- Two steps: preconditioning by cyclonic eddies + upwelling wind
- Step1: Cyclonic eddies precondition the outer continental shelf, by changing along-shelf pressure gradient and inducing frontogenesis
- Step2: Persistent upwelling wind drives a bottom intensified intrusion from the outer shelf to inner shelf
- The intrusion is localized along a bathymetric trough

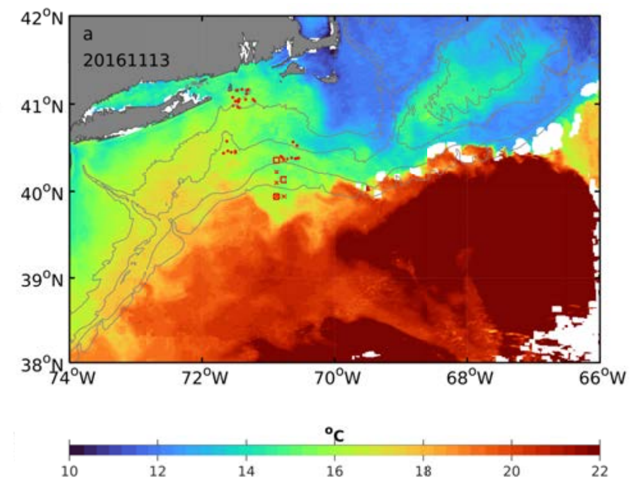
Presence of cyclonic eddies

Model prognostic fields, Nov 13, 2016



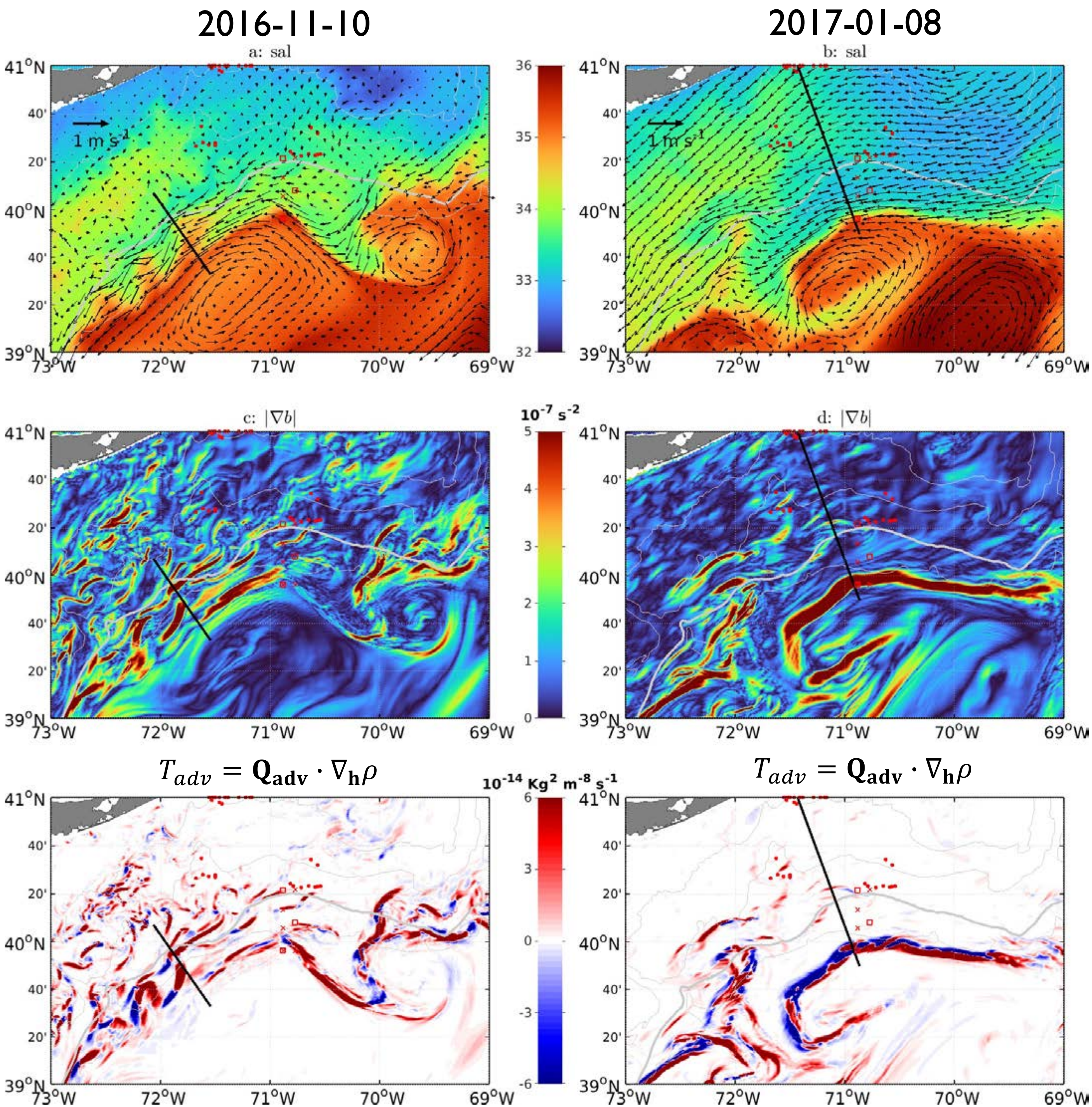
Cyclonic eddies

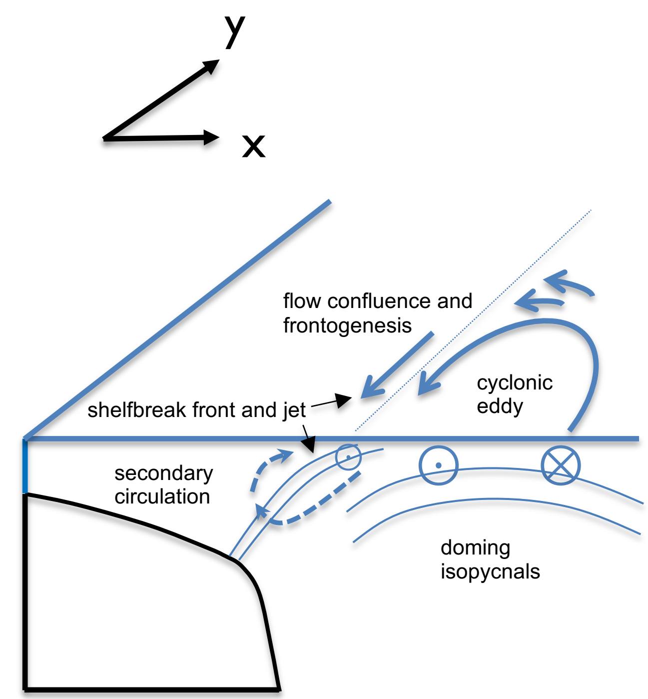
AVHRR SST, Nov 13, 2016



- Model SST compares well with AVHRR
- Model captures cyclonic eddies, which can not be resolved by satellite altimetry or SST alone
- Long discovered (from 1980s), but rarely discussed

Frontogenetical process by cyclonic eddies





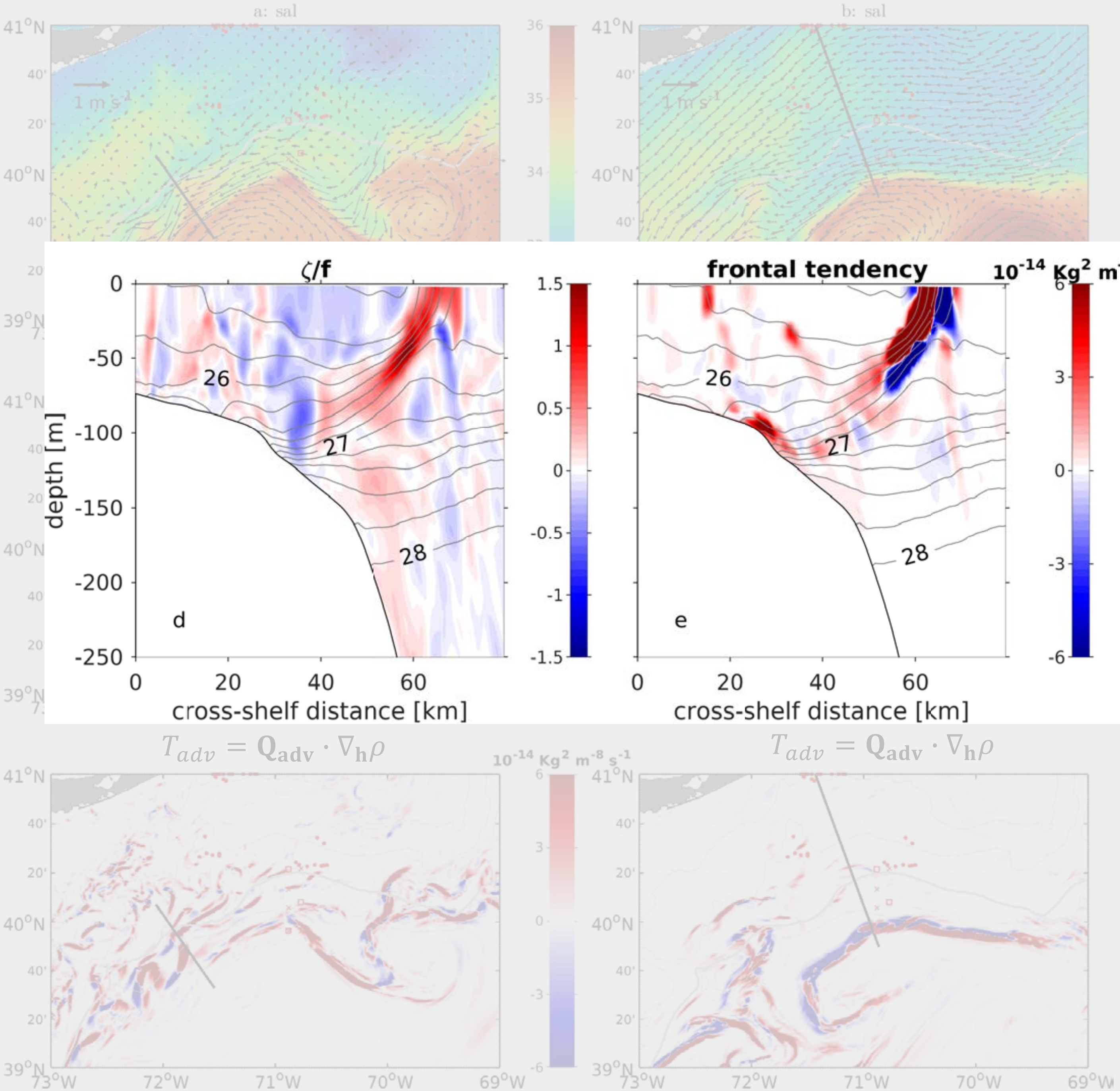
semi-geostrophic jet

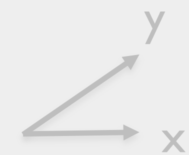
$$\frac{Dv_g}{Dt} = -fu_a$$

Hoskins and Bretherton, 1972; Hoskins, 1982; Spall, 1995

Frontogenetical process by cyclonic eddies

2016-11-10 | 2017-01-08





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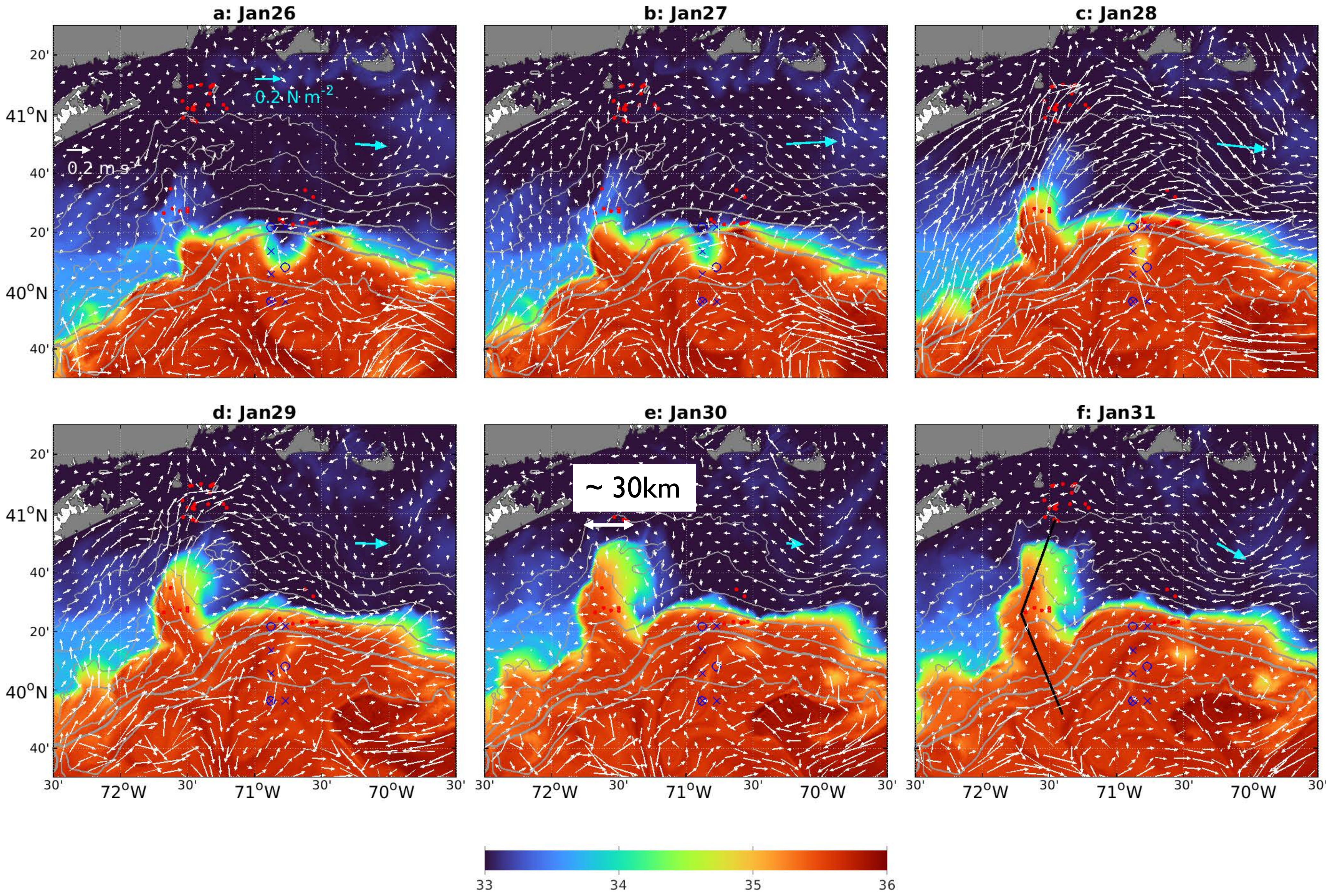
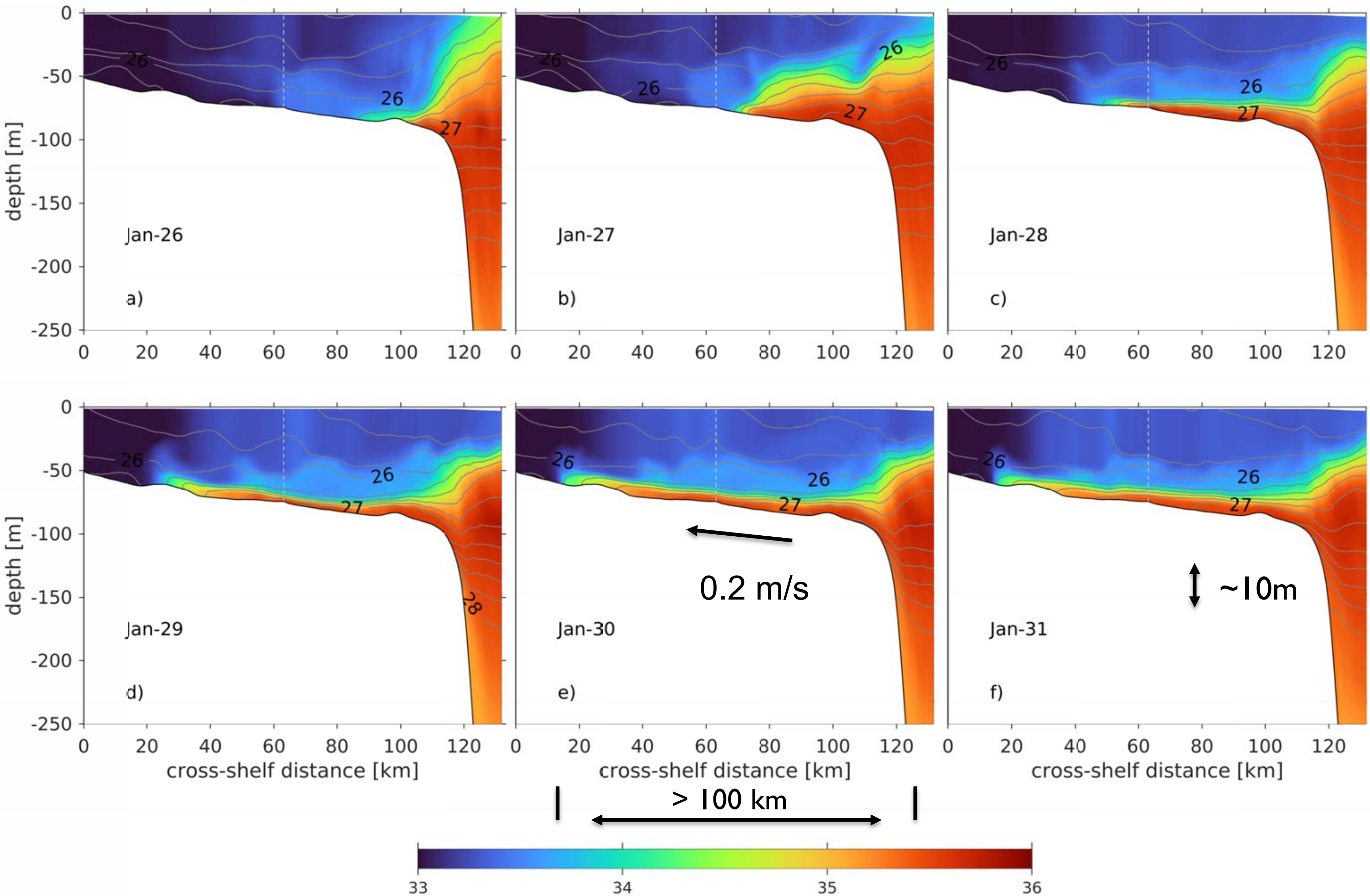
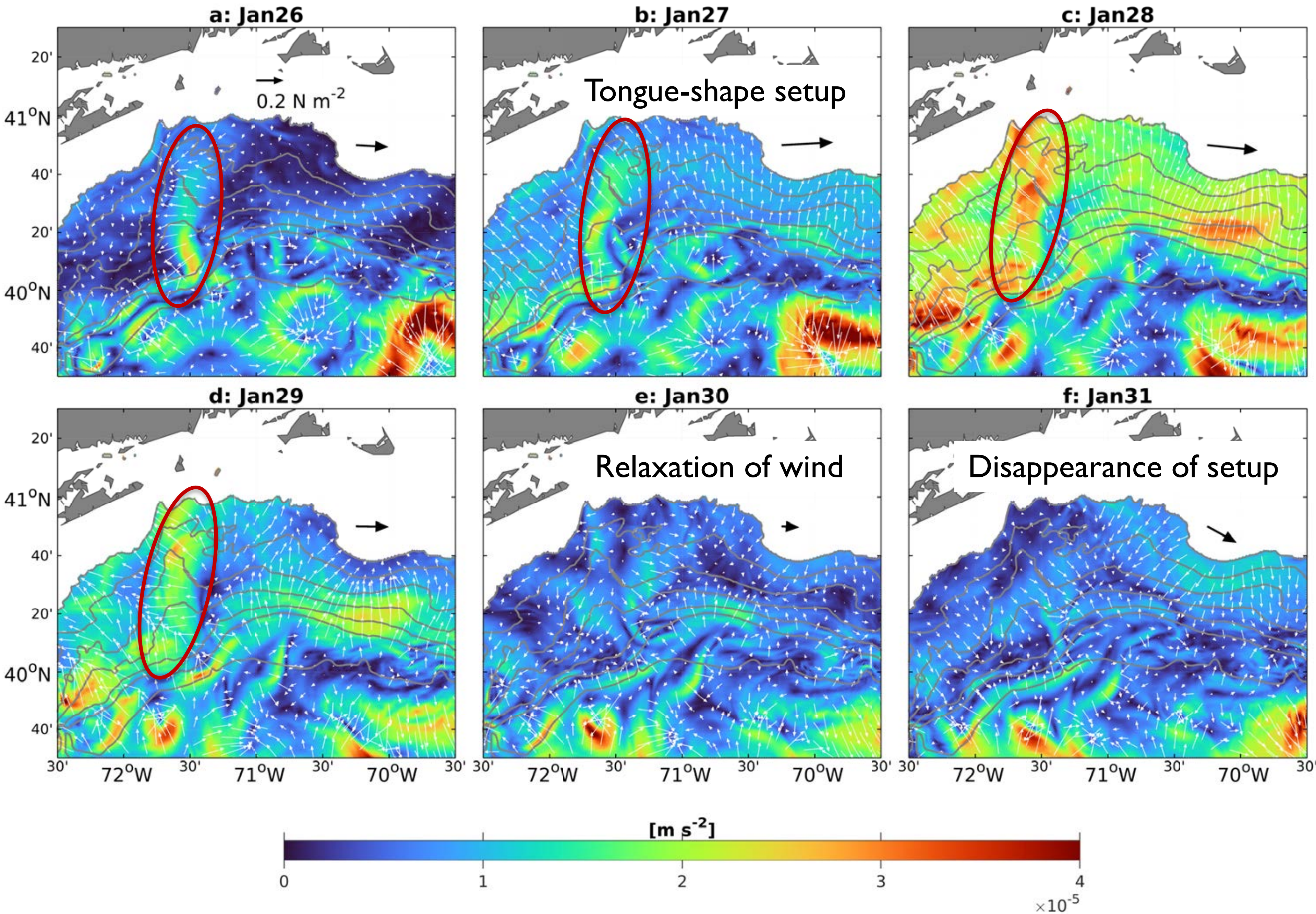
Bottom intensified intrusion



Bottom intensified intrusion



Pressure gradient setup drives intrusion



Summary

- 2012 Marine Heatwave is primarily driven by air-sea fluxes
- 2017 Marine Heatwave is driven by offshore eddies and onshore bottom intrusion
- MHWs involves fundamental yet complex processes including air-sea interaction, large-scale circulation, coastal processes, and multiscale interactions.
- More process studies are needed for deterministic prediction of MHWs
- Long-term, water column observations along with advanced satellite observations are essential for improved understanding

Reference:

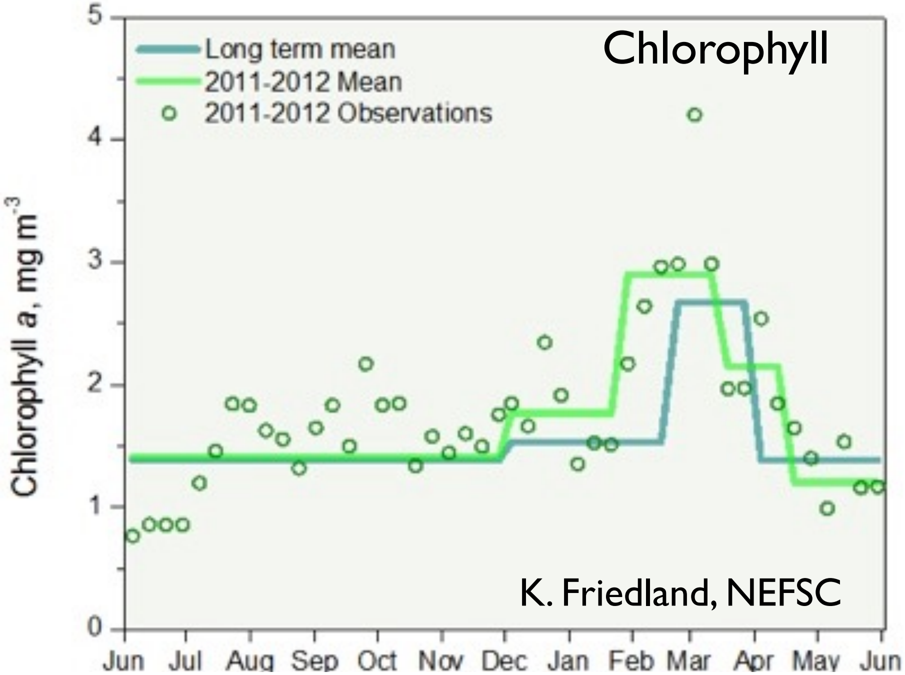
Chen, K., G. Gawarkiewicz, S. Lentz, and J. Bane (2014), Diagnosing the Warming of the Northeastern US Coastal Ocean in 2012: A linkage between the atmospheric jet stream variability and ocean response, J. Geophys. Res., doi:10.1002/2013JC009393.

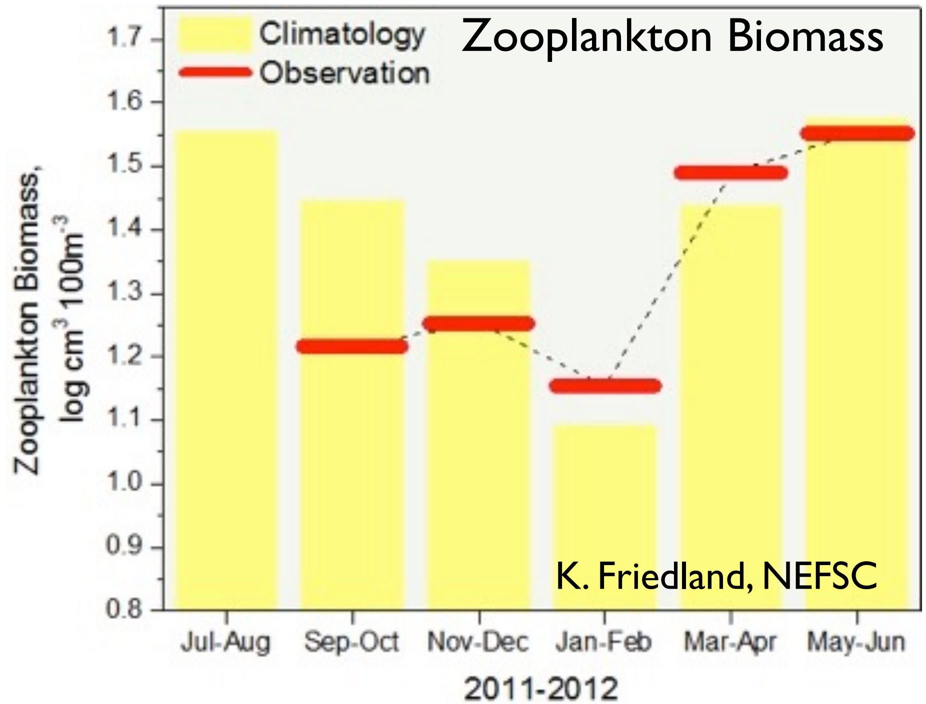
Chen, K., G. Gawarkiewicz, Y.-O. Kwon and W. Zhang (2015), The Role of Atmospheric Forcing versus Ocean Advection during the Extreme Warming on the Northeast U.S. Shelf in 2012, J. Geophys. Res., doi:10.1002/2014JC010547.

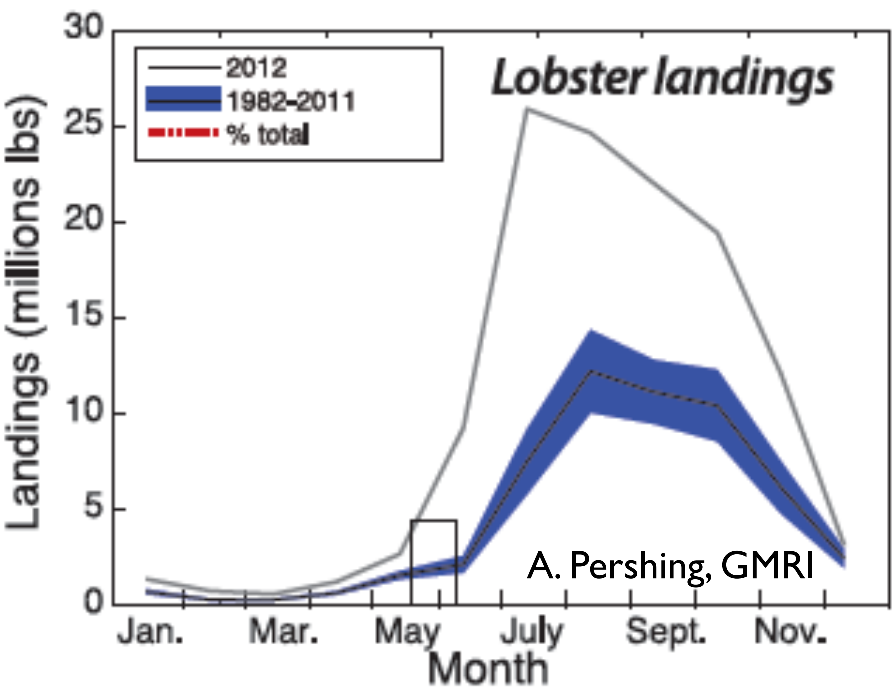
Gawarkiewicz G, Chen K., et al (2019) Characteristics of an Advective Marine Heatwave in the Middle Atlantic Bight in Early 2017. Front. Mar. Sci. 6:712. doi: 10.3389/fmars.2019.00712

Chen, K., Gawarkiewicz, G., and Yang, J., 2022: Mesoscale and submesoscale shelf-ocean exchanges initialize an advective Marine Heatwave. Journal of Geophysical Research: Oceans, 127, e2021JC017927.

Impacts on the Marine Ecosystem in 2012







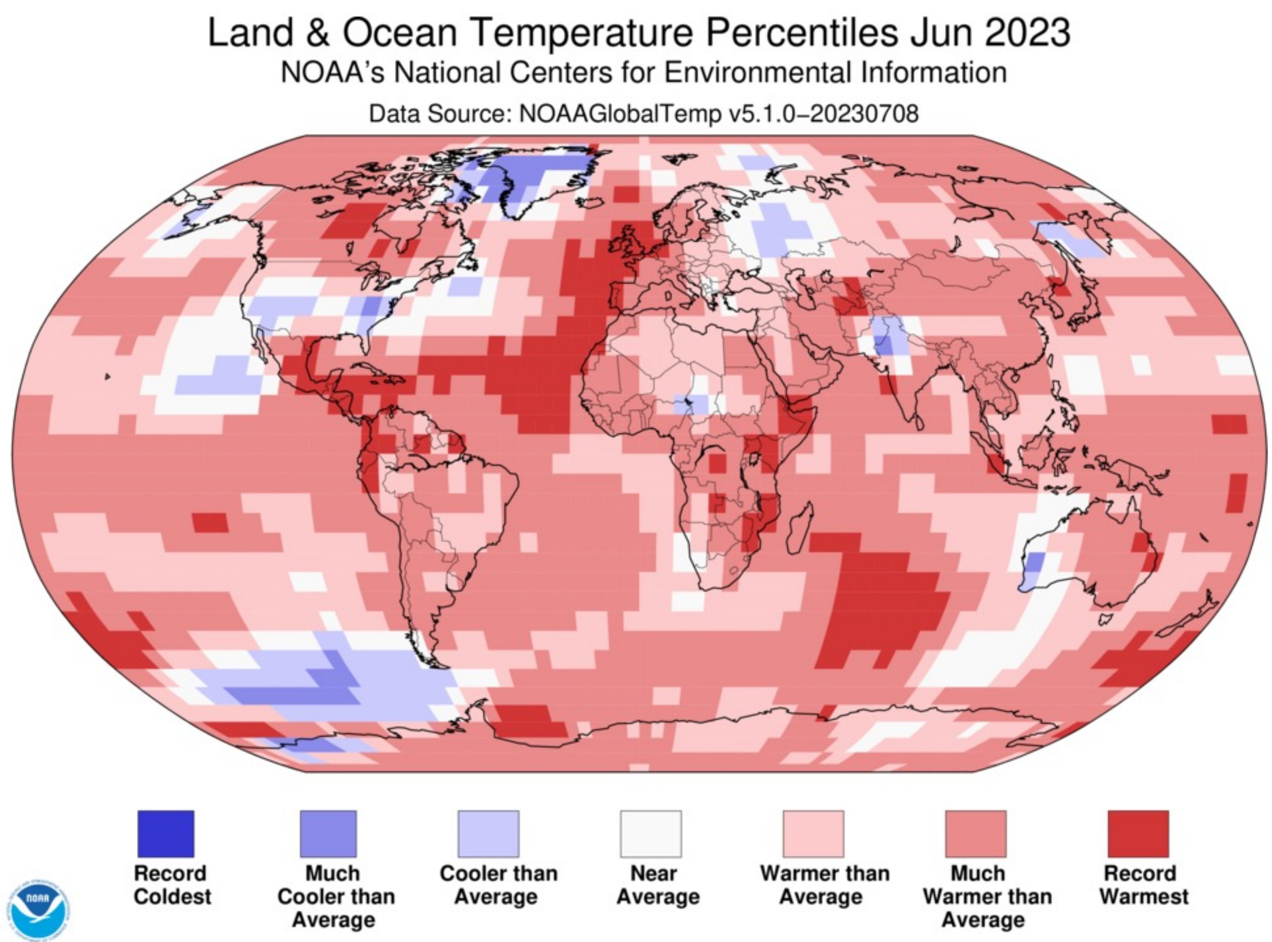
- Earlier and more intense spring bloom
- Higher zooplankton biomass
- Earlier landing and larger catch of lobster
- Northward shift of butterfish, black sea bass, Atlantic cod

NMFS Ecosystem Advisory: http://nefsc.noaa.gov/ecosys/advisory/fall2012/advisory.html

Why care heatwaves/heat balance?

1. Global climate system has been undergoing rapid changes

- Most regions were much warmer than average
- Many regions set the record high temperature
- The warmest June in the 174 years



We need to understand how the global changes are manifested in the coastal oceans, particularly the mechanisms connecting the large-scale and coastal scale.

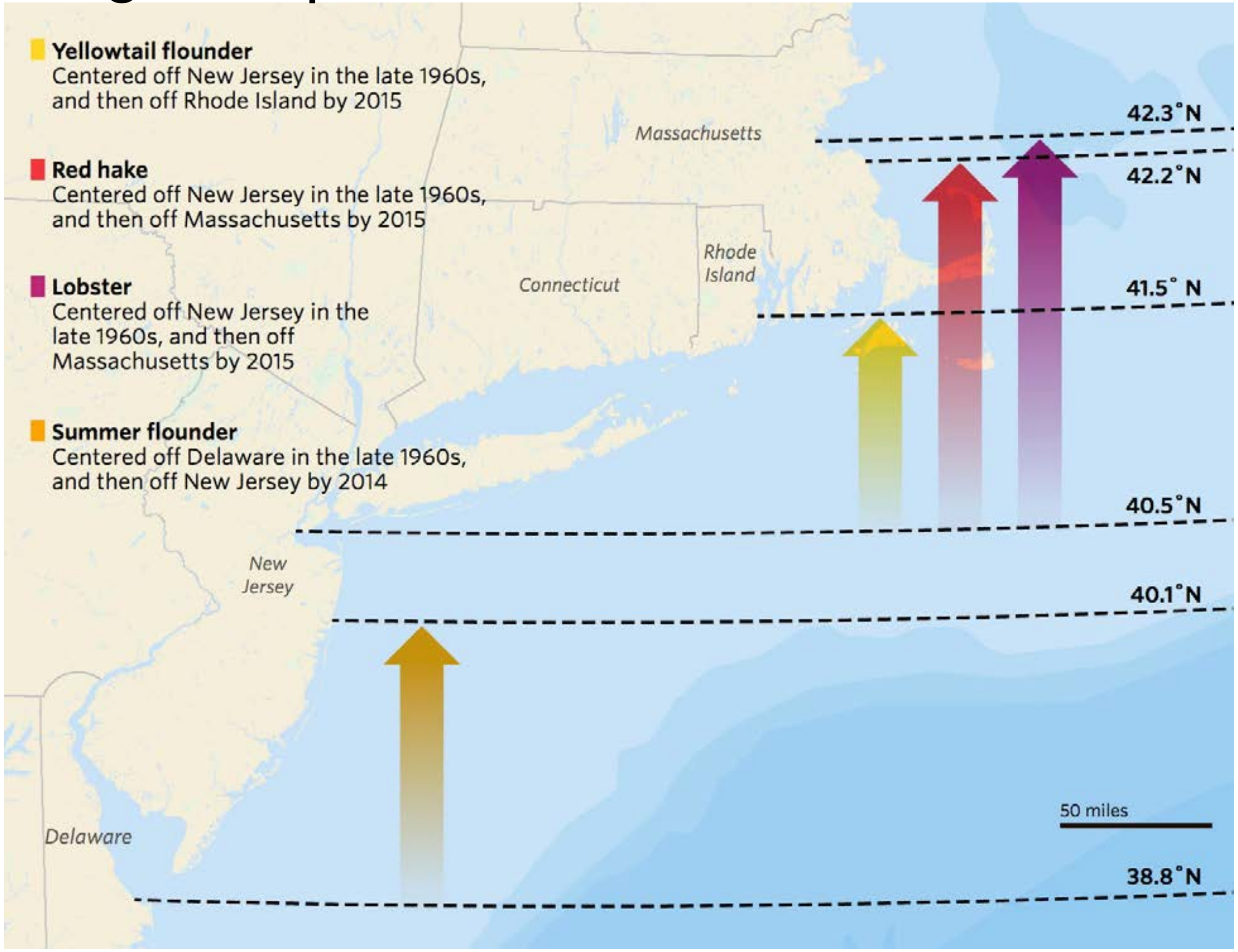
Why care heatwaves/heat balance?

2. Important to ecosystem dynamics and commercial fishing industry

- Northward migration of fish stocks, consistent with warming ocean
- Contributed to overfishing: regional fishing quotas are based on past ocean conditions

Better understanding of the heat balance and temperature change has societal and economic importance

Migration pattern of fish stocks : 1960 - 2015



From Wall Street Journal. Source: Rutgers University