The MARACOOS ROMS 4D-Var "Doppio" Operational Data Assimilative Ocean Forecast System for Northeast U.S. Coastal Waters

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Regional Ocean Modeling System
www.myroms.org

The coast is at the center of human-ocean interactions

Safety

(photo: USCG/ T Sperduto)

- Ocean rescue
- Storm surge
- Oil spill tracking

Oil-covered rocks at Refugio State Beach (photo: NOAA)

Economy

Maritime economy contributed $282 billion & 2.8 million jobs to the U.S. economy in 2011.

- Sustainable fisheries
- Harmful Algal Bloom tracking and prediction
- Offshore energy design, development and operation
- Navigation systems prevent groundings in busy ports
- Forecast ocean conditions for the fishing fleet (safety, harvest) and fishing surveys
- Predicting ocean acidification events for shellfish hatcheries

Environment

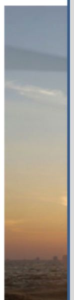
"Chá bă," a new buoy off the coast of Washington, contributes better information about the ocean conditions that oysters can and cannot tolerate.
(photo: J Payne, Pacific Ocean Shelf Tracking Project)

"chay buh"

The coast is at the center of human-ocean interactions

Safety | Economy | Environment

When operated as real-time now-cast or forecast systems … high-resolution coastal models that *__downscale global analyses__* and incorporate *__added dynamics__*, forcing, *__data assimilation__*, and inter-disciplinary interactions (e.g. sediments, ecosystems) provide ***__actionable guidance__*** for decision-making related to water quality, public health, coastal flooding, shipping, maritime safety, and other applications.



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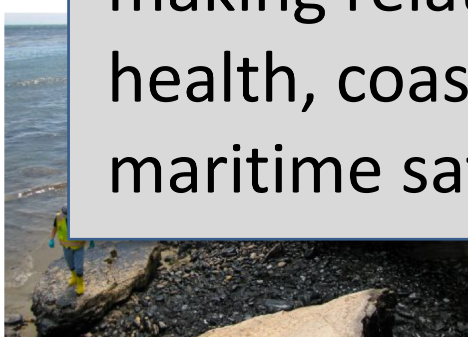


Oil-covered rocks at Refugio State Beach (photo: NOAA)

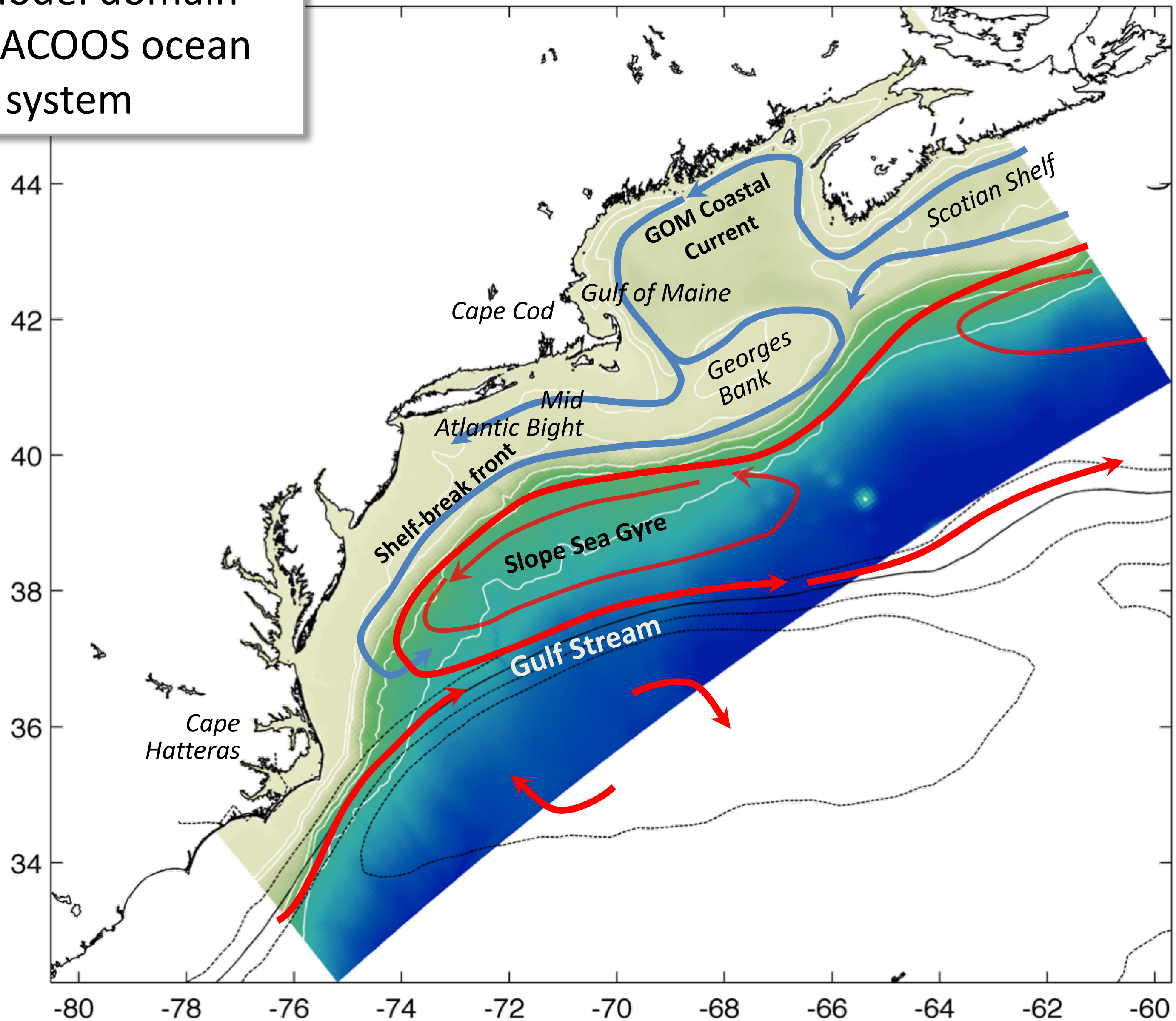
- Predicting ocean acidification events for shellfish hatcheries

pă," a new buoy off the of Washington, contributes information about the conditions that oysters can and cannot tolerate. (photo: J Payne, Pacific Ocean Shelf Tracking Project)

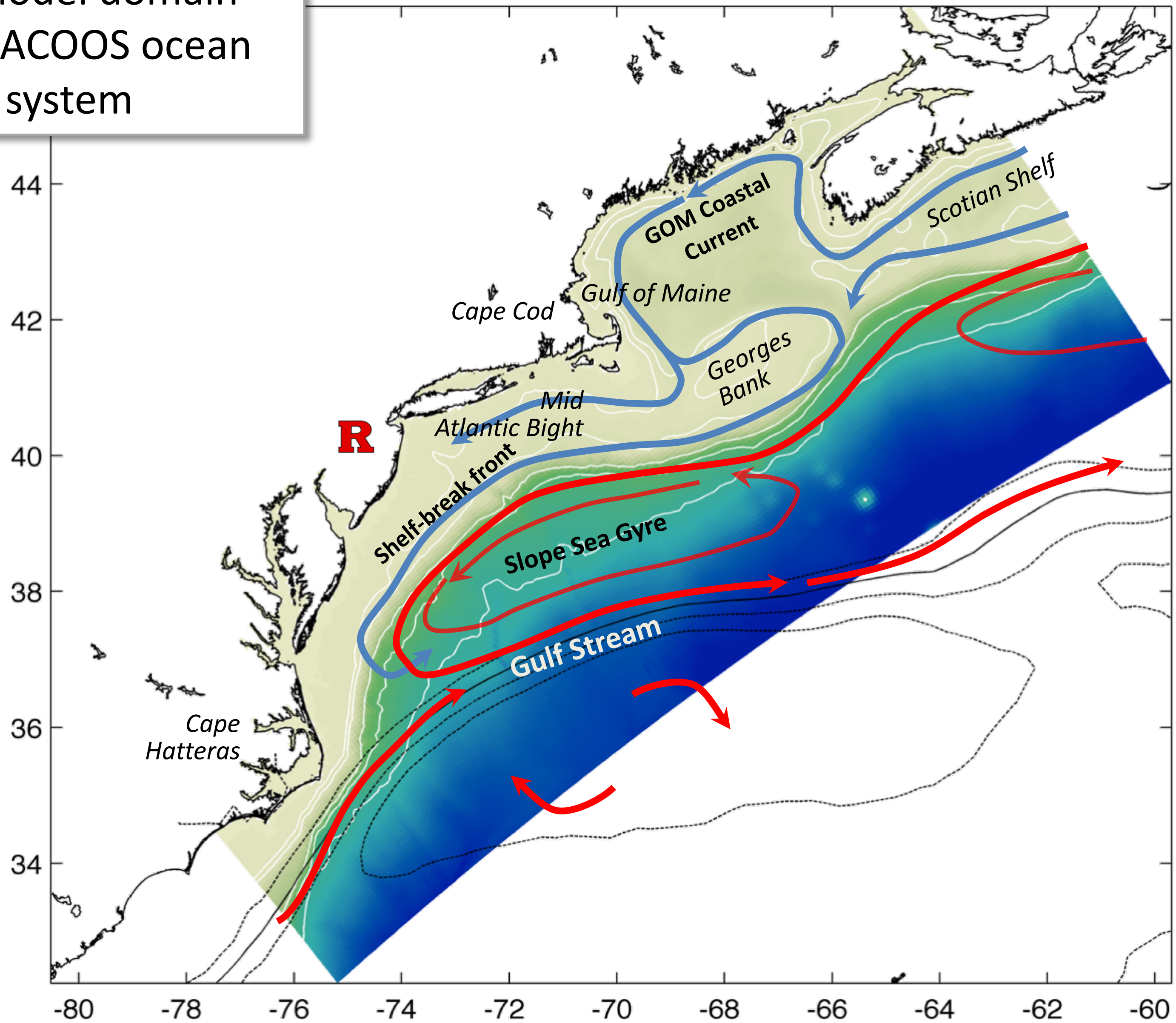
IOOS | Integrated Ocean Observing System

"chay buh"

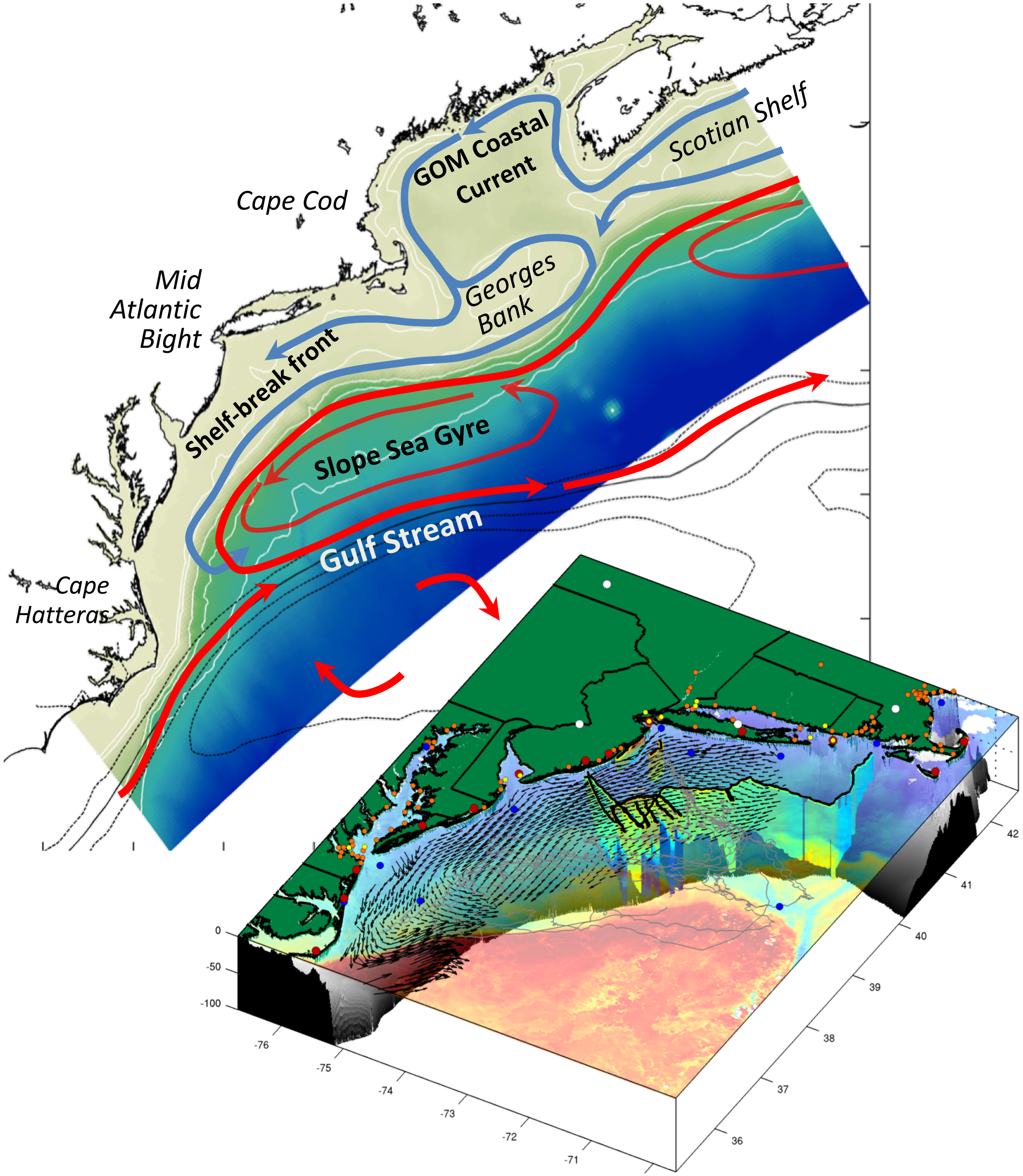
ROMS model domain for MARACOOS ocean forecast system



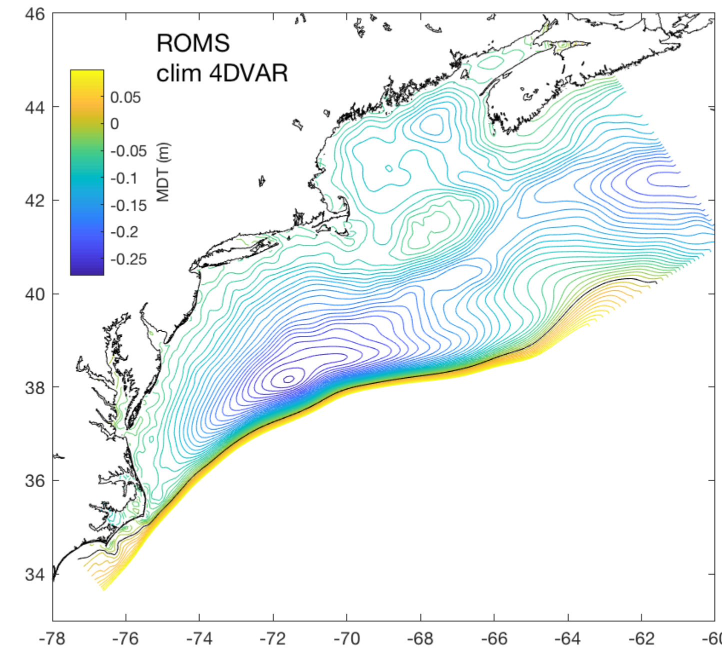
ROMS model domain for MARACOOS ocean forecast system



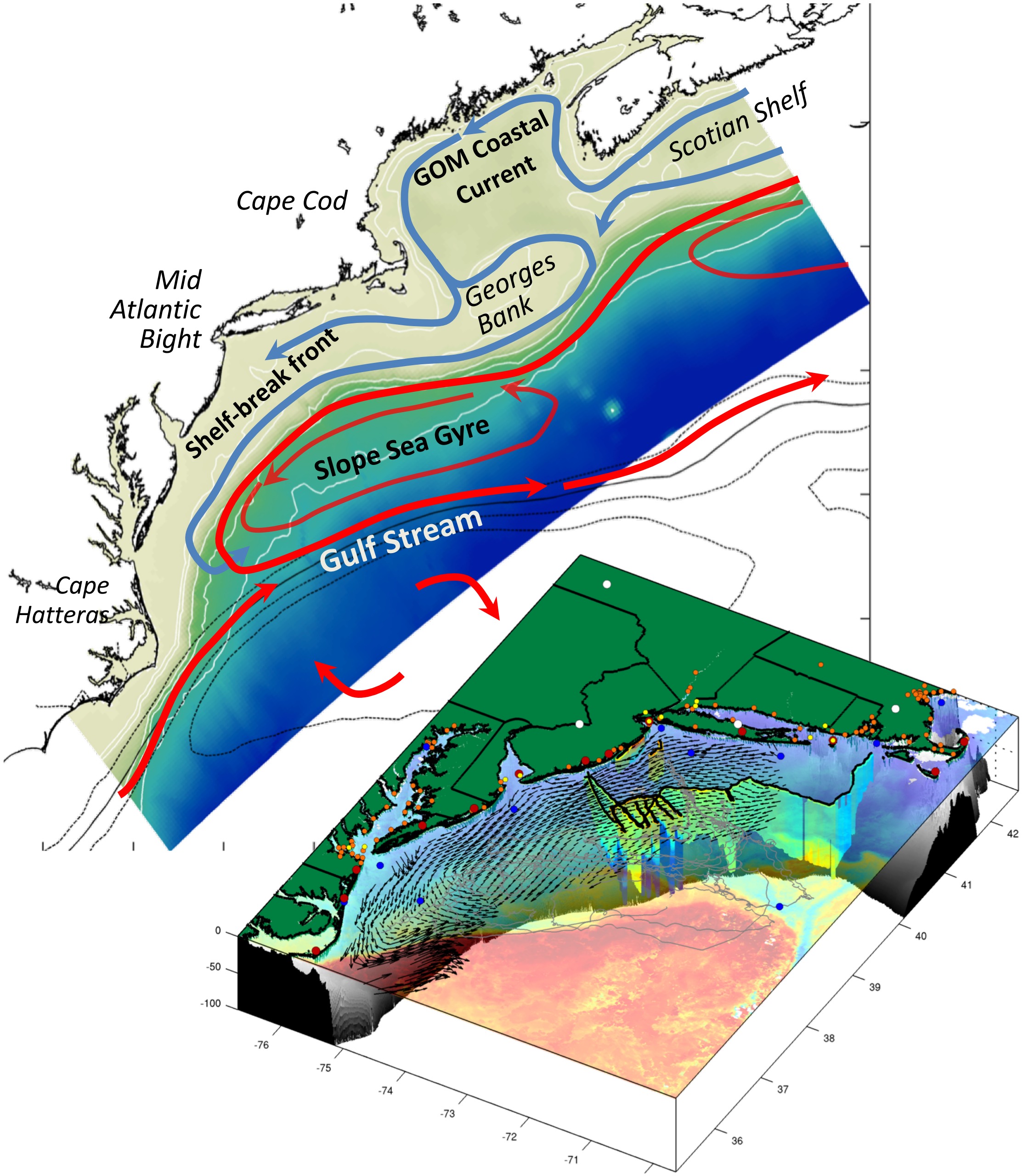
MARACOOS ROMS: Real-time forecast for Mid-Atlantic Bight and Gulf of Maine



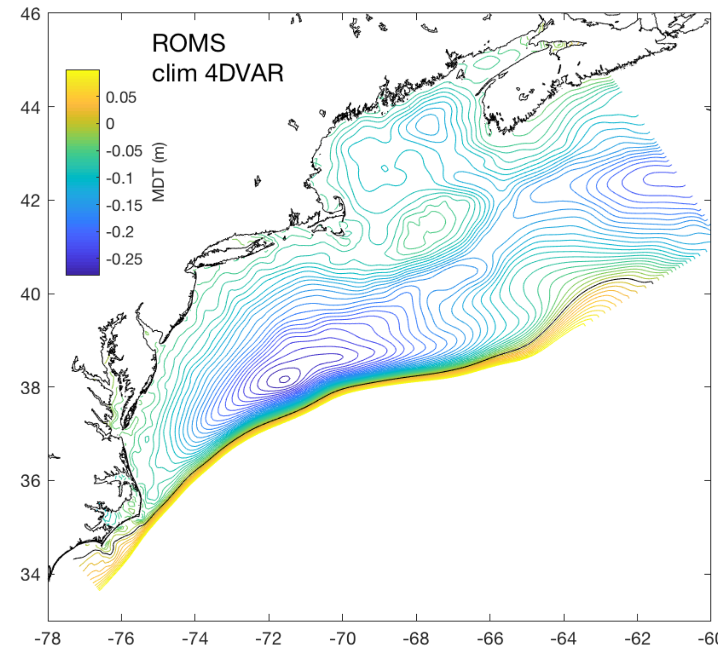
Mean Sea Level from ROMS climatological 4D-Var analysis



MARACOOS ROMS: **Real-time forecast for Mid-Atlantic Bight and Gulf of Maine**

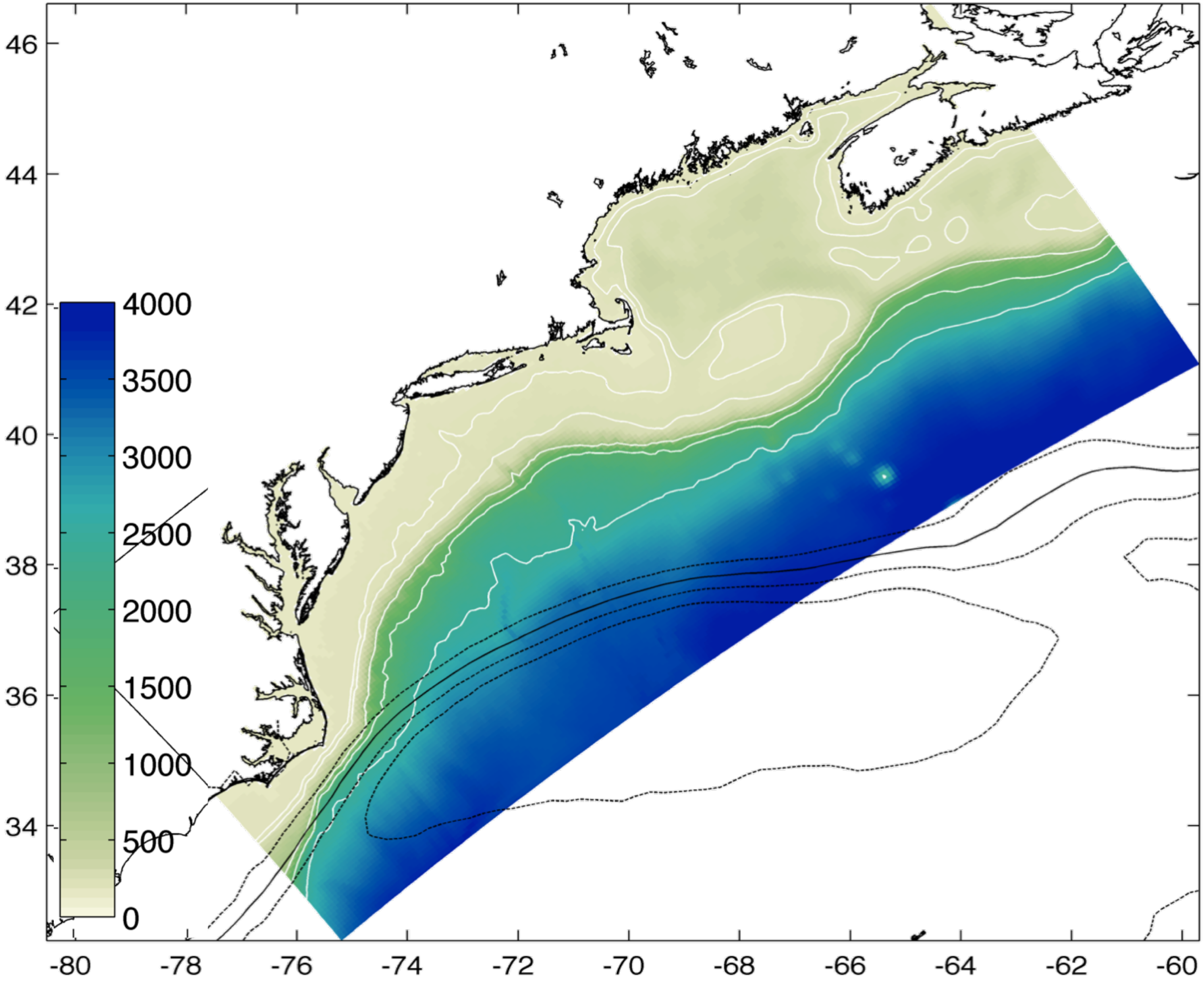


Mean Sea Level from ROMS climatological 4D-Var analysis



ROMS ocean physics …
+ MARACOOS data
+ 4D-Var data assimilation
= 'best' estimate of ocean state

Doppio* real-time and reanalysis ROMS system for the Mid-Atlantic Bight and Gulf of Maine



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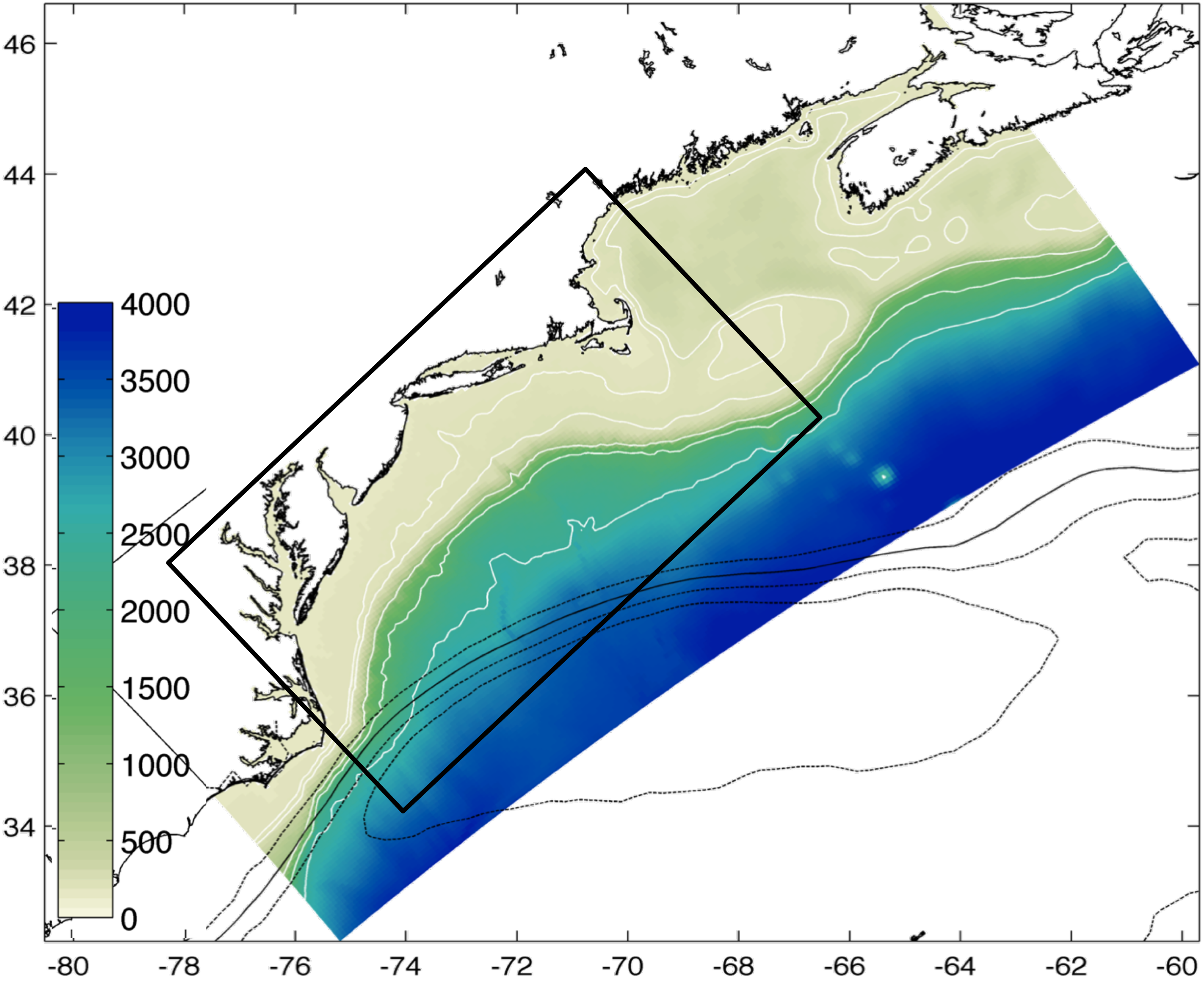
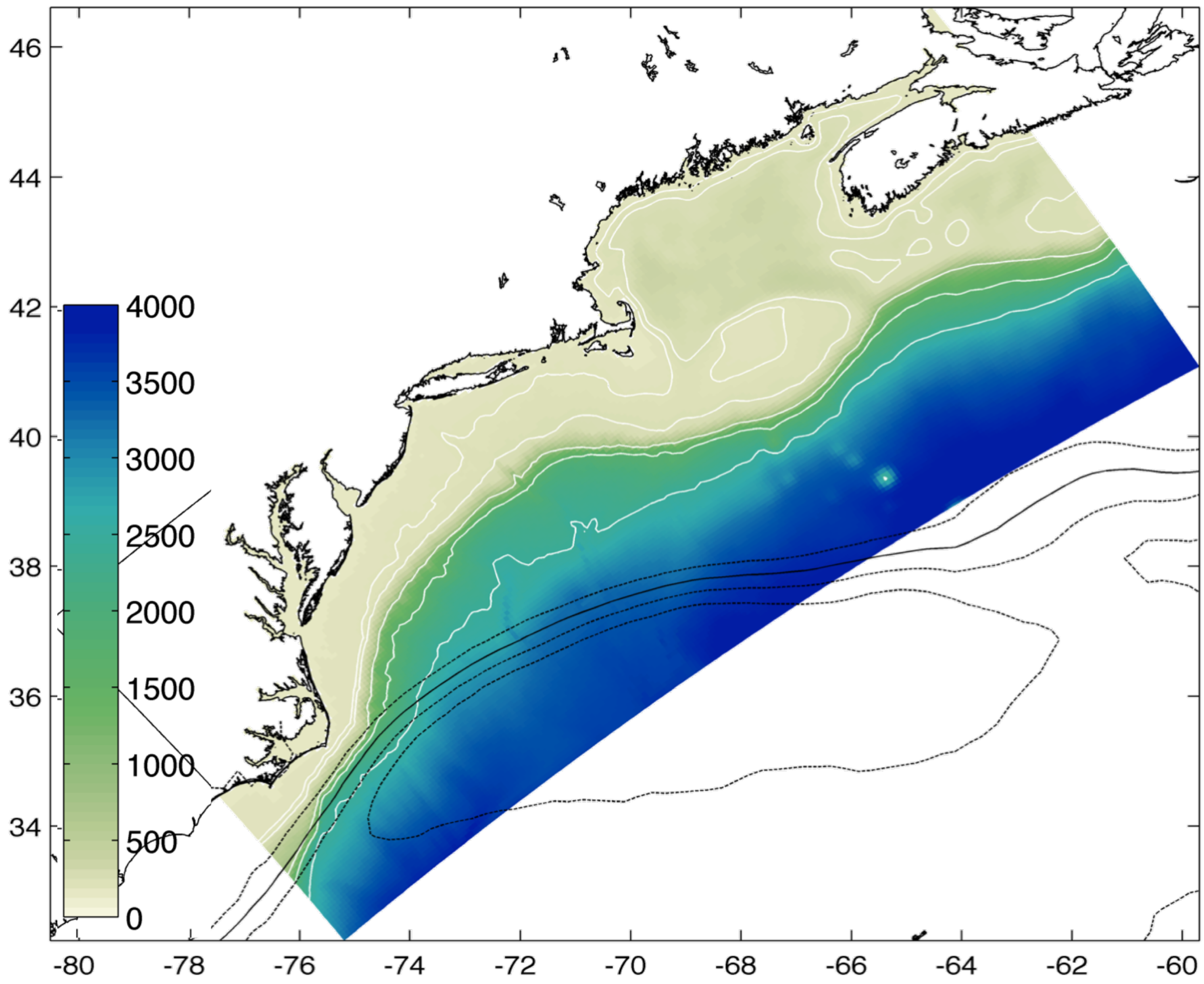


ESPreSSO**

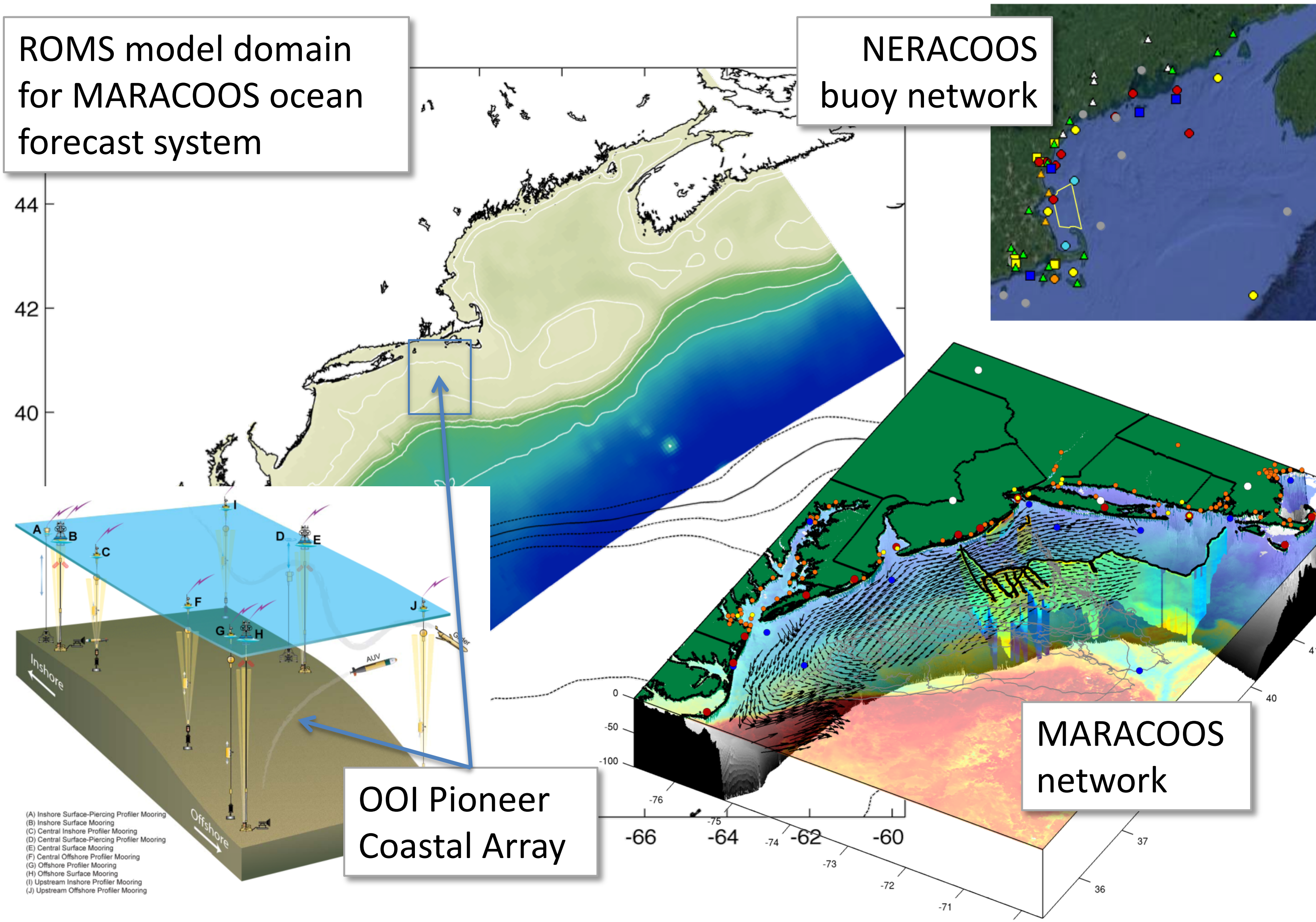
**Experimental System for Predicting Shelf and Slope Optics

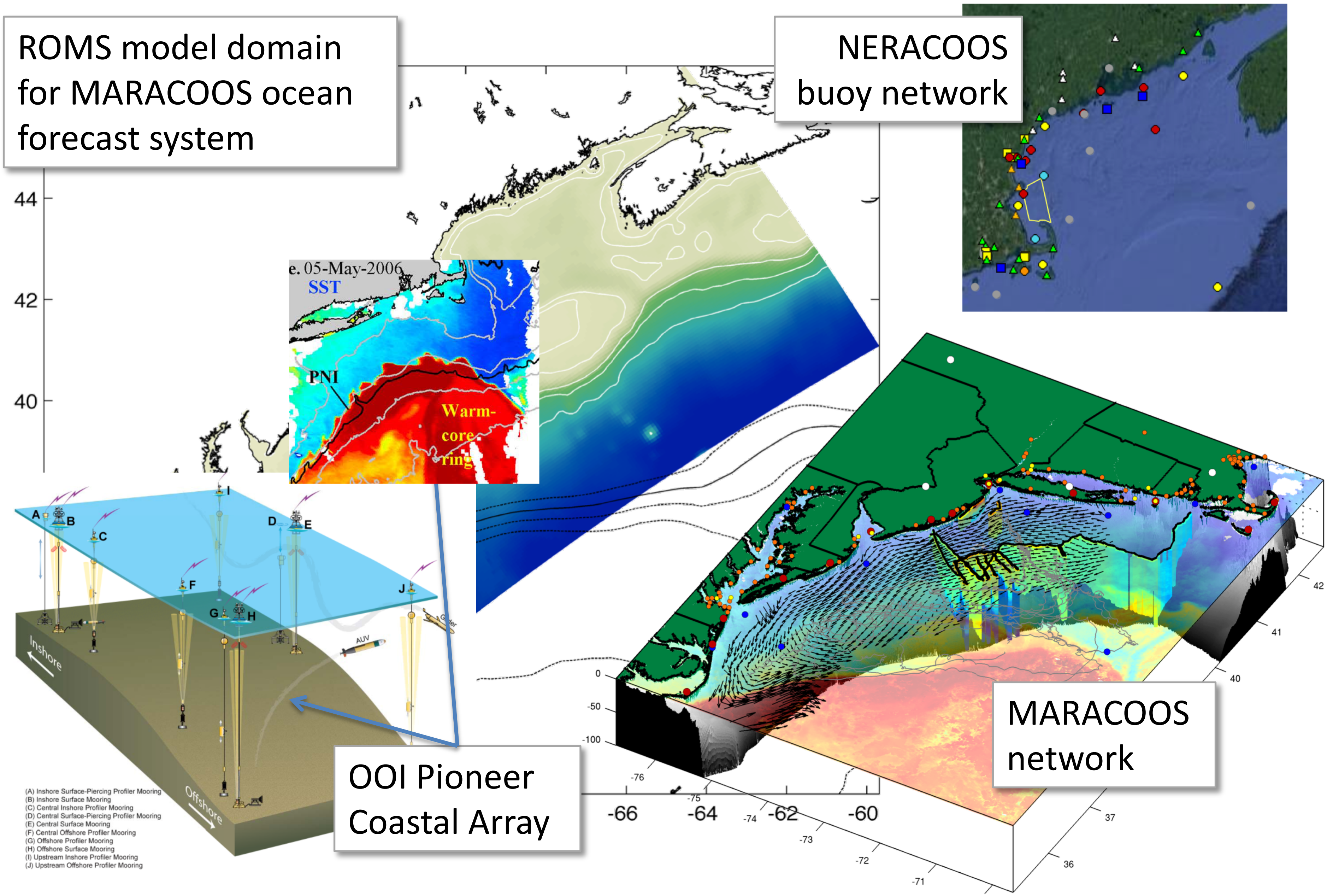
Doppio* real-time and reanalysis ROMS system for the Mid-Atlantic Bight and Gulf of Maine

* It's a double espresso



Doppio


ROMS model domain for MARACOOS ocean forecast system
NERACOOS buoy network
MARACOOS network
OOI Pioneer Coastal Array
44
42
40
-66
-64
-62
-60
Inshore
Offshore
AUV
(A) Inshore Surface-Piercing Profiler Mooring
(B) Inshore Surface Mooring
(C) Central Inshore Profiler Mooring
(D) Central Surface-Piercing Profiler Mooring
(E) Central Surface Mooring
(F) Central Offshore Profiler Mooring
(G) Offshore Profiler Mooring
(H) Offshore Surface Mooring
(I) Upstream Inshore Profiler Mooring
(J) Upstream Offshore Profiler Mooring

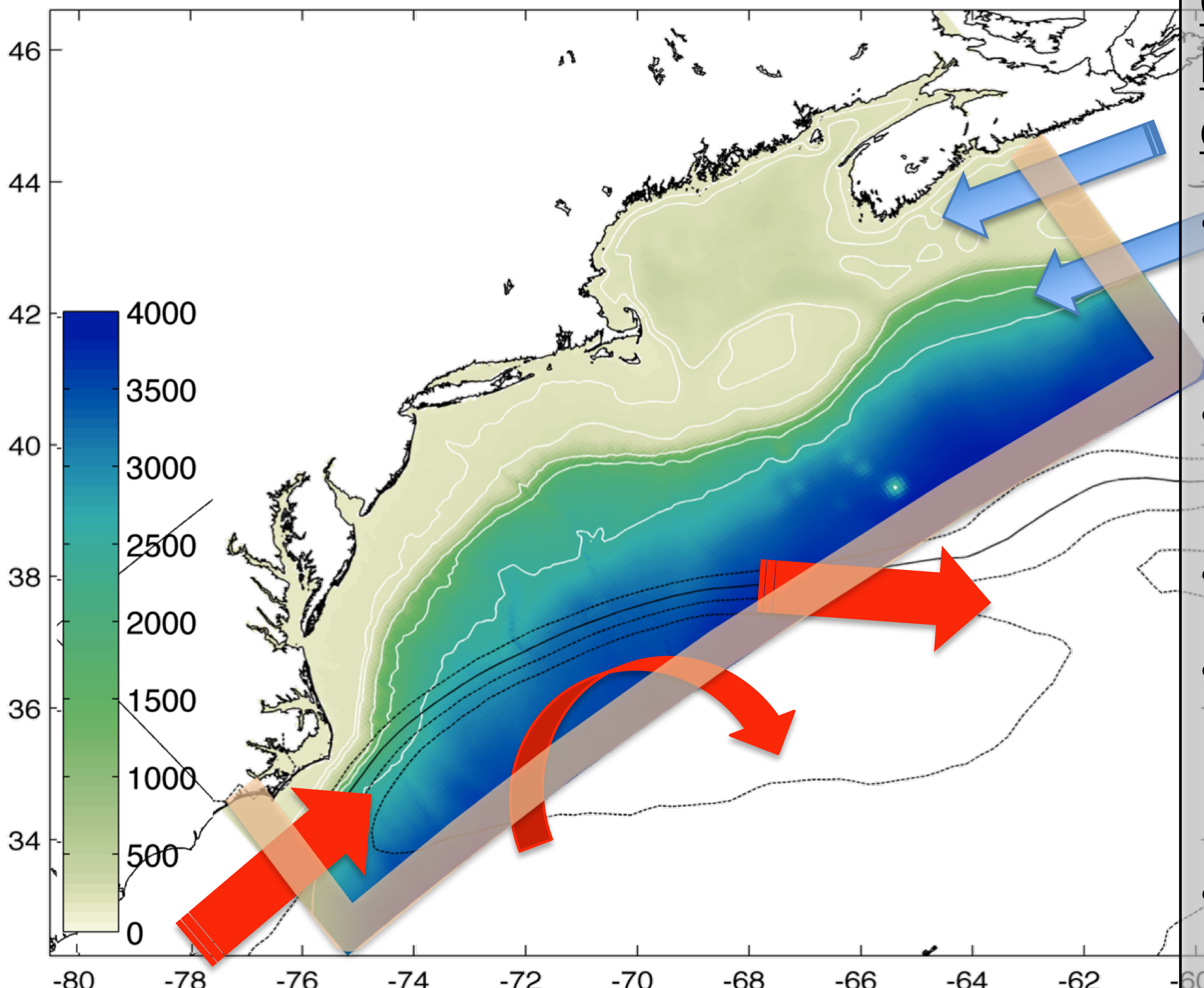


RUTGERS

maracoos.org | oceansmap.maracoos.org

Mid-Atlantic Regional Association of Coastal Ocean Observing Systems

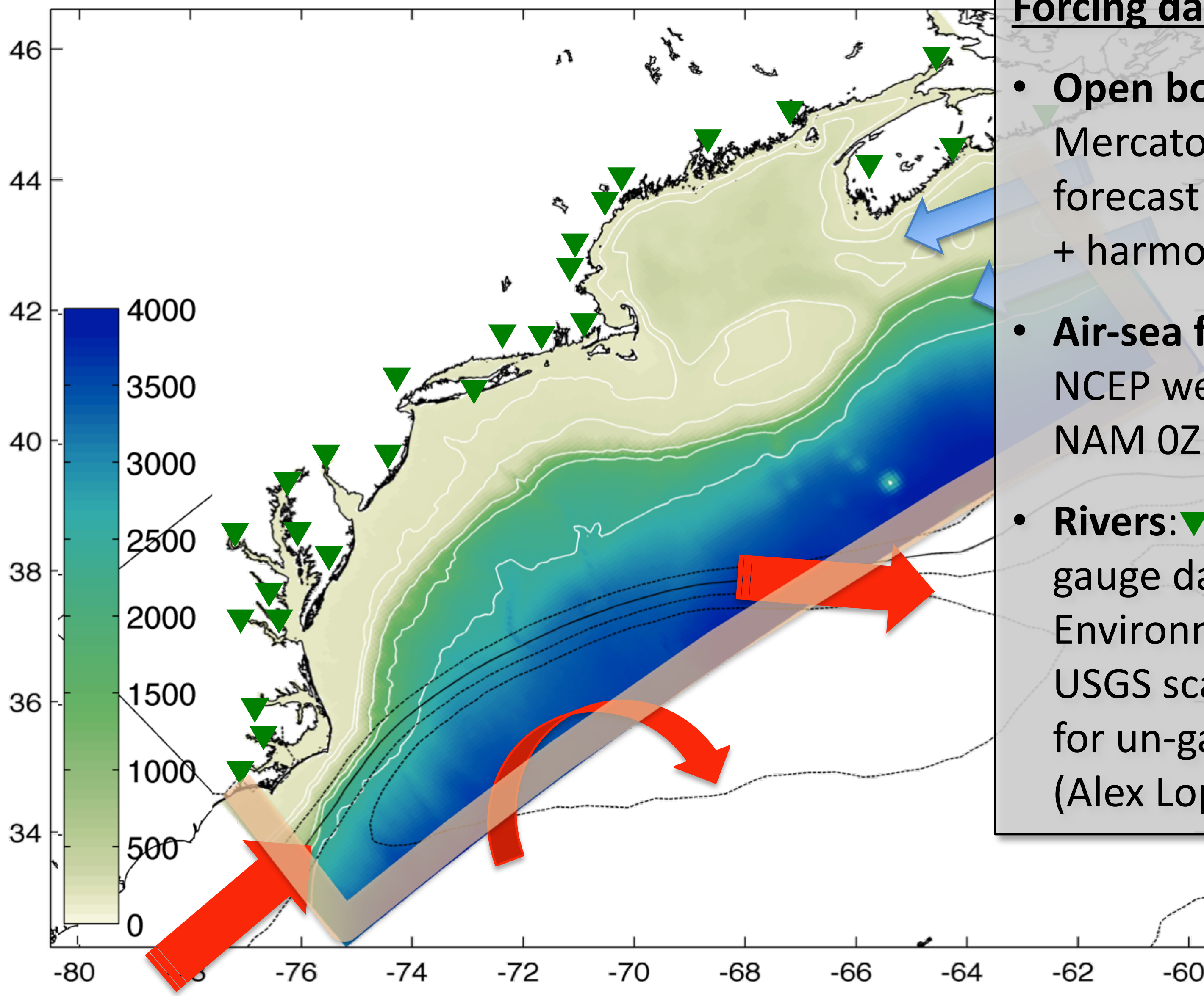
MARACOOS ROMS: Real-time forecast for Mid-Atlantic Bight and Gulf of Maine



GODAE model open boundary conditions for down-scaling:

- MERCATOR 7-day forecast
- Correct for bias in T/S
- Adjust for consistent MDT and mean velocity
- Add harmonic tides
- Active/passive (radiation/nudging) at domain perimeter
- Flow relaxation in boundary "nudging zone"

MARACOOS ROMS: Real-time forecast for Mid-Atlantic Bight and Gulf of Maine



Forcing data:

- **Open boundaries**: Mercator-Océan 7-day forecast (from CMEMS) + harmonic tides
- **Air-sea fluxes**: 72-hour NCEP weather forecast NAM 0Z
- **Rivers**:▼ Daily stream gauge data from Environment Canada and USGS scaled to account for un-gauged watershed (Alex Lopez)

MARACOOS ROMS: Data streams routinely assimilated into the near-real-time 4D-Var 'best' analysis of Mid-Atlantic Bight and Gulf of Maine ocean conditions

Observation type and platform	Source	Sampling frequency and resolution	Latency
AVHRR infrared SST	MARACOOS.org and NOAA CoastWatch	4 passes per day, 1 km	2 hr
GOES infrared SST	NOAA Coast-Watch	hourly, 6 km	12 hr
AMSR2 and WindSat microwave SST	NASA JPL PO-DAAC	daily, 15 km	24 hr
SSH: 4 satellite altimeters: Jason, AltiKa, CryoSat and Sentinel-3 with coastal corrections	Radar Altimeter Database System at TU Delft	~1 pass daily in do-main, ~4 km	4 hr
in situ T, S on GTS from National Data Buoy Center buoys, Argo floats, shipboard XBT, surface drift-ers	NOAA Observing System Monitor-ing Center (OSMC)	varies with platform	~12 hr
Surface currents from CODAR HF-radar	MARACOOS.org	hourly, 1km	4 hr
Glider T, S ~1-2 deployments per month in domain by MARACOOS	IOOS Glider Data Assembly Center	dense along trajectory	2 hr

Table 21.1. A summary of the observational data streams accessed for the ROMS Doppio near real time data assimilation system.

MARACOOS ROMS: **Data streams routinely assimilated into the near-real-time 4D-Var 'best' analysis of Mid-Atlantic Bight and Gulf of Maine ocean conditions**

Typically 200,000 observations in a 3-day analysis cycle

[illegible] platform	Source	Sampling frequency and resolution	Latency
[illegible] SST	MARACOOS.org and NOAA CoastWatch	4 passes per day, 1 km	2 hr
GOES infrared SST	NOAA Coast-Watch	hourly, 6 km	12 hr
AMSR2 and WindSat microwave SST	NASA JPL PO-DAAC	daily, 15 km	24 hr
SSH: 4 satellite altimeters: Jason, AltiKa, CryoSat and Sentinel-3 with coastal corrections	Radar Altimeter Database System at TU Delft	~1 pass daily in do-main, ~4 km	4 hr
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Some details …

Bias removal

- Removing bias from open boundary conditions is crucial
- 4D-Var will not converge if it cannot reconcile model and data error
- Co-variances embodied in the Adjoint and Tangent Linear physics are incorrect if the background state is biased

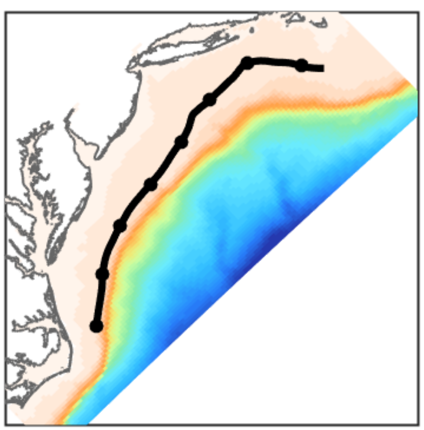
- Open Boundary Conditions (T and S) from MERCATOR are adjusted by matching mean to regional climatology (MOCHA)

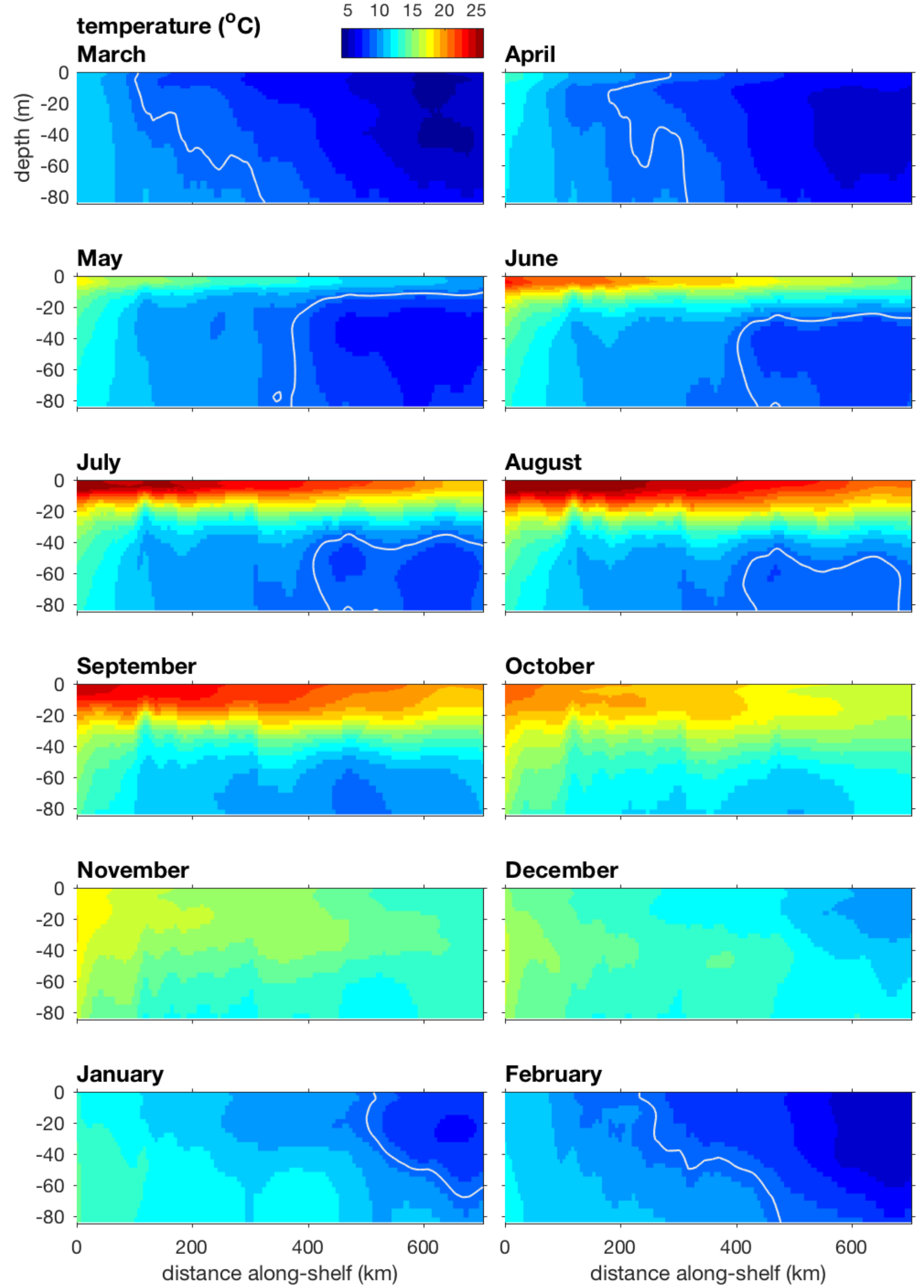
4DVAR analysis of mean climatological ocean state

Combine …

High-res regional T/S climatology (MOCHA)

with …



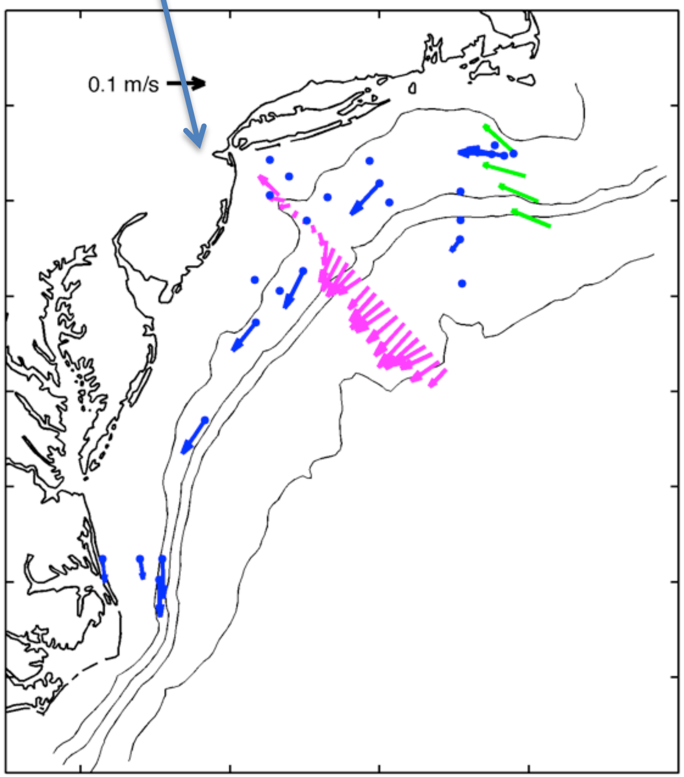


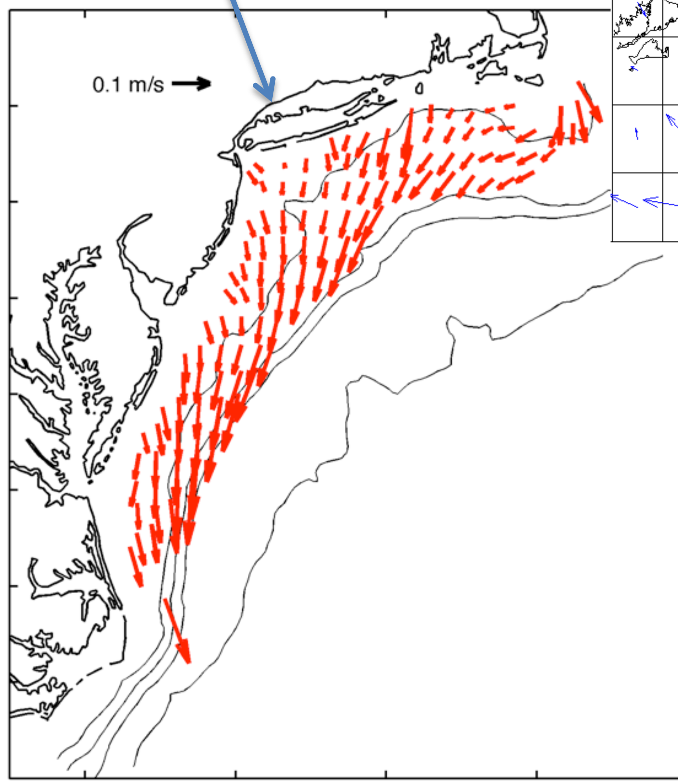
4DVAR analysis of mean climatological ocean state

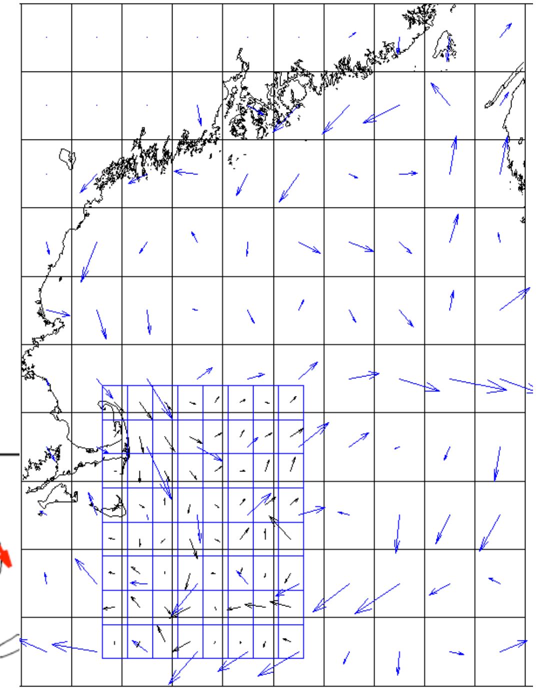
velocity obs. from …
moorings (blue, green)
and ship ADCP (magenta))

surface drifters

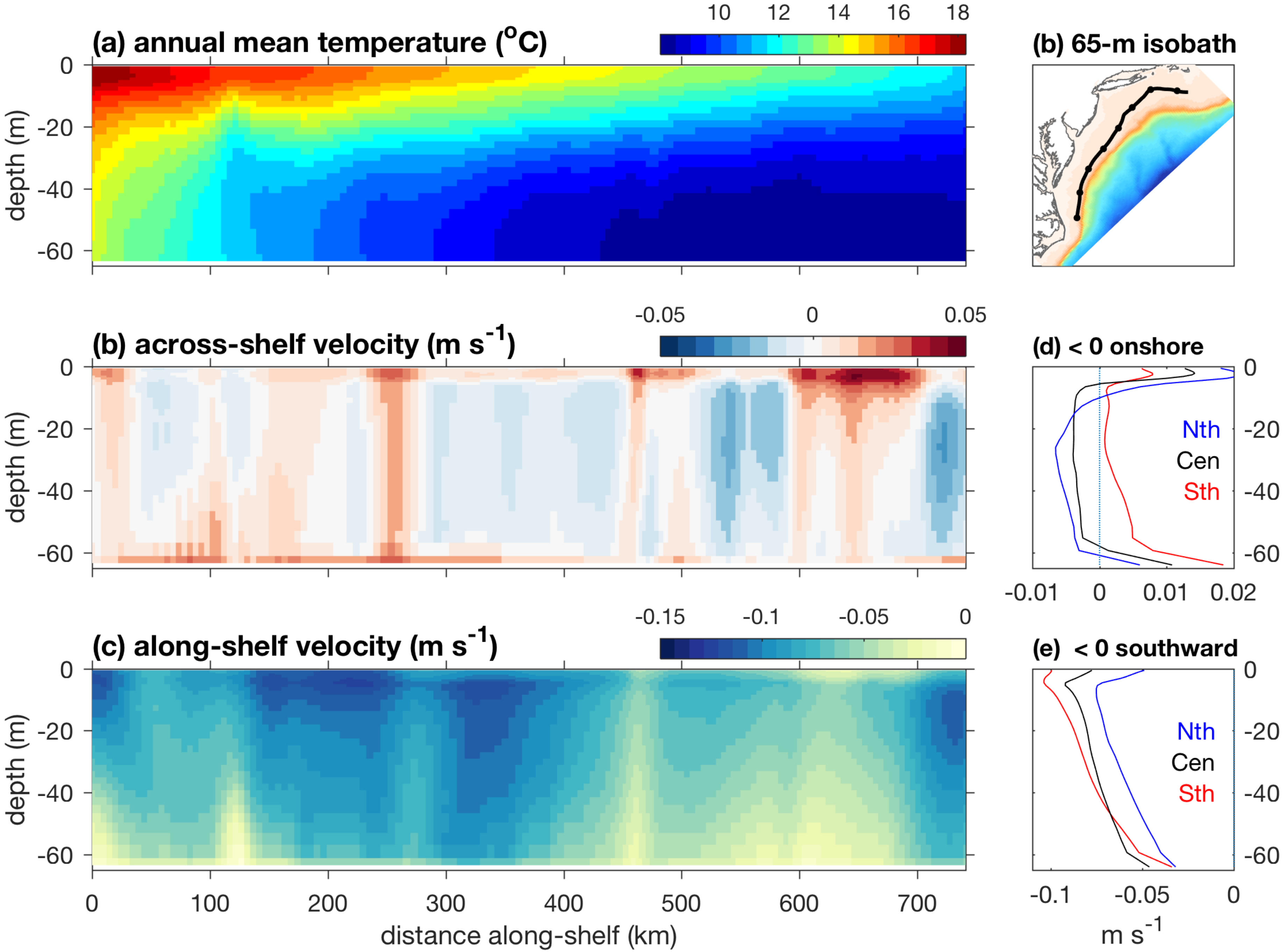
CODAR (red)



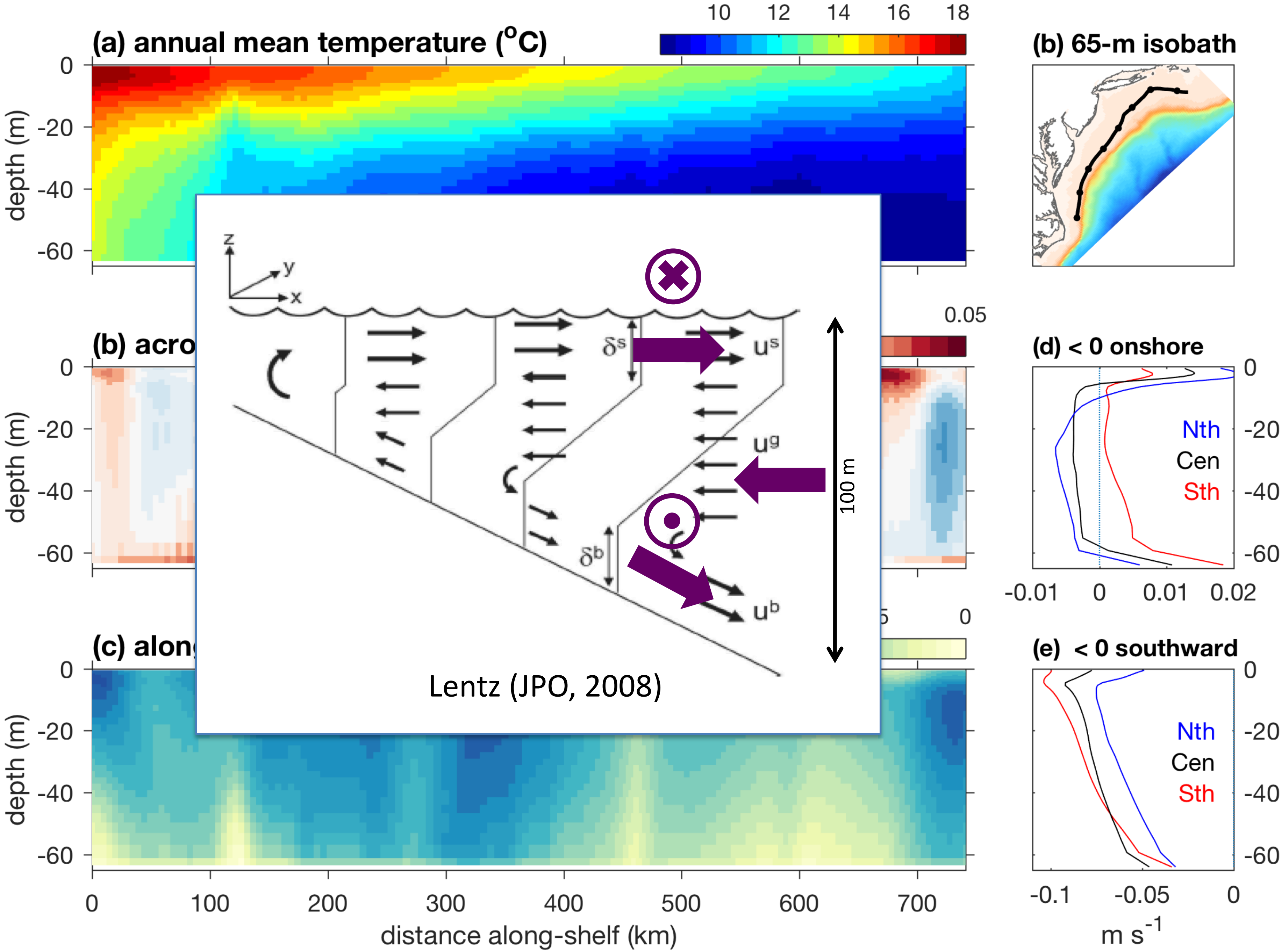




… to get … >>



(a) annual mean temperature (°C)
10 12 14 16 18
(b) 65-m isobath
(b) across-shelf velocity (m s-1)
-0.05 0 0.05
(d) < 0 onshore
Nth
Cen
Sth
(c) along-shelf velocity (m s-1)
-0.15 -0.1 -0.05 0
(e) < 0 southward
Nth
Cen
Sth
depth (m)
0 -20 -40 -60
distance along-shelf (km)
0 100 200 300 400 500 600 700
-0.01 0 0.01 0.02
-0.1 -0.05 0
m s-1



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Nth
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(e) < 0 southward
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depth (m)
distance along-shelf (km)
m s-1
z
y
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us
ug
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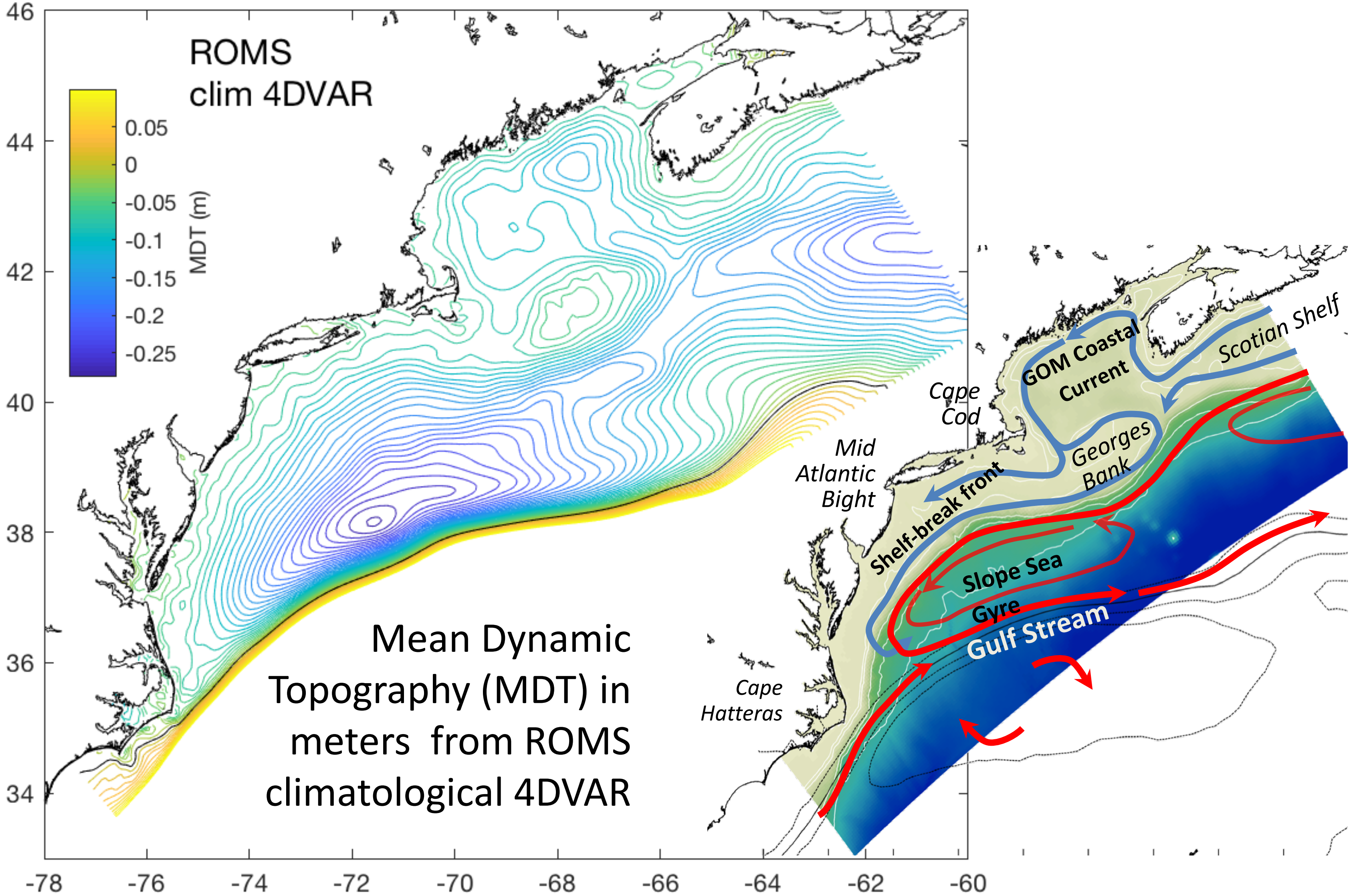
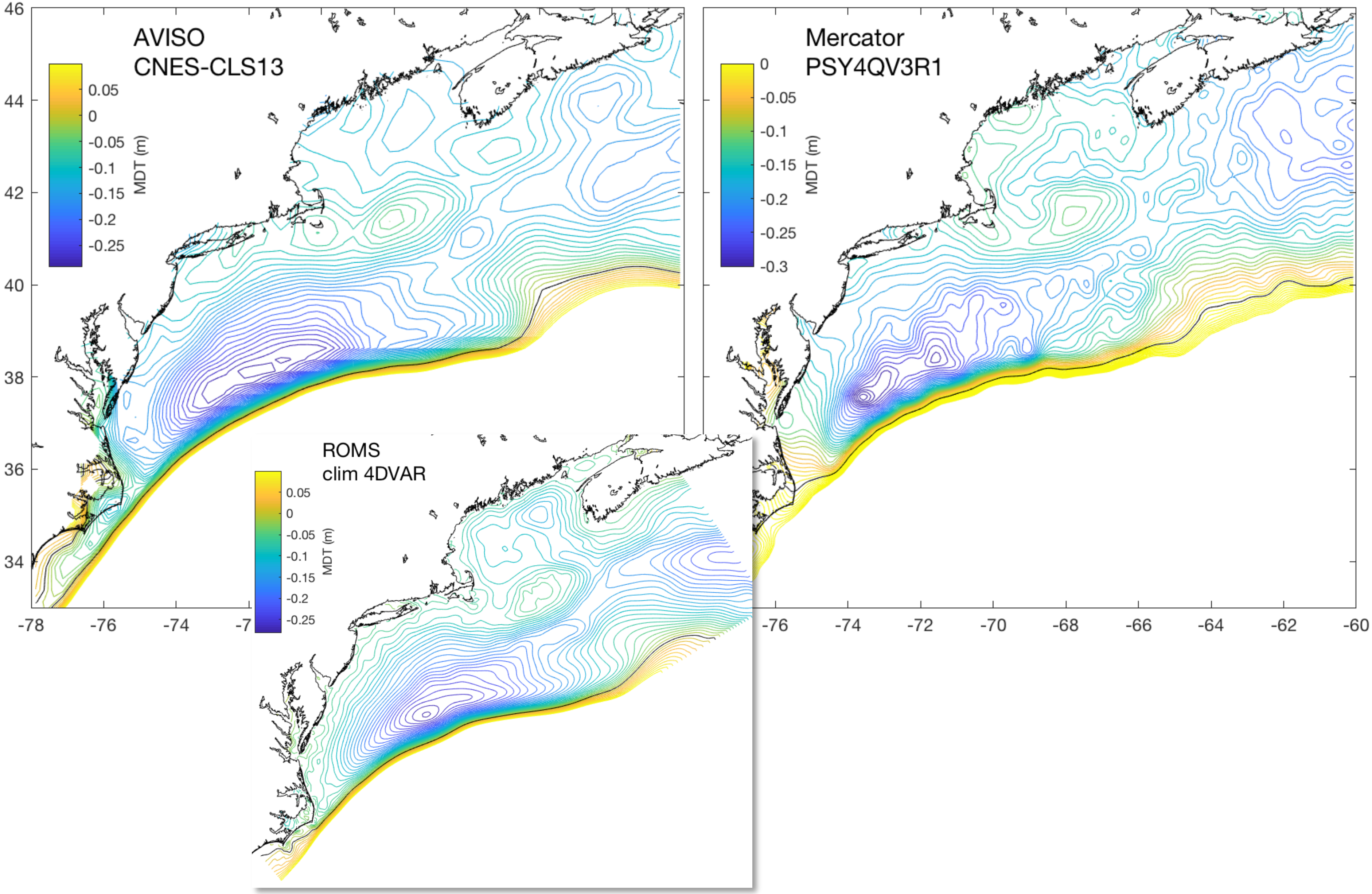
ub
100 m
Lentz (JPO, 2008)

Mean Dynamic Topography of the MAB and GoM

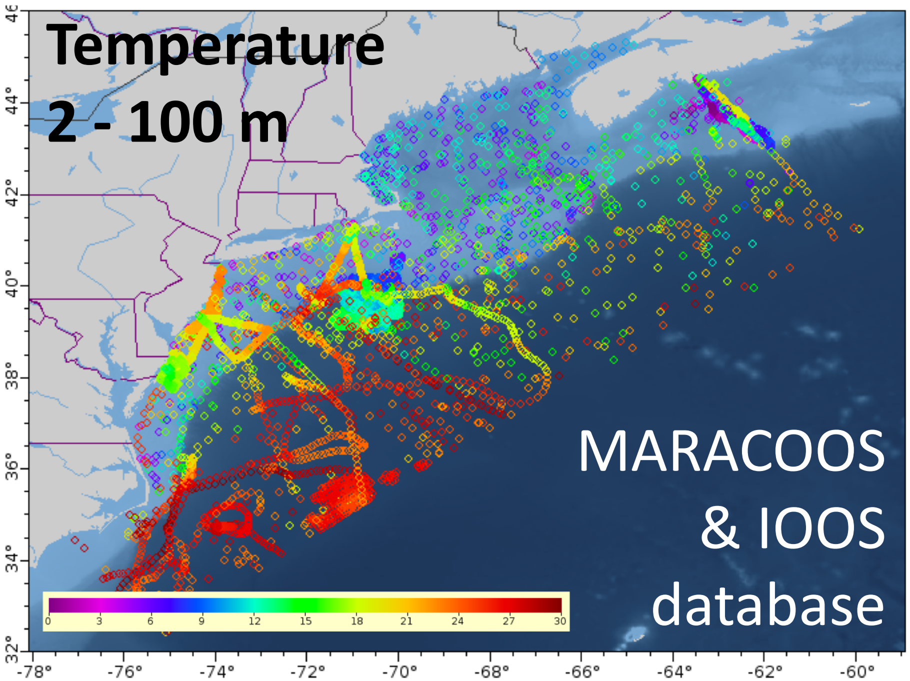


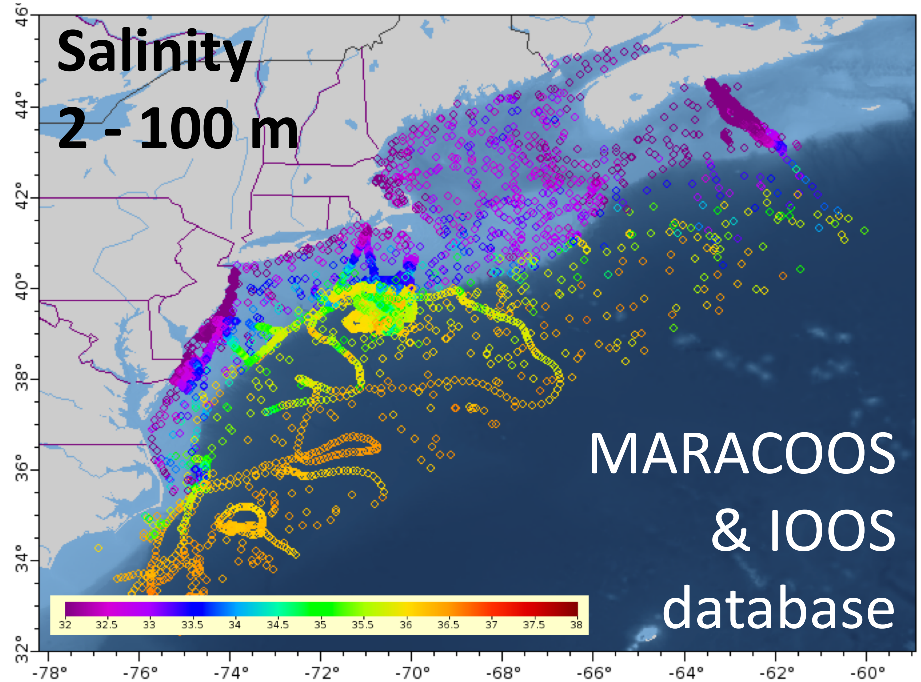
Mean Dynamic Topography (MDT) in meters from ROMS climatological 4DVAR

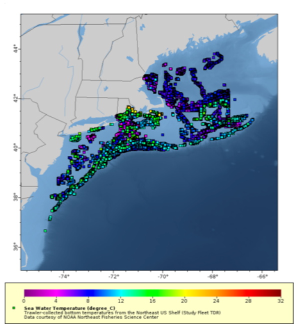
Mean Dynamic Topography of the MAB and GoM

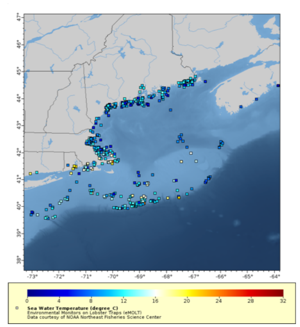


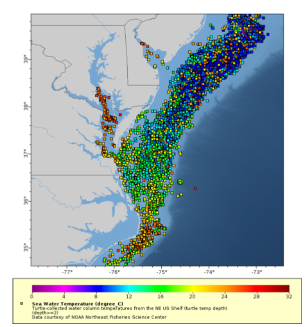
Subsurface in situ ocean observations for the northeast U.S. in 2015

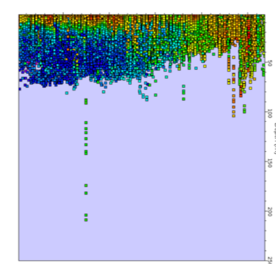




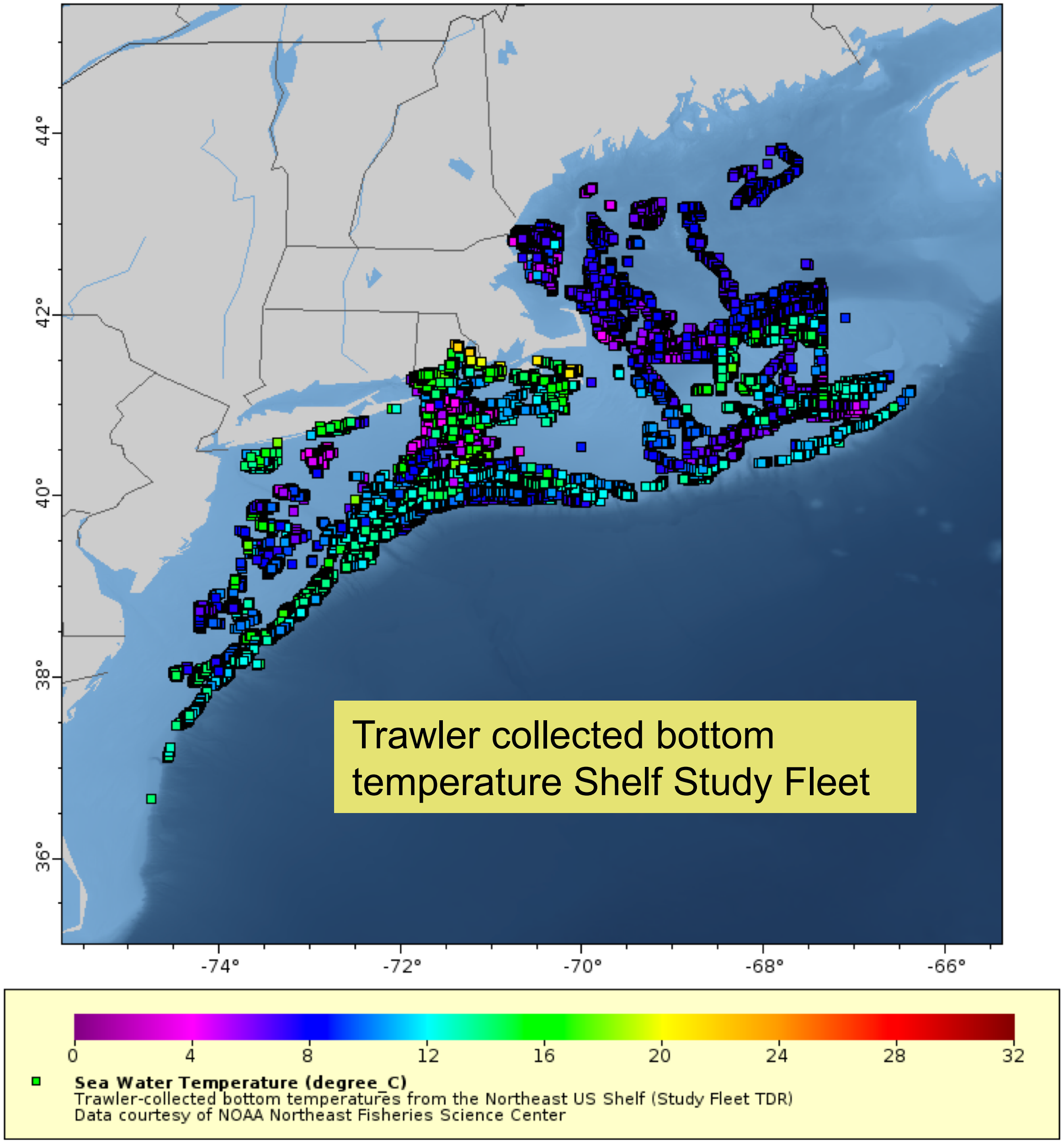








Subsurface in situ ocean observations - delayed



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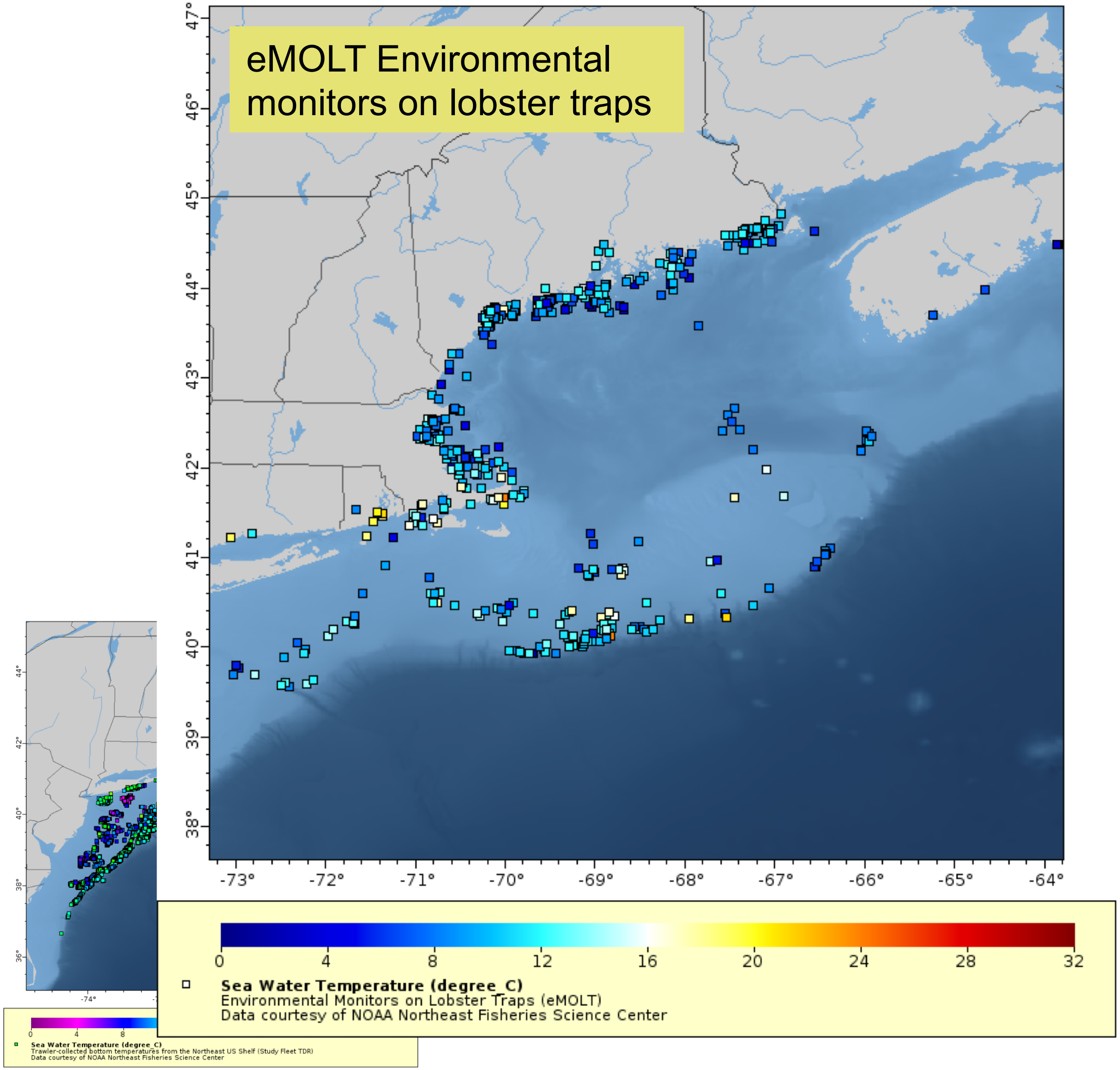
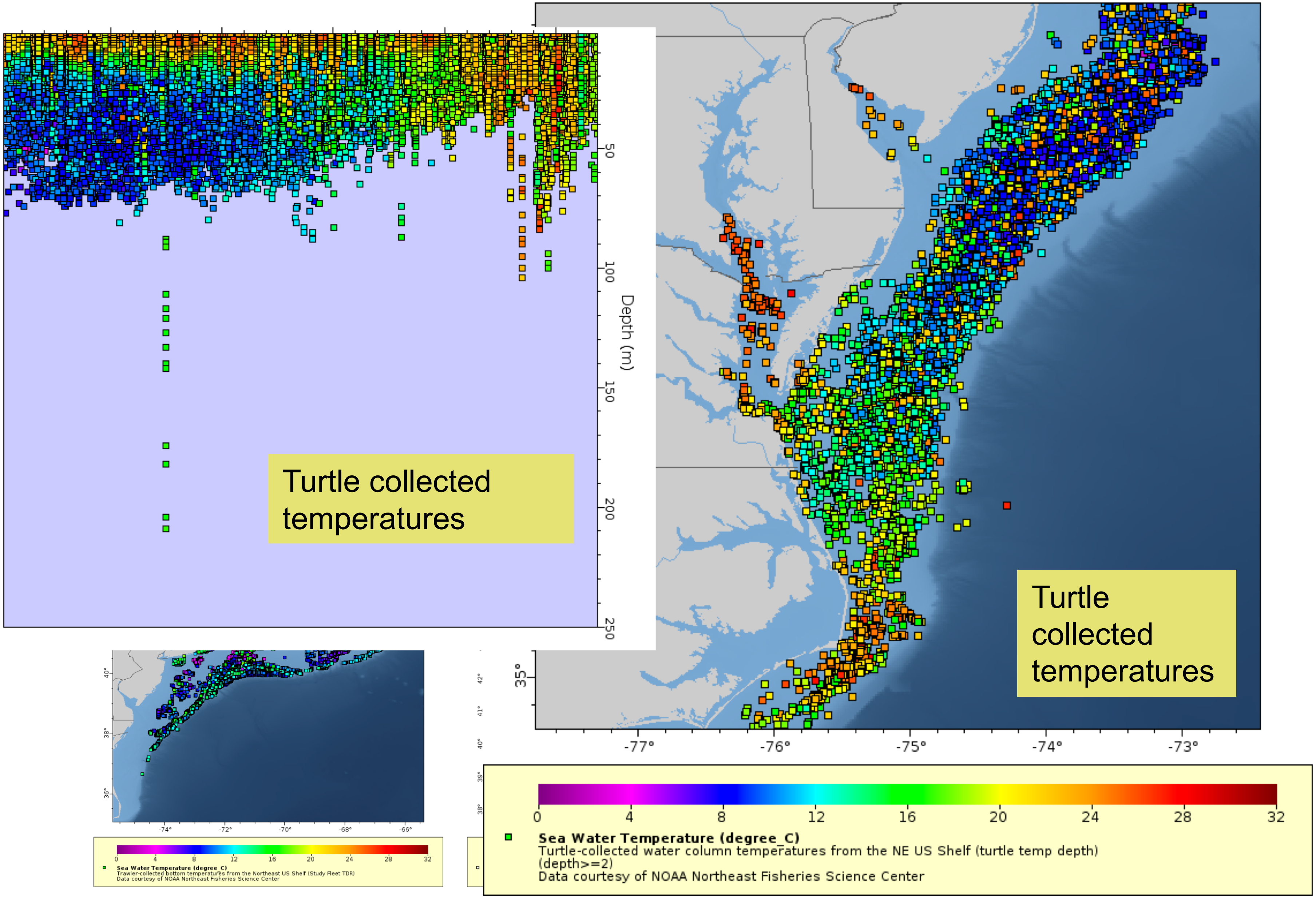
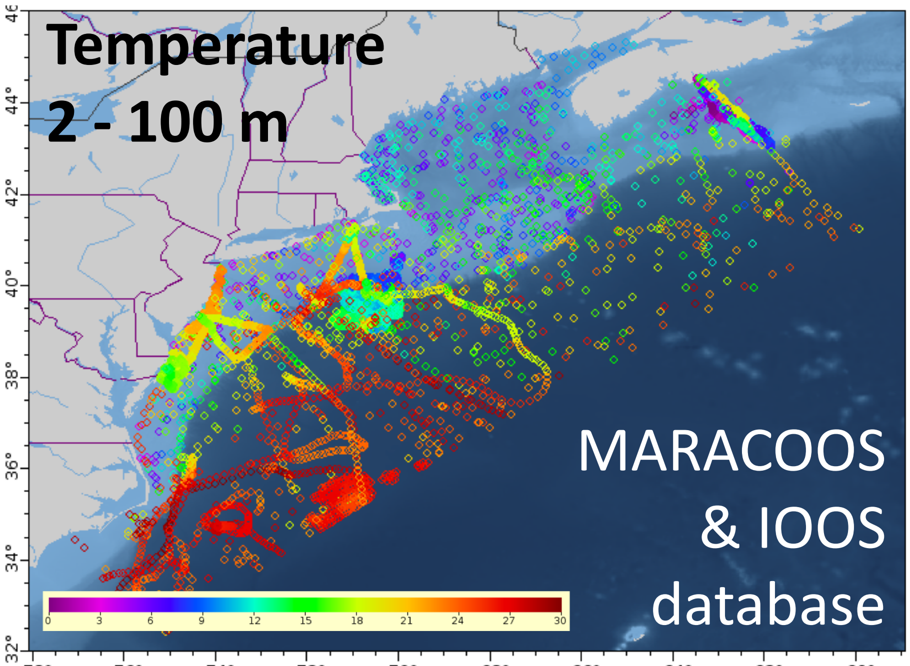
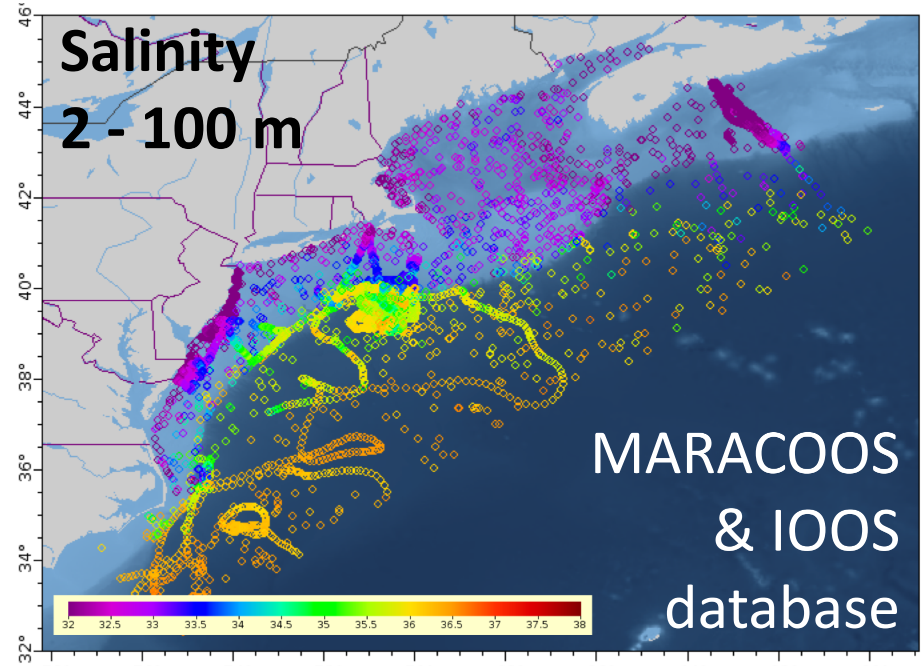


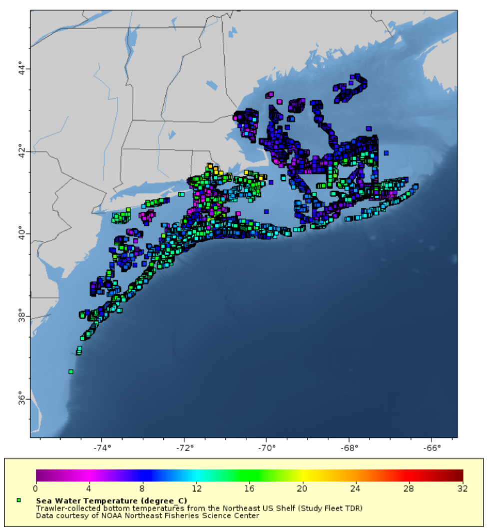
Subsurface in situ ocean observations - delayed

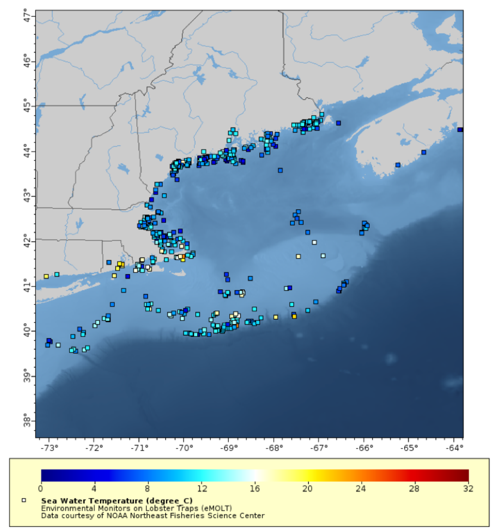


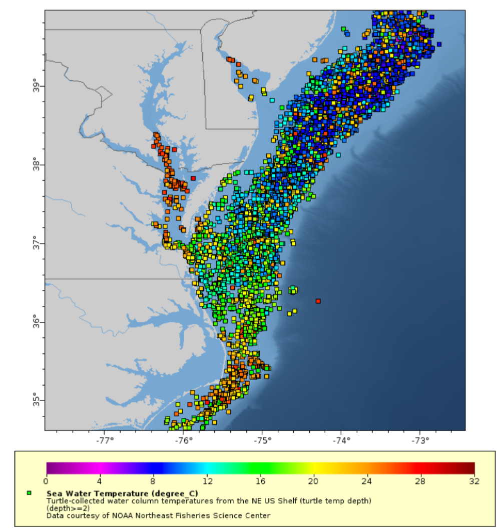
Subsurface in situ ocean observations – ***model skill assessment***



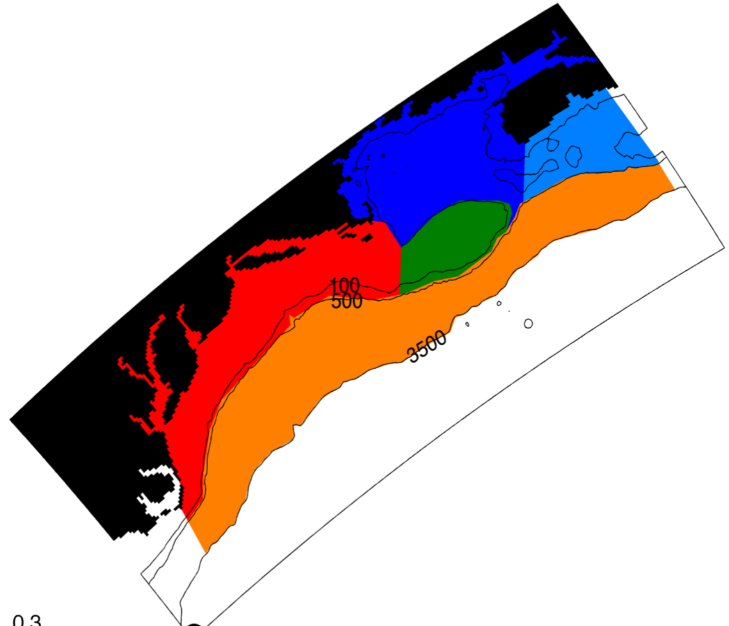


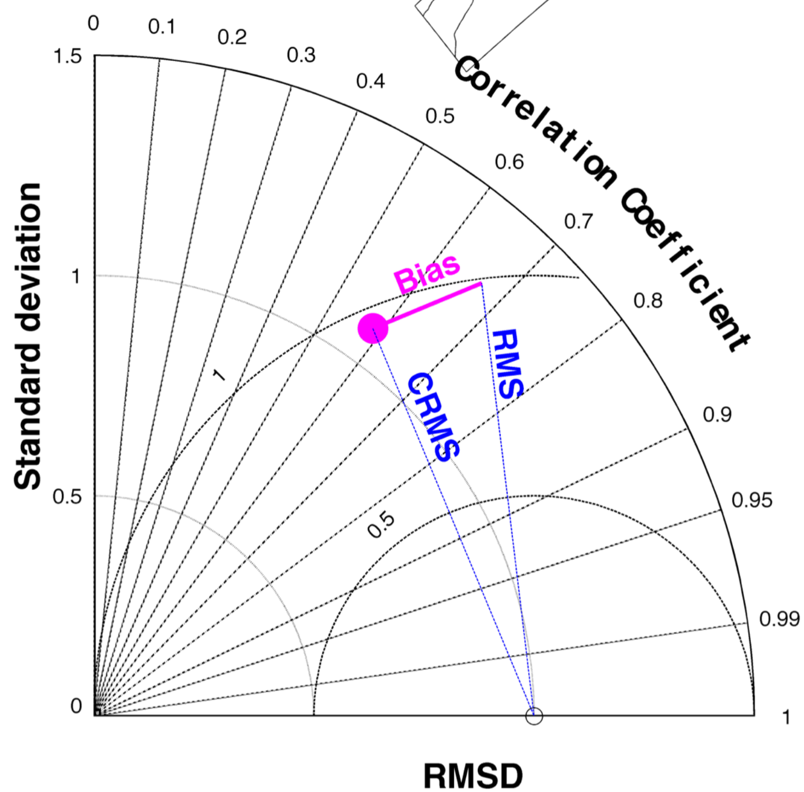




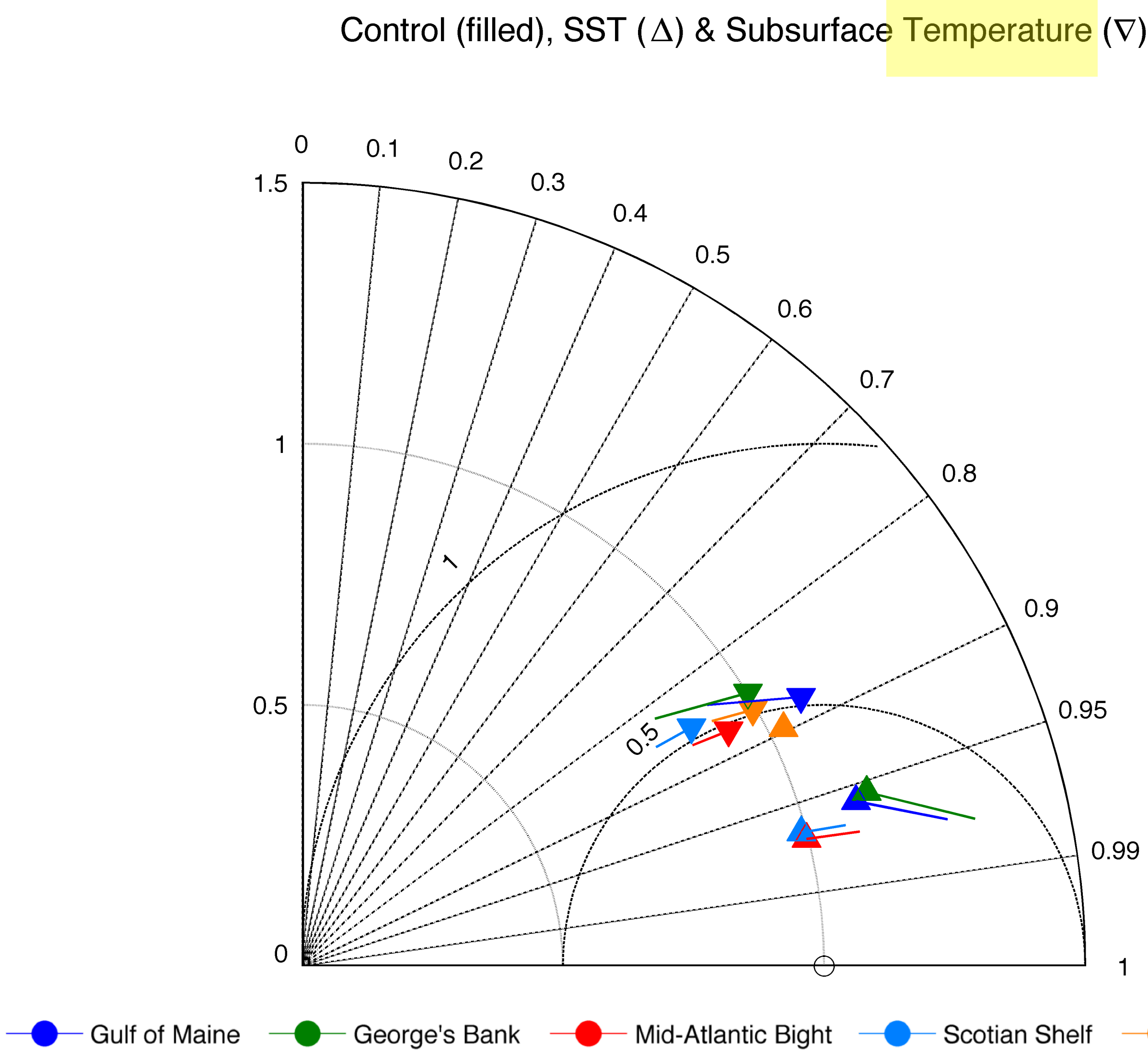


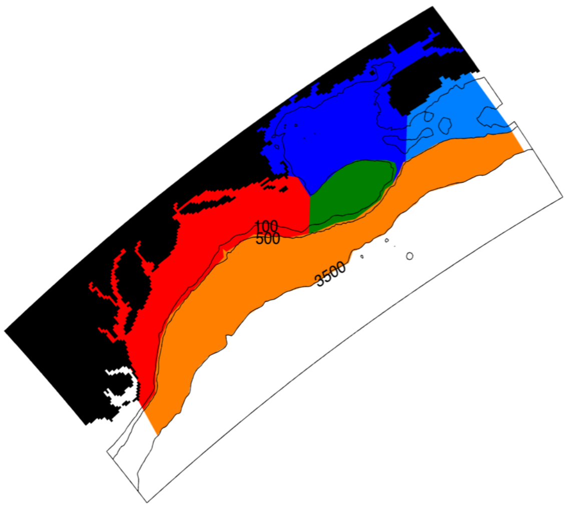
Run	Explanation
Control	The optimal configuration, used as benchmark for other cases
TRMM	Uses precipitation from NASA's Tropical Rainfall Measuring Mission instead of from NCEP's NARR
Unbias corrected Mercator	Uses open boundary files from Mercator-ocean without bias correction to annual mean
Uwind Minus Current	Surface stress calculated from wind relative to surface current
Unbias corrected HYCOM	Uses open boundary files from HYCOM without bias correction to the annual mean





A. Lopez

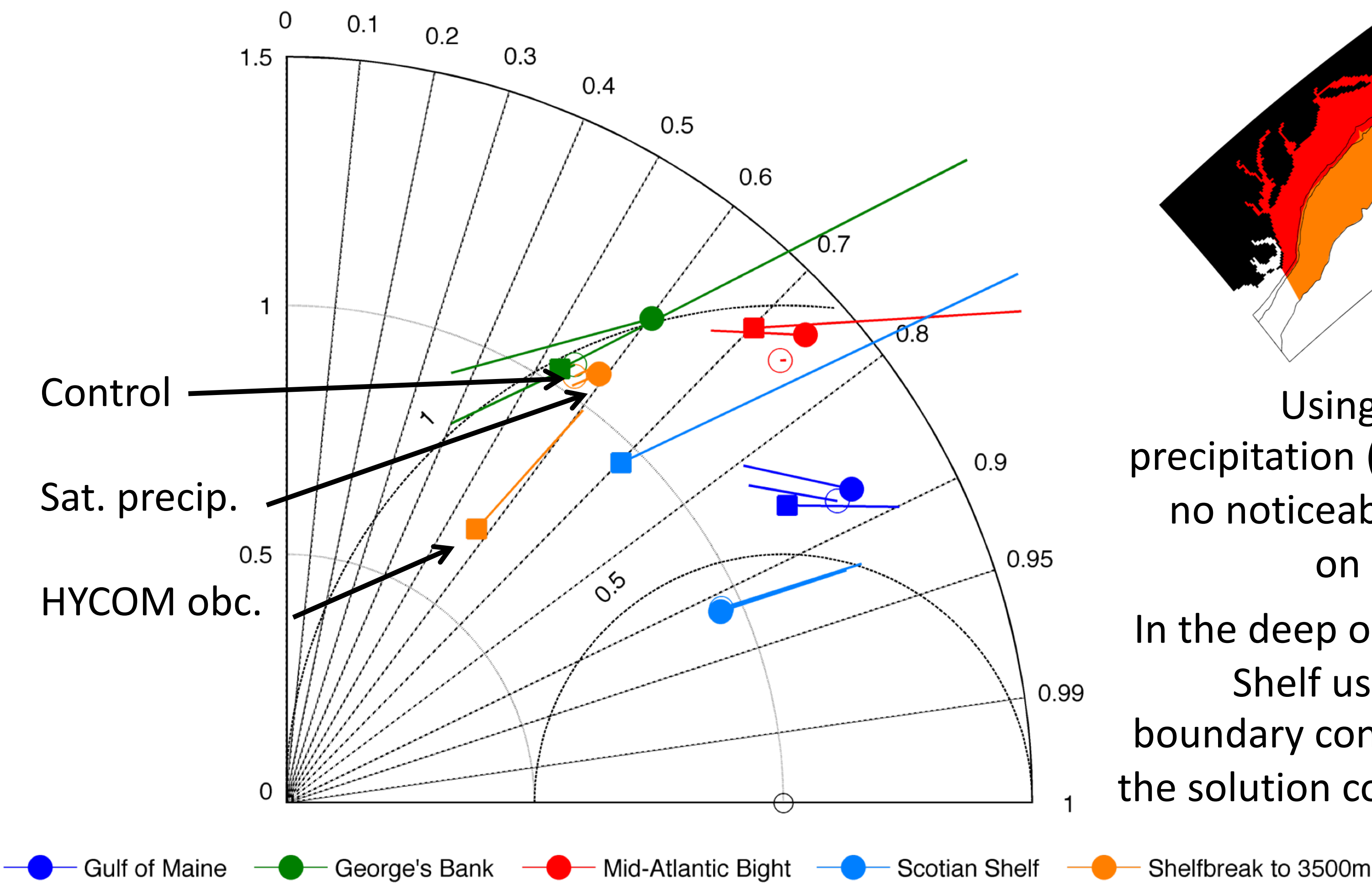


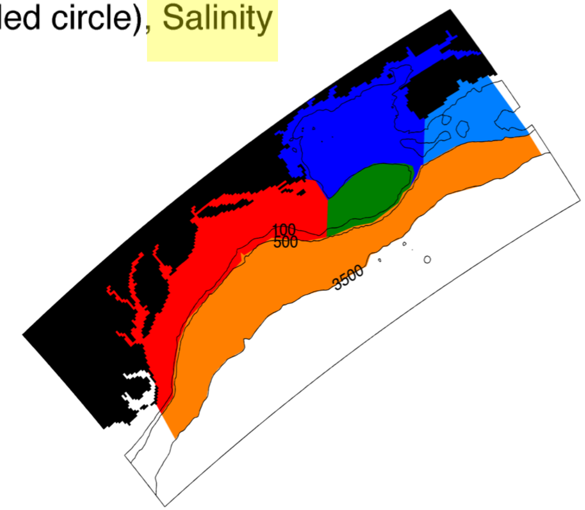


The control case best demonstrates DOPPIO skill when it comes to temperature, both at the sea surface and below.
The number of available observations between the two varies by orders of magnitude

A. Lopez

TRMM (filled circle) & HYCOM (filled square) against Control (unfilled circle), Salinity



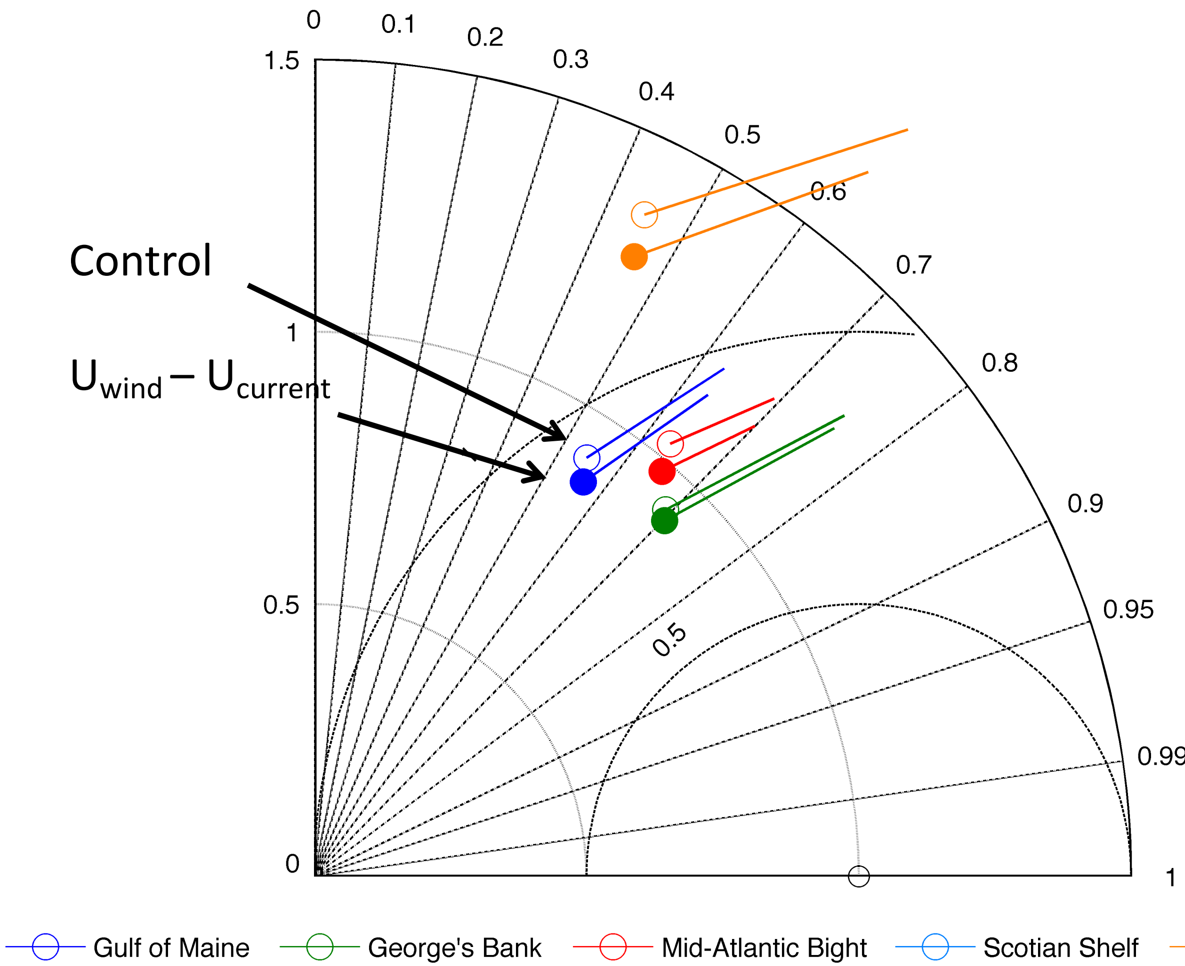


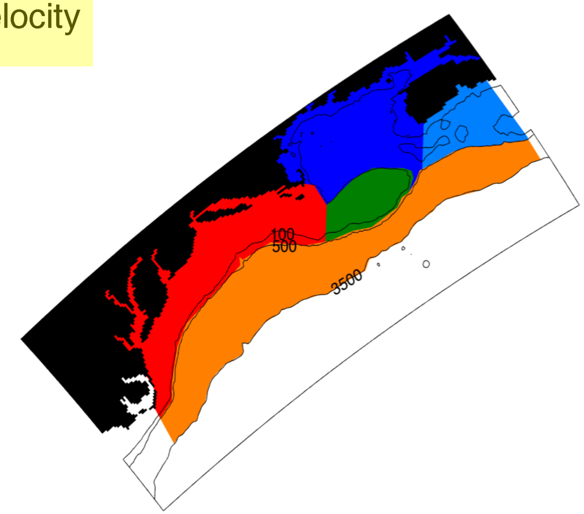
Using satellite derived precipitation (filled circles) has no noticeable positive affect on modeled salinity.

In the deep ocean and Scotian Shelf using HYCOM open boundary conditions degrades the solution compared to using MERCATOR

A. Lopez

Uwind Minus Current (filled) against Control (unfilled), Complex Velocity

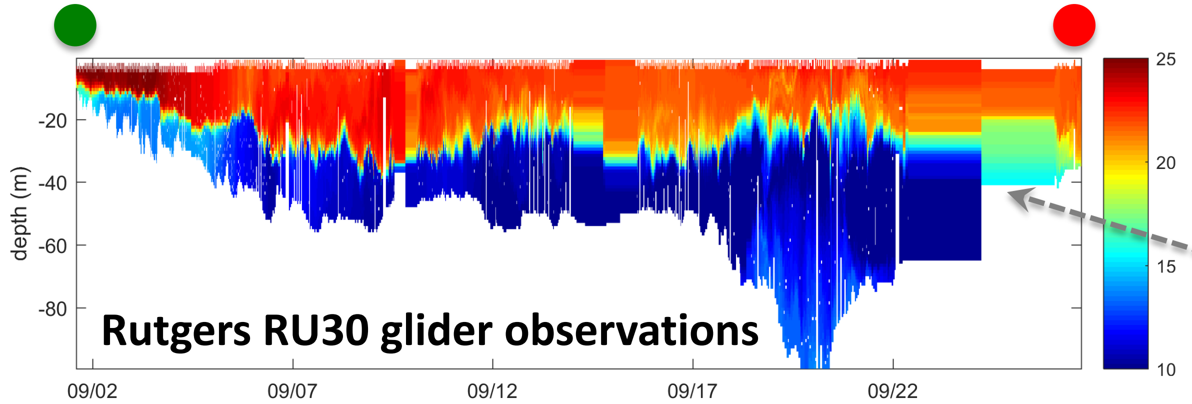


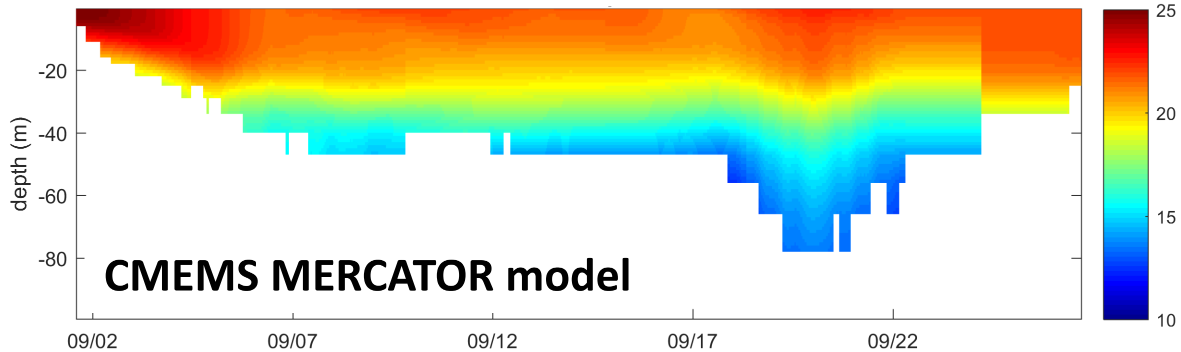


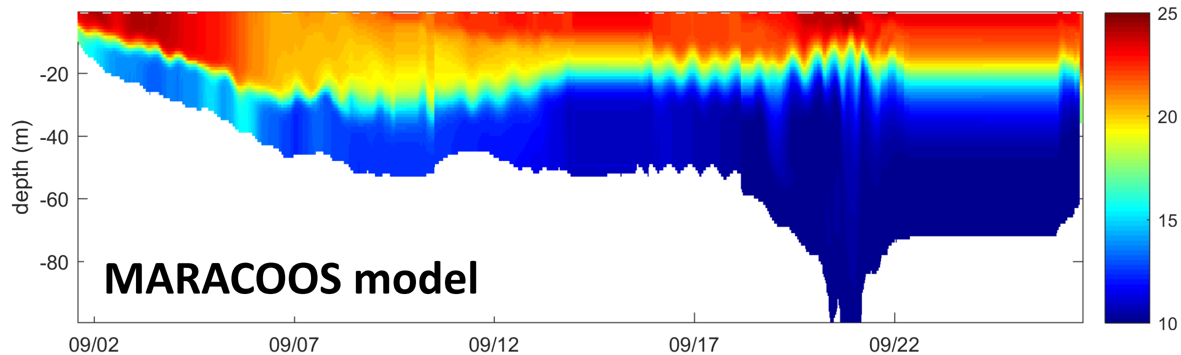
Taking account of the relative speed of water and air in the bulk formula for surface stress brings a modest improvement, so this became our new control case

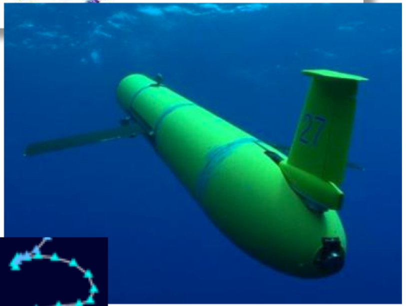
A. Lopez

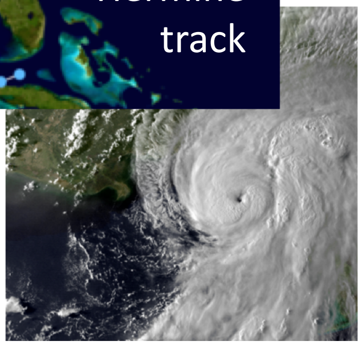
Autonomous underwater glider observations and model predictions during hurricane Hermine, August 2016



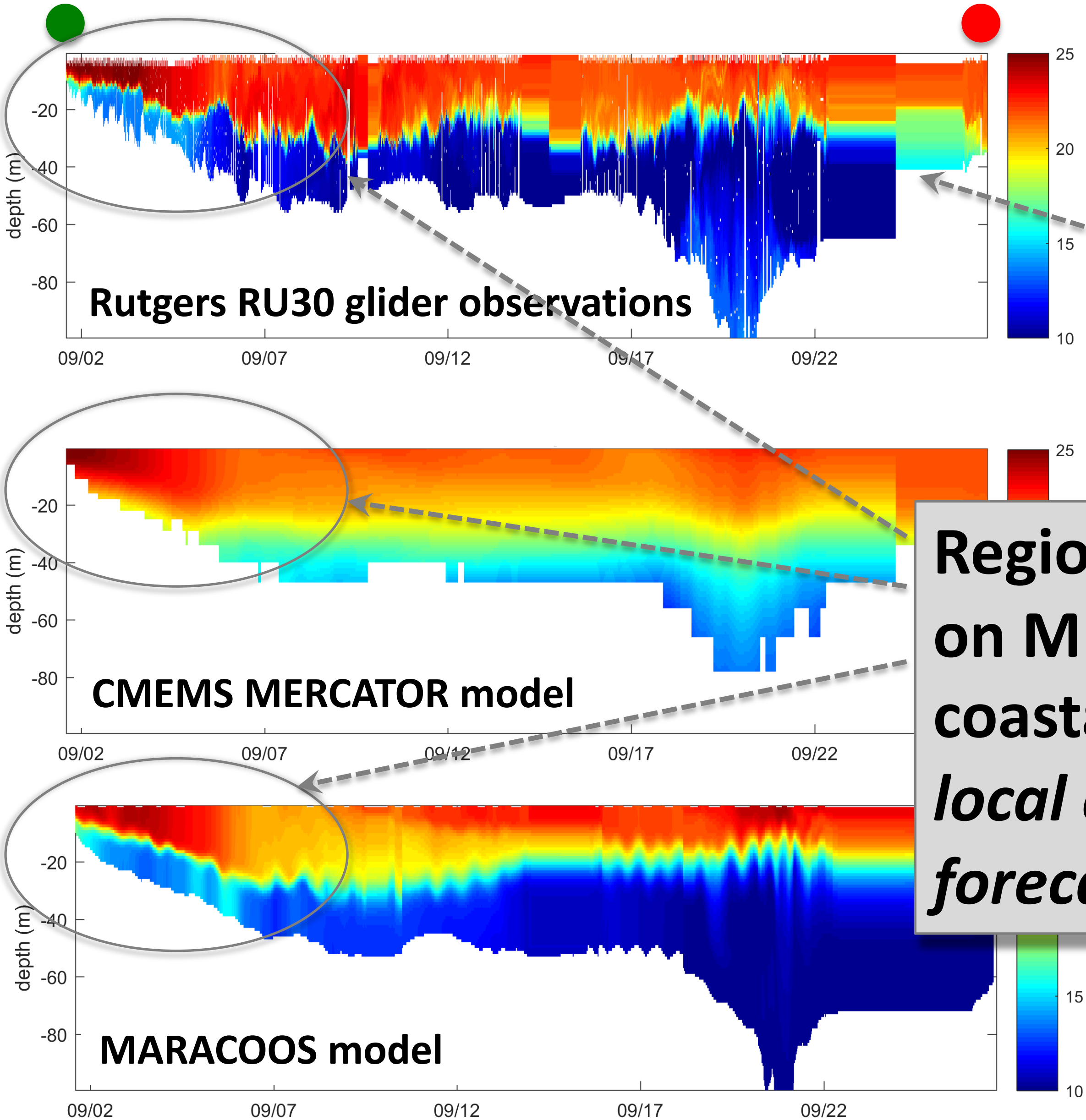


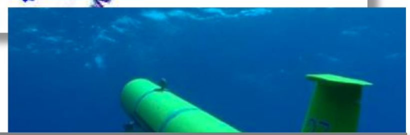


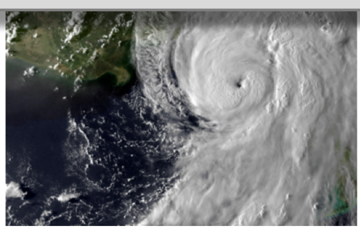




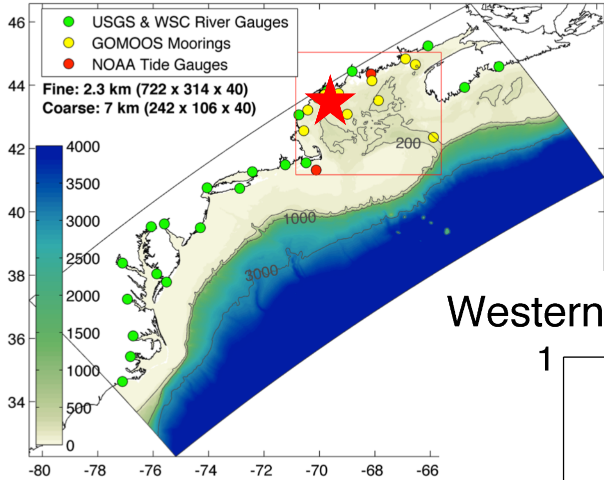
Autonomous underwater glider observations and model predictions during hurricane Hermine, August 2016



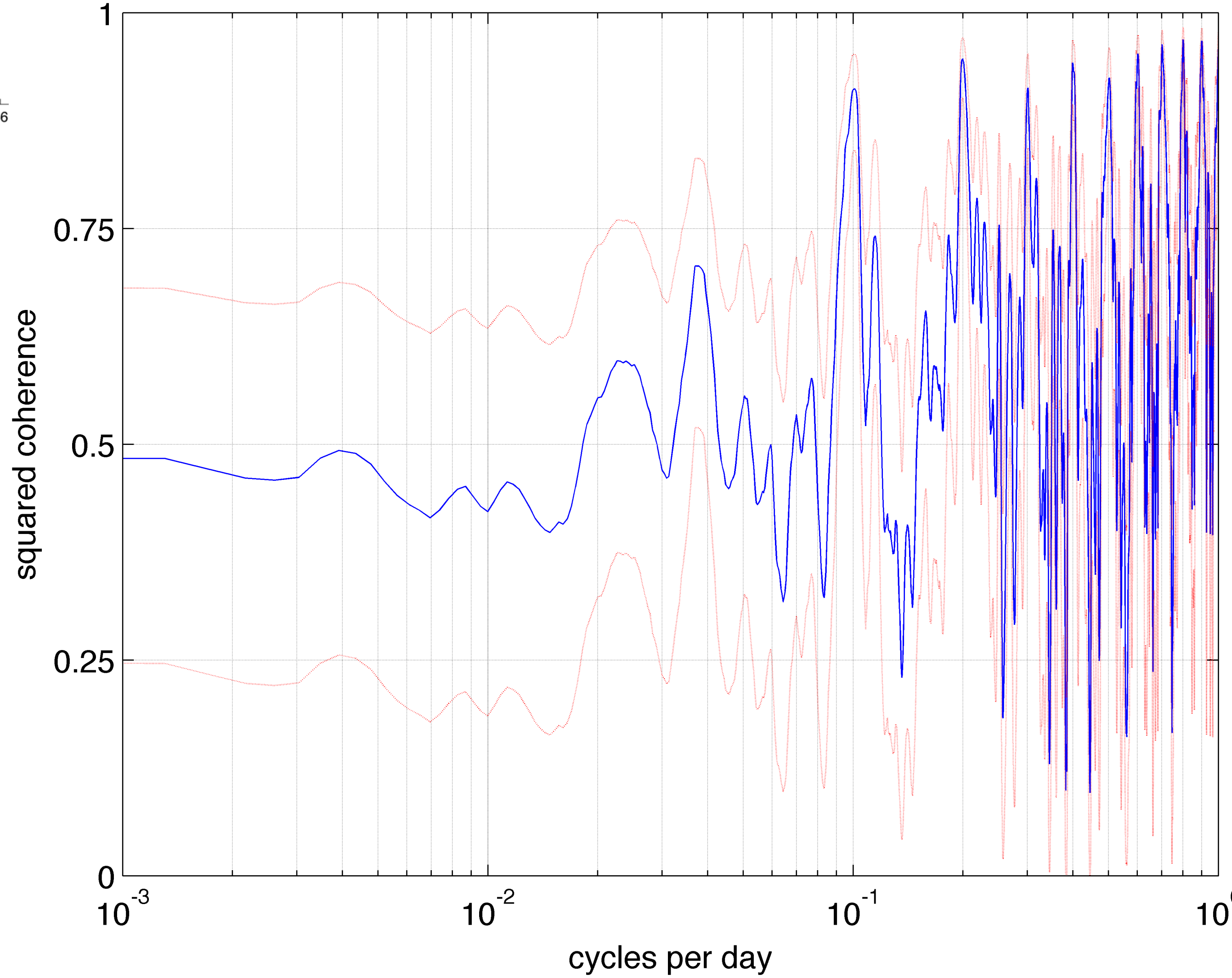




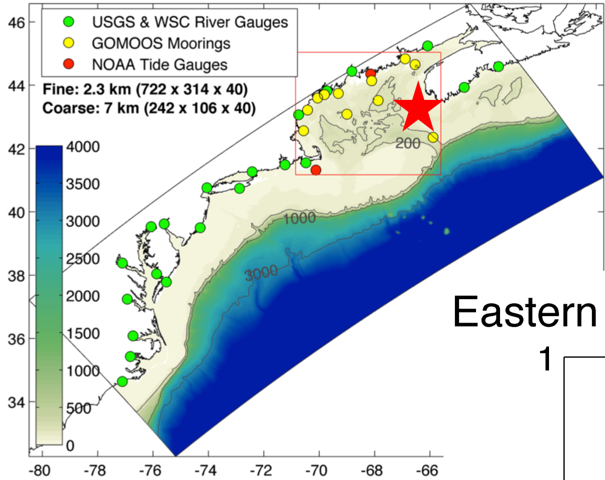
Regional model improves on MERCATOR skill in coastal waters – *vital to local ecosystem forecasting*



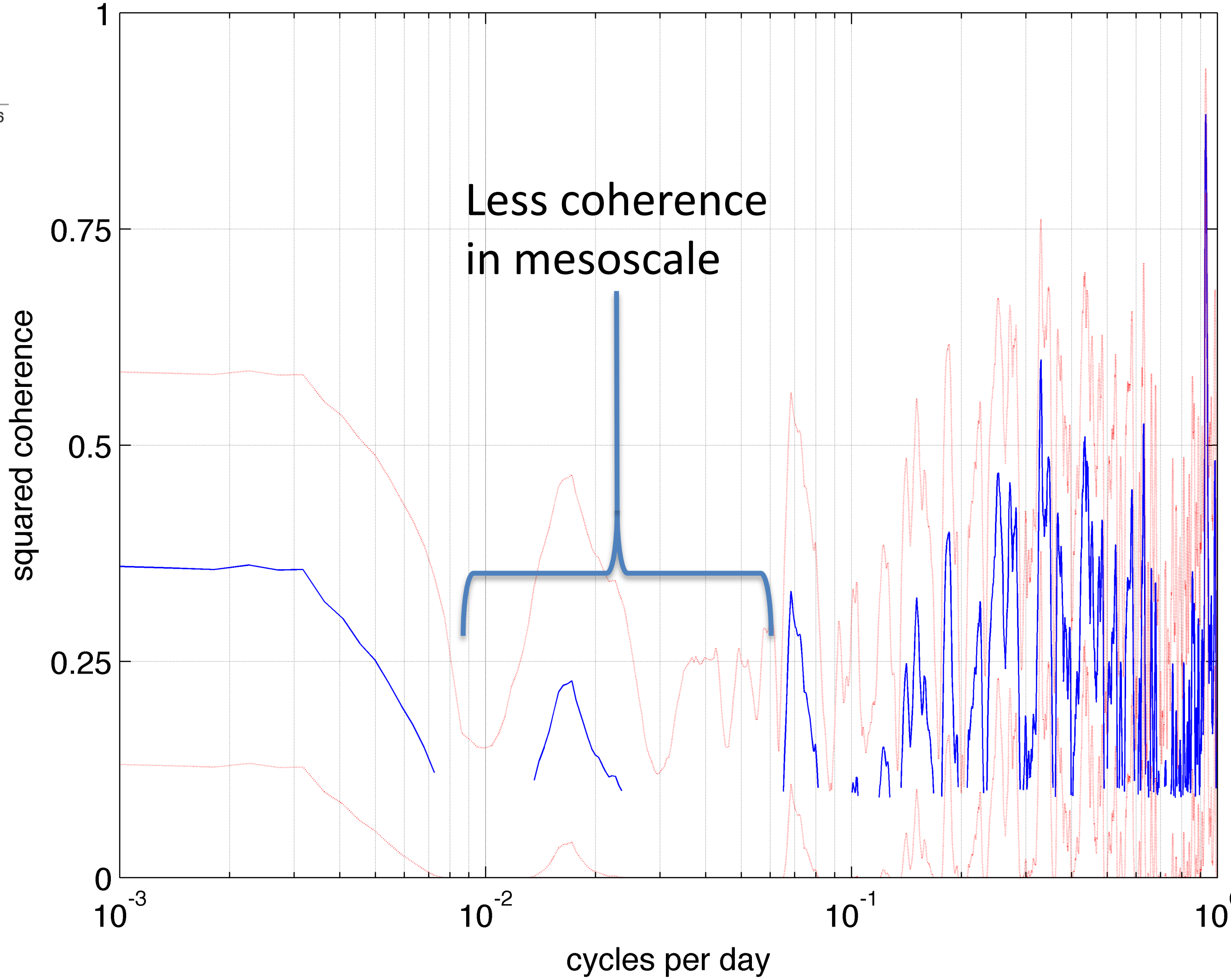
Western Gulf of Maine (Mooring B) Along-Channel Velocity, Surface to 20m



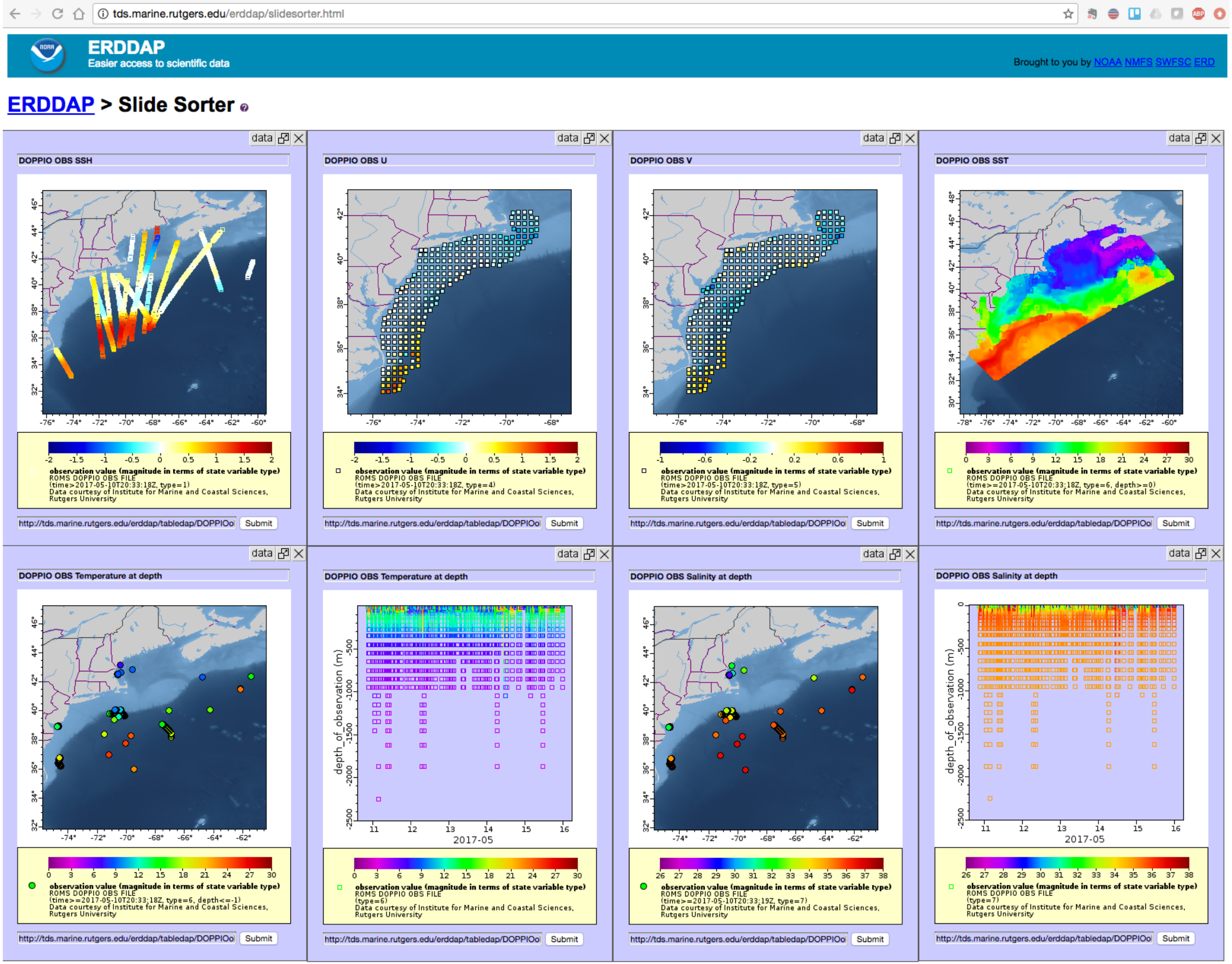
A. Lopez



Eastern Gulf of Maine (Mooring N) Along-Channel Velocity, Surface to 20m



A. Lopez



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DOPPIO OBS SSH
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(time>2017-05-10T20:33:18Z, type=1)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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observation value (magnitude in terms of state variable type)
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Temperature at depth
observation value (magnitude in terms of state variable type)
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Temperature at depth
depth_of_observation (m)
2017-05
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(type=6)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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observation value (magnitude in terms of state variable type)
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Salinity at depth
depth_of_observation (m)
2017-05
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
http://tds.marine.rutgers.edu/erddap/tabledap/DOPPIOo
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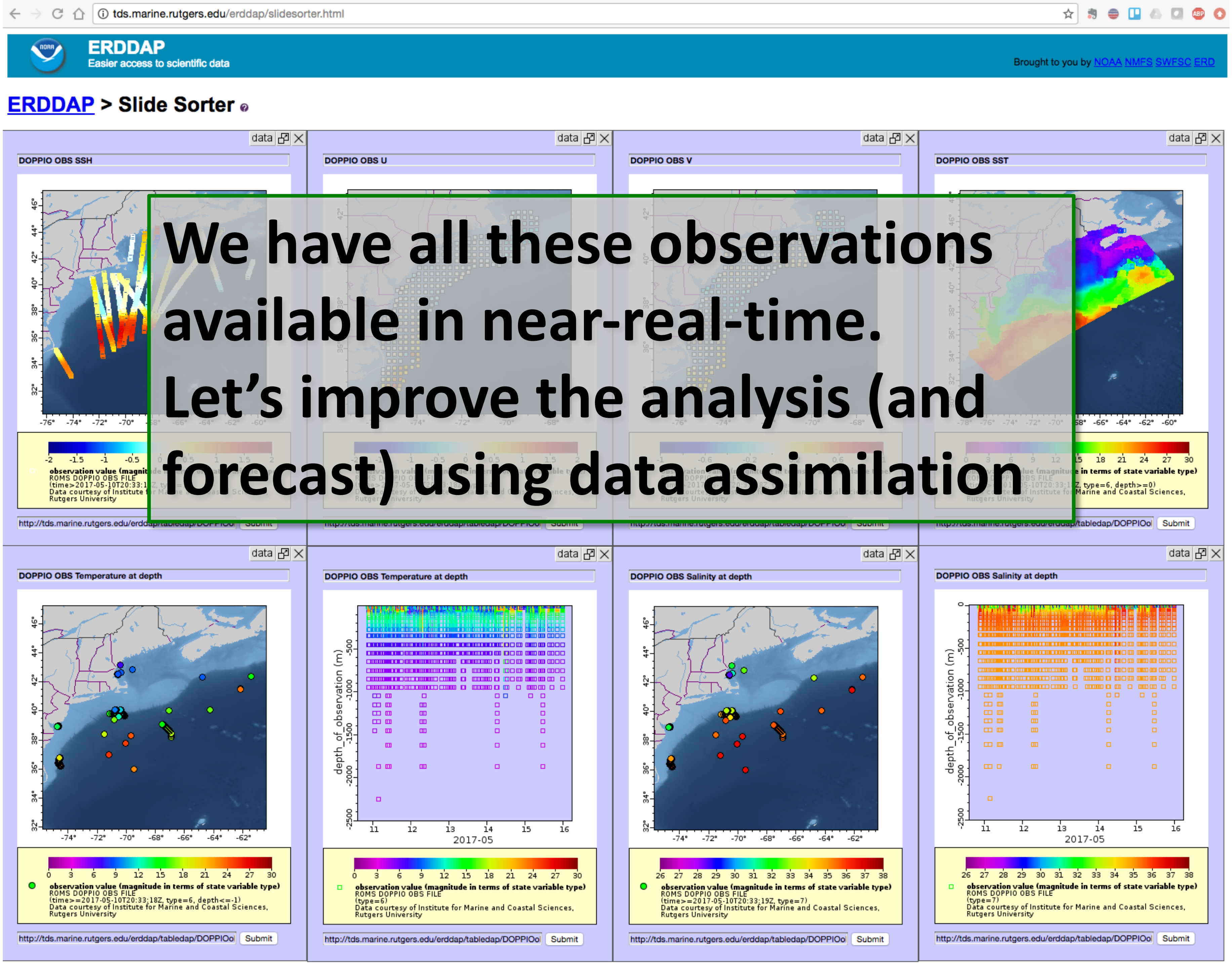
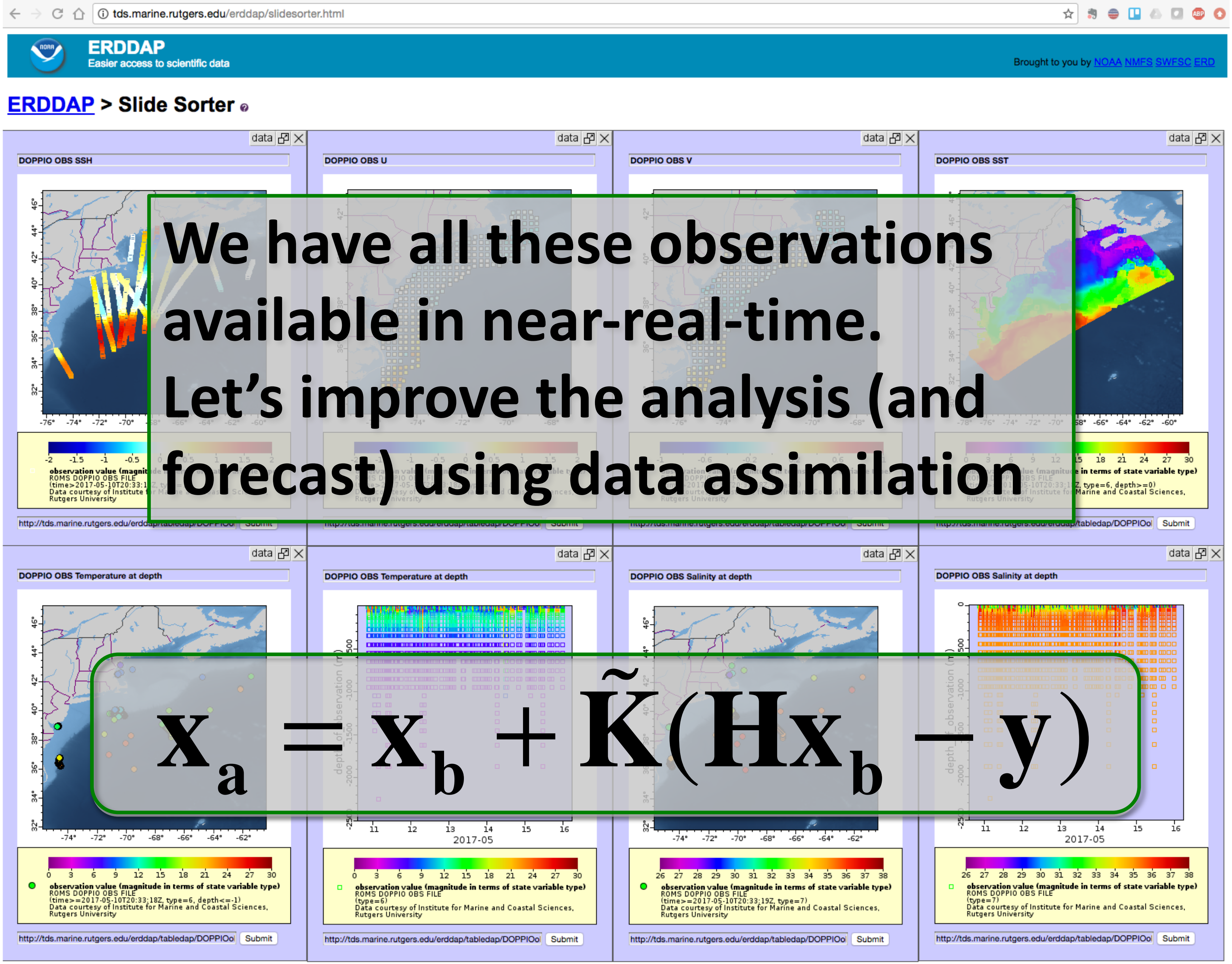


We have all these observations available in near-real-time. Let’s improve the analysis (and forecast) using data assimilation



We have all these observations available in near-real-time. Let's improve the analysis (and forecast) using data assimilation

$$\mathbf{x}_a = \mathbf{x}_b + \tilde{\mathbf{K}}(\mathbf{H}\mathbf{x}_b - \mathbf{y})$$

ROMS includes three variants of 4D-Var data assimilation*

- A primal formulation of incremental strong constraint 4DVar (I4DVAR)
- A dual formulation based on a physical-space statistical analysis system (4D-PSAS)
- A dual formulation Representer-based variant of 4DVar (R4DVAR)

- 4DVar can adjust initial, boundary, and surface conditions
- In reanalysis we adjust *initial conditions*, *open boundary conditions* and *surface fluxes* using I4DVAR in a 3-day cycle not overlapping
- In operational MARACOOS forecast system we adjust *initial conditions and surface fluxes* using 4DVAR PSAS during 3-day analysis, then run 3-day forecast, repeated daily (analysis windows overlap)

* Moore, A. M., H. Arango, G. Broquet, B. Powell, A. T. Weaver, and J. Zavala-Garay (2011), The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilations systems, Part I - System overview and formulation, *Prog. Oceanog.*, *91*(34-39).

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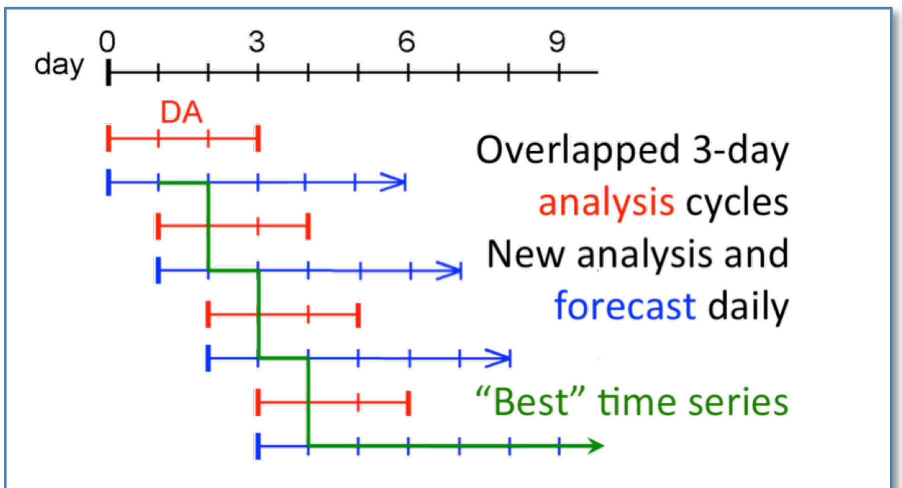

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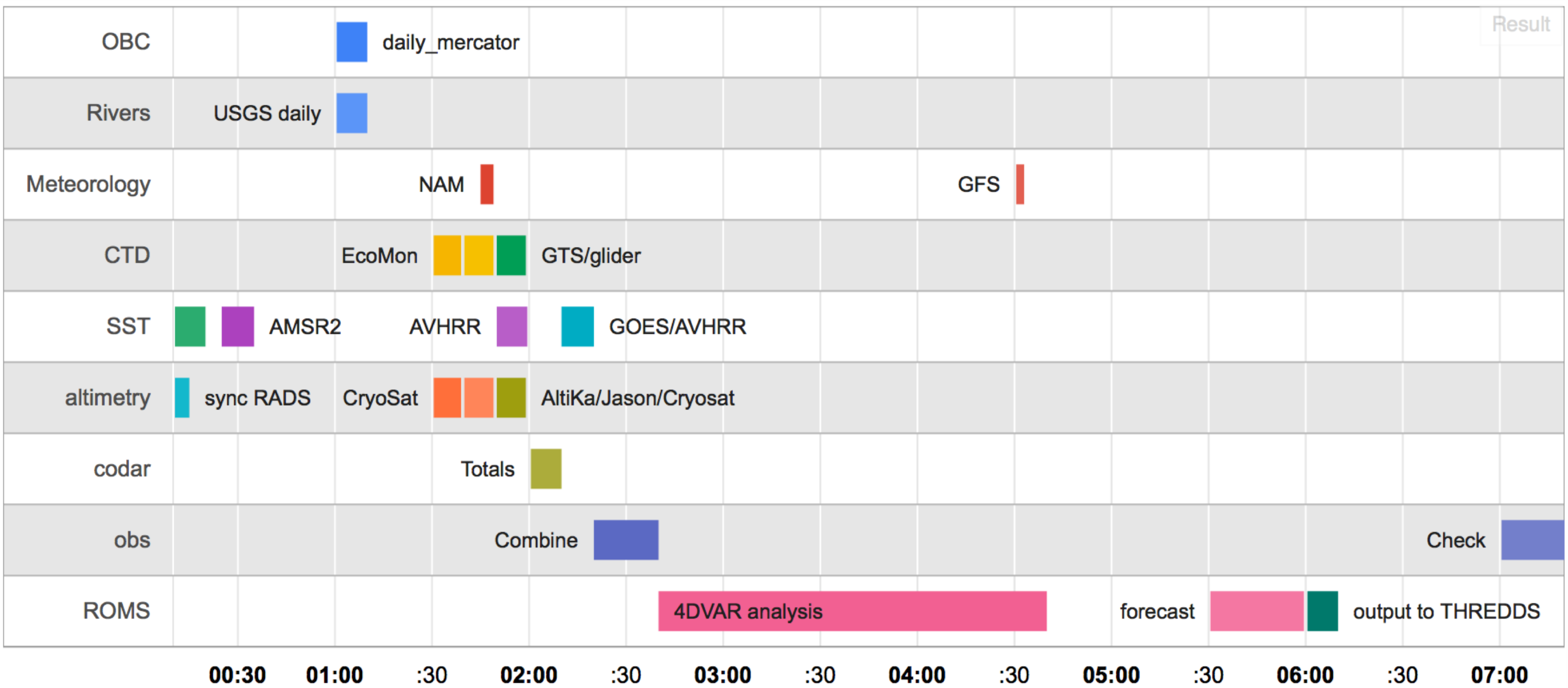
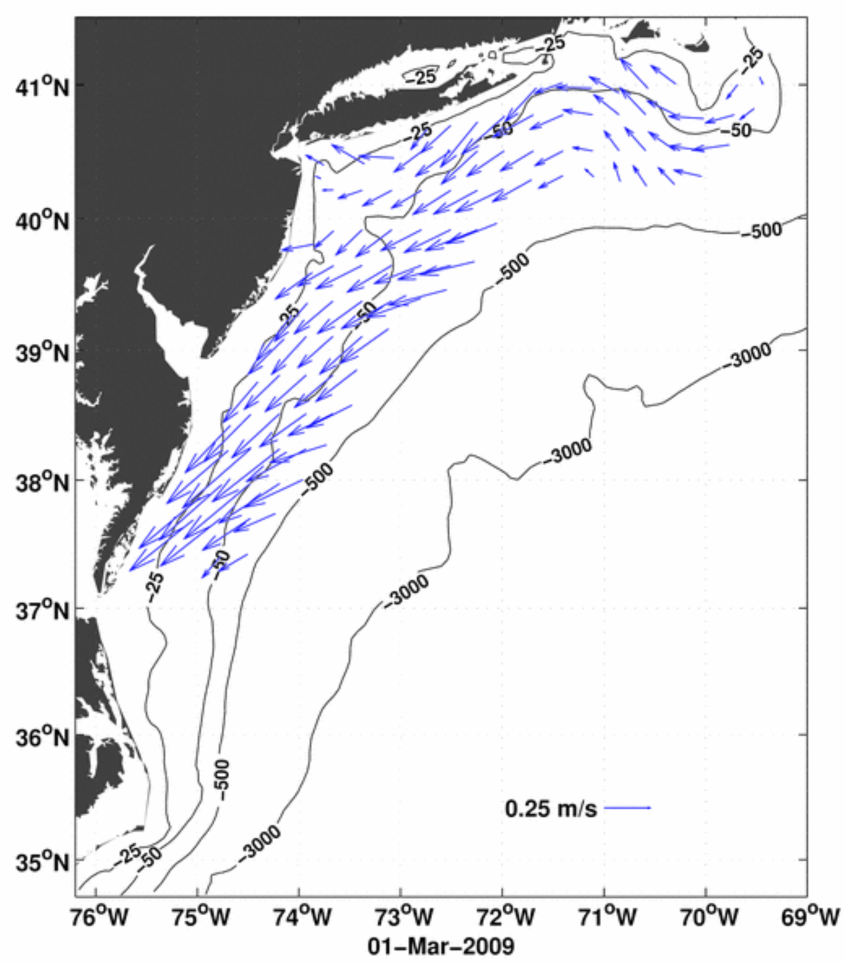
* Moore, A. M., H. Arango, G. Broquet, B. Powell, A. T. Weaver, and J. Zavala-Garay (2011), The Regional Ocean Modeling System (ROMS) 4-dimensional variational data assimilations systems, Part I - System overview and formulation, *Prog. Oceanog.*, *91*(34-39).

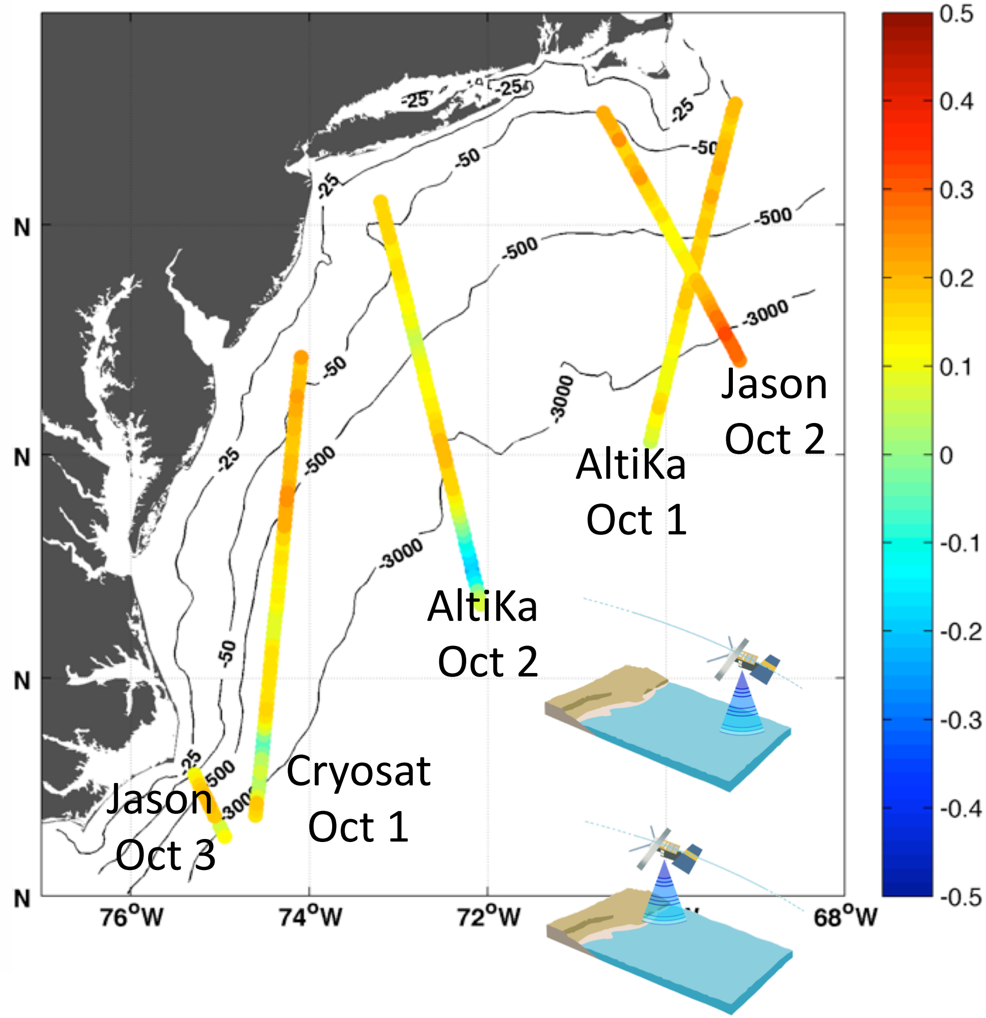
Data pre-processing flow for MARACOOS ROMS 4DVar

Scripts run daily (cron jobs) and use Matlab, Python, perl and NCO tools



All times New York local (U.S. EST)





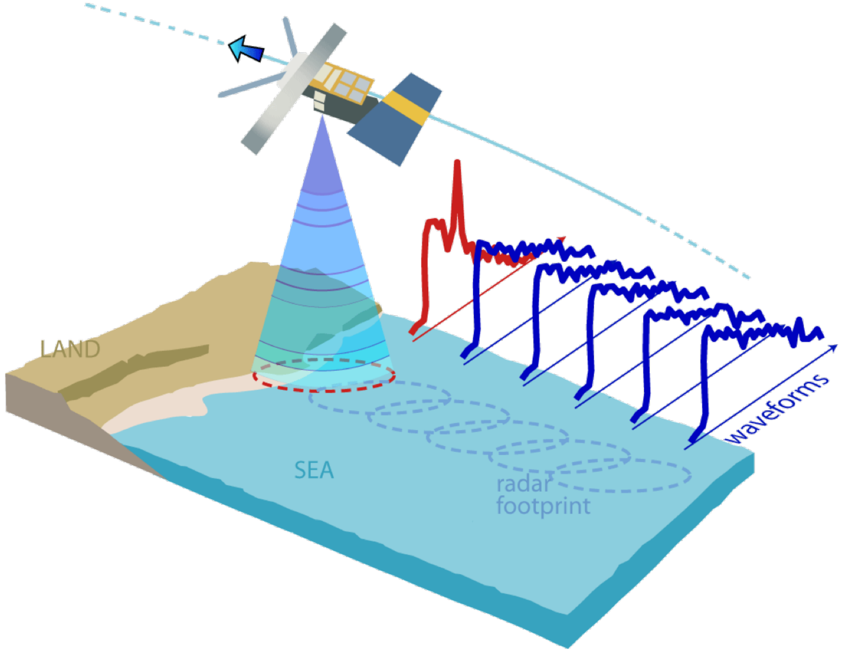
Example of CODAR data after quality control, binning and decimation to a set of independent observations.

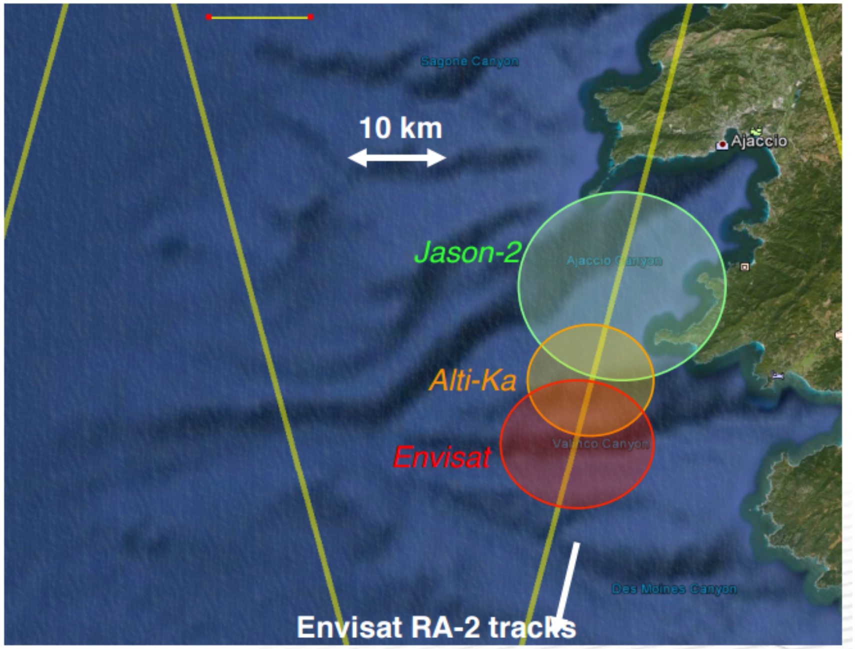
Example of along-track altimeter sea level anomaly data during a single 3-day analysis window.

Coastal Satellite Altimetry

As satellite approaches the coast

- radar reflection from land contaminates the range signal
- microwave emissivity of land contaminates the radiometer water vapor range correction



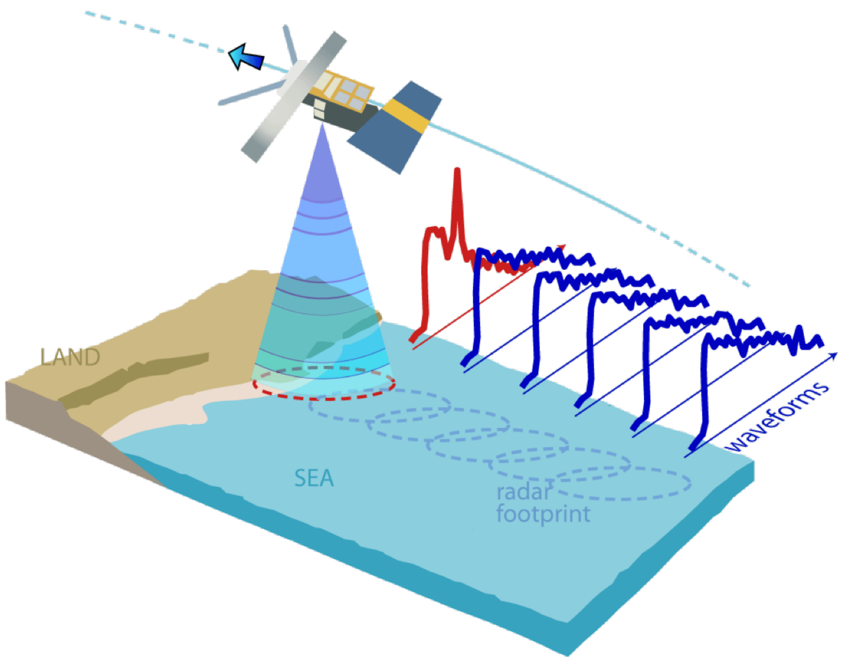


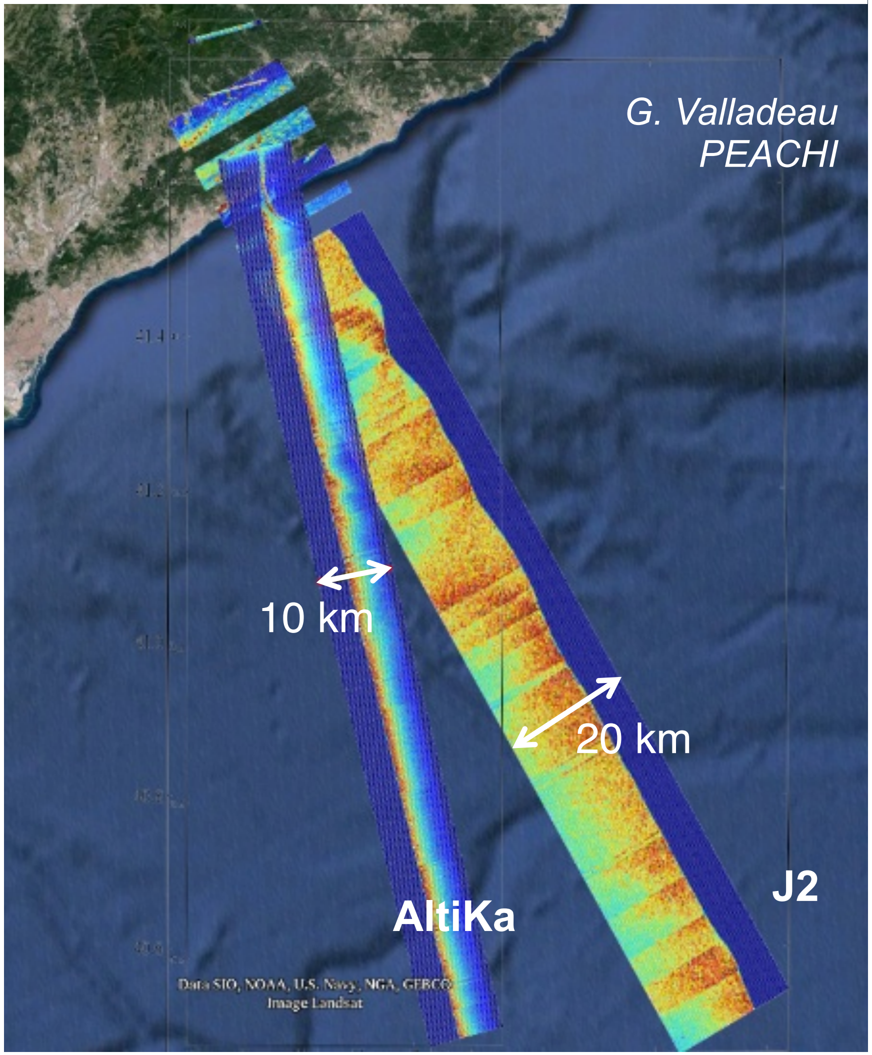
Credits: www.coastalt.eu

Coastal Satellite Altimetry

Technical advances in coastal altimetry now allow for correction of these problems, and altimetry can be used within a few km of the coast

AltiKa / Jason-2 in west Mediterranean Sea



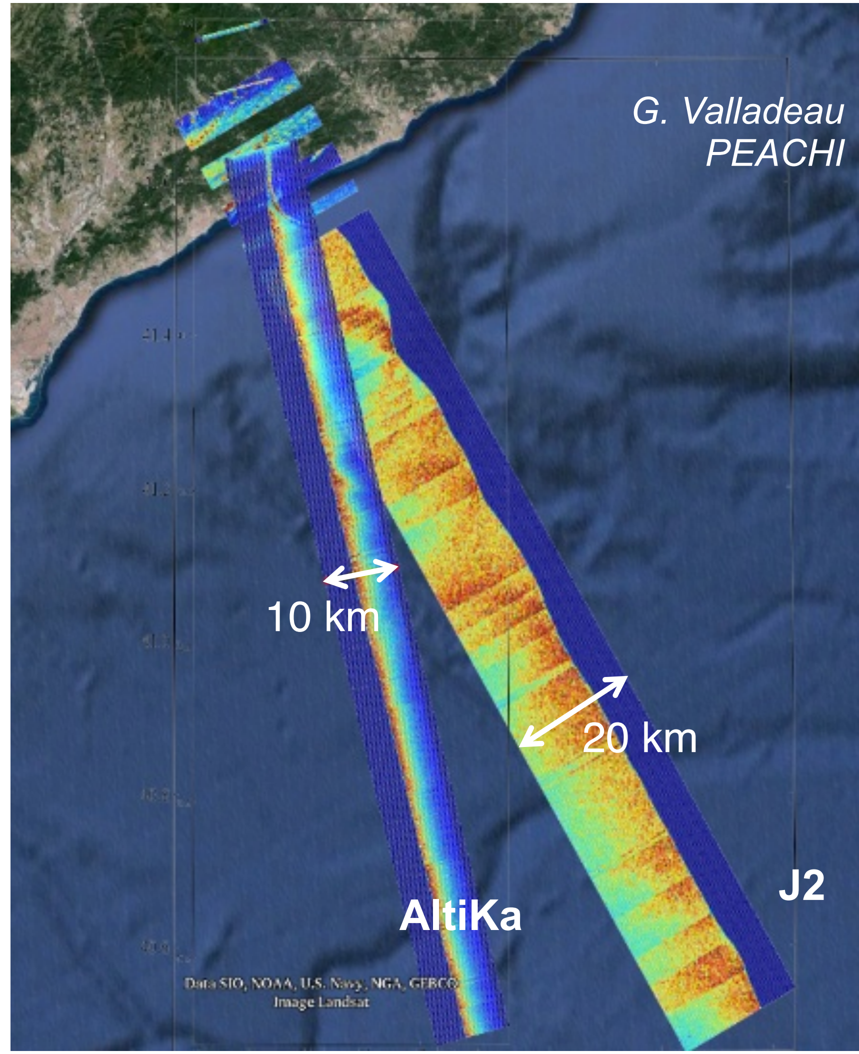


Credits: www.coastalt.eu

Coastal Satellite Altimetry: Technical developments

- Re-tracking of waveforms recovers valid data close to coast
- AltiKa small footprint is advantageous near to coast
- CryoSat-2 *Delayed Doppler* SAR gives refined along-track resolution ~700 m
- Range corrections are customized to coastal setting (e.g. water vapor wet troposphere; local tides)
- Appropriate physics (e.g. DAC)

AltiKa / Jason-2 in west Mediterranean Sea



Credits: www.coastalt.eu

Altimetry in ‘conventional’ mesoscale models

Mesoscale operational forecast models (e.g. Mercator-Océan, HYCOM) typically apply

- Dynamic Atmosphere Correction (DAC)
  - remove Inverted Barometer effect (no dynamic P_{air} in model)
  - remove high-frequency variability that would be aliased by ~10 day satellite sampling interval by using the solution from a high-resolution wind forced barotropic model (T-UGO)
- Remove tides (not modeled)
- Compute anomalies with respect to a Mean Sea Surface (MSS) to remove uncertain geoid
  - 20-year mean on reference mission tracks
  - gridded analysis for others (CryoSat, geodetic, S-3)
- Add Mean Dynamic Topography (MDT) from global analysis
  - 20-year mean from in situ and other data
- Radiometer wet troposphere range correction
- Other standard corrections (sea state bias, earth tides, ionosphere …)

Using coastal altimetry with regional models

Model dynamics and altimeter "corrections" should be consistent

***<u>Our approach</u>*:**

- Air pressure from met. forecast is imposed at model sea surface
  - so we do *<u>not</u>* apply Inverted Barometer correction
- The model simulates CTW generation and propagation within the domain (including stratification influence on dispersion relation)
  - so we do *<u>not</u>* apply DAC
- Mean Sea Surface: Global products are probably inadequate for coastal applications for non-reference missions track altimeters
  - active area of research and experimentation
- Add MDT from regional data assimilation analysis
  - best estimate from long term observations, constrained by coastal model kinematics (effects of bathymetry and coastline)
- Wet troposphere: extrapolate from open ocean or use NWP model
- Other standard corrections (sea state bias, earth tides, ionosphere …)

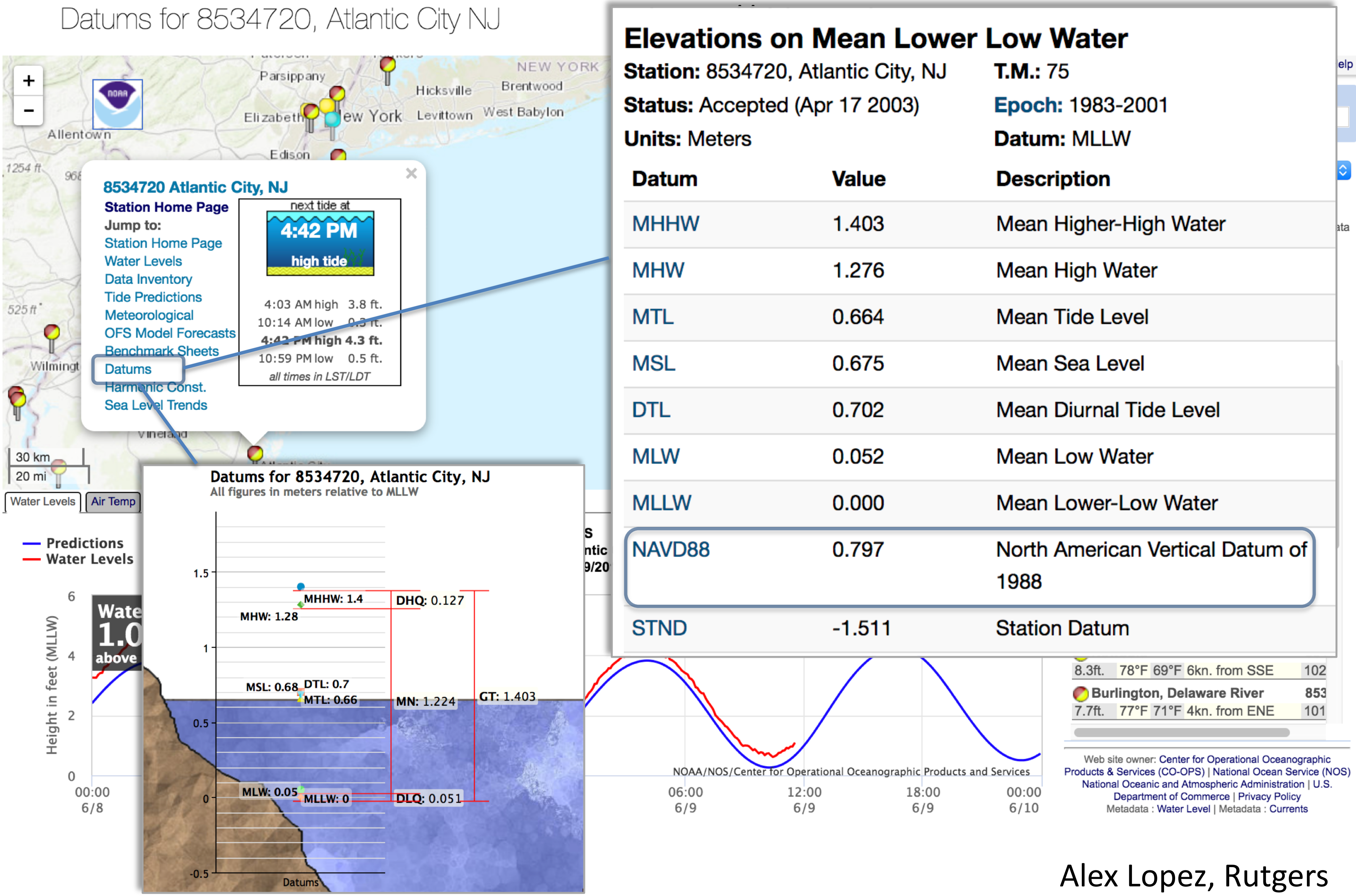
Using coastal altimetry with regional models

Other practical considerations…

***Our approach*:**

- Tides: phase errors between regional model and data can dominate model-data misfit
  - remove tides from altimetry but restore from harmonics of the regional model
- 4D-Var (in our configuration) does not impose time correlation of low frequency sea level anomaly
  - we duplicate altimeter data +/- 3 hours of pass (with appropriate tide signal) which suppresses projection onto fast barotropic waves
- Sea level datum
  - reconcile with local tide gauges referenced to NAVD88 to give Total Water Level above datum useful for storm surge inundation

Mean Sea Level datum



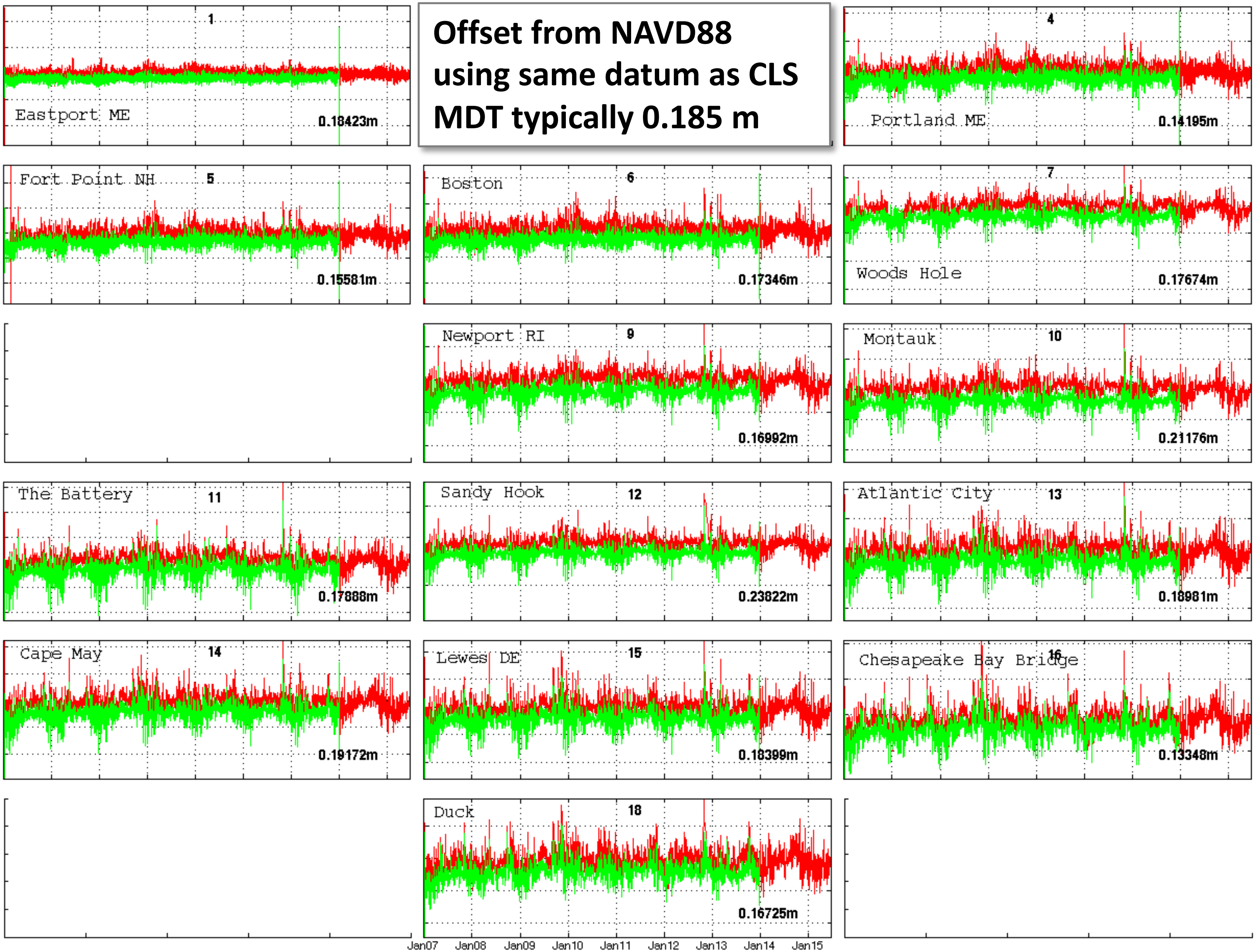
Elevations on Mean Lower Low Water

Station: 8534720, Atlantic City, NJ **T.M.:** 75
Status: Accepted (Apr 17 2003) **Epoch:** 1983-2001
Units: Meters **Datum:** MLLW

Datum	Value	Description
MHHW	1.403	Mean Higher-High Water
MHW	1.276	Mean High Water
MTL	0.664	Mean Tide Level
MSL	0.675	Mean Sea Level
DTL	0.702	Mean Diurnal Tide Level
MLW	0.052	Mean Low Water
MLLW	0.000	Mean Lower-Low Water
NAVD88	0.797	North American Vertical Datum of 1988
STND	-1.511	Station Datum

Alex Lopez, Rutgers

Offset from NAVD88 using same datum as CLS MDT typically 0.185 m

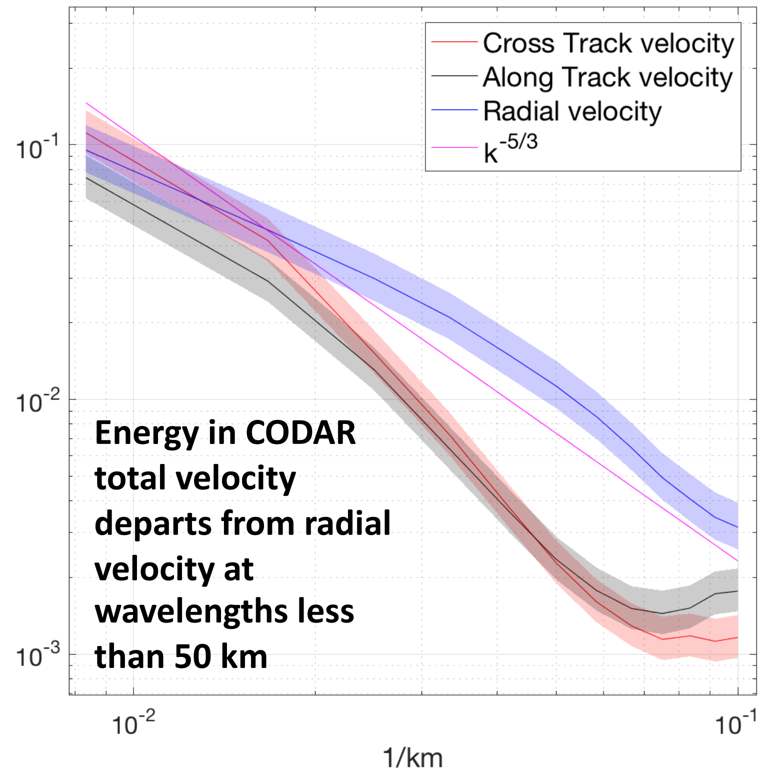


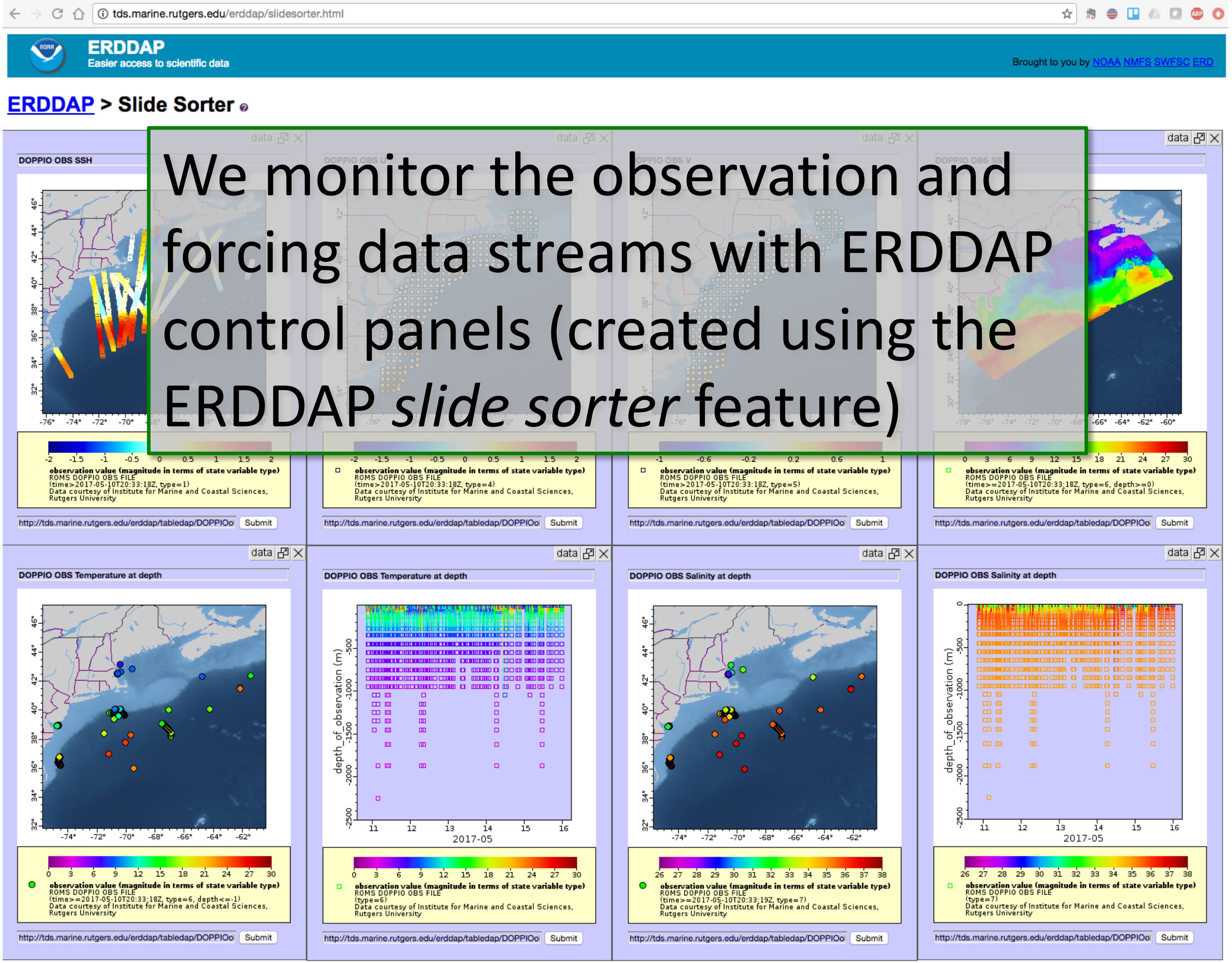
Alex Lopez, Rutgers

Assimilating HF-radar in regional models

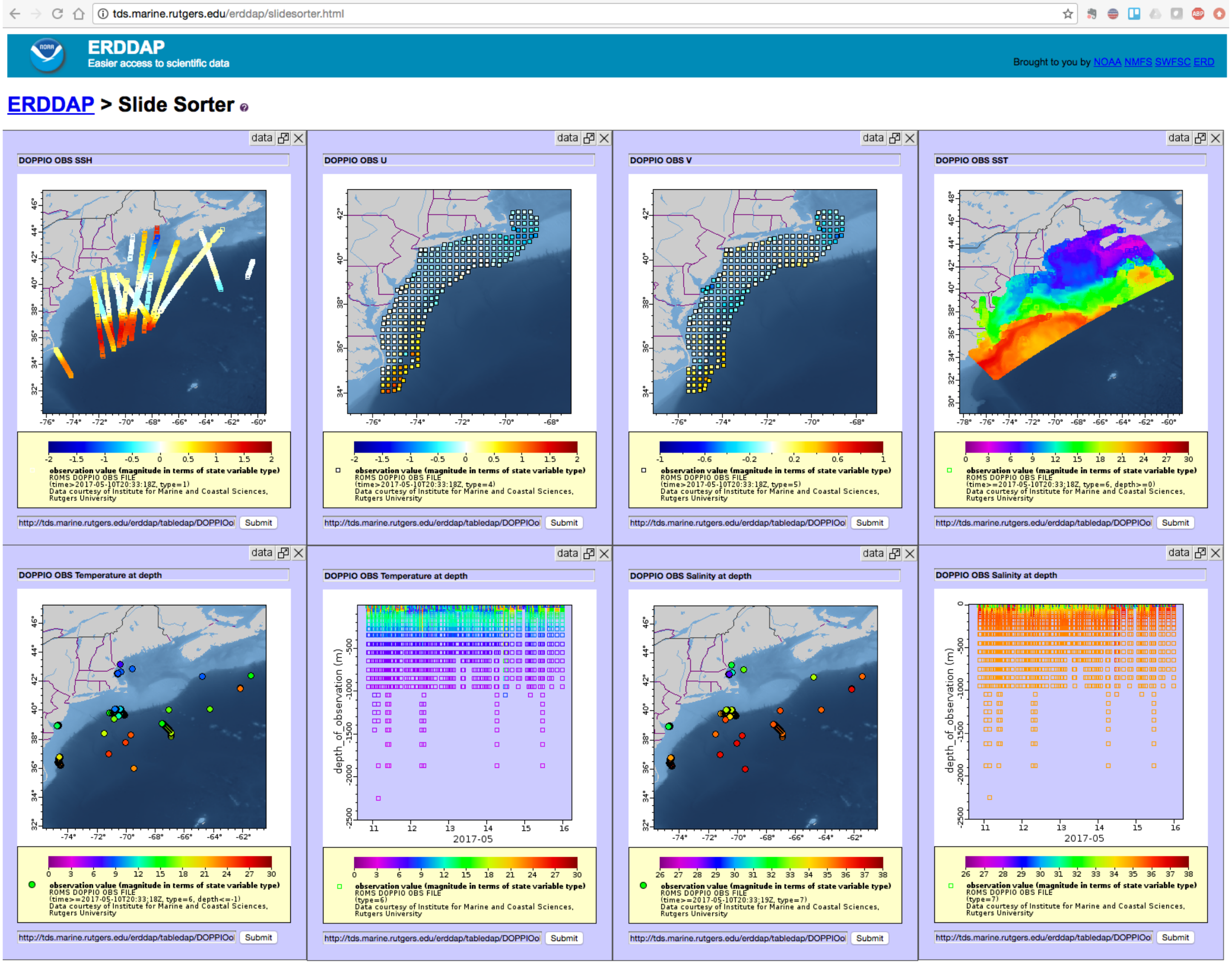
Other practical considerations…
<u>Our approach</u>:

- Hourly HR-radar *total vectors* are assimilated without any adjustment for tides, i.e. the observed tide signal is retained in the data
- MARACOOS *total vectors* are computed by an optimal interpolation combiner step that filters wavelengths < 50 km
- Direct assimilation of *radial component* velocity data, via an appropriate observation operator, would allow 4D-Var to effectively perform the combination constrained by ocean dynamics
- This allows attribution of data impact of individual radar sites in the network





We monitor the observation and forcing data streams with ERDDAP control panels (created using the ERDDAP *slide sorter* feature)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ERDDAP > Slide Sorter
DOPPIO OBS SSH
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(time>2017-05-10T20:33:18Z, type=1)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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observation value (magnitude in terms of state variable type)
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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observation value (magnitude in terms of state variable type)
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(time>=2017-05-10T20:33:18Z, type=6, depth>=0)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Temperature at depth
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(time>=2017-05-10T20:33:18Z, type=6, depth<=-1)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Temperature at depth
depth_of_observation (m)
2017-05
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
(type=6)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Salinity at depth
observation value (magnitude in terms of state variable type)
ROMS DOPPIO OBS FILE
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Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
DOPPIO OBS Salinity at depth
depth_of_observation (m)
2017-05
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ROMS DOPPIO OBS FILE
(type=7)
Data courtesy of Institute for Marine and Coastal Sciences, Rutgers University
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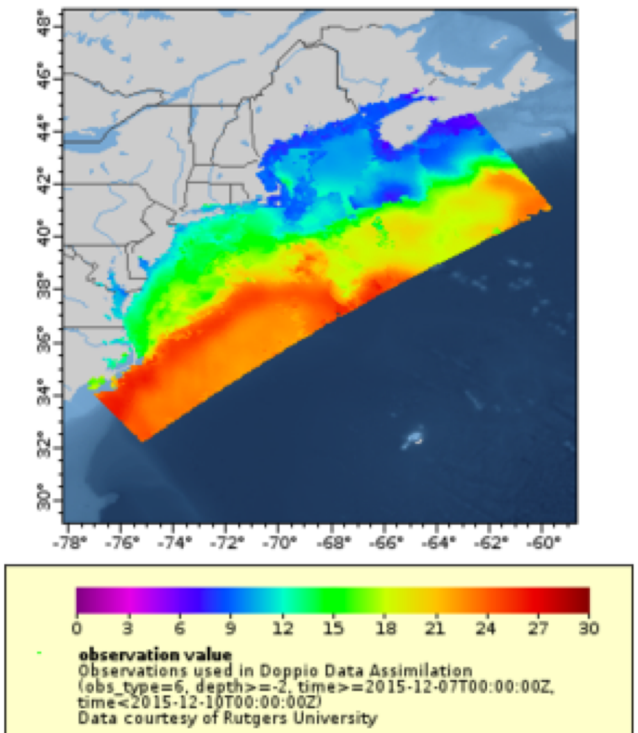
ERDDAP > tabledap > Make A Graph

Dataset Title: **Observations used in Doppio Data Assimilation** RSS
Institution: Rutgers University (Dataset ID: DOPPIO_REANALYSIS_OBS)
Range: longitude = -77.44505 to -59.690285°E, latitude = 32.23944 to 45.95889°N, depth = -4250.0 to 0.0, time = 2007-01-02T00:00:00Z to 2015-12-30T23:00:00Z
Information: Summary | License | FGDC | ISO 19115 | Metadata | Background | Subset | Data Access Form

Graph Type: markers
X Axis: longitude
Y Axis: latitude
Color: obs_value

Click on the map to specify a new center point.
Zoom: Out 8x | Out 2x | Out | Data | In | In 2x | In 8x
Time range: 3 day(s)



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		6		
depth	>=	-2	<=	
time	>=	2015-12-07T00:00:00	<	2015-12-10T00:00:00
	>=		<=	
	>=		<=	

Server-side Functions
distinct()
(" ")

Graph Settings
Marker Type: Dot Size: 3
Color:
Color Bar: Continuity: Scale:
Min: Max: N Sections:
Draw the land mask:
Y Axis Minimum: Maximum: ascending

Redraw the Graph (Please be patient. It may take a while to get the data.)

Optional:
Then set the File Type: .largePng and Download the Data or an Image
or view the URL: http://tds.marine.rutgers.edu/erddap/tabledap/DOPPIO_REANALYSIS_OI
(Documentation / Bypass this form) (File Type information)

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Graph Type: markers
X Axis: longitude
Y Axis: latitude
Color: obs_value - +

Click on the map to specify a new center point.
Zoom: Out 8x | Out 2x | Out | Data | In | In 2x | In 8x
Time range: 3 day(s) - +

Constraints	**Optional Constraint #1**		**Optional Constraint #2**	
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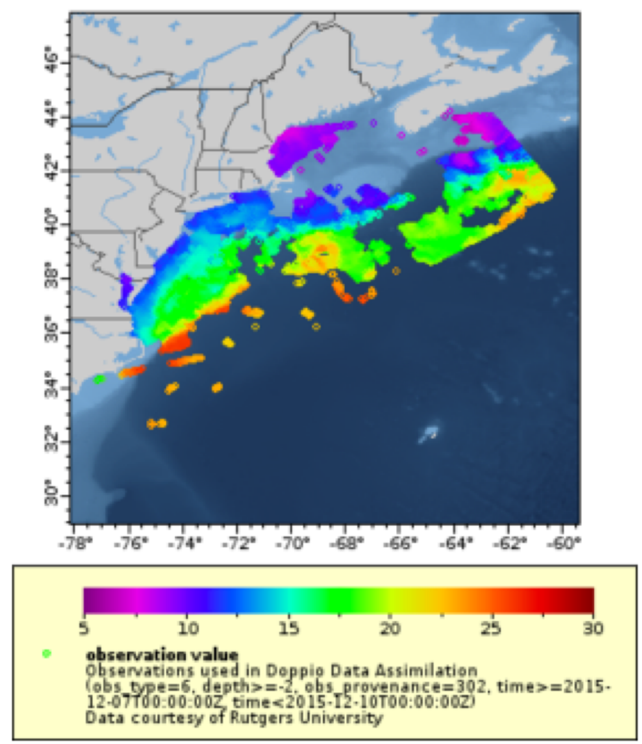
	>=		<=	



Server-side Functions
distinct()
(" ")

Graph Settings
Marker Type: Circle Size: 3
Color:
Color Bar: Continuity: Scale:
Min: Max: N Sections:
Draw the land mask:
Y Axis Minimum: Maximum: ascending

Redraw the Graph (Please be patient. It may take a while to get the data.)

Optional:
Then set the File Type: .htmlTable and Download the Data or an Image
or view the URL: http://tds.marine.rutgers.edu/erddap/tabledap/DOPPIO_REANALYSIS_OI
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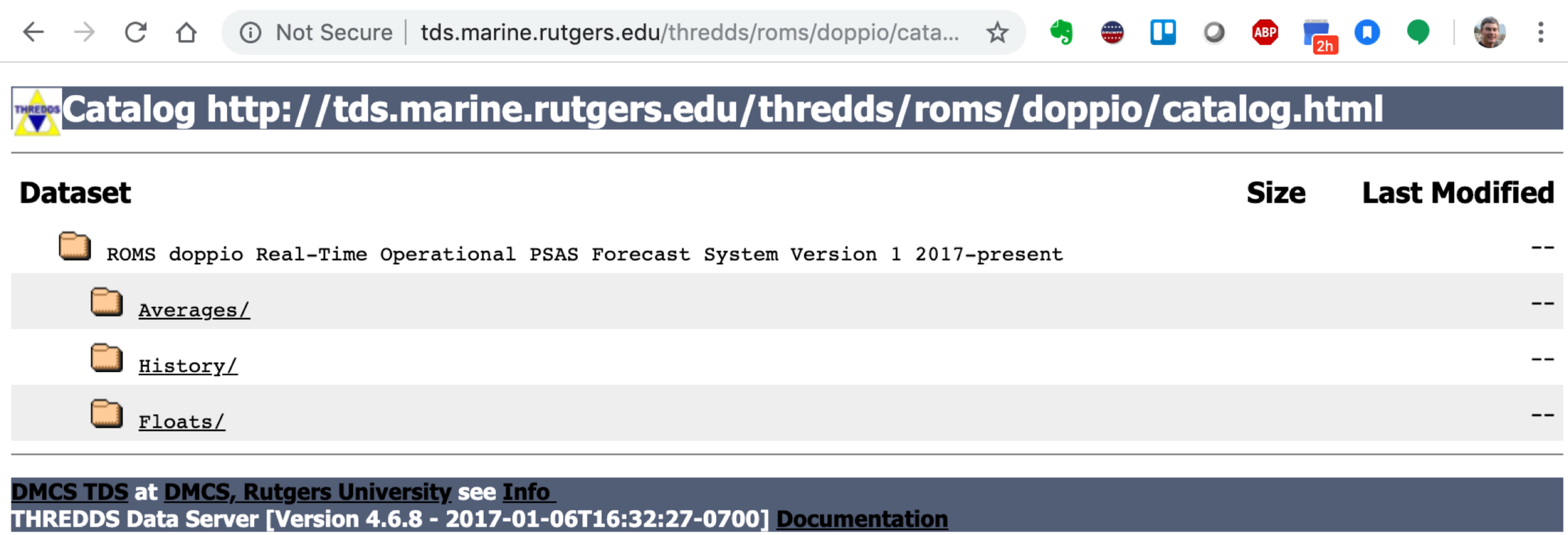
Output goes to THREDDS server Forecast Model Run Collection* (FMRC) at tds.marine.rutgers.edu/thredds

*unidata.ucar.edu



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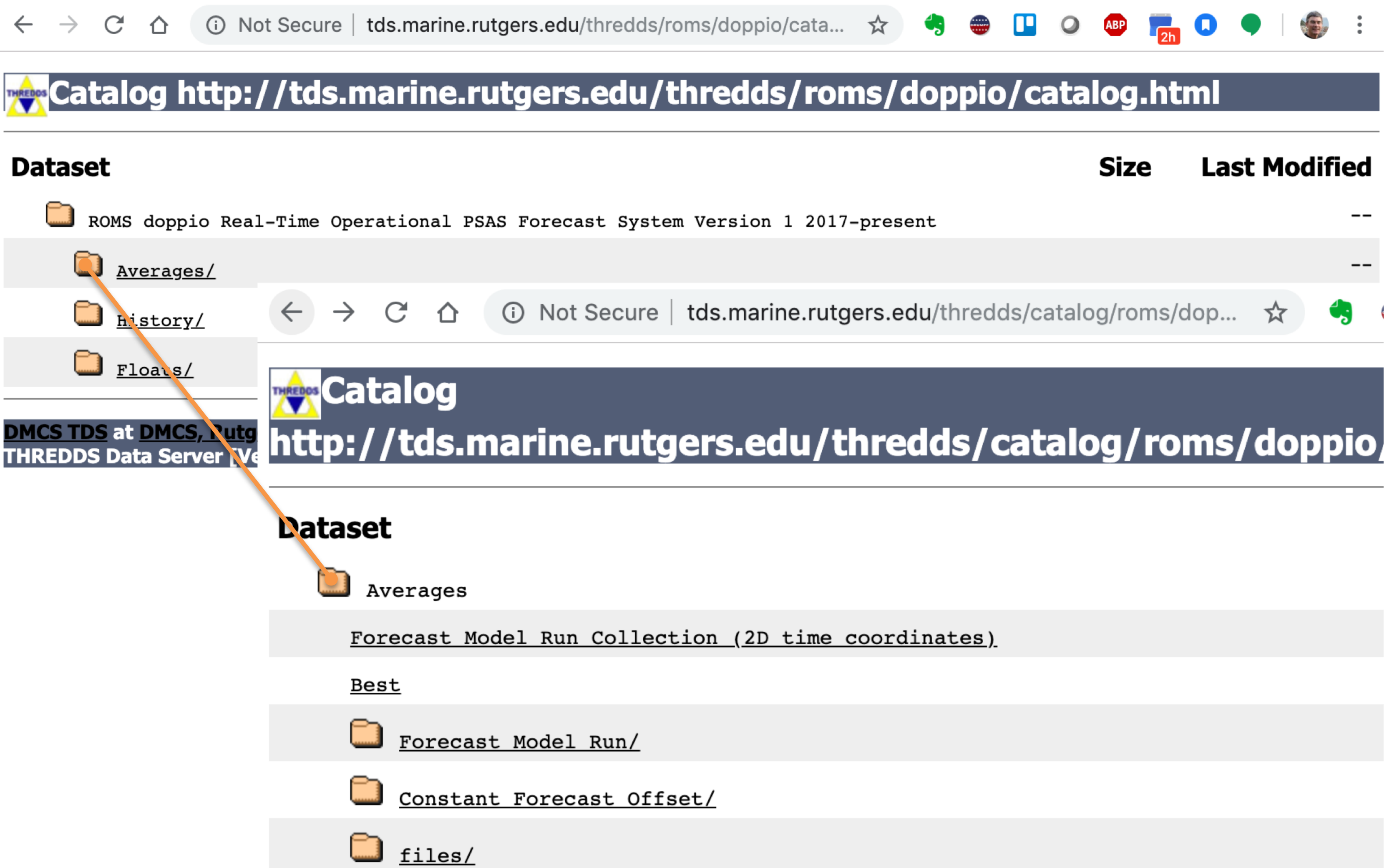

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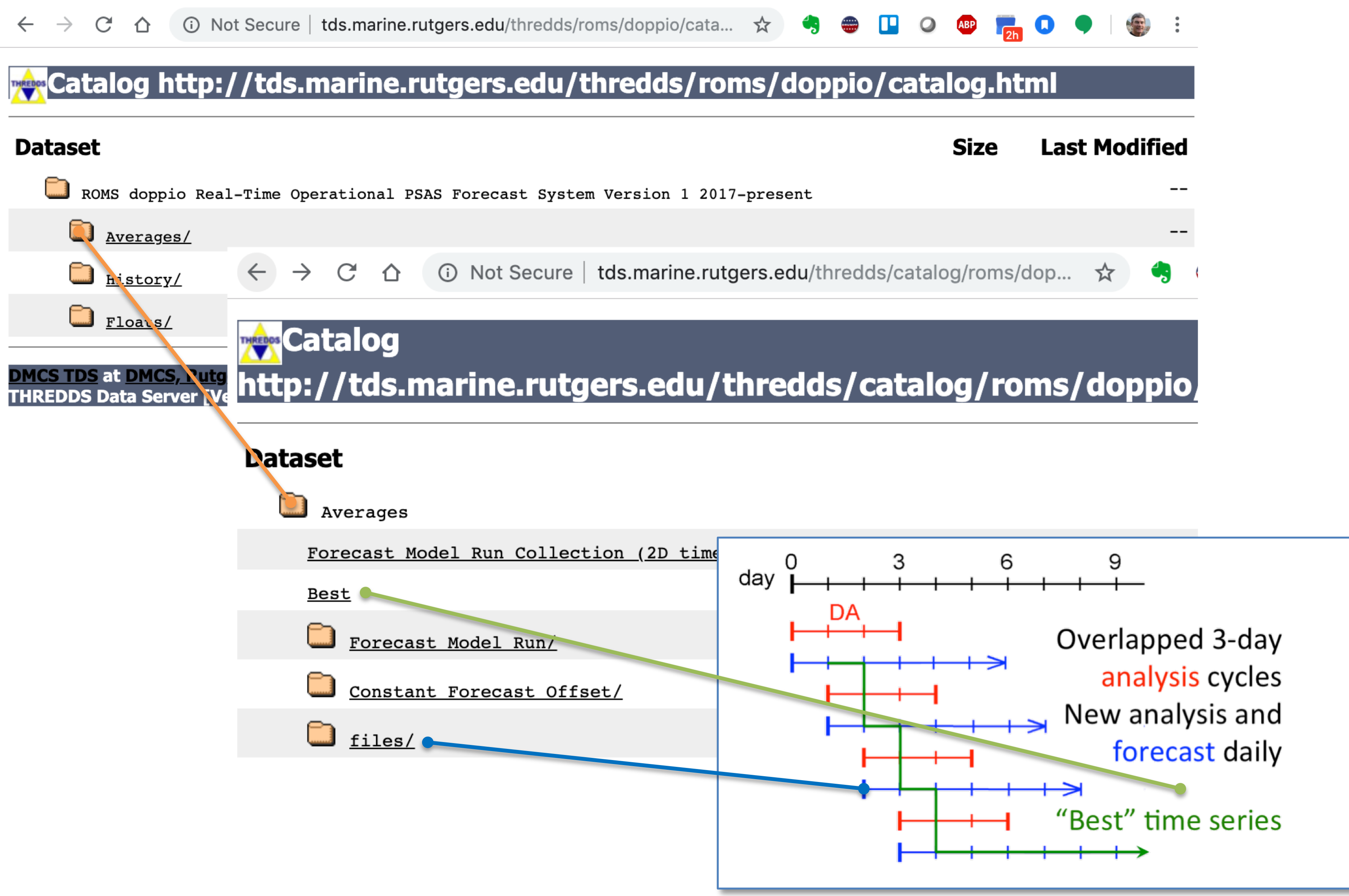


ERDDAP
Easier access to scientific data

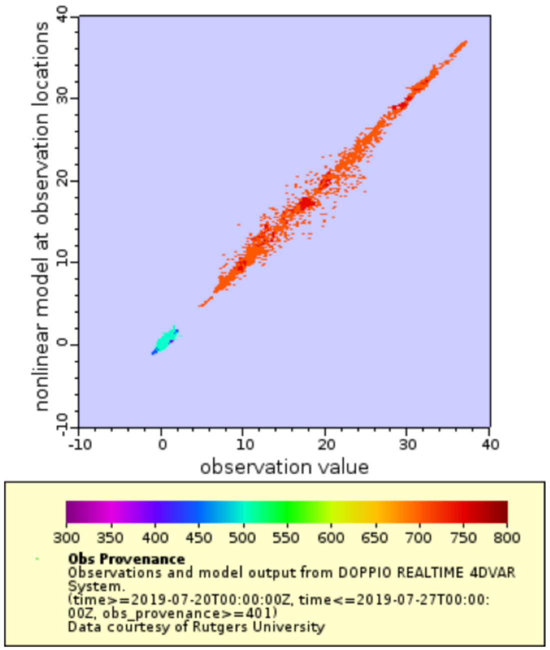
Brought to you by NOAA NMFS SWFSC ERD

ERDDAP > tabledap > Make A Graph

Dataset Title: **Observations and model output from DOPPIO REALTIME 4DVAR System.** RSS
Institution: Rutgers University (Dataset ID: DOPPIO_REALTIME_MOD)
Range: longitude = -79.62816 to -59.690285°E, latitude = 32.23944 to 46.61133°N, depth = -3250.0 to 0.0, time = 2018-04-03T00:00:00Z to 2019-07-26T23:45:00Z
Information: Summary | License | FGDC | ISO 19115 | Metadata | Background | Subset | Data Access Form

Graph Type: markers
X Axis: obs_value
Y Axis: model_value
Color: obs_provenance

Time range: 7 day(s)



Constraints		**Optional Constraint #1**		**Optional Constraint #2**
time	>=	2019-07-20T00:00:00	<=	2019-07-27T00:00:00
obs_provenance	>=	401	<=	
	>=		<=	
	>=		<=	
	>=		<=	

Server-side Functions
distinct()
(" ")

Graph Settings
Marker Type: Dot Size: 6
Color:
Color Bar: Continuity: Scale:
Min: Max: N Sections:
Y Axis Minimum: Maximum: ascending

Redraw the Graph (Please be patient. It may take a while to get the data.)

Optional:

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X Axis: obs_value
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Constraints | **Optional Constraint #1** | **Optional Constraint #2**
time >= 2019-07-20T00:00:0 <= 2019-07-27T00:00:0
obs_provenance

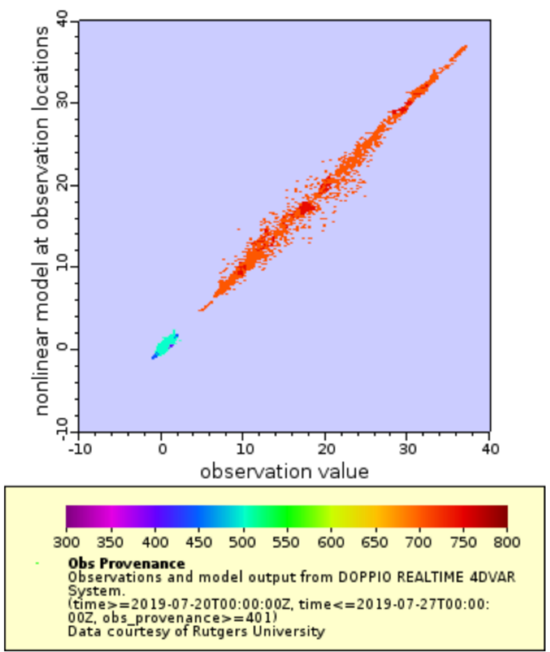
Server-side Functions
distinct()

Graph Settings
Marker Type: Dot
Color:
Color Bar:
Min: Max: N Sections:
Y Axis Minimum: Maximum: ascending

Redraw the Graph (Please be patient. It may take a while to get the data.)

Optional:

Time range: 7 day(s)



Since we are operationally downloading and pre-processing the Mercator-Océan output for open boundary conditions, we also interpolate that analysis to the observation locations for near-real-time analysis of comparative model skill.

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ERDDAP > tabledap > Make A Graph

Dataset Title: **Observations and model output from DOPPIO REALTIME 4DVAR System.** RSS
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Range: longitude = -79.62816 to -59.690285°E, latitude = 32.23944 to 46.61133°N, depth = -3250.0 to 0.0, time = 2018-04-03T00:00:00Z to 2019-07-26T23:45:00Z
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Graph Type: markers
X Axis: obs_value
Y Axis: merc_value
Color: obs_provenance - +

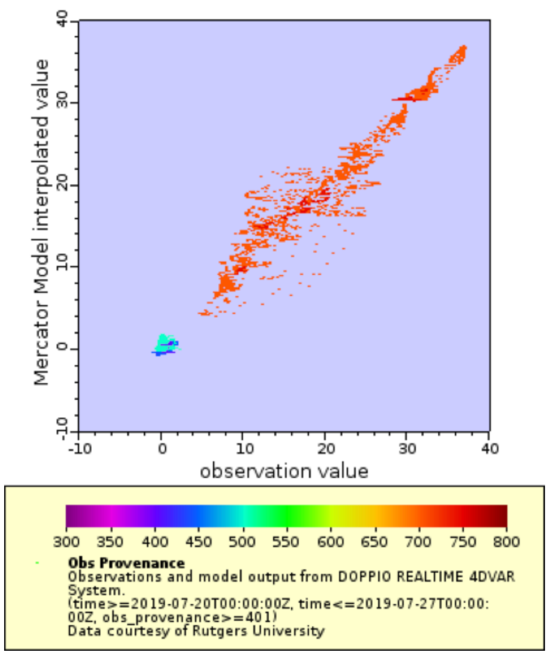
Time range: 7 day(s) -

Constraints	**Optional Constraint #1**		**Optional Constraint #2**	
time	>=	2019-07-20T00:00:0(	<=	2019-07-27T00:00:0(
obs_provenance	>=	401	<=	
		- +		
	>=		<=	
	>=		<=	
	>=		<=	

Server-side Functions
distinct()
(" ")

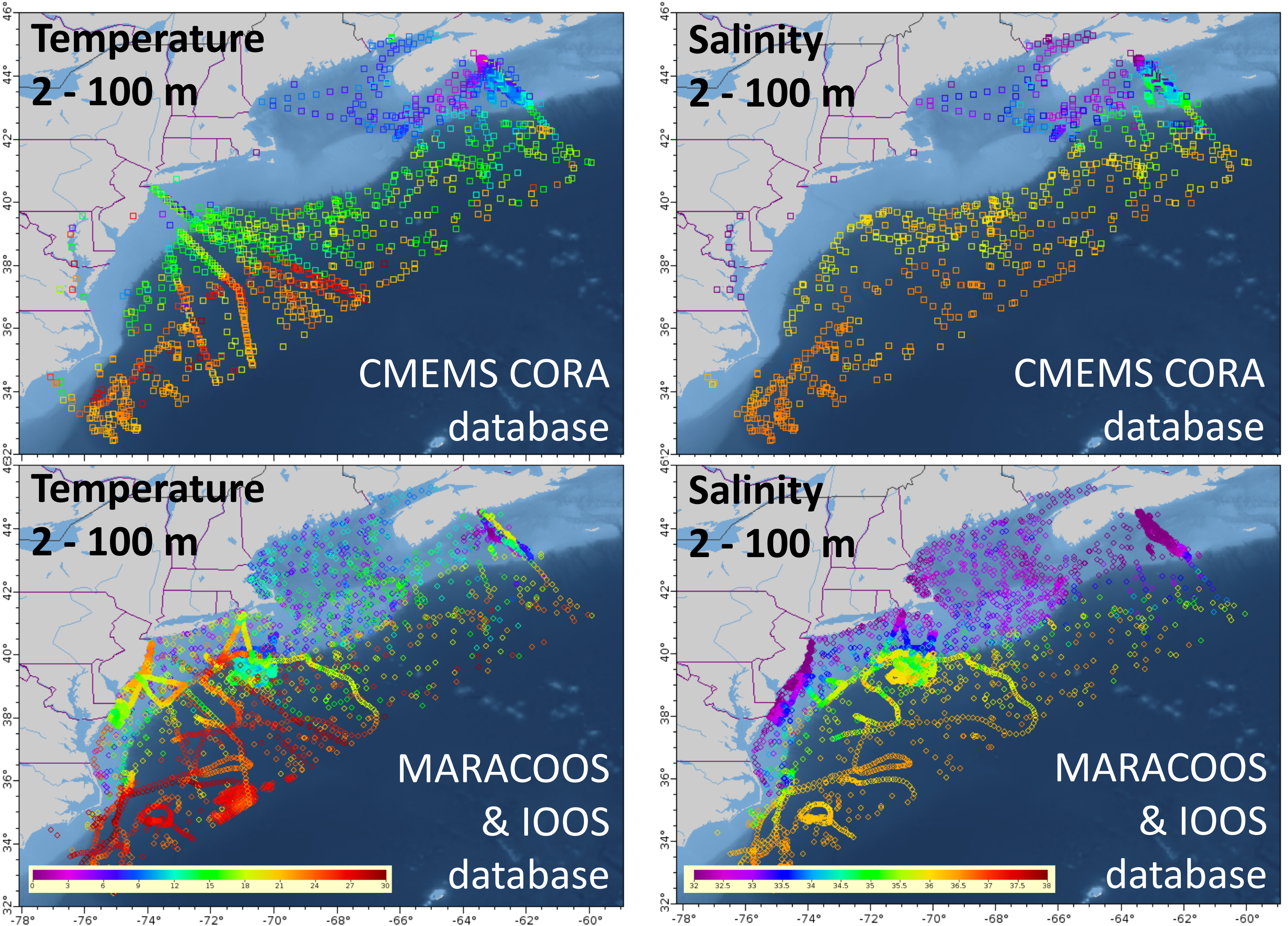
Graph Settings
Marker Type: Dot Size: 6
Color:
Color Bar: Continuity: Scale:
Min: Max: N Sections:
Y Axis Minimum: Maximum: ascending

Redraw the Graph (Please be patient. It may take a while to get the data.)

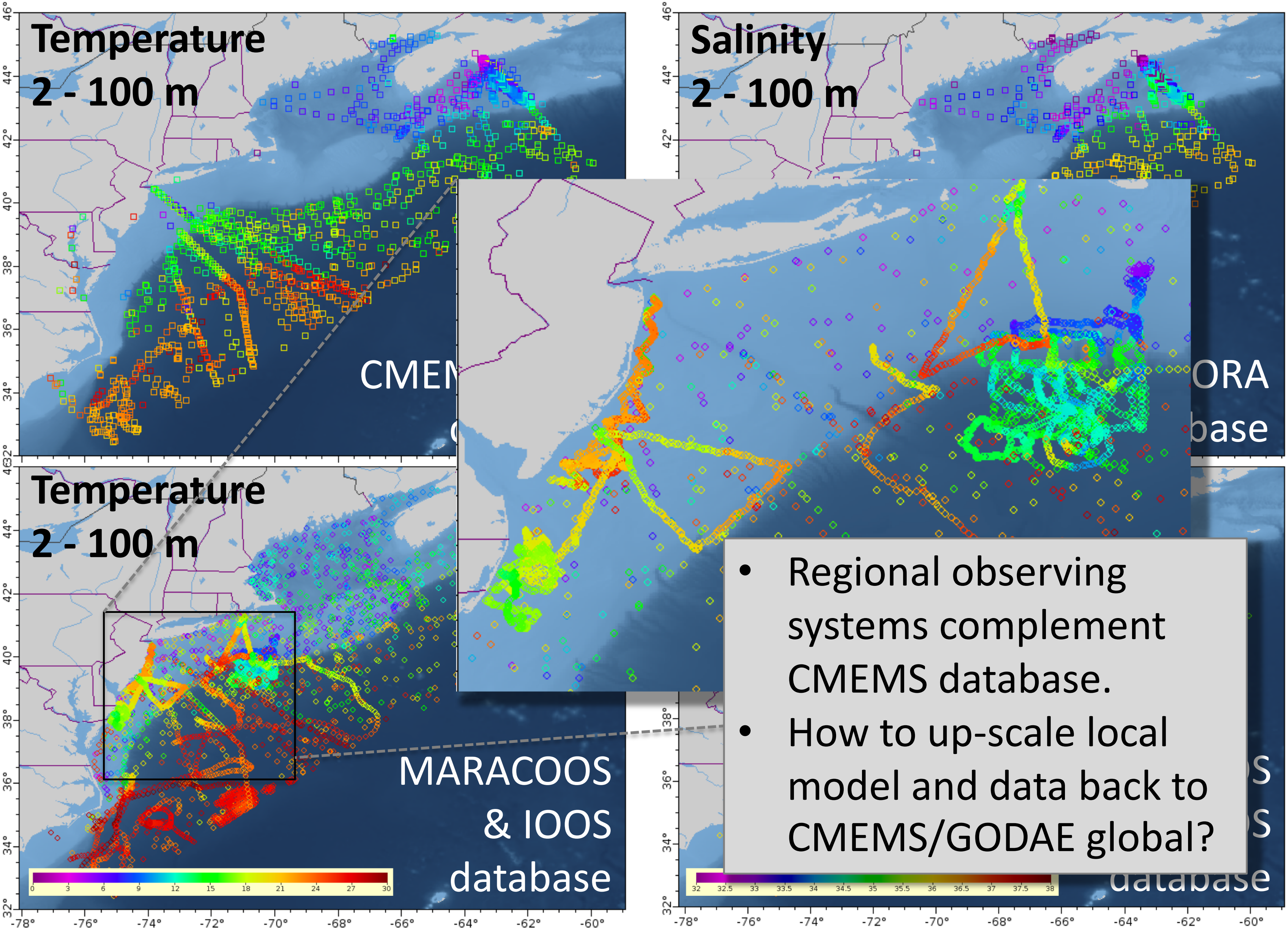


Optional:

Subsurface in situ ocean observations for the northeast U.S. in 2015



Subsurface in situ ocean observations for the northeast U.S. in 2015



- Regional observing systems complement CMEMS database.
- How to up-scale local model and data back to CMEMS/GODAE global?

Observation impact

Evaluate the influence of individual observations on the analysis

$$\mathbf{x}_a = \mathbf{x}_\mathbf{b} + \tilde{\mathbf{K}}(\mathbf{y} - H(\mathbf{x}_\mathbf{b}))$$

analysis = prior + gain x innovation $\quad \mathbf{d} = \mathbf{y} - H(\mathbf{x}_\mathbf{b})$

Observation impact

Evaluate the influence of individual observations on the analysis

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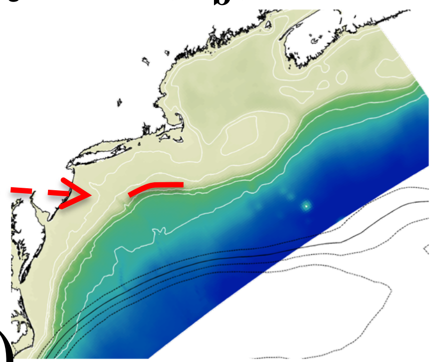
analysis = prior + gain x innovation $\quad \mathbf{d} = \mathbf{y} - H(\mathbf{x}_\mathbf{b})$

Define some scalar functional of model state: $I(\mathbf{x})$

e.g. transport through a section:



Change due to 4DVAR: $\Delta I = I(\mathbf{x}_\mathbf{a}) - I(\mathbf{x}_\mathbf{b})$

$$= I(\mathbf{x}_\mathbf{b} + \tilde{\mathbf{K}}\mathbf{d}) - I(\mathbf{x}_\mathbf{b})$$

from 1st order Taylor series expansion

$$\simeq \mathbf{d}^T \underbrace{\tilde{\mathbf{K}}^T (\partial I / \partial \mathbf{x})\big|_{\mathbf{x}_\mathbf{b}}}$$

innovation ^{T} • *sensitivity of I mapped in to observation space*

Observation impact

Evaluate the influence of individual observations on the analysis

$$\mathbf{x}_a = \mathbf{x}_\mathbf{b} + \tilde{\mathbf{K}}(\mathbf{y} - H(\mathbf{x}_\mathbf{b}))$$

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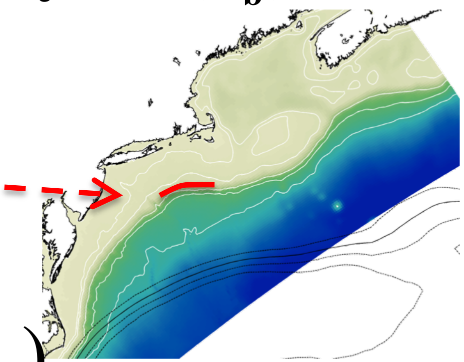

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from 1st order Taylor series expansion

$$\simeq \mathbf{d}^T \boxed{\tilde{\mathbf{K}}^T (\partial I / \partial \mathbf{x})\big|_{\mathbf{x}_\mathbf{b}}}$$

$$\Delta I = \mathbf{d}^\mathbf{T}\mathbf{g} = \sum_{i=1}^{N} d_i g_i$$

Each element of g is *uniquely* associated with each of the *N* observations.

We will group by observation type the elements of $\Delta I = \sum_{i=1}^{N} d_i g_i$ to examine the respective impact of SSH, SST, etc.

Observation impact

Evaluate the influence of individual observations on the analysis

$$\mathbf{x}_a = \mathbf{x_b} + \tilde{\mathbf{K}}(\mathbf{y} - H(\mathbf{x_b}))$$

analysis = prior + gain x innovation $\quad \mathbf{d} = \mathbf{y} - H(\mathbf{x_b})$

Define some scalar functional of model state: $I(\mathbf{x})$

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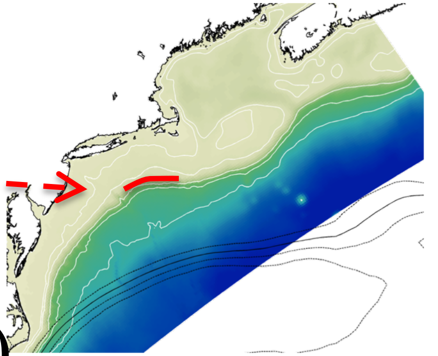

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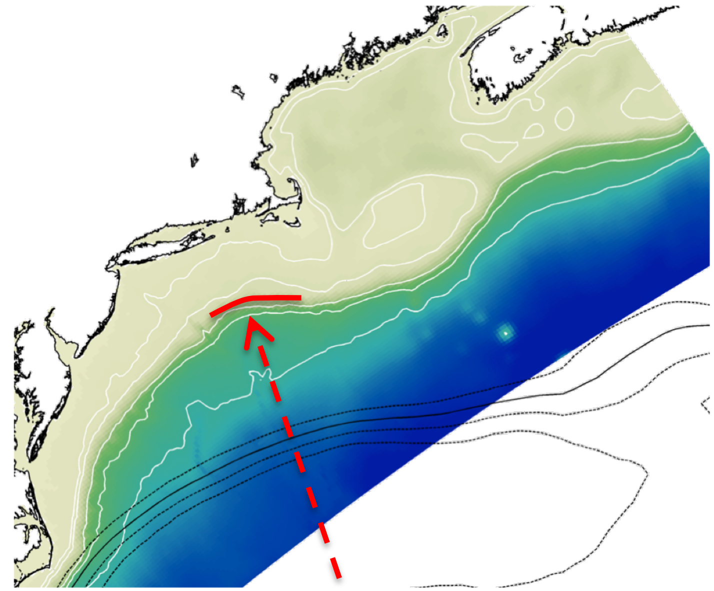
Cross-Shelf Exchange Circulation Metrics

Volume transport and heat flux

Cross-shelf volume transport:

$$I_1 = \frac{1}{\tau}\int_0^{\tau}\int_S\int_{-h}^{\zeta} u_n \, dz\, ds\, dt$$



Cross-shelf heat transport:

$$I_2 = \frac{\rho c_p}{\tau}\int_0^{\tau}\int_S\int_{-h}^{\zeta} (u_n - \bar{u}_n)(T - \bar{T})\, dz\, ds\, dt$$

Historical context:

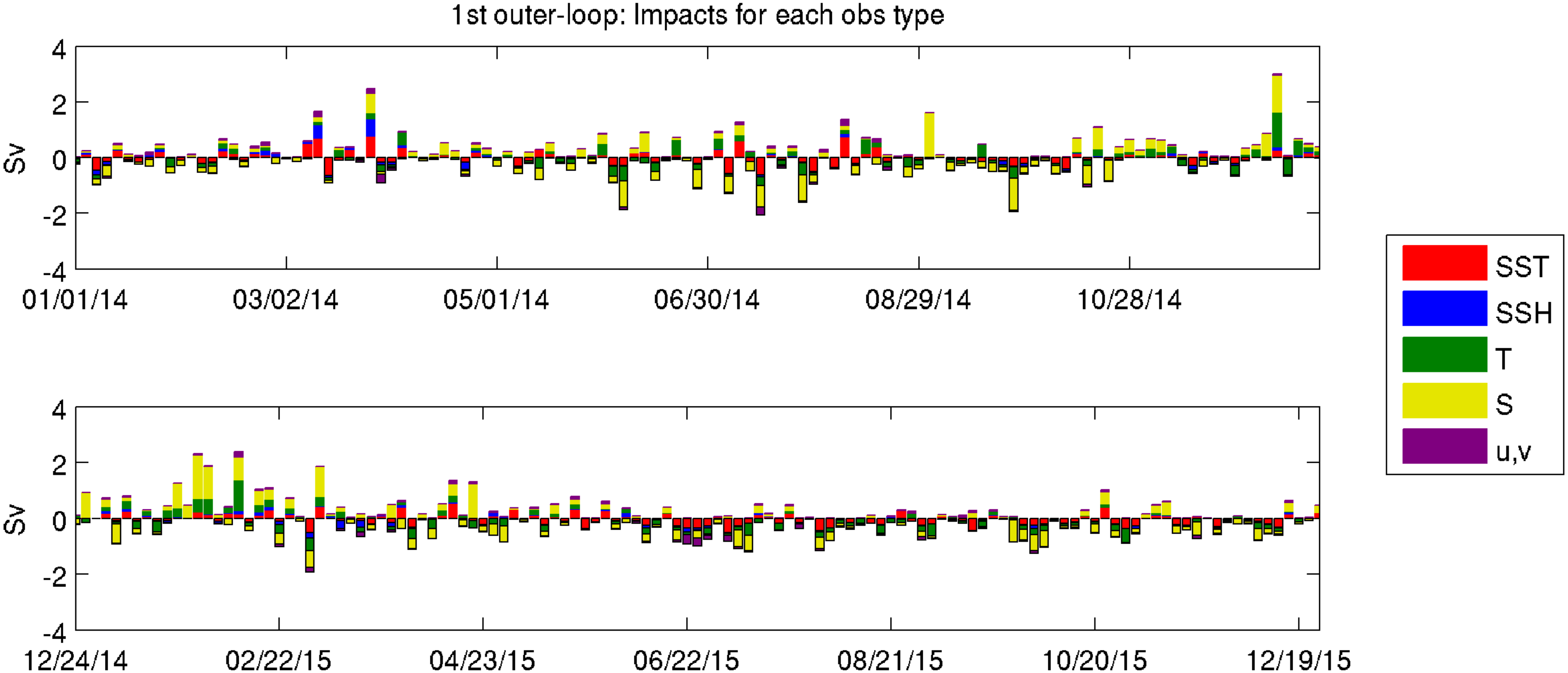
Linder and Gawarkiewicz (1998)

Chen and He (2014)

Zhang et al. (2015)

*Along-shelf and vertical section following the 200 m isobath and passing through **OOI Pioneer Array***

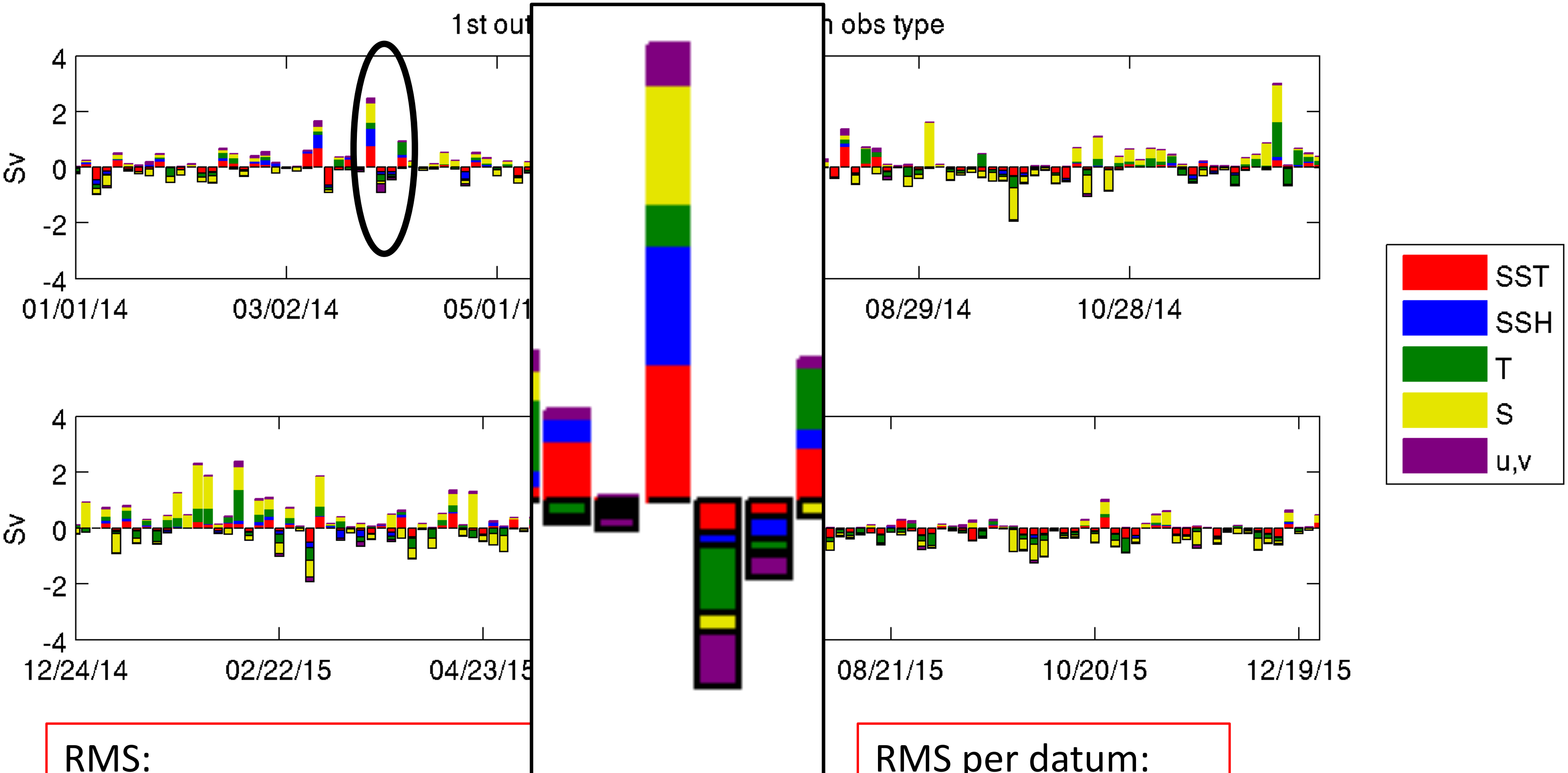
Cross-shelf volume transport increments $\Delta I_1 = I_1(\mathbf{x_a}) - I_1(\mathbf{x_b})$



RMS:			
SST	0.22 Sv		
SSH	0.08 Sv	Jason 2	0.031 Sv
(u,v)	0.07 Sv	CryoSat	0.025 Sv
in situ T	0.22 Sv	AltiKa	0.029 Sv
in situ S	0.37 Sv		

RMS per datum:	
SST	1.8e-6 Sv
SSH	3.3e-5 Sv
(u,v)	5.6e-6 Sv
in situ T	1.1e-4 Sv
In situ S	2.2e-4 Sv

Cross-shelf volume transport increments $\Delta I_1 = I_1\left(\mathbf{x_a}\right) - I_1\left(\mathbf{x_b}\right)$



RMS:			
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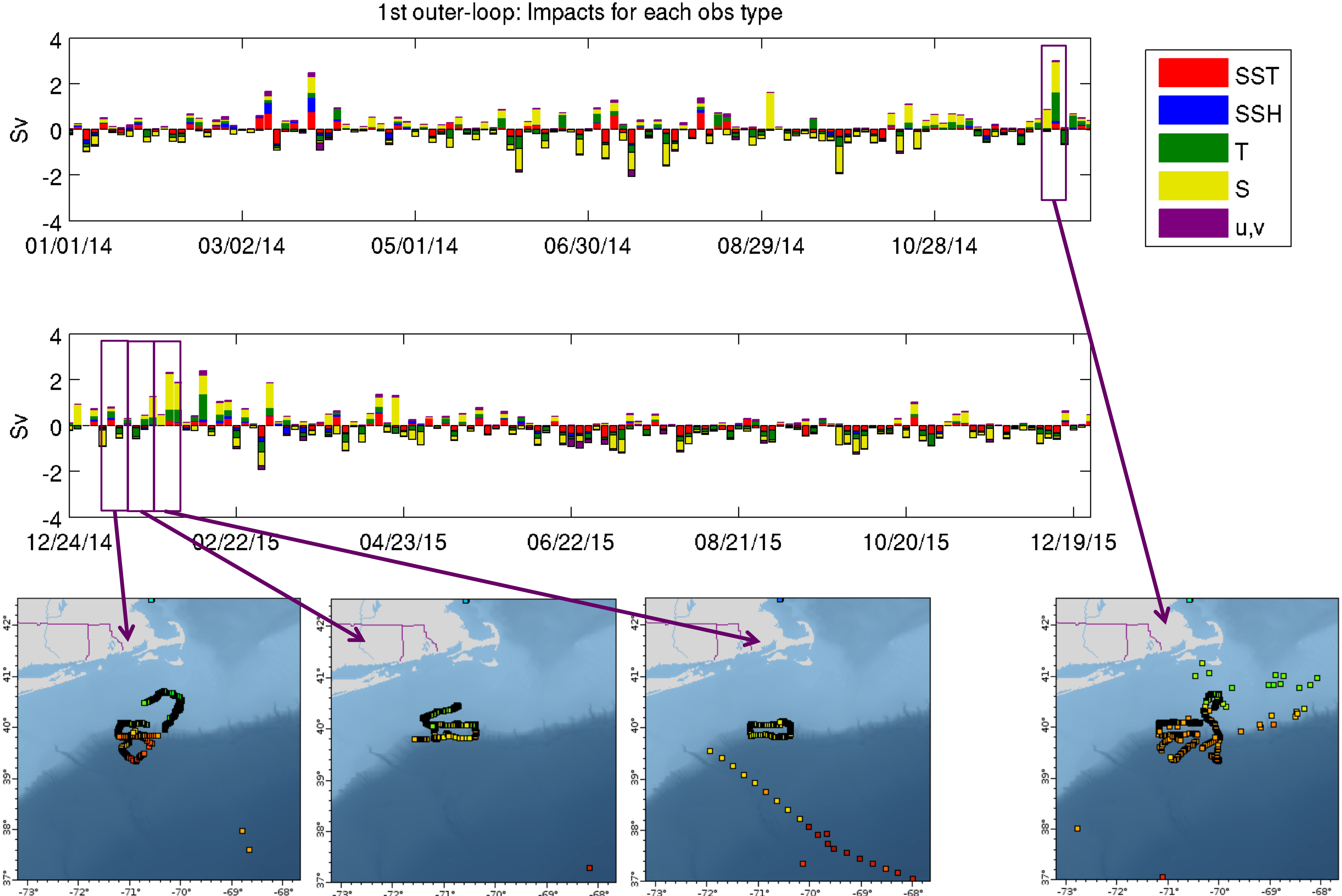
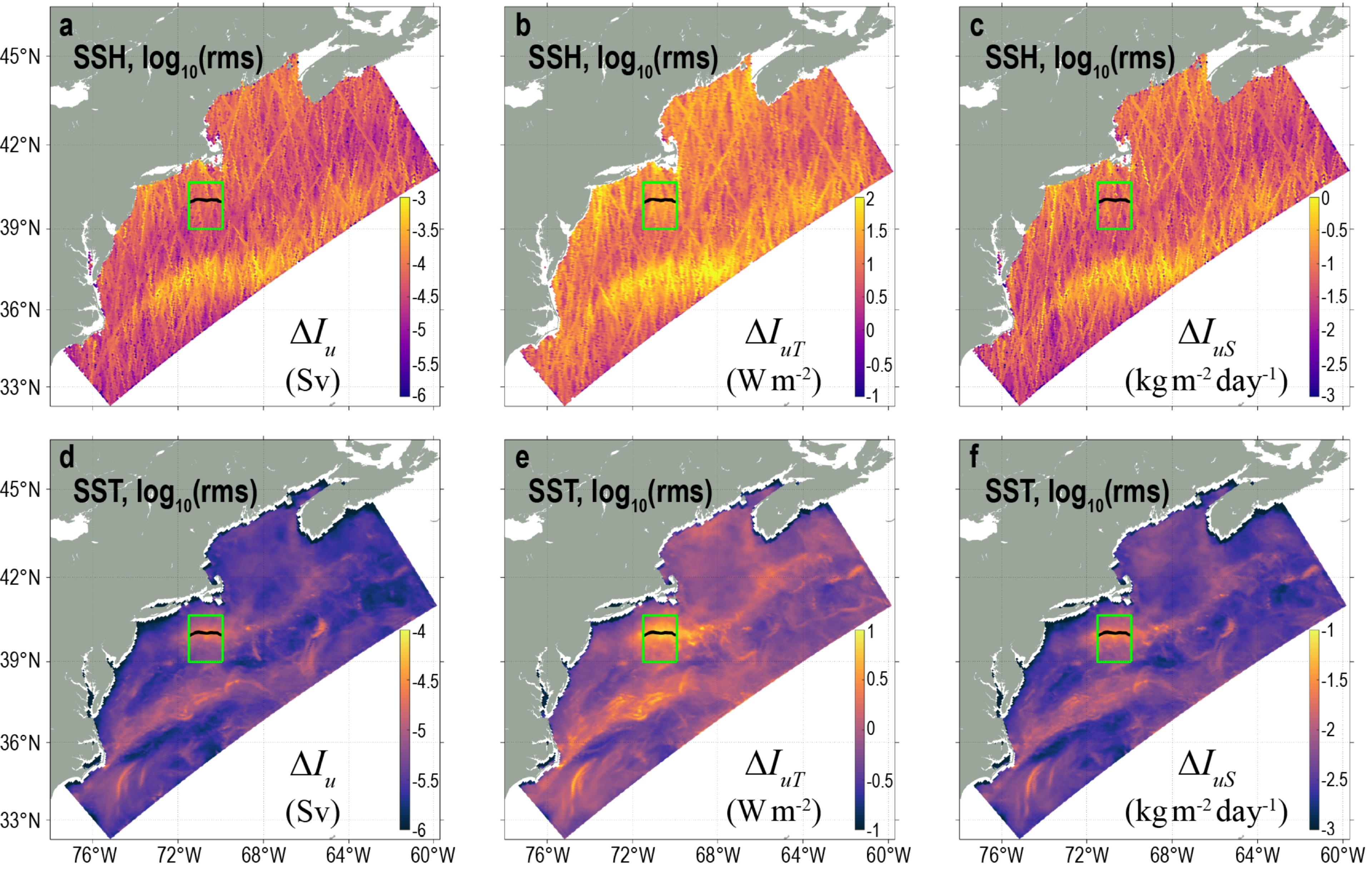
Cross-shelf volume transport increments

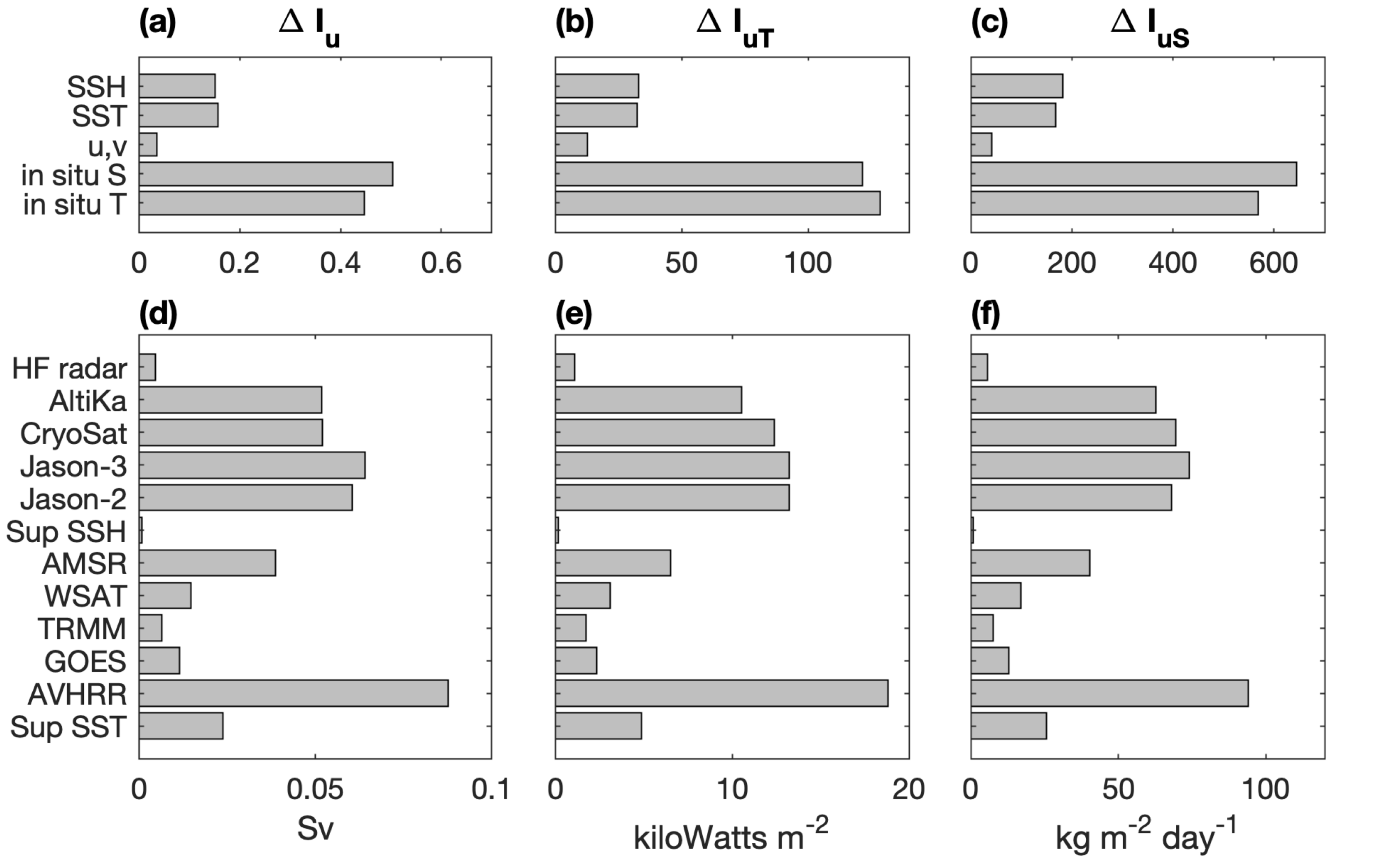
$$\Delta I_1 = I_1(\mathbf{x_a}) - I_1(\mathbf{x_b})$$



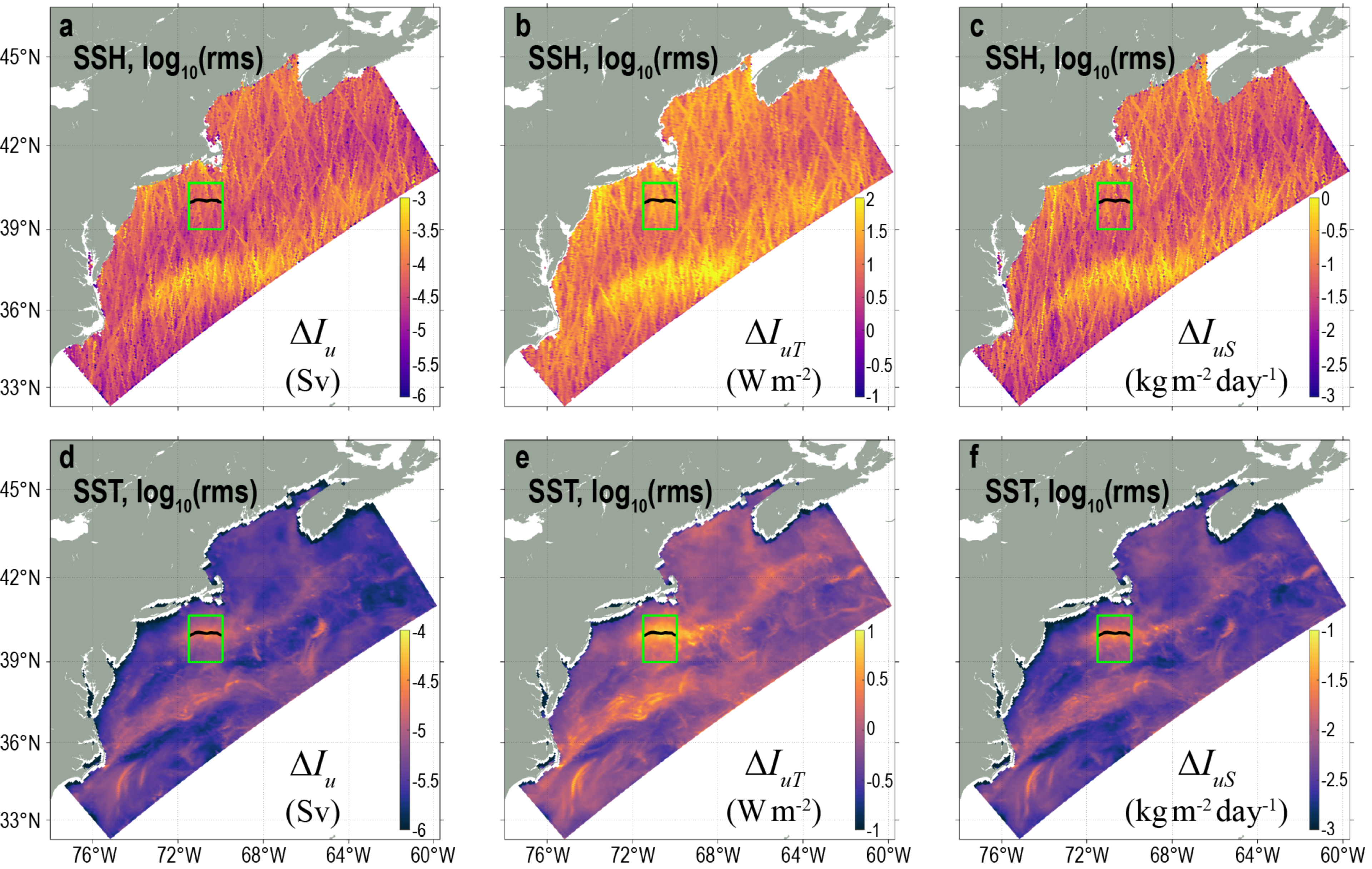
Observation impact



Observation impact



Observation impact



Doppio 4D-Var observation and background error assumptions have been driven by practical demands – needs further analysis and improvement

Type & platform	Source	Sampling rate and resolution	Super-obs averaging[1]	Obs error
AVHRR IR SST	MARACOOS.org & NOAA Coastwatch	4 passes per day, 1 km	3 hr	σ_b
GOES IR SST	NOAA Coastwatch	hourly, 6 km	3 hr	$2\sigma_b$
AMSR2, TRMM, and WindSat microwave SST	NASA JPL PODAAC	daily, 15 km		$1.25\sigma_b$
SSH: Jason, AltiKa, CryoSat	RADS, TU Delft	$\sim$ 1 pass daily, $\sim$ 4 km		$0.04\ m$
in situ T, S: NDBC buoys, Argo floats, XBT, surface drifters	Met Office En4.2	variable[2]	standard levels[2]	$0.25\sigma_b\sigma_o/\sigma_{\max}{}^3$
Surface currents: CODAR HF-radar	MARACOOS.org	hourly, 1 km	1 hr, 24 km	$0.5\sigma_b$
Glider T, S: MARACOOS	IOOS Glider DAC	variable[2]	standard levels[2]	$0.25\sigma_b\sigma/\sigma_{\max}{}^3$
In situ T,S: GoM[5] buoys	NERACOOS.org[4]	hourly, 10 buoys	1 hr	σ_b
In situ u,v: GoM[5] buoys	NERACOOS.org[4]	hourly, 9 buoys[1]	1 hr	$0.5\sigma_b$

Table 1: A summary of the observational data assimilated into ROMS during 2014-2017, the procedure for forming super observations, and the observation errors assigned to each observation type. 1: All data that were sampled at a horizontal resolution higher than that of the model were formed into super observations at the resolution of the ROMS grid unless otherwise indicated. 2: Profile data were binned in the vertical using the WOD atlas standard depths (Boyer et al., 2009). 3: Here σ is the standard deviation of all observations that fall within a vertical bin (see comment 1) and $\sigma_{\max}$ is the maximum value of all σ in a vertical profile. 4: NERACOOS = North East Regional Association Coastal Ocean Observing System. 5: GoM=Gulf of Maine.

State variable	Horizontal decorrelation scale (km)	Background quality control parameter α
SSH	40	5
Velocity	40	3
Temperature	40	6
Salinity	15	6

Table 2: A summary of the decorrelation scales assumed for background errors in each state variable. The vertical decorrelation length scale for all state variables was chosen to be 10 m. The parameter α used for the background quality control rejection criteria is also indicated.

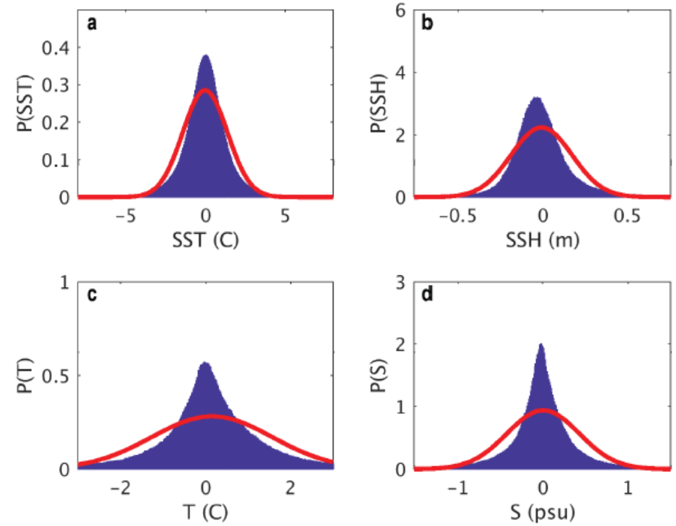
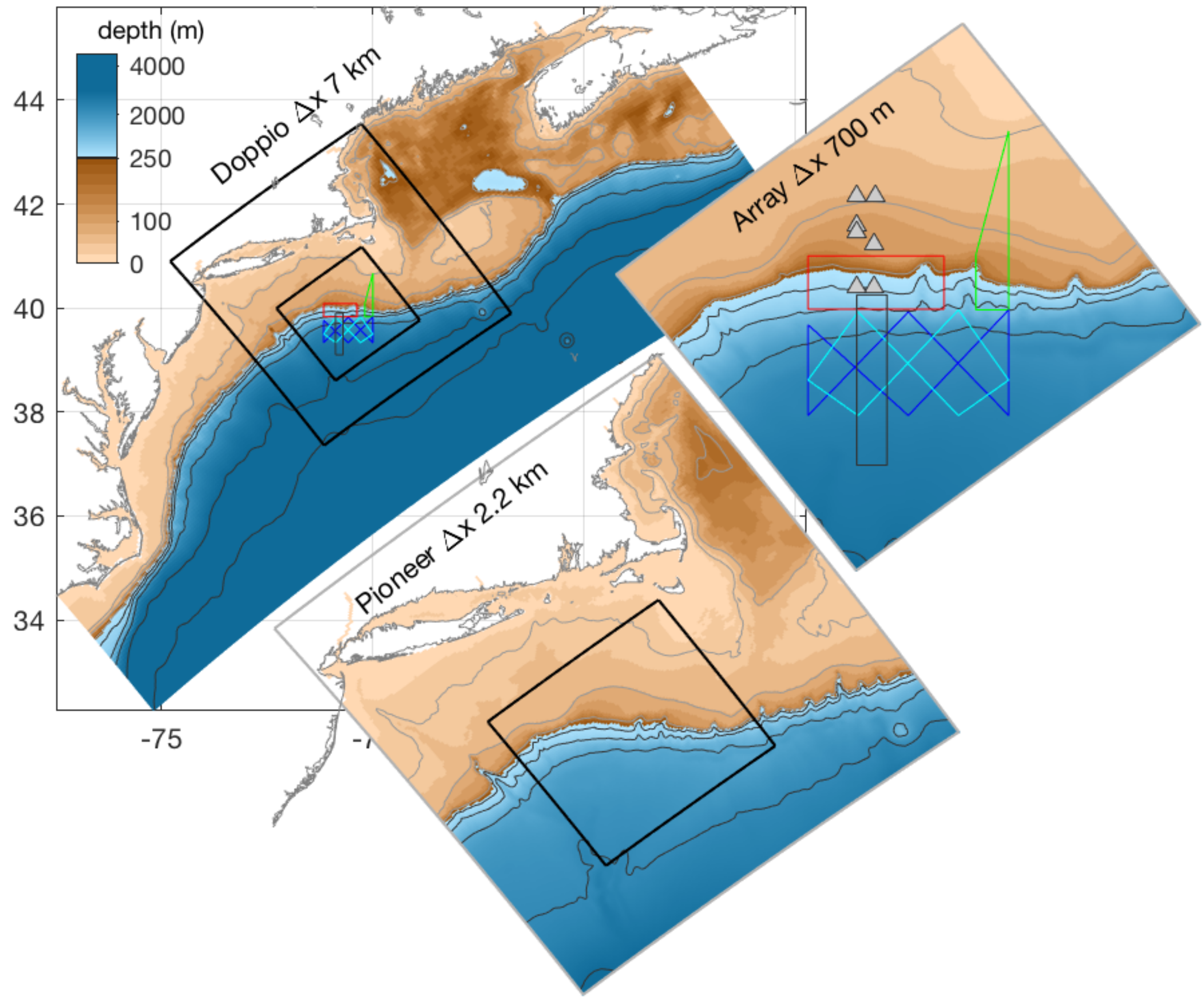
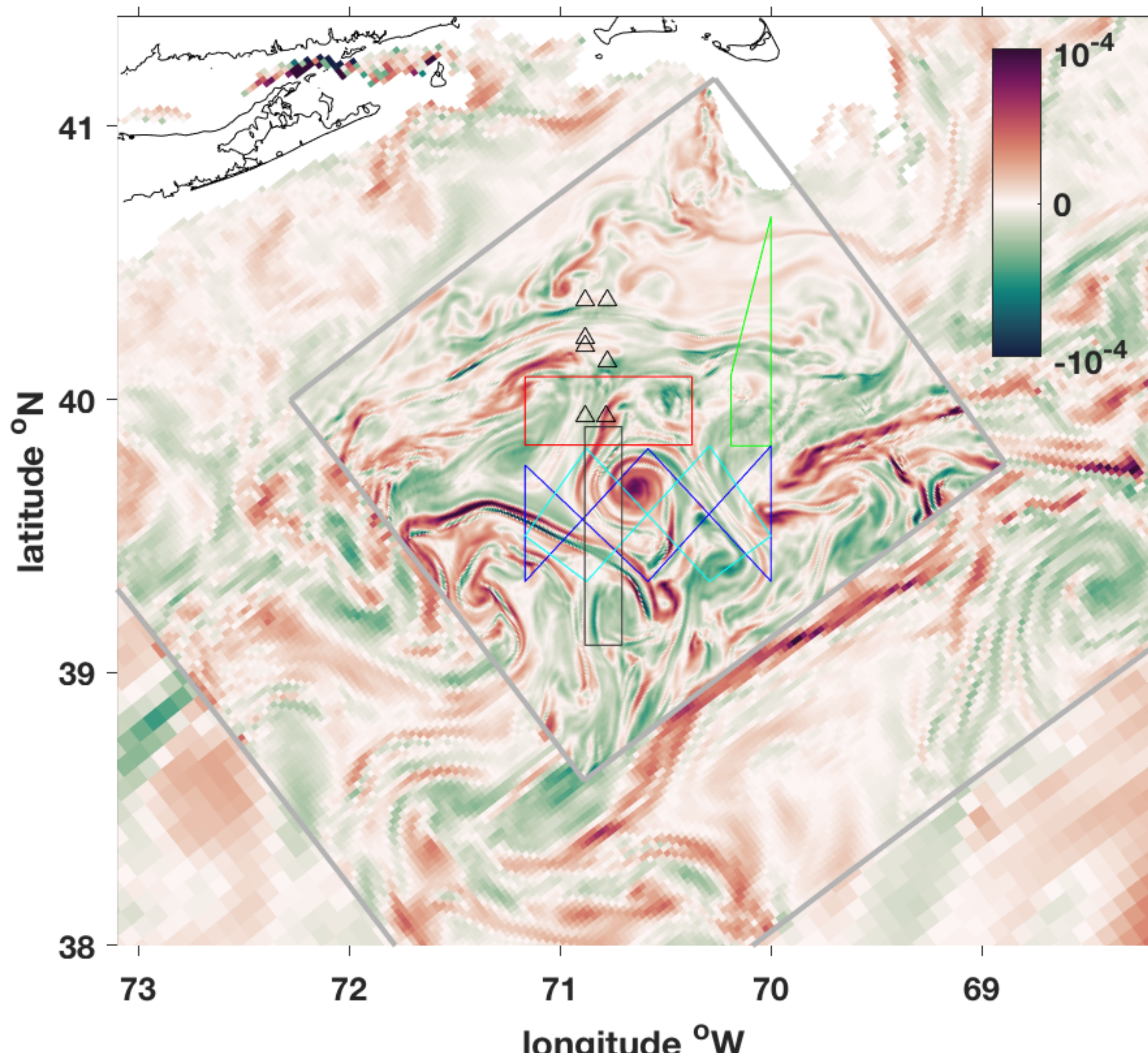


Figure 3: Probability density functions (pdfs) of the 4D-Var increments in (a) SST, (b) SSH, (c) *in situ* temperature, and (d) *in situ* salinity computed from all 4D-Var cycles spanning the 2014-2017 period.

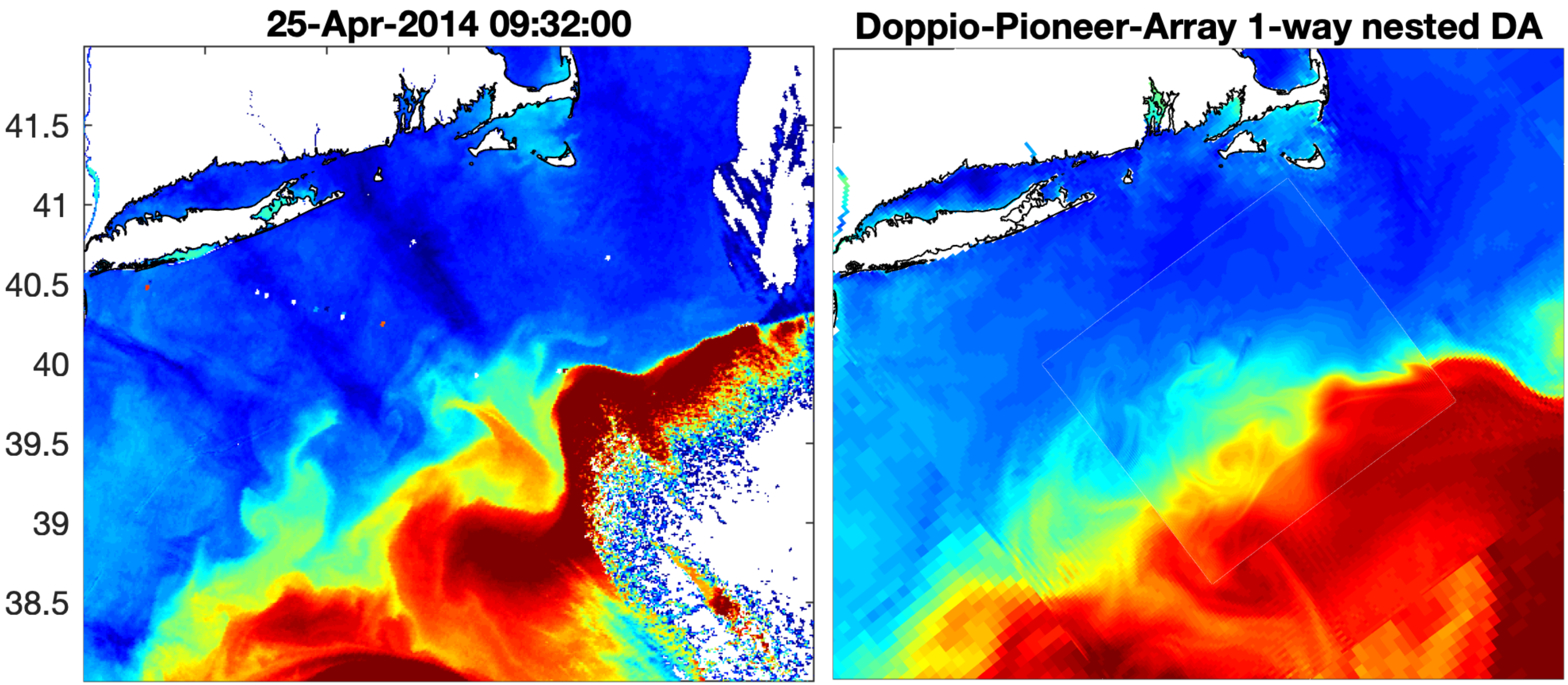
Nested modeling for local grid refinement



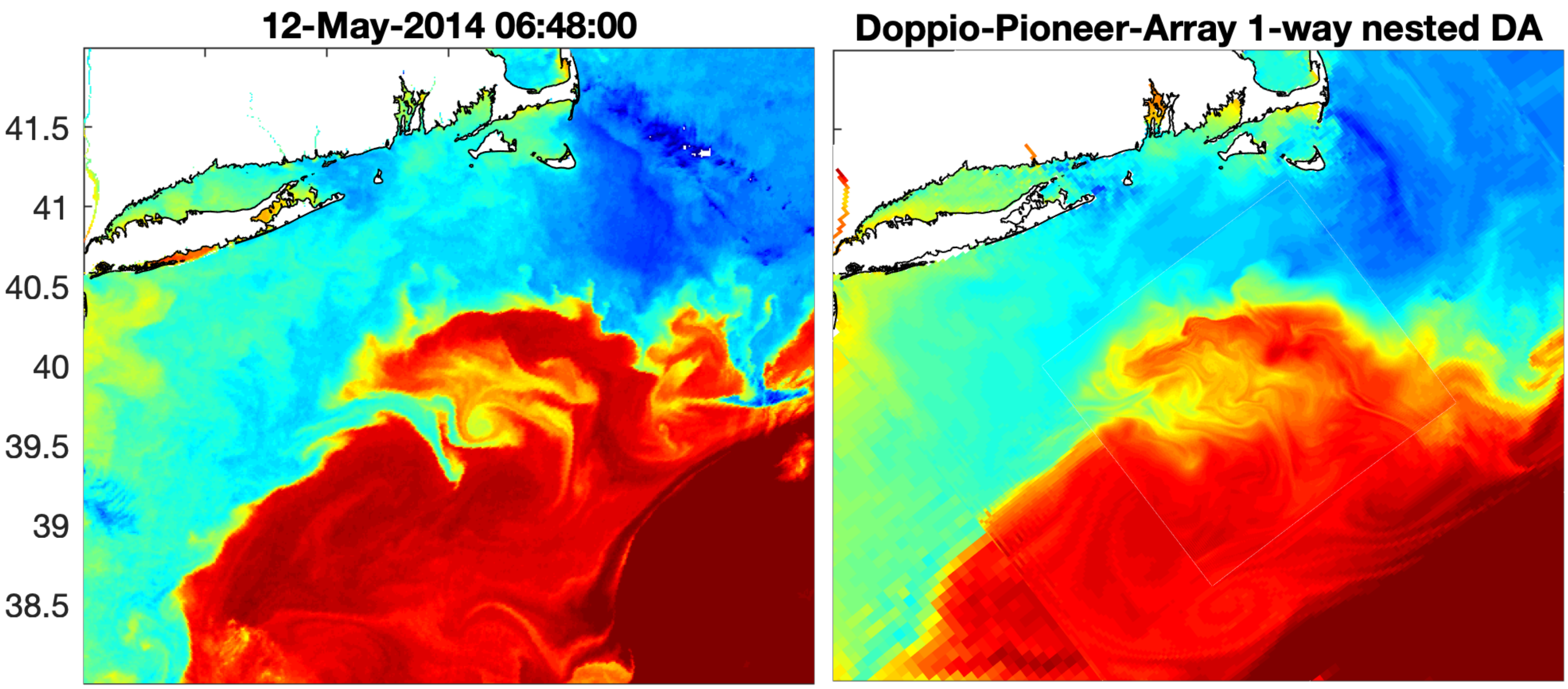
Doppio <-> Pioneer <-> Array 2-way nesting at all levels – free running forward model



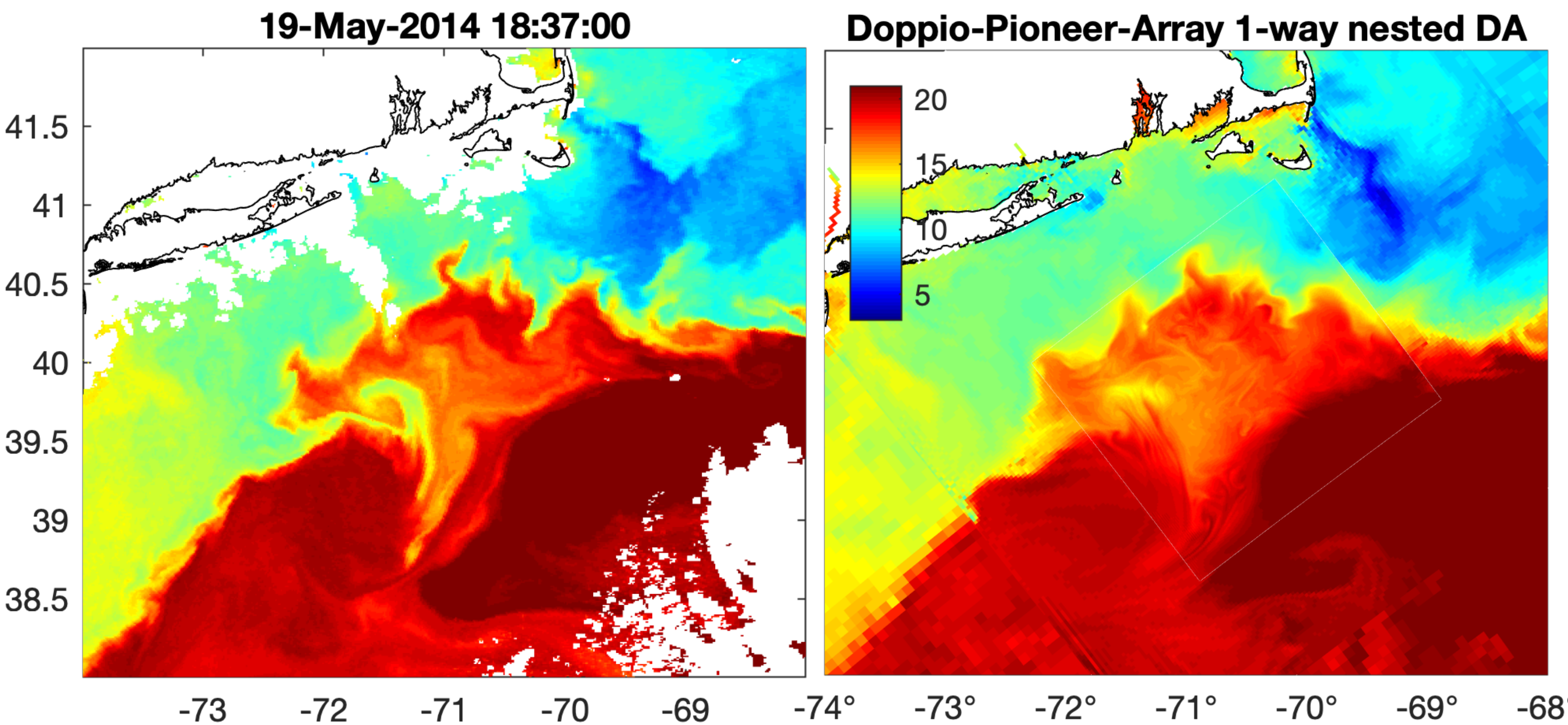
Doppio -> Pioneer -> Array Successive 1-way downscaling with data assimilation in each grid



Doppio -> Pioneer -> Array Successive 1-way downscaling with data assimilation in each grid



Doppio -> Pioneer -> Array Successive 1-way downscaling with data assimilation in each grid



Zhang, W. G., and G. G. Gawarkiewicz (2015), Dynamics of the direct intrusion of Gulf Stream ring water onto the Mid-Atlantic Bight shelf, Geophys. Res. Lett., 42, doi:10.1002/2015GL065530.

Summary (1/2)

Rutgers MARACOOS ROMS forecast system with 4DVAR DA uses all available data from a modern coastal ocean observing system

- Satellite SSH and SST, HF-radar, gliders, Argo, GTS XBT/CTD
- More and diverse data is better
- Pre-processing for QC; tides in altimetry; binning to independent obs.
- OBC bias removal essential: use mean state from 4DVAR-based climatology
- Data ingest and output exploits web services (OPeNDAP/THREDDS) and interoperability of data conventions (CDM, CF-conventions, NetCDF/HDF)

Useful skill for real-time applications

- 4 days for temperature and salinity; 1-2 days for velocity

Output to THREDDS/FMRC Forecast Model Run Collection

- Surface currents to U.S. Coast Guard; Bottom temperatures to NOAA Fisheries …

Summary (2/2)

Observation Impact Analysis

quantifies the influence of data on user-defined circulation metrics

- Impact assessment can be extended into the forecast interval
- We are working toward:
  - Real-time monitoring of IOOS observing elements (for QA/QC, etc.)
  - Observing system evaluation (e.g. long-term impact of individual radar sites in the network)
  - Adaptive sampling for moveable assets (e.g. OOI Pioneer gliders)

myroms.org Development Path

- 2-way nested forecasts (NOAA)
- Hybrid EnKF/4D-Var using DART to advance background covariance $\mathbf{B}$ (ONR)
- Coupling using ESMF/NUOPC (NOPP):
  ROMS <–> CICE <-> WRF/COAMPS <–> SWAN/WW3 and <u>hybrid model *nesting*</u>
- 2-way nested 4D-Var (NSF OOI Pioneer)
- Physics+bio (optical/IOP) joint assimilation