Regional Ocean Data Assimilation using DART-ROMS

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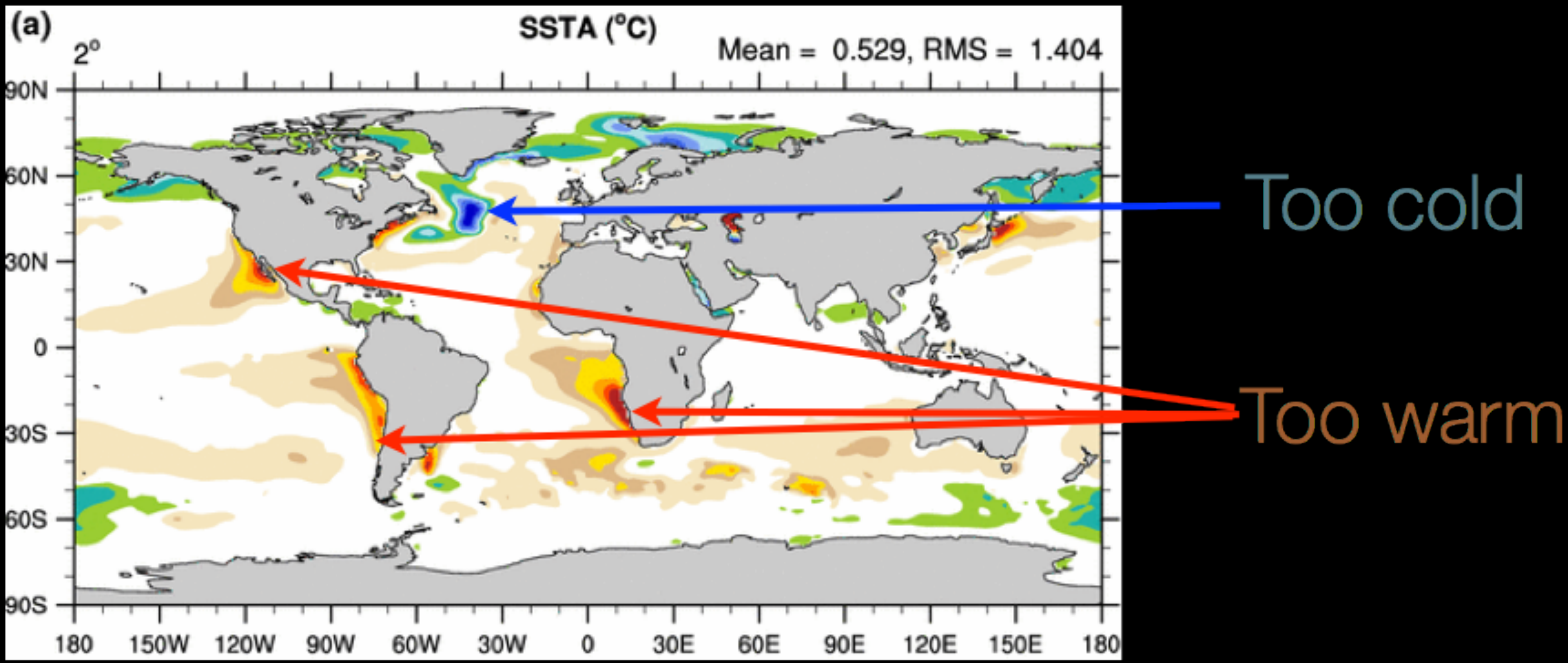
Outline

- Motivation
- ROMS implementation in the NW Atlantic (NWA)
- ROMS-DART development
- ROMS-DART in NWA
- Summary and future work

Why regional models?

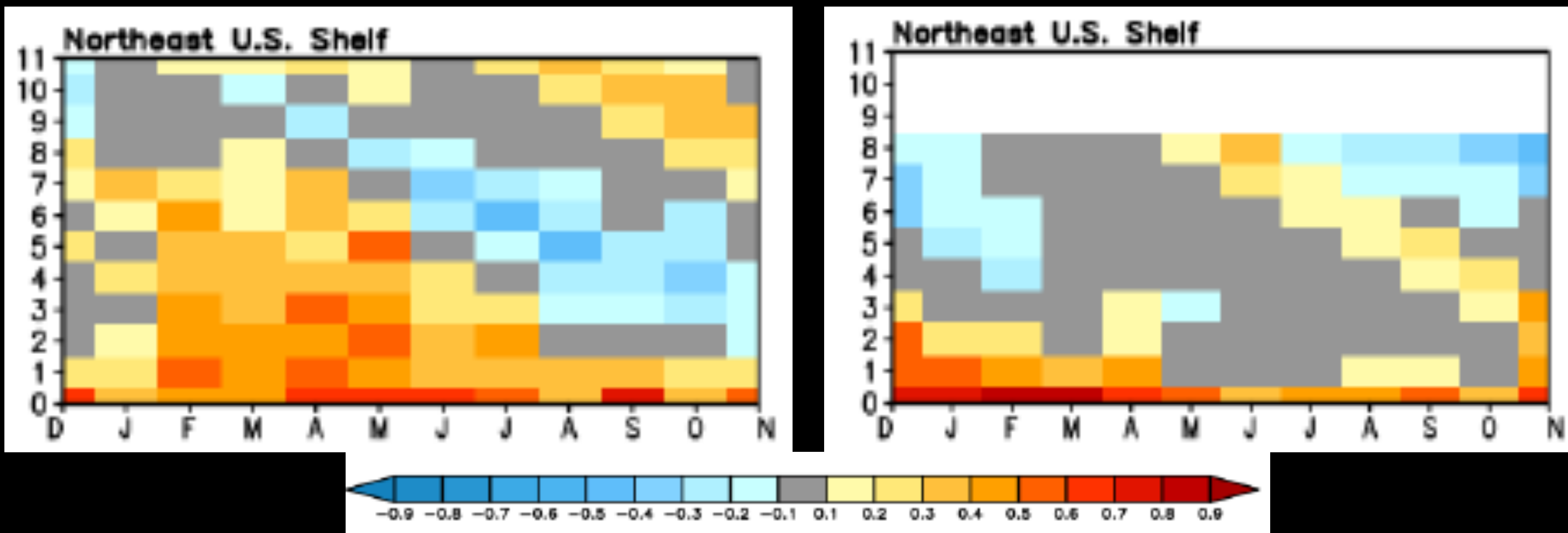
Climate model biases (SST)



Why Regional Ocean DA?

- Predictability in coastal systems
- Ocean (high-resolution) reanalysis
- Can it help us understand missing dynamics?

Predictability?

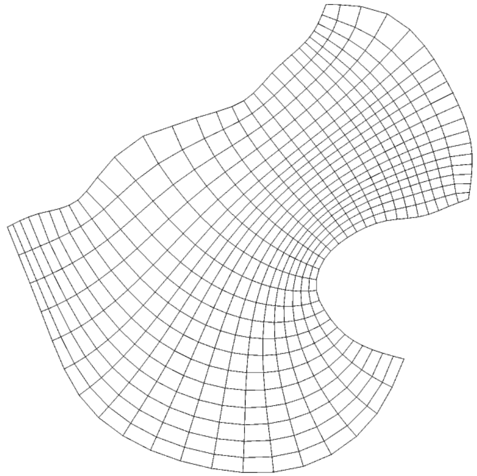


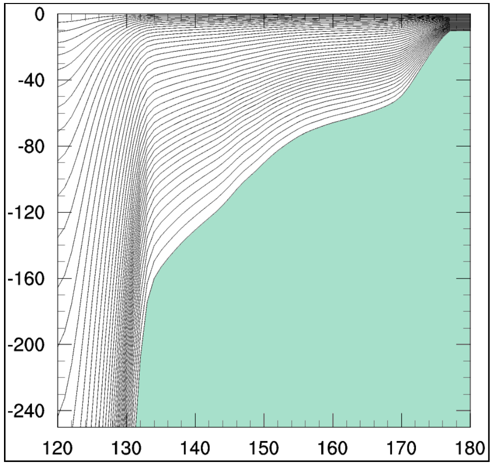
Anomaly correlation coefficient between the predicted and observed SST anomalies for the Northeast U.S. Large Marine Ecosystem from GFDL's CM2.1 Seasonal Forecast system (Delworth et al. 2006) and NCEP's CFSv2 (Saha et al.2014) seasonal forecast system. The x-axis corresponds to the start month of each forecast, the y-axis corresponds to the lead-time in months (figure courtesy of K. Pegion, Stock et al., in review). Note that correlations are < 0.4 for nearly all starts and leads

Our Ocean Model

ROMS

- Hydrostatic, Boussinesq equations of fluid motion.
- Boundary fitted, orthogonal horizontal coordinates on an Arakawa C-grid.
- Generalized terrain-following vertical coordinate system.
- High-order advection scheme, continuous monotonic reconstruction of vertical gradients.



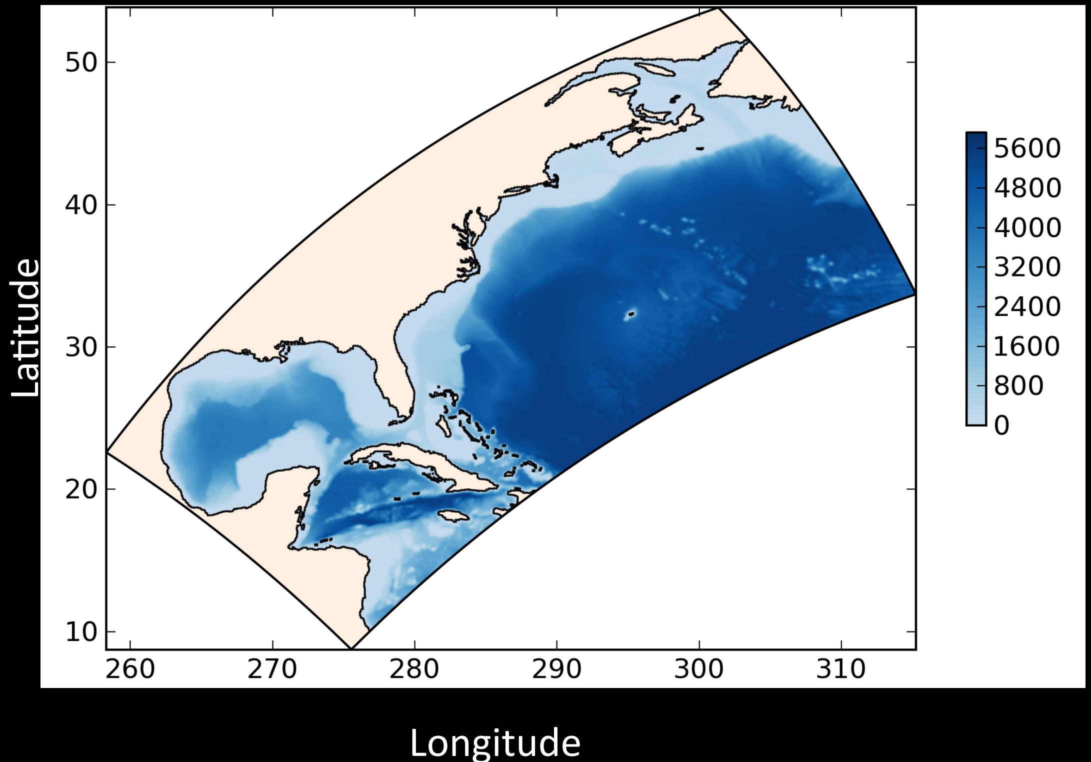


ROMS: Other Features

- Non-linear free surface
- Bulk Fluxes
- Open boundary conditions
- Vertical mixing: KPP, GLS.
- Sea Ice and ice-shelves
- Bio-geochemistry: COBALT, Fasham, NEMURO and more
- Upper trophic level models (fish, fleets)
- Lagrangian particle tracking
- Tides
- Sediment transport

ROMS in the NW Atlantic

- **Domain & Bathymetry**

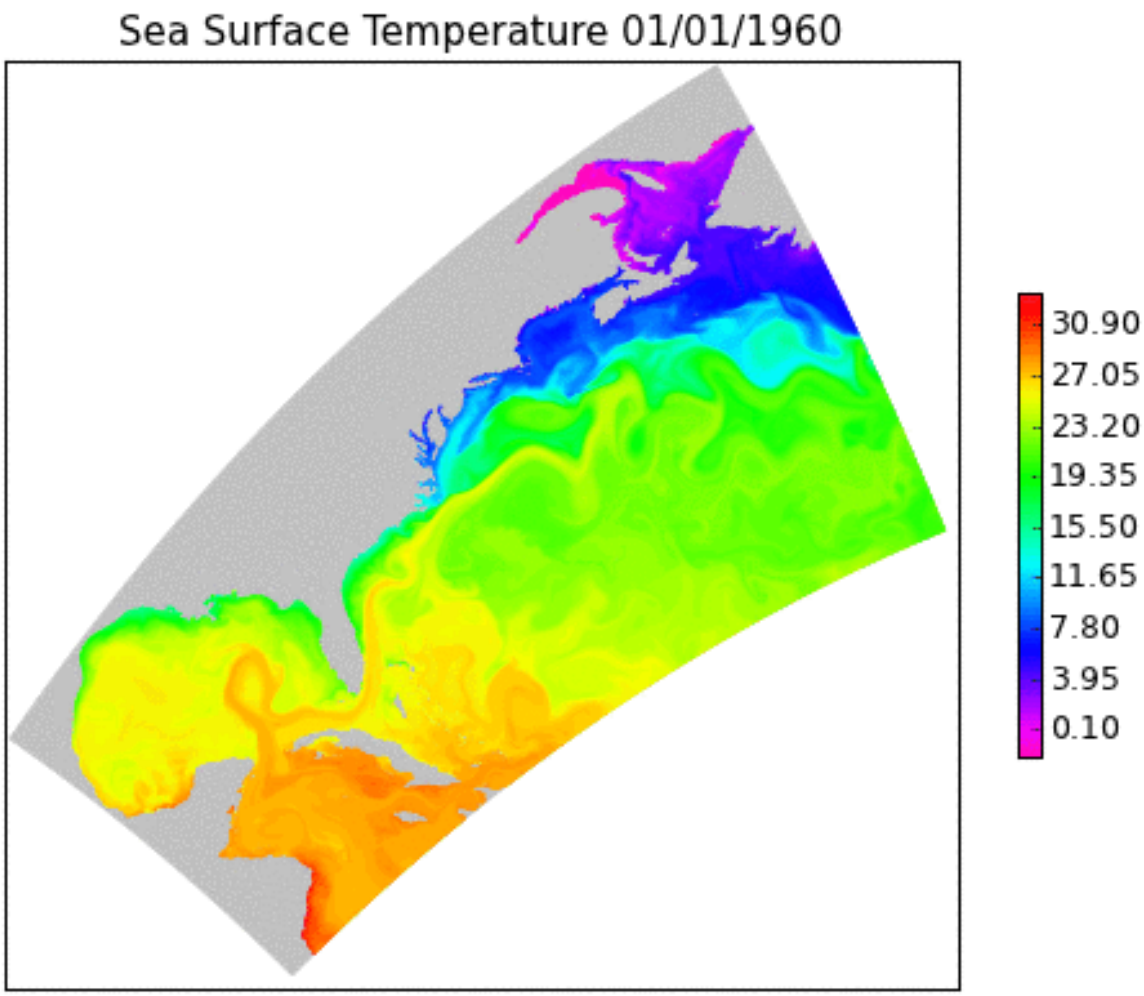


- **Grid**
  - horizontal: ~7 km
  - vertical: 40 s-levels

- **Forcing**
  - BC, IC: SODA 2.0.1 or HYCOMM
  - Surface : CORE-II or MERRA
  - Runoff: Dai & Trenberth
  - Tides: TPXO

- **Simulations**
  - 50-year hindcast (1958 – 2007)
  - 2011 for DART-ROMS (for now)

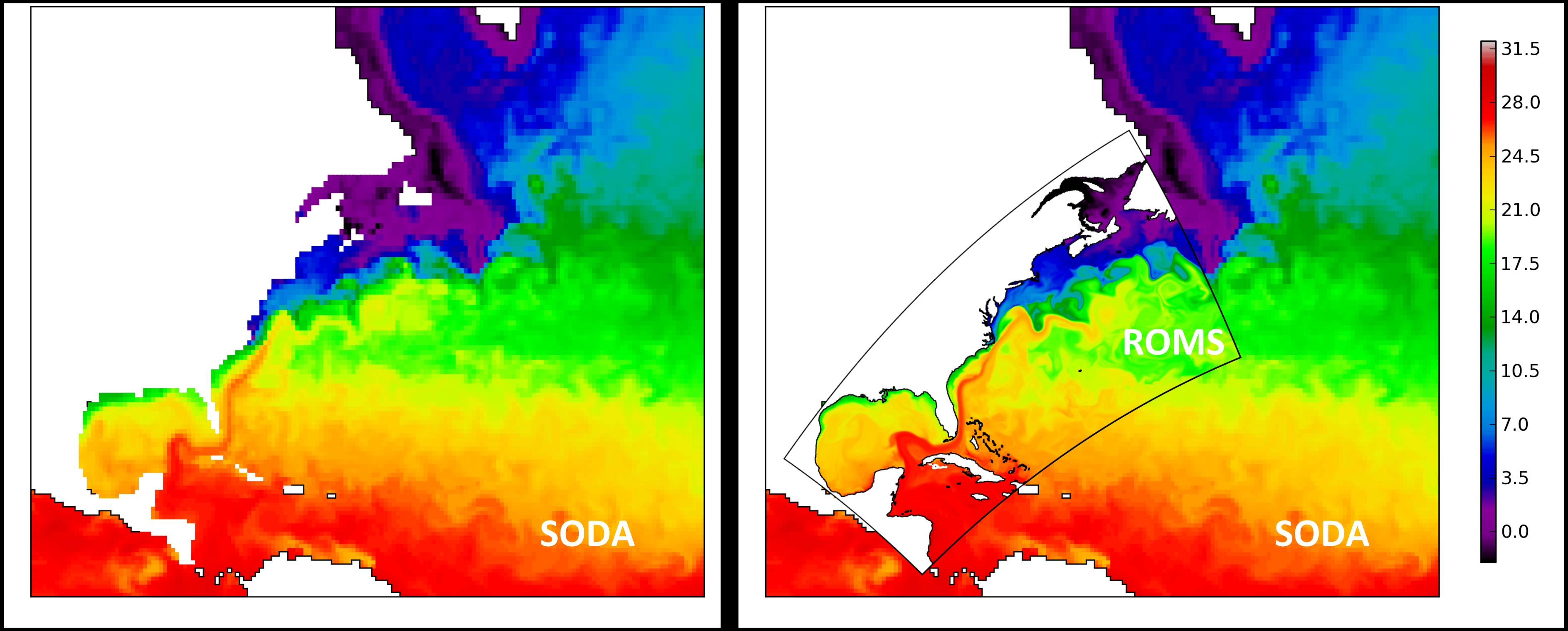
ROMS: Simulated SST



Kang and Curchitser (2013, 2015)

Regional Models: Boundary Conditions

- 5-Day Mean Sea Surface Temperature

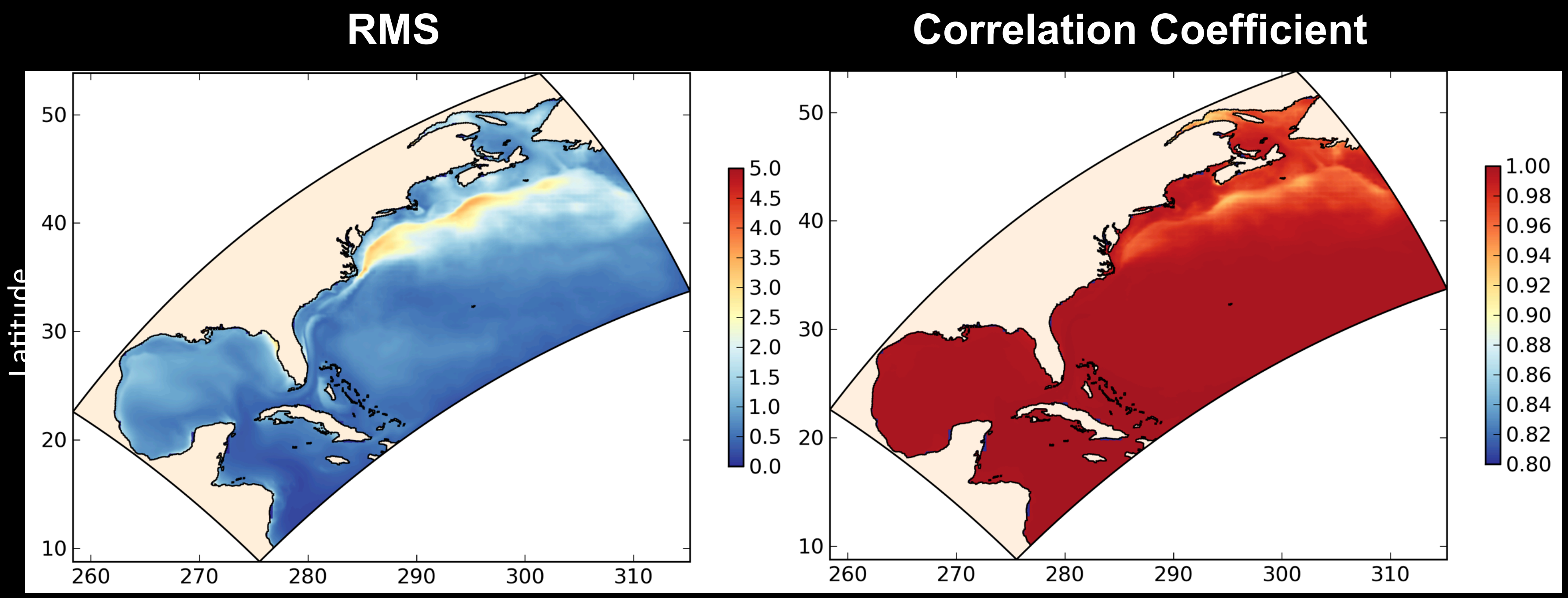


SODA: 0.5 degree

ROMS: 7 km

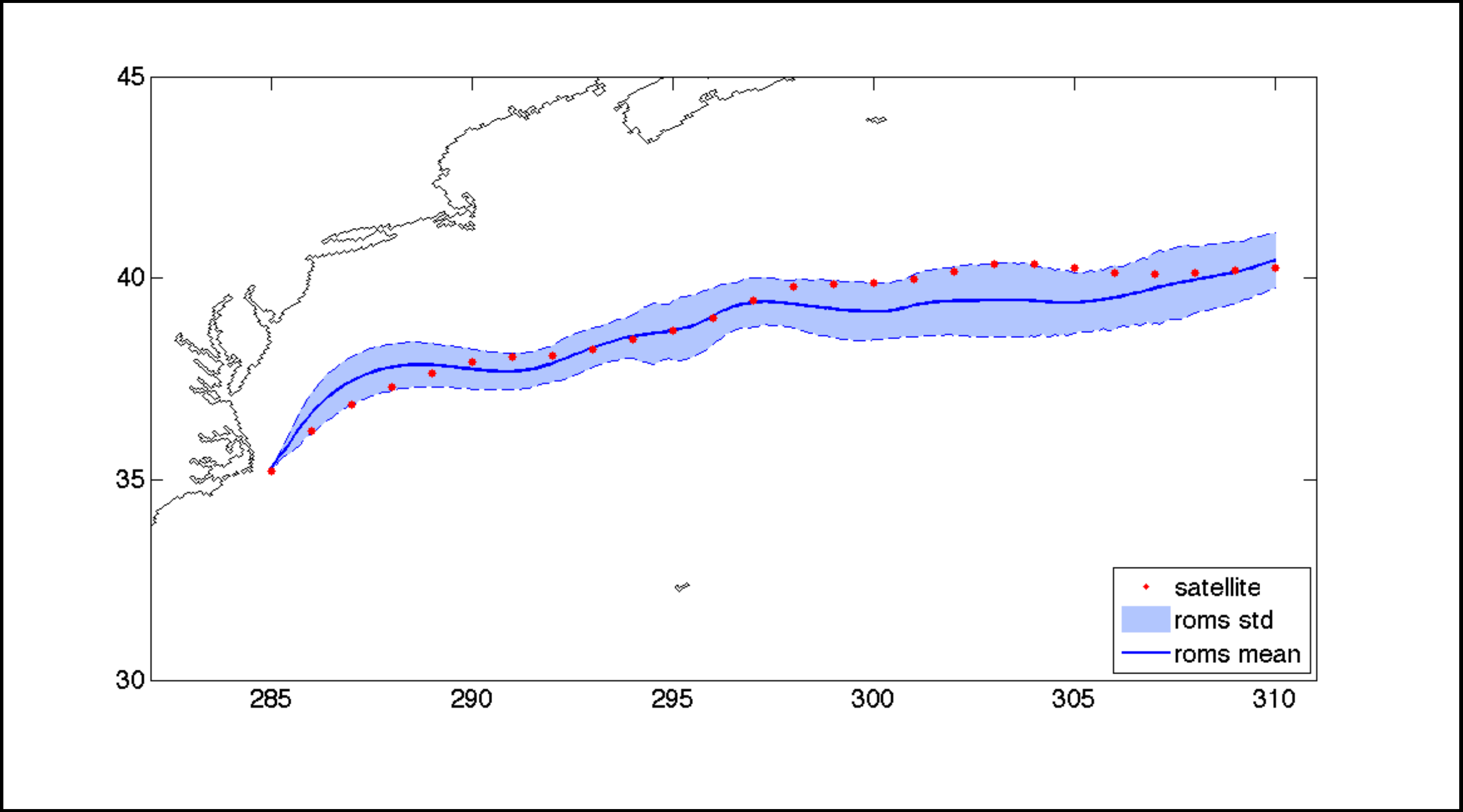
Model Evaluation

- Compare SST between ROMS and SODA for 1958–2007



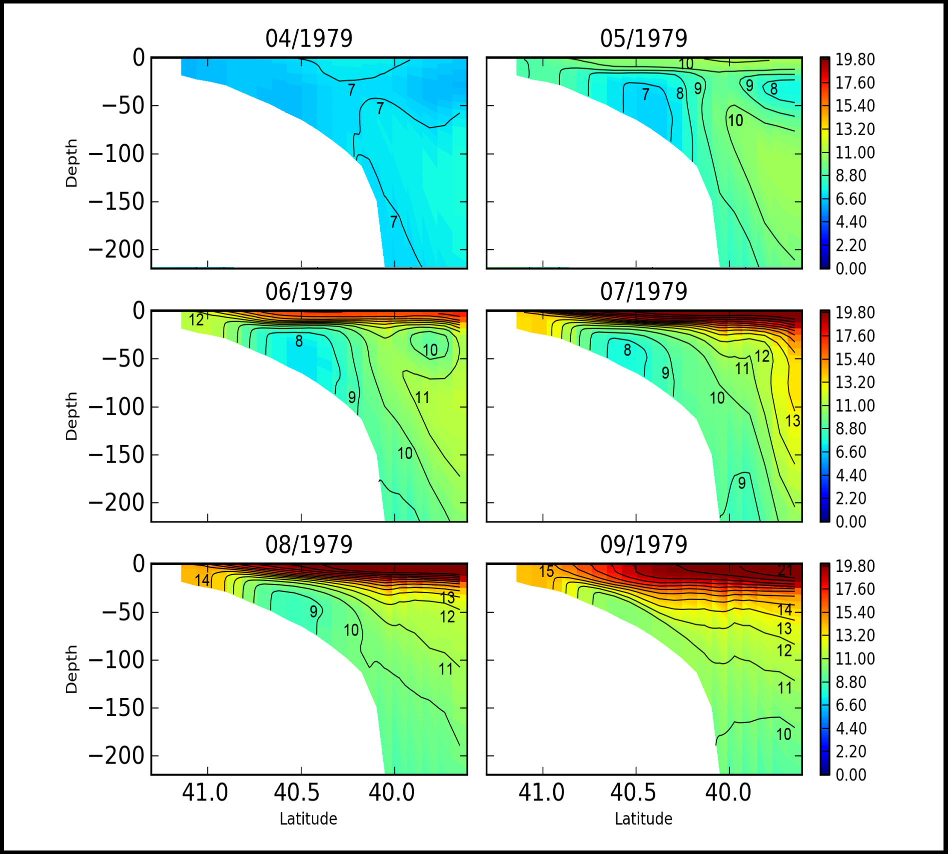
Model Evaluation

- **Compare Gulf Stream path with satellite observation**



Model Evaluation

- **Comparison with Houghton et al. (1982) Fig 2**



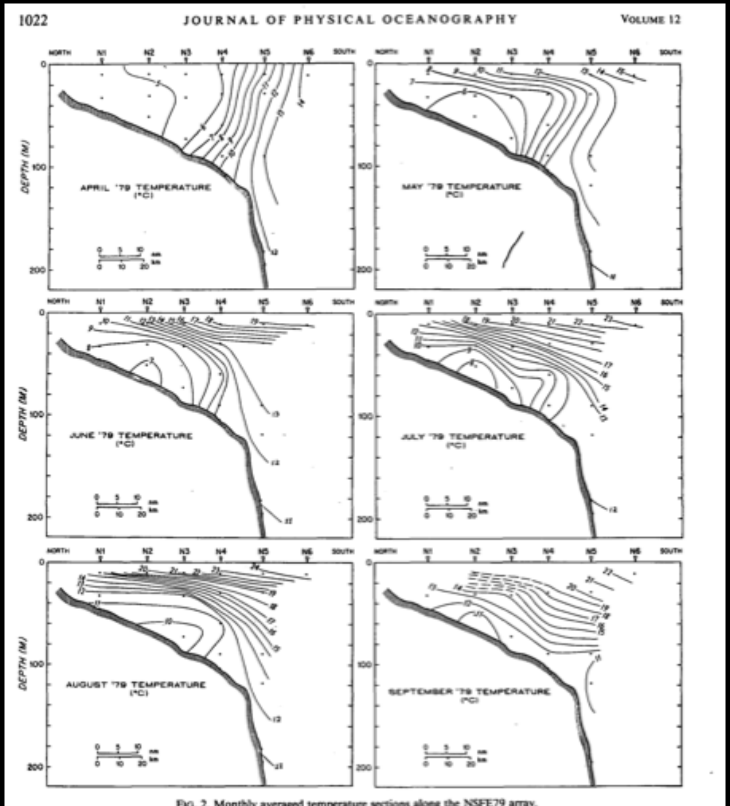
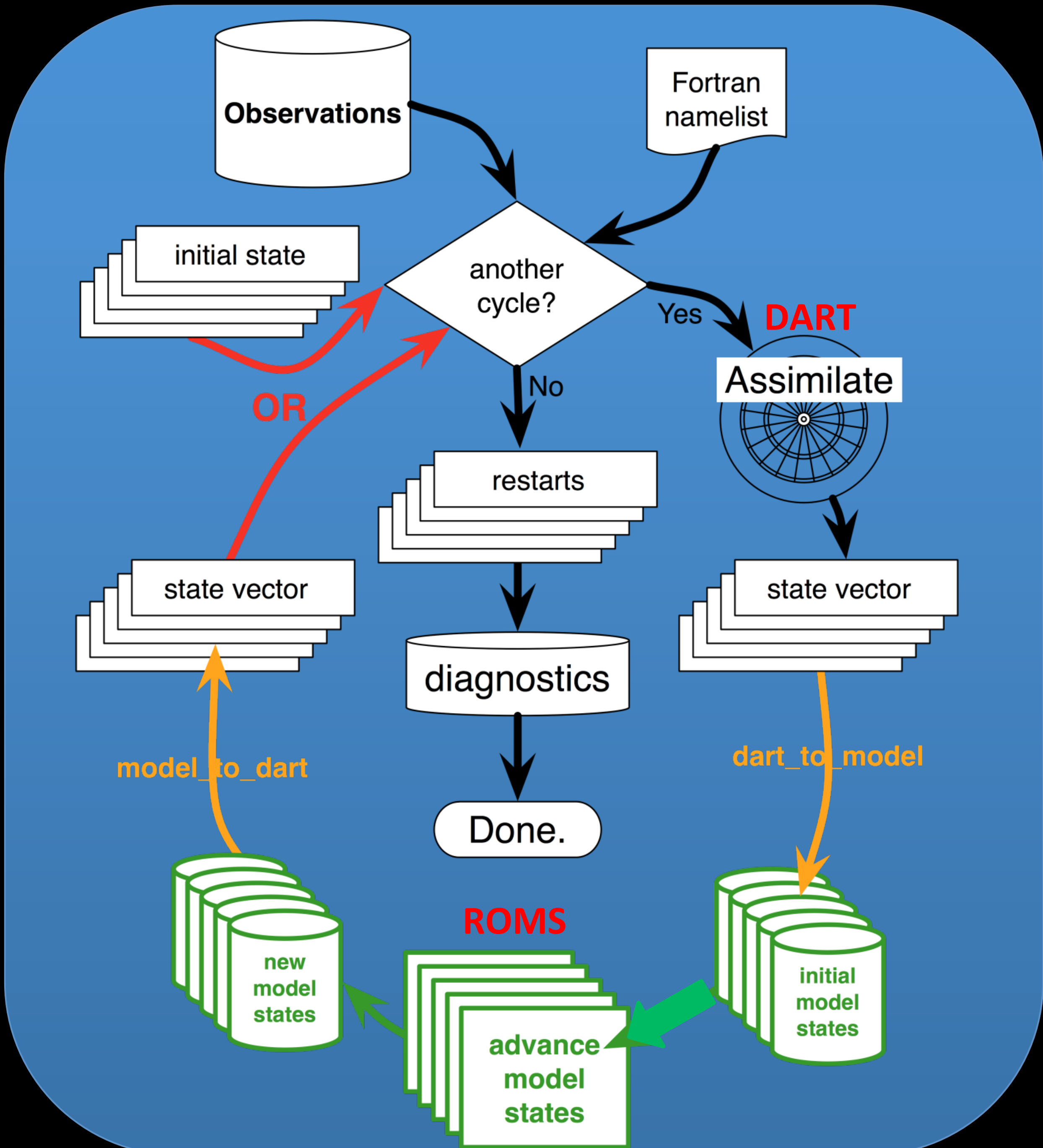


FIG. 2. Monthly averaged temperature sections along the NSFE79 array.

Ensemble data assimilation with DART-ROMS

Example: 5 members



Ensemble data assimilation with DART-ROMS

A. ROMS/DART Coupling:

- models communicate via: roms_to_dart.f90, dart_to_roms.f90
- compile and link DART routines

B. ROMS:

- 30 initial states (30 ensemble members)
- daily boundary data from global HYCOM
- atmospheric forcing: MERRA 3 hourly data with perturbations

C. Observations for 2011:

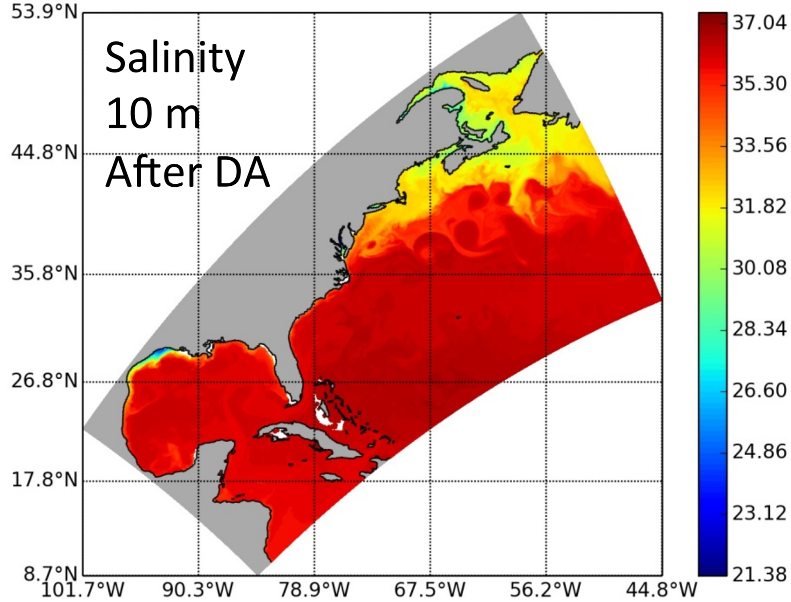
- daily SST from NOAA OI SST
- Temperature and Salinity profiles
  from GTSPP (Argo floats, CTD, XBT, mooring)

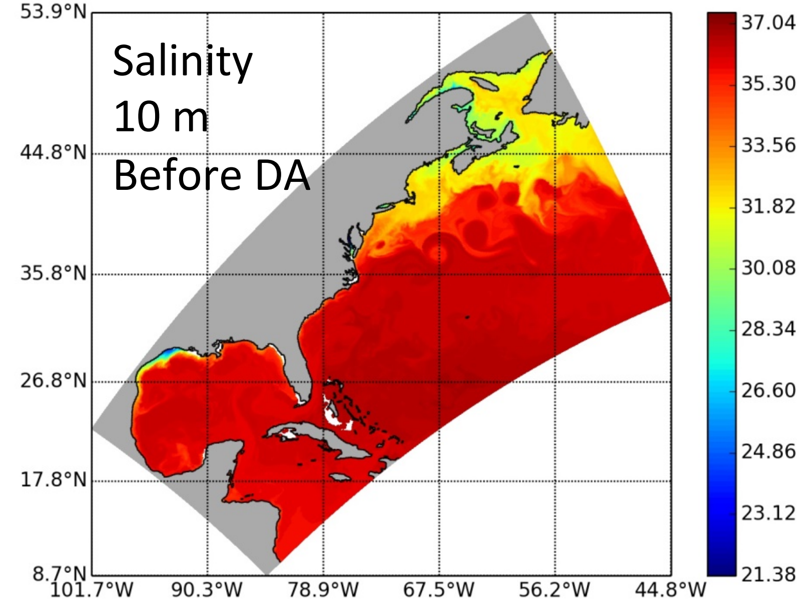
&assim_tools_nml
filter_kind = 2 ensemble Kalman filter
cutoff = 0.02 (half-width) radian, 1 radian=6366km
= 127 km in horizontal
= 200 m in vertical
&cov_cutoff_nml
select_localization = 1 Gaspari-Cohn function

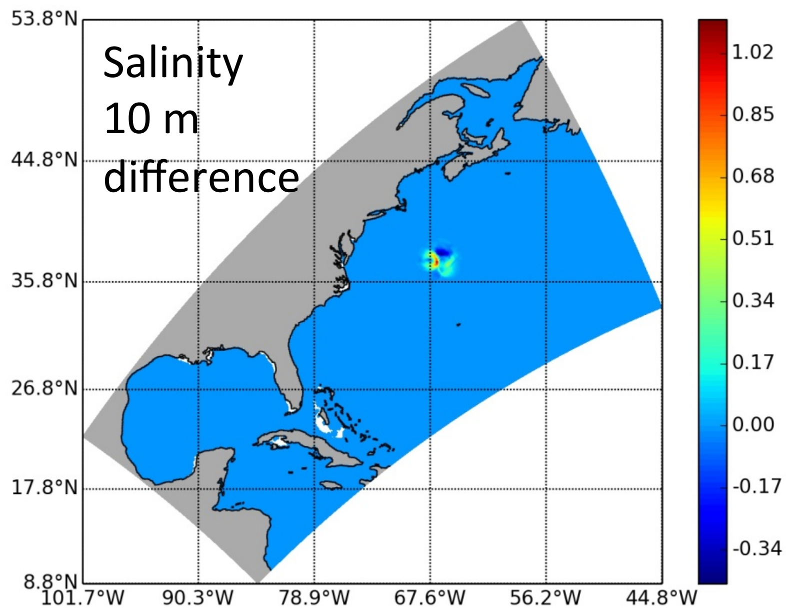
&location_nml
vert_normalization_height = 10000.0,

&model_nml
NX = 722, !xi grid size at rho points
NY = 362, !eta grid size at rho points
NZ = 40,
hc = 250.0,
vert_localization_coord = 3 !3= height (in meters)

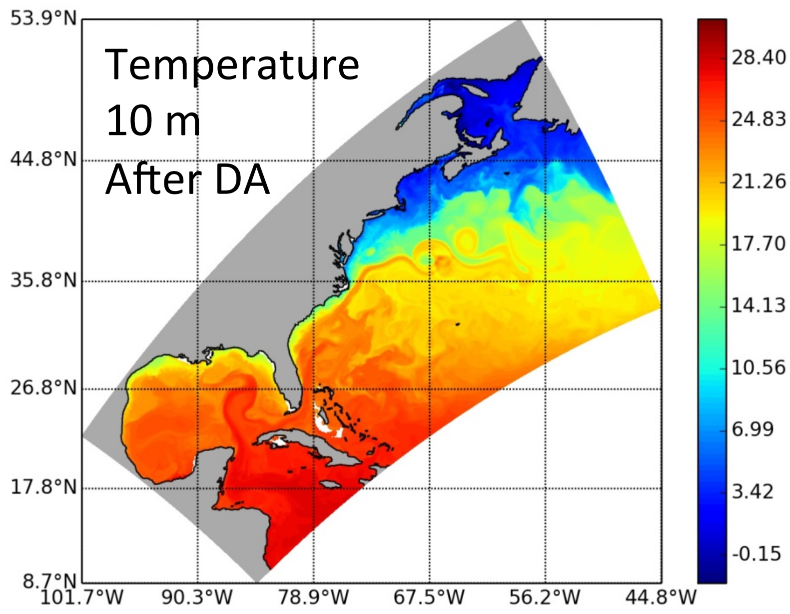
```
&filter_nml
ens_size                    = 30
inf_flavor                  = 2        time and space adaptive inflation
inf_initial                 = 1.01
inf_sd_initial              = 0.6
inf_damping                 = 0.9
inf_lower_bound             = 1.00
inf_upper_bound             =  1.05
inf_sd_lower_bound = 0.6
```

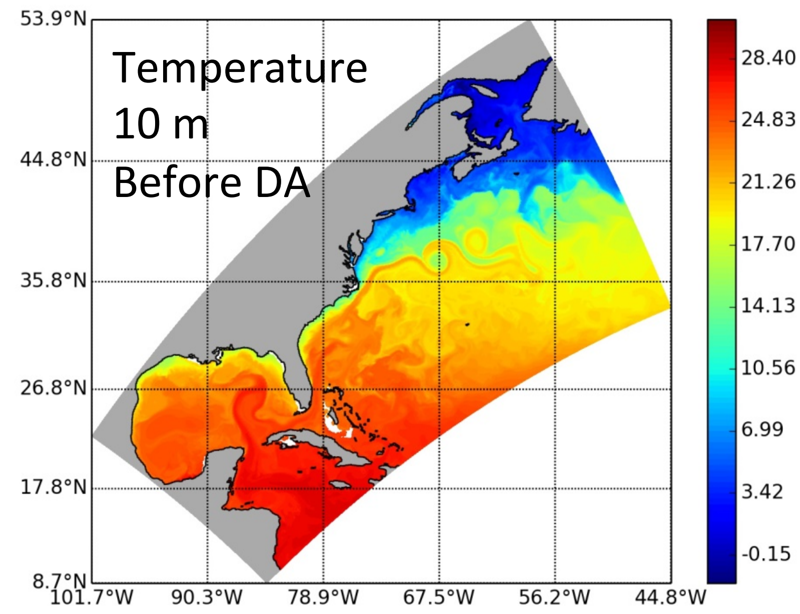


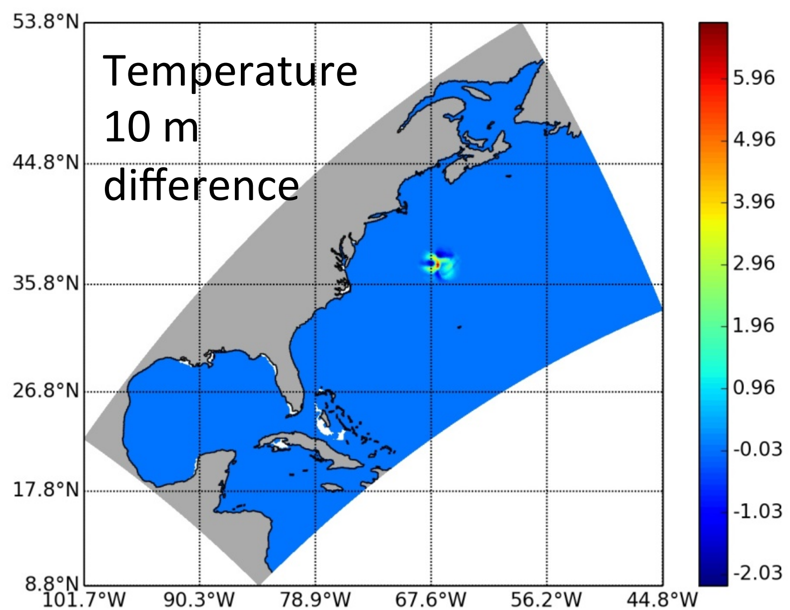




Effect of assimilating a single salinity data point at 5 m depth on salinity

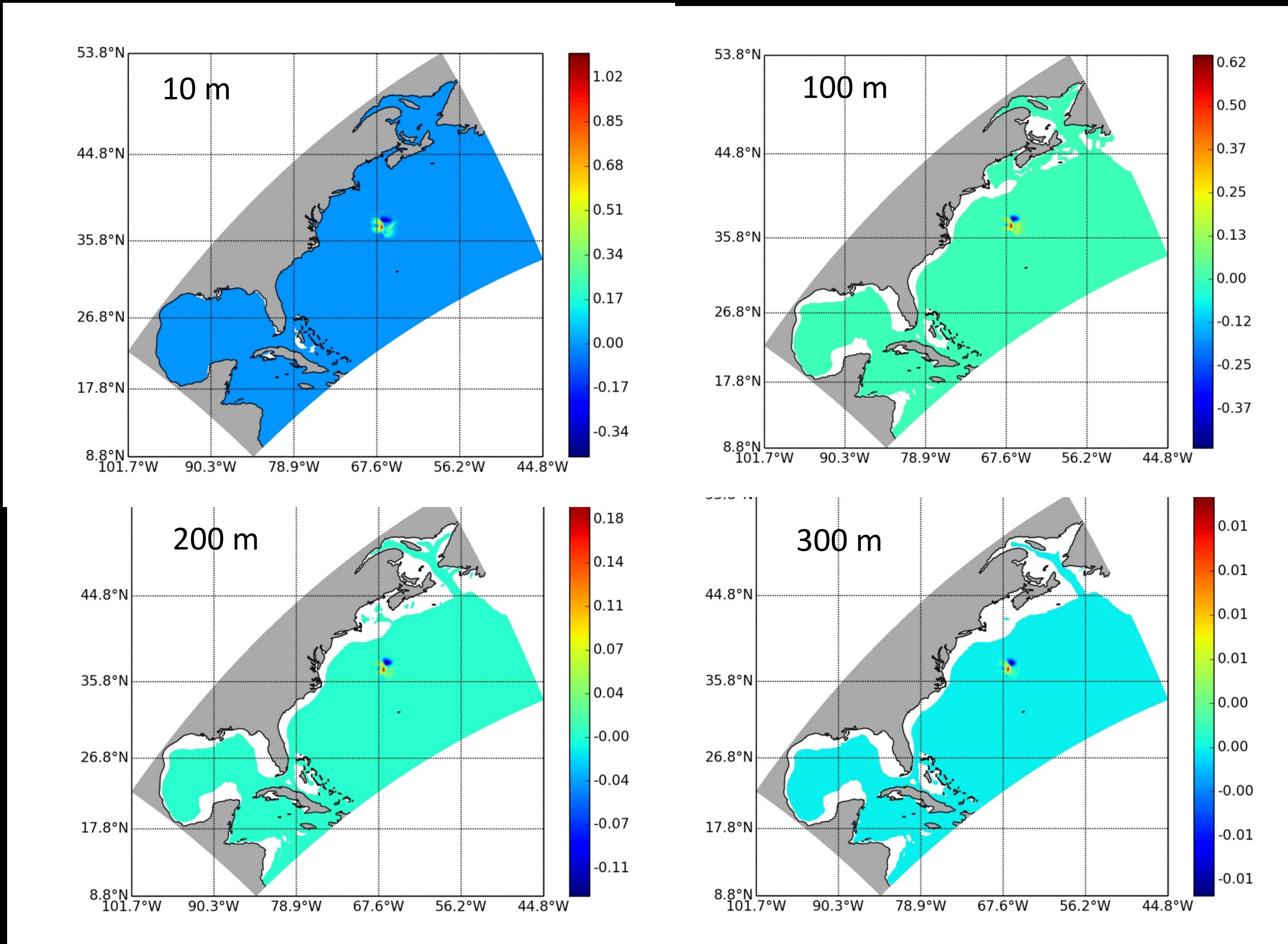




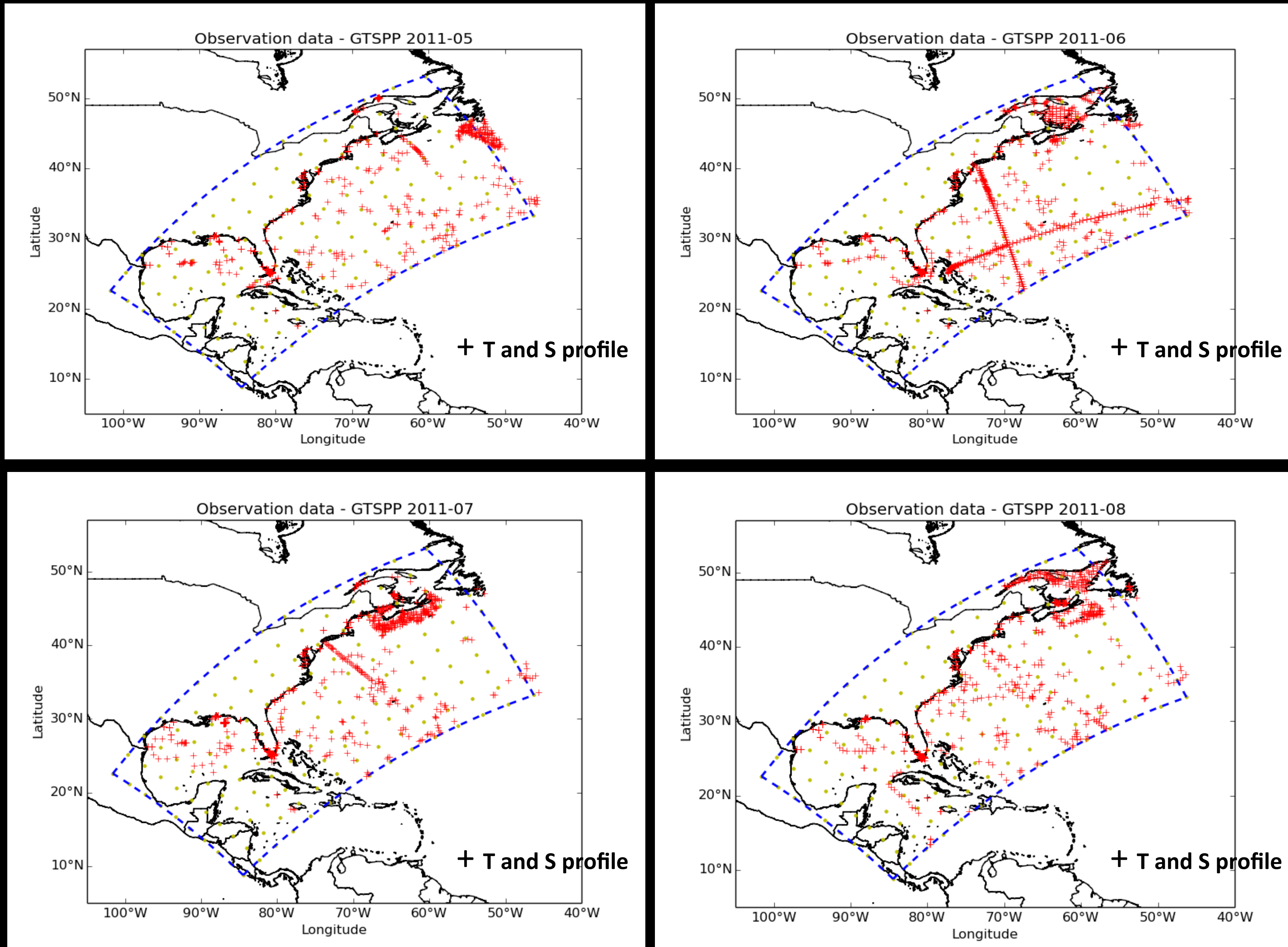


Effect on temperature

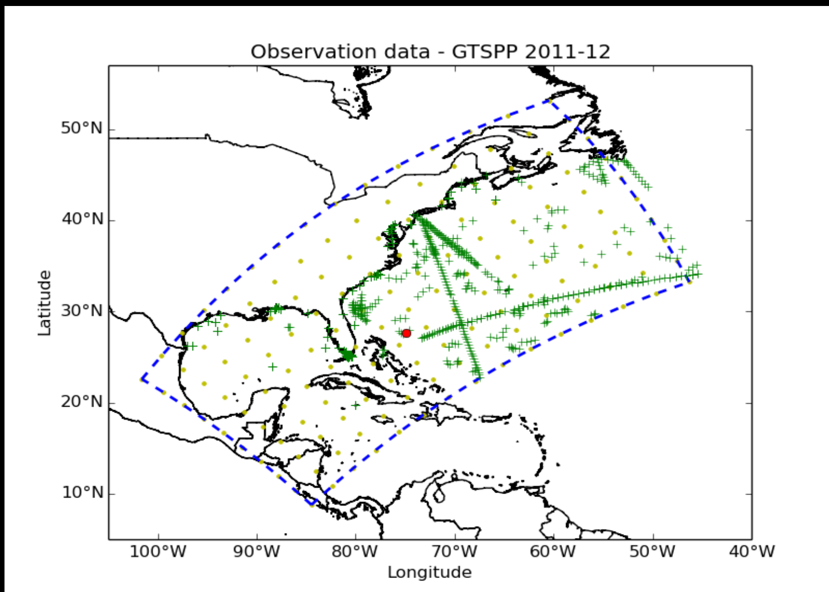
Adjustment with depth

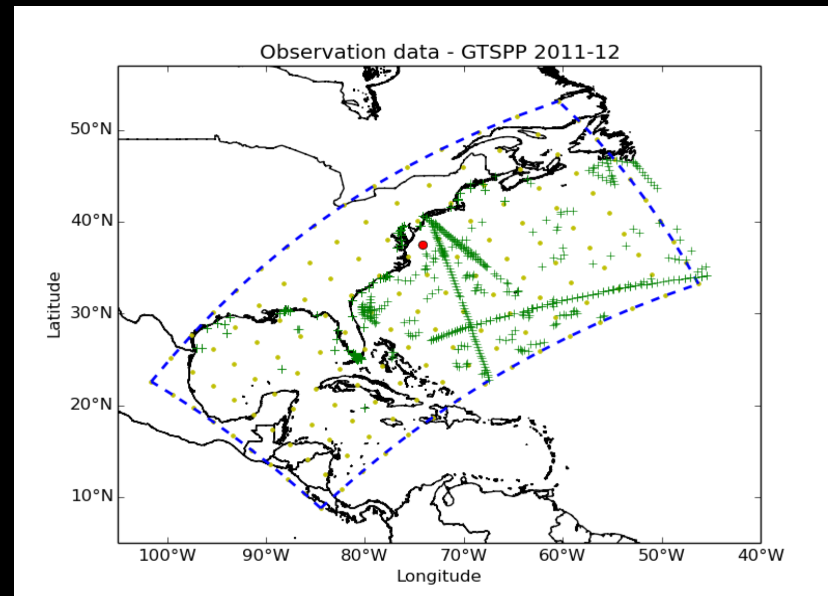


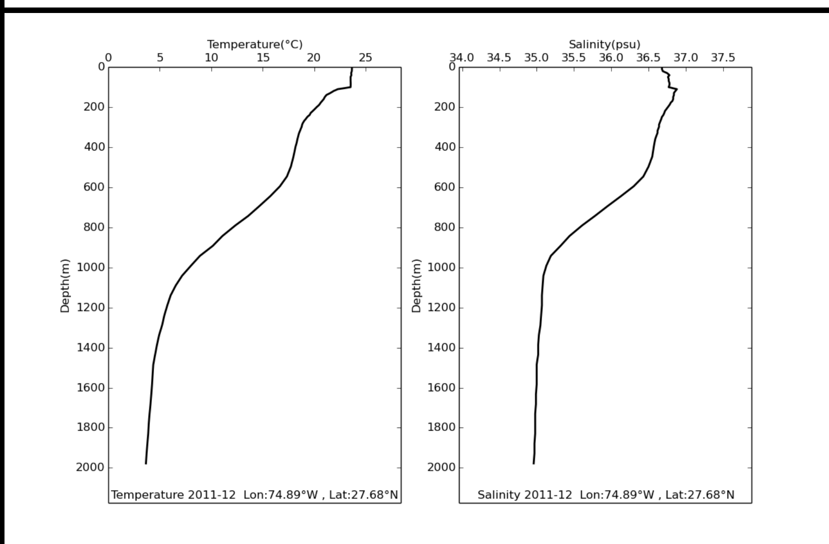
GTSPP Profiles

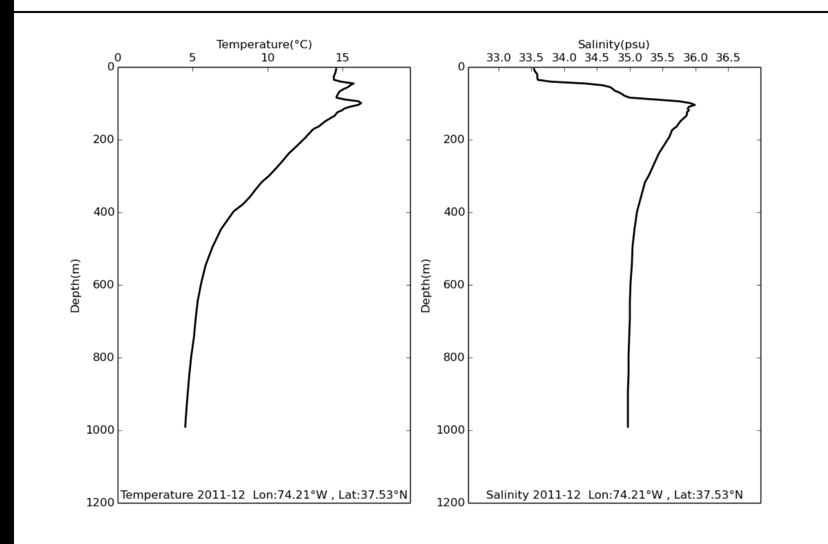


Sample GTSPP Profiles









Chronology of a simulation

30 different initial condition
@ Jan 1, 2011

run ROMS for 1 day
with pert. atm. forcing

30 members
@ Jan 2

DART assimilate
SST, T, and S

run ROMS for 1 day
with pert. atm. forcing

30 members
@ Jan 3

DART assimilate
SST, T, and S

run ROMS for 1 day
with pert. atm. forcing

30 members
@ Jan 4

DART assimilate
SST, T, and S

. . . .

run ROMS for 1 day
with pert. atm. forcing

30 members
@ Dec 29

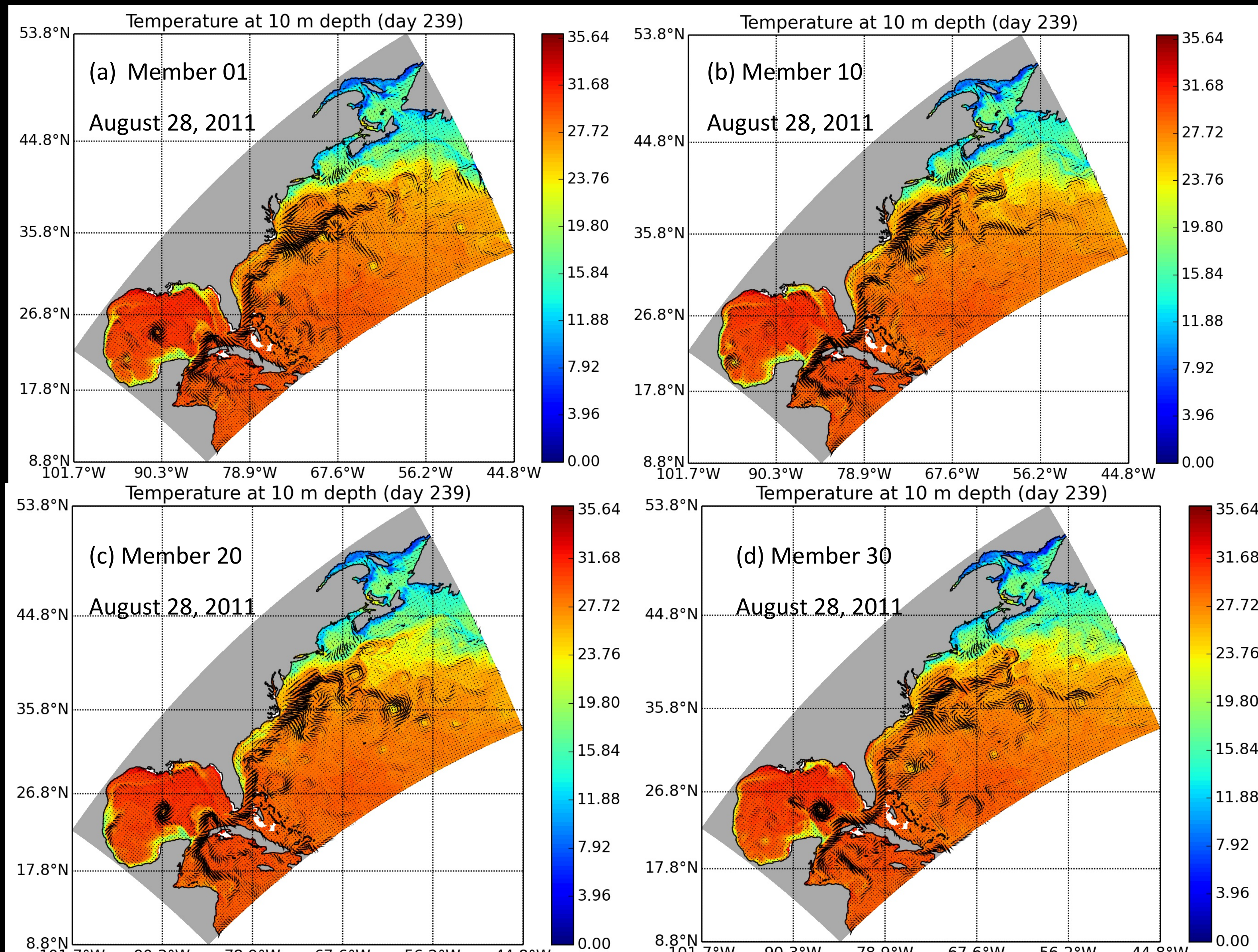
DART assimilate
SST, T, and S

run ROMS for 1 day
with pert. atm. forcing

30 members
@ Dec 30

DART assimilate
SST, T, and S

It runs, but...



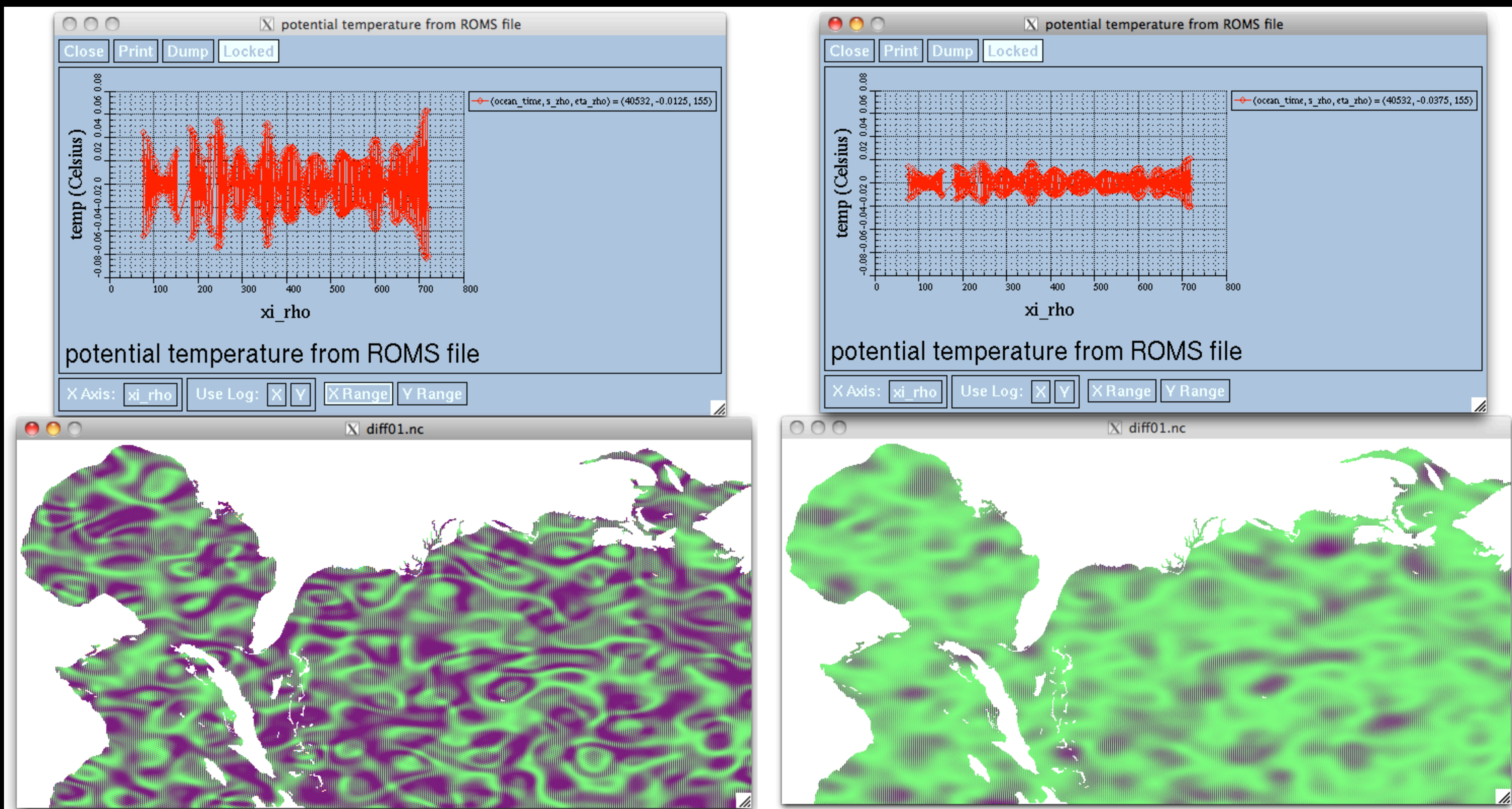
Temperature at 10 m depth (day 239)
(a) Member 01
August 28, 2011
Temperature at 10 m depth (day 239)
(b) Member 10
August 28, 2011
Temperature at 10 m depth (day 239)
(c) Member 20
August 28, 2011
Temperature at 10 m depth (day 239)
(d) Member 30
August 28, 2011
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00

Iteration #2

- Perturbation of initial condition
- Perturbation of atmospheric forcing with random noise.
  - It will maintain the ensemble spread and have better background error statistics
- Assimilate SST data every grid point (25 km spacing)
  - previous assimilation was done with every 4th SST data grid point (100 km spacing)
- Assimilate SST and GTSPP profiles from January to December 2011
- Evaluation of the assimilated product against independent datasets.
  - Calculate ensemble spread, plot multivariate background error covariance

Perturbation of Initial condition

- Temperature fields in the upper 5 layers were perturbed by adding random fields with 100 km de-correlation length scale and the perturbation fields are vertically correlated.
- Each ensemble member will have slightly different initial condition.



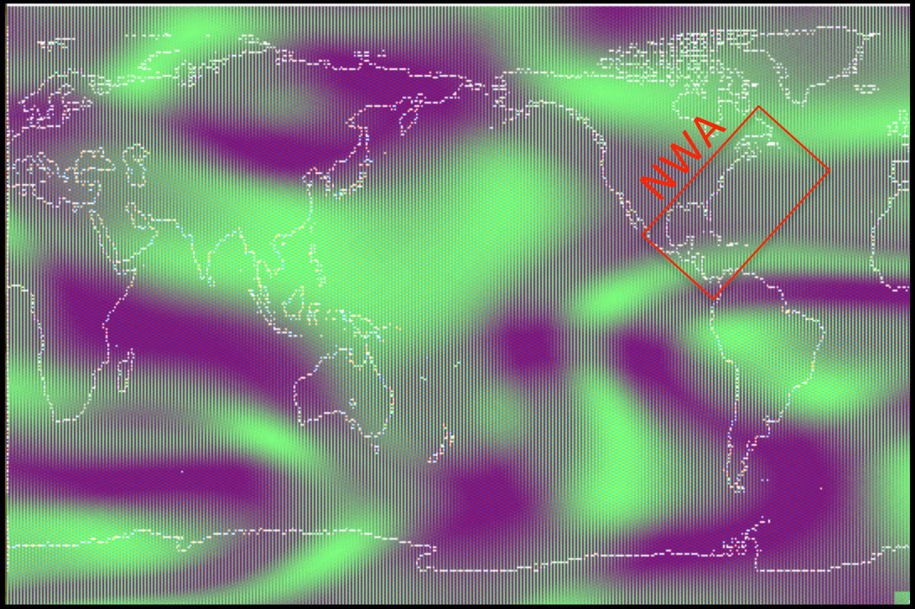
Perturbation of Atmospheric Forcing

- Atmospheric forcing fields are perturbed by adding random fields with 500 km de-correlation length scale and 5 days de-correlation time scale.

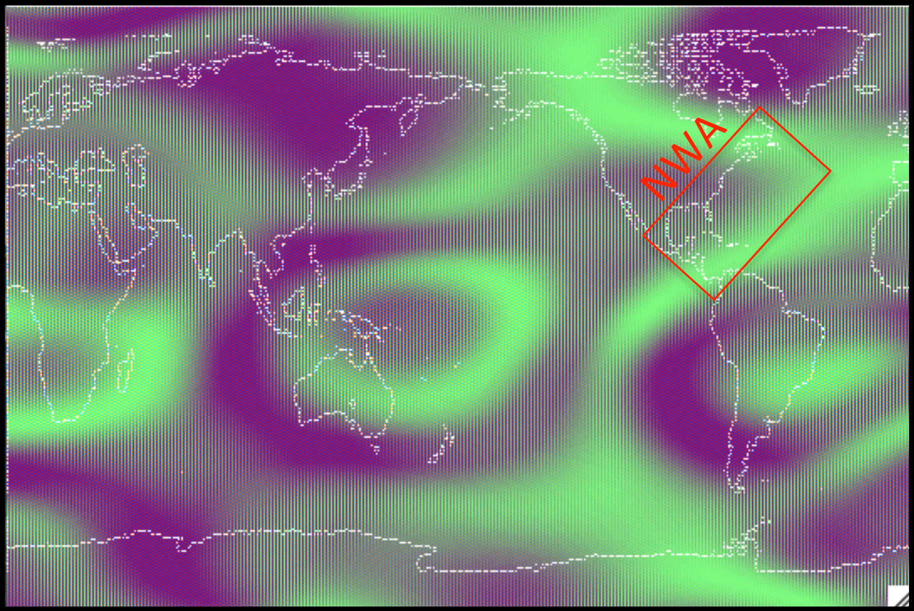
- We perturb U-wind, V-wind, air temperature, and short-wave radiation.

- Each ensemble member will have different atmospheric forcing.

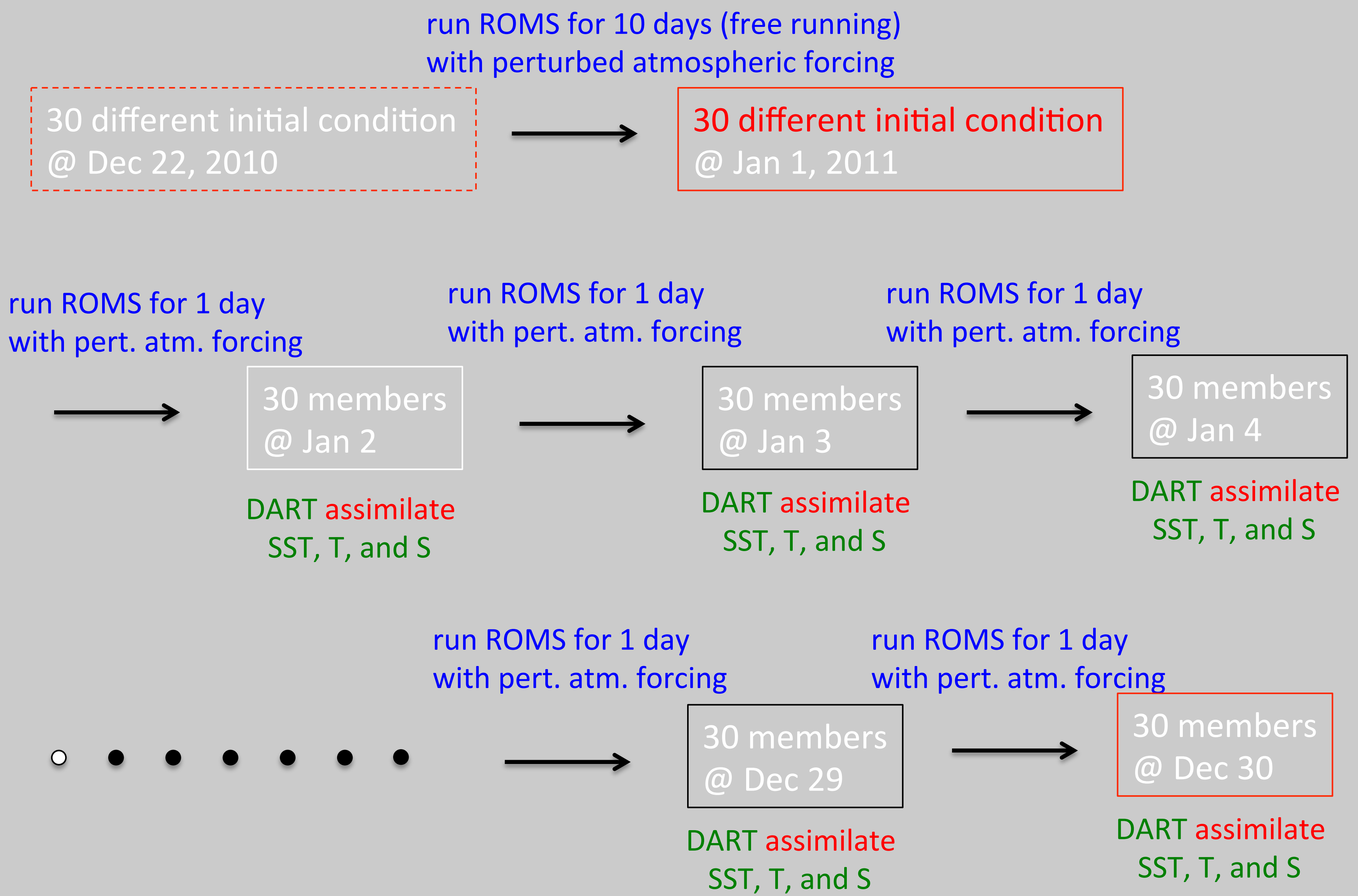
Example of random field (Uwind)



Example of random field (Tair)

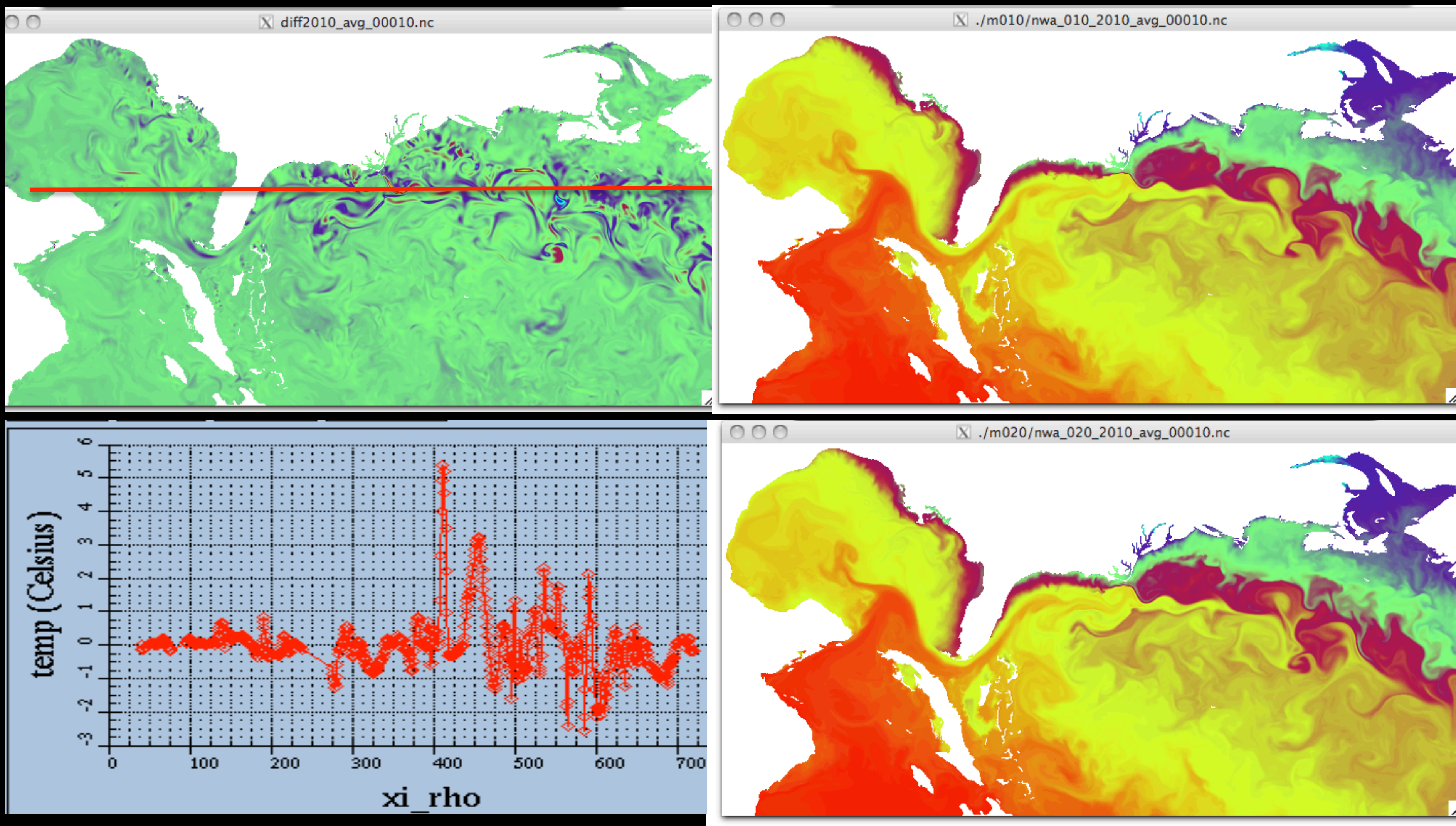


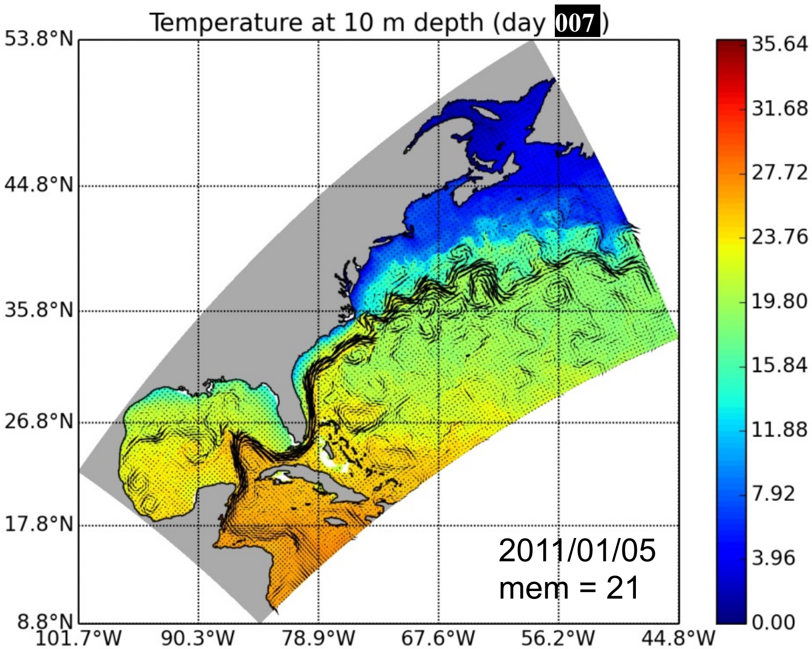
Chronology of a simulation

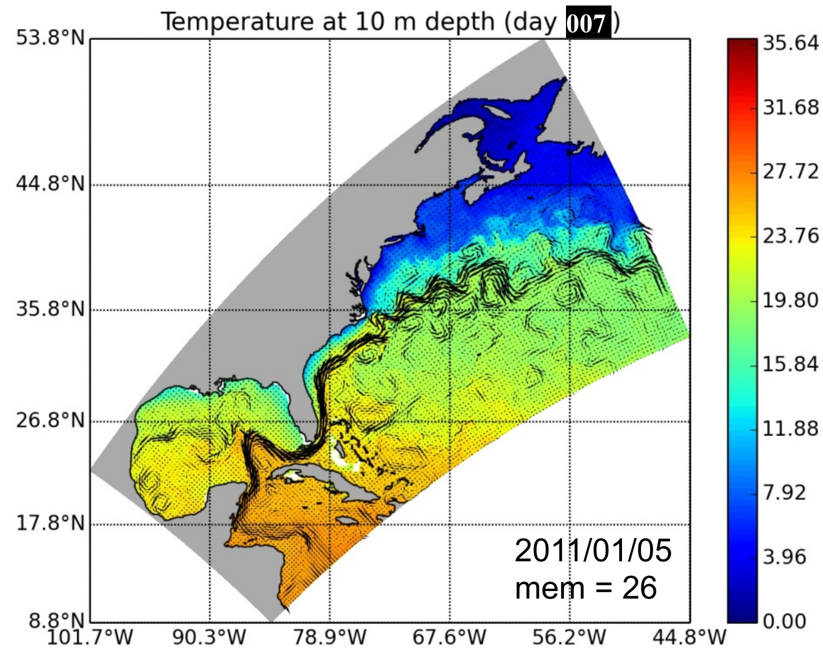


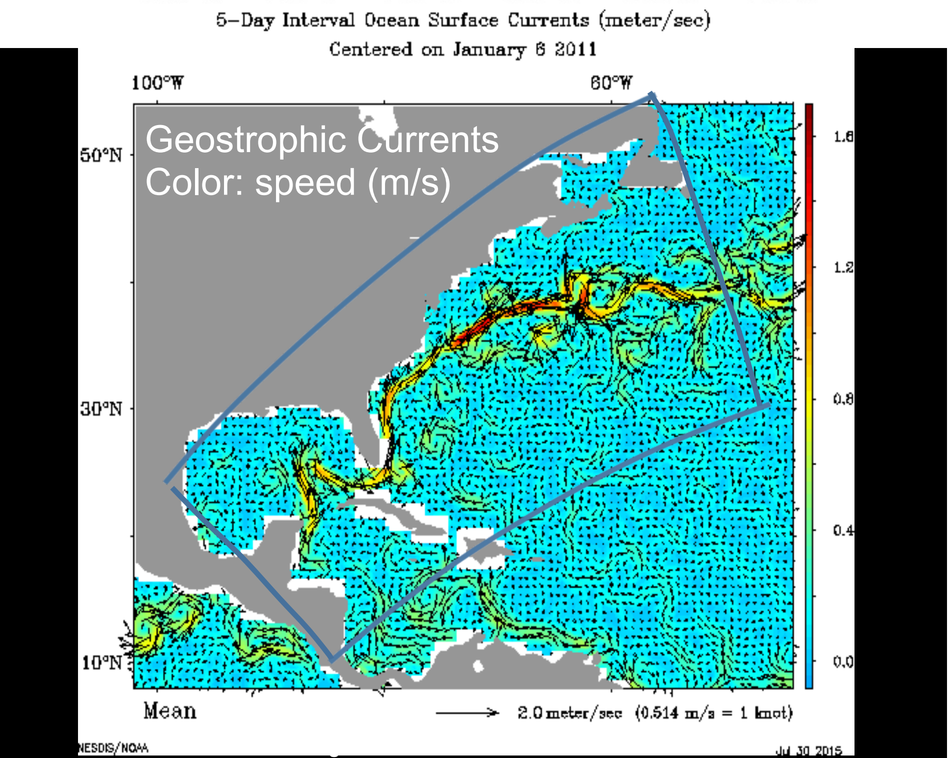
After 10 days of free running, we have initial condition for data assimilation.

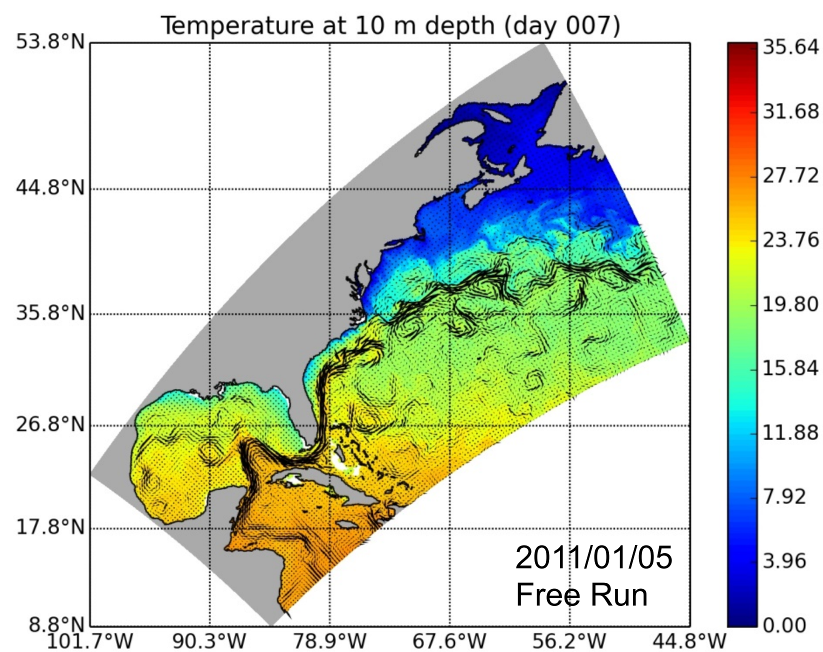
Sea Surface Temperature on January 1, 2011.

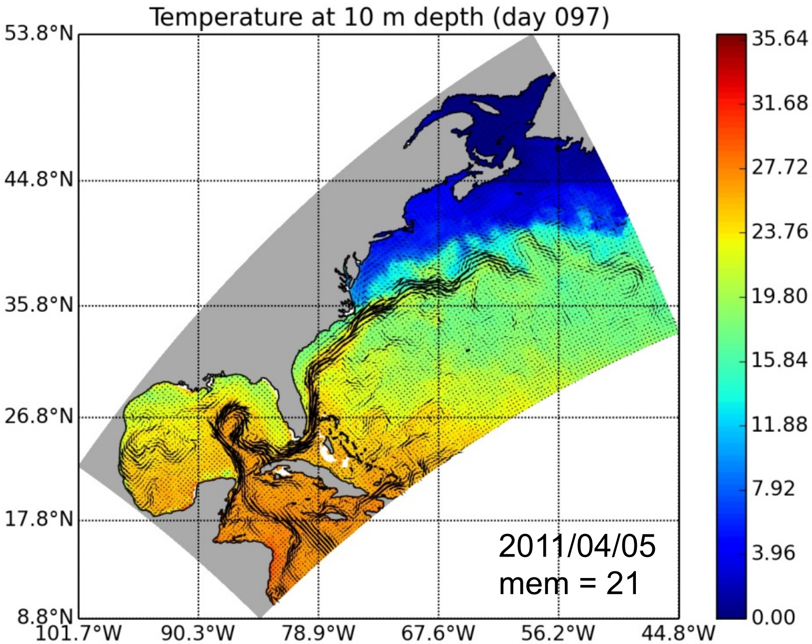


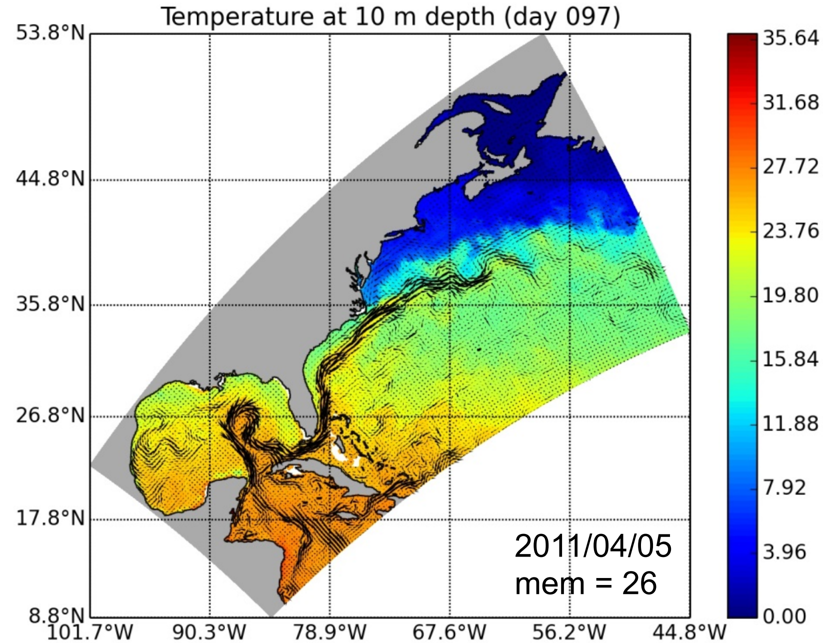

Temperature at 10 m depth (day 007)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/01/05
mem = 21

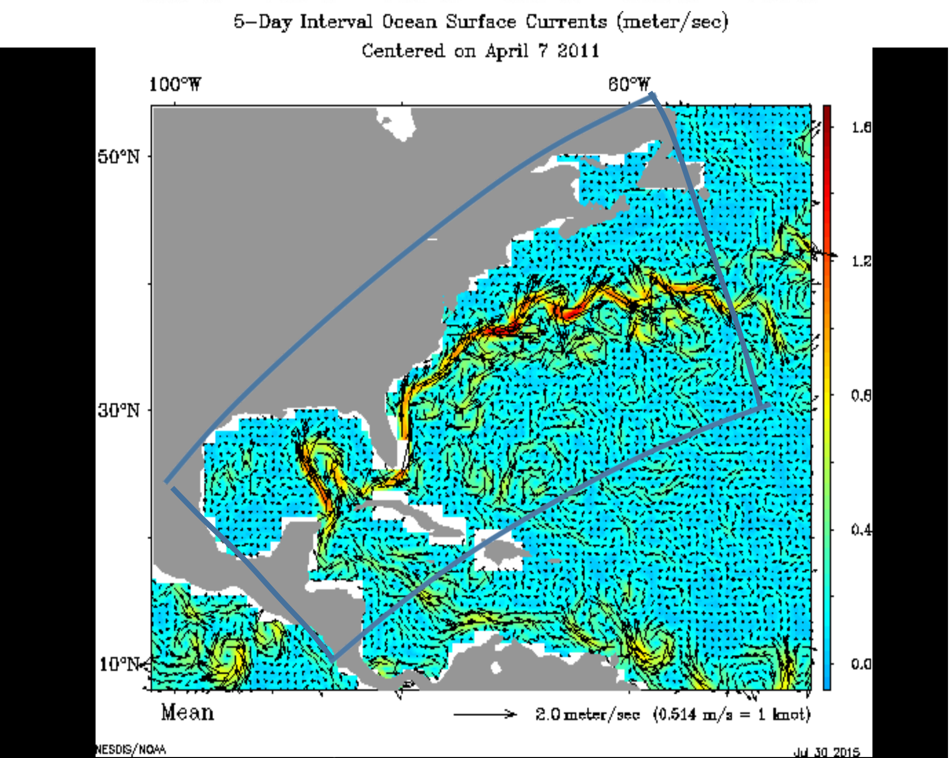

Temperature at 10 m depth (day 007)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/01/05
mem = 26

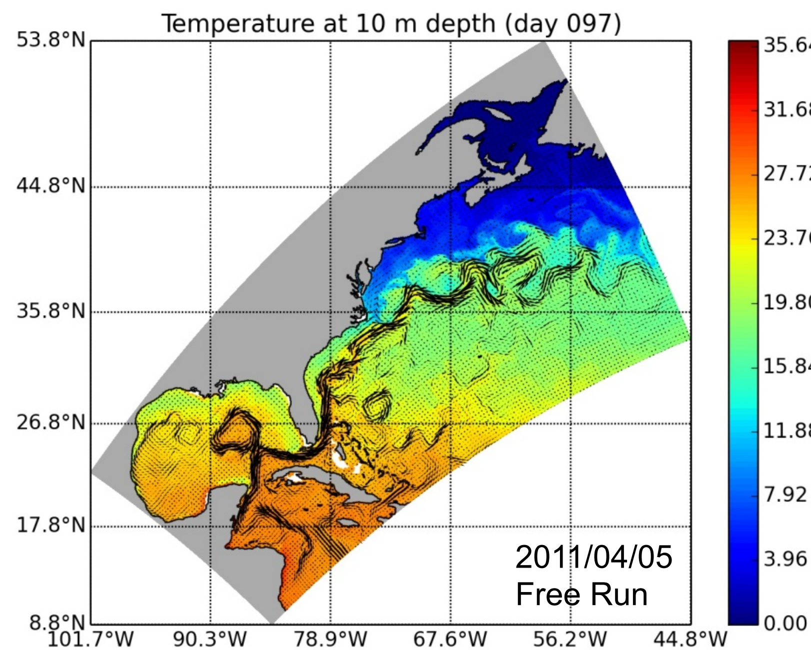

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on January 6 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Jul 30 2015

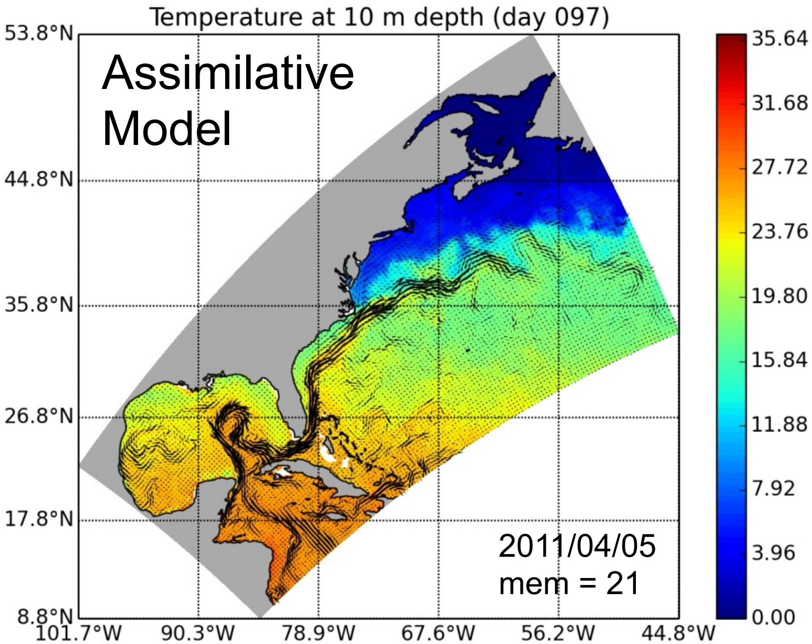

Temperature at 10 m depth (day 007)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/01/05
Free Run

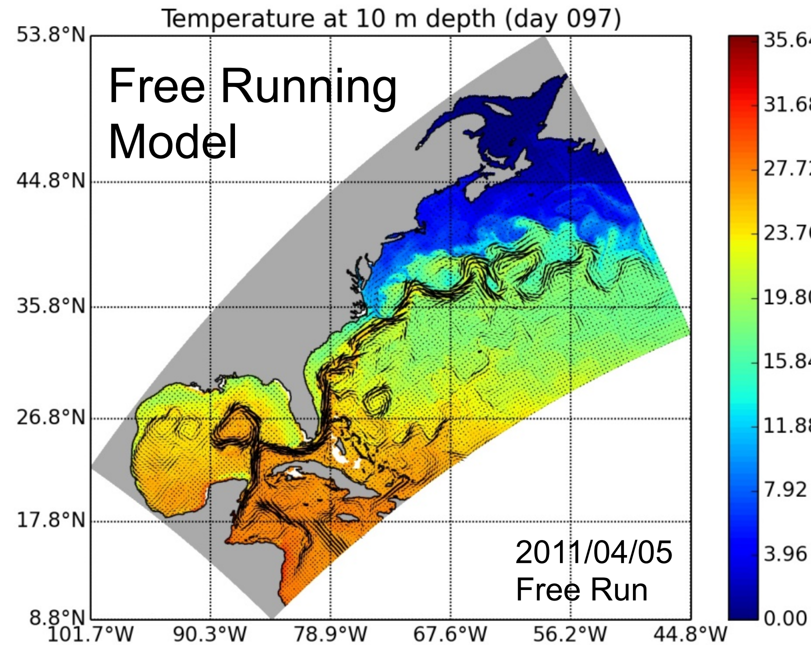

Temperature at 10 m depth (day 097)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/04/05
mem = 21

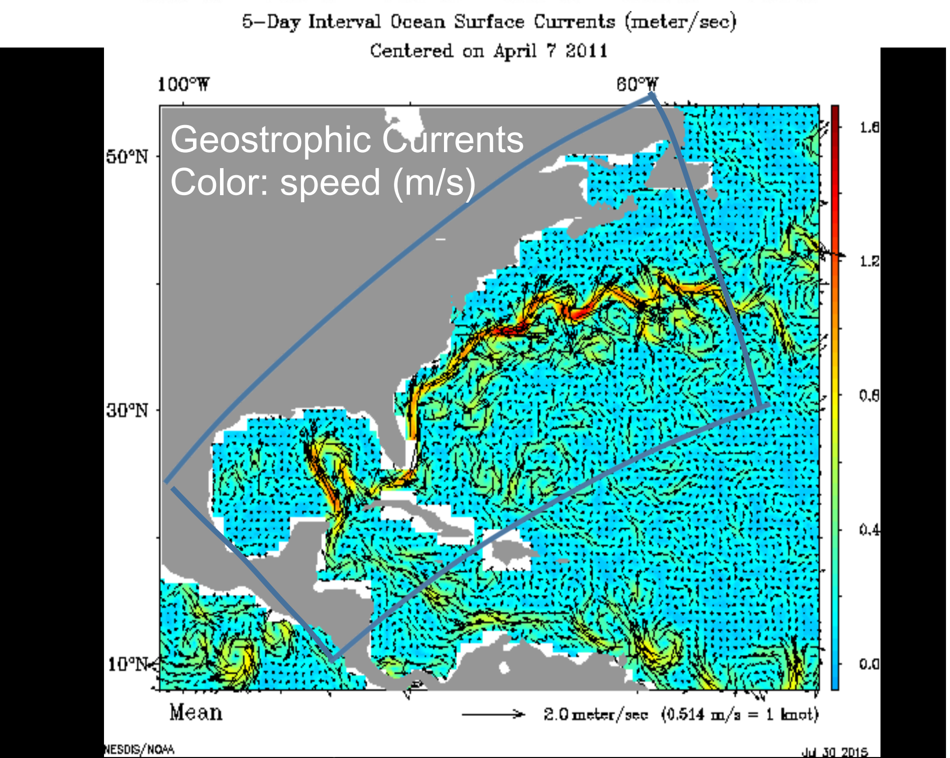

Temperature at 10 m depth (day 097)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/04/05
mem = 26


5–Day Interval Ocean Surface Currents (meter/sec)
Centered on April 7 2011
100°W
60°W
50°N
30°N
10°N
1.6
1.2
0.8
0.4
0.0
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Jul 30 2015


Temperature at 10 m depth (day 097)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/04/05
Free Run


Temperature at 10 m depth (day 097)
Assimilative Model
2011/04/05
mem = 21
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00


Temperature at 10 m depth (day 097)
Free Running Model
2011/04/05
Free Run
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00


5-Day Interval Ocean Surface Currents (meter/sec)
Centered on April 7 2011
Geostrophic Currents
Color: speed (m/s)
100°W
60°W
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30°N
10°N
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
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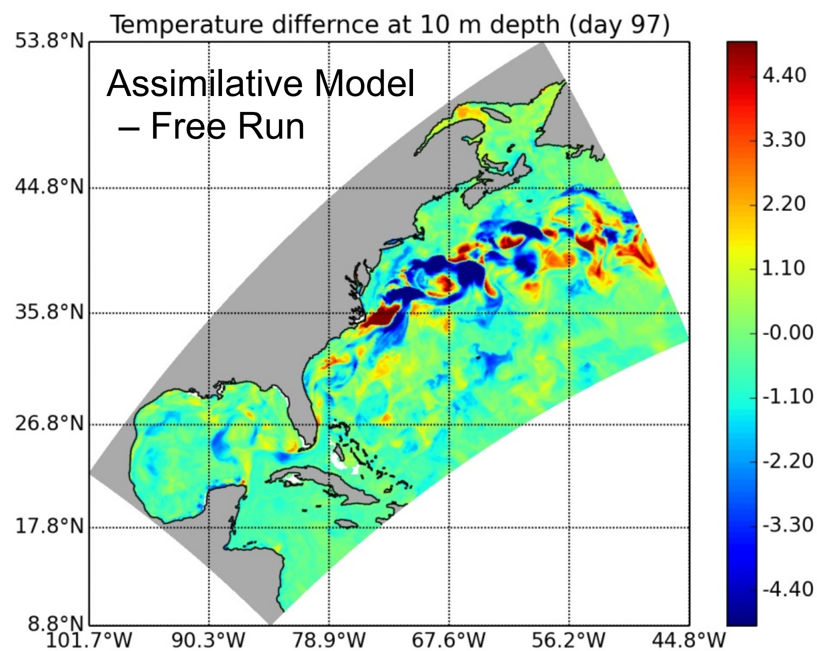
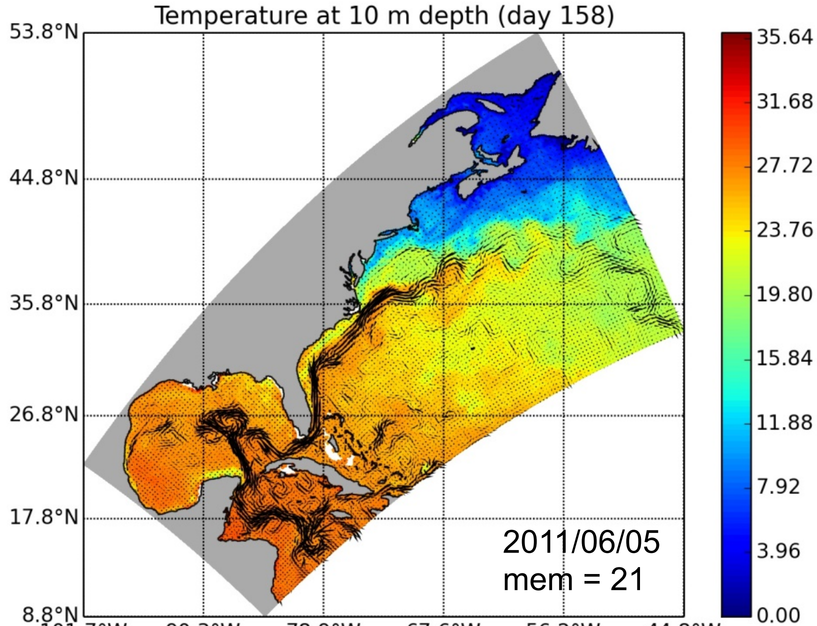
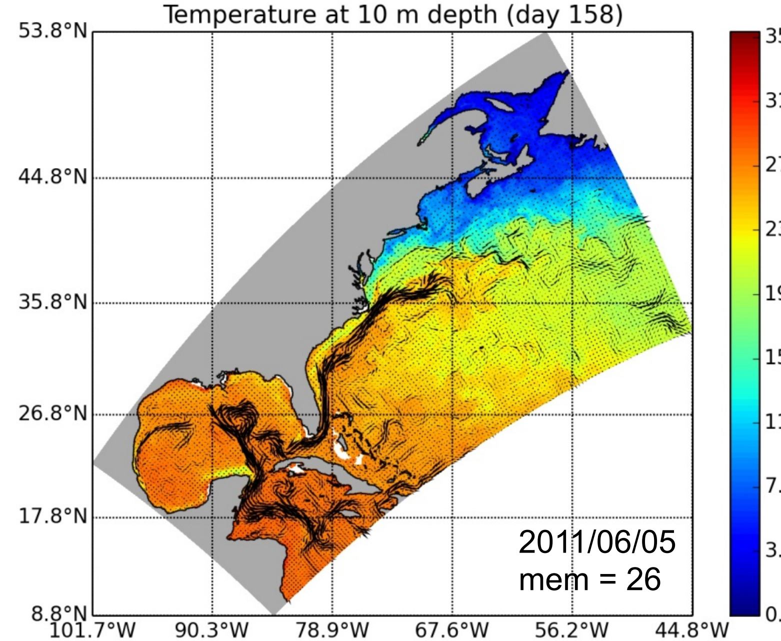
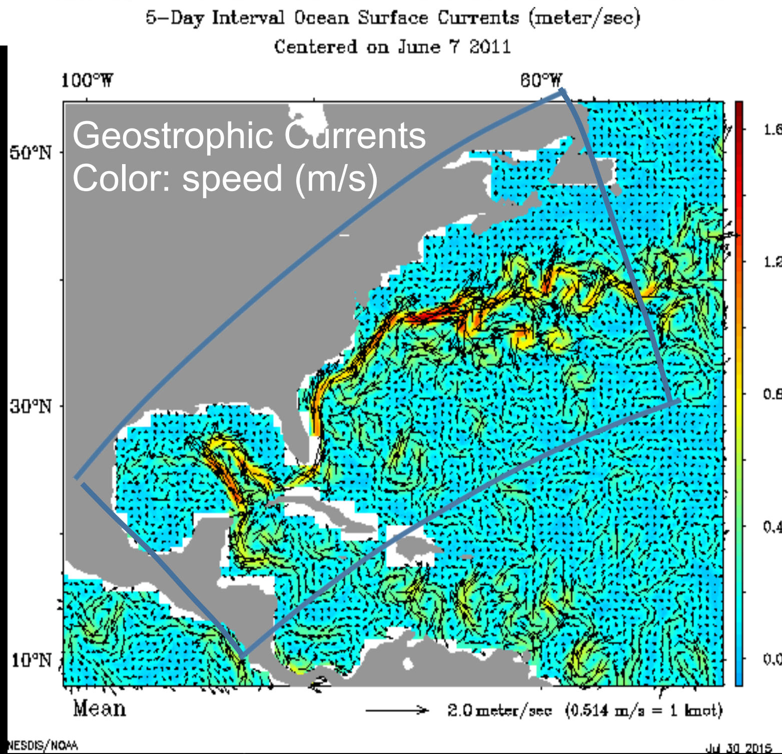
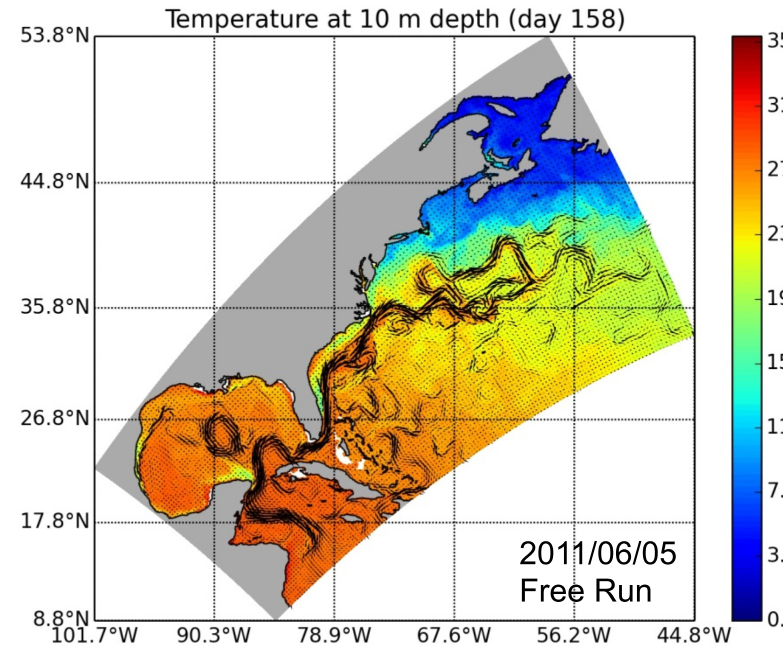
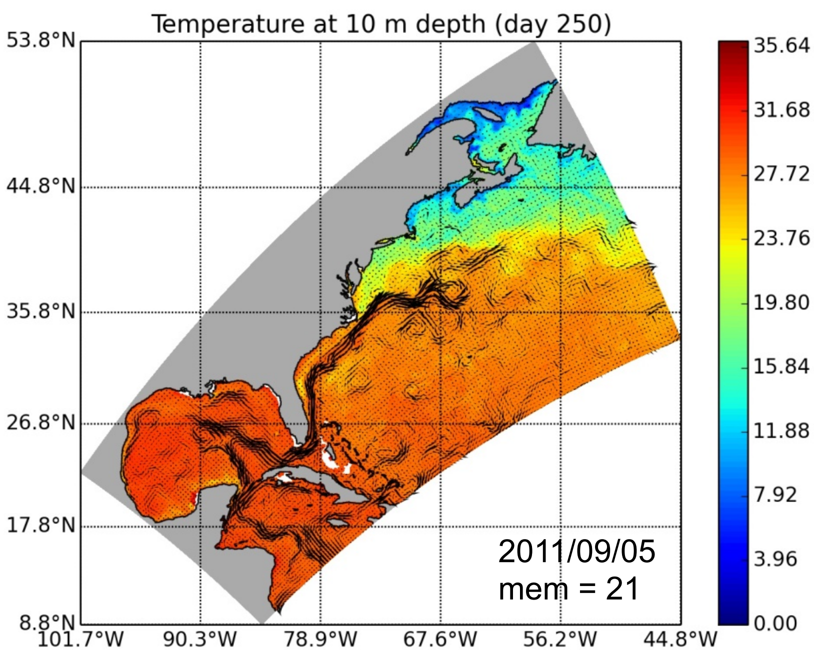

Temperature differnce at 10 m depth (day 97)
Assimilative Model
– Free Run
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
4.40
3.30
2.20
1.10
-0.00
-1.10
-2.20
-3.30
-4.40

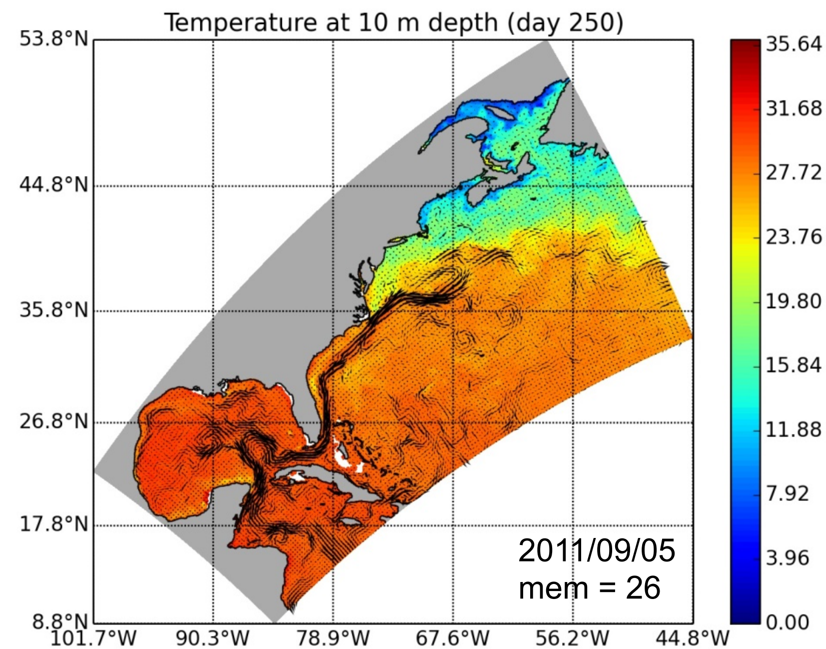

Temperature at 10 m depth (day 158)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/06/05
mem = 21

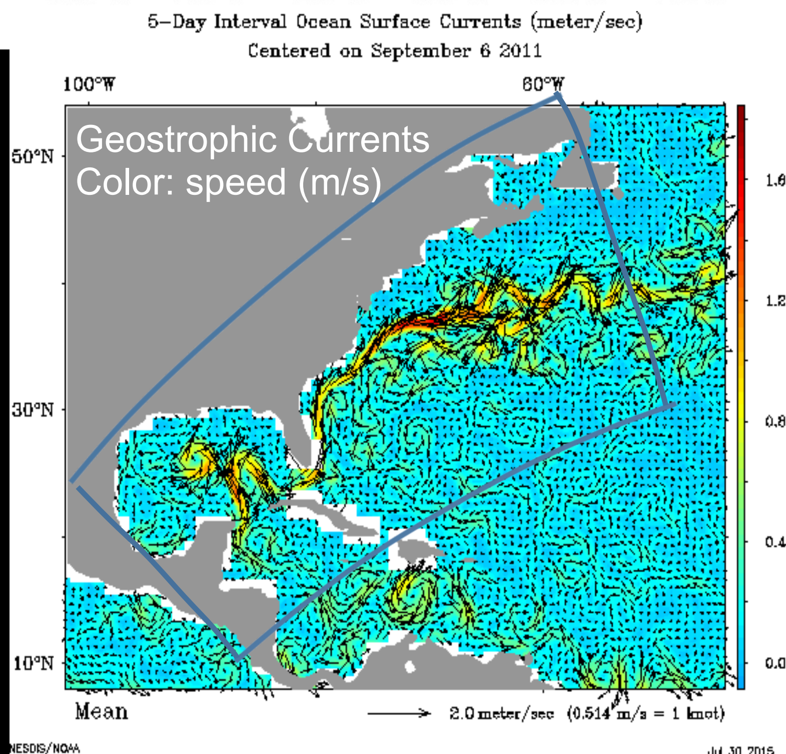

Temperature at 10 m depth (day 158)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/06/05
mem = 26

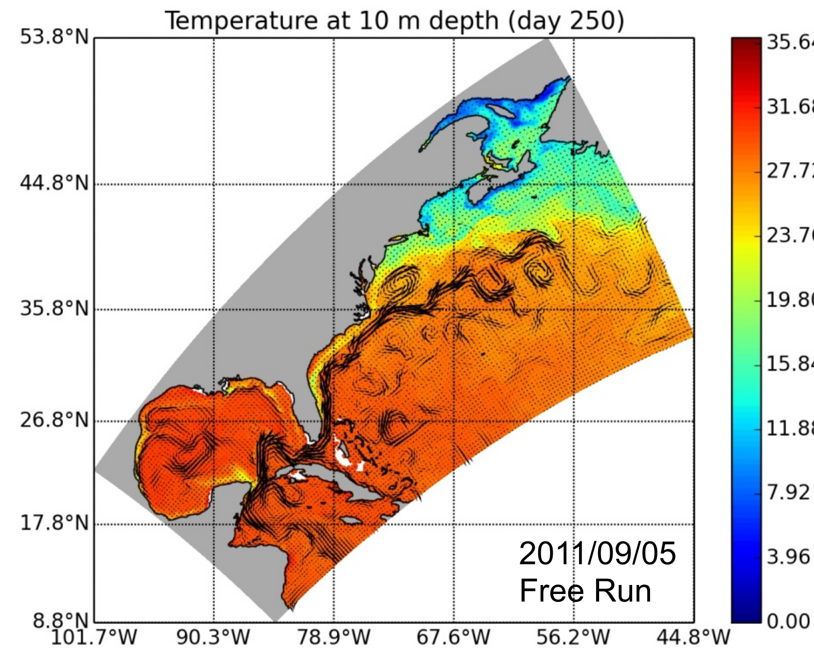

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on June 7 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
1.6
1.2
0.8
0.4
0.0
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Jul 30 2015

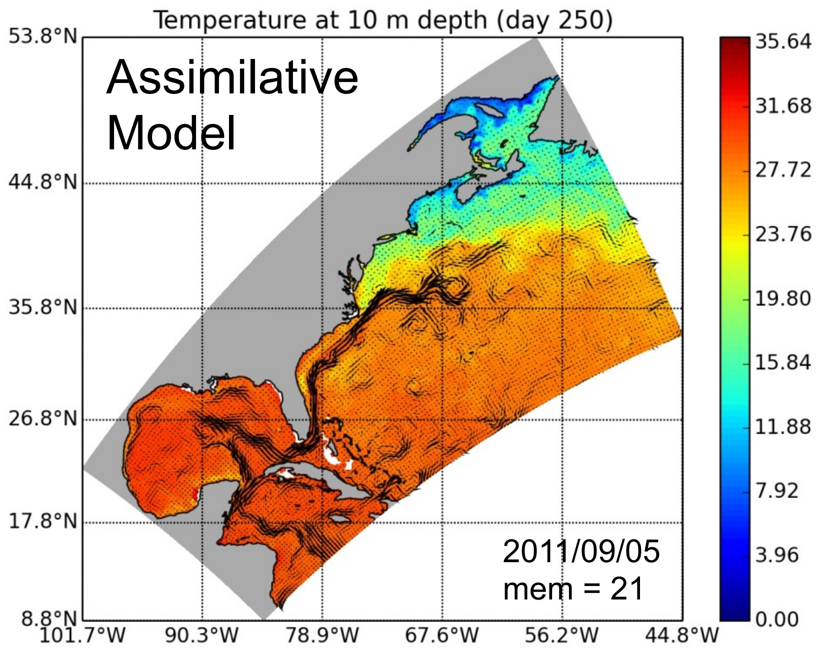

Temperature at 10 m depth (day 158)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/06/05
Free Run

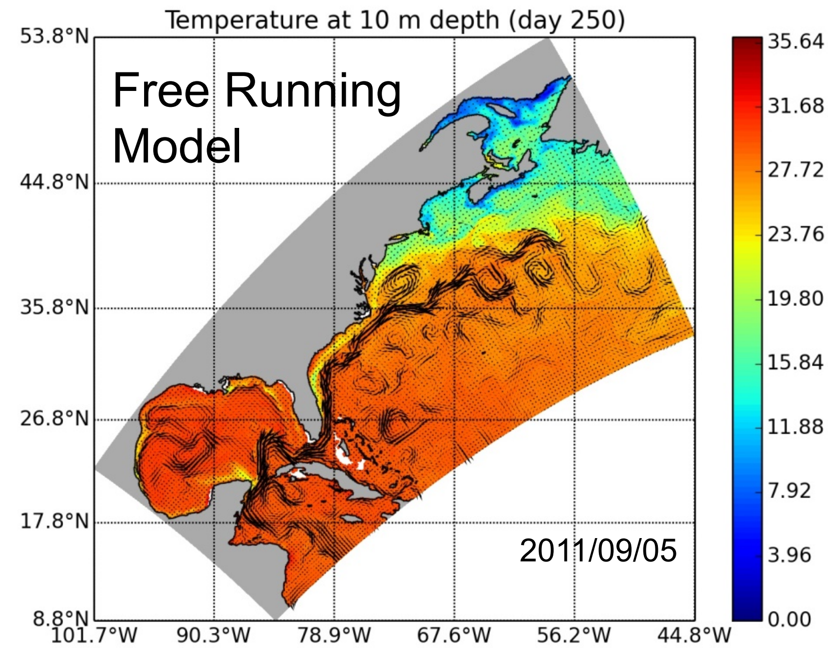

Temperature at 10 m depth (day 250)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/09/05
mem = 21

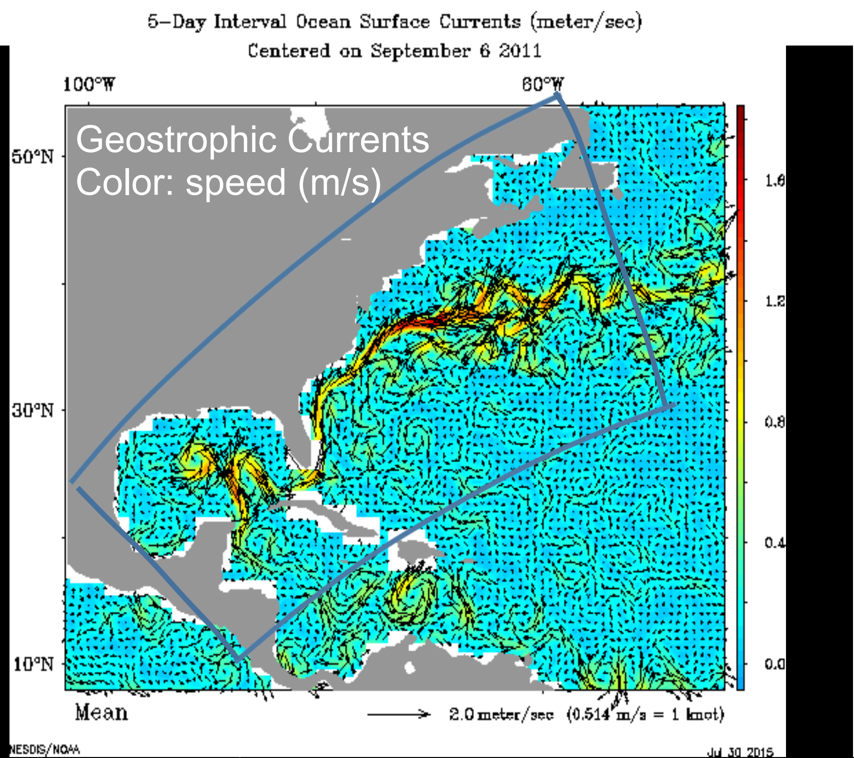

Temperature at 10 m depth (day 250)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/09/05
mem = 26

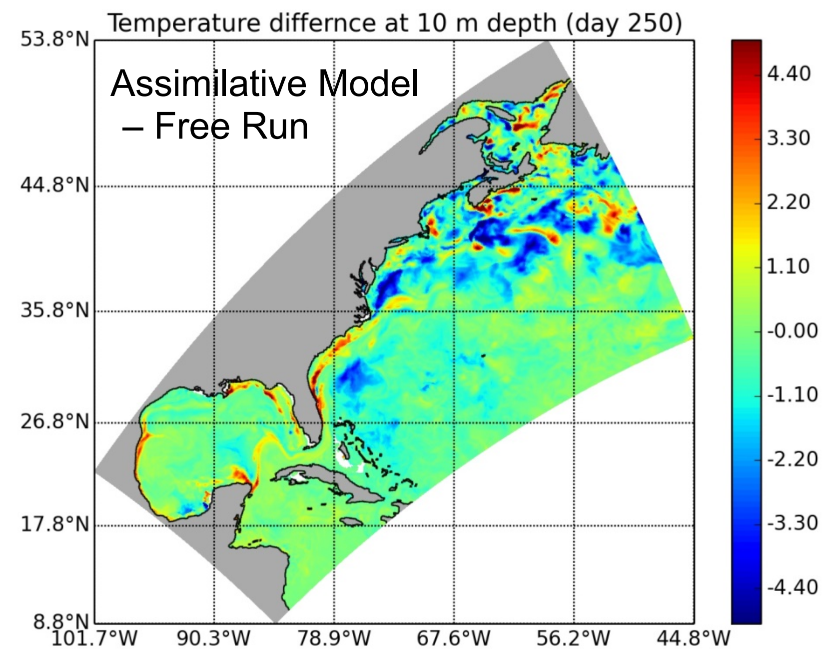

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on September 6 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
1.6
1.2
0.8
0.4
0.0
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Jul 30 2015

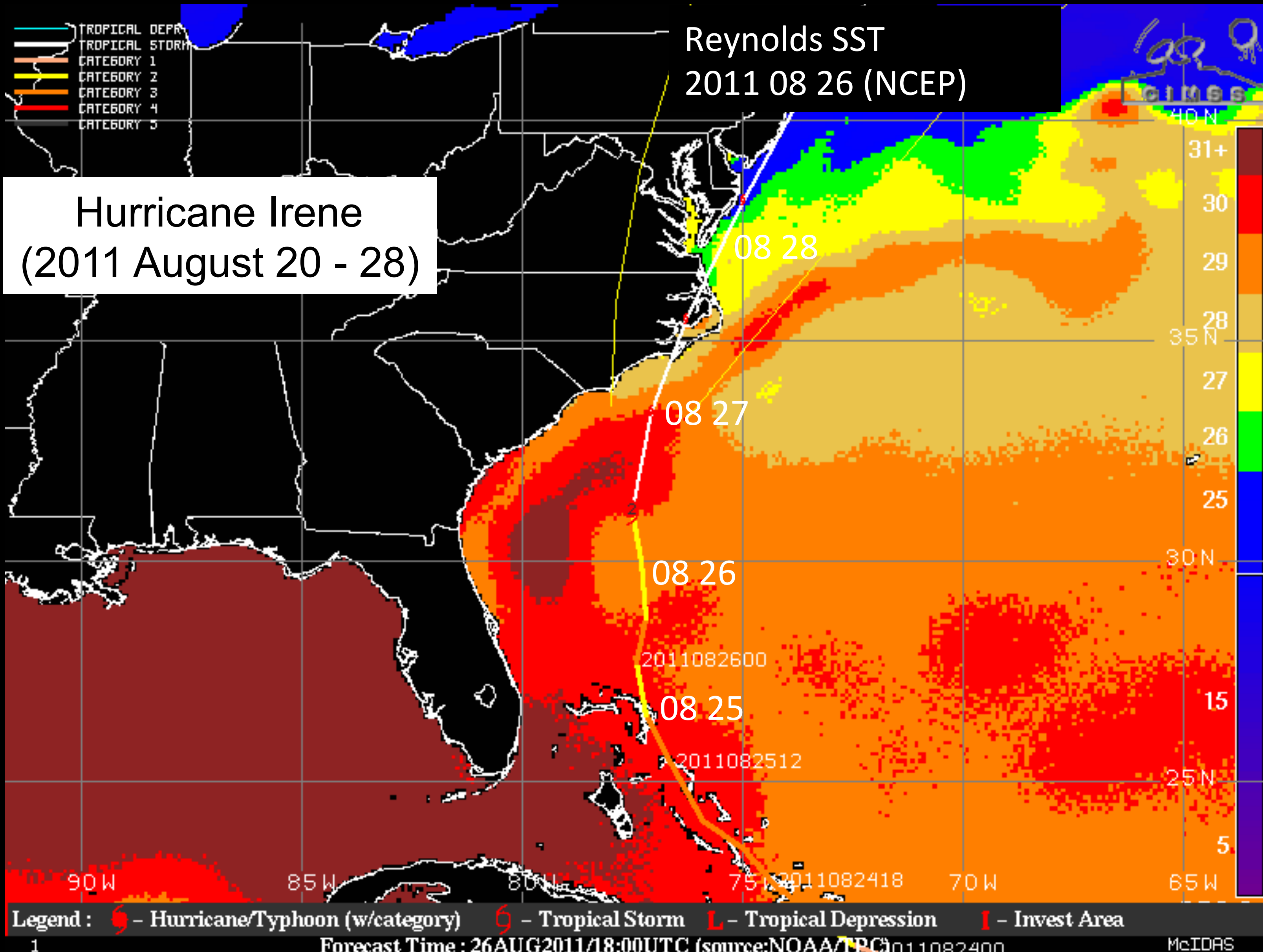

Temperature at 10 m depth (day 250)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/09/05
Free Run

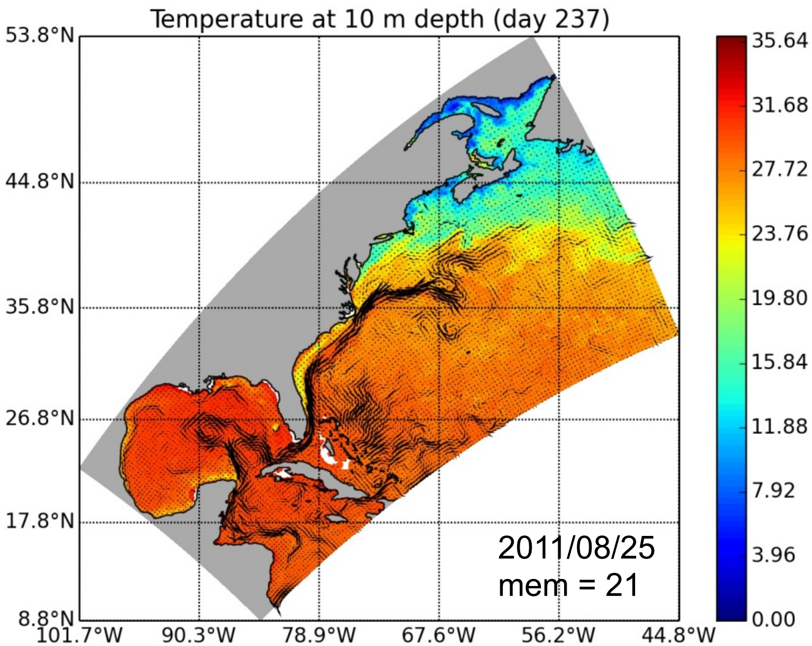

Temperature at 10 m depth (day 250)
Assimilative Model
2011/09/05
mem = 21
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00

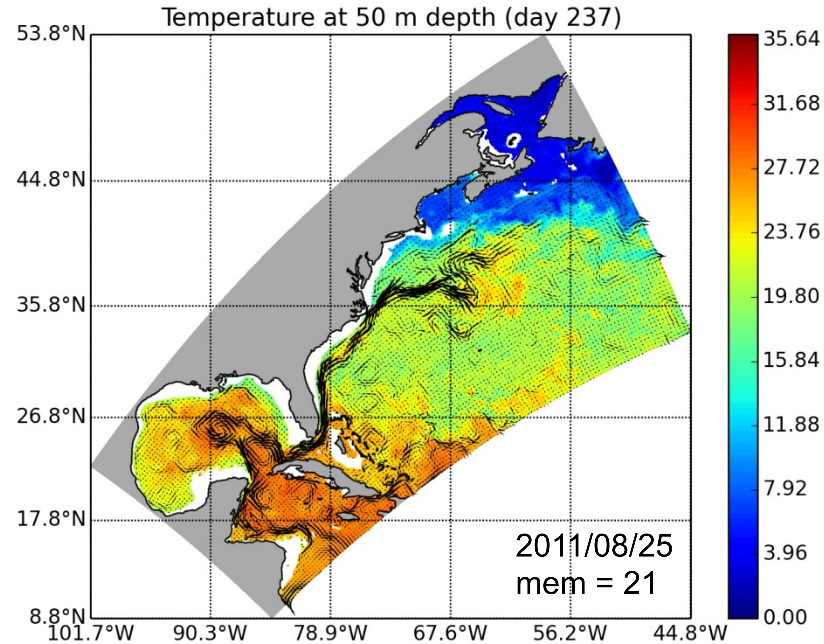

Temperature at 10 m depth (day 250)
Free Running Model
2011/09/05
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00

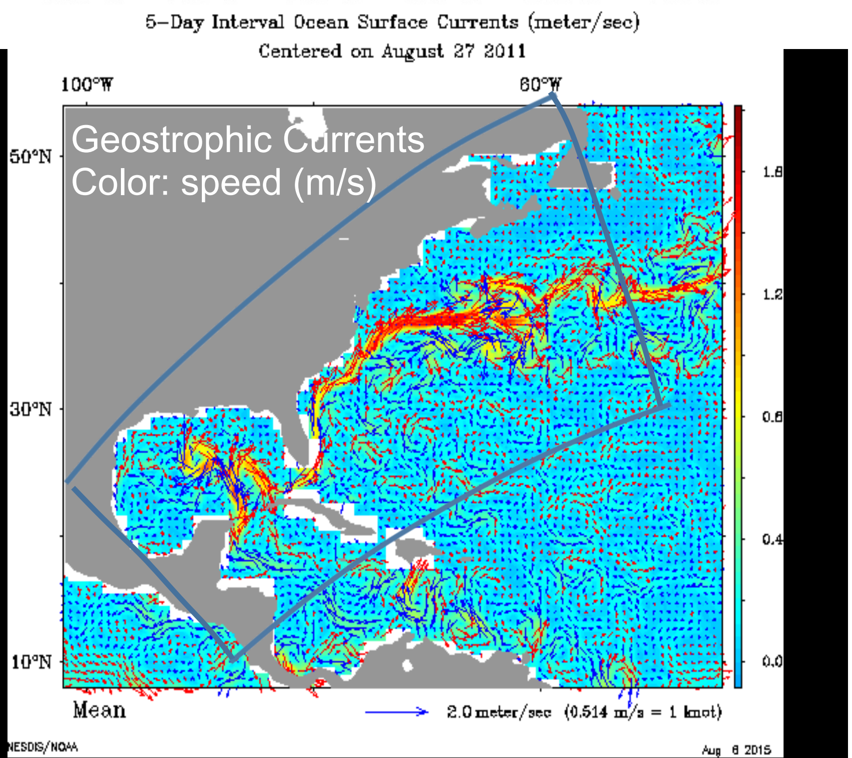

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on September 6 2011
Geostrophic Currents
Color: speed (m/s)
100°W
60°W
50°N
30°N
10°N
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA

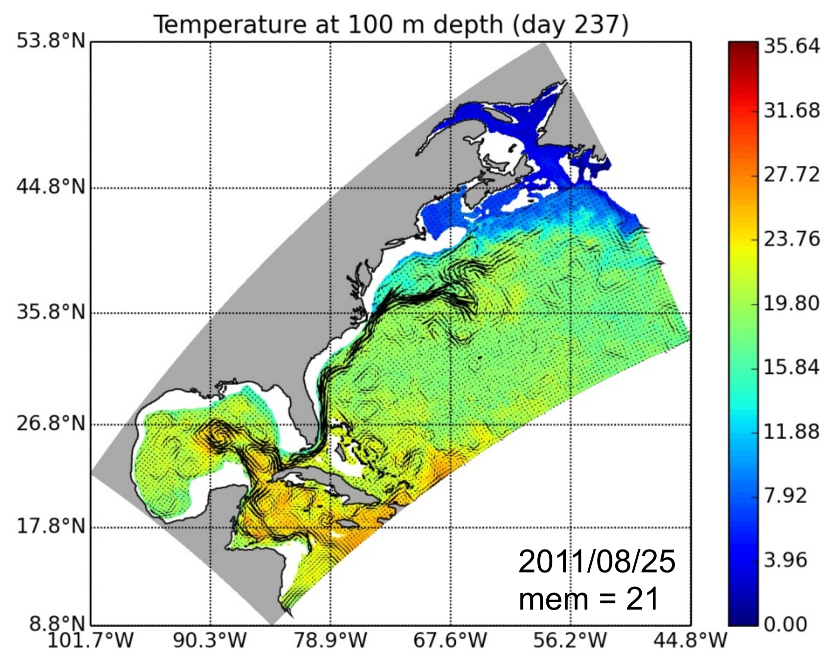

Temperature differnce at 10 m depth (day 250)
Assimilative Model
– Free Run
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
4.40
3.30
2.20
1.10
-0.00
-1.10
-2.20
-3.30
-4.40

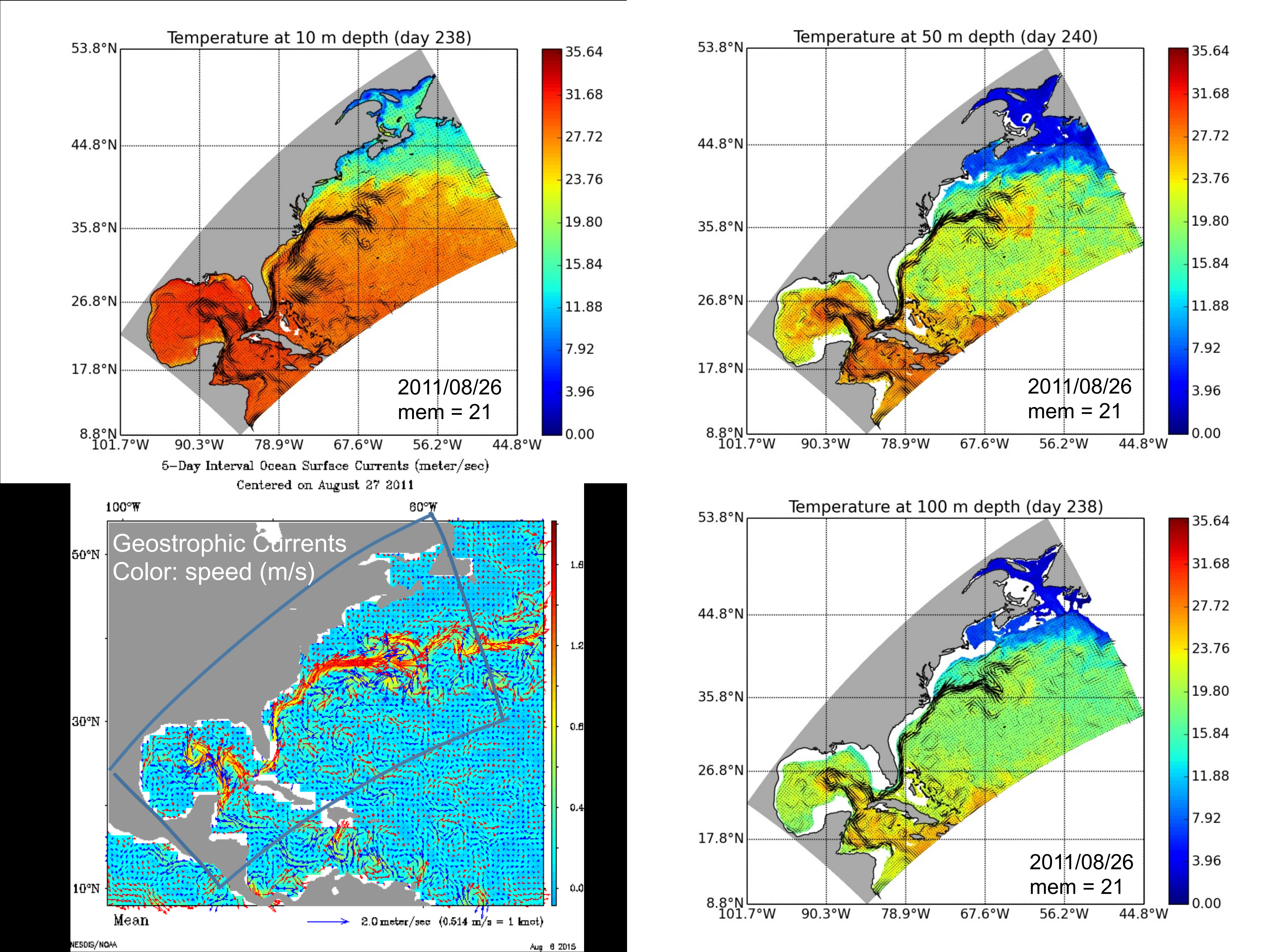

Hurricane Irene
(2011 August 20 - 28)
Reynolds SST
2011 08 26 (NCEP)
TROPICAL DEPR
TROPICAL STORM
CATEGORY 1
CATEGORY 2
CATEGORY 3
CATEGORY 4
CATEGORY 5
08 28
08 27
08 26
08 25
2011082600
2011082512
2011082418
40 N
35 N
30 N
25 N
90 W
85 W
80 W
75 W
70 W
65 W
31+
30
29
28
27
26
25
15
5
Legend : – Hurricane/Typhoon (w/category) – Tropical Storm L – Tropical Depression I – Invest Area
Forecast Time : 26AUG2011/18:00UTC (source:NOAA/TPC)
McIDAS


Temperature at 10 m depth (day 237)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/25
mem = 21

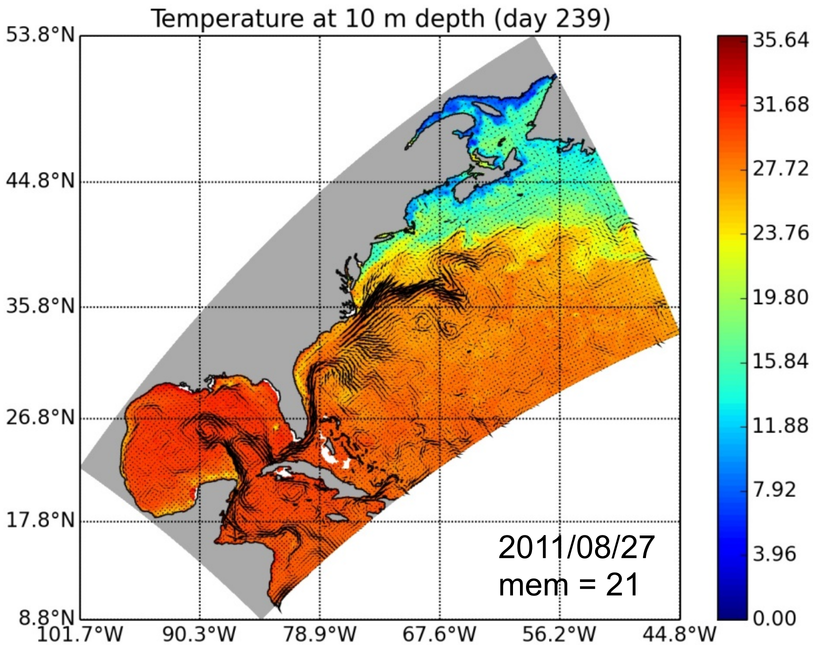

Temperature at 50 m depth (day 237)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/25
mem = 21

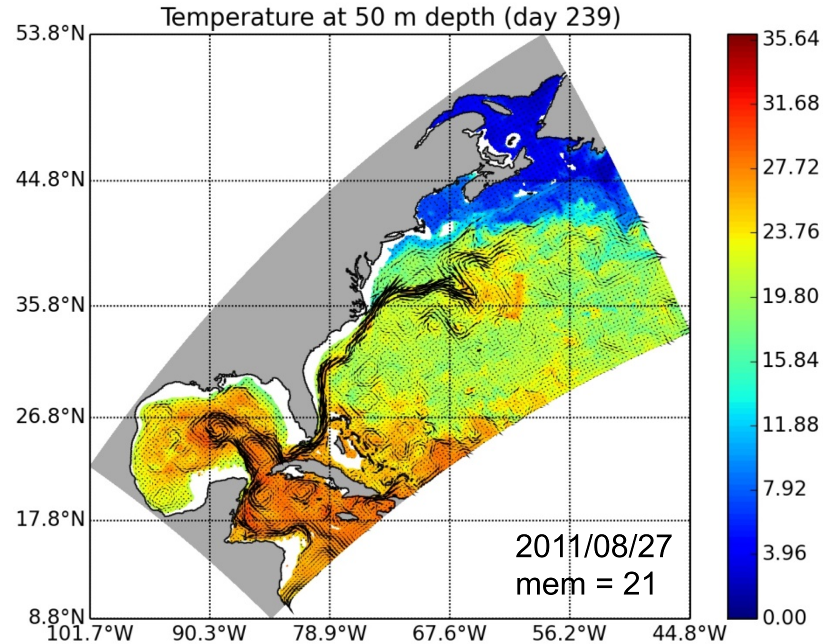

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on August 27 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Aug 6 2015

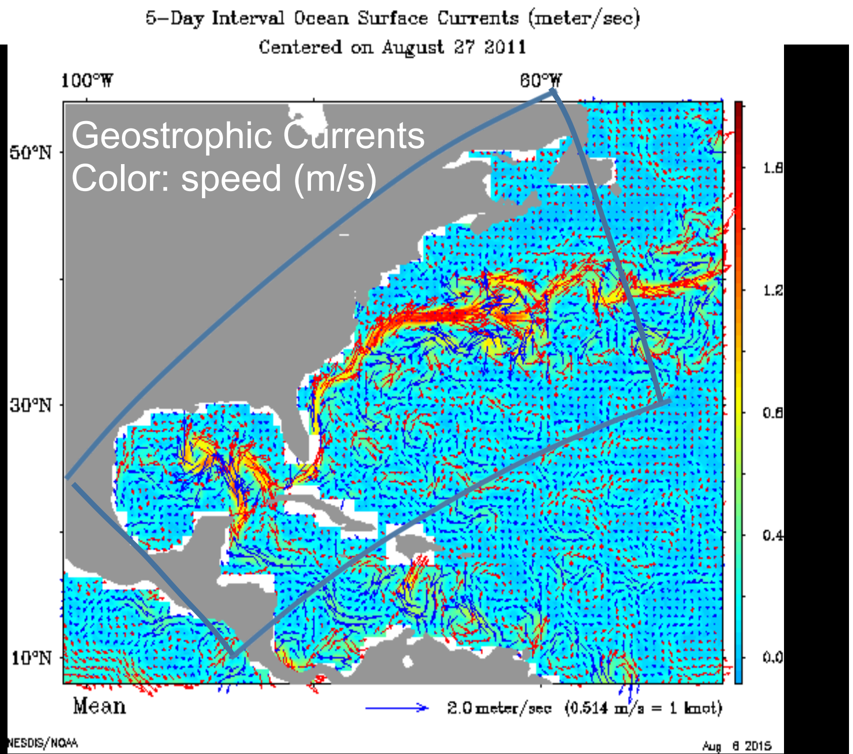

Temperature at 100 m depth (day 237)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/25
mem = 21

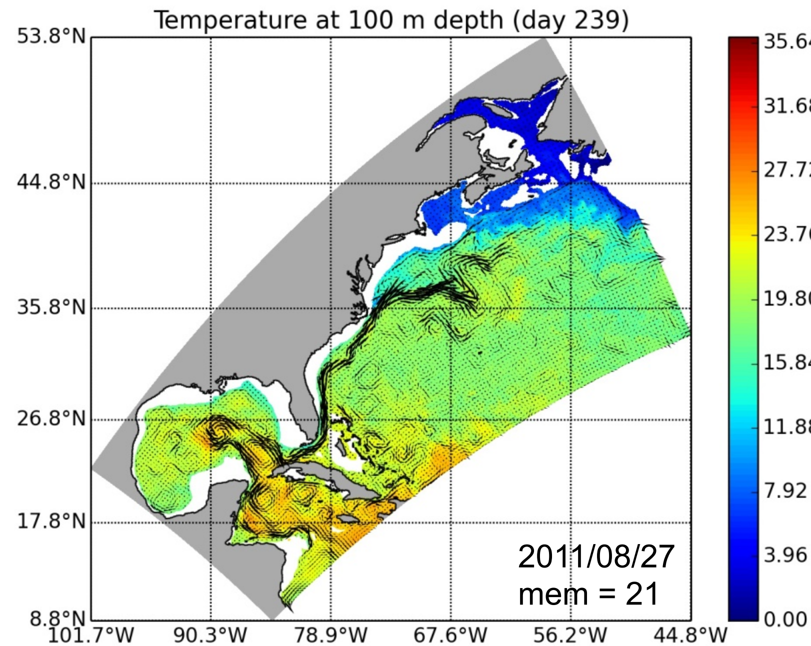


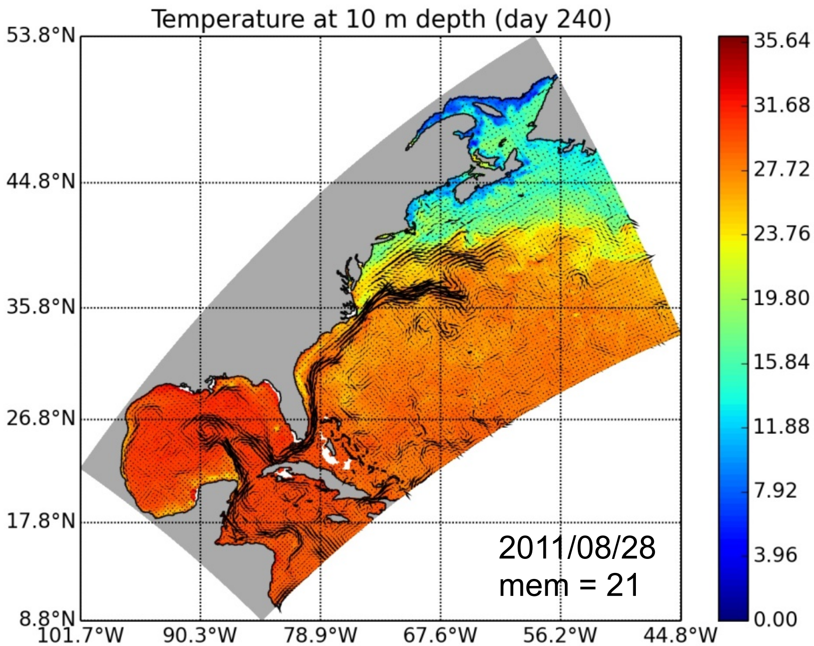
Temperature at 10 m depth (day 238)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/26
mem = 21
Temperature at 50 m depth (day 240)
2011/08/26
mem = 21
Temperature at 100 m depth (day 238)
2011/08/26
mem = 21
5-Day Interval Ocean Surface Currents (meter/sec)
Centered on August 27 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Aug 8 2015

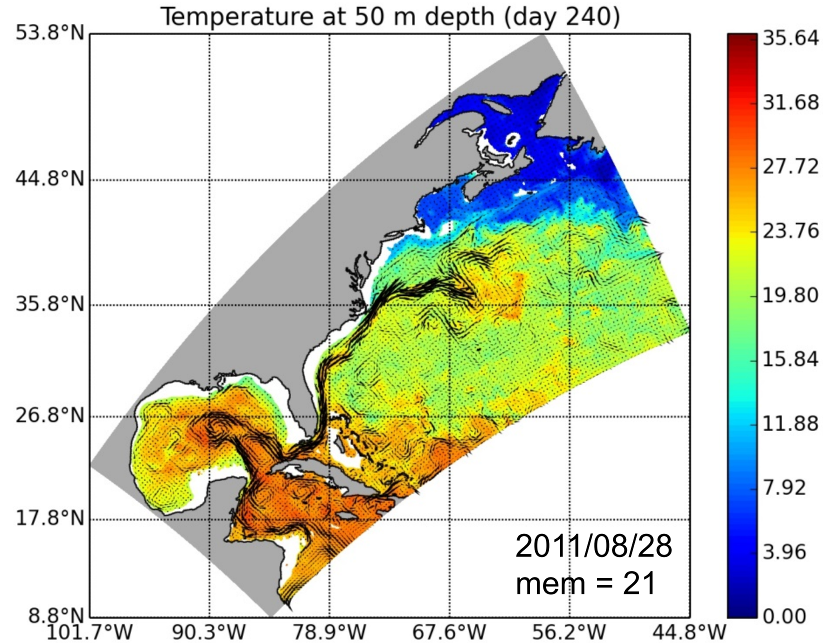

Temperature at 10 m depth (day 239)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/27
mem = 21

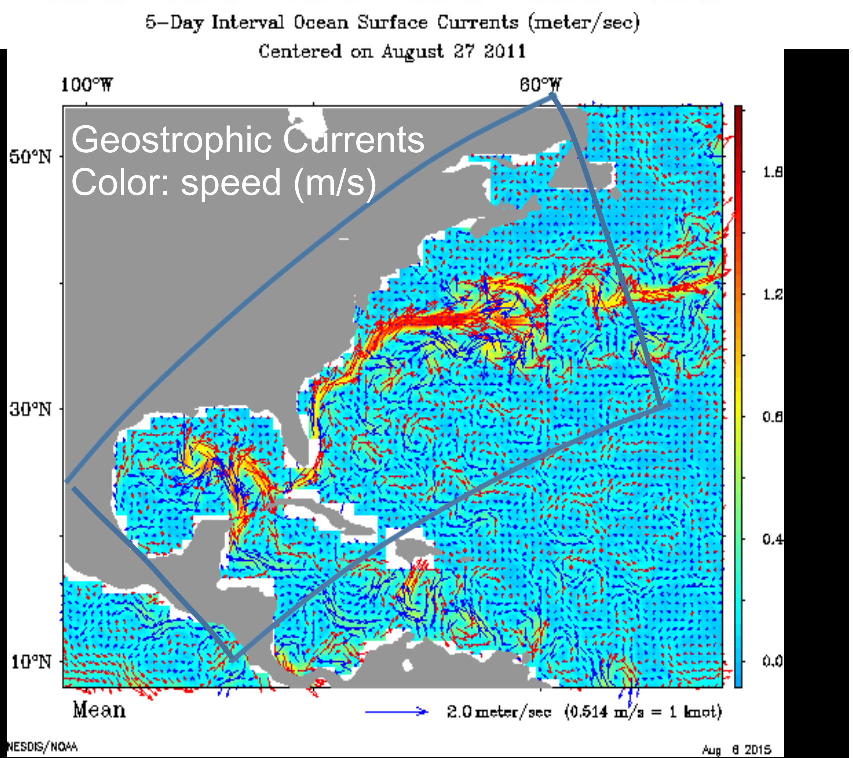

Temperature at 50 m depth (day 239)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/27
mem = 21

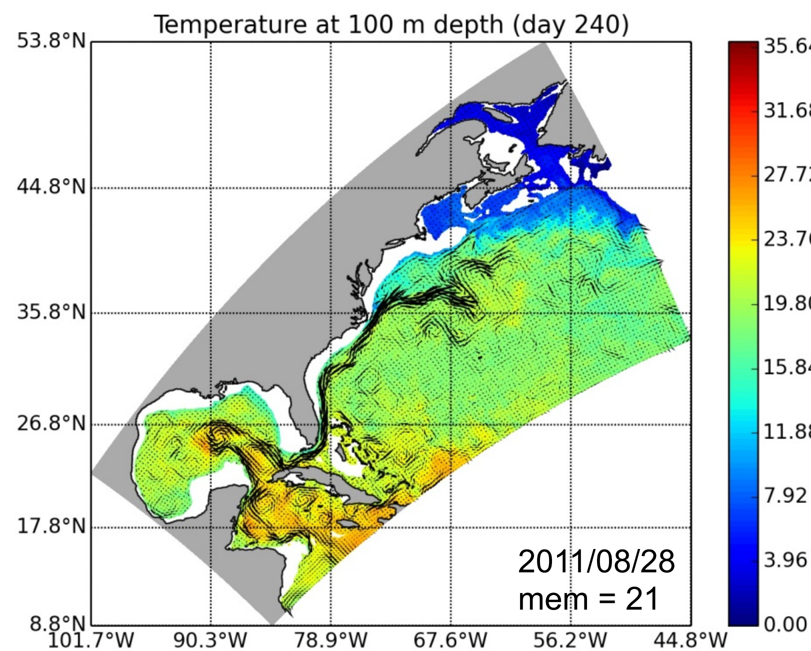

5-Day Interval Ocean Surface Currents (meter/sec)
Centered on August 27 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Aug 8 2015


Temperature at 100 m depth (day 239)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/27
mem = 21


Temperature at 10 m depth (day 240)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/28
mem = 21


Temperature at 50 m depth (day 240)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/28
mem = 21


5-Day Interval Ocean Surface Currents (meter/sec)
Centered on August 27 2011
100°W
60°W
50°N
30°N
10°N
Geostrophic Currents
Color: speed (m/s)
Mean
2.0 meter/sec (0.514 m/s = 1 knot)
NESDIS/NOAA
Aug 6 2015


Temperature at 100 m depth (day 240)
53.8°N
44.8°N
35.8°N
26.8°N
17.8°N
8.8°N
101.7°W
90.3°W
78.9°W
67.6°W
56.2°W
44.8°W
35.64
31.68
27.72
23.76
19.80
15.84
11.88
7.92
3.96
0.00
2011/08/28
mem = 21

Summary

- Implemented regional ocean model (ROMS) within the DART ecosystem
- Assimilated T and S
- Qualitatively promising simulations
- Some next steps:
  - Quantitative assessment of ensemble
  - Work on predictability of NWA
  - Dynamics of events (Hurricanes, GS intrusions…)
  - Assimilate SSH
  - Long-term reanalysis

Additional Slides

*http://www.image.ucar.edu/DAReS/DART/DART_Intro.php#**add_new_model***

Adding a model to DART - Overview

DART is designed to work with many models *without* modifications to the DART routines **or** the model source code. DART can 'wrap around' your model in two ways. One can be used if your model can be called as a subroutine, the other is for models that are separate executables. Either way, there are some steps that are common to both paths.

Please be aware that several of the high-order models (CAM and WRF, in particular) have been used for years and their scripts have incorporated failsafe procedures and restart capabilities that have proven to be useful but make the scripts complex - more complex than need be for the initial attempts. Truly, some of the complexity is no longer required for available platforms. Then again, we're not running one instance of a highly complicated computer model, we're running N of them.

The basic steps to include your model in DART

Copy the template directory and files to your own DART model directory.

Modify the model_mod.f90 file to return specifics about your model.

This module MUST contain all the required interfaces (no surprise) but it can also contain many more interfaces as is convenient.

[optional step] Modify the matlab routines to know about the specifics of the netCDF files produced by your model (sensible defaults, for the most part.)

ROMS-DART flowchart (*recipe*)

1. use the tools in observation folder to create obs sequence files.
   use obs_tools to combine them

2. get ensemble model restart files (you could simply add random numbers to one file)

3. run roms_to_dart to convert restart files to dart files,
   one by one, e.g., dart.ics.0001, dart.ics.0002,...
4. use restart_file_tool to combine the ensemble files into one file,
   e.g., from dart.ics.0001, dart.ics.0002,... to dart.ic.all
5. edit input namelist
6. run filter using run_filter.csh
7. run restart_file_tool to convert combined dart output in to ensemble files,
   e.g., from dart.restart to dart.restart.0001,dart.restart.0002,...
8. run dart_to_roms to convert each ensemble back to ROMS restart files,
   (overwrite the initial ones)

9. run ROMS for each member using advance_model.csh