4DVAR Data Assimilation with Chesapeake Bay Operational Forecasting System

Bin Zhang[1], Matt Hoffman[2], Lyon Lanerolle[3], Chris Brown[1,4]

1 Cooperative Institute of Climate & Satellites/Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
2 School of Mathematical Sciences, Rochester Institute of Technology, Rochester, NY, USA
3 NOAA/National Ocean Service, Silver Spring, MD 20910, USA;
4 NOAA Satellite Climate Studies Branch, University of Maryland, College Park, MD, USA

CICS Meeting
11/13/2014

Outline

- Project brief introduction and objectives
- Comparison of CBOFS with observations
- 4DVAR Data assimilation with CBOFS
- Comparison results before and after 4DVAR assimilation
- Summary and future works

Scientific Basis/Approach

- Temperature is critical in understanding the coastal ocean, yet difficult to forecast synoptically
- NOAA's operational Chesapeake Bay Operational Forecasting System (CBOFS) forecasts SST, but would benefit from the assimilation of satellite-derived SST
- Several data assimilation techniques available; evaluate whether 4D-VAR (Moore et al.,2011) or LETKF (Hunt et al. 2007) is better for assimilating SST retrievals into CBOFS
- Satellite SST retrievals have previously been assimilated into hydrodynamic models, but not operationally by NOAA

Overall Goal:

- Determine whether 4DVAR or LETKF should be used when assimilating VIIRS SST into CBOFS.
- Quantify the improvement of retrievals from VIIRS vs AVHRR SST.

Only 4DVAR results are reported here.

Funded by Joint Polar Satellite System Proving Ground and Risk Reduction Program.

Chesapeake Bay Operational Forecasting System

- Currently Running at NOAA NOS CO-OPS

  With Regional Ocean Modeling System 3.0

  Small bugs needed to be fixed.

  No full support for latest 4DVAR scheme.

- Update the CBOFS to ROMS 3.6

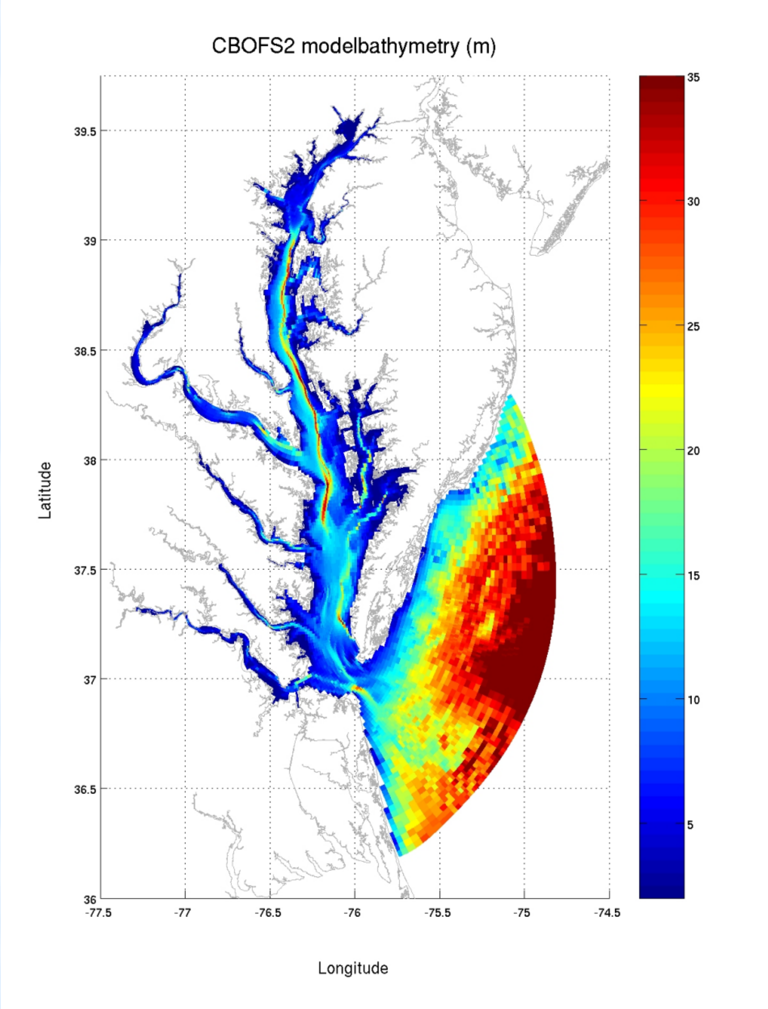
  Open boundary condition suitable for two-way nesting, moved into the input files instead of CPP options.

- Forcing and open boundary files

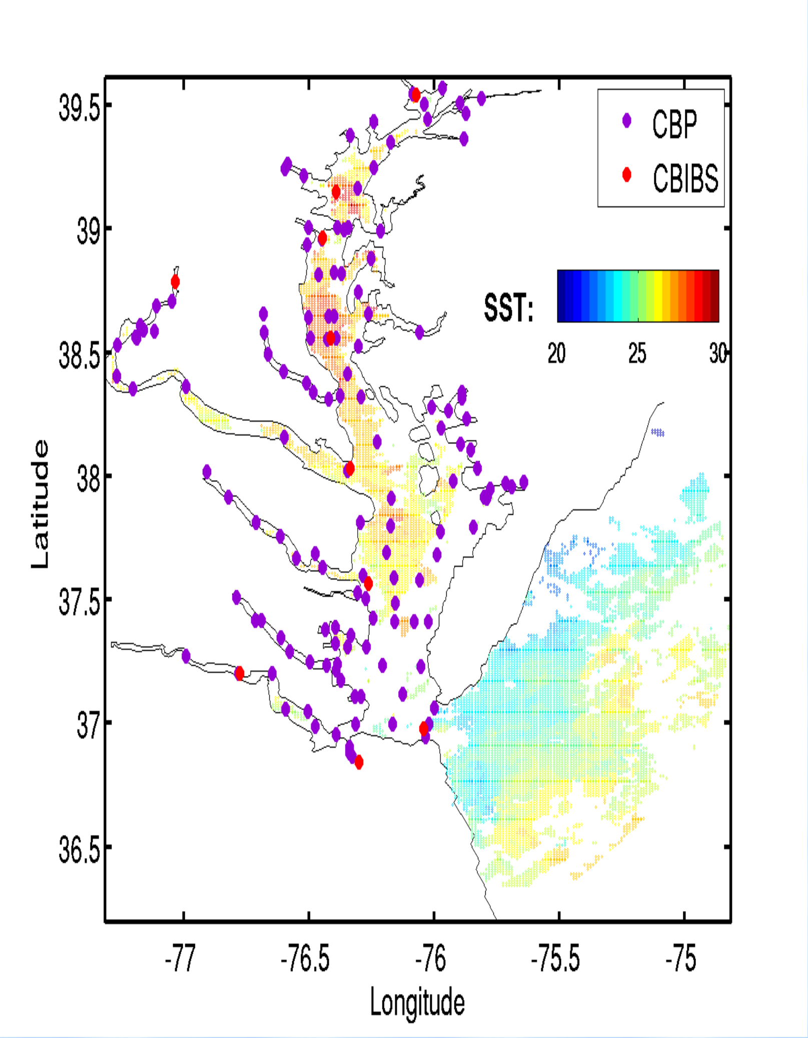
  NAM, USGS rivers, RTOFS

  Provided by Aijun Zhang and Ainsley Gibson of NOAA

- Fine resolution at river area, up to 33 m.

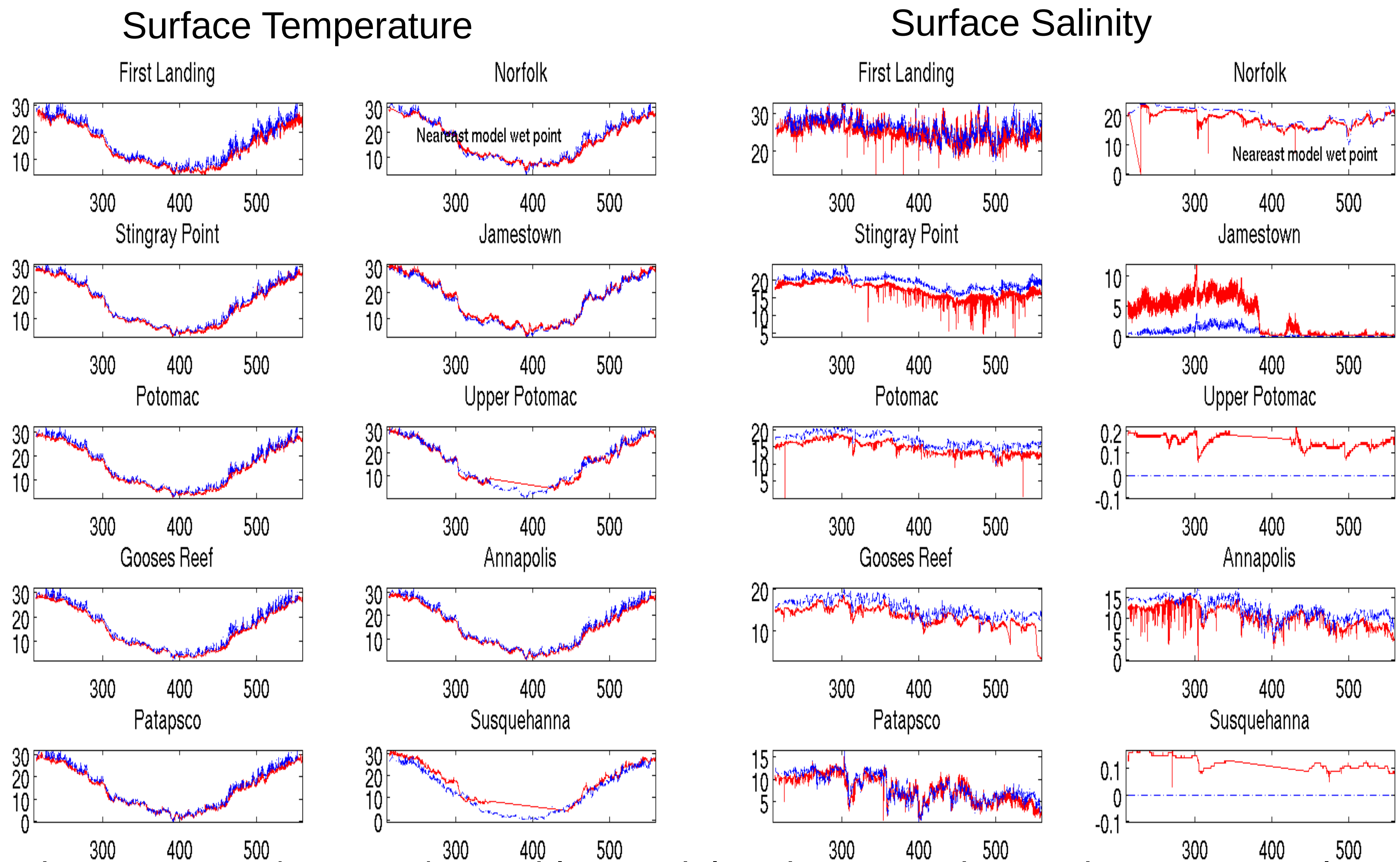


Chesapeake Bay Water/Current Observations



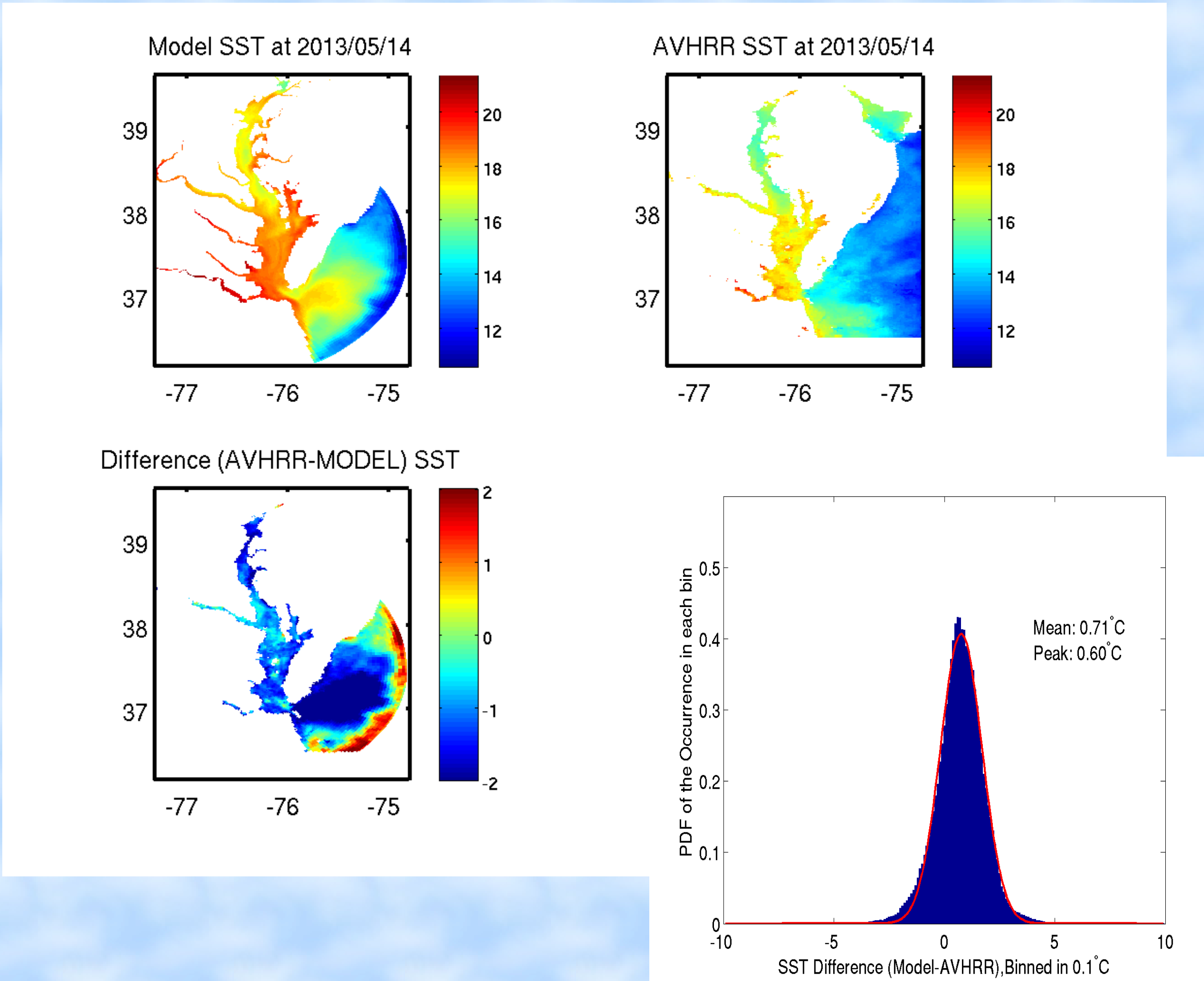
- Chesapeake Bay Program (CPB):
  ~ Every two weeks CTD casting of T/S
- Chesapeake Bay Interpretive Buoy System (CBIBS)
  15 minutes surface T/S, real time.
- SST from NOAA
  AVHRR (1km, composite and granule)
  GOES (SST)
  Terra/Aqua MODIS SST
  S-NPP VIIRS SST (750 m at nadir)
- HF Radar from ODU
  1km resolution surface current near Bay mouth
- Occasionally in-situ CTD/ADCP
- USGS river
- Tide gauges

CBOFS Comparison with Observations



Time range: 08/2012-08/2013, blue model, red, CBIBS observations, a general warm and saline bias.

CBOFS Comparison with Observations



AVHRR SST is from NOAA coastal watch daily composite.

ROMS 4DVAR

- Incremental Strong Constraint (IS4DVAR)

  Primal form

  Initial conditions, surface forcing, open boundary conditions

- Physical-Space Statistical Analysis (PSAS)

  Dual forms, in model and observational spaces.

  Strong constraint; Weak constraint (Considering model errors).

- Representer 4DVAR (R4DVAR)

Here, we use IS4DVAR and adjust initial condition only. Other forms will be test in later studies.

IS4DVAR Preparation

- $J(\delta x)=\frac{1}{2}\delta x^T B^{-1}\delta x+\frac{1}{2}\sum\left(H\delta x-y\right)^T O^{-1}\left(H\delta x-y\right)$

Background Error Covariance

Observational Error Covariance

$$B=K_b\Sigma C\Sigma^T K_b{}^T$$

Balanced Operator

Standard deviation

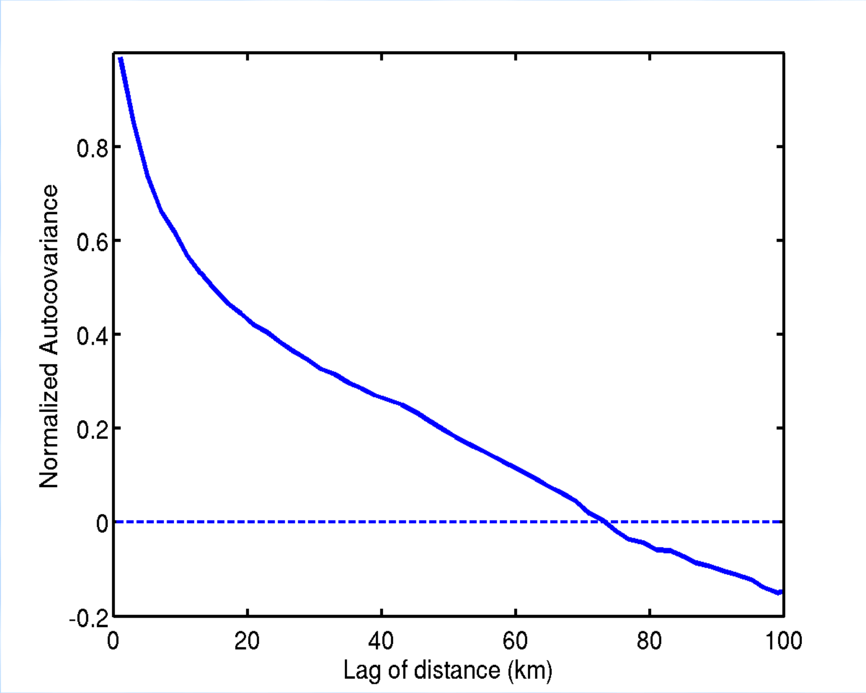
Correlation Matrix

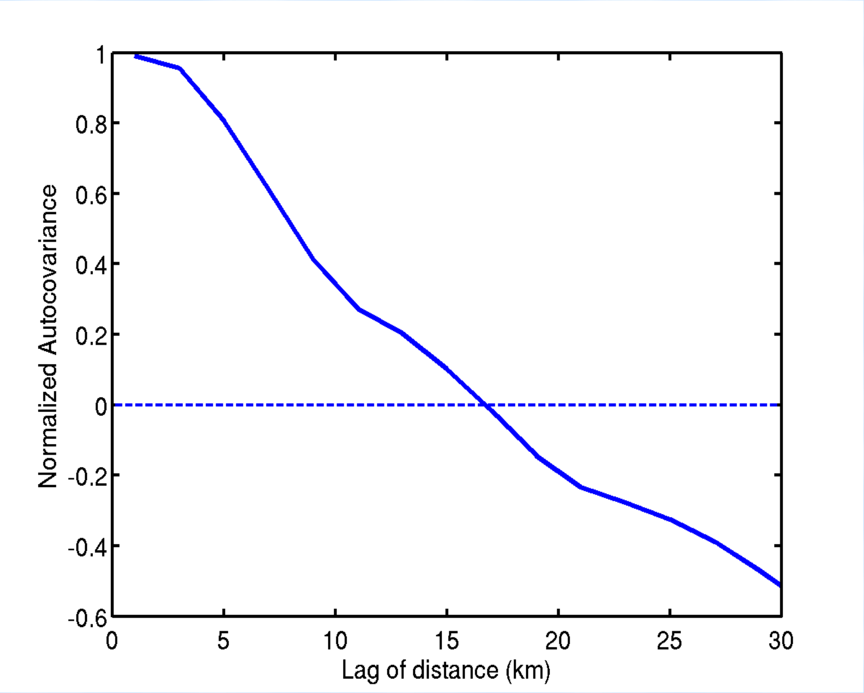
Given: Horizontal and Vertical Decorrelation Length Scale

Calculated from Forward ROMS

ROMS NORMALIZATION OPTION

Decorrelation Scales (from SST)





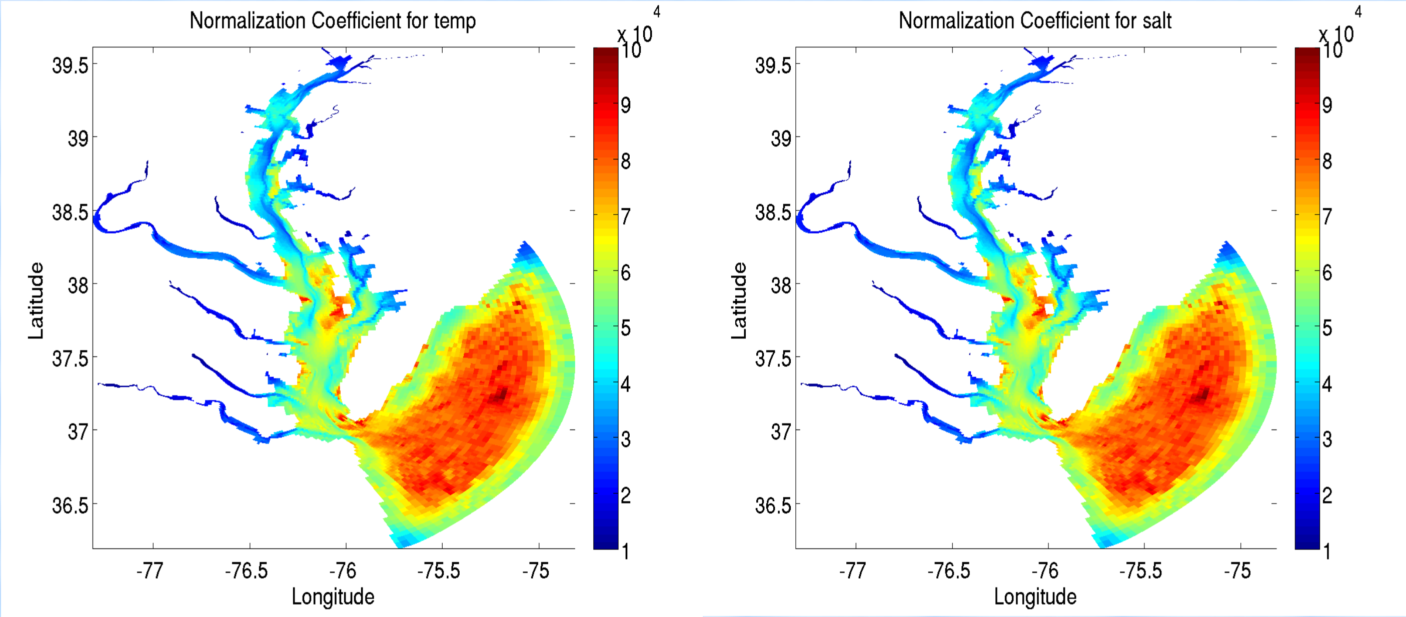
Overall: 73Km

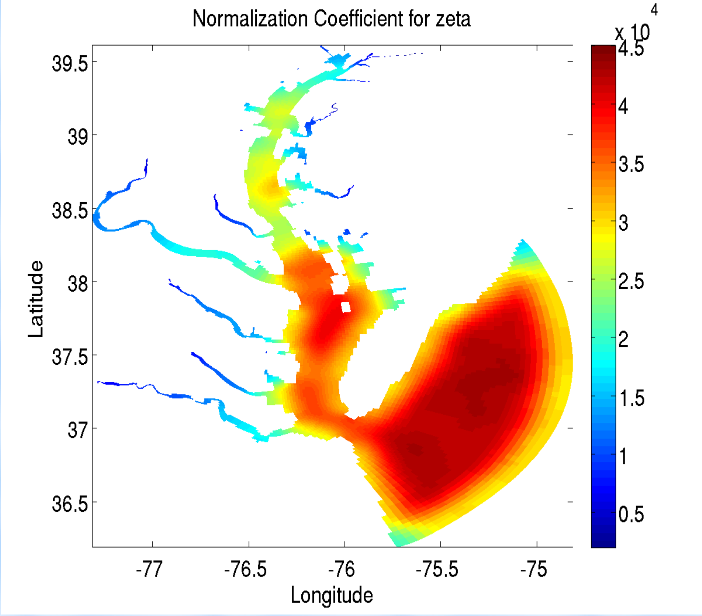
East Direction: 17Km

In the vertical, it is hard to get a statistically meaningful decorrelation scale with the shallow depth, we just choose the minimum vertical mixed layer depth to avoid over smoothing. Here we choose it to be 3 m. The surface mixed layer depth ranges from 3m -10m

Ref: http://aslo.org/meetings/santafe1999/abstracts/CS57FR0900E.html

Normalization Coefficients

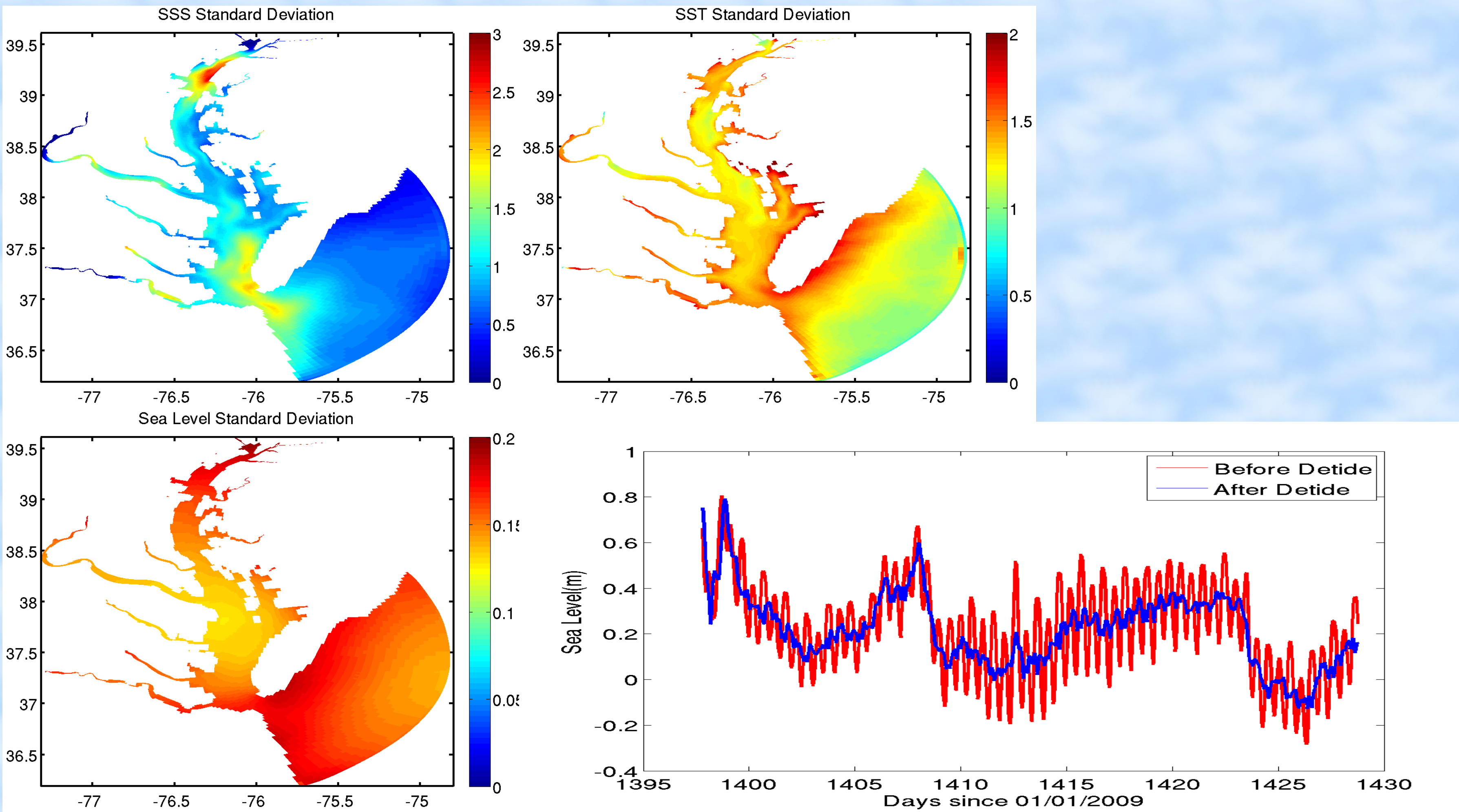




- Solve a heat diffusion equation
- Randomized method
- Need sufficient iterations.
- Lengthy Calculations
- Only one time suppose the model grids do not change.

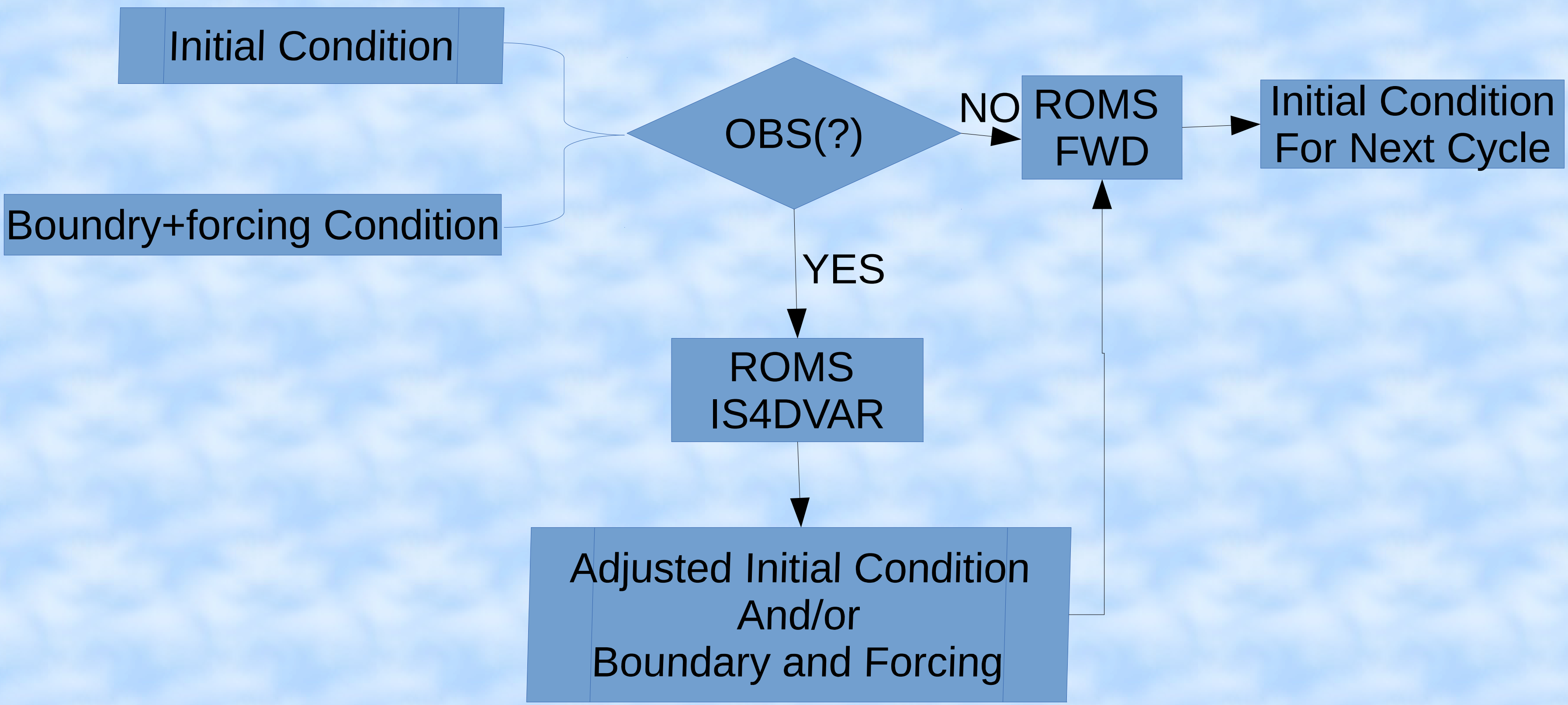
(Background) Standard Deviation

- Model hindcast for one year, save data with three hourly interval.
- Inline least square analysis to calculate tidal harmonics for (T,S,u,v,η).
- Remove periodical signals in the three hourly data (tides and annual signal), and calculate the standard deviation.



Flow Chart for IS4DVAR

Forward Run Window

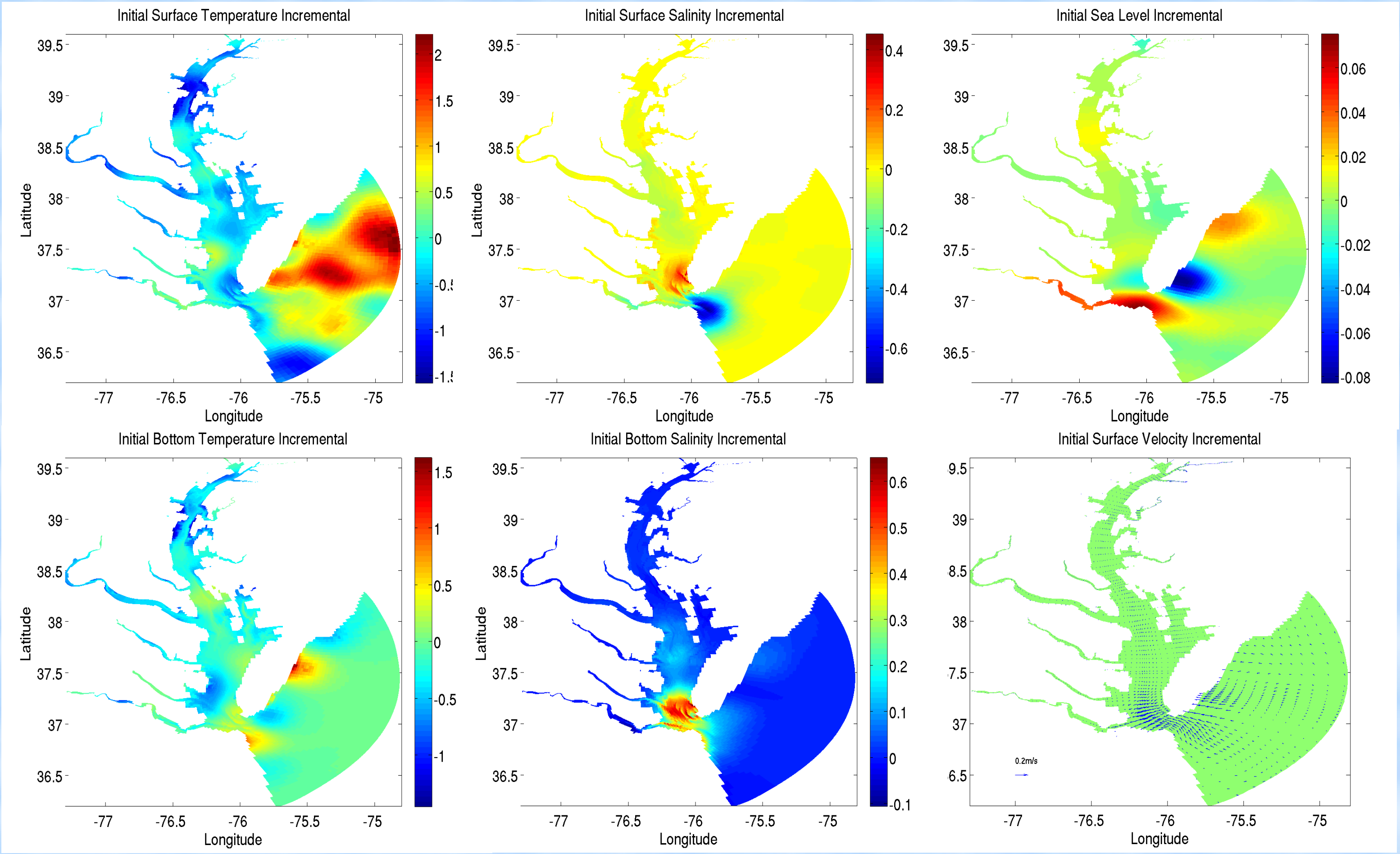


Forward Run Window/Assimilation Window (6 hours)

Sequential run from 08/14/2012 12:00 to 09/16/2012 00:00

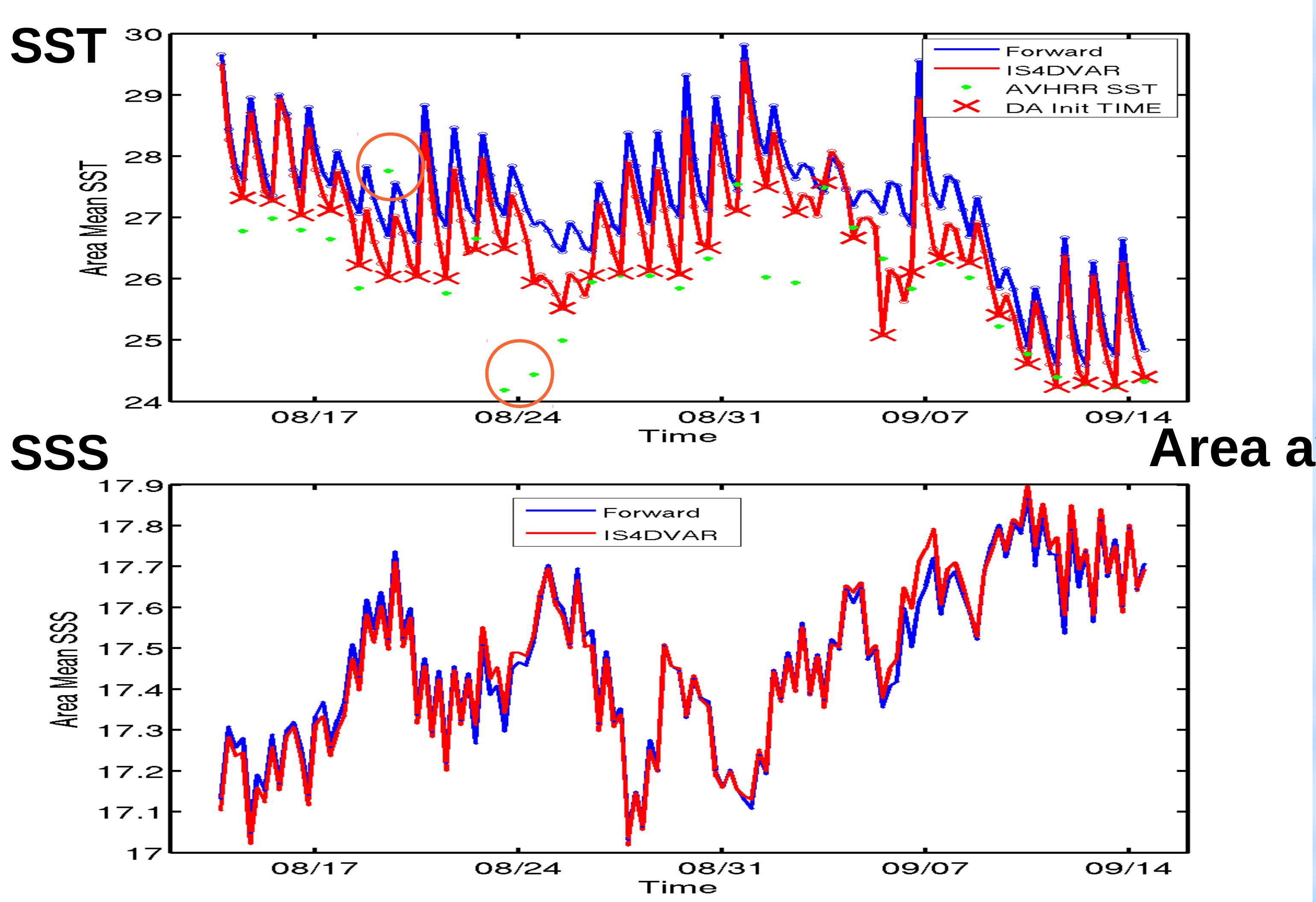
IS4DVAR (Incrementals)

Initial Condition Difference before and after IS4DVAR. 08/15/2012 12:00



The temperature is modified by SST assimilation but salinity and velocity changes mostly in the Chesapeake Bay mouth region. The adjustment of salinity and velocity in the mouth area is more sensitive to the SST than other area.

One month Sequential Adjustment of Initial Condition with AVHRR SST



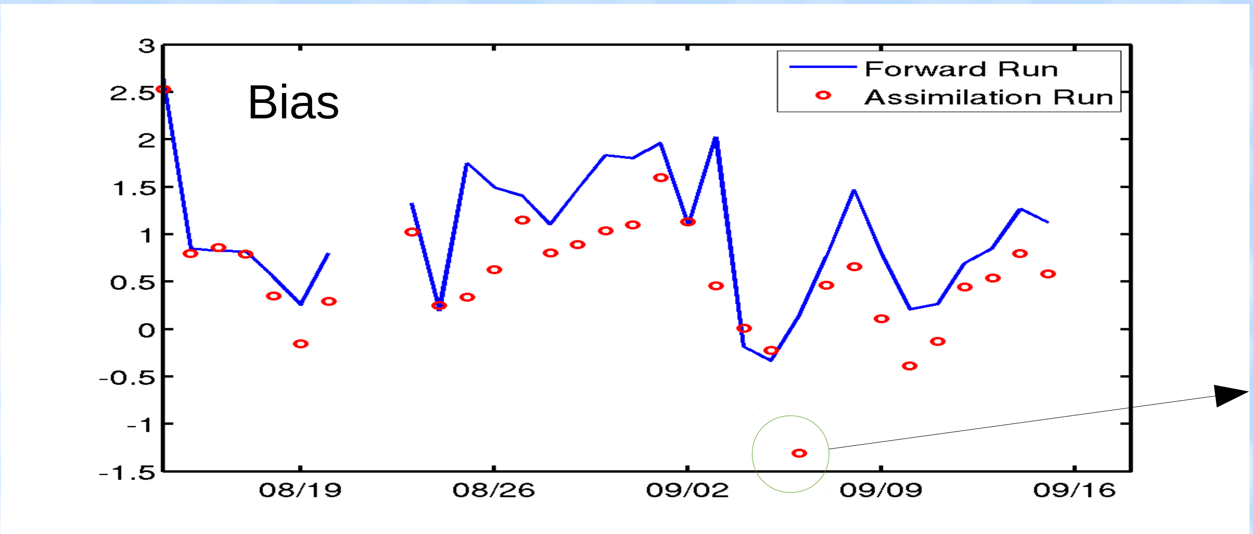
Area averaged

Mean FWD SST: 26.74 Mean DA SST: 27.25; Mean Sat SST: 25.89

Mean FWD SSS: 17.469; Mean DA SSS: 17.467;

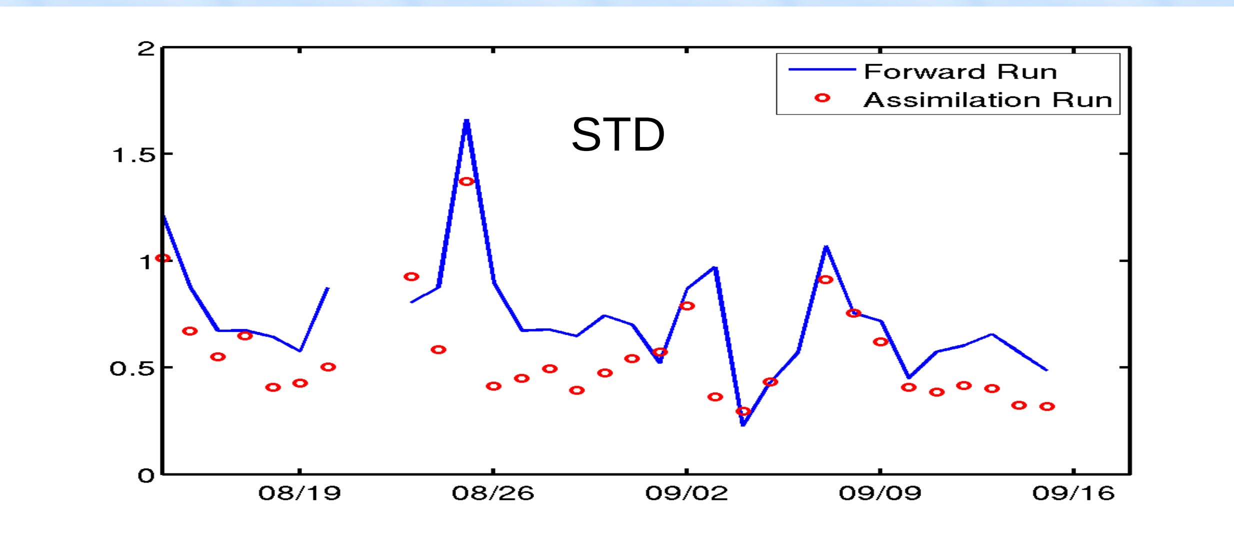
Comparison with observations (AVHRR)

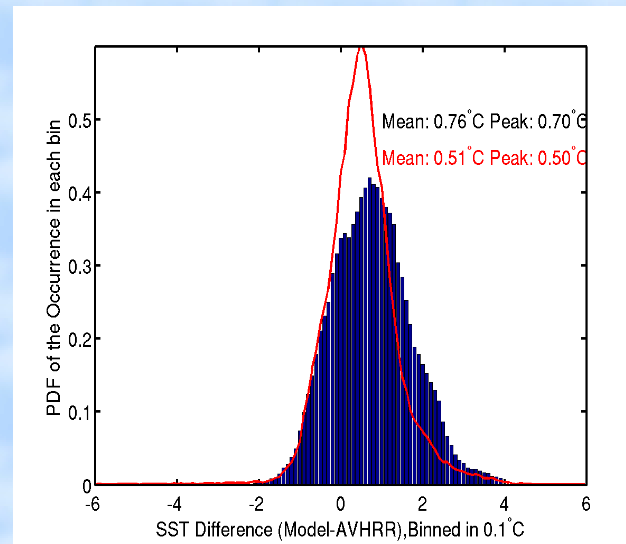
Difference between model and observations at observational location



Total bias reduction: 0.45 Deg_C and Standard deviation of difference also reduced by 0.1

A few low SST values are assimilated here.



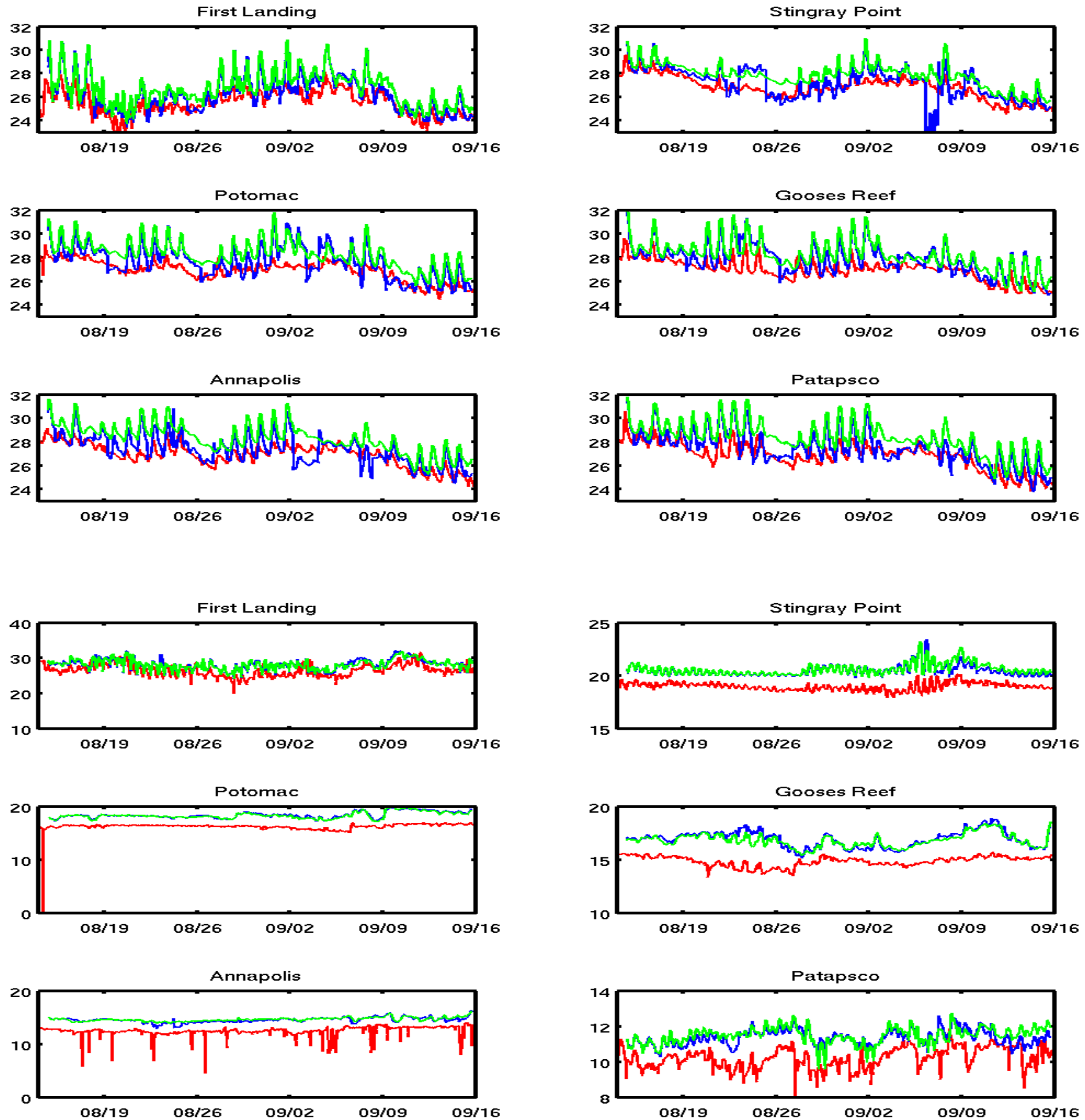


Comparison with observations (CBIBS)

Surface Temperature

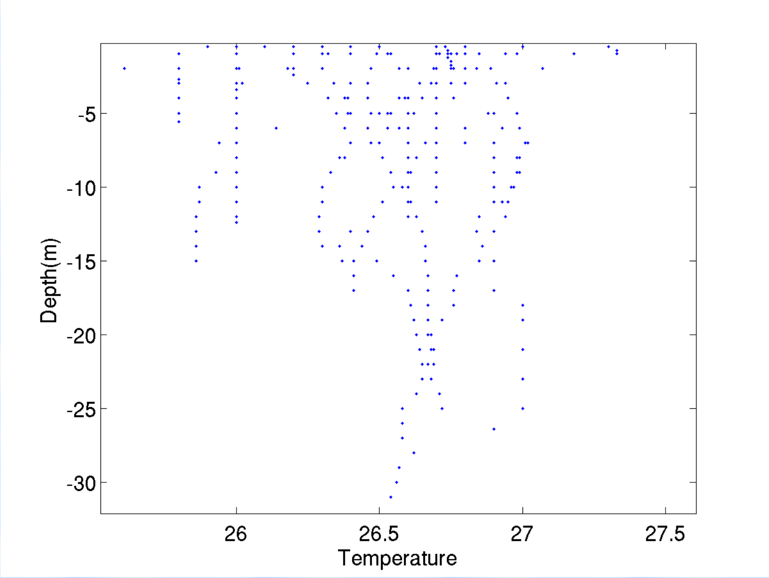
Forward
Assimilation
Observation

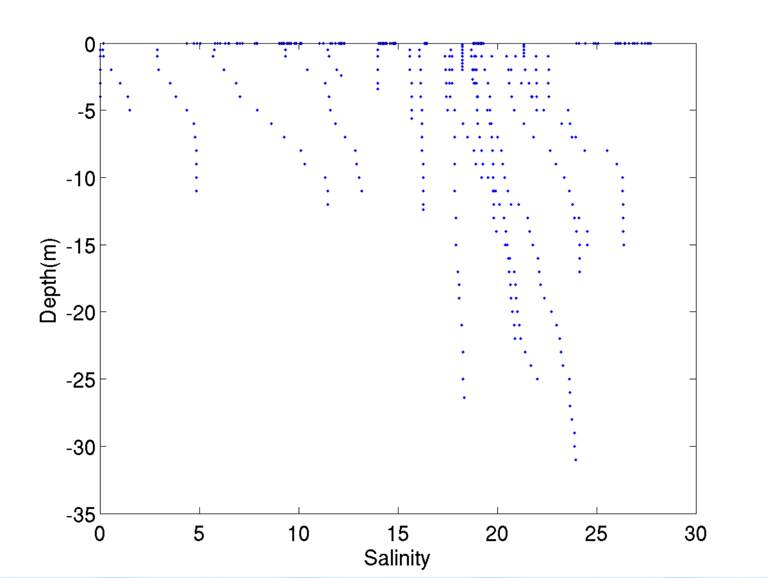
Surface Salinity

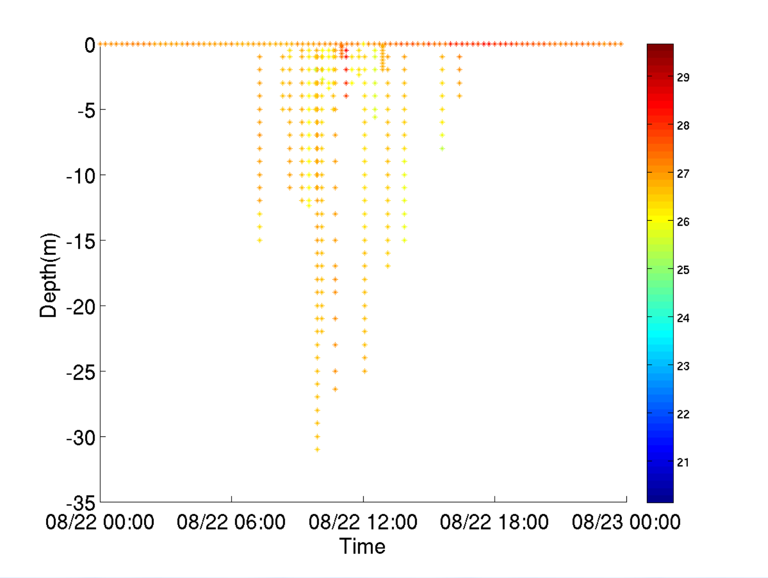


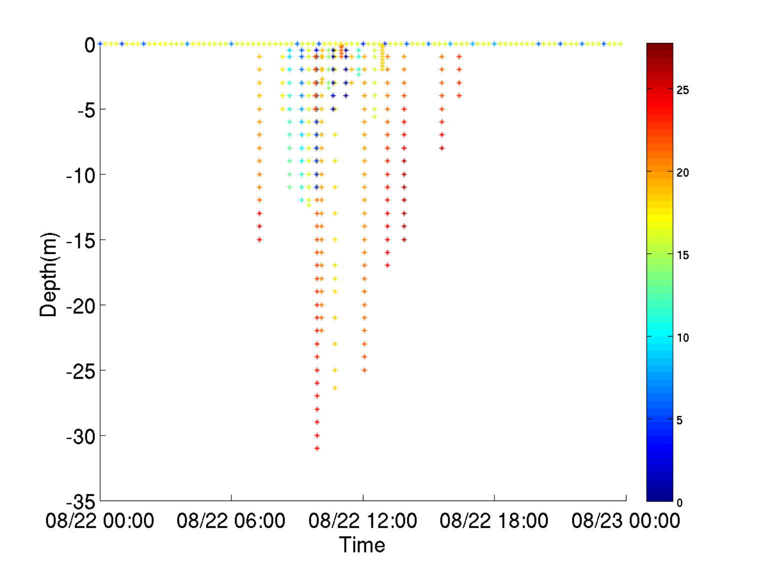
Assimilation with T/S Profiler data

Observational Data at CBIBS (surface) and CBP





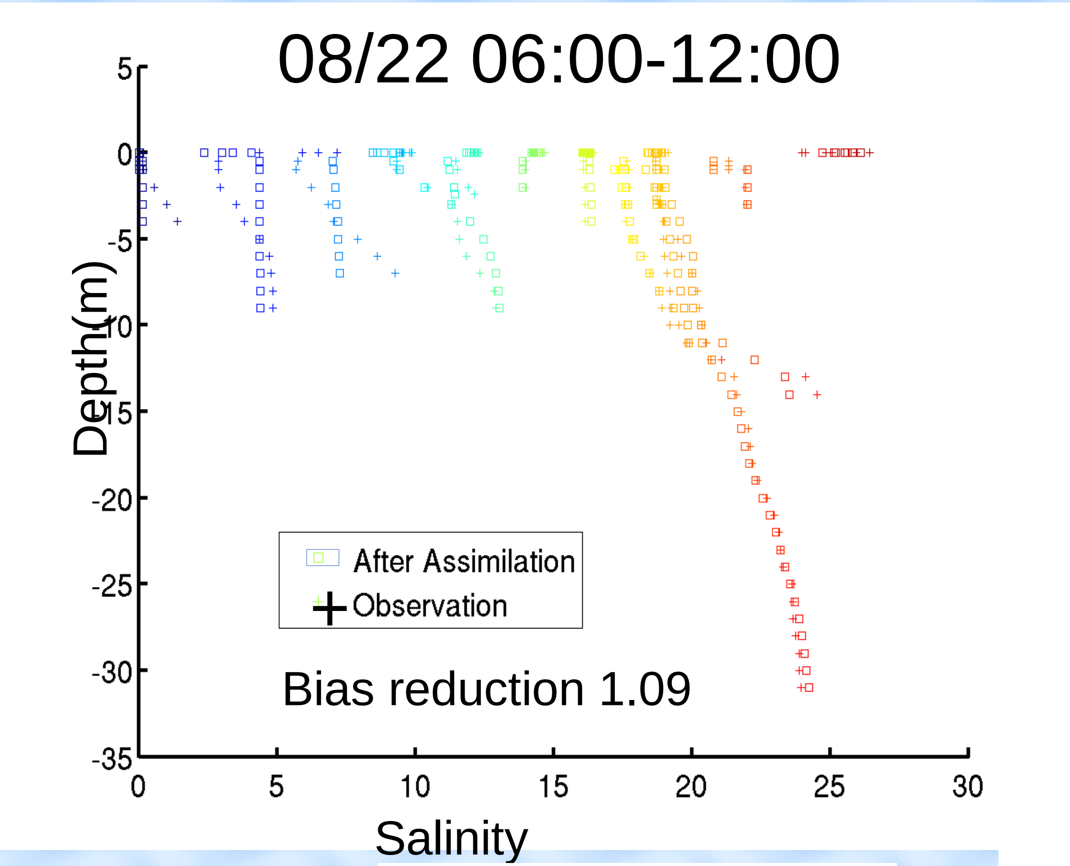


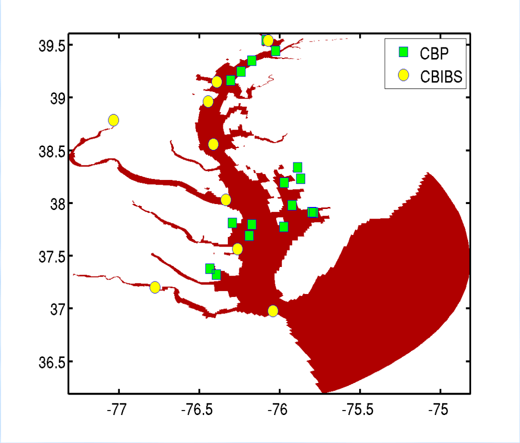


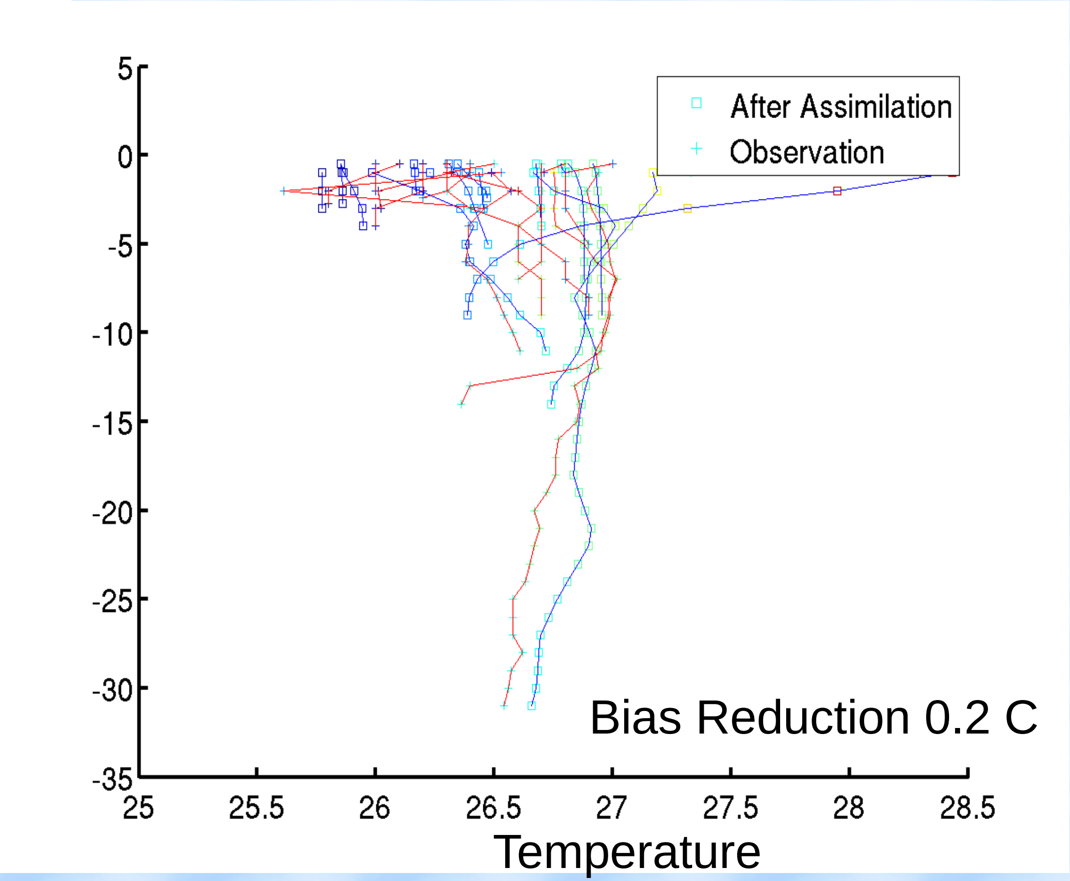
Assimilated Temperature

Assimilated Salinity

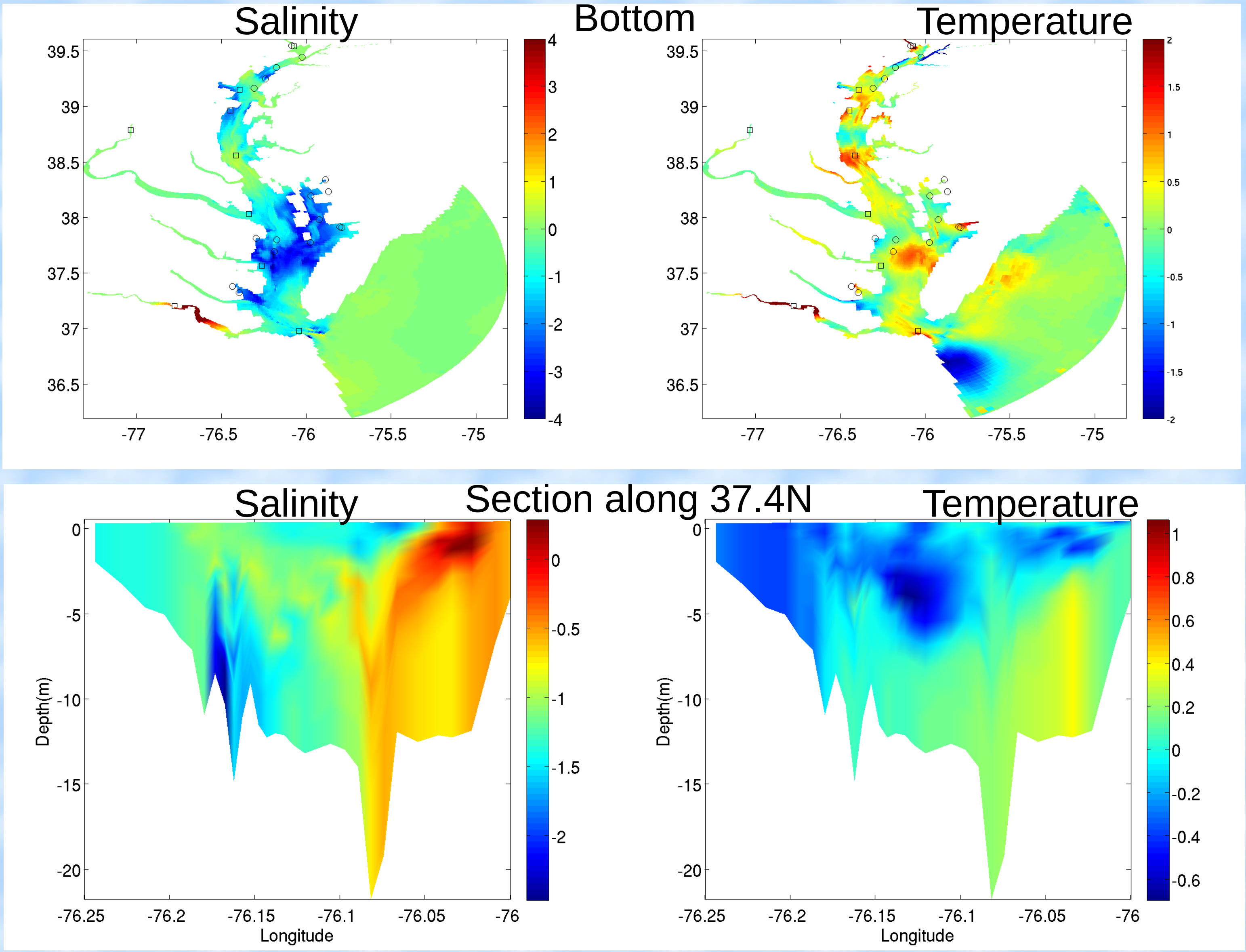
Assimilation with T/S data







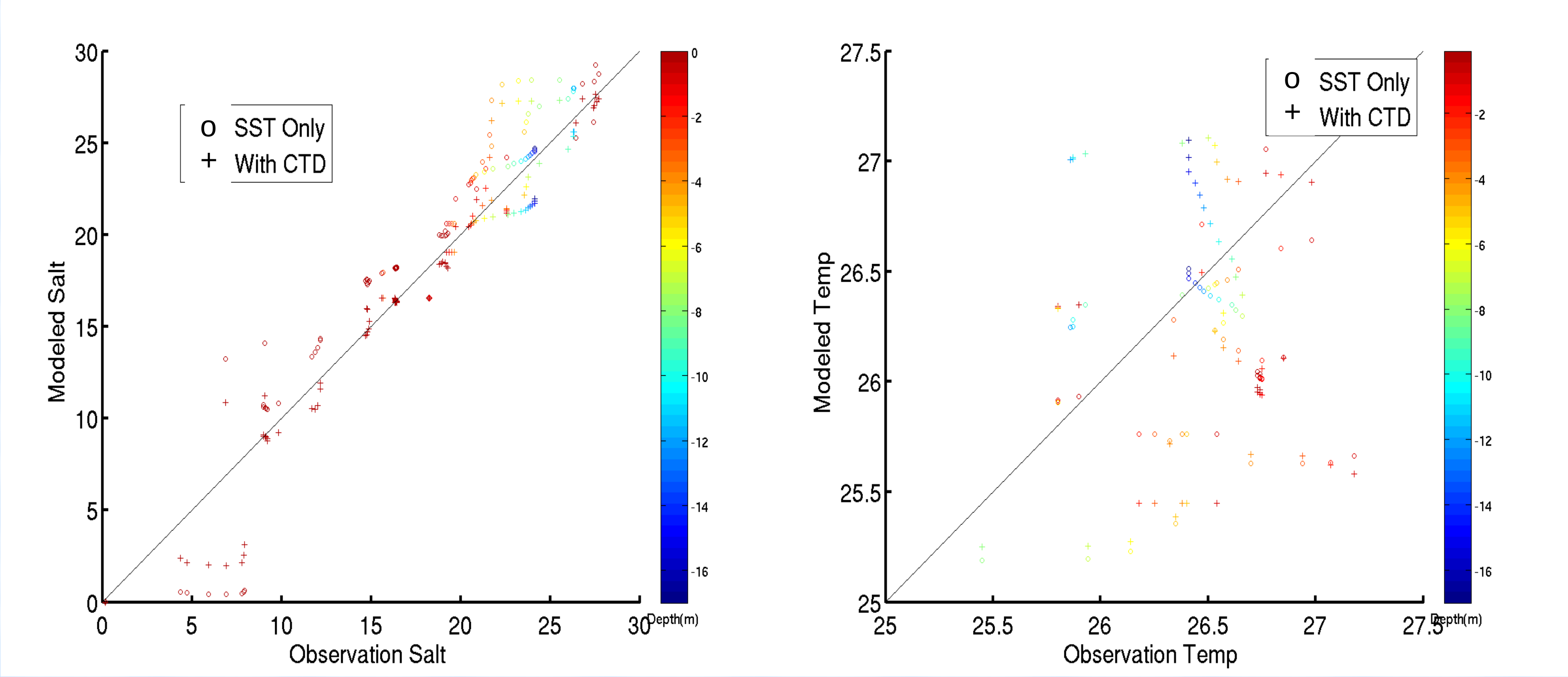
Salt/Temp Changes



Temperature and salinity difference of model runs with and without assimilation of CBP and CBIBS temperature and salinity observations at 18:00 22 August 2012 along a transect 37.41ºN. Both cases are assimilated with AVHRR SST.

Validation using unassimilated data at forecasting window

08/22 12:00-18:00



Summary

- IS4DVAR has been successfully adapted to CBOFS.
- Assimilating satellite-derived SST not only modifies the initial surface temperature but also changes the vertical profiles of T/S. The impact to other variables mainly occurs near the lower Chesapeake Bay and its mouth area.
- A one month sequential assimilation of AVHRR SST reduces surface SST bias by 0.5°C and the variance compared to observation.
- Assimilating T/S profiles with SST data significantly improves the three dimensional temperature and salinity fields even with small number of CTD observations. Specifically, salinity bias is reduced from 1.09 to -0.38 at the observational locations in the next forward run window. The mean salinity over the whole model grids is reduced by 0.13 within one assimilation window. The total bias in temperature reduction is not significant compared to results with only SST assimilation, at the observational locations around 0.2 Deg_C.
- 4DVAR is computationally expensive.

Ongoing/Future work

- Move simulation to 2014 with VIIRS SST available.
- Compare and Assimilate VIIRS SST (and with CTD/Buoy observations).
- Compare results from LETKF.
- Transfer one of data assimilation method into operational mode (regarding the computational cost, performance etc) to CSDL/CO-OPS.

Thanks

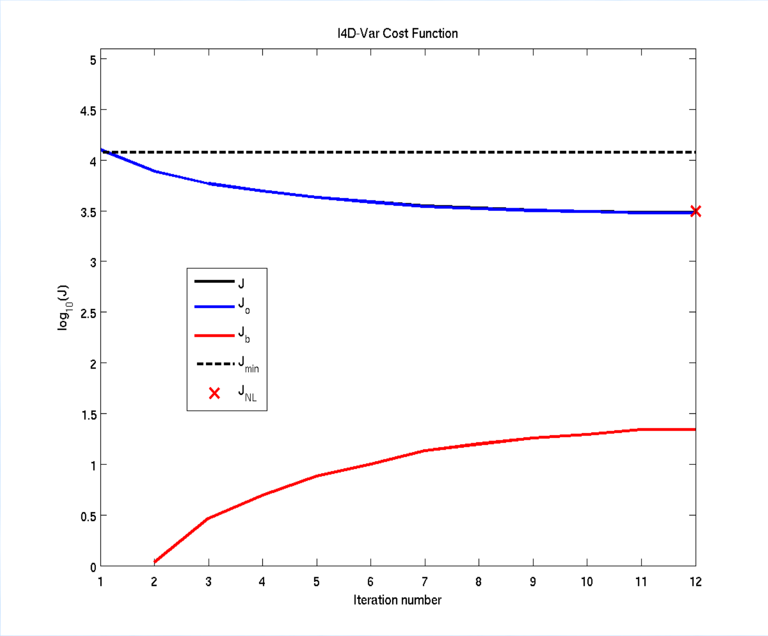
Computational Time Evaluation

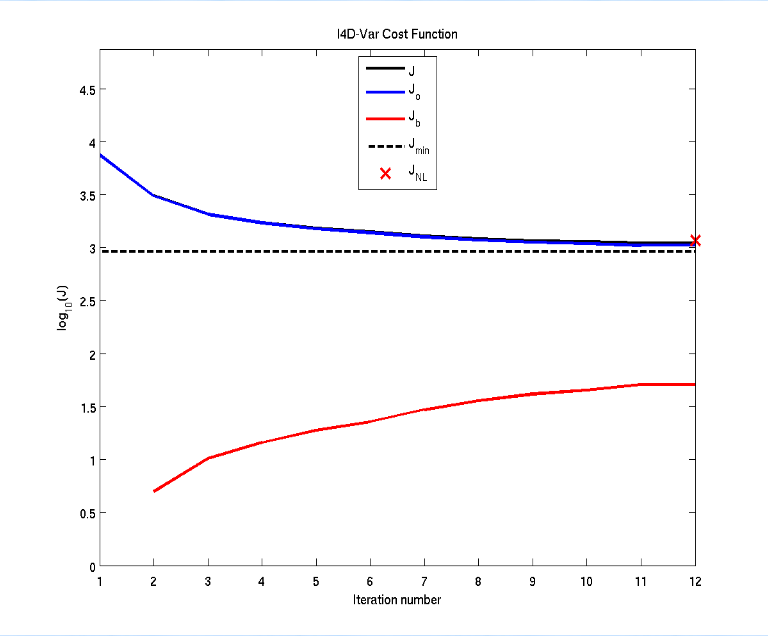
Forward Run (6 hour window)	IS4DVAR with SST only(10 Inner loops)	IS4DVAR with all data (30 inner loops)	Normalization Coefficients (3200 Randomized Steps)
3 minutes	4 hours	18 hours	72 hours /3D; 12hours/2D

Can be manipulated by changing such as assimilation window and inner loop numbers.

NASA NCCS DISCOVER vs UMD DEEPTHTHOUGHT-2

IS4DVAR Cost Function (Adjustment of Initial Condition only)





08/14/2012 12:00
Nobs=23806

08/23/2012 12:00
Nobs=1817

The total penalty function J decreases to a near-stable number in a 10 inner loops.

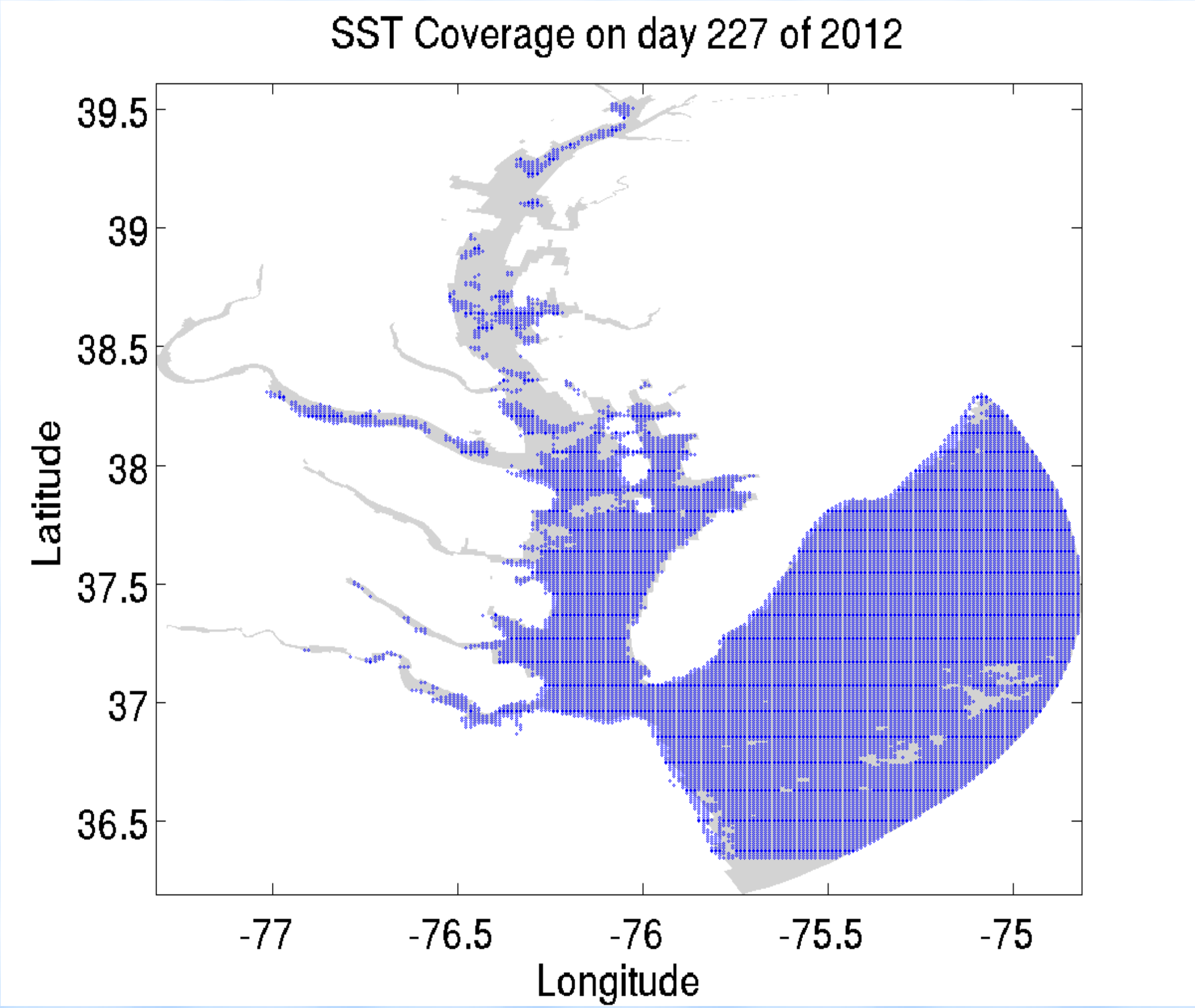
Correlation Matrix C

- Solve a heat diffusion Equations to get C in $[0,\tau_d]$
- $\partial\varphi/\partial\tau=\kappa\nabla^2\varphi\cdots\varphi(\tau)=(4\pi\kappa\tau)^{-1/2}C\varphi(0)$
- $L^2=2\pi\tau_d$ Correlation length scale
- Further Decompose C

$$C=\Lambda_h L_h^{\frac{1}{2}} W_h^{-1}(L_h^{\frac{1}{2}})^T \Lambda_h^T$$

- Range of C is in [-1,1], and Λ is the Normalized Coefficient Matrix, W is the model grid area (Moore et al. 2011).
- ROMS Normalization routine saves Λ as output and use it in 4DVAR (exact and random method).

SST Observational Matrix



Convert observational lon/lat to I/J index in CBOFS