U.S. NAVAL RESEARCH LABORATORY

An overview of past and current ocean data assimilation efforts at the US Naval Research Laboratory (NRL)

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INTRODUCTION

Numerical models have matured over the years and are now simulating the ocean at very high resolution.

Ocean forecasts still contain errors, especially at smaller scales, due to various sources: boundary conditions (for regional models), external forcing, parameterizations of physics and unresolved processes.

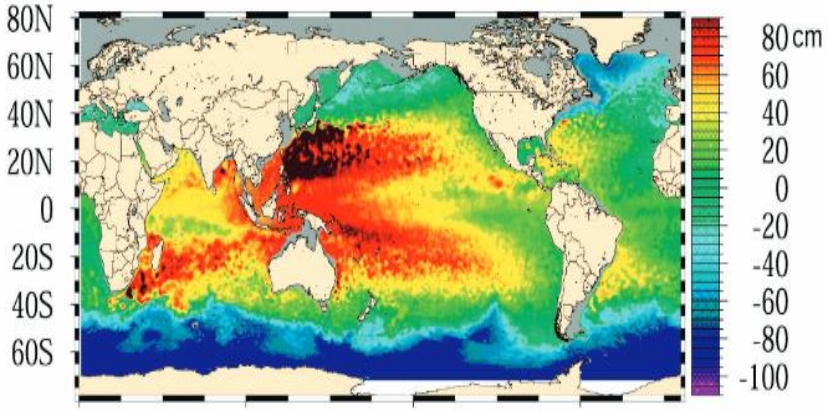
The evolution of ocean DA at NRL also includes the types of observations, as well as how sea surface height (SSH) observations have been projected to the interior: from statistical inference and Cooper-Haines to synthetic profiles and direct assimilation.

Over the past few decades, the U.S. Naval Research Laboratory (NRL) has implemented progressively advanced data assimilation methods (from univariate optimal interpolation to 3D and 4D variational techniques) with increasingly sophisticated models (the Navy Layered Ocean Model (NLOM), the Navy Coastal Ocean Model (NCOM), the Hybrid Coordinate Ocean Model (HYCOM)), ice and waves (SWAN, WW3).

THE MODELS

NLOM

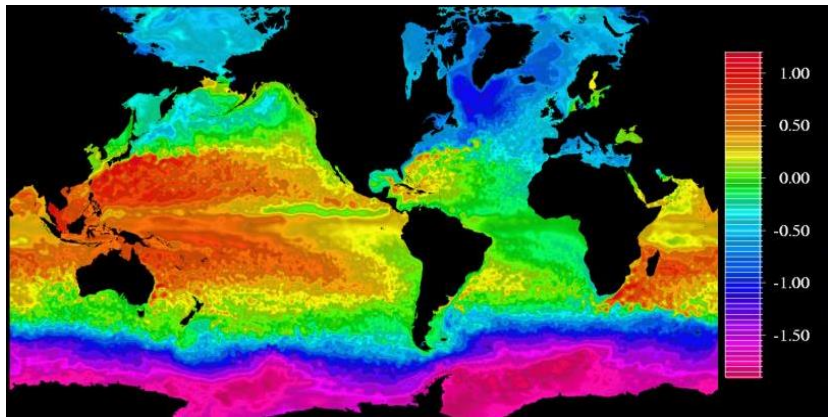
Primitive equation layered model
Free surface, eddy-resolving
72S-65N, no polar latitudes
Depths > 200m
1/16 and 1/11.4 lat-lon resolution
6 vertical layers



Global SSH from NLOM

NCOM

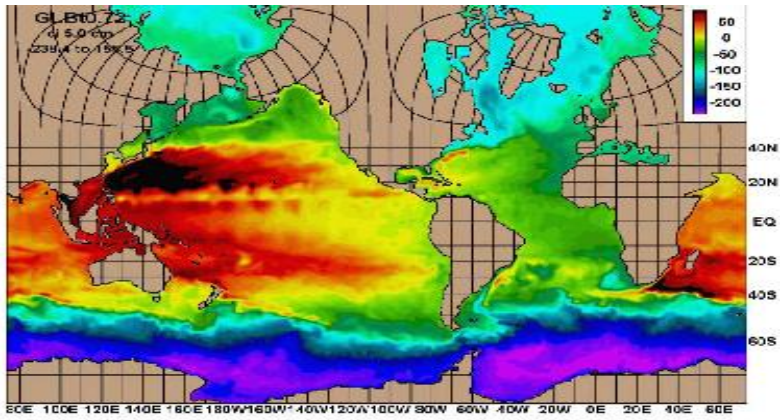
Primitive equation layered model
Free surface, eddy-permitting
80S-Arctic cap
Depths > 5m
1/8 lat-lon resolution
41 sigma-z vertical layers



Global SSH from NCOM

HYCOM

Primitive equation layered model
Free surface
86S-Arctic cap
Depths > 5m
1/25 lat-lon resolution
41 hybrid vertical layers



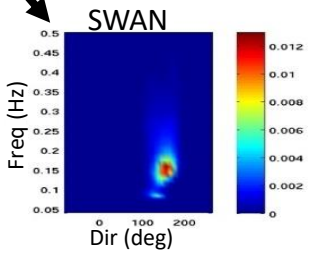
Global SSH from HYCOM

THE MODELS

SWAN

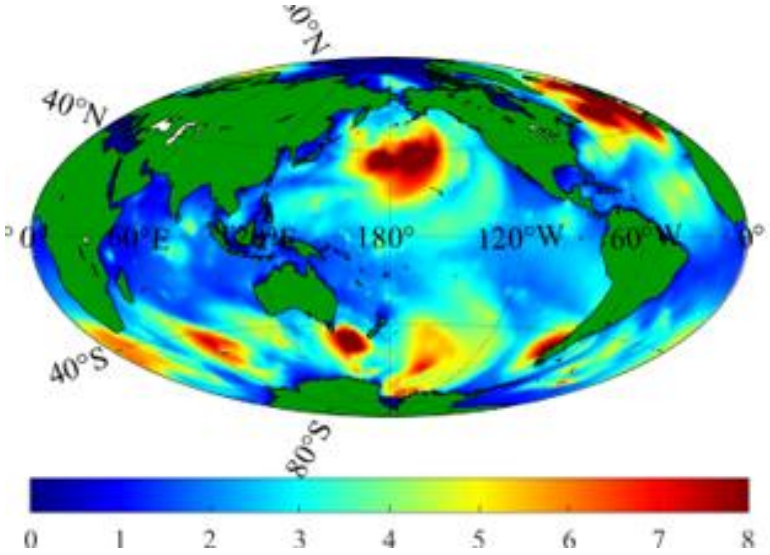
Third generation spectral wave model for nearshore, based on the wave action balance equation with sources and sinks.

SWAN Assimilation Domain & Mini-Buoy Array



WAVEWATCH3

Third-generation phase-averaged wave model solving for spectral action-density
1/2 to 1/10th degree resolution

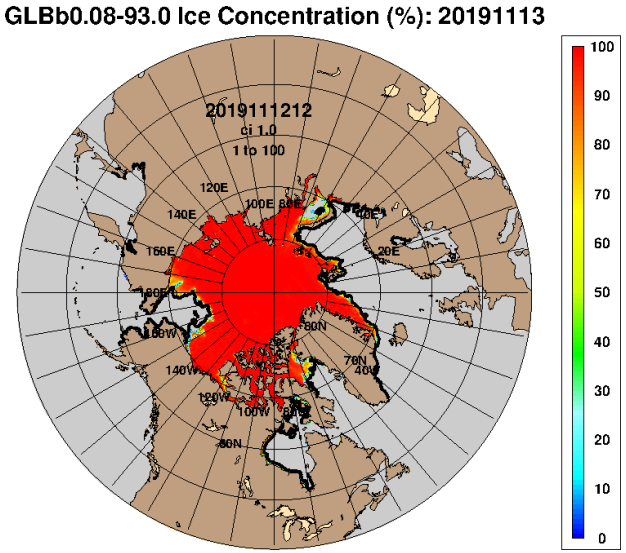


Significant wave Height

CICE

From Polar Ice Prediction System (PIPS) 127 km to 27 km

CICE at 1/12th coupled with HYCOM
Get info from David Hebert



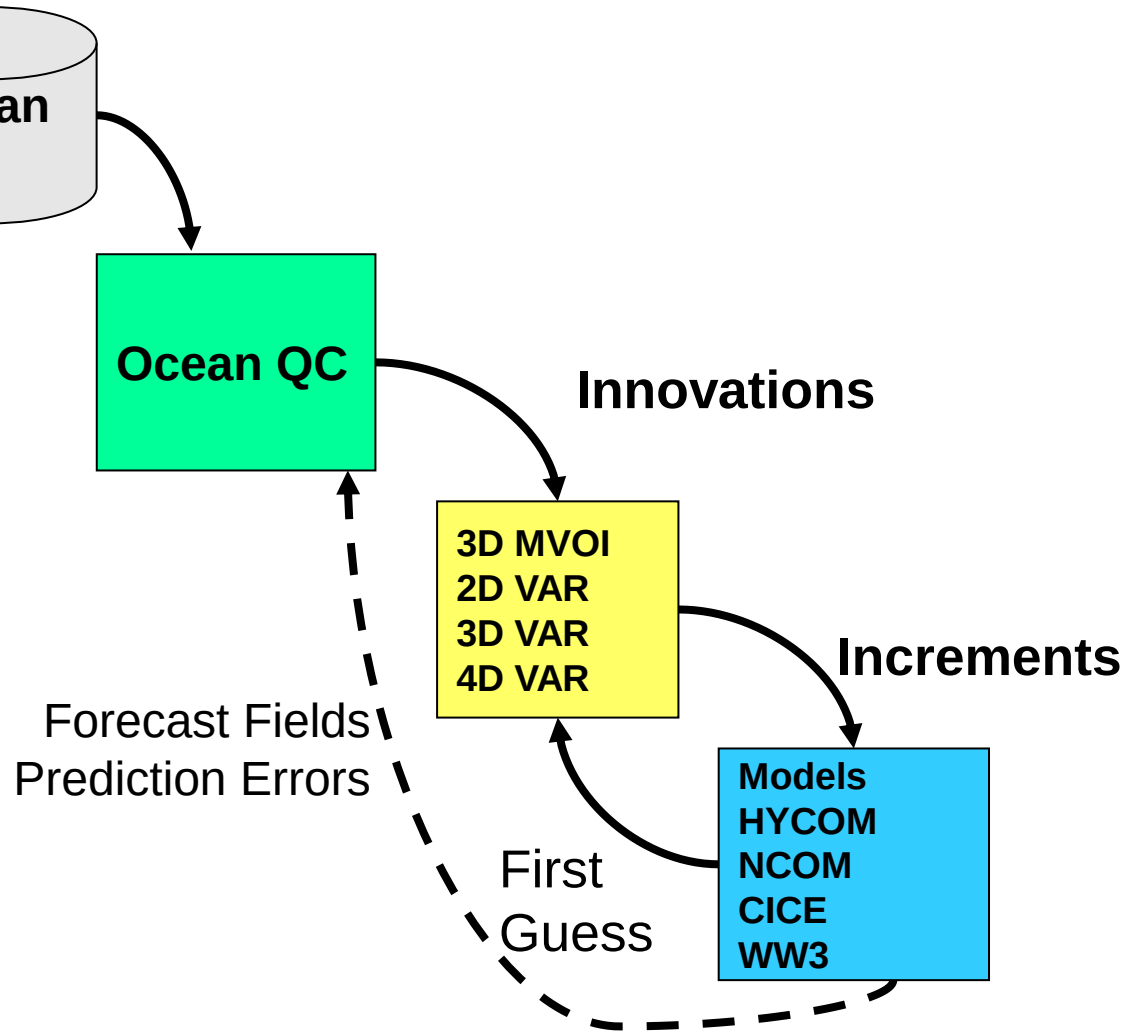
DA METHODS: OCEAN

- **Navy Coupled Ocean Data Assimilation System (NCODA)**
- **Cycling Analysis-Forecast-Analysis system using the incremental analysis update method**

Ocean
- SST (sat & buoy)
- SSHA (Nadir and SWOT altimeters)
- T/S profiles (CTD, XBT, float, glider)
- Velocity profiles (ADCP)
- Surface currents (drifters, HF radar)

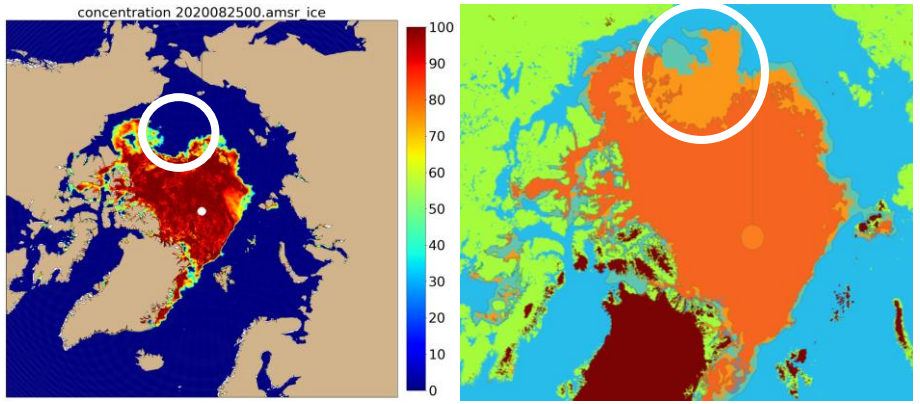
Wave
- Significant wave height
- Wave spectra (in progress)

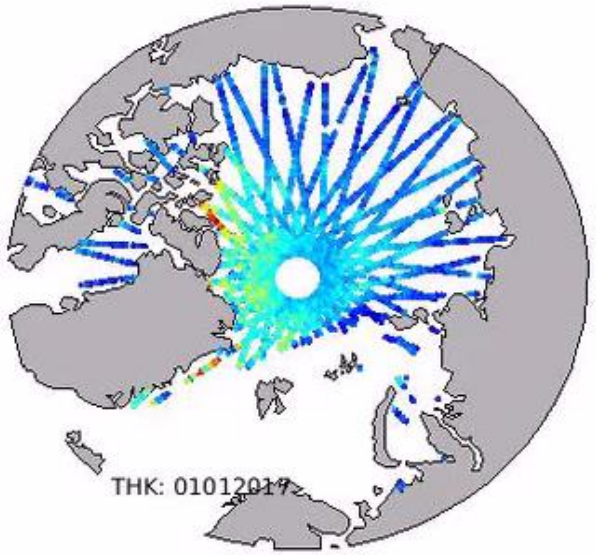
CICE
- Ice concentration
- Ice thickness (in progress)



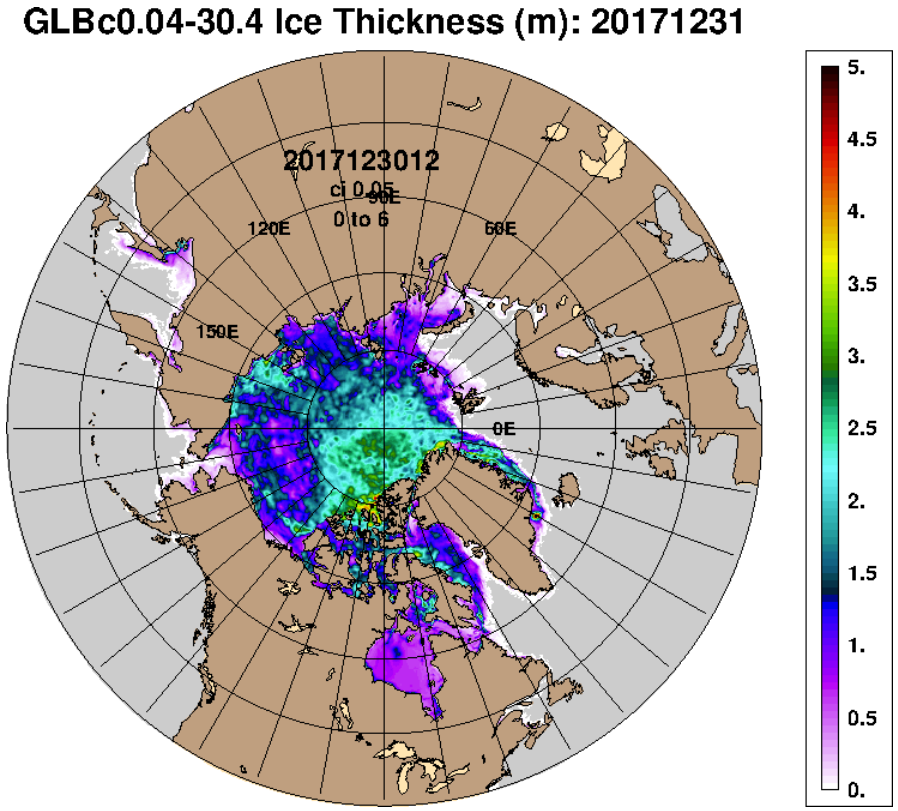
DA APPLICATIONS: ICE

2D assimilation of concentration from SSMI and AMSR2 supplemented by the Interactive Multisensor Snow and Ice Mapping System (IMS)





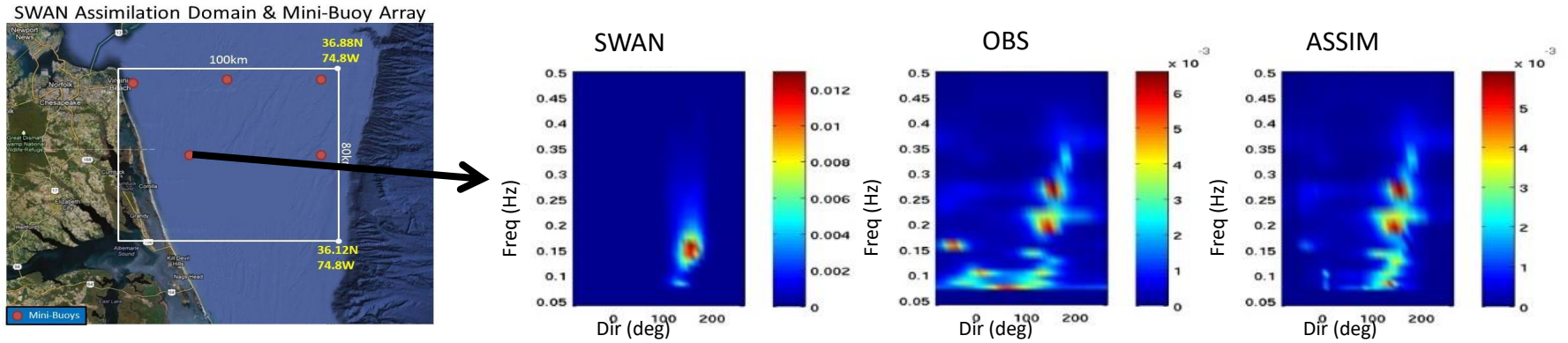
We are currently testing and validating the assimilation of Ice thickness from CryoSat



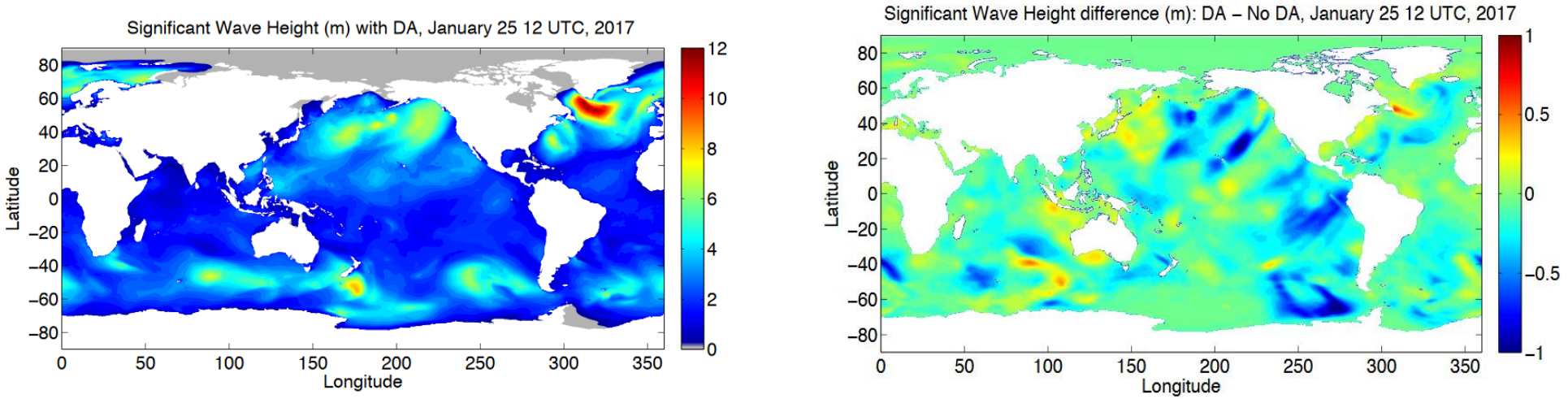
Combined assimilation of ice concentration and ice thickness

DA APPLICATIONS: WAVE

SWAN 4DVAR (SWANFAR)



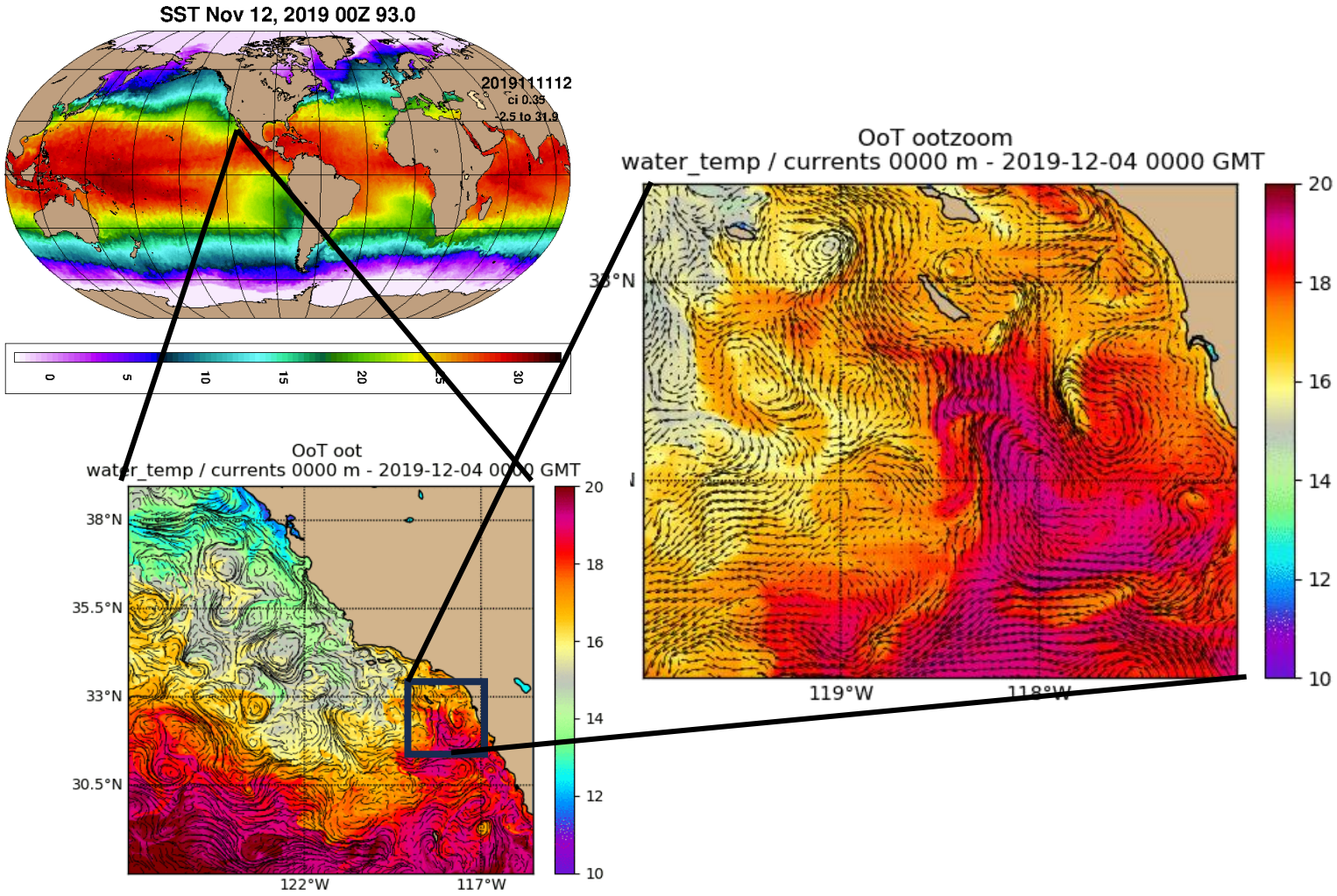
2DVAR HS WW3



4DVAR WW3: Developing tangent linear and adjoint models towards a WW3 4DVAR assimilation of wave spectra data

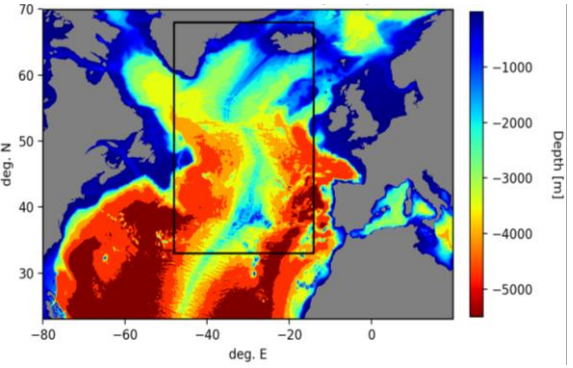
DA APPLICATIONS: OCEAN

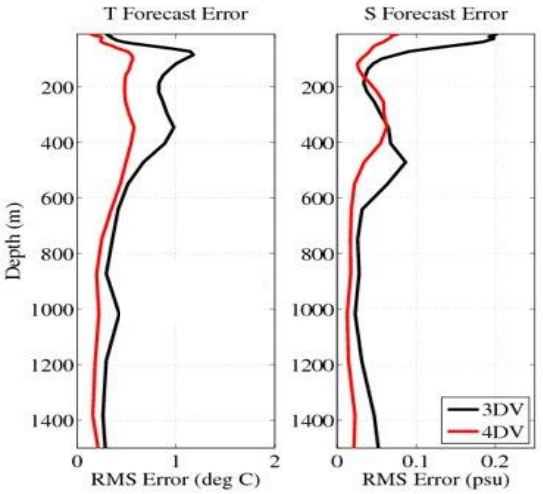
Global model: 3DVAR
SST, T/S profiles, SSH anomalies as synthetic T/S profiles through ISOP
Large scale corrections (Rossby radius of deformation as background error correlation scale

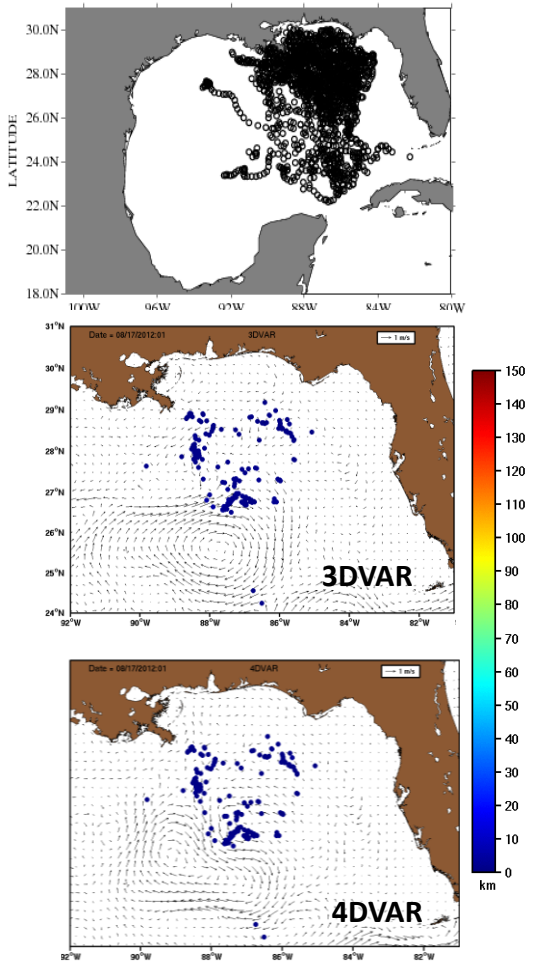


DA APPLICATIONS: OCEAN

North Atlantic NCOM

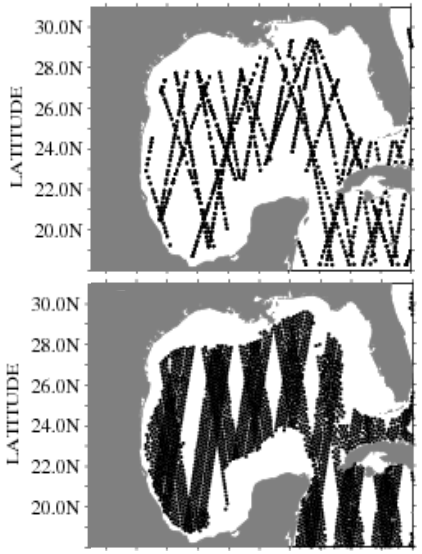




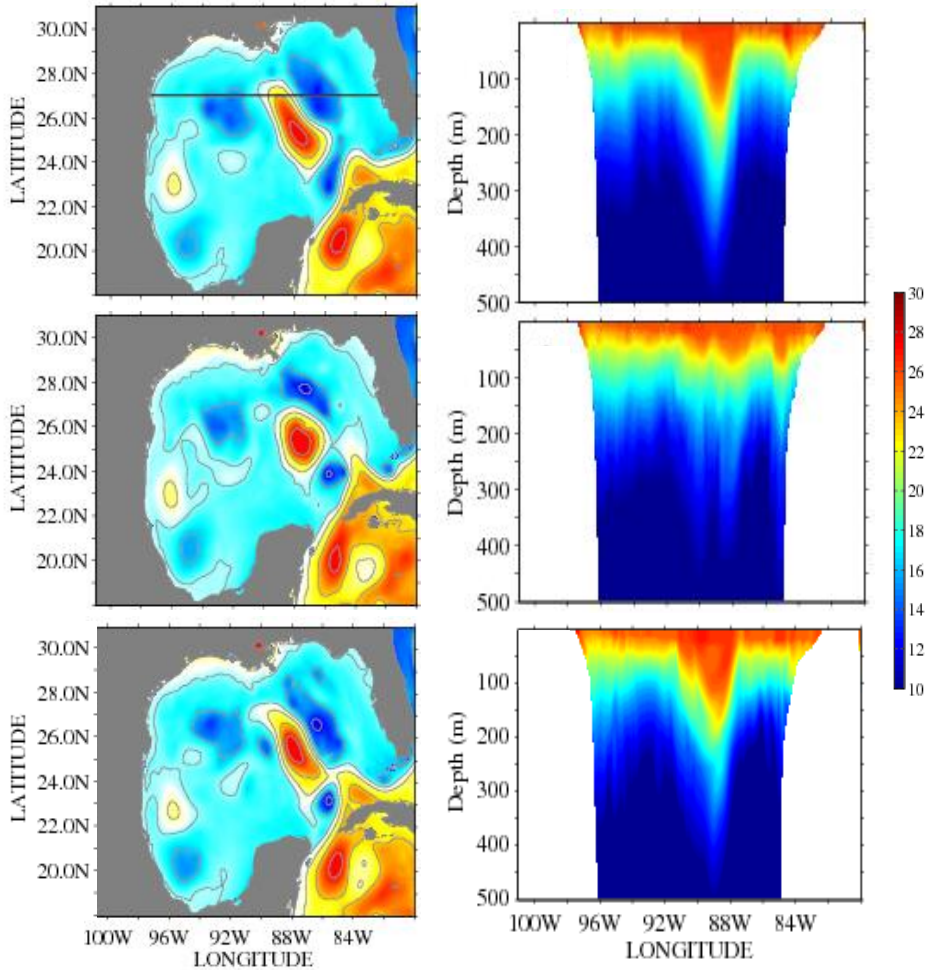


Color represents the distance between the model and real drifters over time

120 hours standard altimetry data



120 hours of SWOT

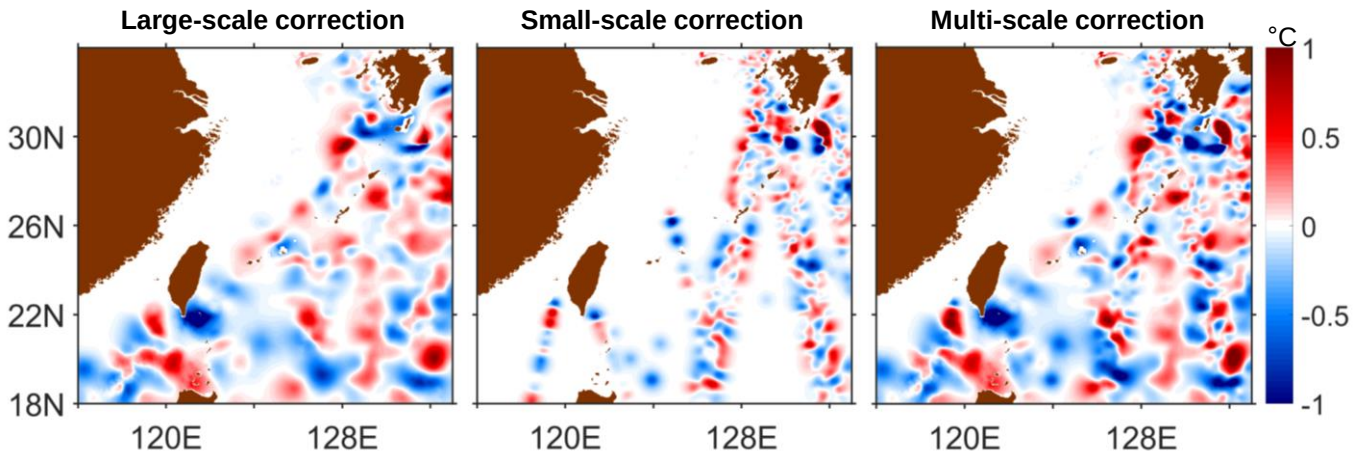


DA APPLICATIONS: OCEAN

Multi-scale DA

$$\delta \mathbf{x} = \mathbf{B}_L \mathbf{H}_L^{\mathrm{T}} \left(\mathbf{H}_L \mathbf{B}_L \mathbf{H}_L^{\mathrm{T}} + \mathbf{R}_L \right)^{-1} \left(\mathbf{y}_L - \mathbf{H}_L \mathbf{x} \right)$$

$$+ \mathbf{B}_S \mathbf{H}_S^{\mathrm{T}} \left(\mathbf{H}_S \mathbf{B}_S \mathbf{H}_S^{\mathrm{T}} + \mathbf{R}_S \right)^{-1} \left(\mathbf{y}_S - \mathbf{H}_S \mathbf{x} \right)$$

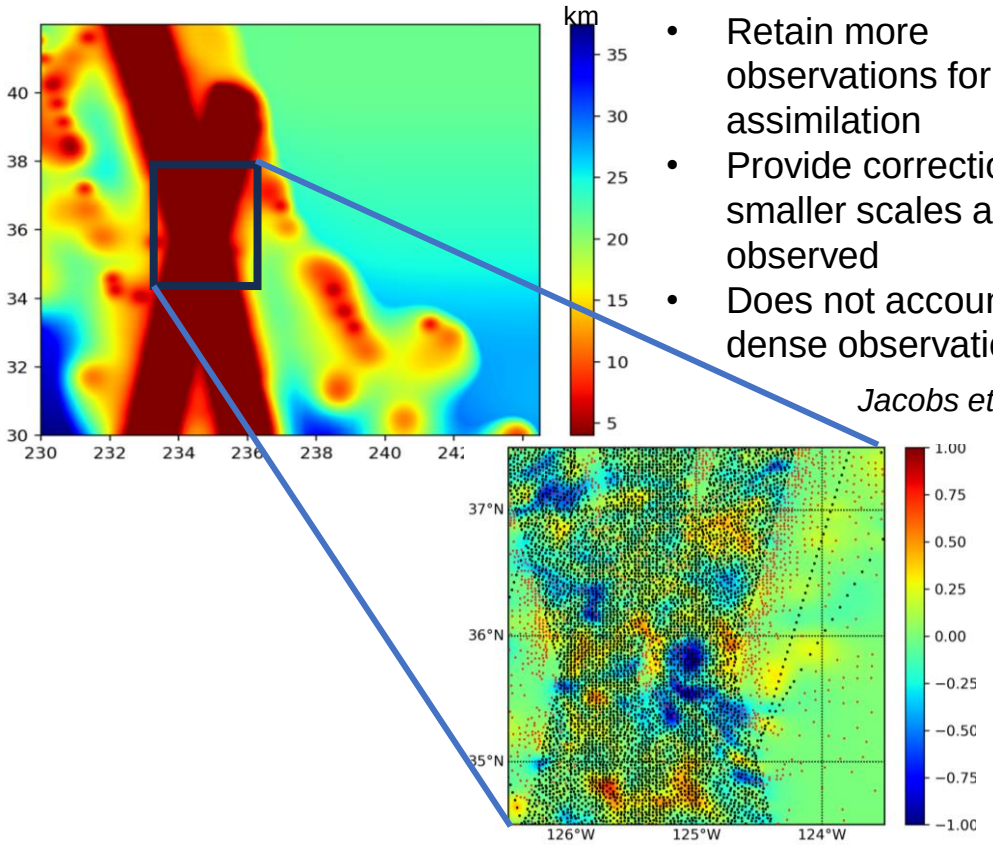


- Good step in the right direction
- Better solution than single-scale
- Scales are arbitrarily divided
- 2-step, but can we afford more?
- Does not account for all dense observations

Adaptive-scale DA

$$\delta \mathbf{x} = \mathbf{B}\mathbf{H}^{\mathrm{T}} \left(\mathbf{H}\mathbf{B}\mathbf{H}^{\mathrm{T}} + \mathbf{R} \right)^{-1} \left(\mathbf{y} - \mathbf{H}\mathbf{x} \right)$$

$$\mathbf{B}(x, x') = V^{1/2}(x) C(x, x', l(x)) V^{1/2}(x')$$



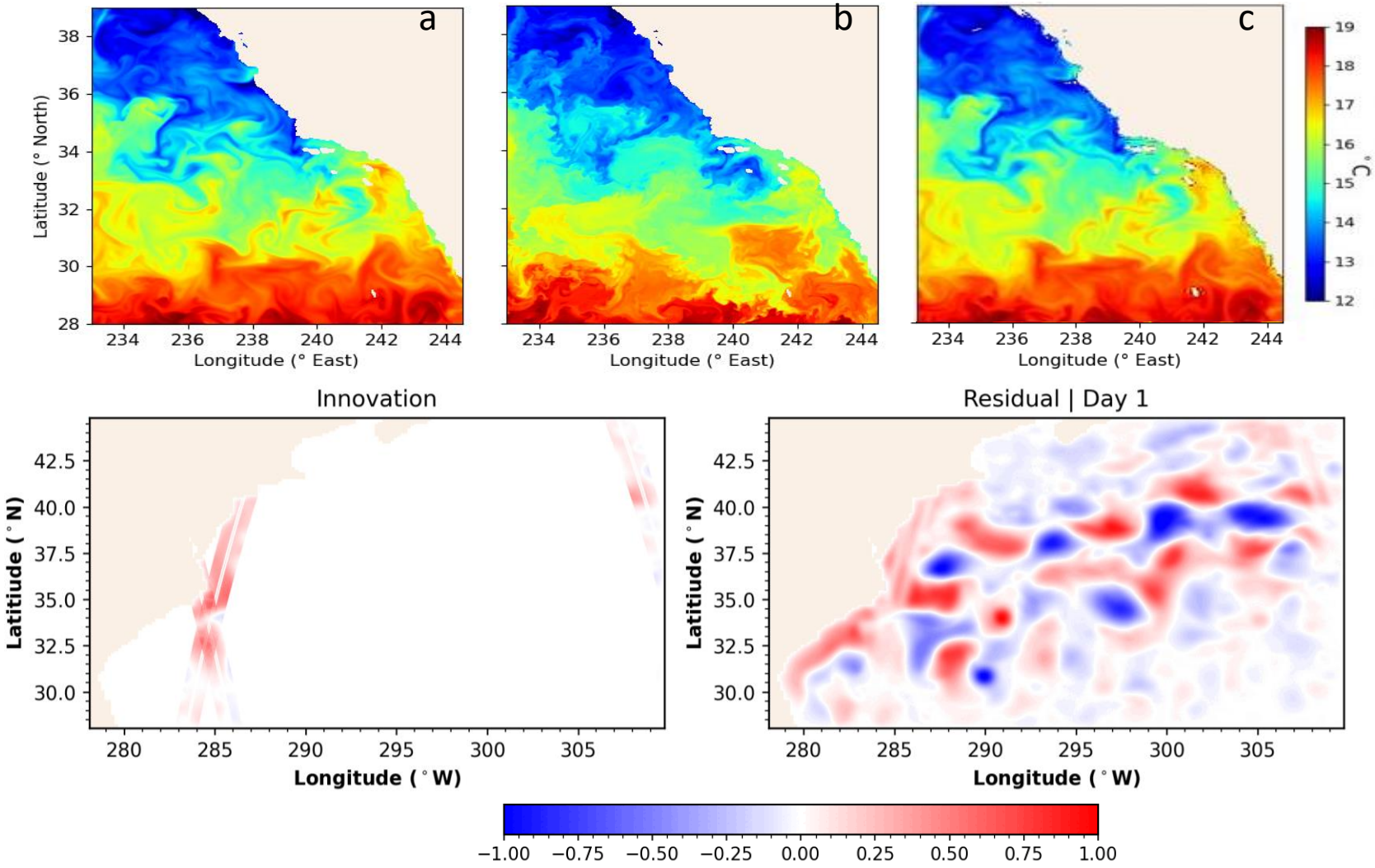
- Retain more observations for assimilation
- Provide corrections at smaller scales as observed
- Does not account for all dense observations

Jacobs et al. 2023

DA APPLICATIONS: OCEAN

Dense observations:
SST assimilation in NCOM
Wavelets vs super-obs

Dense observations:
SWOT assimilation in
QG model



DA APPLICATIONS: OCEAN

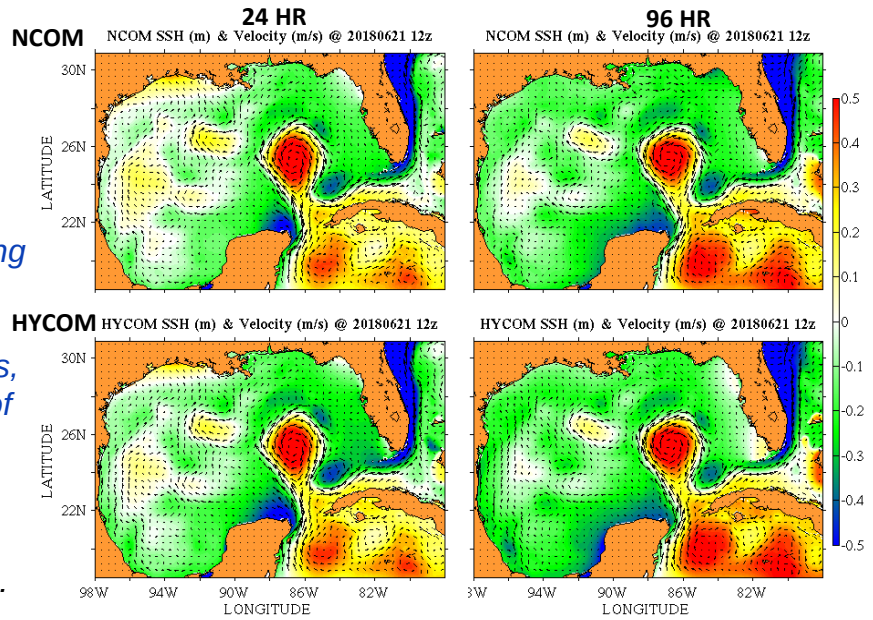
Hypothesis

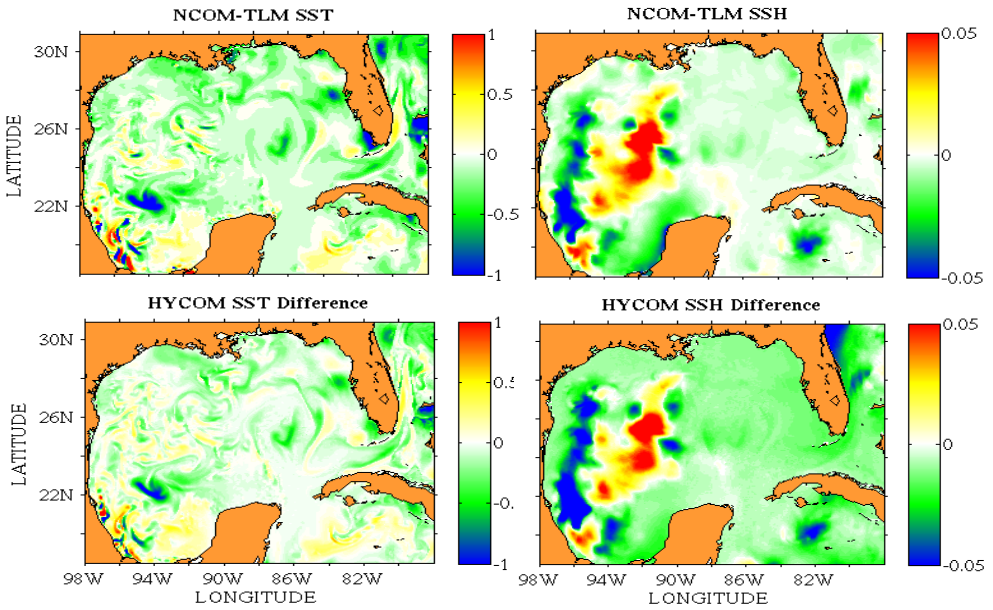
1. NCOM and HYCOM are different numerical representations of the same equations
2. *Given the same set of initial conditions (IC), boundary conditions (BC) and forcing (F) in the same domain with same horizontal resolution, both NCOM and HYCOM should produce similar solutions, over a typical assimilation time window of a few days.*

That is, $N(I) \approx H(I)$, where I=(IC, BC, F)

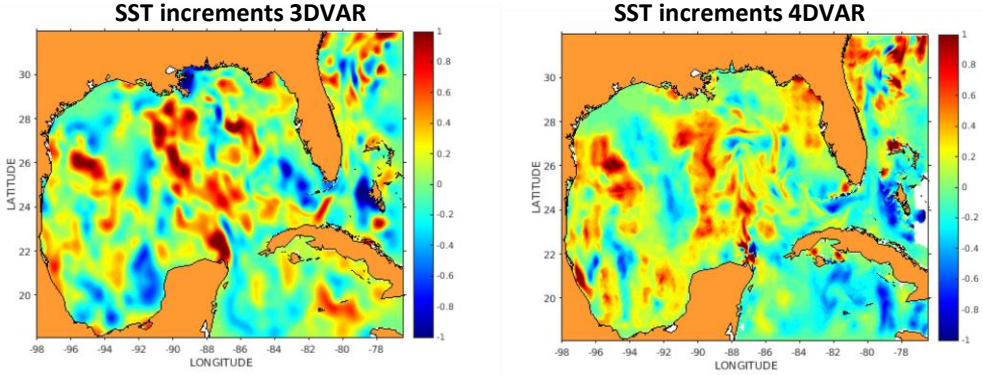
$N(I+\delta I) \approx H(I+\delta I)$, and thus

$N'(I).\ \delta I \approx N(I+\delta I) - N(I) = H(I+\delta I) - H(I) \approx H'(I).\ \delta I$, hence $(N')^T \approx (H')^T$





1. Interpolate z-level output to sigma-Z levels for NCOM and 4DVAR (IC).
2. Run NCOM forecast (to be used as background state for TLM-adjoint)
3. Run NCODA prep (to gather observations and calculate Obs-HYCOM innovations)
4. Run NCOM-based 4DVAR
5. Interpolate 4DVAR increments from sigma-Z to z-levels
6. Convert outputs into file format expected by HYCOM for model updating
7. Run HYCOM forecast



DA APPLICATIONS: OCEAN

Configure the existing 4DVAR system for the Navy Coastal Ocean Model (NCOM) to run in single precision instead of double precision, following the work Hatfield et al (2000).

Compared to the double precision, the single precision provides same accuracy and number of iterations, but much lower computational cost (wall clock time).

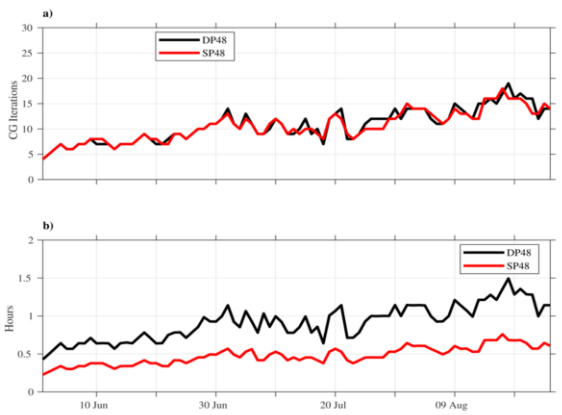
The computational savings with the single precision are invested in outer loops of the 4DVAR system.

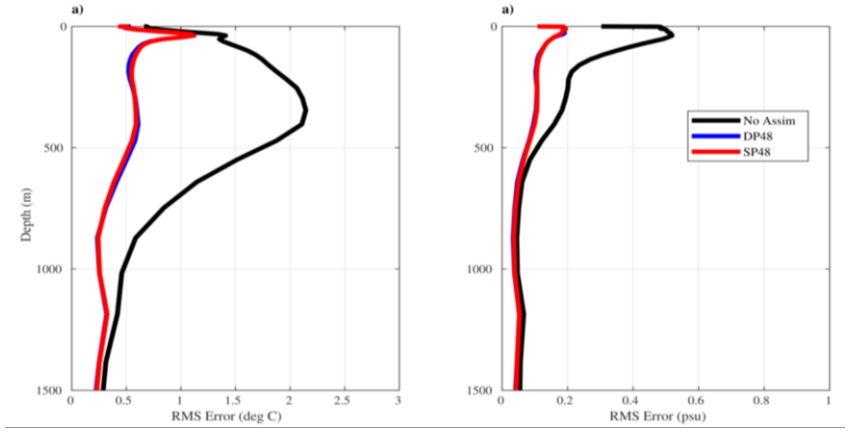
Instead of assimilating all observations at once in one loop, 3 outer loops as follows:

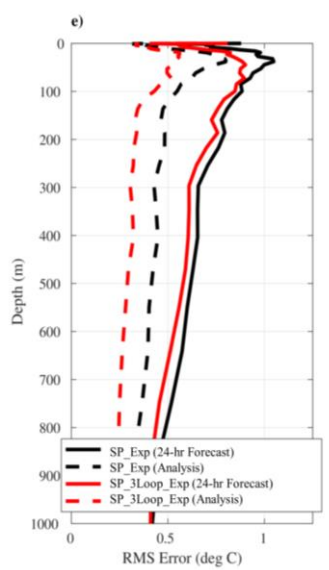
Loop 1: SST assimilation

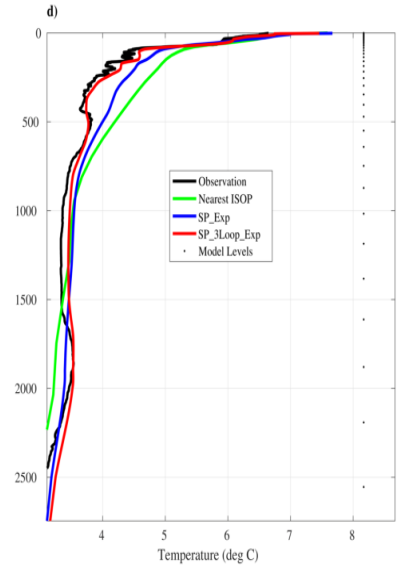
Loop 2: SSHA assimilation via synthetics (needs loop 1)

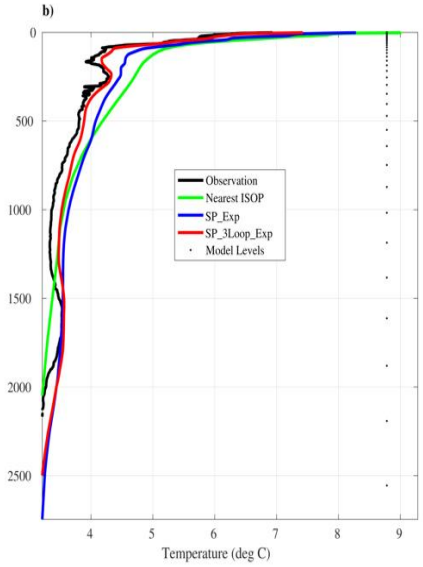
Loop 3: in-situ profiles











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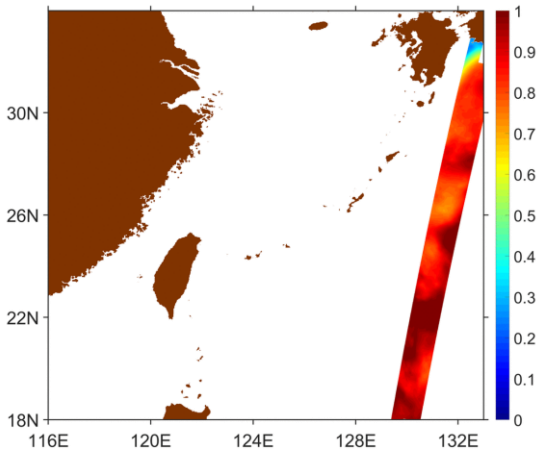

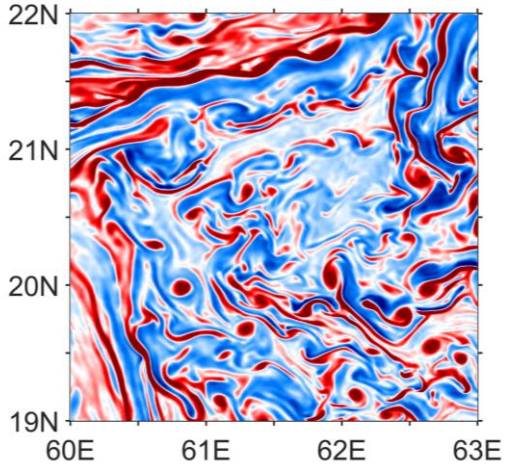

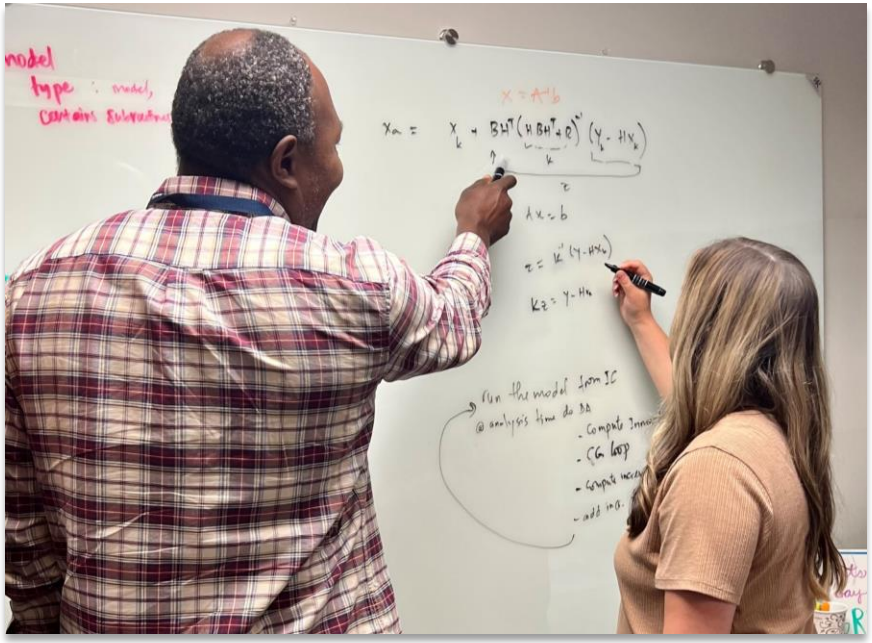

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