ROMS: Advances on Nesting Algorithms

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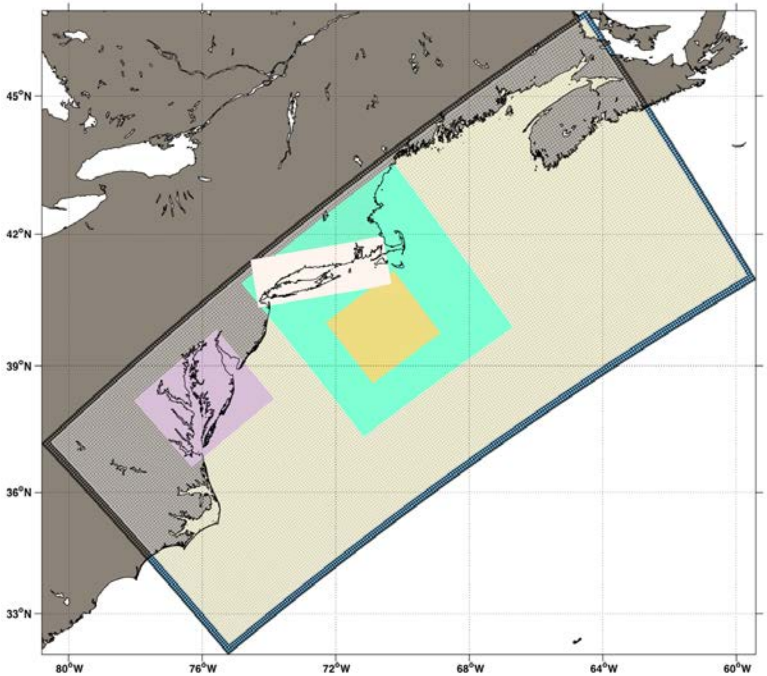

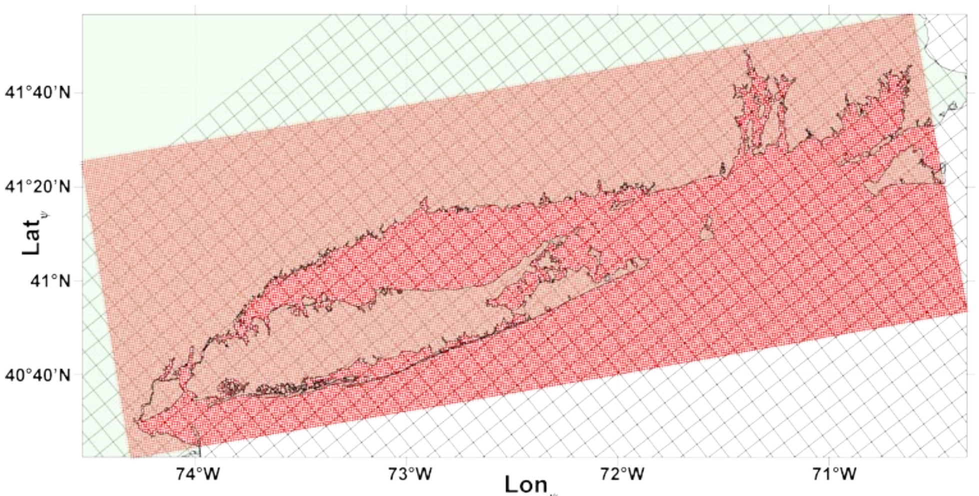

Collaborators

- Andrew M. Moore, U. California Santa Cruz
- John L. Wilkin, DMCS, Rutgers University
- Julia Levin, DMCS, Rutgers University
- John Warner, USGS, WHOI

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Regional Ocean Prediction

To have successful and accurate regional ocean forecasting, the modeling system needs:

- **Atmospheric forcing for the forecast window or by coupling directly to an Atmosphere Model.**
- **To resolve the dynamical spatial and temporal scales for reduction of forecast error. Spatial High-resolution can be achieved with nesting in particular areas while preserving the regional-scale circulation at an affordable computational cost in both atmosphere and ocean grids.**
- **Appropriate lateral, open boundary conditions that minimize forecast error.**
- **Surface and sub-surface observations (in ocean).**
- **Advanced data assimilation schemes to combine models and observations optimally. In ROMS, we have**
  - **Variational Data Assimilation based on either the primal (I4D-Var) or dual (4D-PSAS, R4D-Var) formulation**
  - **Ensemble Adjustment Kalman Filter (EAKF) interface to the Data Assimilation Research Testbed (DART; Jeff Anderson and collaborators at NCAR)**

ROMS Nesting Algorithms

The nesting algorithms in ROMS are unique an flexible to allow complex nested grid configurations in coastal applications. It supports various nested grid classes and capabilities:

- **Aligned and nonaligned composite grids**
- **Aligned and nonaligned refinement grids**
- **Refinement and composite grid combinations**
- **Logically ordered nested grids layers: time-step size arrangement and order for the numerical kernel**
- **Hybrid nesting to other models or external data: Heterogenous Nested Open Boundary Conditions (One-Way only)**
- **One-Way or Two-Way (default) data exchanges**
- **Nested 4D-Var (nested algorithms adjointed)**
- **Nesting and Coupling**

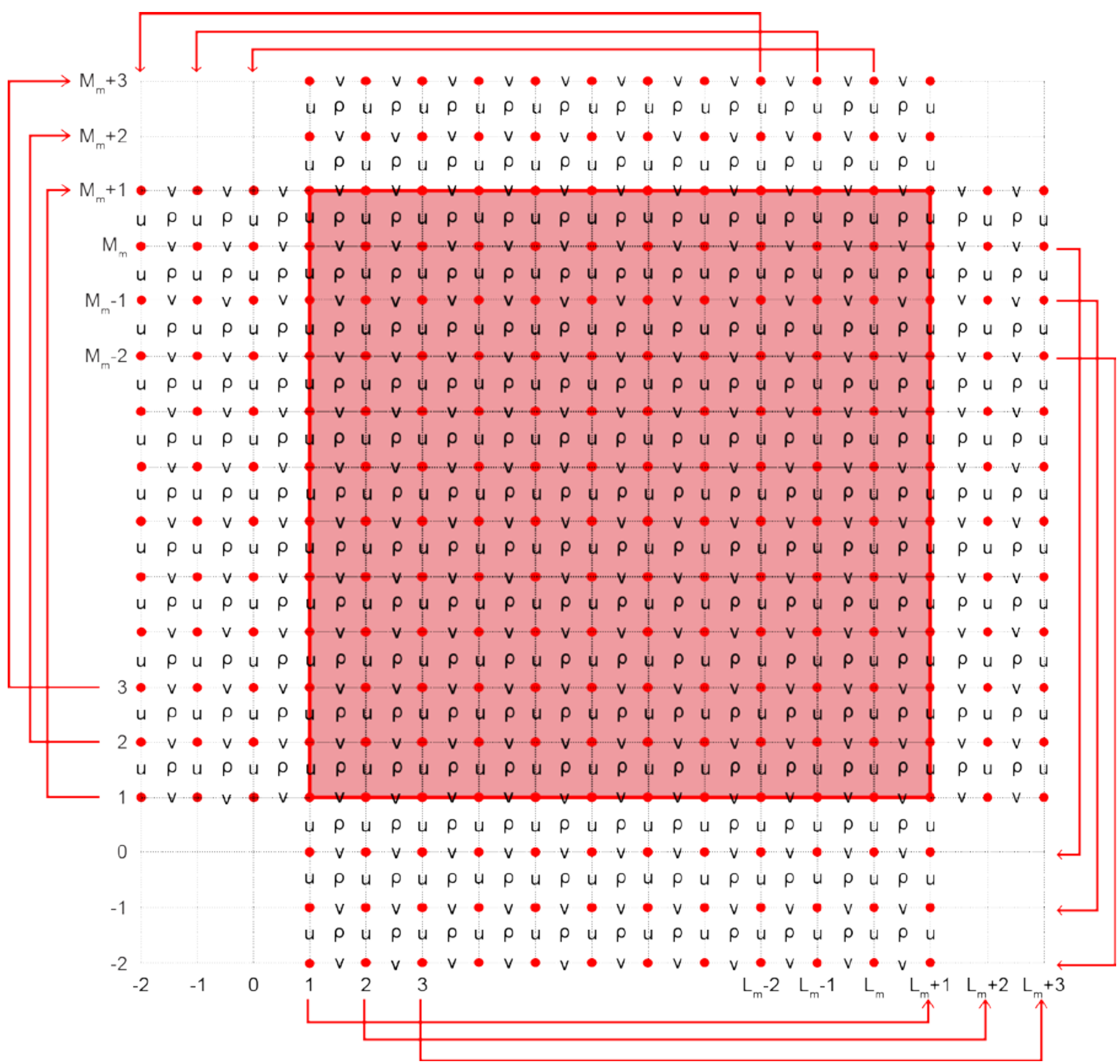
Double-Periodic Physical and Computational Mesh

Nesting Inspiration

East-West Exchange

South-North Exchange

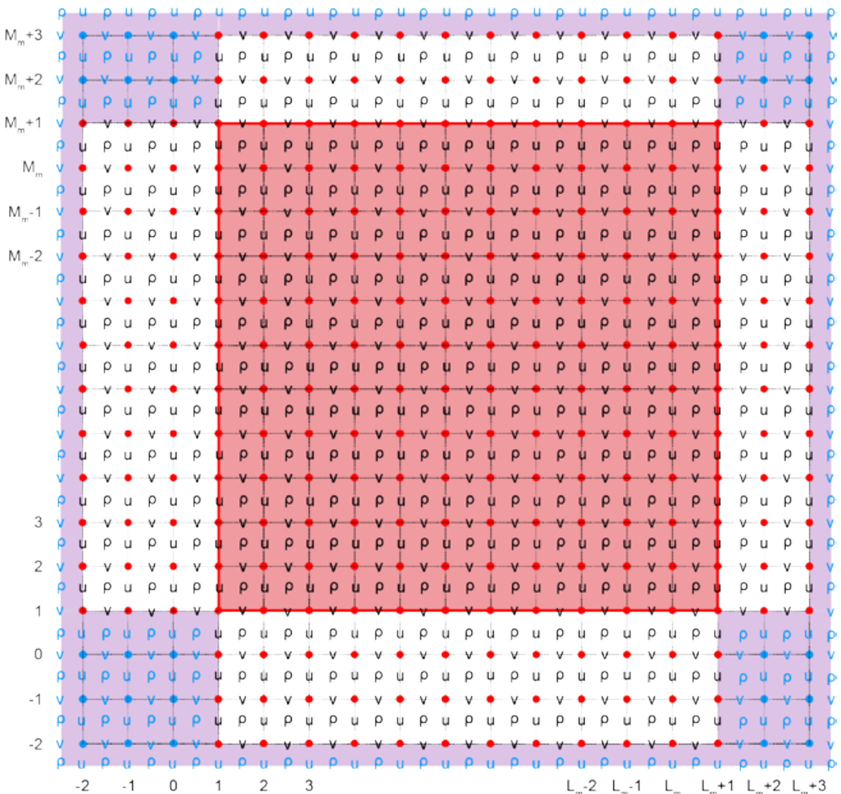
North-South Exchange



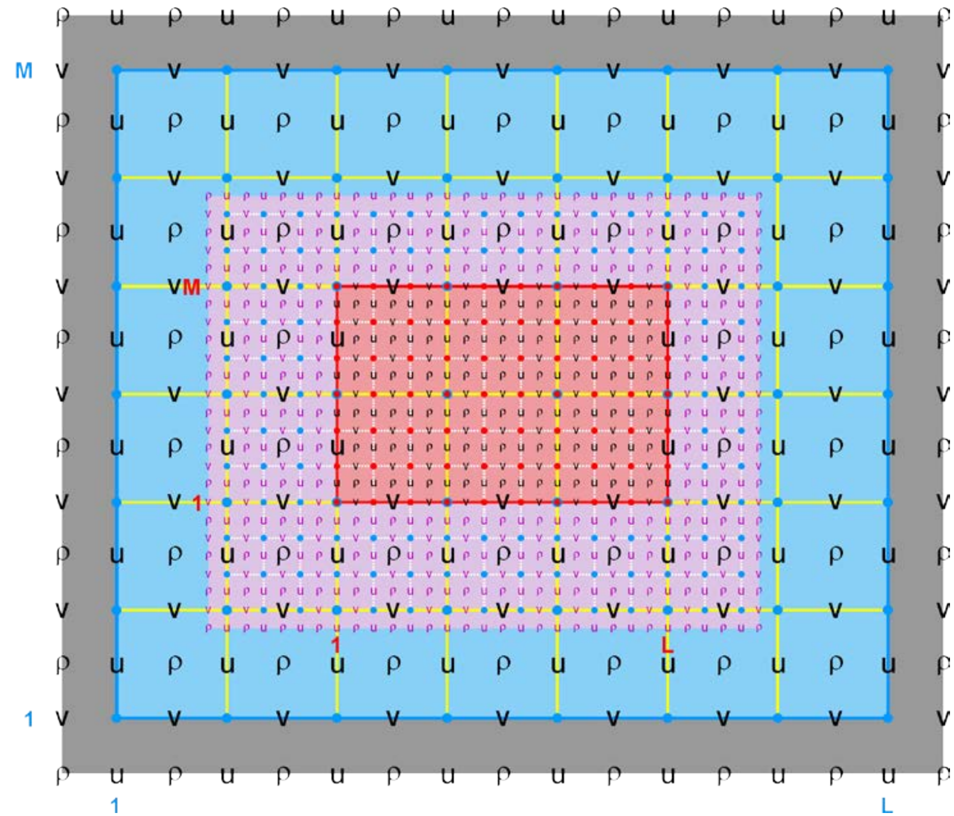
West-East Exchange

Nested Grids: Refinement

(Arakawa C-grid)



Double-Periodic to Refinement



Blue: Coarser Donor Grid

Red: Finer Receiver Grid

Purple: Contact Region and Contact Points

Each Contact Region has a Donor and Receiver grid. The Receiver grid data is interpolated from the Donor grid cell containing the Contact Point. The full governing equations horizontal operator is evaluated at the Contact Points giving the correct flux/gradient at the Receiver grid physical boundary, as in periodic boundary conditions.

Tile I- and J-Ranges

get_bounds.F

```
Istr    = BOUNDS(ng) % Istr    (tile)
IstrB   = BOUNDS(ng) % IstrB   (tile)
IstrM   = BOUNDS(ng) % IstrM   (tile)
IstrP   = BOUNDS(ng) % IstrP   (tile)
IstrR   = BOUNDS(ng) % IstrR   (tile)
IstrT   = BOUNDS(ng) % IstrT   (tile)
IstrU   = BOUNDS(ng) % IstrU   (tile)

Iend    = BOUNDS(ng) % Iend    (tile)
IendB   = BOUNDS(ng) % IendB   (tile)
IendP   = BOUNDS(ng) % IendP   (tile)
IendR   = BOUNDS(ng) % IendR   (tile)
IendT   = BOUNDS(ng) % IendT   (tile)

Jstr    = BOUNDS(ng) % Jstr    (tile)
JstrB   = BOUNDS(ng) % JstrB   (tile)
JstrM   = BOUNDS(ng) % JstrM   (tile)
JstrP   = BOUNDS(ng) % JstrP   (tile)
JstrR   = BOUNDS(ng) % JstrR   (tile)
JstrT   = BOUNDS(ng) % JstrT   (tile)
JstrV   = BOUNDS(ng) % JstrV   (tile)

Jend    = BOUNDS(ng) % Jend    (tile)
JendB   = BOUNDS(ng) % JendB   (tile)
JendP   = BOUNDS(ng) % JendP   (tile)
JendR   = BOUNDS(ng) % JendR   (tile)
JendT   = BOUNDS(ng) % JendT   (tile)
```

```
Istrm3  = BOUNDS(ng) % Istrm3  (tile)     Istr-3
Istrm2  = BOUNDS(ng) % Istrm2  (tile)     Istr-2
Istrm1  = BOUNDS(ng) % Istrm1  (tile)     Istr-1
IstrUm2 = BOUNDS(ng) % IstrUm2 (tile)     IstrU-2
IstrUm1 = BOUNDS(ng) % IstrUm1 (tile)     IstrU-1

Iendp1  = BOUNDS(ng) % Iendp1  (tile)     Iend+1
Iendp2  = BOUNDS(ng) % Iendp2  (tile)     Iend+2
Iendp2i = BOUNDS(ng) % Iendp2i (tile)     Iend+2  interior
Iendp3  = BOUNDS(ng) % Iendp3  (tile)     Iend+3

Jstrm3  = BOUNDS(ng) % Jstrm3  (tile)     Jstr-3
Jstrm2  = BOUNDS(ng) % Jstrm2  (tile)     Jstr-2
Jstrm1  = BOUNDS(ng) % Jstrm1  (tile)     Jstr-1
JstrVm2 = BOUNDS(ng) % JstrVm2 (tile)     JstrV-2
JstrVm1 = BOUNDS(ng) % JstrVm1 (tile)     JstrV-1

Jendp1  = BOUNDS(ng) % Jendp1  (tile)     Jend+1
Jendp2  = BOUNDS(ng) % Jendp2  (tile)     Jend+2
Jendp2i = BOUNDS(ng) % Jendp2i (tile)     Jend+2  interior
Jendp3  = BOUNDS(ng) % Jendp3  (tile)     Jend+3
```

Suffix:

R : tile RHO-points
U : tile U-points
V : tile V-points

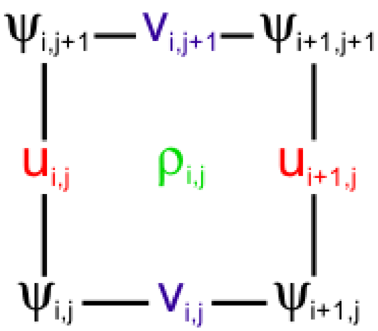
B : Boundary tile RHO- and V-points
M : Boundary tile PSI- and U-points
P : Nesting PSI-, U-, and V-points
T : Nesting RHO-points

Boundary Tile Indices

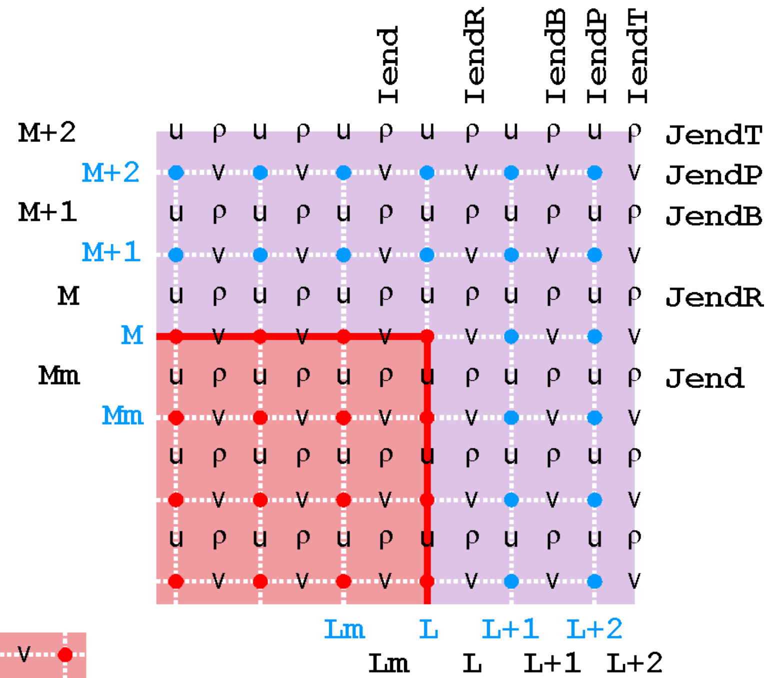
If not nesting grids, the additional boundary tile indices associated with nesting are set to:

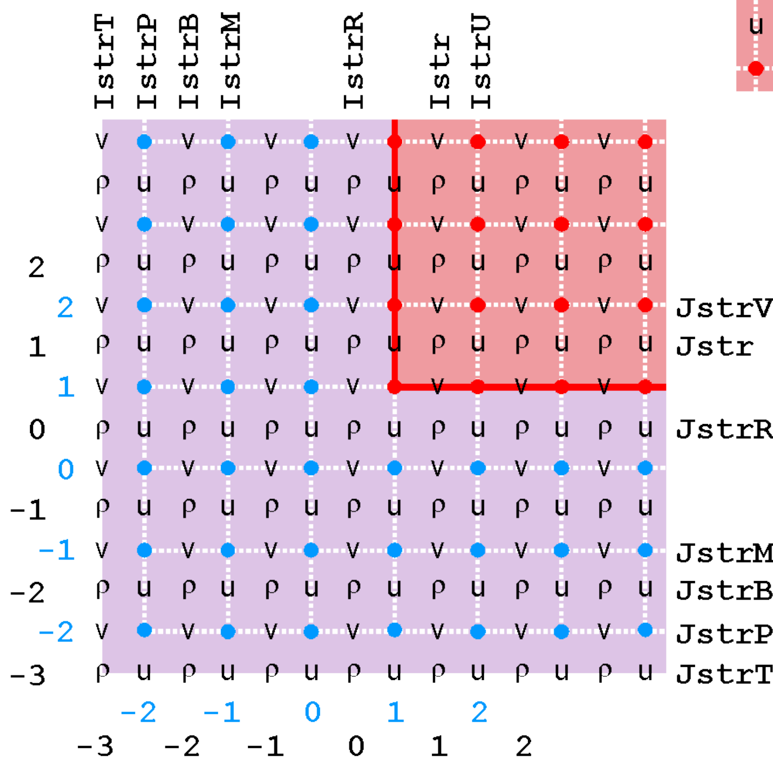
`IstrT = IstrR`	full range, starting I- direction (RHO-point)
`IendT = IendR`	full range, ending I- direction (RHO-point)
`JstrT = JstrR`	full range, starting J-direction (RHO-point)
`JendT = JendR`	full range, ending J-direction (RHO-point)
`IstrP = Istr`	full range, starting I- direction (PSI-, U-point)
`IendP = Iend`	full range, ending I- direction (PSI-point)
`JstrP = Jstr`	full range, starting J-direction (PSI-, V-point)
`JendP = Jend`	full range, ending J-direction (PSI-point)
`IstrB = Istr`	interior range, starting I- direction (RHO-, V-point)
`IendB = Iend`	interior range, ending I- direction (RHO-, V-point)
`JstrB = Jstr`	interior range, starting J-direction (RHO-, U-point)
`JendB = Jend`	interior range, ending J-direction (RHO-, U-point)
`IstrM = IstrU`	interior range, starting I- direction (PSI-, U-point)
`JstrM = JstrV`	interior range, starting J-direction (PSI-, V-point)

Tile Indices Locations



Right-Handed Indexing





The **Contact Points** in the **Contact Region** (purple) are interpolated from the **Donor** Grid.

The discreate horizontal operators are evaluated at the **Contact Points** yielding a full exchange of information between **Donor** and **Receiver** grids.

The approach is generic to any discrete horizontal operator (like gradient, advection, diffusion , etc.)

Transport Mass Flux

- **The donor (coarser) grid vertically-integrated mass flux is imposed at the receiver (finer) grid physical boundary:**

$$\bar{u}(i_b, :, indx1)_f = \left[\frac{\left(\Delta y_f^{i_b}\right)_u}{\left(\Delta y_c^{i_b}\right)_u} \right] \frac{\left(n_f^{i_b}\right)_u \; DU\_avg2(i_b, :)_c}{D(i_b, :)_f}$$

East and West boundaries

$$\bar{v}(:, j_b, indx1)_f = \left[\frac{\left(\Delta x_f^{j_b}\right)_u}{\left(\Delta x_c^{j_b}\right)_u} \right] \frac{\left(m_f^{j_b}\right)_u \; DV\_avg2(:, j_b)_c}{D(i_b, :)_f}$$

North and South boundaries

where *DU_avg2* and *DV_avg2* are the time-averaged (over all barotropic steps) mass fluxes (m^3/s) used in the 3D momentum equations

Tracer Transport Correction

- If two-way refinement, the coarser grid tracer value is adjusted at the finer grid physical boundary:

$$T_c(i_b - i_o, j_b, k, itrc) = T_c(i_b - i_o, j_b, k, itrc) - MAX\left[0, r\, F_f^{i_b}(j_b) - F_c^{i_b}(j_b)\right]$$

East (i_o=0), West (i_o=1)

$$T_c(i_b, j_b - j_o, k, itrc) = T_c(i_b, j_b - j_o, k, itrc) - MAX\left[0, r\, F_f^{j_b}(i_b) - F_c^{j_b}(i_b)\right]$$

North (j_o=0), South (j_o=1)

where

$$r = \frac{\Delta t_c}{\Delta t_f}$$

time-refinement ratio

and vertically-integrated, horizontal advective fluxes:

$$F_f^{i_b}(j_b) = \sum_{n=1}^{r}\left[\int_{-h}^{\zeta}\left(\frac{H_z u T}{n}\right)_f^{j_b} dz\right] \qquad F_c^{i_b}(j_b) = \frac{mn}{D}\int_{-h}^{\zeta}\left(\frac{H_z u T}{n}\right)_c^{j_b} dz$$

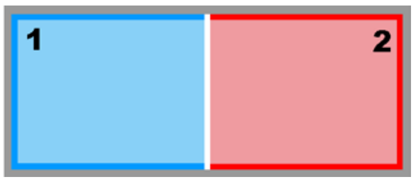
East, West finer and coarser flux

$$F_f^{j_b}(i_b) = \sum_{n=1}^{r}\left[\int_{-h}^{\zeta}\left(\frac{H_z v T}{m}\right)_f^{i_b} dz\right] \qquad F_c^{j_b}(i_b) = \frac{mn}{D}\int_{-h}^{\zeta}\left(\frac{H_z v T}{m}\right)_c^{i_b} dz$$

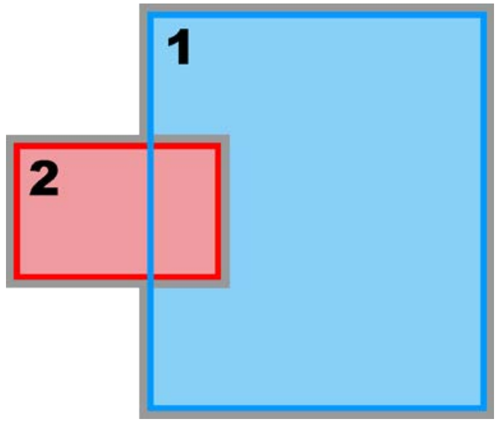
North, South finer and coarser flux

Nesting Configuration Types

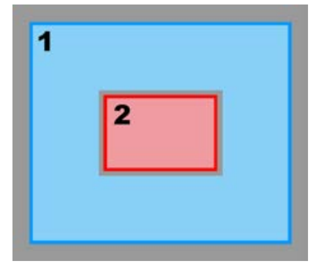
Mosaic



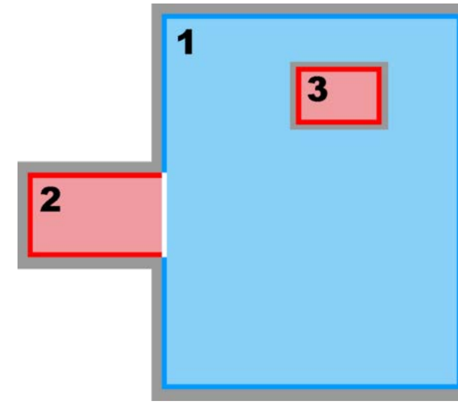
Composite

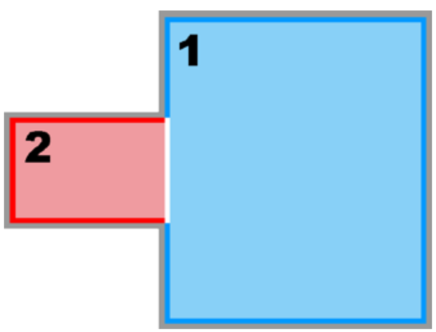


Refinement

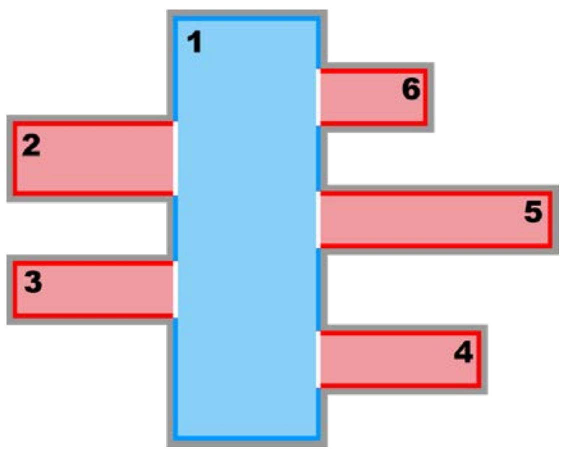


Composite/Refinement

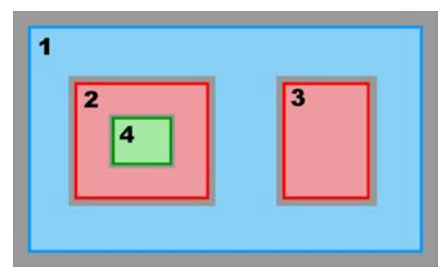




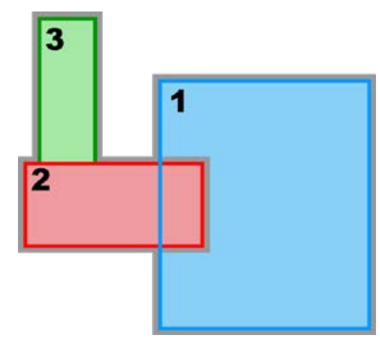
Partial Boundary



Complex Estuary

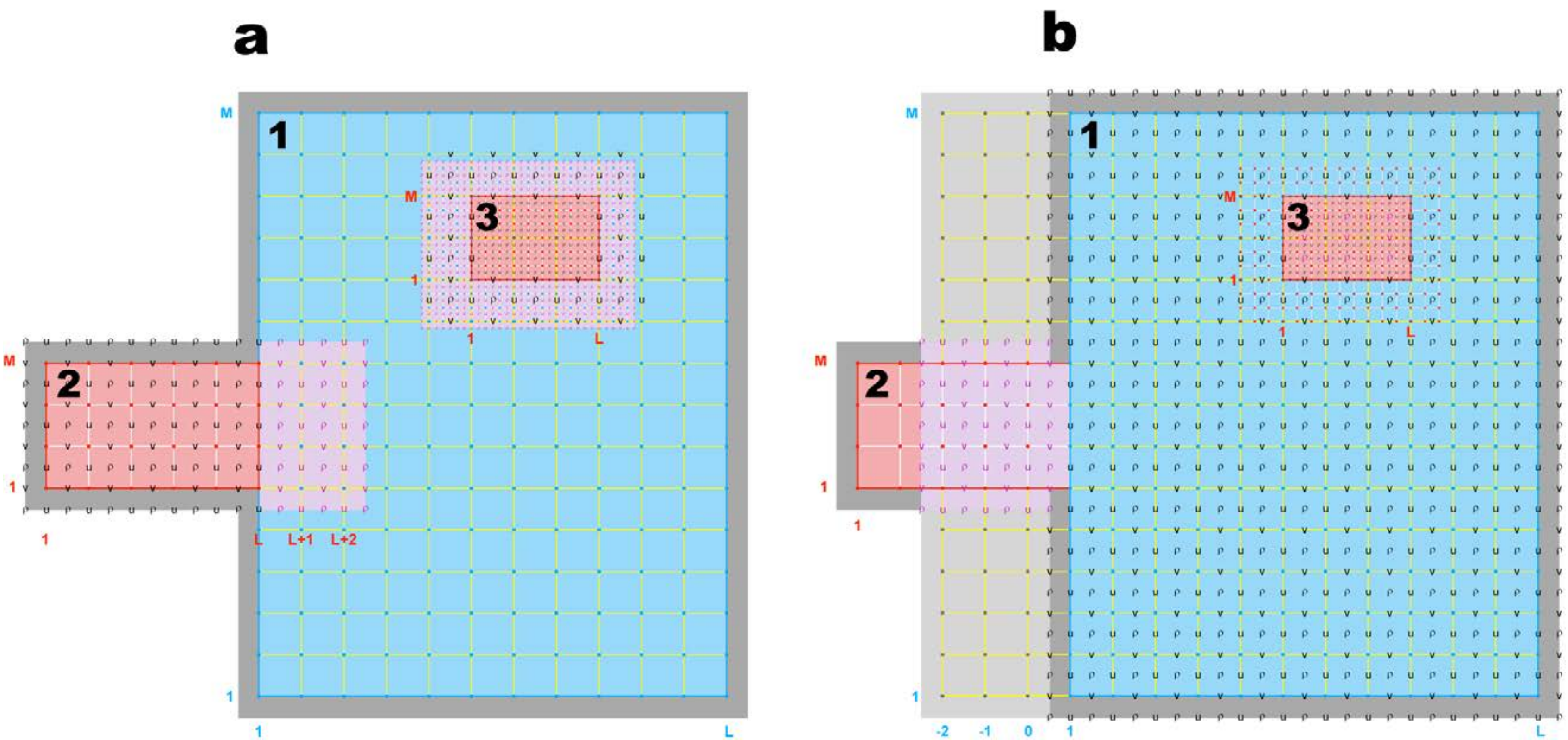


Multiple Refinement



Composite/Refinement Estuary

Contact Regions and Contact Points (Donor and Receiver Grids Duality)

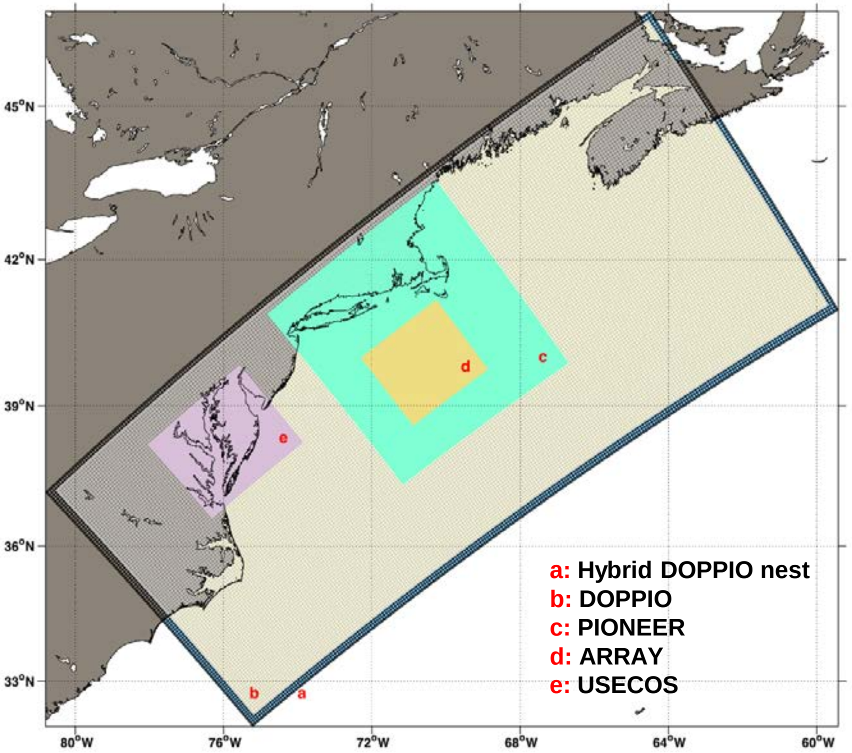


Blue Donor, Red Receiver
Coarse-to-Fine

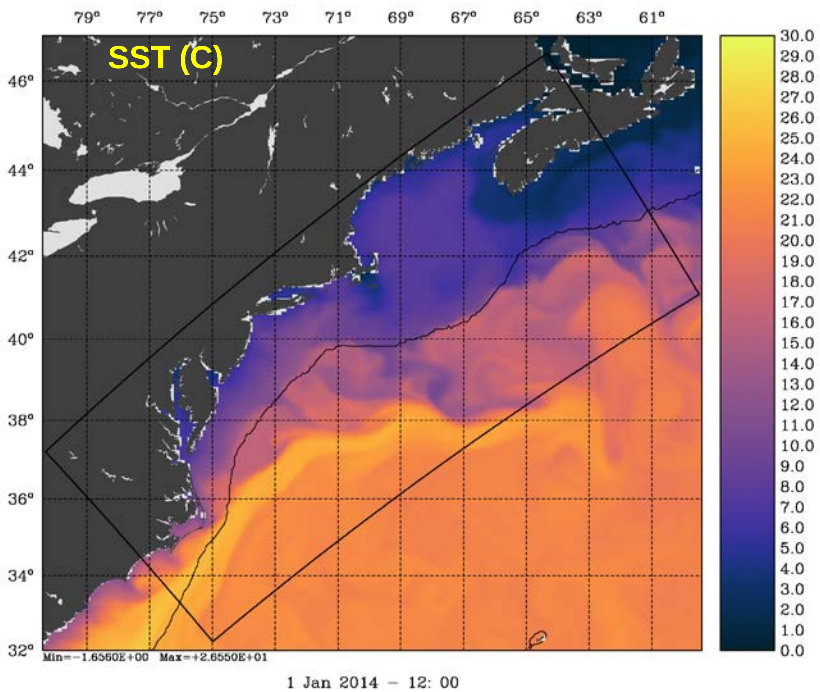
Blue Receiver, Red Donor
Fine-to-Coarse

There are four contact regions in this application, Ncontact = (Ngrids-1) * 2

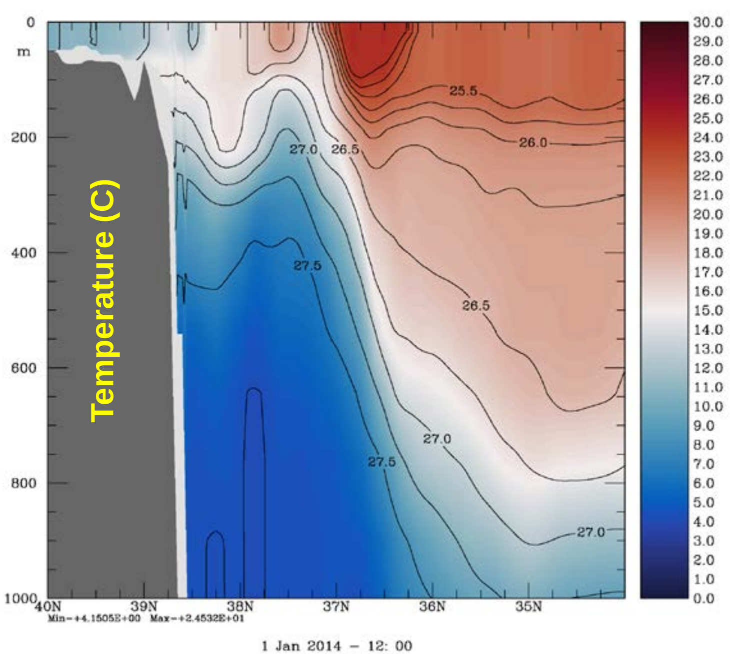
Nesting and Data Assimilation: US East Coast Application

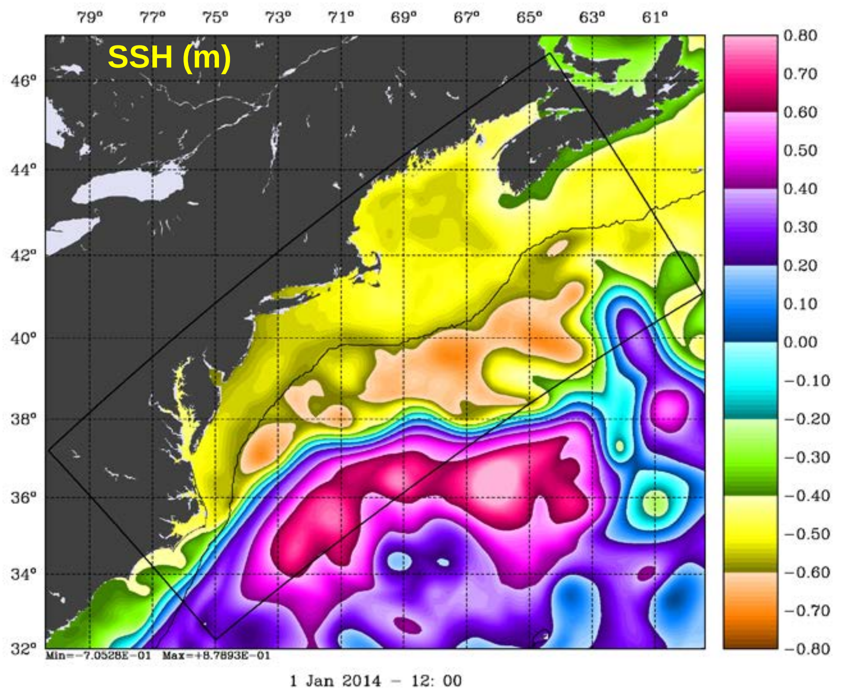


Mercator Daily Lateral Boundary Conditions (PSY4QV3R1)



- Open boundary conditions mean (T and S) are adjusted by matching mean to regional climatology (MOCHA)
- Removing bias from open boundary conditions is necessary for 4D-Var convergence





The Mid-Atlantic Bight and Gulf of Maine ROMS Application

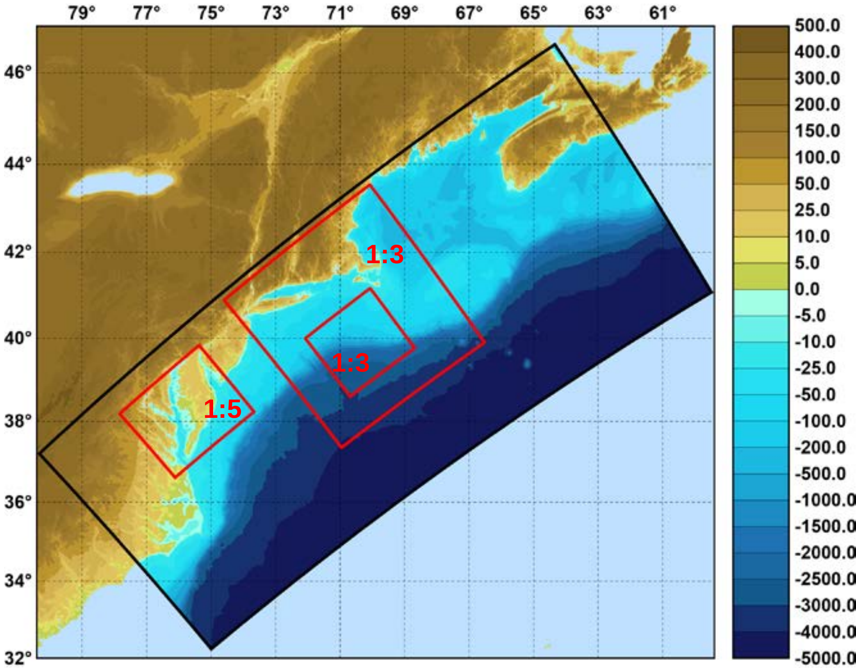
Data Assimilation System:

ROMS ~7km/~2.3/~1km, 40 levels
3 nested grids solutions (2014 & 2015)
4D-Var data assimilation (4D-PSAS)
Dual formulation (augmented RPCG)
2 outer-loops, 7 inner-loops
3 day assimilation windows (2014 & 2015)

Assimilation Data Sets:	*[Real-Time Source]*
Regional CODAR hourly	*[RU TDS]*
IOOS glider T,S (1-hr delay)	*[RU ERDDAP]*
AVHRR IR passes 6/day	*[MARACOOS TDS]*
AMRS2+OceanSat mu-wave SST	*[NASA PODAAC]*
Jason-2, CryoSat, AltiKa	*[RADS.tudelft.nl]*
GTS XBT/CTD, Argo floats	*[OSMC NOAA ERDDAP]*

Model surface and boundary forcing:

Surface forcing derived from NAM	*[NCEP NOMADS]*
USGS daily average flow	*[waterdata.USGS.gov]*
Mercator open boundary conditions	

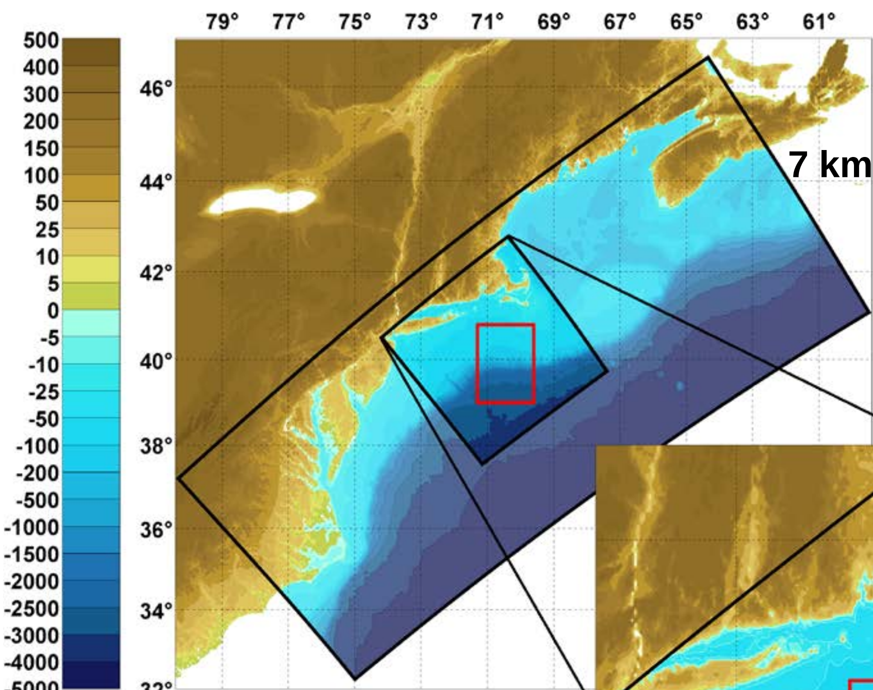


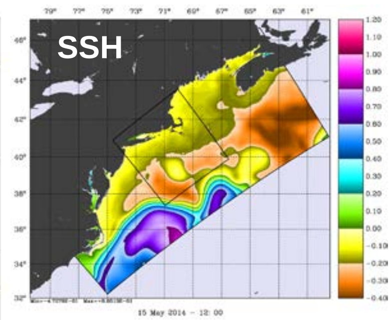
Bathymetry (m)

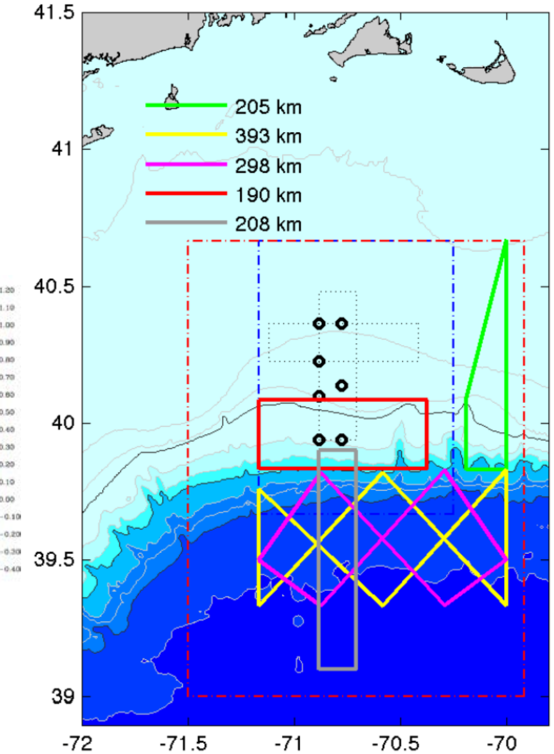
Observations per 3 day cycle:

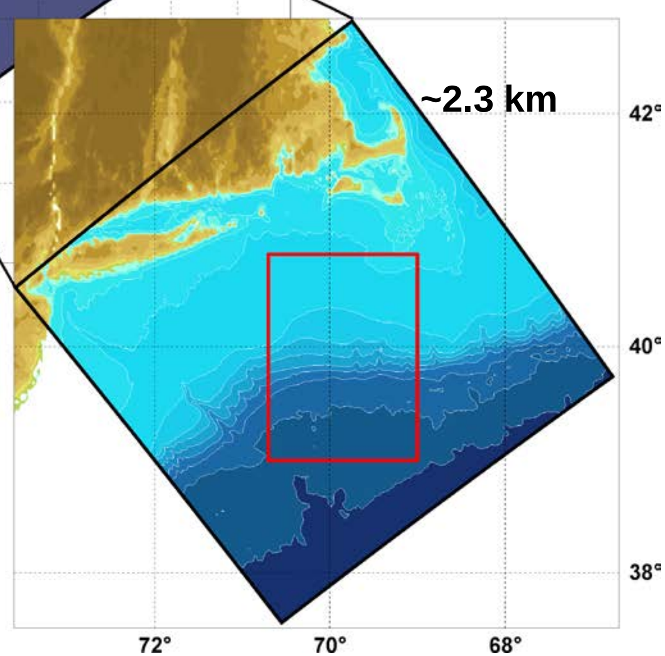
SST ~10^5
HF radar ~10^4
in situ ~$5X10^3$
Altimetry ~10^3

Downscaling with Nested Grids: DOPPIO and PIONEER

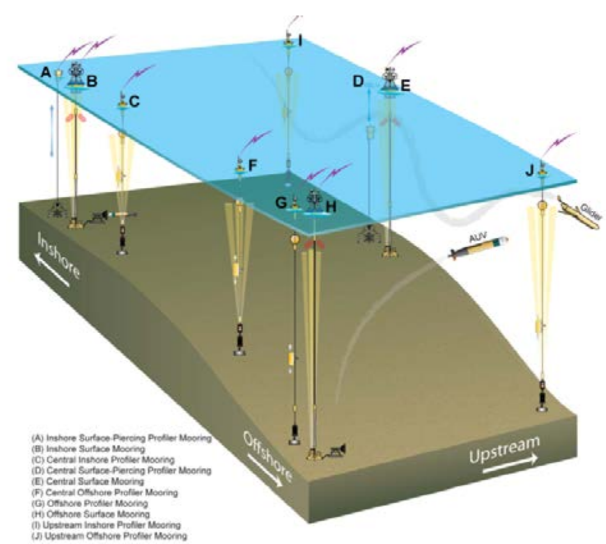






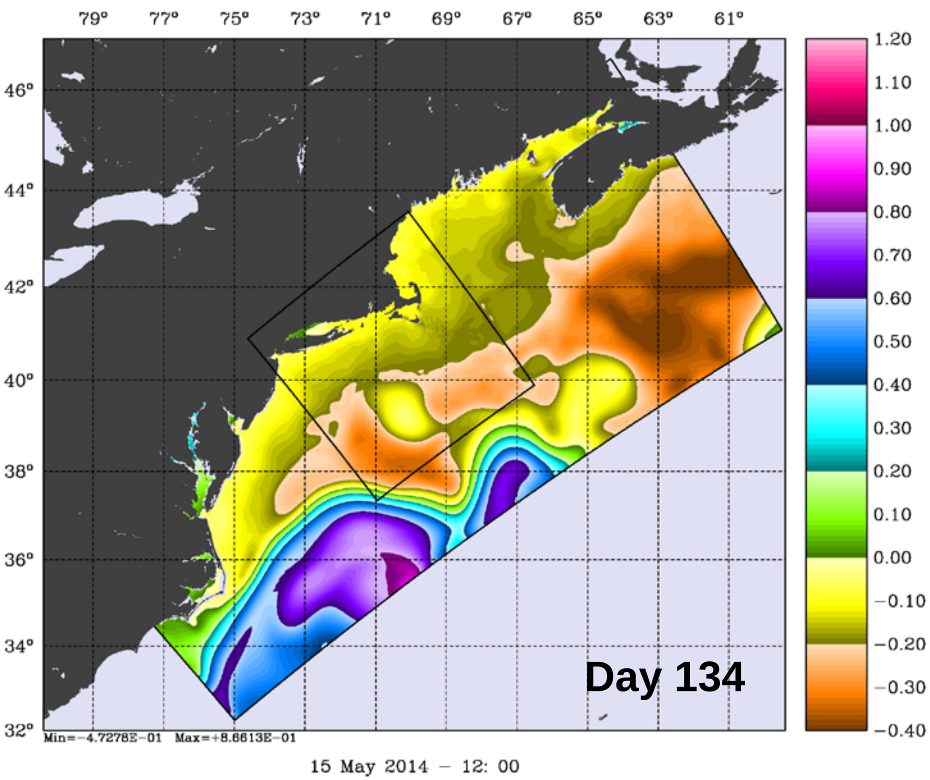


Nested grids for the MAB model. The red box indicates the location of the NSF OOI Pioneer Coastal Array

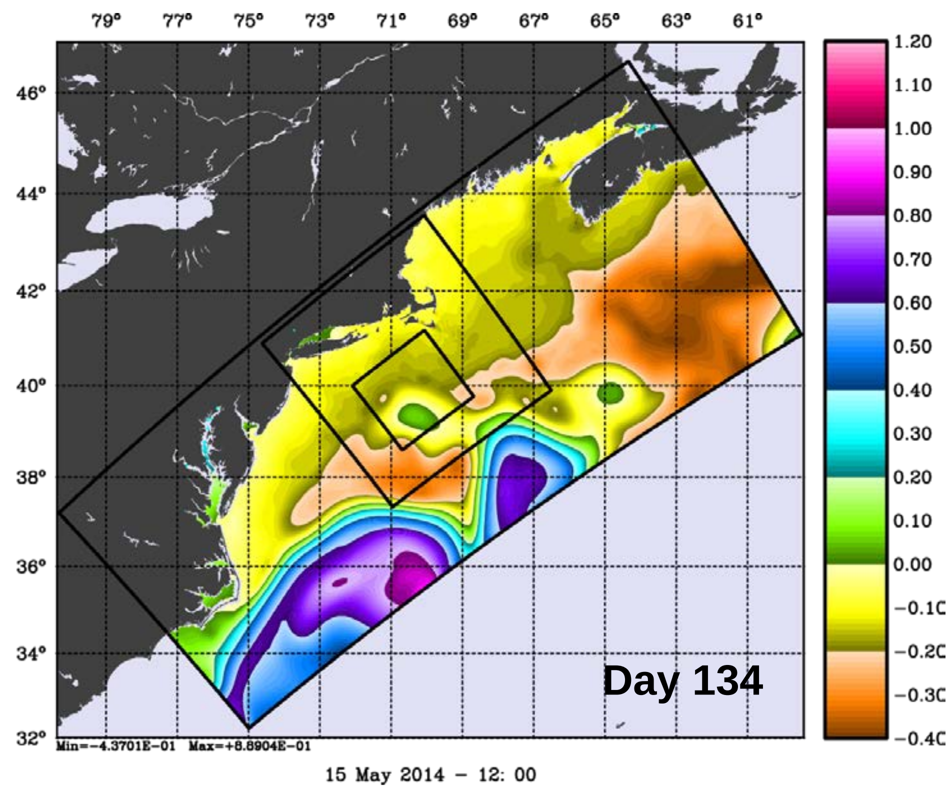


The Mid-Atlantic Bight and Gulf of Maine
Two-Way Nesting

Two Nested Grids



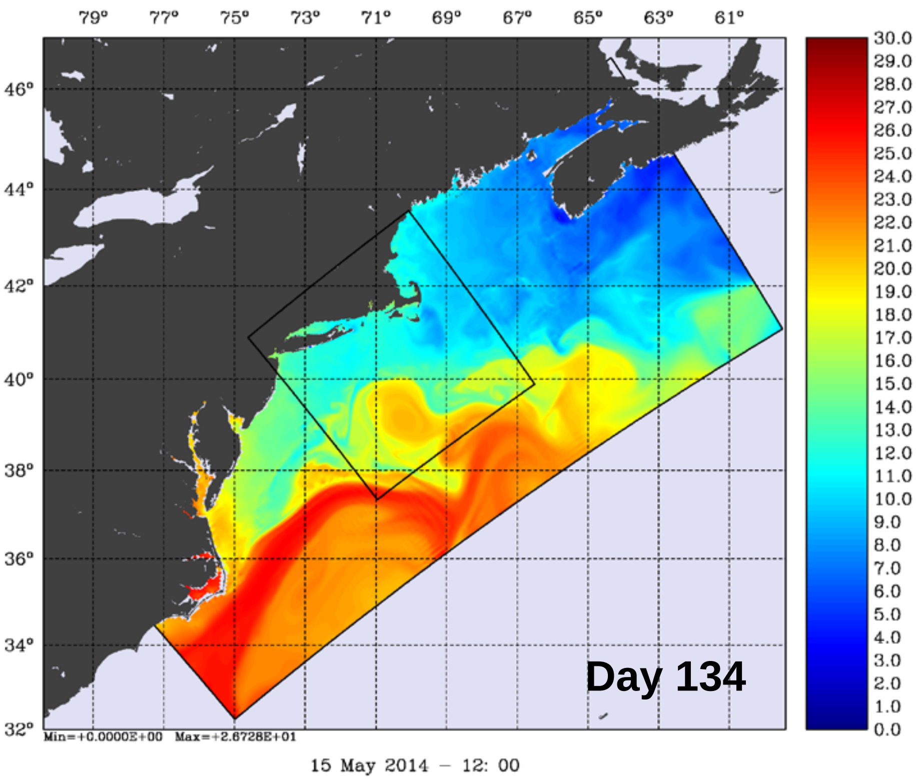
Three Nested Grids



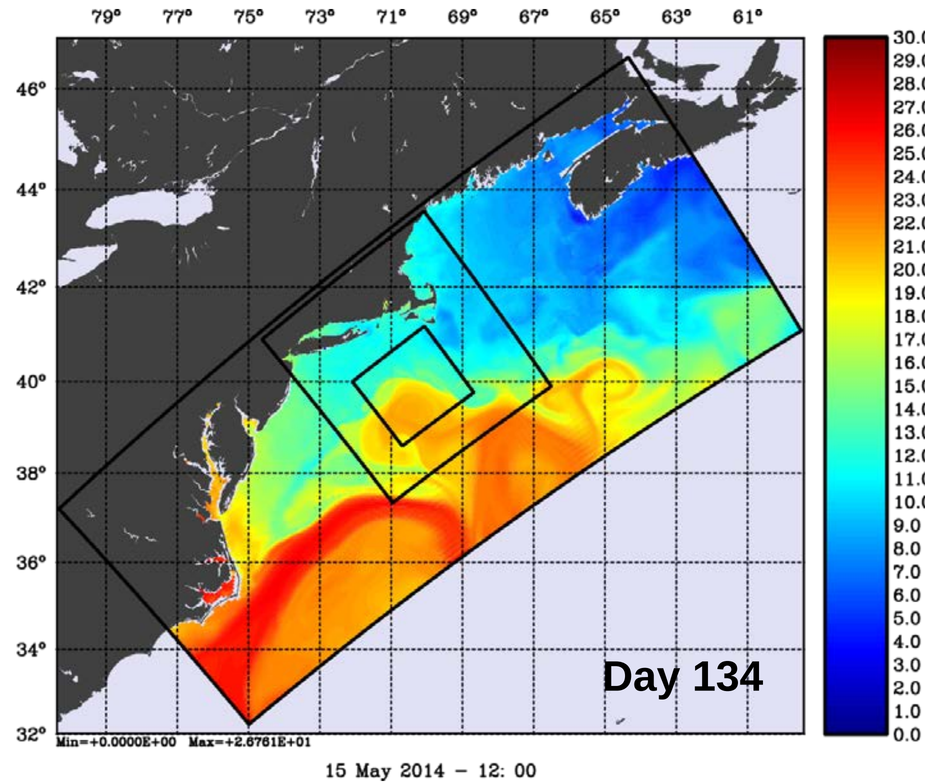
Free-Surface (m)

The Mid-Atlantic Bight and Gulf of Maine Two-Way Nesting

Two Nested Grids



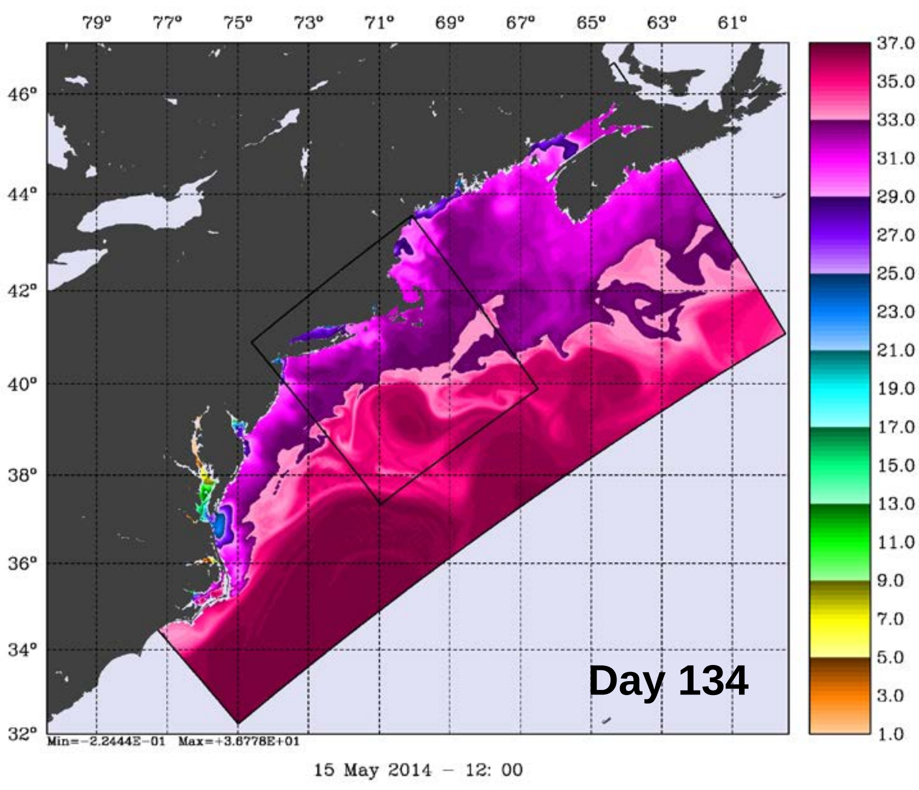
Three Nested Grids



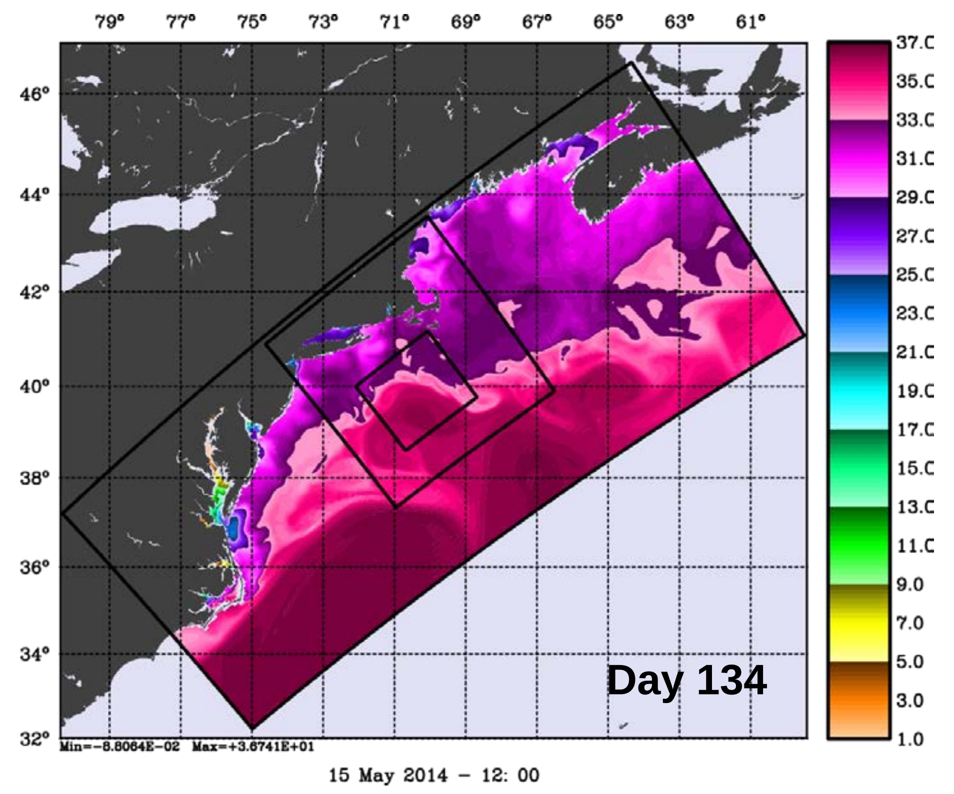
Surface Temperature (Celsius)

The Mid-Atlantic Bight and Gulf of Maine
Two-Way Nesting

Two Nested Grids



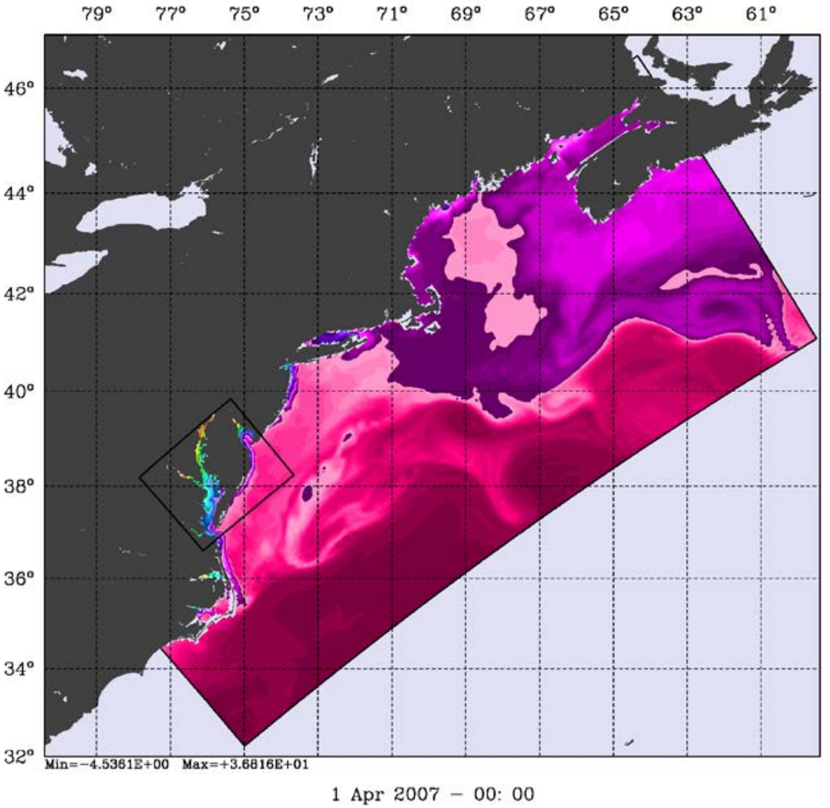
Three Nested Grids

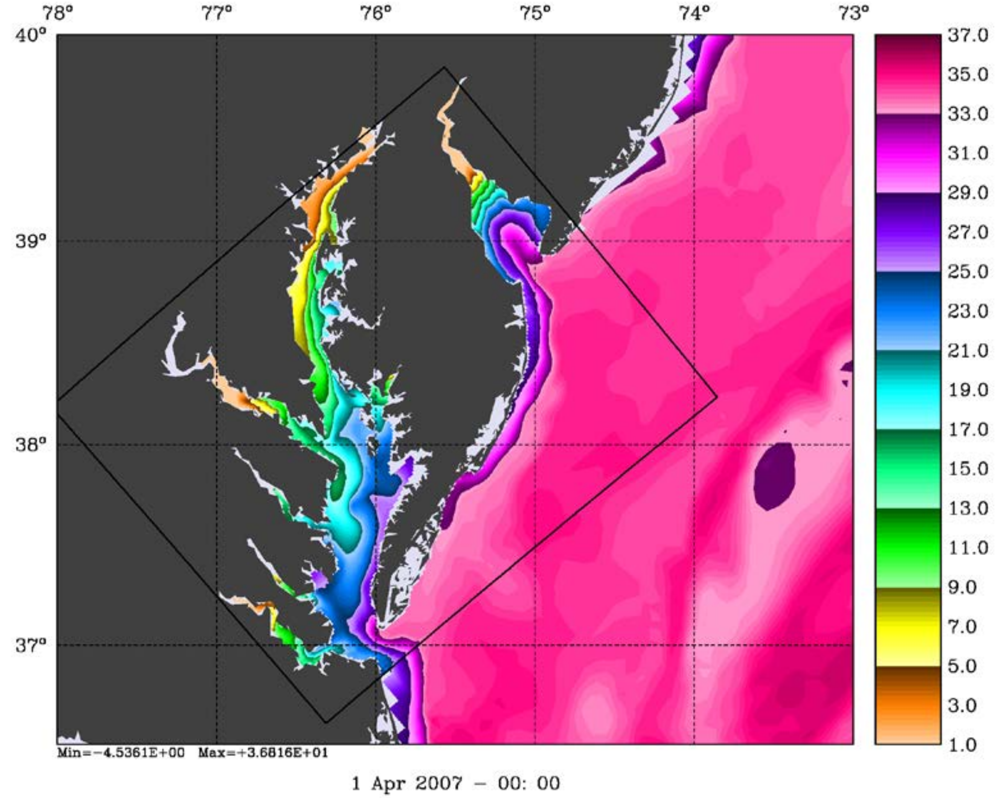


Surface Salinity

Chesapeake and Delaware Estuaries Grid Two-Way Nesting

1:5 Refinement





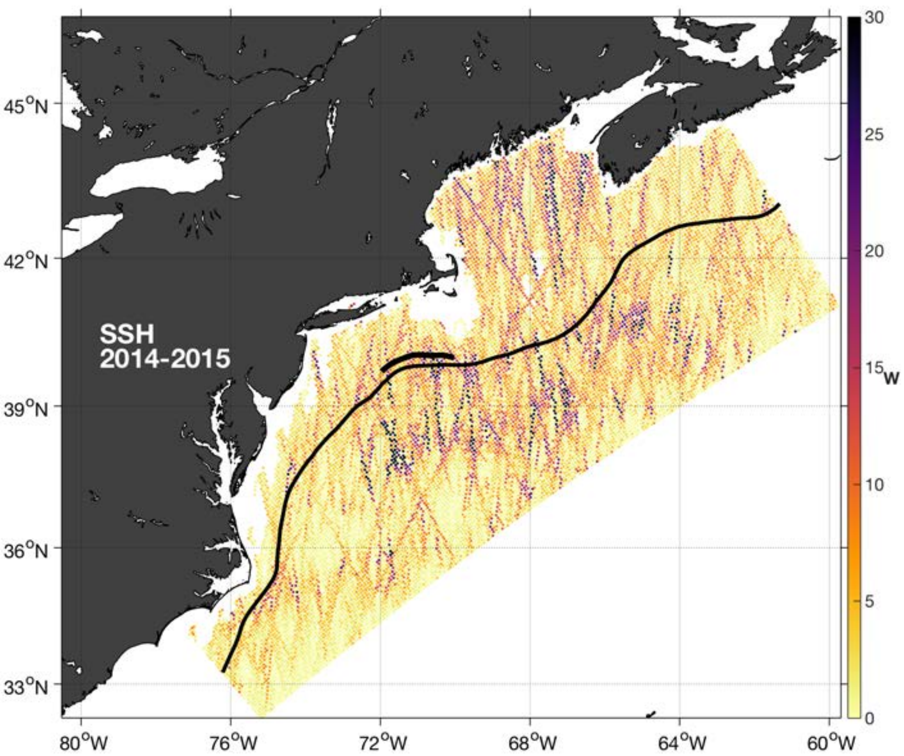
Surface Salinity

RMS impact per datum on Target cross-shelf Heat Transport (W) for the Period 2014-2015

$$I_2 = \rho c_p / \tau \int_0^{\tau} \int_S \int_{-h}^{0} \left(u_n - \bar{u}\right)\left(T - \bar{T}\right) dz\, ds\, dt$$

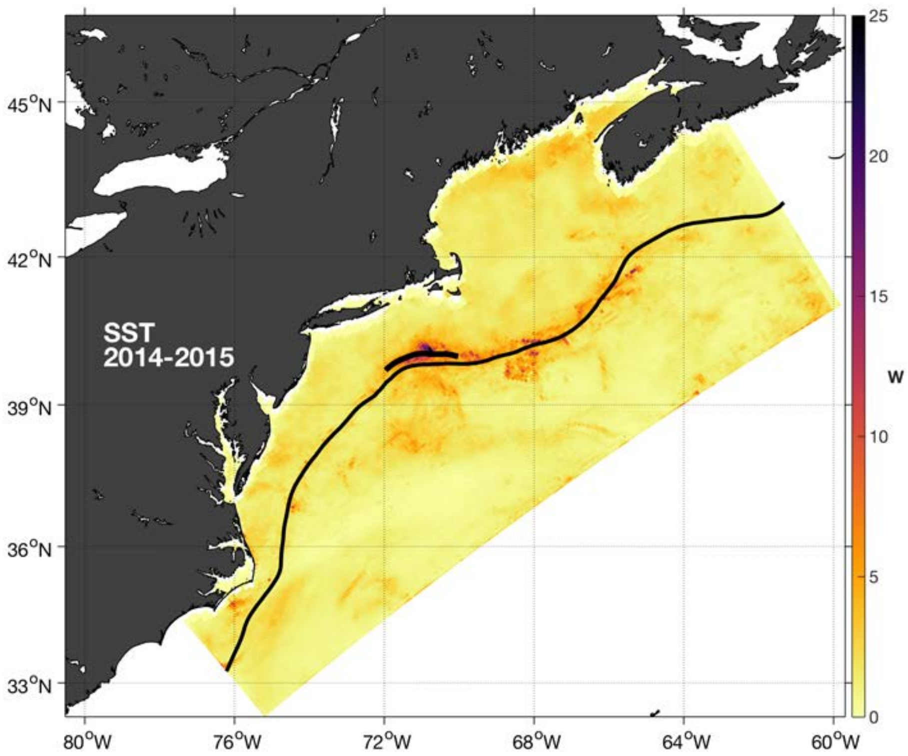
The target area is an alongshelf-vertical section following the 200 m isobath and passing through OOI Pioneer Array

Satellite Altimetry



Jason-2, Altika, CryoSat

Satellite SST

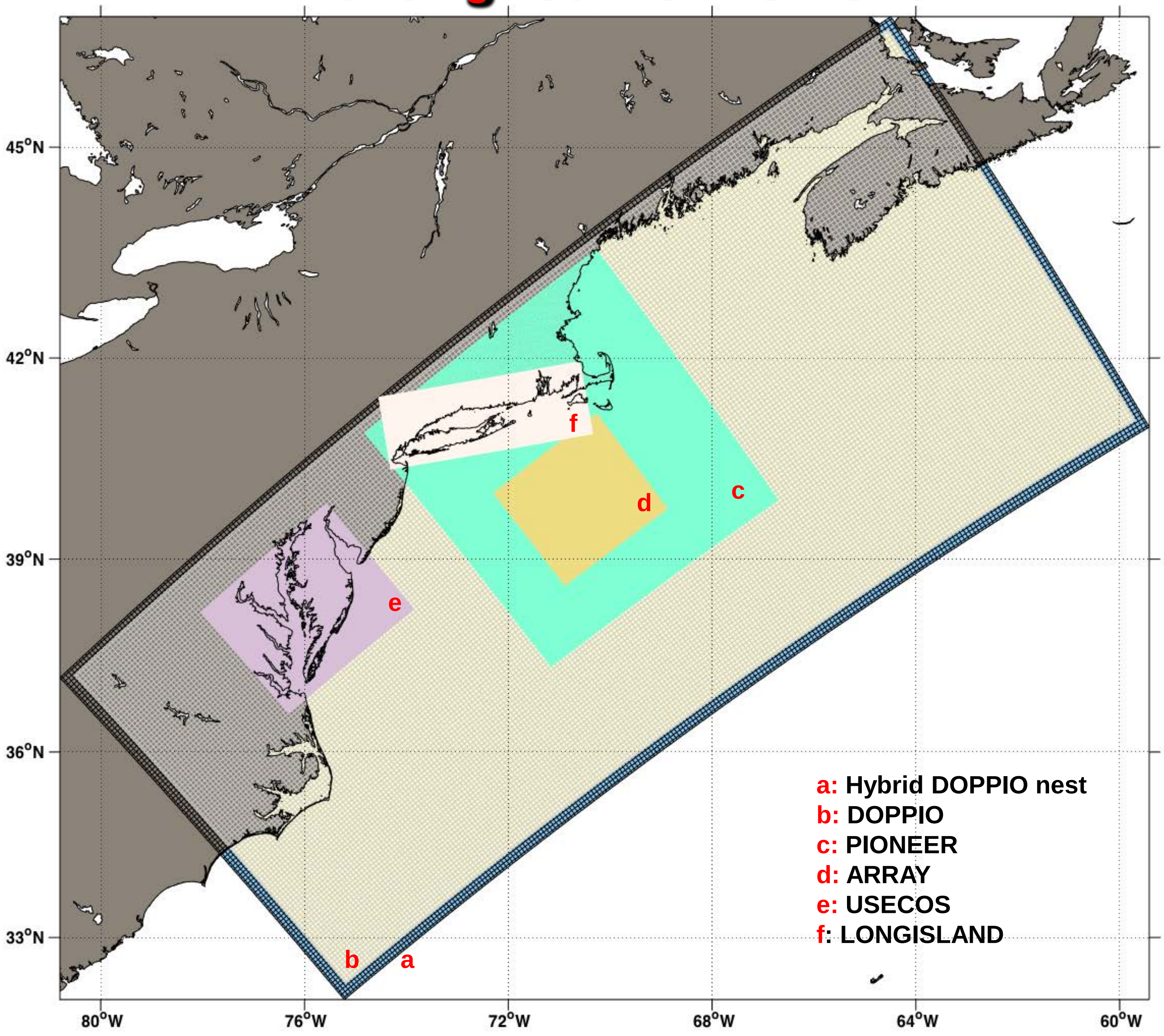


AVHRR, GOES, AMSR2

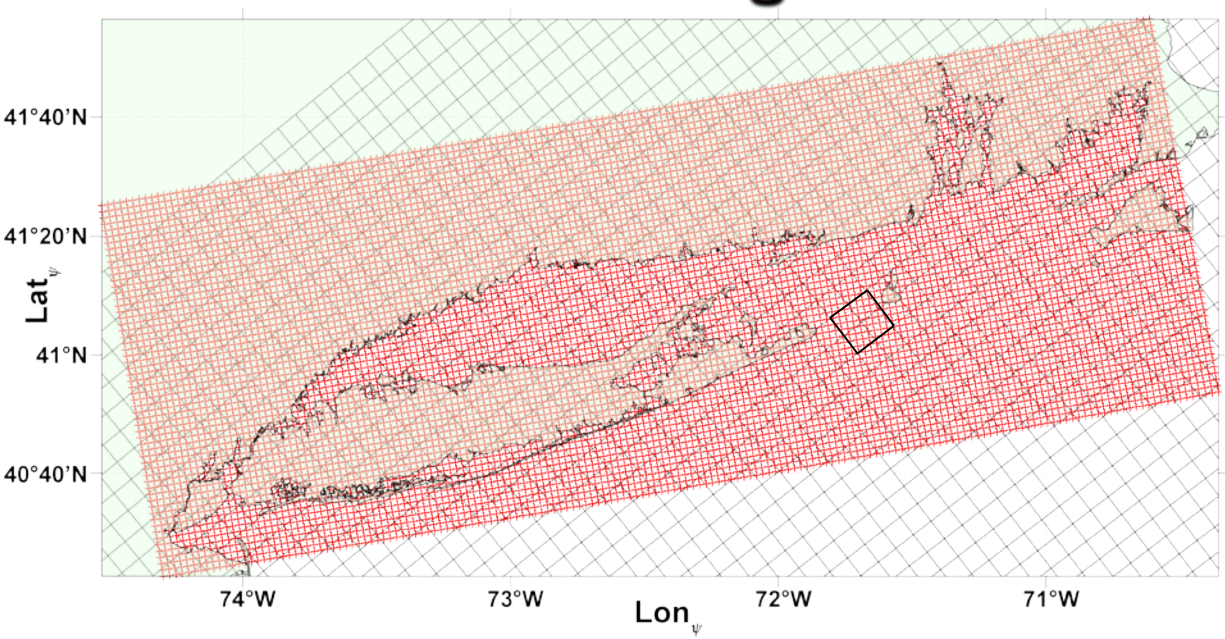
SSH observations on and off the continental shelf are important including Gulf of Maine

SST observations along the shelf-break down stream of the target site are important

Nonaligned Refinement



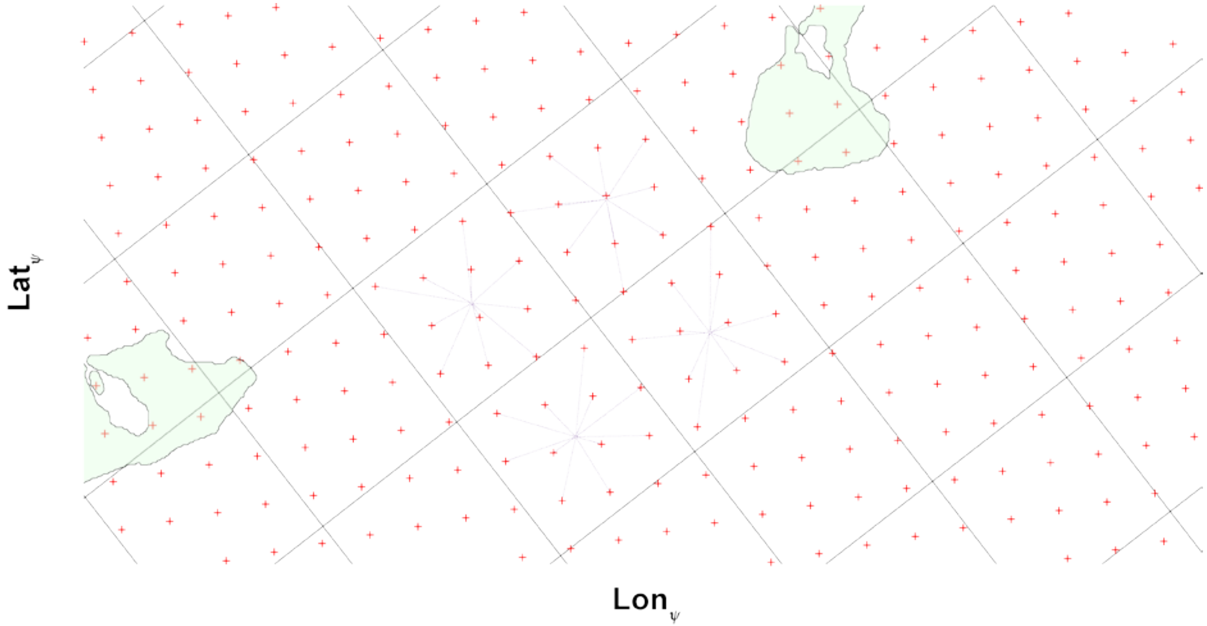
Nonaligned Refinement



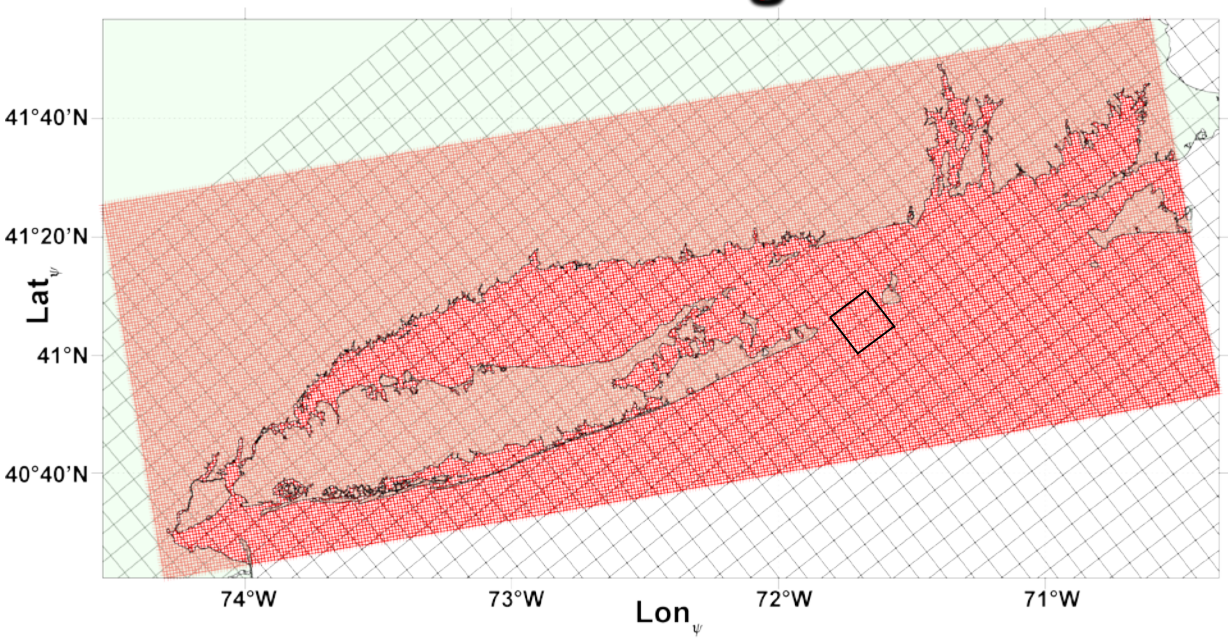
Long Island Sound
2x2 km Grid

Two-way fine-to-coarse exchange: Inverse Distance Weighting (IDW) average at center of coarse grid cell

$$\overline{v_c} = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} v_i}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \quad \textbf{\textit{with}}\ p = 2$$



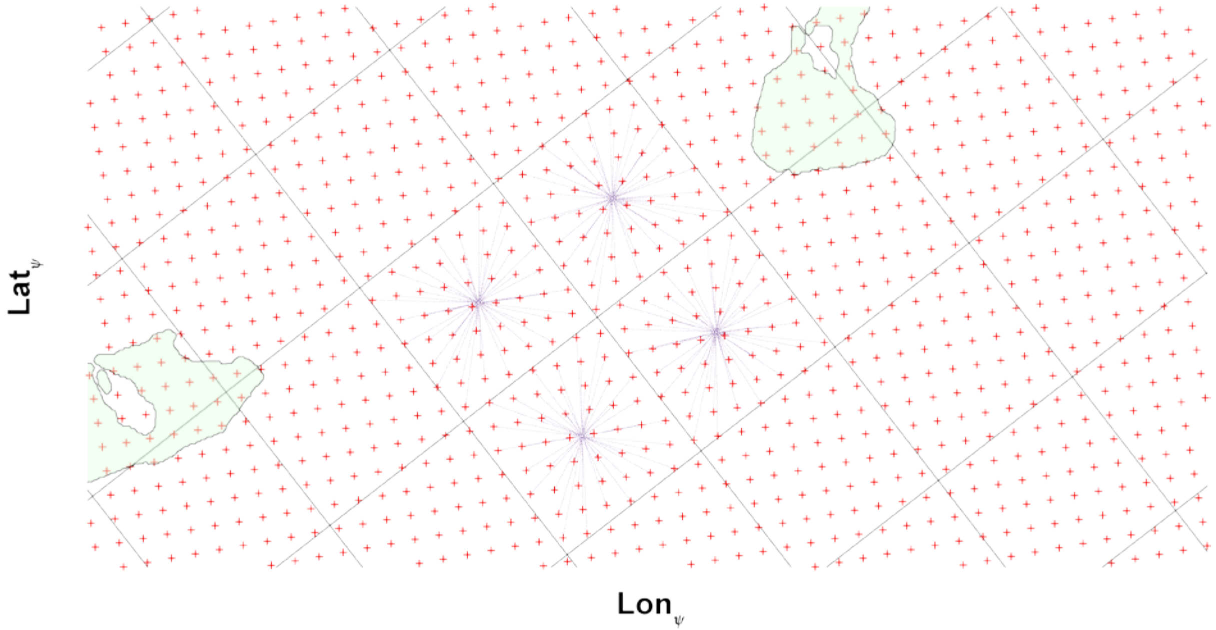
Nonaligned Refinement



Long Island Sound
1x1 km Grid

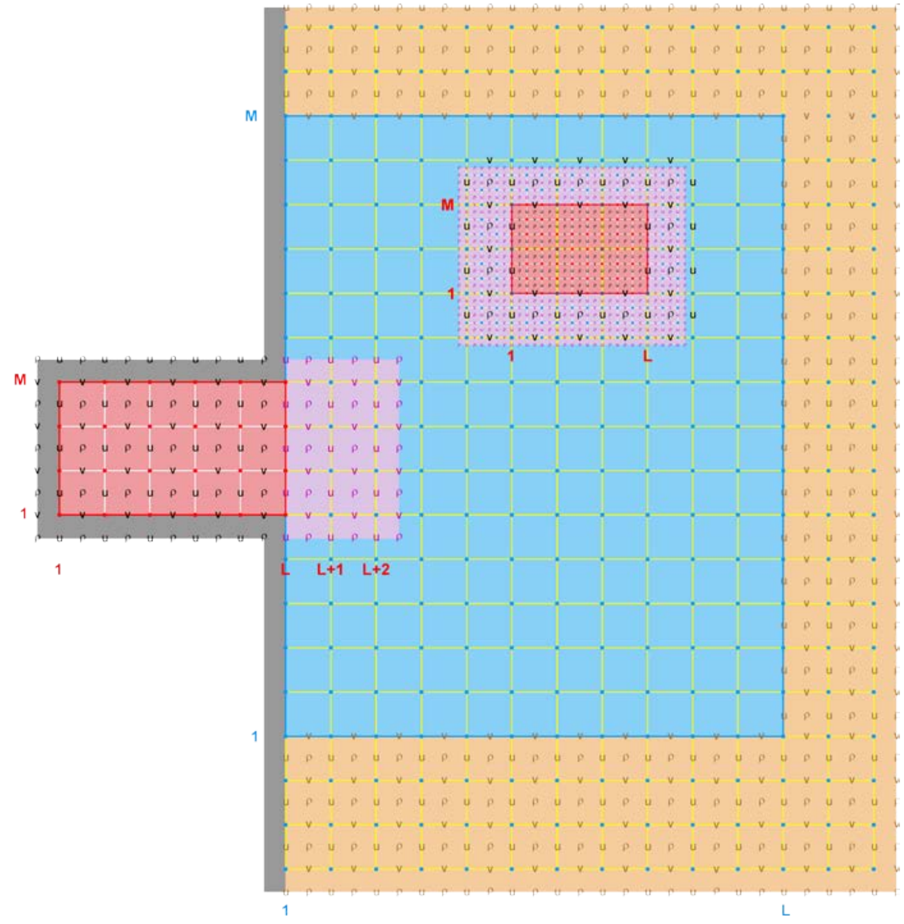
Two-way fine-to-coarse exchange: Inverse Distance Weighting (IDW) average at center of coarse grid cell

$$\overline{v_c} = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} v_i}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \quad \textit{with } p = 2$$

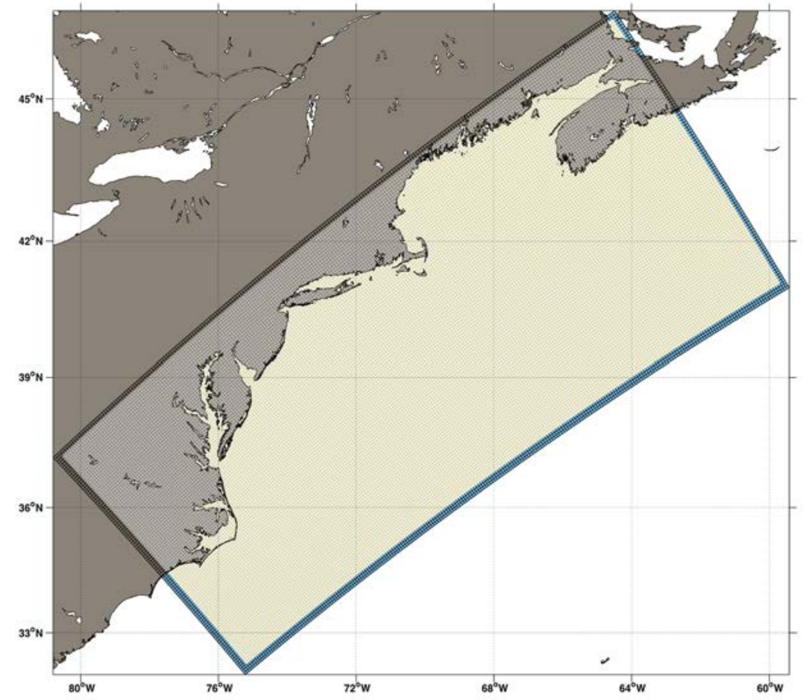


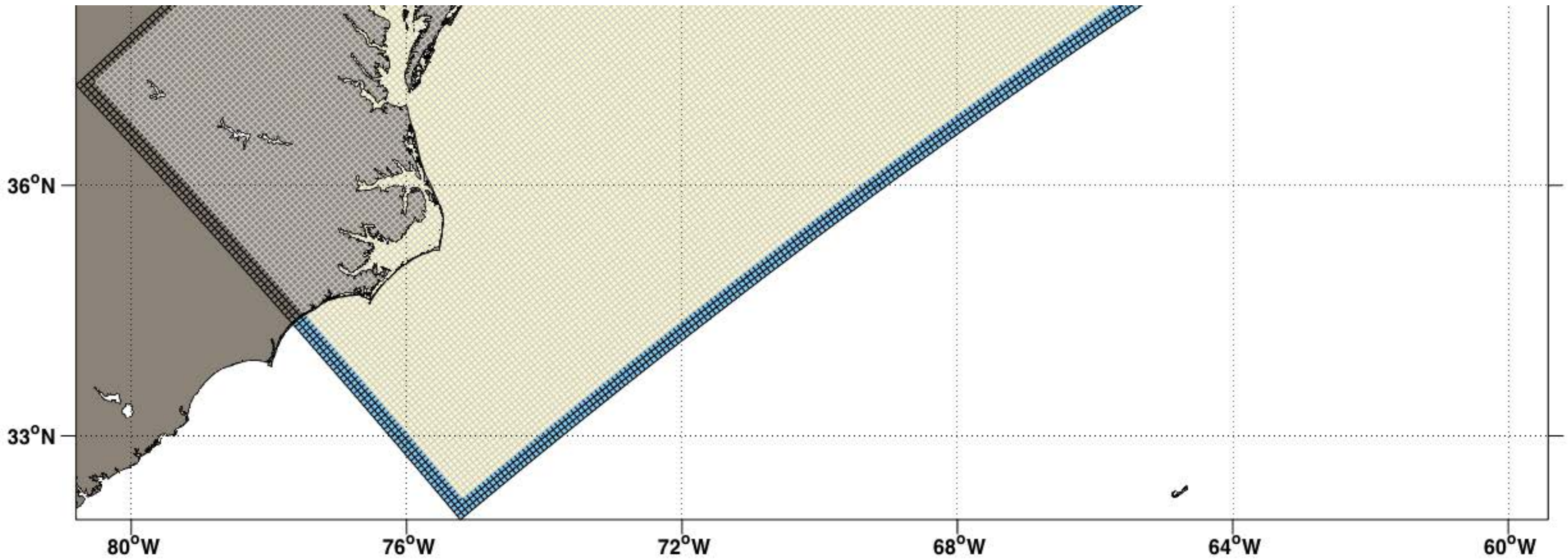
Hybrid, Heterogeneous Model Nesting
(One-Way Open Boundary Conditions)

- **The nesting strategy in ROMS is to evaluate the spatial horizontal operators (gradients, advection, diffusion) in the contact regions (purple area) yielding the full exchange of information between donor and receiver grids**
- **A new hybrid nesting approach is to exchange information between any basin-scale and ROMS over the hybrid contact region (orange area)**
- **The exchange of information can occur concurrently via ESMF/NUOPC library or independently offline with NetCDF files**

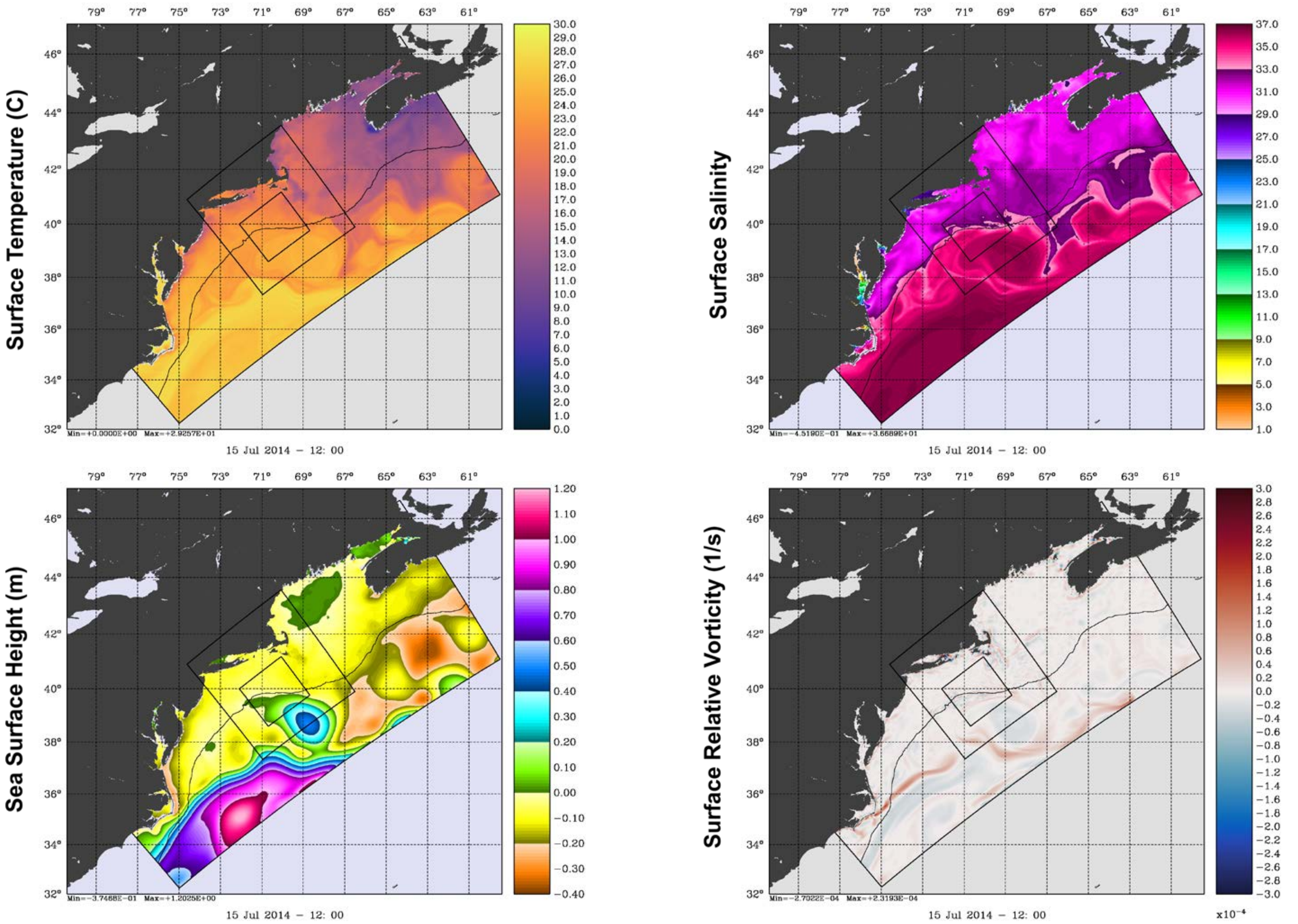


U.S. East Coast: Hybrid Nesting

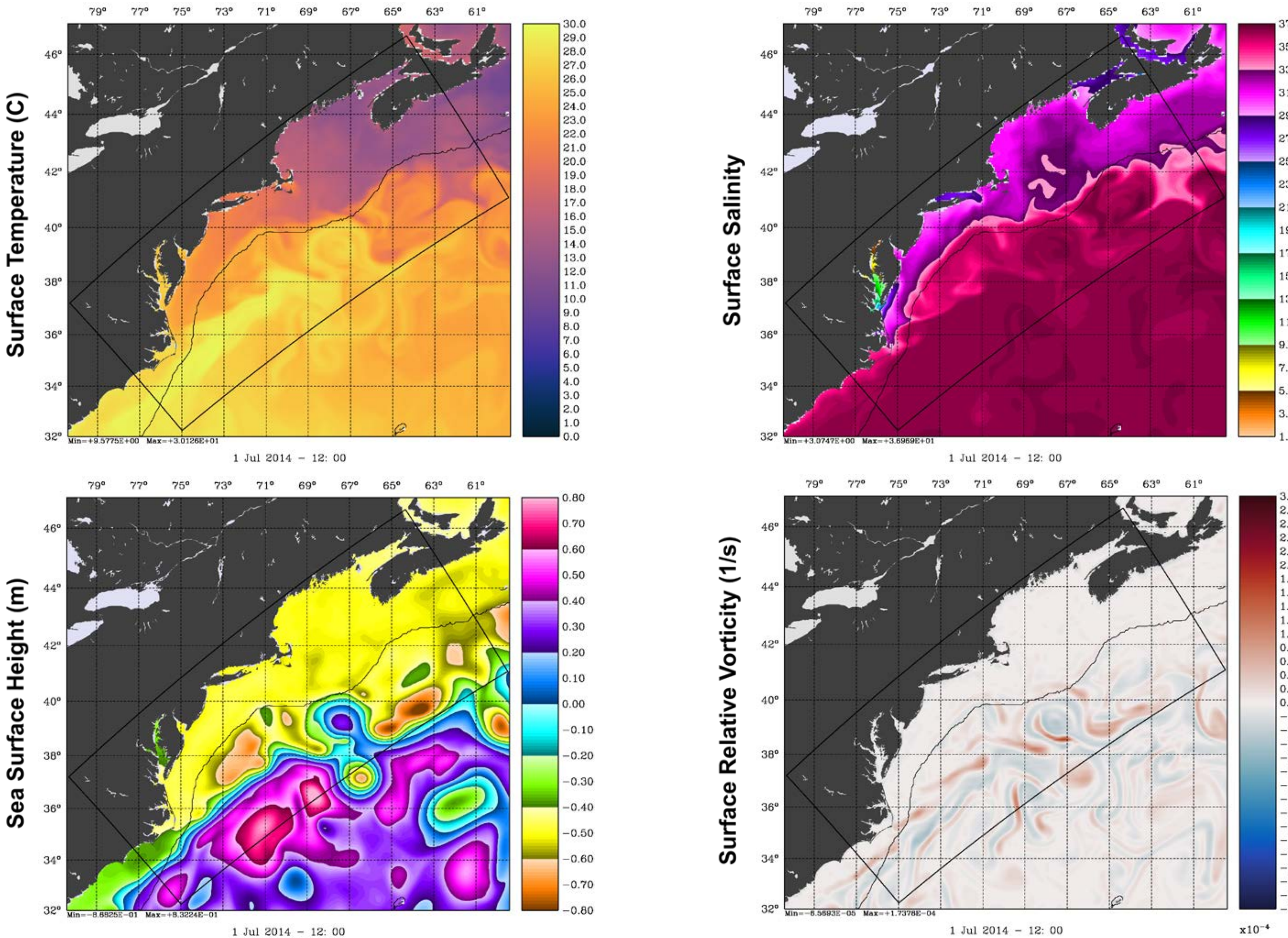




Working on Hybrid Nesting and Nested 4D-Var



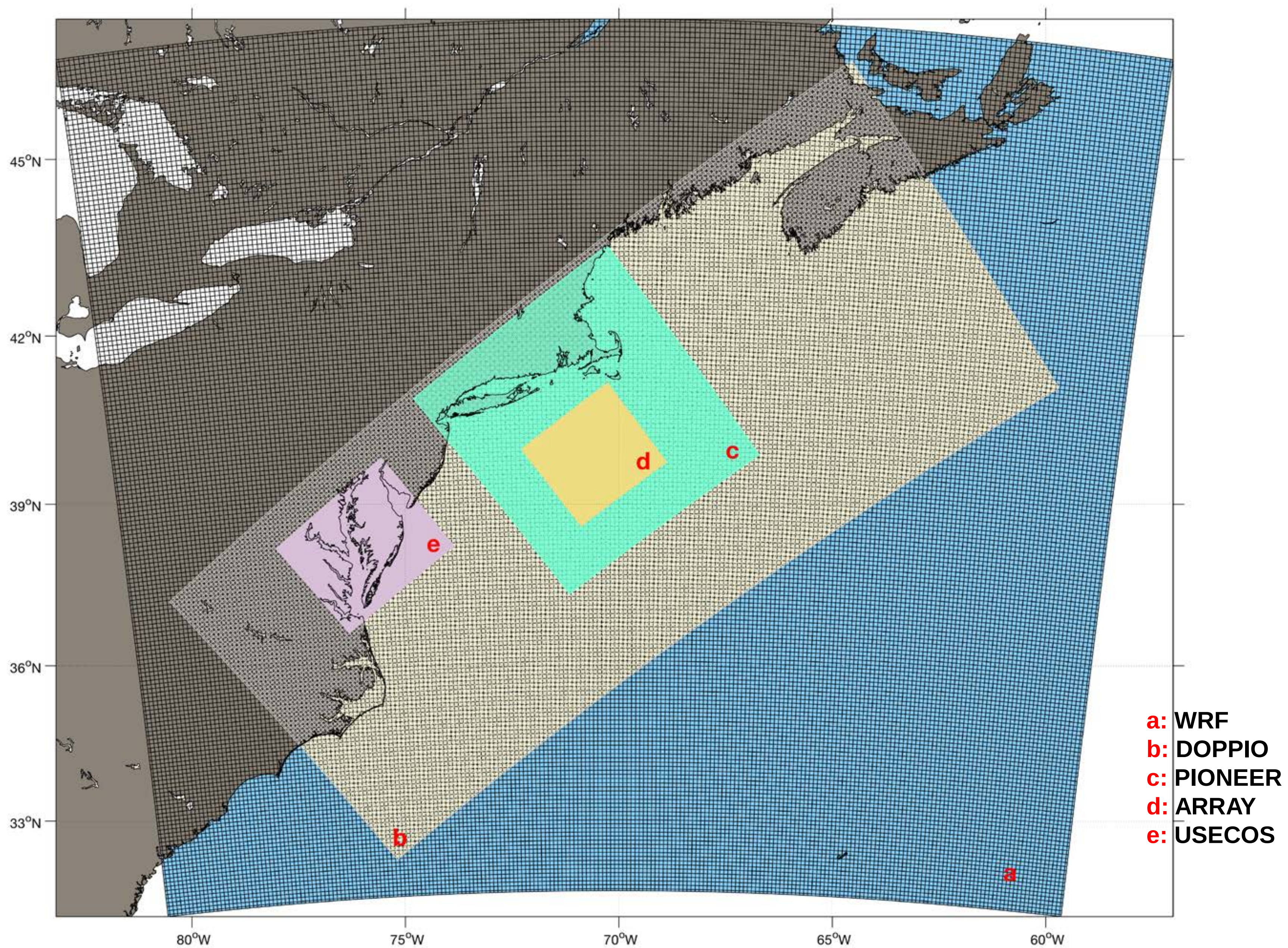
Hybrid Nesting Source: Mercator PSY4QV3R1



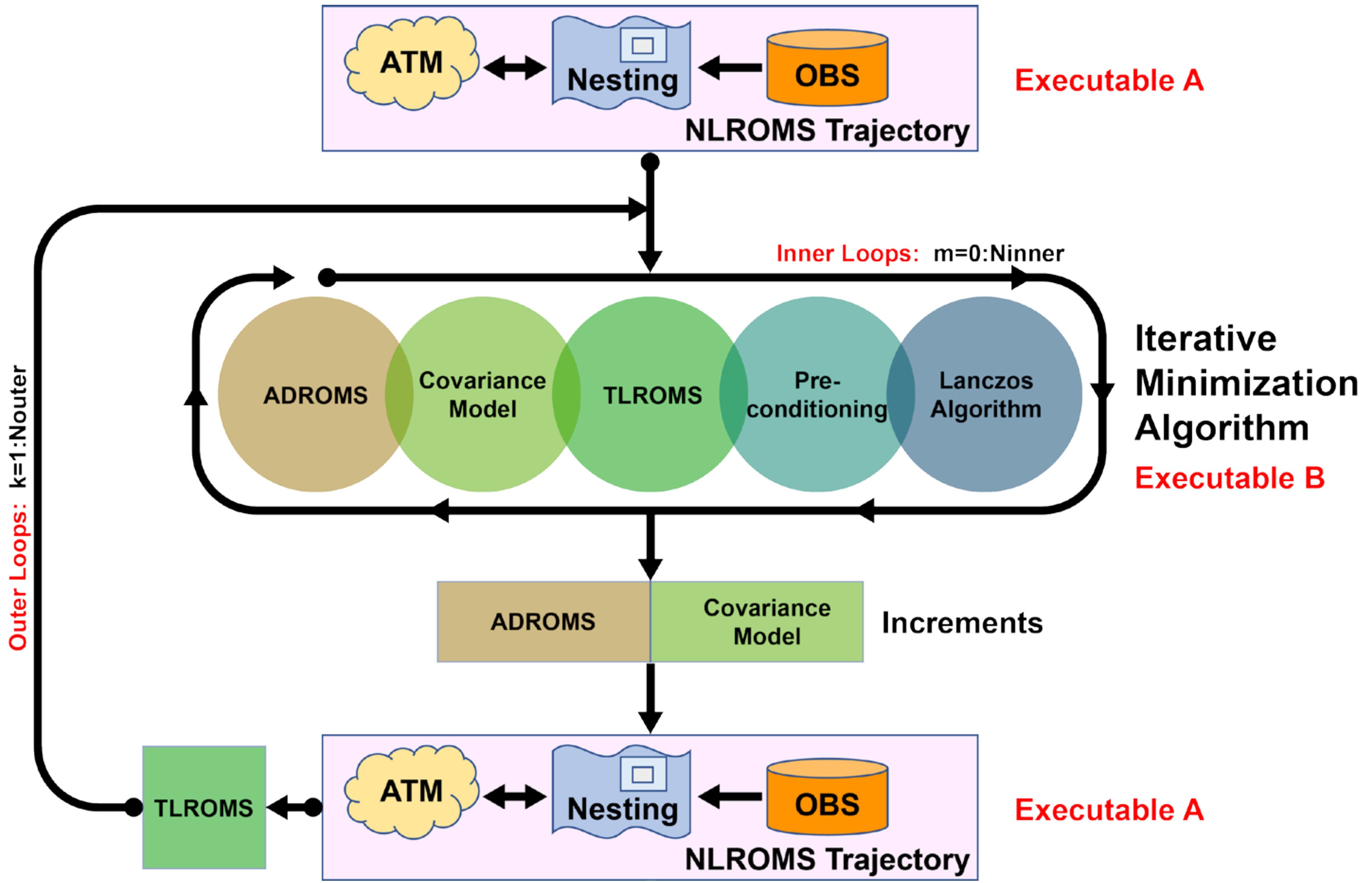
Nesting Summary

- ROMS nesting capabilities are unique and allow complex estuary and coastal configurations with unlimited number of composite and refined grids
- Coincident composite and mosaic grids produce identical solutions when compared to one large continuous grid
- Both one-way and two-way nesting are possible
- Placement of nested grids is application dependent and subject to geometrical and dynamical constrains
- Hybrid nesting as open boundary conditions is the way of the future to reduce forecast error
- Nonaligned refinement adds flexibility in complex coastal applications. We should no exceed 1:7 ratios in shallowed applications. Recommend to use 1:3 or 1:5 ratios. I finer resolution is needed, use telescoping grids

Future Work: Coupling and Nesting



Future Work: Coupling, Nesting, and 4D-Var



Split 4D-PSAS

Thank you!