Adaptive Subdomain Modeling in ADCIRC++

Alper Altuntas
T. Dyer, F. Bukhari, J. Baugh

Department of Civil, Construction and Environmental Engineering
North Carolina State University

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Introduction

Ocean Models:

- Large temporal and spatial scales
- Many local variations to be analyzed

Conventional Subdomain Modeling (CSM):

- Assessment of multiple local changes with less computational effort

A New Adaptive Approach

Adaptive subdomain modeling:

- Concurrent analysis of multiple child domains and a parent domain
- Adaptively moving child domain boundaries

ADCIRC++:

- Object oriented design and data abstraction
- Dynamic behavior
- Same input files

Outline

Subdomain Modeling

Enables the assessment of multiple local changes without requiring a full scale simulation for each local change. (Baugh et al., 2015)

- Boundary conditions: water surface elevation, velocity and wet/dry status
- A GUI for extracting subdomains (Dyer and Baugh, 2016)
- Incorporated in ADCIRC release

Subdomain Modeling Work Flow

1. **Construct a subdomain**
   - Locate regions of interest, subdomains, within a full-scale domain
   - Perform the full domain run to generate boundary conditions
   - Preprocess boundary condition files
   - Perform the subdomain runs
2. **Generate engineering scenarios**
   - Verify the subdomain
   - Apply local alterations
   - Perform the subdomain runs with alterations
   - Verify the alterations

Subdomain Modeling

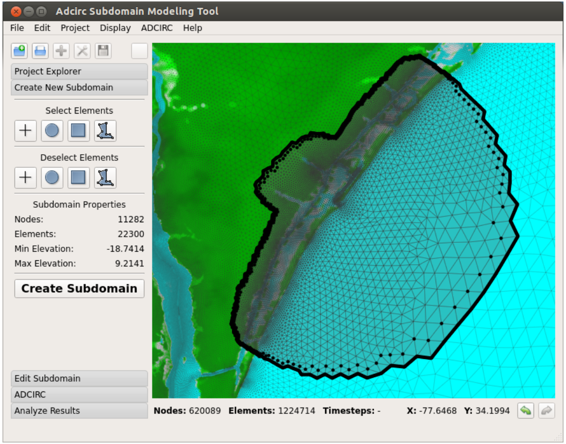


Figure: Subdomain extraction with SMT

Subdomain Modeling Requirements

- **User judgment to determine subdomain sizes:**
  - large enough to contain the altered hydrodynamics
  - small enough to minimize redundant computations
- **Verification steps:**
  - Verify subdomain grids
  - Verify alterations
- **Pre- and post-processing of large input and output files**:
  - Conventional ADCIRC input files: `fort.{13,14,15,22,...}`
  - Boundary conditions files: `fort.019`

A New Adaptive Approach

Adaptive subdomain modeling (ASM):

- The spatial extent of each child domain is **determined automatically**.
  No user judgment required.
- Boundaries are **moved adaptively**.
  Verification is inbuilt.
- Boundary conditions are transferred through primary memory.
  No bc files required.
- Child domain instances are copy-constructed.
  No conventional ADCIRC input files required for child domains.

Adaptive Subdomain Modeling

Patch: Designates computationally active regions of ADCIRC++ grids. Only active nodes and elements participate in computations.

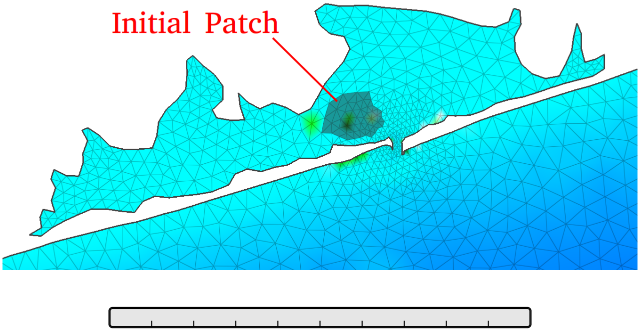
- Moving boundaries
- May be non-contiguous.

Extent of patches:

- Parent domain: the entire grid
- Child domain: regions of altered hydrodynamics

Shinnecock Inlet Child Domain Patch

Initial size = 78 elements (1.35% of the entire grid)
Maximum size = 1090 elements (18.85% of the entire grid)



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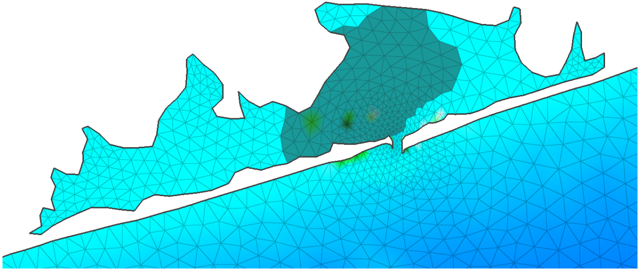

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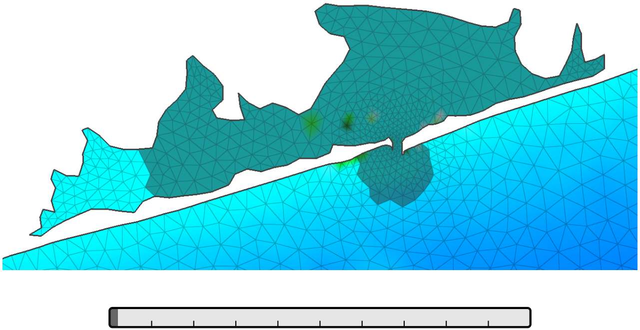

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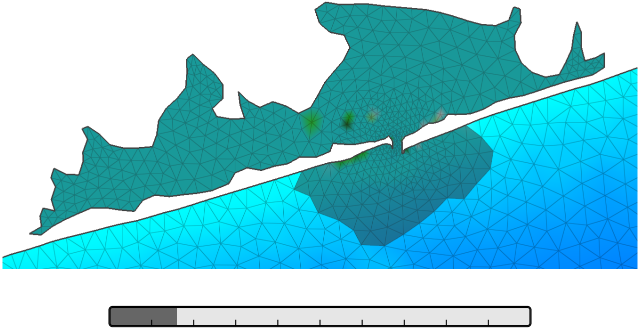

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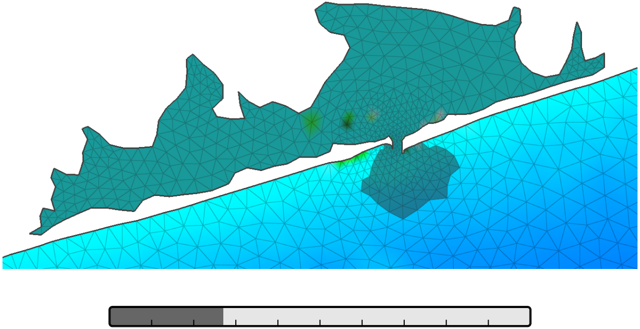

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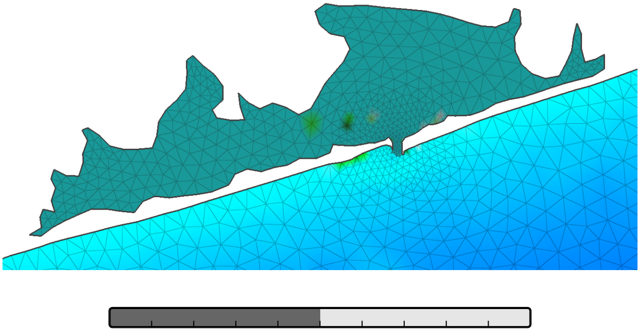

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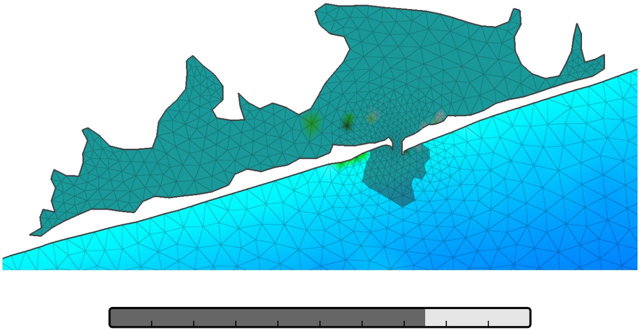

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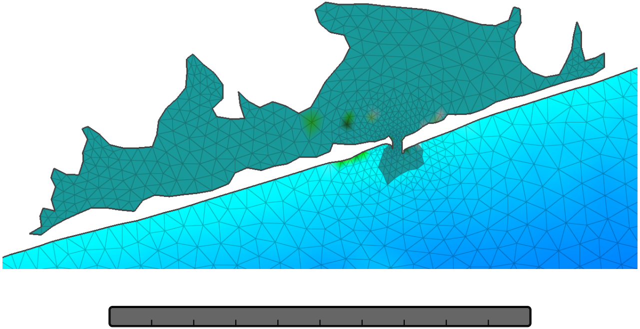


Adjusting Patch Boundary Locations

Three essential components:

- Error Indicator
- Expansion/Contraction Algorithm
- Prescription of Boundary Conditions

Adaptive Subdomain Modeling

Error: Discrepancy between the modified child domain and the parent domain with same modifications.

Error Indicator: A measure of difference between the solutions of the modified child domain and original parent domain.

$$\rho = max(\rho_\eta, \rho_u, \rho_v)$$

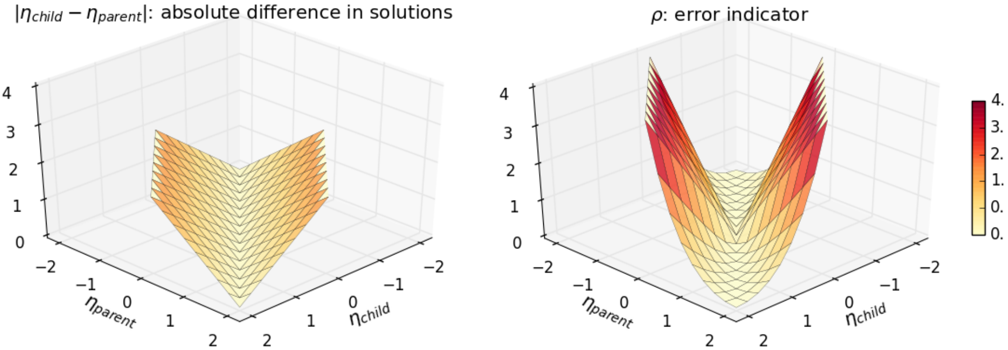
where,

$$\rho_\eta = \left(\frac{|\eta_{child} - \eta_{parent}|}{\sqrt{0.5(|\eta_{child}| + |\eta_{parent}|)}} \right)^2$$

$$\rho_u = \left(\frac{|u_{child} - u_{parent}|}{\sqrt{0.5(|u_{child}| + |u_{parent}|)}} \right)^2 \Delta t$$

$$\rho_v = \left(\frac{|v_{child} - v_{parent}|}{\sqrt{0.5(|v_{child}| + |v_{parent}|)}} \right)^2 \Delta t$$

Absolute Difference vs. Error Indicator



Expansion/Contraction Algorithm

ASM control parameters:

tolerance (τ): compared with the computed values of error indicators to determine whether a patch grows or shrinks, or stays the same.

safety factor (σ): Error indicator values are compared with the tolerance multiplied by the safety factor to determine the contraction of patches.

minimum activation interval (θ): minimum number of timesteps during which a newly activated node must stay active.

decay constant (λ): exponential decay constant of locally increased tolerances.

Expansion/Contraction Algorithm

Main steps of the algorithm:

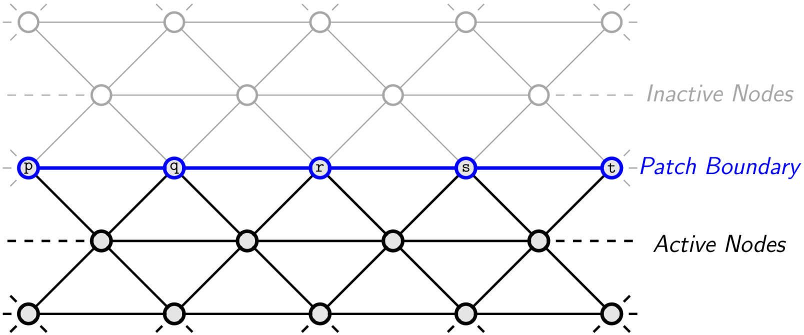
1. Assessment of altered hydrodynamics
2. Expansion
3. Contraction
4. Post-processing

Step-1: Assessment of altered hydrodynamics

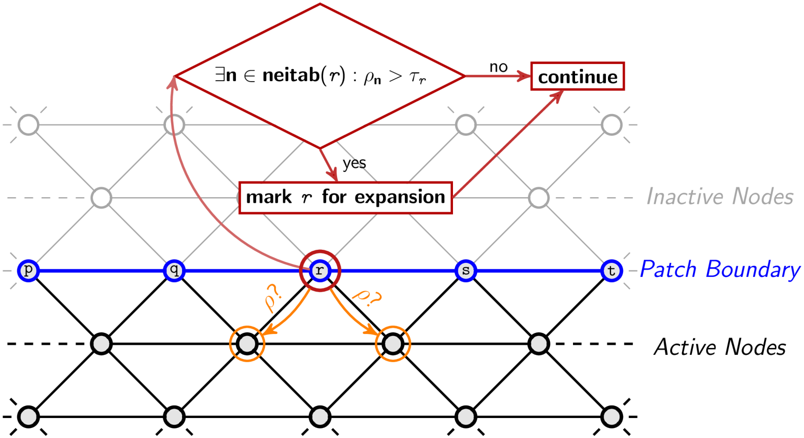
- **Expansion Criteria** for patch boundary node *i*:
  - $\exists n \in neitab(\mathtt{i}) : \rho_n > \tau_{\mathtt{i}}$
  - *i* not adjacent to a grid boundary (except island or mainland)
- **Contraction Criteria** for patch boundary node *i*:
  - $\forall n \in neitab(\mathtt{i}) : \rho_n < \sigma\tau^0$ **and** $\forall m \in neitab(n) : \rho_m < \sigma\tau^0$
  - *i* is activated at least θ timesteps ago.
  - *i* is not adjacent to an expansion node
  - *i* is not included in the initial patch

where `neitab(i)` is the set of neighboring nodes of `i`.

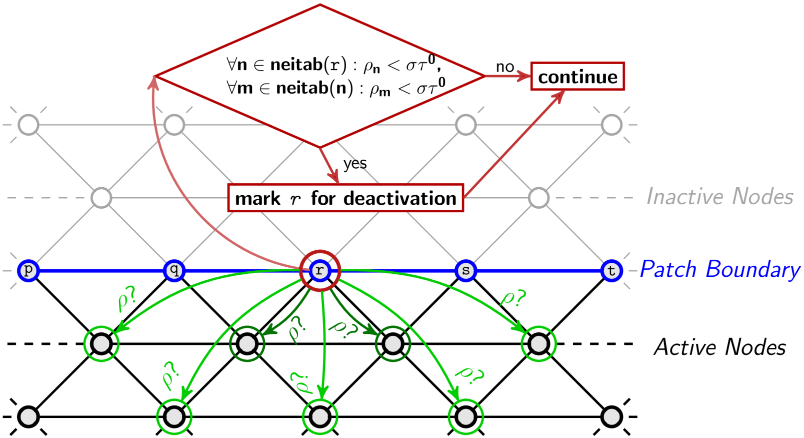
Step-1: Assessment of altered hydrodynamics



Step-1: Assessment of altered hydrodynamics



Step-1: Assessment of altered hydrodynamics



Steps 2-4

2. **Expansion:**
   - Move boundary outwards by one layer of nodes and elements
   - Update the tolerances of the new boundary nodes
3. **Contraction:**
   - Move boundary inwards by one layer of nodes and elements
4. **Post-processing: (in case any expansion/contraction occurs)**
   - Reset and resize the system of equations.
   - Update the invalidated and outdated containers and properties.
   - Apply an exponential decay for locally increased tolerances.

Boundary Conditions

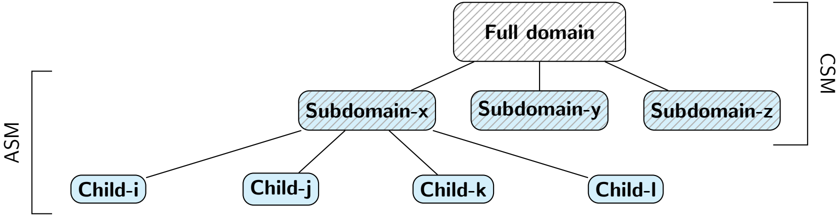
In ASM, boundary conditions are enforced as in CSM subdomains, except:

- No boundary conditions file is required.
- No interpolation is required.

ASM and CSM are complementary

Hierarchical nesting of ASM and CSM:

- Combines the advantages of both methods
- Allows sequential variations



Implementation

Work flow:

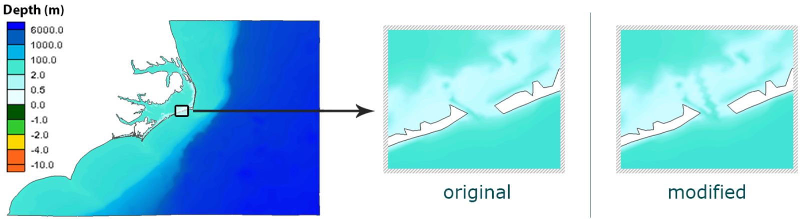
0. Begin with a full-scale ADCIRC domain: `fort.{13,14,15,22,...}`
1. Generate .dif files for child domains
2. Run ADCIRC++

Test Cases

- **Parametric Study** to evaluate the impacts of control parameters on accuracy:
  - Beaufort Inlet
- **Sensitivity Analysis** to demonstrate the applicability and computational efficiency of the method:
  - Hurricane Irene (2011)

Beaufort Inlet

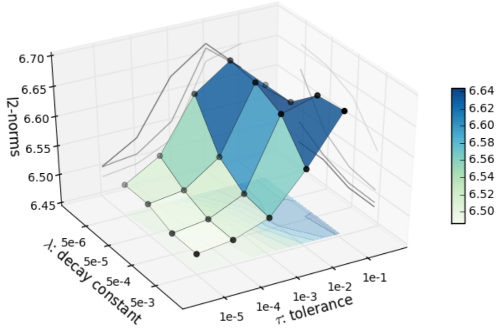
A tidal model available from ADCIRC website. nodes:32,218, elements:58,641, δt=5 sec, `RNDAY`=40.

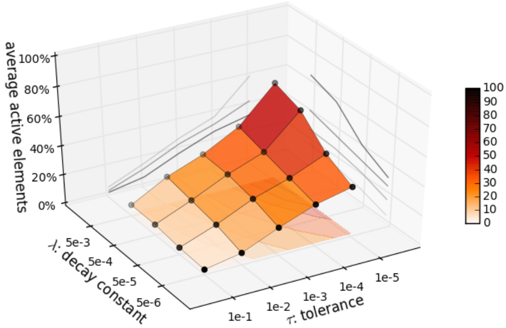


80 child domains run concurrently:

- **Same local change:** The depths of 20 nodes at Hatteras Inlet are increased by 1.425m on avg.
- **Varying sets of control parameters:** $\tau = \{10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}\}$, $\sigma = \{10^{-1}, 10^{-2}\}$, $\lambda = \{5 \times 10^{-3}, 5 \times 10^{-4}, 5 \times 10^{-5}, 5 \times 10^{-6}\}$, $\theta = \{10, 100\}$

Beaufort Inlet: varying control parameters

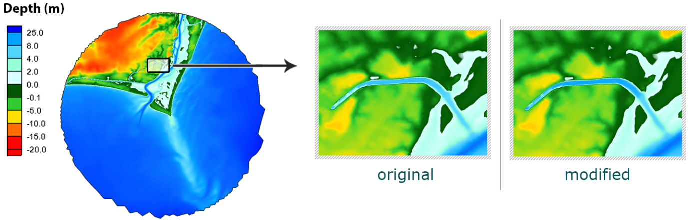




max errors$\rightarrow$ worst case: 19cm, best case: 5cm

Hurricane Irene - Sensitivity Analysis

A storm surge model. Full-scale grid: NC Mesh Version 9.98, nodes=622,946, elements=1,230,430, δt=0.5 sec, RNDAY=8 days. Subdomain grid: nodes=39,234, elements=78,114.

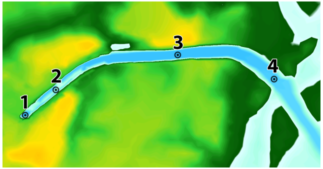


68 child domains run concurrently:

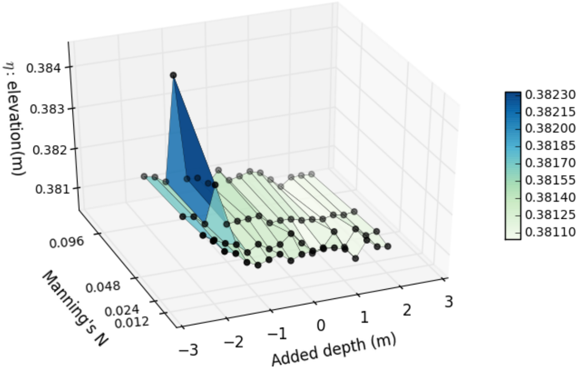
- **Varying local change:** Throughout the intake canal, Manning's N and depth are varied.
- **Same set of control parameters:** $\tau = 10^{-4}$, $\sigma = 10^{-2}$, λ=10^{-5}, $\theta = 100$.

Hurricane Irene

Change in η as the depth and Manning's N are varied throughout the canal



(a) Recording stations



(b) Maximum water surface elevations at Station-4

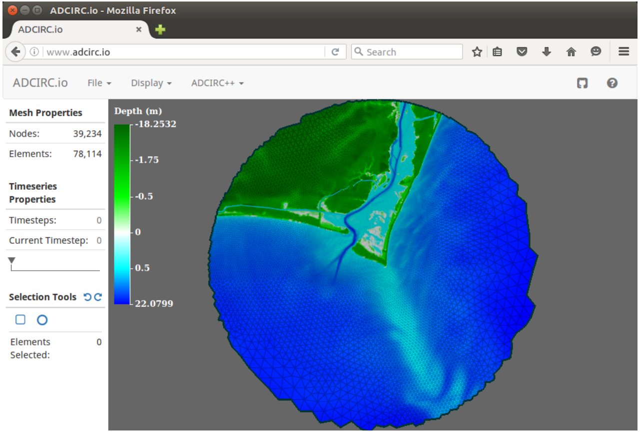
Hurricane Irene - Computational Efficiency

Cost of an additional simulation:

Grid	**Runtime (CPU-hrs)**	**%**
Full-scale	1487.6	
CSM subdomain	102.3	6.88
ASM child domain	3.6	0.24

Errors less than 1 mm

An Online Visualization Tool: **www.adcirc.io**



ADCIRC++: ADCIRC in C++14

Original ADCIRC

- FORTRAN with procedural abstraction.
- Global and non-reentrant data structures

ADCIRC++

- Object oriented design and data abstraction.
- Concurrent executions of multiple domains.
- Facilitates adaptive subdomain modeling.
- Non-optimized, has abstraction penalty, yet is only ∼15% less efficient.

Reimplemented capabilities:

- Consistent and lumped mass matrix solvers
- Wetting and drying
- Non-conservative momentum equations solver (new formulation)
- Tidal forcing
- Meteorological forcing: `NWS=8` (Holland), `NWS=12` (OWI)

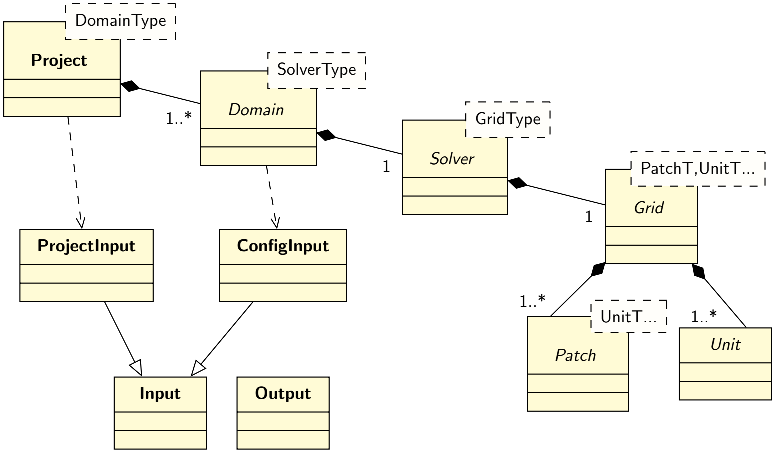
Core capabilities NOT reimplemented yet:

- SWAN coupling
- Hotstarting
- 3D solver
- Parallelism (in progress)

Code Structure

1. **Generic & Polymorphic source code**
    - Class templates
    - Abstract classes
2. **ADCIRC-Specific code**
    - Hand-written: 19k lines (incl. Level 1)
    - Translated with Fable: 4k lines (ITPACKV)
    - Replaced libraries with C++ version: 1k lines (KDTREE)

Class diagram of the Architecture



Remarks

- A multi-analysis technique and an updated software architecture is presented for ocean models when a number of design and failure scenarios are to be considered.
- Test results show that both the method and the software architecture are highly efficient and reliable.
- In addition to supporting what-if scenarios, the method can also facilitate formal optimization strategies and parametric studies for coastal development.

Future work

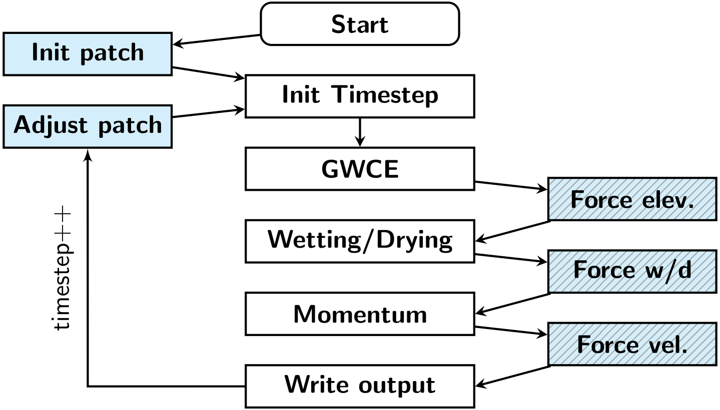
- Optimization and parallelization of ADCIRC++
- Incorporation of Adaptive Mesh Refinement in ADCIRC++

References

- Baugh, et al. *An exact reanalysis technique for storm surge and tides in a geographic region of interest.* Coastal Engineering 97 (2015): 60-77.
- Dyer and Baugh. *SMT: An interface for localized storm surge modeling.* Advances in Engineering Software 92 (2016): 27-39.
- Baugh and Rehak. *Data abstraction in engineering software development.* Journal of Computing in Civil Engineering 6.3 (1992): 282-301.
- Baugh and Altuntas. *Modeling a Discrete Wet-Dry Algorithm for Hurricane Storm Surge in Alloy.* 5th International ABZ Conference (2016)

Appendix

Child Domain Timestepping Loop



Patch Initialization

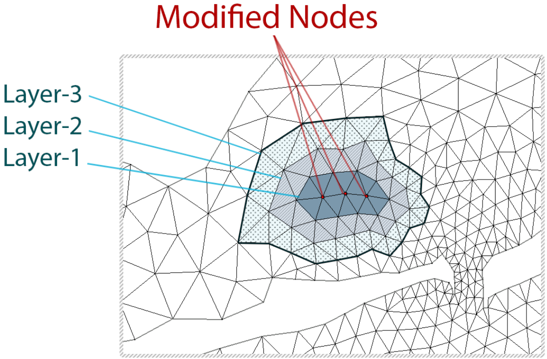


Figure: Initial patch of Shinnecock Inlet child domain

ASM is not wetting and drying

When a node is **made dry**:

- Its off-diagonal terms in GWCE set to zero. (The size of the system of equations remains unchanged.)
- Outputs set to alternative value (-99999.0).

When a node is **deactivated**:

- Completely removed from the computations. (System of equations resized.)
- Outputs obtained from the corresponding parent node.

Step-2: Expansion

At the nodes that are marked for expansion:

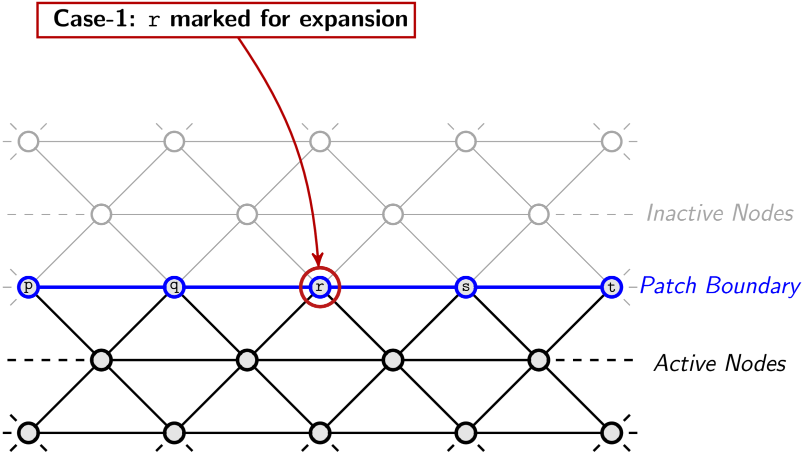
- The patch boundary is moved outwards by one layer of nodes and elements.

At the NEW boundary nodes:

- The tolerances of the new patch boundary nodes are set as:

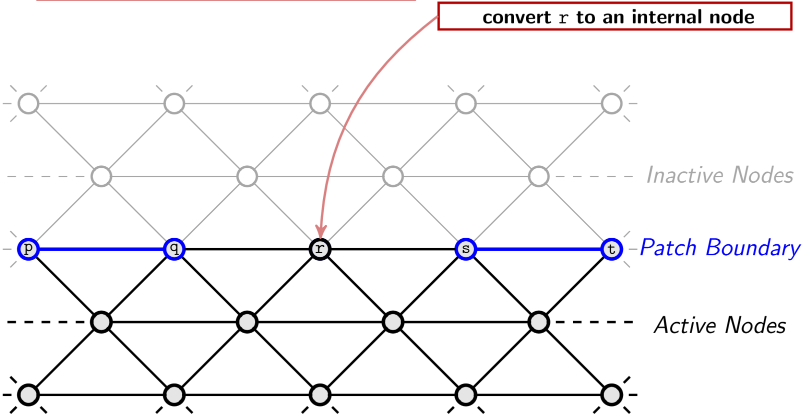
$$\tau_i^t = \tau^0 + max(\rho)$$

Step-2: Expansion



Step-2: Expansion

Case-1: `r` marked for expansion



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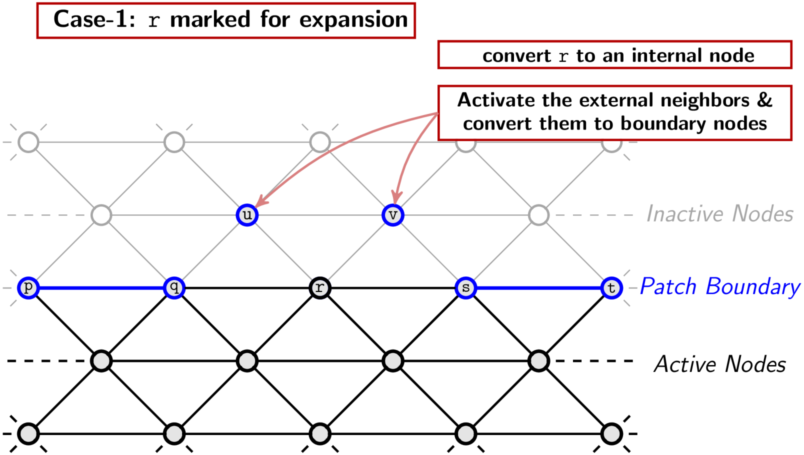

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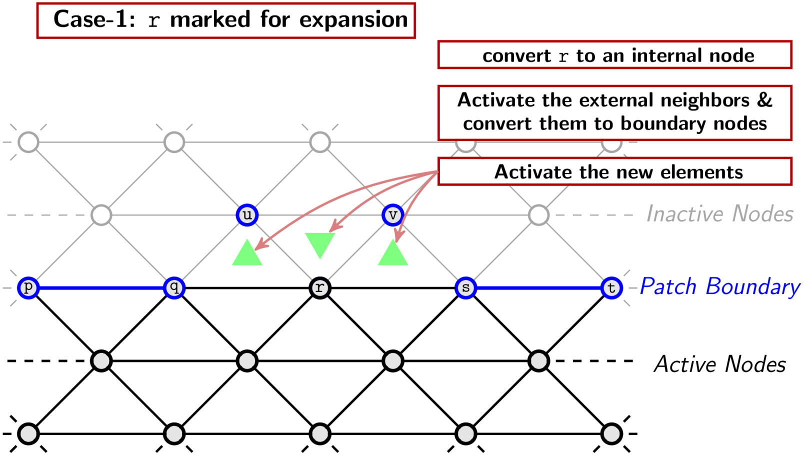

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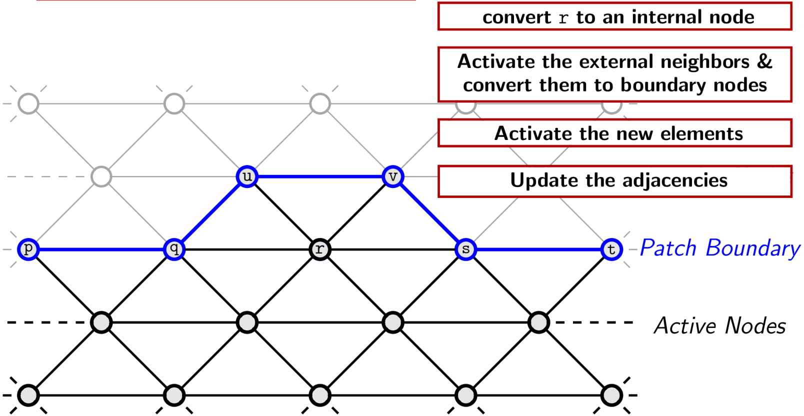


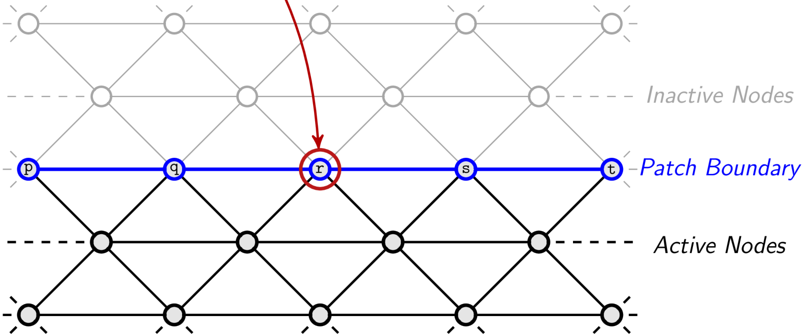
Step-3: Contraction

At the boundary nodes marked for contraction:

- The patch boundary is moved inwards by one layer of nodes and elements.

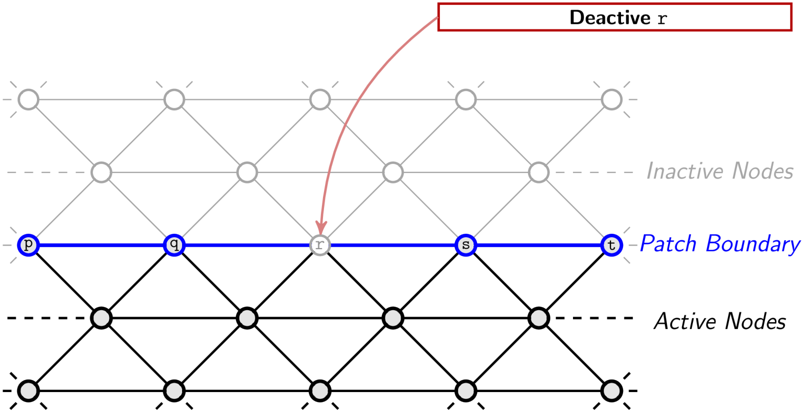
Step-3: Contraction

Case-2: `r` marked for deactivation



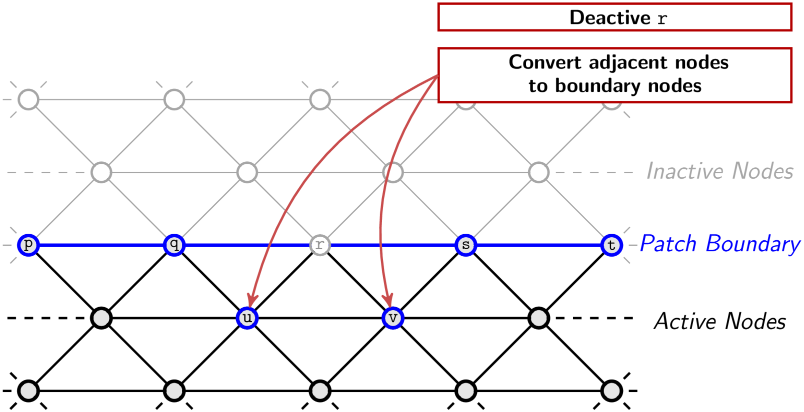
Step-3: Contraction

Case-2: `r` marked for deactivation



Step-3: Contraction

Case-2: r marked for deactivation



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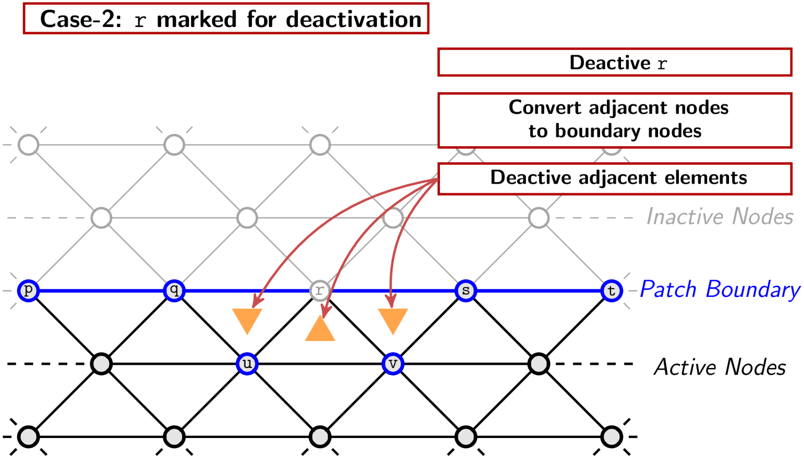


Step-3: Contraction

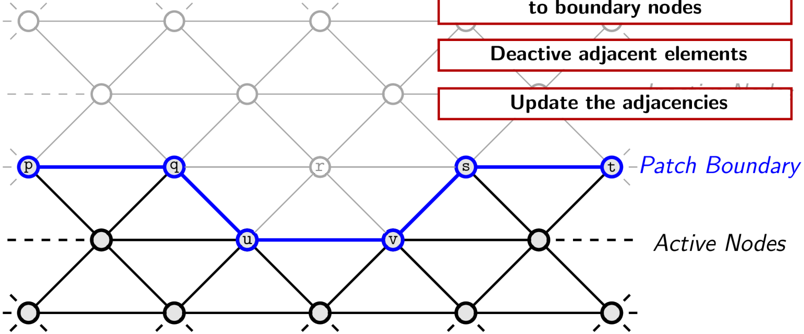
Case-2: `r` marked for deactivation

Deactive `r`

Convert adjacent nodes to boundary nodes

Deactive adjacent elements

Update the adjacencies

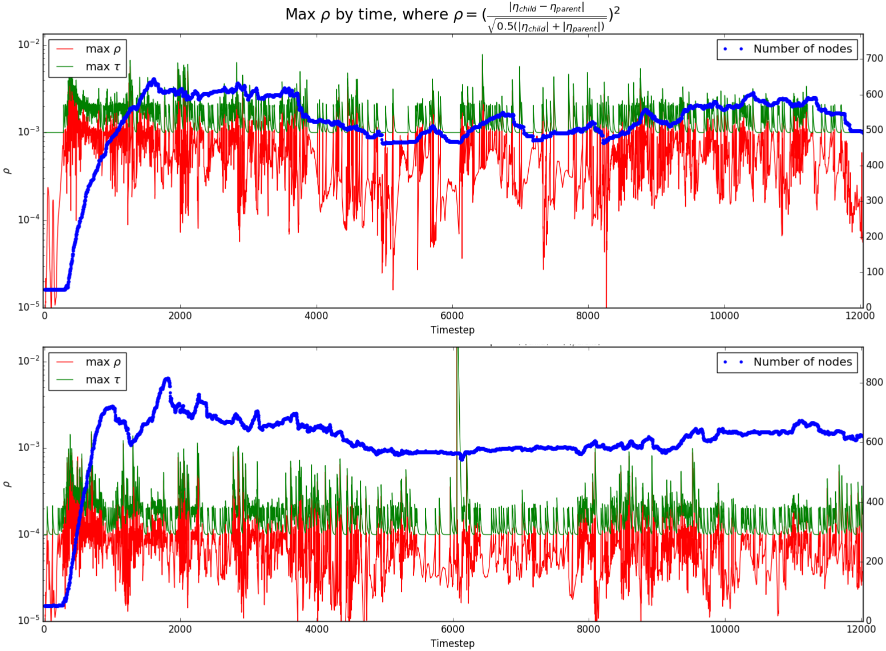


Step-4: Post-processing

In case of expansion/contraction:

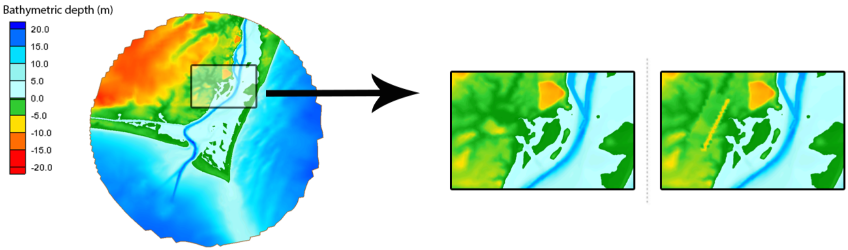
- The system of equations is reset and resized.
- Invalidated and outdated containers and properties are updated.
- Locally increased tolerances are subjected to an exponential decay:

$$\tau_j^t = (\tau_j^{t-1} - \tau^0)e^{-\lambda} + \tau^0$$


Max ρ by time, where $\rho = \left(\frac{|\eta_{child} - \eta_{parent}|}{\sqrt{0.5(|\eta_{child}| + |\eta_{parent}|)}}\right)^2$
max ρ
max τ
Number of nodes
ρ
Timestep
max ρ
max τ
Number of nodes
ρ
Timestep

Hurricane Fran

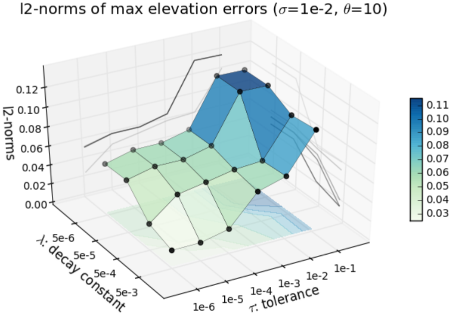
A storm surge model. Full-scale grid: NC FEMA Mesh Version 9.92, nodes=620,089, elements=1,224,714, δt=0.5 sec, $\texttt{RNDAY}$=3.9 days. Subdomain grid: nodes=28,643, elements=56,983.

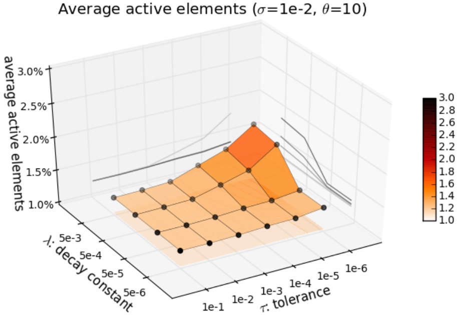


144 child domains run concurrently:

- **Same local change:** The topography is arbitrarily raised to add a 2.5-mile protective structure.
- **Varying sets of control parameters:** $\tau = \{10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$, σ=$\{10^{-1}, 10^{-2}, 10^{-3}\}$, λ=$\{5 \times 10^{-3}, 5 \times 10^{-4}, 5 \times 10^{-5}, 5 \times 10^{-6}\}$, θ=$\{10, 100\}$

Hurricane Fran: varying control parameters





max errors$\rightarrow$ worst case: 3.5cm, best case: 0.69 cm

Hurricane Fran

Child domain patch extents at various timesteps for $\tau = 10^{-5}$, $\sigma = 10^{-2}$, λ=5 $\times$ 10^{-4}, $\theta = 10$