ABSTRACT

ALTUNTAS, ALPER. Downscaling Storm Surge Models for Engineering Applications. (Under the direction of John Baugh.)

Storm surge modeling can be used to simulate the effects of hurricanes on coastal regions and to determine the weaknesses of civil infrastructure systems, to take the required precautions, and to formulate actions and countermeasures. Such simulations typically require substantial computation times and large amounts of secondary storage especially when several hypothetical scenarios are to be considered. This thesis presents several improvements to subdomain modeling, an approach that reduces runtime and storage requirements by operating on a smaller domain or grid. Subdomain modeling works by recording the time-varying states of nodes during an initial, full scale simulation and then using them as the boundary conditions of a smaller grid in subsequent simulations. By obtaining the boundary conditions for the smaller grid –a subdomain– different test case scenarios can be applied without needing to perform the full simulation again. The approach is implemented in ADCIRC, a computer program widely used to simulate and analyze hurricane storm surge. In addition to subdomain modeling, a new method called subduration modeling is introduced to further improve runtime performance. The approach makes use of ADCIRC's hot-start feature, whereby simulations can be restarted and allowed to resume in the event of a program crash. The hot-start feature records the state of the entire simulation at specified time intervals and then uses it as the initial condition of the hot started model. By making use of this feature, the runtime of a series of simulations can be reduced when different test cases are to be performed on the same geographic region but with local changes made to the terrain. Instead of starting the simulation from the beginning, the subduration approach is designed to start the run at the particular timestep at which those changes begin to affect the course of the simulation. Both of these enhancements to ADCIRC are described, and several test cases are presented in order to validate the approaches. As the frequency at which boundary conditions are enforced increases, subdomain models converge toward the solutions obtained in full scale runs. Therefore, by using these methods it is possible for engineers to perform accurate storm surge simulations at much less computational cost, and time.

Downscaling Storm Surge Models for Engineering Applications

by
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DEDICATION

To my family

BIOGRAPHY

Alper Altuntas was born on March 20, 1989 in Giresun, Turkey. He graduated from high school in 2006. He completed his undergraduate degree in civil engineering at Istanbul Technical University in 2010, and joined the Master of Science program in civil engineering at North Carolina State University.

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The views and conclusions contained in this study are my own and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security.

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Chapter 1 – Introduction

The vulnerability of coastal areas to storm surge has led scientists and engineers to develop methods that predict and analyze the effects of hurricanes, which may result in loss of human life and property. Storm surge modeling is a powerful computational method of forecasting inundation caused by potential hurricanes. It is widely used by civil engineers to examine the performance of civil infrastructure and to design hurricane resistant structures in coastal regions. To obtain sufficient information from a storm surge model, it is often necessary to consider multiple storm surge and flooding scenarios. Consequently, storm surge models are expected to provide reliable information and to perform efficiently.

In order to capture the natural characteristics of hurricane storm surge realistically, computational models are generally required to cover large domains using high resolution grids, increasing the computational requirements to perform such simulations (Luettich, Westerink & Scheffner, 1992). This research presents two approaches, subdomain modeling and subduration modeling, that improve the efficiency of storm surge simulations when various inundation scenarios are to be examined. These approaches are implemented in ADCIRC, a finite element based storm surge model widely used by the US Army Corps of Engineers, FEMA, and others. The basic formulation of ADCIRC and its wetting and drying algorithm, which has an impact on the approach taken and on the accuracy of ADCIRC itself, are presented in Chapter 2.

The subdomain modeling approach, originally introduced by Simon and Baugh (2011), is based on forcing the data of boundary nodes of a smaller grid within the original, larger grid. The approach is used to reduce the total runtime of a series of hurricane storm surge simulations where alternative topographies and configurations in a geographical region of interest are examined. Improvements in the approach are presented in Chapter 3, where finite state models of ADCIRC's wetting and drying algorithm reveal an interaction with the subdomain approach that must be accommodated. Additional enhancements are presented that increase the accuracy and accessibility of the approach, and test cases are presented to examine its reliability and performance.

In Chapter 4, the subduration modeling approach is presented for downscaling hurricane storm surge models in time. The hot-start feature of ADCIRC is a capability allowing the restart of a simulation at a particular timestep. This feature is drawn upon to reduce the runtime of a series of simulations when various local changes to the terrain are applied. The changes made to the hot-start algorithm and several test cases are presented.

Finally, conclusions are presented in Chapter 5, and a user's guide for the modified subdomain approach and other changes made to ADCIRC are provided in the appendices.

Chapter 2 – ADCIRC Background

ADCIRC is a storm surge model widely used by scientists and engineers to analyze the effects of hurricanes on coastal regions. ADCIRC performs with high accuracy and efficiency as a result of numerical algorithms, optimization of governing equations, and extreme grid flexibility (Luettich, Westerink & Scheffner, 1992). An ADCIRC run can be performed in serial or in parallel, and hydrodynamic equations can be solved with two-dimensional depth-integrated (2DDI) or three-dimensional equations.

2.1 ADCIRC Formulation

For the ADCIRC-2DDI, the version used throughout this research, the equation solved to determine the water surface elevation is the Generalized Wave Continuity Equation (GWCE), and the equation solved to determine the depth-averaged velocity is the vertically-integrated momentum equation (Luettich & Westerink, 2004). The GWCE is derived from the primitive depth-integrated continuity equation and the primitive depth-integrated conservation of momentum equations, which lead to a discrete system of equations (Luettich et al., 1992).

Numerical discretization in time is performed using finite differences (Luettich et al., 1992). Time discretization of the GWCE using the finite difference method is achieved by implementing a variably weighted, three-time-level scheme, while the time discretization of momentum equations is achieved by implementing a two-time-level variably weighted scheme (Luettich et al., 1992). Finally, numerical discretization in space is performed using the finite element method to complete the conversion of the governing equations into algebraic equations (Luettich et al., 1992). Three-node linear triangular elements, which have proved to be flexible and cost-effective, are used for finite element discretization (Luettich et al., 1992).

After fully discretizing the GWCE, the following global system of equations is obtained (Luettich et al., 1992):

$$\sum_{j=1}^{N} \left\{ {}^{g}M_{ij}^{GWCE} \right\} \left\{ {}^{g}\zeta_{j}^{k+1} \right\} = \left\{ {}^{g}P_{i}^{GWCE} \right\} \qquad i = 1, \ldots N$$

where

N: number of nodes

$\left\{{}^{g}M_{ij}^{GWCE}\right\}$: the global banded system matrix

$\left\{{}^{g}P_{i}^{GWCE}\right\}$: the global load vector

$\left\{{}^{g}\zeta_{j}^{k+1}\right\}$: the global nodal elevation vector

After fully discretizing the momentum equations, the following global system of equations is obtained (Luettich et al., 1992):

$$\sum_{j=1}^{N}\left\{{}^{g}M_{ij}^{1ME}\right\}\left\{{}^{g}U_{j}^{k+1}\right\}+\left\{{}^{g}M_{ij}^{2ME}\right\}\left\{{}^{g}V_{j}^{k+1}\right\}=\left\{{}^{g}\mathbf{P}_{i}^{XME}\right\} \qquad i = 1, ...N$$

$$\sum_{j=1}^{N}\left\{{}^{g}M_{ij}^{2\,ME}\right\}\left\{{}^{g}U_{j}^{k+1}\right\}+\left\{{}^{g}M_{ij}^{1\,ME}\right\}\left\{{}^{g}V_{j}^{k+1}\right\}=\left\{{}^{g}\mathbf{P}_{i}^{YME}\right\} \qquad i = 1, ...N$$

where

${}^{g}M_{ij}^{1\,ME}$, ${}^{g}M_{ij}^{2\,ME}$ = global diagonal system matrices

${}^{g}\mathbf{P}_{i}^{XME}$, ${}^{g}\mathbf{P}_{i}^{YME}$ = global right-hand-side load vectors,

U_{j}^{k+1}, ${}^{g}V_{j}^{k+1}$ = global velocity vectors in the x and y directions

2.2 Wetting and Drying Algorithm

The wetting and drying algorithm in ADCIRC is used to determine whether nodes and elements inside the grid should be activated or deactivated within a timestep (Luettich & Westerink, 1995). Activated (wet) areas inside the grid are included in hydrodynamic calculations while deactivated (dry) areas are excluded from the calculations (Luettich & Westerink, 1995).

In an ADCIRC timestep, the wetting and drying algorithm appears after the solution of the continuity equation and before the solution of the momentum equation (Dietrich, Kolar & Luettich, 2004). Given the discrete nature of these calculations within a finite difference timestepping scheme, it is particularly important to be mindful of its effects both on the approach used for subdomain modeling and on the accuracy and stability of ADCIRC itself.

2.2.1 Initialization of Wetting and Drying

The wetting and drying algorithm in ADCIRC is controlled by three variables: (1) nnodecode maintains the wet/dry status of a node and is updated frequently within the wet/dry algorithm in a timestep. (2) nodecode maintains the wet/dry status of a node, but is updated after the wetting and drying algorithm is completed. (3) noff maintains the wet/dry status of an element. These variables are initialized in accordance with the bathymetry of the grid and the configuration of the model:

- Nodes that have less water height than H_0 (minimum water depth) are initialized as dry nodes and the surface elevation of these nodes are set to H_0-DP (DP: bathymetric depth). Remaining nodes are initialized as wet nodes. However, if a node is configured to be dry (a user-defined setting), ADCIRC will initialize the node as dry, even though it is below mean sea level.
- If a wet node is connected to dry nodes only, the node will be initialized as a dry node (landlocking).
- All the elements are set to be wet at the beginning of the simulation unless it is hot started.

2.2.2 Wetting and Drying Criteria

Several criteria are applied on the grid to specify the states of nodes and elements. The wetting and drying criteria taken from the ADCIRC source code (Version 50.51) are as follows:

- First, the water surface elevations of the nodes are checked to determine whether they are greater than H_0; the minimum water depth for a node to be considered wet. If the water height is greater than H_0, the node remains wet. Otherwise, the node becomes dry and is excluded from the hydrodynamic calculations.
- Second, a nodal wetting criterion is applied on the elements when a node is dry but the rest of the nodes are wet. If the water column heights of both wet nodes are greater than or equal to $H_{off} = 1.2xH_0$, and if the water level of the dry node is less than the water level of one of the wet nodes, the dry node is made wet if the steady state velocity is greater than V_{min} (Dietrich et al., 2004).
- Third, an elemental drying criterion is applied. If one of the two nodes with higher water surface elevation in an element has less water depth than $H_{off} = 1.2xH_0$, the element is made dry.

- Finally, wet nodes that are only connected to dry elements are dried.

After the implementation of the wetting and drying algorithm, the wet/dry states of the nodes and elements are updated within the timestep.

2.3 Parallel ADCIRC

ADCIRC can be run in parallel on computer clusters to reduce the computing time of a large model. Decomposition of the domain for a parallel ADCIRC run is done using METIS (Karypis and Kumar, 1998), and Message Passing Interface (MPI) is used for communication between each processor. Message passing between neighboring subdomains is done using a communication layer: data of the inner nodes is sent to neighboring subdomains and data of the outer nodes is received from the neighboring subdomains (Tanaka et al., 2010). Additionally, a global communication is performed among all processors to calculate the dot product in the iterative solver (Tanaka et al., 2010).

To demonstrate the effects of parallelization on accuracy of ADCIRC, an example problem is run on a large domain containing 620,089 nodes and 1,224,714 elements. A serial run and several parallel runs using different numbers of processors are performed. These runs are compared on a small, circular area containing 28,643 nodes. The maximum surface elevations of the nodes for each run are compared. Maximum elevation comparison plots show that parallel ADCIRC introduces small deviations from the serial simulation (Figures 2.1, 2.2, and 2.3). In addition, an error convergence plot (Figure 2.4) shows that increasing the number of the cores used in a parallel run exacerbates these deviations.

It is observed that the divergence between serial and parallel solutions, which is negligible in most cases, is caused by the iterative solver and the precision of the MPI library. These errors appear to be occurring at regions of complex topography. Although the differences between serial and parallel runs are negligible during the initial timesteps of the model, they accumulate and eventually result in errors which can be observed.

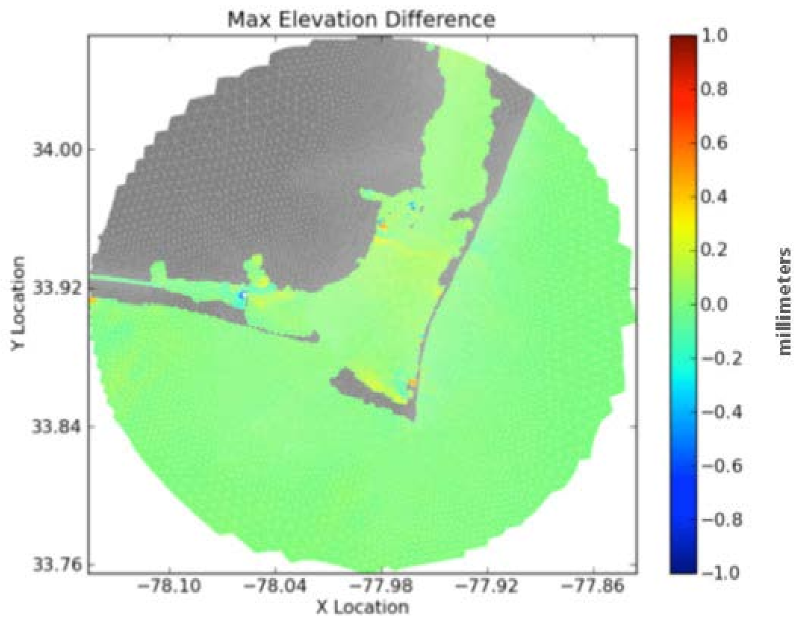


Figure 2.1: Maximum elevation comparison between serial run and 4-processor parallel run

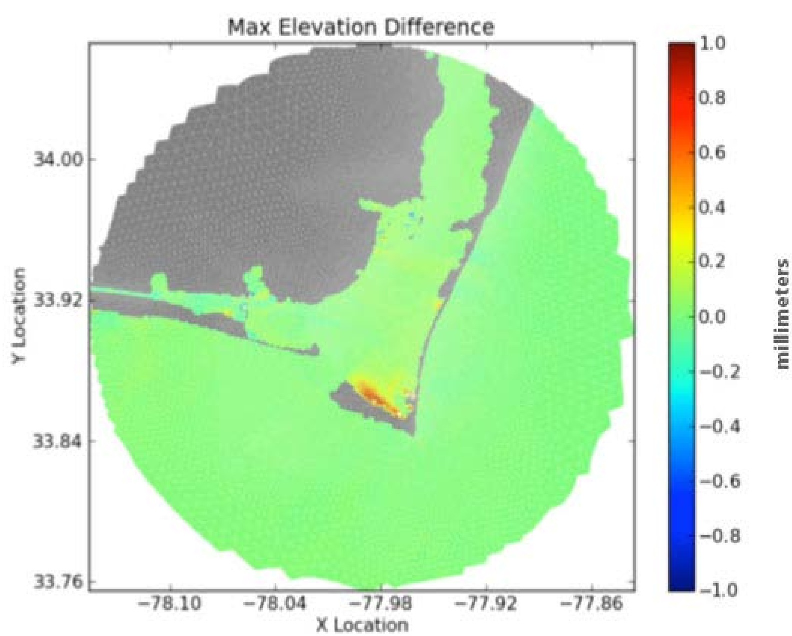


Figure 2.2: Maximum elevation comparison between serial run and 8-processor parallel run

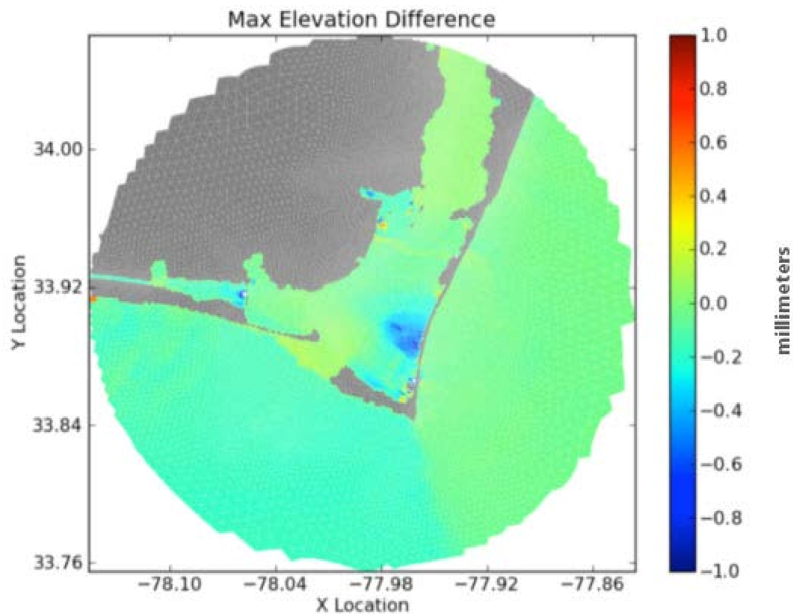


Figure 2.3: Maximum elevations comparison between serial run and 40-processor parallel run

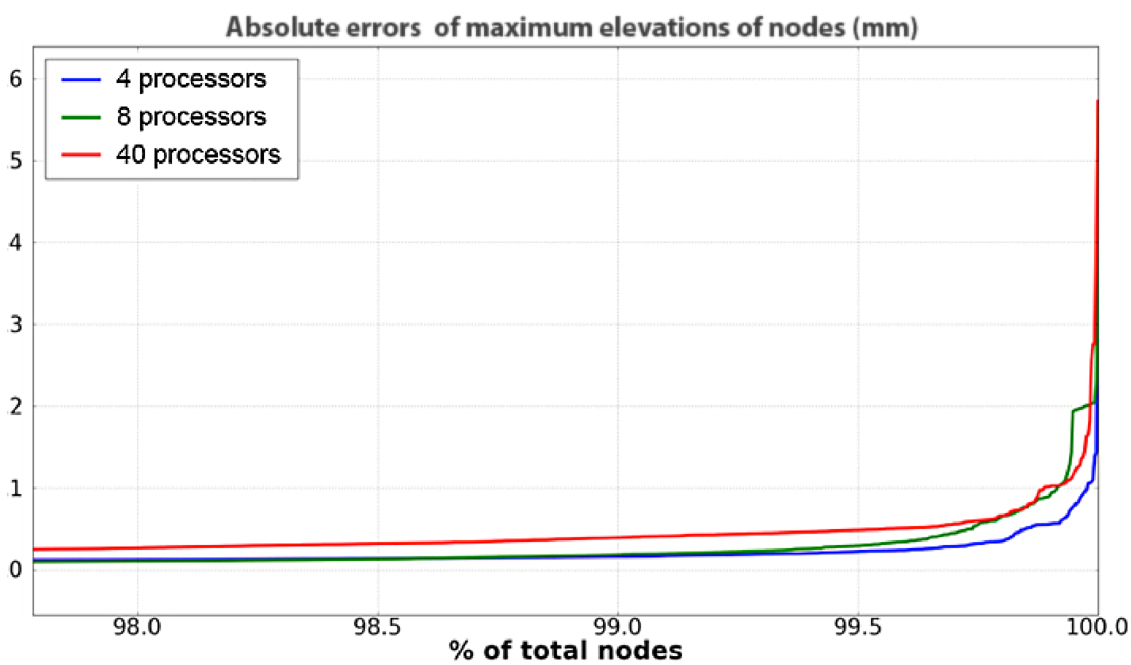


Figure 2.4: Absolute errors of Parallel ADCIRC runs using various number of processors

Chapter 3 – Improvements in Subdomain Modeling

Subdomain modeling in ADCIRC reduces the total runtime of a series of hurricane storm surge simulations to be performed for a particular storm on multiple, alternative topographies in a geographical region of interest. The approach is based on forcing the data of boundary nodes of a considerably smaller grid called a subdomain within the original, larger grid. Boundary conditions of subdomains are obtained from the output files of an original full run and are then used as input files for the subdomain runs. Boundary node data of subdomains are enforced once they are read from input files at specified time intervals, and are linearly interpolated at intermediate timesteps. Approaches designed to improve the accuracy and accessibility of the technique are described below.

3.1 Wet/Dry Forcing in Subdomain Modeling

The approach to subdomain modeling originally outlined by Simon (2011) enforces only elevations and velocities as boundary conditions and omits the wet/dry states of boundary nodes due to their ineligibility for interpolation and the concomitant increase in secondary storage. In the following sections, the effects of the wetting and drying algorithm on subdomain modeling are described, and wet/dry forcing is then introduced in ADCIRC to improve the fidelity of the approach.

3.1.1 LTSA Model of Wetting and Drying Algorithm

In this section, ADCIRC's wetting and drying algorithm is modeled as a finite state machine to look for potential conditions under which the wet/dry states of boundary nodes may fail to be properly determined in a subdomain model. The presence of such conditions would imply that wet/dry states along a subdomain boundary cannot simply be recomputed from available information within a subdomain run and must therefore be saved from a full run and subsequently imposed on the boundaries of a subdomain. LTSA, a finite state model-checking tool (Magee and Kramer, 2006), is used to model and analyze the algorithm.

LTSA Background:

LTSA is a model checking tool that supports the representation and analysis of finite state systems. Actions in LTSA denote a transition between states and are depicted as arcs between nodes. In Figure 3.1, the `dry` action causes a node to become (or stay) dry (State 0). Likewise, the action `wet` causes a node to become (or stay) wet (State 1). In LTSA, this graphical representation is defined as a process, NODE, using a syntax comparable to other process algebraic languages, as shown in Figure 3.2. The expressive power of the language is enhanced through the use of indexing, which may be applied to both processes and actions.

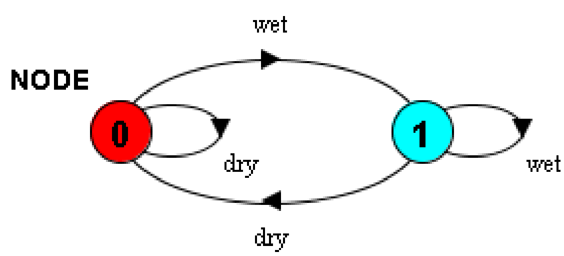


Figure 3.1: LTSA drawing of a process NODE.

```
NODE = NODE[0],
NODE[i:0..1] =  ( wet -> NODE[1]
                | dry -> NODE[0] ).
```

Figure 3.2: A basic LTSA model of a node.

In this particular case indexing of the NODE process results in the following expected unfolding:

```
NODE[0] =  ( wet -> NODE[1]
           | dry -> NODE[0]
NODE[1] =  ( wet -> NODE[1]
           | dry -> NODE[0]).
```

Additional examples and applications may be found in Magee and Kramer (2006).

Wetting and Drying Model:

The LTSA model of wetting and drying described below consists of six nodes and five elements. These nodes and elements form two basic grids, as shown in Figure 3.3. The first grid models a full domain consisting of four elements and the second grid models a subdomain, which is the equivalent of element 1 in the full domain, and node 6 in the subdomain corresponds to node 1 in the full domain.

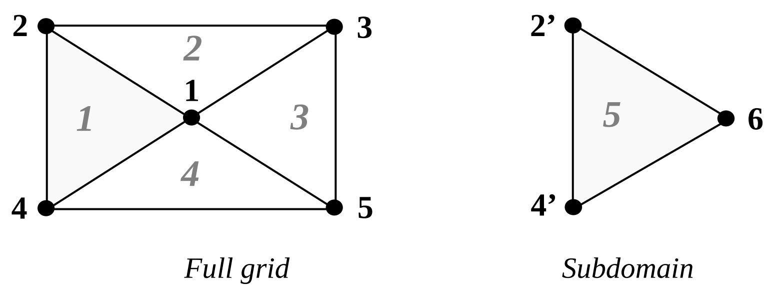


Figure 3.3: Representations of grids modeled in LTSA

3.1.1.1 Node

First, the behavior of a node in a grid is modeled. Since a node in ADCIRC uses two variables to designate its wet/dry status, `nnodecode` and `nodecode`, the process `NODE` in the LTSA model similarly has two indices: `nnc` and `nc`. The actions `wet_node` and `dry_node` signal the transition of the wet/dry status of a node. When the status of a node is changed by these actions, the index `nnc` is set accordingly. The action `update_nc` updates the `nodecode`. The actions `is_wet` and `is_dry` are used as output actions by subsequent processes. It should be noted that the process `NODE` is labeled with the set of nodes to disjoin the alphabets of all six nodes. Prefixing is used to label each action in the process with the number of the node. For example, the action `wet_node` of the third node is transformed into `node[3].wet_node`.

```
const NP = 6
set Nodes = {node[n:1..NP]}
set NodesAlpha = {node[n:1..NP].{wet_node,dry_node,update_nc,is_wet,is_dry}}
NODE = NODE[1][1],
NODE[nnc:0..1][nc:0..1] = ( wet_node -> NODE[1][nc]
                          | dry_node -> NODE[0][nc]
                          | update_nc -> NODE[nnc][nnc]
                          | when(nc==1) is_wet -> NODE[nnc][nc]
                          | when(nc==0) is_dry -> NODE[nnc][nc]).
||NODES = ( Nodes:NODE ).
```

Figure 3.4: LTSA model of the process NODE.

Descriptions of variables used in the LTSA model of the `NODE` process:

`NP`: number of nodes in the model.

`Nodes`: set of nodes.

`NodesAlpha`: action alphabet of the process `NODE`.

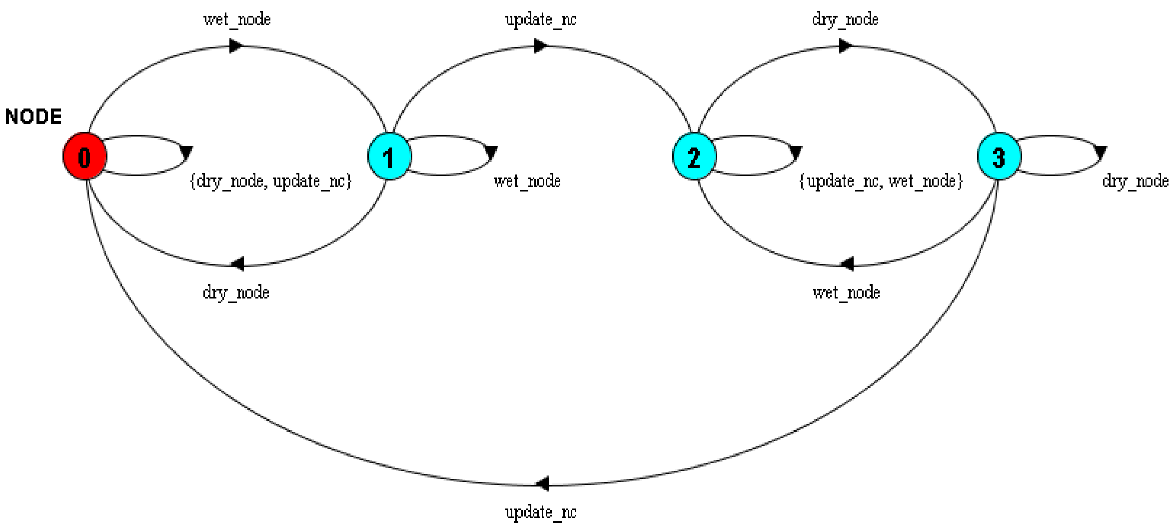


Figure 3.5: LTSA Diagram of the process NODE. (Output actions are omitted.)

Table 3.1: Descriptions of the states of the process NODE.

	nnc	nc	Description
State 0:	0	0	Node is dry.
State 1:	1	0	Node is wet, but not yet updated.
State 2:	1	1	Node is wet.
State 3:	0	1	Node is dry, but not yet updated.

3.1.1.2 Elements

In similar fashion, the behavior of an element can be modeled. The index `nf` represents the wet/dry status of an element. The actions `wet_element` and `dry_element` signal the transition of the wet/dry status of the element. The actions `is_wet_ele` and `is_dry_ele` are used as output actions by remaining processes. The process `ELEMENT` is also prefixed with the set of elements to disjoin the alphabets of all five elements.

```
const NE = 5
set Elements = {ele[e:1..NE]}
set ElementsAlpha = {ele[e:1..NE].{wet_element,dry_element,is_wet_ele,is_dry_ele}}
ELEMENT = ELEMENT[1],
ELEMENT[nf:0..1] = ( wet_element ->  ELEMENT[1]
                   | dry_element ->  ELEMENT[0]
                   | when(nf==1) is_wet_ele -> ELEMENT[nf]
                   | when(nf==0) is_dry_ele -> ELEMENT[nf] ).
||ELEMENTS = ( Elements:ELEMENT ).
```

Figure 3.6: LTSA model of the process ELEMENT.

Descriptions of variables used in the LTSA model of the `ELEMENT` process:

`NE`: number of elements in the model.

`Elements`: set of elements.

`ElementsAlpha`: action alphabet of the process `ELEMENT`.

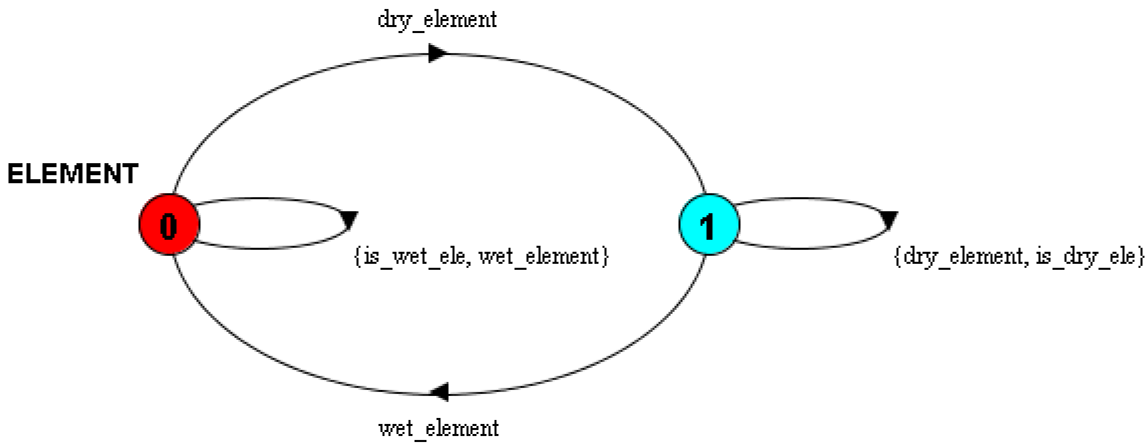


Figure 3.7: LTSA Diagram of the process ELEMENT.

3.1.1.3 Algorithm

The wetting and drying algorithm in ADCIRC consists of four main criteria as described in section 2.2.2. Each criterion is separately modeled and a parallel composition of nodes, elements, and parts of the algorithm is performed to complete the model. Minimized LTSA diagrams of the components of the wetting and drying algorithm are provided in Appendix C.

`PART1`: If the total water height of a wet node is less than H_0, the node is made wet and updated. First, the process is initiated when the action `part1.start` is signaled. Wet/dry states of the nodes are sequentially determined using synchronized output actions; `is_wet` or `is_dry`. The index n of subprocess `PART1_main` represents the node numbers and is also used to determine the end of the process. When the node is dry, the process skips to the next node; n+1. If the node is wet, a non-deterministic choice is made: total water height is either greater or less than H_0. If the height is less than H_0, node is made dry (`dry_node)` and updated (`update_nc`). If the height is greater than H_0, subprocess skips to next node. When the index n exceeds the number of nodes of the model (`when(n==NP+1)`), the process engages in the only available action, `part1.end`, and returns to the beginning for the evaluation of the next timestep.

```
PART1 = ( part1.start -> PART1_main[1]),
PART1_main[n:1..NP+1] =
( when(n!=NP+1) node[n].is_wet -> node[n].htot_le_h0 -> node[n].dry_node
                                -> node[n].update_nc -> PART1_main[n+1]
| when(n!=NP+1) node[n].is_wet -> node[n].htot_gt_h0 -> PART1_main[n+1]
| when(n!=NP+1) node[n].is_dry -> PART1_main[n+1]
| when(n==NP+1) part1.end -> PART1 ).
```

Figure 3.8: LTSA model of the process PART1.

PART2: If an element has two wet nodes, and if the steady state velocity is greater than V_{min} (represented with the action v_gt_velmin), the third dry node of the element is also made wet. First, the number of the wet nodes of an element is counted in subprocess PART2_main using the synchronized actions; is_wet and is_dry. The index nctot of PART2_main is increased by one if a node inside an element is determined to be wet, and the index is passed to PART2_eval to evaluate the element. Then, the steady state velocities of elements having two wet nodes are non-deterministically chosen to be greater or less than V_{min} in the subprocess PART2_eval. If the velocity is greater than V_{min}, it is ensured that all the nodes of the elements are wet. Otherwise, the process skips to next element. When the index e exceeds the number of elements of the model (when (e==NE+1)), the process engages in only available action part2.end, and returns to the beginning for the evaluation of the next timestep.

```
PART2 = ( part2.start -> PART2_main[1][1][0]),
PART2_main[e:1..NE+1][n:1..4][nctot:0..3] =
 ( when(e==NE+1) part2.end -> PART2
 | when(e!=NE+1 && n!=4 && nctot!=3) ele[e].node[n].is_wet -> PART2_main[e][n+1][nctot+1]
 | when(e!=NE+1 && n!=4 && nctot!=3) ele[e].node[n].is_dry -> PART2_main[e][n+1][nctot]
 | when(e!=NE+1 && n==4) ele[e].evaluate2 -> PART2_eval[e][nctot]),
PART2_eval[e:1..NE][nctot:0..3] =
 ( when(nctot==2) velmin -> v_gt_velmin -> ele[e].node[1].wet_node
                                     -> ele[e].node[2].wet_node
                                     -> ele[e].node[3].wet_node -> PART2_main[e+1][1][0]
 | when(nctot==2) velmin -> v_le_velmin -> PART2_main[e+1][1][0]
 | when(nctot!=2) pass2 -> PART2_main[e+1][1][0] ).
```

Figure 3.9: LTSA model of the process PART2.

It should be noted that the nodal actions are prefixed with the elements to imply the assembly of the grid. For example, `node[5].wet_node` action of node 5, which is the second node of element 3, is represented by `ele[3].node[2].wet_node` (to complete the assembly, relabeling is implemented in the composite process: `node[5]/ele[3].node[2]`).

`PART3`: The number of wet nodes in an element is counted in the subprocess `PART3_main` as is done in `PART2_main`. If an element has only one wet node, the element is taken to be dry. If two or more nodes of an element are wet, a non-deterministic choice is made in the subprocess `PART3_eval`: h is defined to be either greater or less than H_{off}.

```
PART3 = ( part3.start -> PART3_main[1][1][0]),
PART3_main[e:1..NE+1][n:1..4][nctot:0..3] =
 ( when(e==NE+1) part3.end -> PART3
 | when(e!=NE+1 && n!=4 && nctot!=3) ele[e].node[n].is_wet -> PART3_main[e][n+1][nctot+1]
 | when(e!=NE+1 && n!=4 && nctot!=3) ele[e].node[n].is_dry -> PART3_main[e][n+1][nctot]
 | when(e!=NE+1 && n==4) ele[e].evaluate3 -> PART3_eval[e][nctot]),
PART3_eval[e:1..NE][nctot:0..3] =
 ( when(nctot<=1) ele[e].dry_element -> PART3_main[e+1][1][0]
 | when(nctot>=2) hoff -> ele[e].dry_element -> PART3_main[e+1][1][0]
 | when(nctot>=2) hoff -> ele[e].wet_element -> PART3_main[e+1][1][0] ).
```

Figure 3.10: LTSA model of the process PART3.

`PART4`: The land-locking criterion is applied: if a wet node is not connected to an active (wet) element, the node is dry. To implement this criterion, an additional process called `MJU` is introduced. This process maintains an index `mju` for each node in the model. If the node is connected to at least one wet element, the index `mju` is set to 1. The alphabet of the process is synchronized with the process `PART4`. Note that this process is also prefixed with the set of nodes for synchronization.

The subprocess `PART4_main` of `PART4` evaluates the elements of the model. If an element is wet, the `active_ele` action occurs for three nodes connected to this element. Since the action is synchronized with the process `MJU`, the index `mju` for all three nodes are set to 1. After the elemental evaluation, the process skips to subprocess `PART4_eval` to evaluate the nodes of the model. If the index `mju` of a node n is previously set to 1, the process engages in only eligible action `node[n].has_active_ele`. After the occurrence of this action, `node[n].reset` action is signaled to reset the index `mju` of the node for the next timestep. However, if the node does not have any active element, only eligible action left is `node[n].no_active_ele`. This action is followed by `node[n].landlocking`, which eventually results in drying of the node.

```
MJU = MJU[0],
MJU[mju:0..1] = ( active_ele -> MJU[1]
                | reset -> MJU[0]
                | when(mju==1) has_active_ele -> MJU[mju]
                | when(mju==0) no_active_ele -> MJU[mju] ).
||MJUS = ( Nodes:MJU ).
```

Figure 3.11: LTSA model of the process MJU.

```
PART4 = ( part4.start -> PART4_main[1]),
PART4_main[e:1..NE+1] =
 ( when(e==NE+1) end_main -> PART4_eval[1]
 | when(e!=NE+1) ele[e].is_dry_ele -> PART4_main[e+1]
 | when(e!=NE+1) ele[e].is_wet_ele -> ele[e].node[1].active_ele
                                   -> ele[e].node[2].active_ele
                                   -> ele[e].node[3].active_ele -> PART4_main[e+1] ),
PART4_eval[n:1..NP+1] =
 ( when(n==NP+1) part4.end -> PART4
 | when(n!=NP+1) node[n].has_active_ele -> node[n].reset -> PART4_eval[n+1]
 | when(n!=NP+1) node[n].no_active_ele -> node[n].landlocking -> node[n].dry_node
                                                             -> PART4_eval[n+1] ).
```

Figure 3.12: LTSA model of the process PART4.

`UPDATE`: After the implementation of the wetting and drying criteria in a timestep, nodecodes of the nodes are updated as in ADCIRC.

```
UPDATE = ( update.start -> UPDATE[1] ),
UPDATE[n:1..NP+1] = ( when(n==NP+1) update.end -> UPDATE
                    | when(n!=NP+1) node[n].update_nc -> UPDATE[n+1] ).
```

Figure 3.13: LTSA model of the process UPDATE.

`REPORTNODES`: This process is added to simplify the analysis. The actions `report_wet` or `report_dry` are signaled depending on the state of the node.

```
REPORTNODES = ( report.start -> REPORTNODES[1] ),
REPORTNODES[n:1..NP+1] =
( when(n!=NP+1) node[n].is_wet -> node[n].report_wet -> REPORTNODES[n+1]
| when(n!=NP+1) node[n].is_dry -> node[n].report_dry -> REPORTNODES[n+1]
| when(n==NP+1) report.end -> REPORTNODES ).
```

Figure 3.14: LTSA model of the process REPORTNODES.

`INITIALIZATION`: This process is implemented to initialize the nodes of the model at the beginning of the execution. The nodes are started either dry or wet, and updated. When the initialization ends, the process moves to subprocess `IDLE` and waits until the end of the execution.

```
Initialization = Initialization[1],
Initialization[n:1..NP+1] =
( when(n!=NP+1) { node[n].dry_node, node[n].wet_node }
                    -> node[n].update_nc -> Initialization[n+1]
| when(n==NP+1) end.initialization ->  IDLE ),
IDLE = ( {idle, end.initialization} -> IDLE)/{{NodesAlpha,ElementsAlpha}/idle}.
```

Figure 3.15: LTSA model of the process INITIALIZATION.

`PART0`: This process is implemented to initialize the elements of the model at the beginning of a timestep. Elements of the model are started wet, as is done ADCIRC code. After the end of the initialization of elements, the process waits for the next timestep.

```
PART0 = ( part0.start -> PART0_main[1]),
PART0_main[e:1..NE+1] = ( when(e==NE+1) part0.end -> PART0
                        | when(e!=NE+1) ele[e].wet_element -> PART0_main[e+1] ).
```

Figure 3.16: LTSA model of the process PART0.

3.1.1.4 Parallel Composition

Finally, the processes are combined using the parallel composition operator. In ADCIRC, the parts of the wetting and drying algorithm in a timestep are executed in sequence. However, a concurrent LTSA model operates interleaved and asynchronous (Magee and Kramer, 2006). To ensure that the processes are sequentially executed, an additional process called SEQUENCE is implemented.

```
SEQUENCE =  ( end.initialization -> part0.start -> part0.end
            -> part1.start -> part1.end -> part2.start -> part2.end
            -> part3.start -> part3.end -> part4.start -> part4.end
            -> update.start -> update.end -> report.start -> report.end -> SEQUENCE ).
```

Figure 3.17: LTSA model of the process SEQUENCE.

Since `start` and `end` actions of all the parts are synchronized and put in order with this process, it is ensured that the processes are executed in the desired sequence.

Another problem of parallel composition results from synchronized actions. Shared actions are required to occur at the same time in all the processes. However, the wetting and drying algorithm in a timestep is sequential, which means that only one participant of the algorithm is active at a time. Since the other processes are not yet started, they cannot engage in shared actions. For instance, if the process `PART1` is required to engage in the action `node[1].dry_node`, all other constituent processes sharing the action are also required to participate in it, which is not possible since they cannot be started until `PART1` ends; this leads to deadlock.

To overcome this problem, modifications are made to all constituent processes of the sequential procedure: PART0, PART1, PART2, PART3, PART4, UPDATE, REPORTNODES. These modifications are:

1. Add the action idle as an alternative of the action start.
2. Using a relabeling function, replace the action idle with the actions in the alphabets of the processes NODE and ELEMENT.

For example, the process PART1 is modified as shown in Figure 3.18.

```
PART1 = ( idle -> PART1
        | part1.start -> PART1_main[1]),
PART1_main[n:1..NP+1] =
 ( when(n!=NP+1) node[n].is_wet -> node[n].htot_le_h0 -> node[n].dry_node
                                   -> node[n].update_nc -> PART1_main[n+1]
 | when(n!=NP+1) node[n].is_wet -> node[n].htot_gt_h0 -> PART1_main[n+1]
 | when(n!=NP+1) node[n].is_dry -> PART1_main[n+1]
 | when(n==NP+1) part1.end -> PART1 )
/{{NodesAlpha,ElementsAlpha}/idle}.
```

Figure 3.18: Modified LTSA model of the process PART1.

These modifications ensure that, when the processes forming the sequential algorithm are not yet started, they do not restrain the active process from engaging in shared actions in the alphabets of NODES or ELEMENTS.

The parallel composition of the entire model is shown in Figure 3.19. As mentioned, a relabeling function is used to assemble the grids of the model. Idle actions, which are replaced with the alphabets of nodes and elements, can occur anytime during the execution. To restrain the model from arbitrary occurrences of these actions, the alphabets of nodes and elements are given lower priority.

The composite process has 96,039 states for a model comprised of five elements and six nodes, and results in no deadlock. In addition to deadlock analysis, a basic safety analysis is performed using two safety properties: The property Check_Element specifies that an element having less than two wet nodes cannot be wet. The property `Check_Element2` states that if an element is wet, the nodes connected to it should have an active element. Since the ERROR states for both properties are unreachable, no violation is detected.

```
||PARTS  = ( Initialization || PART0 || PART1 || PART2 || PART3
                                                          || PART4 || UPDATE || REPORTNODES )
/{node[1]/ele[1].node[1], node[4]/ele[1].node[2], node[2]/ele[1].node[3],
  node[3]/ele[2].node[1], node[1]/ele[2].node[2], node[2]/ele[2].node[3],
  node[3]/ele[3].node[1], node[5]/ele[3].node[2], node[1]/ele[3].node[3],
  node[5]/ele[4].node[1], node[4]/ele[4].node[2], node[1]/ele[4].node[3],
  node[2]/ele[5].node[1], node[4]/ele[5].node[2], node[6]/ele[5].node[3]}.

||ALGORITHM = ( NODES || ELEMENTS || MJUS || PARTS || SEQUENCE)
>>{NodesAlpha,ElementsAlpha}.
```

Figure 3.19: Parallel composition of the model of wetting and drying algorithm

```
property Check_Element = Check_Element[0][0][0],
Check_Element[n1:0..1][n2:0..1][n3:0..1] =
    ( node[1].wet_node -> Check_Element[1][n2][n3]
    | node[2].wet_node -> Check_Element[n1][1][n3]
    | node[3].wet_node -> Check_Element[n1][n2][1]
    | node[1].dry_node -> Check_Element[0][n2][n3]
    | node[2].dry_node -> Check_Element[n1][0][n3]
    | node[3].dry_node -> Check_Element[n1][n2][0]
| when((n1+n2+n3)<=1) ele[1].is_wet_ele -> ERROR
| when((n1+n2+n3)>=2) ele[1].is_wet_ele -> Check_Element[n1][n2][n3]).

property Check_Element2 = Check_Element2[0][0][0],
Check_Element2[n1:0..1][n2:0..1][n3:0..1] =
( ele[1].is_wet_ele -> ( node[n:1..3].has_active_ele -> Check_Element2[n1][n2][n3]
                        | node[n:1..3].no_active_ele -> ERROR )
| node[n:1..3].no_active_ele ->  Check_Element2[n1][n2][n3]
| node[n:1..3].has_active_ele ->  Check_Element2[n1][n2][n3]).

||CONTROL = ( SYSTEM || Check_Element || Check_Element2).
```

Figure 3.20: LTSA models of elemental properties.

3.1.2 Analysis of LTSA Model of Wetting and Drying Algorithm

First, one of the possible faulty traces due to the lack of forcing wetting and drying in the subdomain approach is revealed by implementing the property Subdomain1. This property leads to an error when node 1 is wet and node 6 is dry. Examining the trace-to-violation of this property, it is observed that when node 1 is wet, node 6 is dry due to land locking. Node 1 has three other elements connected, which can prevent it from land locking when element 1 is dry. However, since node 6 is connected to only one element (which may occur on boundary nodes of subdomains regardless of the size of the grid), it is dry due to land locking whenever element 5, which is the equivalent of element 1, is dry.

```
property Subdomain1 = Subdomain1[0],
Subdomain1[i:0..1] = ( node[1].report_wet -> Subdomain1[1]
                     | node[1].report_dry -> Subdomain1[0]
                     | when(i==0) node[6].report_dry -> Subdomain1[i]
                     | when(i==1) node[6].report_dry -> ERROR ).
```

Figure 3.21: LTSA model of property Subdomain1.

Another possible faulty trace is revealed using the property Subdomain2. This property leads to error when node 1 is dry and node 6 is wet. Examining the trace to violation of this property, it is observed that even small differences in water height and velocity of boundary elements may result in different wet/dry states, which could potentially magnify the divergence of solutions obtained for a subdomain when compared with those of the full domain.

```
property Subdomain2 = Subdomain2[0],
Subdomain2[i:0..1] = ( node[1].report_wet -> Subdomain2[1]
                     | node[1].report_dry -> Subdomain2[0]
                     | when(i==0) node[6].report_wet -> ERROR
                     | when(i==1) node[6].report_wet -> Subdomain2[i] ).
```

Figure 3.22: LTSA model of property Subdomain2.

These results imply that the wet/dry states of nodes and elements just outside of a subdomain are needed by ADCIRC's wet/dry algorithm to faithfully reproduce wet/dry states within a subdomain. By recording and later enforcing these states on the boundary of a subdomain, however, the algorithm has sufficient boundary information in the context of a subdomain run to reproduce the states found in a full run.

3.2 Methodology

As shown in the previous section, the wetting and drying of nodes on the boundaries of subdomains must be recorded from full runs and then enforced in subdomain runs to ensure the accuracy of the approach. The boundary nodes of subdomains are assigned as "elevation specified" boundary nodes (`NBFR=0 & NOPE>0`), and non-periodic elevation boundary condition file, which is previously extended to include velocity (Simon, 2011), is now extended also to include wet/dry status of the boundary nodes. Flow across the "elevation specified" boundary nodes is allowed.

Since ADCIRC output reports the elevation and velocity of nodes, that information may be conveniently obtained from full runs to create input files (boundary conditions) for subdomain runs. Wet/dry states, on the other hand, are generally not reported, so ADCIRC must be modified to report them at specified time intervals. Having obtained the wet/dry states of nodes in a full-scale run, the content of the boundary conditions is extended by adding these states to the input files of subdomains.

Finally, ADCIRC code for a subdomain run is modified to read in the states of the boundary nodes and to enforce wetting and drying to ensure that the subdomain boundary nodes have the same wet/dry states as the corresponding nodes in the full-scale run. Since it is impossible to interpolate between binary states, they are instead forced to remain the same until the next timestep when reading the next collection of boundary conditions occurs. By increasing the forcing frequency, as subsequently described, it is possible to eliminate potential inconsistencies caused by the need to interpolate. The complete list of the modifications made in ADCIRC source code is provided in Appendix B. Flowchart of the modified subdomain modeling approach is shown in Figure 3.23. In addition, a diagram that summarizes the modifications made to ADCIRC code is shown in Figure 3.24.

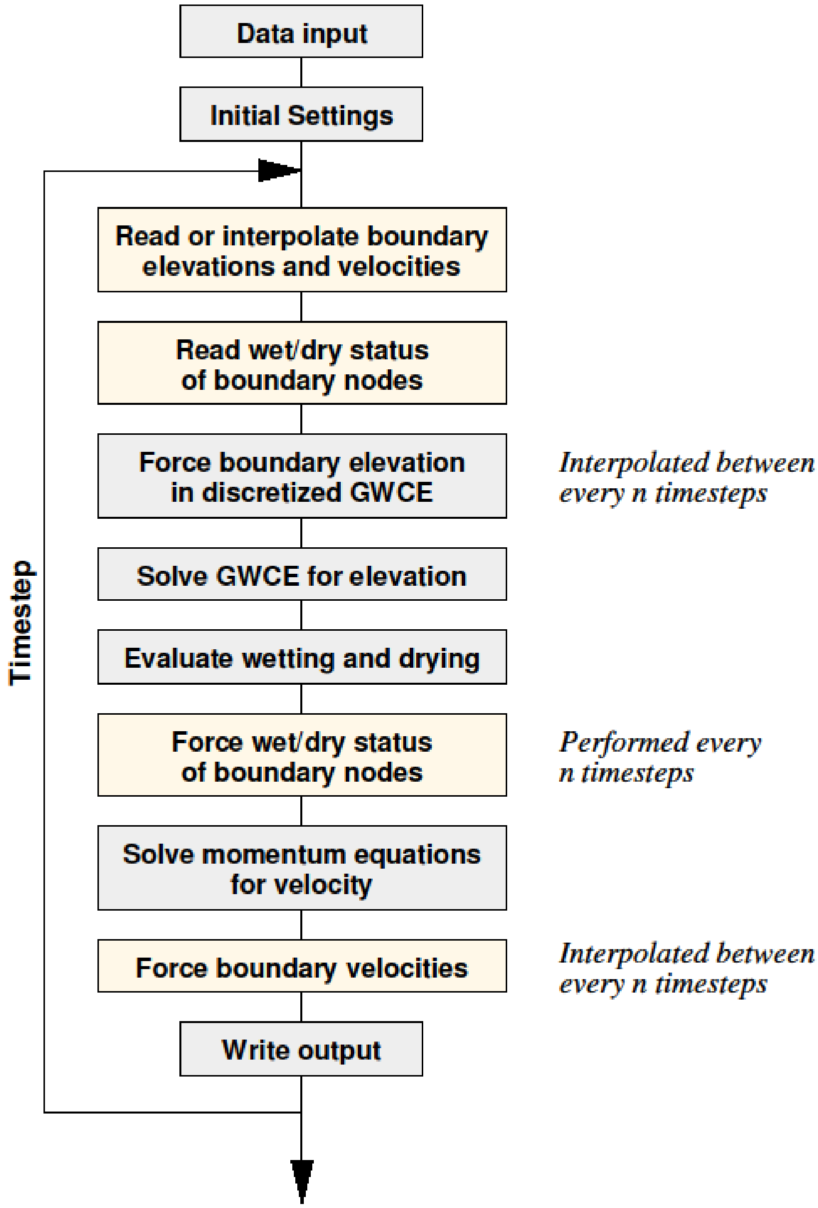


Figure 3.23: Flowchart of the modified subdomain modeling approach. Adapted from Tanaka et al. (2010).

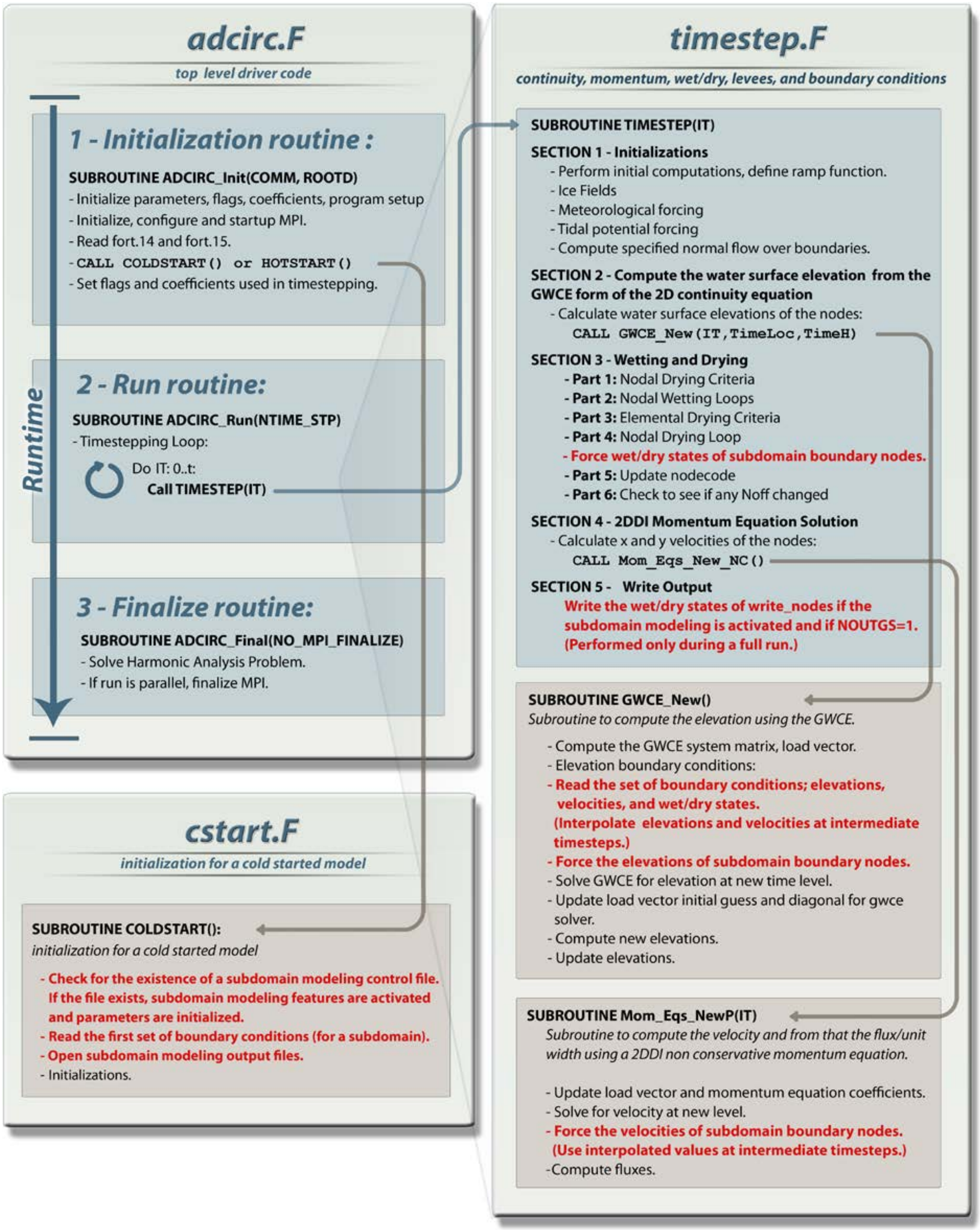


Figure 3.24: Timestepping scheme of subdomain modeling. (Modifications made to the original ADCIRC code are in red.)

3.3 Frequency of Forcing

Another improvement introduced for subdomain modeling is to increase the frequency at which boundary conditions are enforced. In our original implementation, writing the output of all the nodes in a grid at high frequency required large amounts of secondary storage and decreased the runtime performance of ADCIRC. In order to overcome these problems, the output scheme of the simulation is slightly changed: (1) Instead of reporting all node data in full-scale run, only those nodes on the boundaries of subdomains are written to output files. (2) An additional set of output files is introduced to report the data of anticipated subdomain boundary nodes, so that the original set of output files is reserved for use in examining the entire full run. These modifications enable the subdomain modeling approach to have a higher frequency of forcing without having a significant decrease in ADCIRC runtime performance or an increase in secondary storage. As such, it is possible to eliminate the errors caused by potential instabilities of low frequency wet/dry forcing and linear interpolation of elevation and velocity.

3.4 Packaging

In order to increase the practicality of the subdomain approach, several changes have been made to the implementation. The approach is reduced to four main steps: (1) Generate subdomain and full domain control file, (2) Run ADCIRC on the full domain, (3) Extract subdomain boundary conditions, (4) Run ADCIRC on the subdomain. Only two of these steps are new to ADCIRC, and these are automated with additional scripts so that users are only required to input the parameters of the subdomain model. Adjustability of the approach is also improved by allowing users to configure the boundary forcing of subdomains.

Using this new subdomain approach, ADCIRC now checks for the existence of a subdomain modeling control file at startup. If the file exists, subdomain modeling features are activated. Otherwise, ADCIRC runs normally, ensuring that conventional runs are unaffected. In addition, the data of a full run used to create the boundary conditions of a subdomain are written to a different set of files to allow the user to examine the entire model using the original output files.

3.5 Example Problems

In this section, several test cases are presented to confirm that the modified subdomain modeling approach is capable of downscaling hurricane storm surge models accurately, allowing engineers to assess a variety of test case scenarios in a considerably shorter runtime and using less secondary storage.

3.5.1 Quarter Annular Test Case

The quarter annular test case, first developed by Lynch and Gray (1978), is a simple example commonly used to evaluate the performance of numerical approaches for solving hydrodynamic problems (Westerink, Luettich & Scheffner, 1994). The ADCIRC model of this problem consists of 63 nodes and 96 elements, as shown in Figure 25. The outside arc of the grid is an open ocean boundary, which is subject only to tidal forces, and the inside arc is a land boundary that reflects the tidal forces.

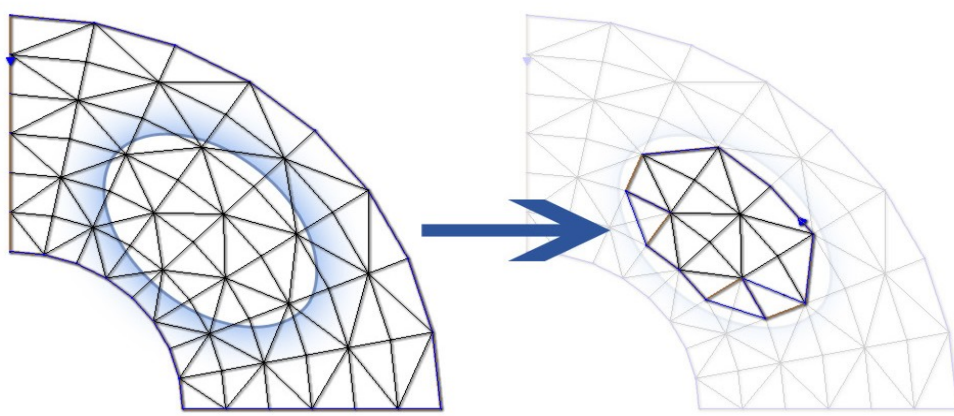


Figure 3.25: Subdomain modeling applied to the quarter annular problem

An elliptical subdomain consisting of 16 nodes and 18 elements is created from the original quarter annular grid, also shown in Figure 3.25. A boundary conditions file containing elevations, velocities, and wet/dry states of the boundary nodes obtained from the original run is created and used to enforce the subdomain grid. It is observed that the maximum difference between maximum water surface elevations of a node located in both grids is 2.8×10^{-6} m. Therefore, results obtained from the quarter annular test case confirm the accuracy of subdomain modeling approach.

Table 3.2: Maximum values and absolute errors of quarter annular problem

	Elevation (m)		x Velocity (m/s)		y Velocity (m/s)	
Node	Max Value	Max Error	Max Value	Max Error	Max Value	Max Error
7	0.5092	1.101E-6	-0.1637	6.000E-7	-0.3640	4.700E-7
8	0.4511	1.550E-6	-0.1955	6.000E-7	0.3208	7.780E-7
9	0.3777	1.097E-6	-0.2033	3.040E-7	0.2368	4.260E-7
12	0.4996	1.855E-6	-0.1444	6.200E-7	-0.3059	10.600E-7
13	0.4393	2.798E-6	-0.1563	5.540E-7	0.3255	7.000E-7
14	0.4116	1.228E-6	0.1959	7.140E-7	0.2425	8.400E-7

3.5.2 Hurricane Fran – Cape Fear Region

To demonstrate the scope of application and accuracy of the approach, a physically realistic storm surge event on a large grid located along the Atlantic coast of North America is studied. To be able to properly reflect the physical aspects of storm surge of Hurricane Fran, the original grid covers a large geographical area along the Atlantic coast from Venezuela to Nova Scotia, as shown in Figure 3.26. A significantly smaller grid inside the original grid is created as a subdomain in the Cape Fear region, as shown in Figure 3.27. As previously studied by Simon (2011), the aim of this example is to make the subdomain modeling approach available for engineers to examine various inundation scenarios, to investigate the effects on existing civil infrastructure, and to make engineering decisions that better protect the region from the future hazards of a storm surge.

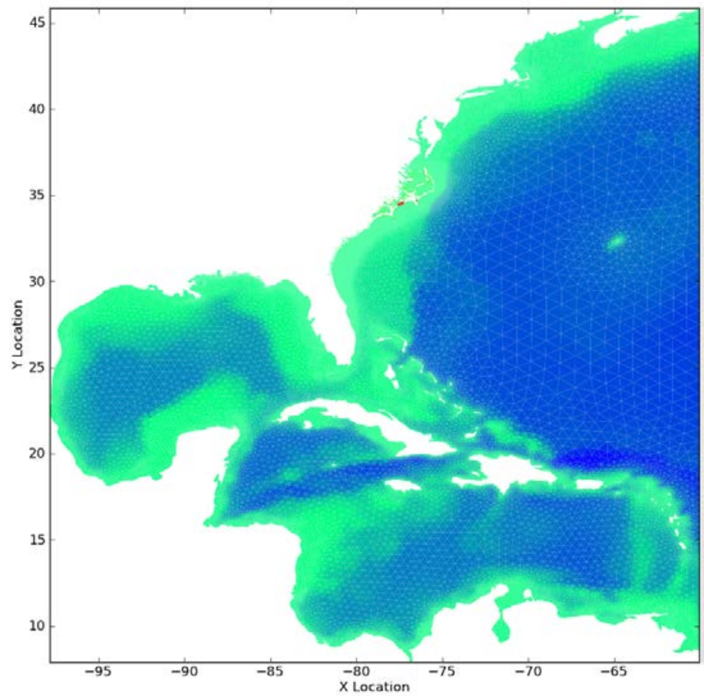


Figure 3.26: Full grid consisting of 620,089 nodes and 1,224,714 elements

3.5.2.1 Model Setting

A circular subdomain consisting of 28,643 nodes and 56,983 elements is generated from a full grid consisting of 620,089 nodes and 1,224,714 elements. The model type is a barotropic 2DDI run. Nodal attributes are: surface directional effective roughness length, canopy coefficient, Manning's n at sea floor, primitive weighting in continuity equation, and average horizontal eddy viscosity in the sea.

The total simulated runtime of the model is 3.9 days using a timestep of 0.5 seconds. The minimum water height for a node to be considered wet is 0.1 m and the minimum velocity is 0.01 m/s. The subdomain has 302 boundary nodes that are forced every 100 timesteps (50 seconds). First, a full run on the original grid is performed. The output files of the full run are used to create the boundary conditions file of the subdomain grid. Then, a subdomain run is performed and the results are compared to evaluate the accuracy of the approach for a realistic storm event.

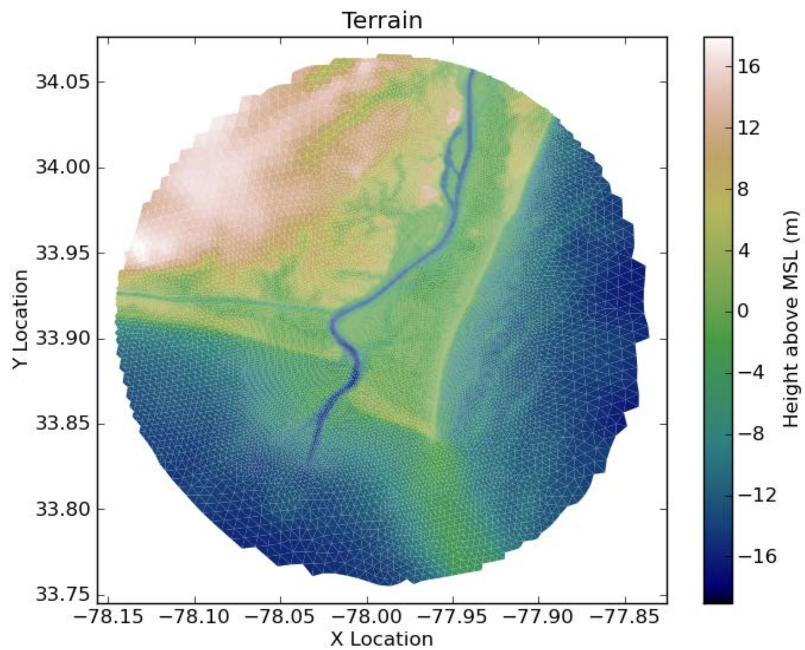


Figure 3.27: Subdomain grid consisting of 28,643 nodes and 56,983 elements

Full Domain Specifications:

NC FEMA Mesh Version 9.92, ADCIRC Version 50

Model Type: Barotropic 2DDI / GWCE, Momentum equation

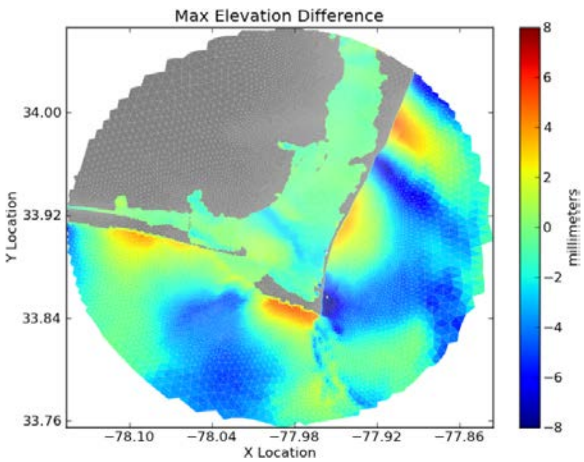
Subdomain Specifications:

Radius: 10.8 miles, Area: 366.5 sq miles

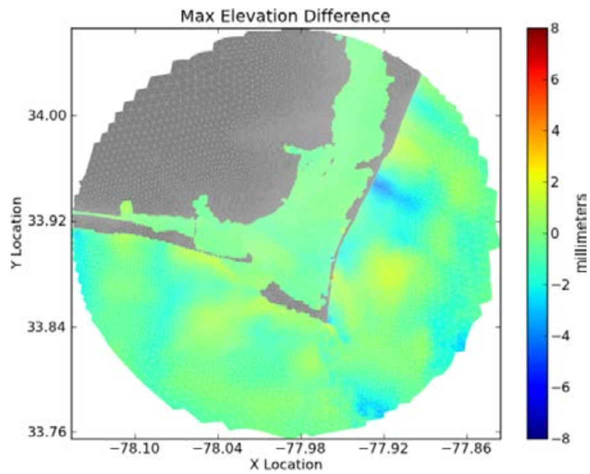
3.5.2.2 Analysis

By using subdomain modeling, 600 CPU-hours of runtime are reduced to 40 CPU-hours. The maximum water elevations of the full domain and the subdomain are compared. It is observed that the largest elevation difference occurring in a node is 3.6 millimeters, and that 99.7% of the nodes have differences less than a millimeter. The maximum water velocities are also compared, and it is seen that only one node has a maximum velocity difference exceeding 0.3 m/s. Referring back to the original problem (Simon, 2011), where several nodes had elevation differences exceeding 15 cm and velocity differences exceeding 1.5m/s, it is concluded that modifications made in the subdomain approach result in a more accurate modeling scheme.

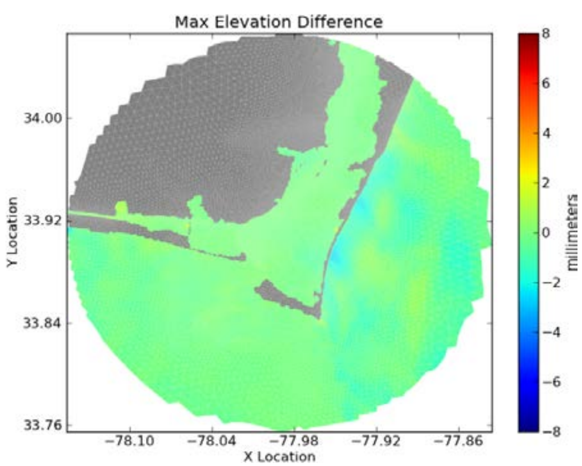
Additionally, the effect of the boundary forcing frequency on the accuracy of the subdomain modeling is examined. Here, the same subdomain run is performed with various N values (timestep intervals at which the boundary conditions are read from the subdomain input file), and the results are compared to a full run. As can be seen from Figure 3.28 and Figure 3.29, the accuracy of the approach improves with forcing frequency.



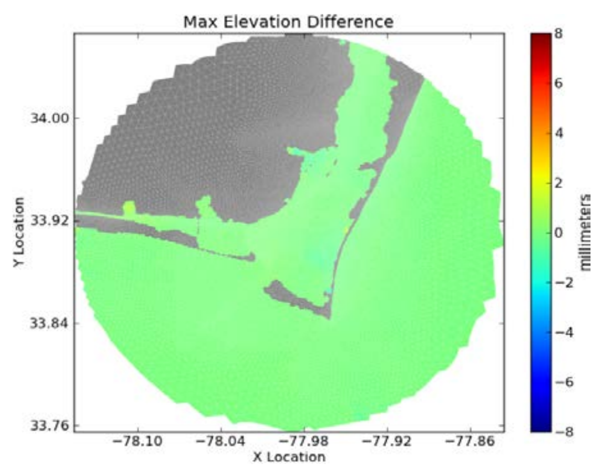
(a)



(b)

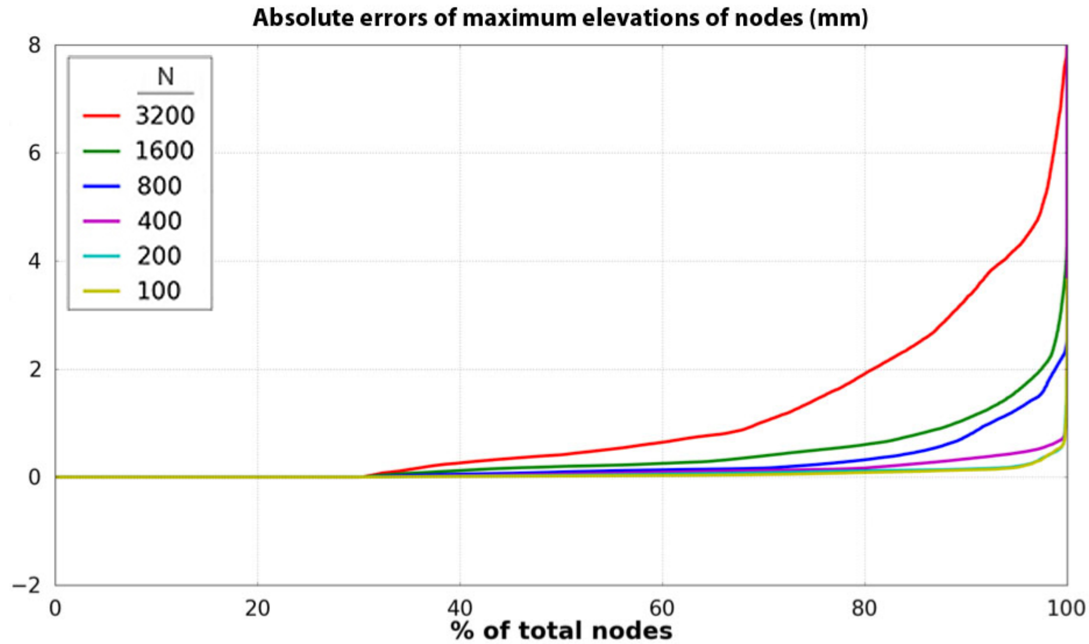


(c)

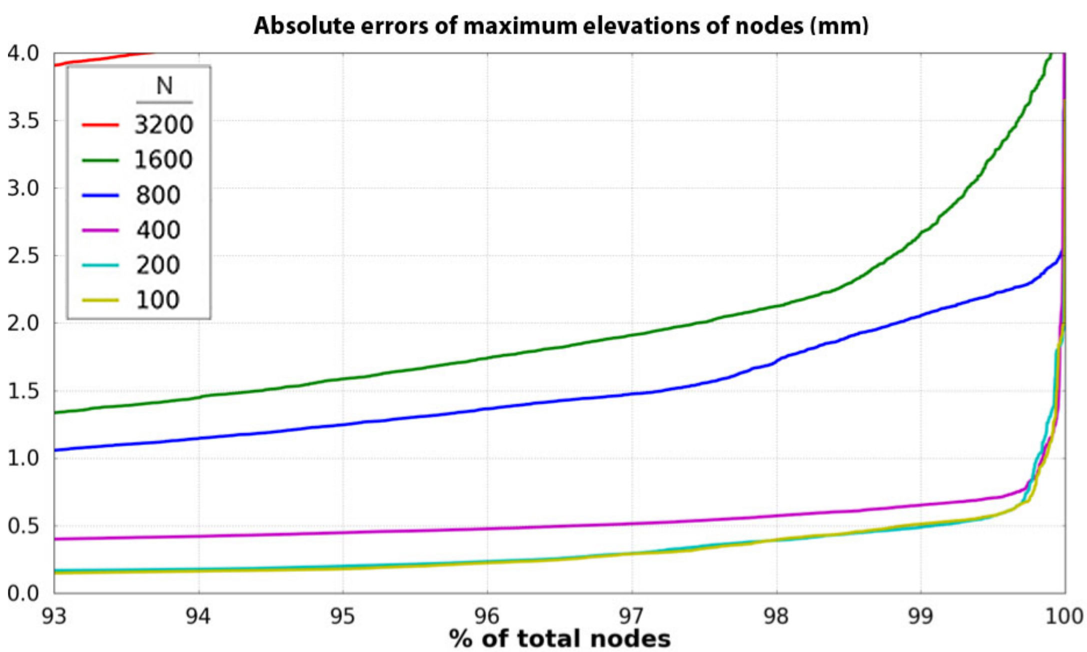


(d)

Figure 3.28: Hurricane Fran – Cape Fear, Maximum elevation differences at various forcing intervals. (a) N = 3600 timesteps, (b) N = 1600 timesteps, (c) N = 800 timesteps, (d) N = 100 timesteps



(a)



(b)

Figure 3.29: Hurricane Fran – Cape Fear, Maximum elevation differences at various forcing frequencies. (a): 0-100%, (b): 93-100%

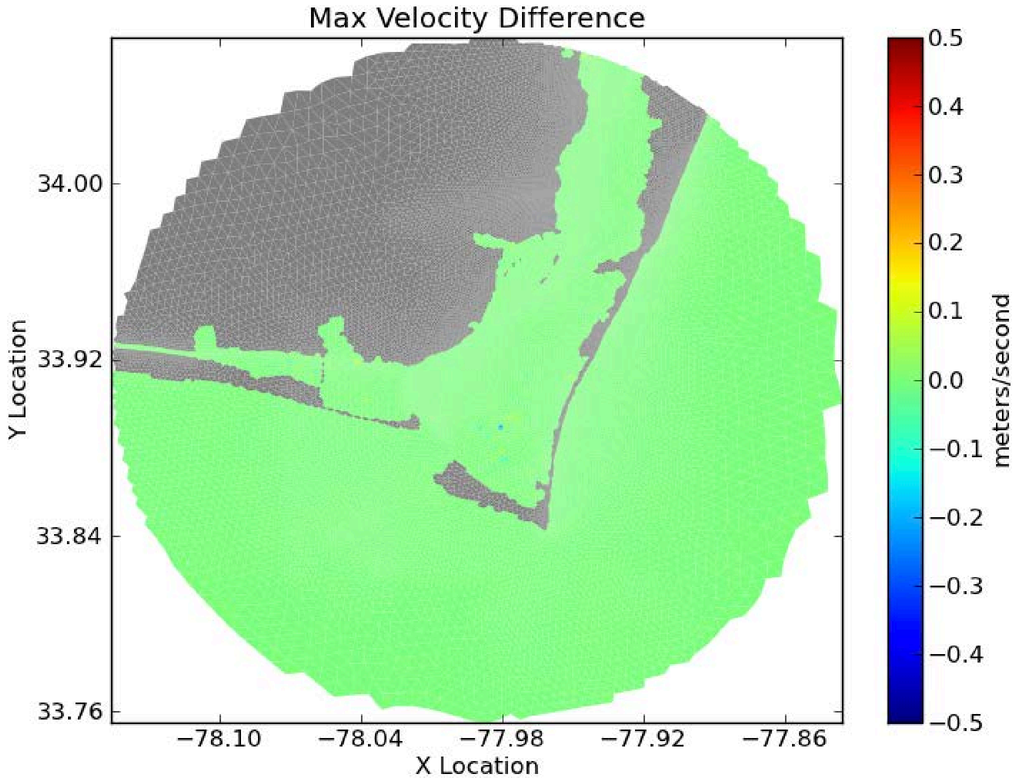


Figure 3.30: Hurricane Fran – Cape Fear, Maximum velocities comparison (Subdomain forced every 100 timesteps).

3.5.3 Hurricane Isabel – Cape Hatteras Region

Another realistic storm surge event, Hurricane Isabel is studied to evaluate the accuracy of the modified subdomain approach. The full grid used in the previous example is also used as the original grid in this problem. The Cape Hatteras region, located on the North Carolina coast, is selected as the subdomain location. In contrast with the example presented by Simon (2011), an elliptical subdomain is defined as shown in Figure 3.31.

3.5.2.1 Model Setting

An elliptical subdomain consisting of 8,248 nodes and 16,310 elements is generated from the original full grid. Total runtime of the model is 5.5 days using a timestep of 1.0 second. The subdomain has

185 boundary nodes that are forced every 100 seconds. The remaining model parameters are the same as the previous example.

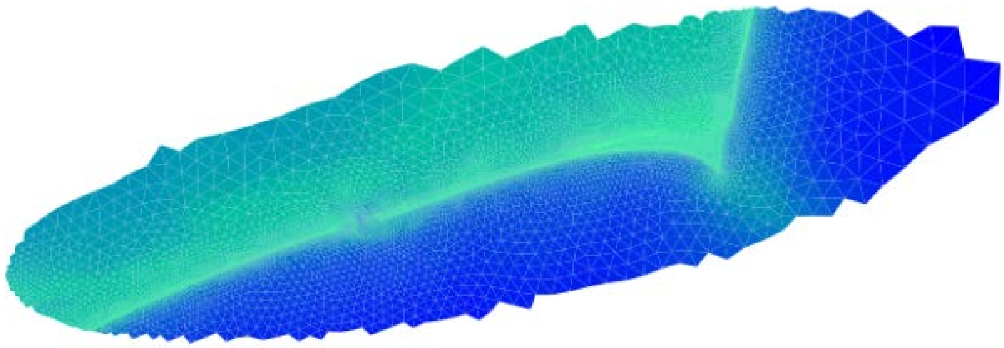


Figure 3.31: Elliptical Cape Hatteras Subdomain Grid

3.5.2.2 Analysis

Results obtained from the Hurricane Isabel full run are used to enforce the subdomain boundary conditions. By using subdomain modeling, 400 CPU-hours of runtime are reduced to 7 CPU-hours. Maximum water surface elevations of the original run and the subdomain run are compared to evaluate the accuracy of the approach. It is seen that the largest elevation difference occurring in a node is 10 cm and only 4 nodes have maximum elevation error greater than 1 cm. In addition, maximum velocities are compared. It is observed that only 5 nodes have maximum velocity error larger than 0.5 m/s. It is confirmed that modified subdomain modeling approach enables engineers to have accurate storm surge simulations in a considerably shorter runtime.

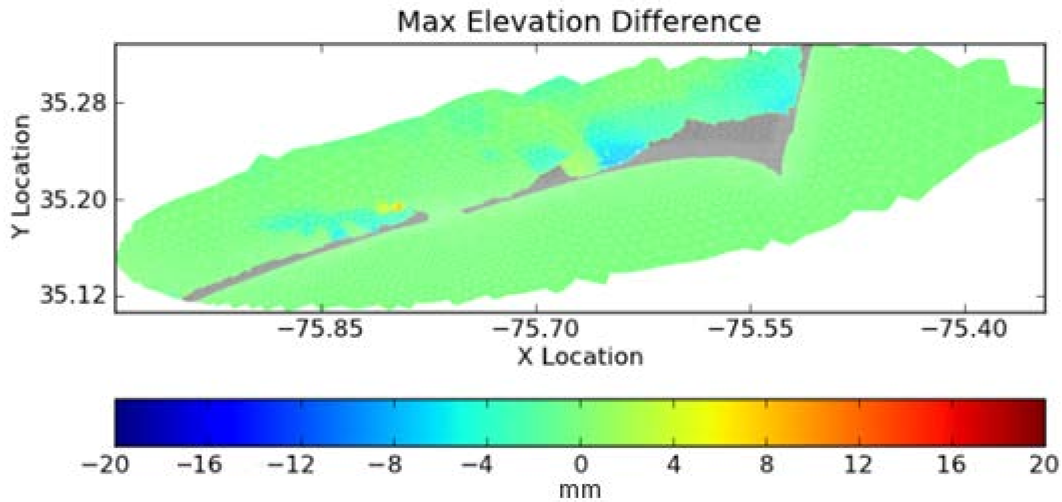


Figure 3.32: Hurricane Isabel – Cape Hatteras, Maximum elevation differences.

Chapter 4 – Subduration Modeling

Subduration modeling in ADCIRC is introduced as a means of downscaling hurricane storm surge models in time. The hot-start feature of ADCIRC, which allows users to begin a run from a specified timestep using initial conditions obtained from a previously performed run, is used to reduce the total runtime of series of simulations where users have made topographic or other changes to a model. This chapter describes the hot-start feature of ADCIRC as well as its use in reducing computation time when certain changes need to be made to a simulation and then re-run. The approach and scope of changes that can be addressed in this manner are described, and several test cases are presented.

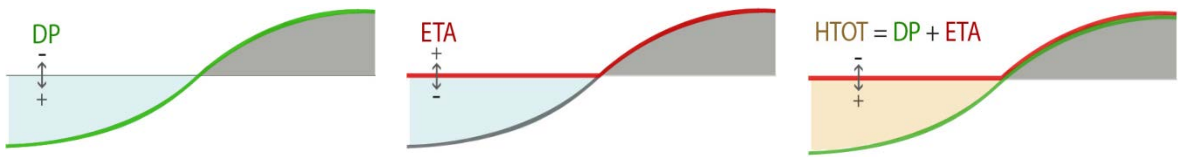
4.1 Hot-Starting in ADCIRC

A conventional use of the hot-start feature in ADCIRC is to restart a simulation in the event of a computer failure during a run (Westerink, Luettich & Scheffner, 1994). When the feature is activated, the data of the entire grid —including water surface elevation, depth-averaged velocity, and wet/dry flags— are recorded at specified timesteps in two hot-start files on an alternating basis. Recording hot-start files in this way ensures that at least one of the files is written successfully (Westerink et al., 1994). Once a simulation is hot-started, ADCIRC reads the data of the grid from the hot-start input files, and starts the model from the timestep when the latest hot-start file is written.

4.2 Implementation of Subduration Modeling

By making use of the hot-start feature of ADCIRC, it is possible to skip calculations of a model until some specified timestep. Doing so can save significant amount of runtime especially when the runs are performed repeatedly. This method can be used to change model parameters of a run at a particular timestep. In addition, topographic changes can be made in order to examine different design and failure scenarios. A potential hurdle, however, is that ADCIRC does not allow users to change the grid information file if the model is hot-started. In other words, grid information files of both the original run and hot-started run must be identical.

To further describe the problem, a simple terrain is used to illustrate the basic concepts of hot-starting in ADCIRC. Figure 4.1 represents the state and the properties of a cold started model at the initial stage. DP, shown as the green curve in Figure 4.1.a, is the bathymetric depth of a node with respect to the geoid, and is positive below the geoid. ETA is the surface elevation of a node and is shown as the red curve in Figure 4.1.b. It is positive above sea and zero at mean sea level. HTOT is total water height and is calculated by adding DP to ETA. It is shown as the beige area in Figure 4.1.c.



(a) (b) (c)

Figure 4.1: Initial states of a cold-started Model. (a) Bathymetric depth, (b) Surface Elevation, (c) Total water height.

During the initialization of a cold-started model, bathymetric depths (DP) of nodes are read from the grid and boundary information file. Water surface elevation (ETA) is determined in accordance with DP: if the node is above the mean sea level, ETA is set to the absolute value of DP and the node is dry. Otherwise, ETA is set to 0. During the initialization of a hot-started model, the DPs of nodes are read from the grid and boundary information file as in a cold-started run. However, ETA is read from the hot-start file and is different from the cold-started case. Therefore, making changes to the grid of a hot-started file leads to a discrepancy between DP and ETA.

4.3 Modifications Made to the Hot-start Algorithm

To overcome the problem described above, two main changes have been made in hot-start feature of ADCIRC:

1 To avoid discrepancy between the DPs and the ETAs of a hot-started model, water surface elevations of modified nodes in the grid are calculated as if the model is cold-started. This

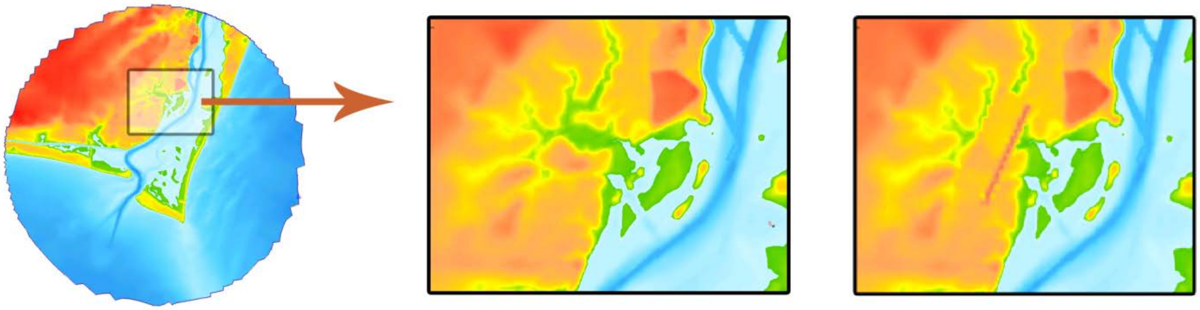
prevents the modified nodes of the grid from having erroneous water surface elevations read from the hot-start file.

2 Normally the maximum elevations and velocities of a hot-started file are evaluated throughout the entire runtime including the timesteps before hot-starting. This may lead to erroneous outputs especially when a wet node in the original run is changed to be dry in the hot-started model. Therefore, the values belonging to original run are excluded from the evaluation of the maximum elevations and velocities. Since a model should be hot-started before the occurrence of the storm surge, excluding the data of the original run does not affect the accuracy of the approach.

4.4 Test Case – Levee 1

A test case is studied using modified ADCIRC hot-start algorithm. Subdomain run presented in section 3.5.2 is hot-started using an initial conditions file obtained from a previously performed subdomain run.

In the original subdomain run, area shown in Figure 4.2.b is flooded roughly at timestep 530,000. (The length of the entire run is 670,000 timesteps). To prove that a grid of a model using subduration approach can be modified, a levee is placed as shown in Figure 4.2.c. An initial conditions file recorded before the surge event (at timestep 500.000) is used to hot-start the simulation. In addition the hot-started simulation, a cold-started model of modified grid is performed for comparison. It is seen that the maximum elevations of hot-started model is the same as the cold-started model (Figure 4.3). It is confirmed that a modified grid can be hot-started using initial conditions obtained from the original run. Therefore, significant amount of timestep calculations (75% of the cold-started model) is saved using subduration method.



(a) (b) (c)

Figure 4.2: (a) Hot-started Subdomain grid, (b) Area flooded during a cold-started run, (c) Levee added to hot-started run.

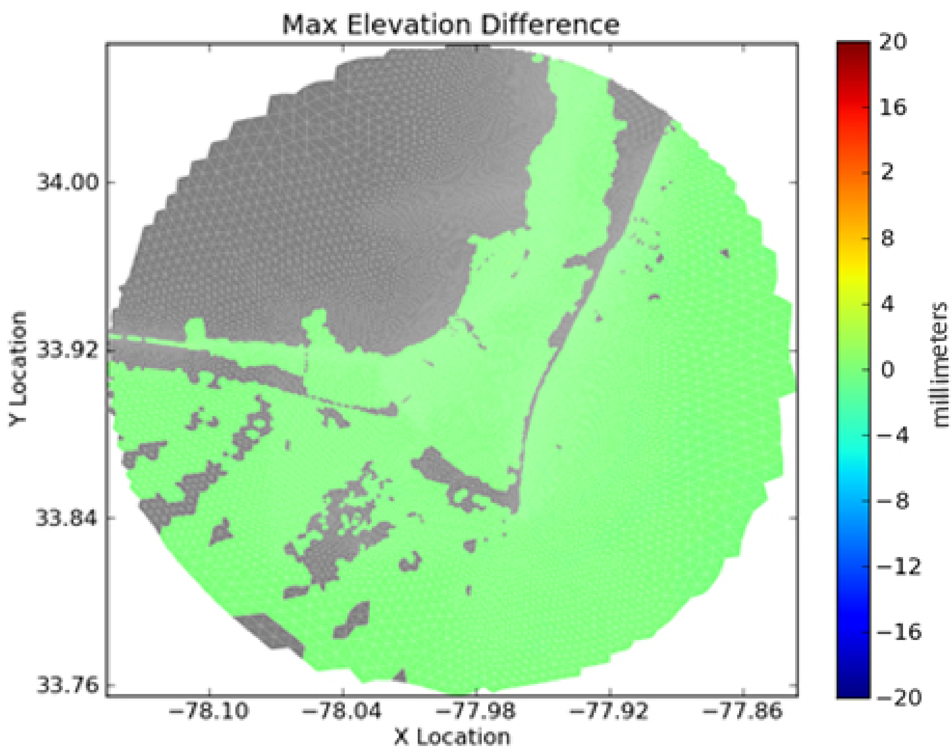


Figure 4.3: Maximum Elevation Comparison between hot-started and cold-started run

4.5 Test Case – Levee 2

Another flooding scenario is studied using modified ADCIRC hot-start algorithm. Subdomain grid presented in section 3.5.2 is modified to prevent the hypothetical coastal community from flooding. A larger levee is added along the coast of the community as shown in Figure 4.4. This levee expands to the wet nodes of the original subdomain grid to further examine the applicability of the subduration modeling approach.

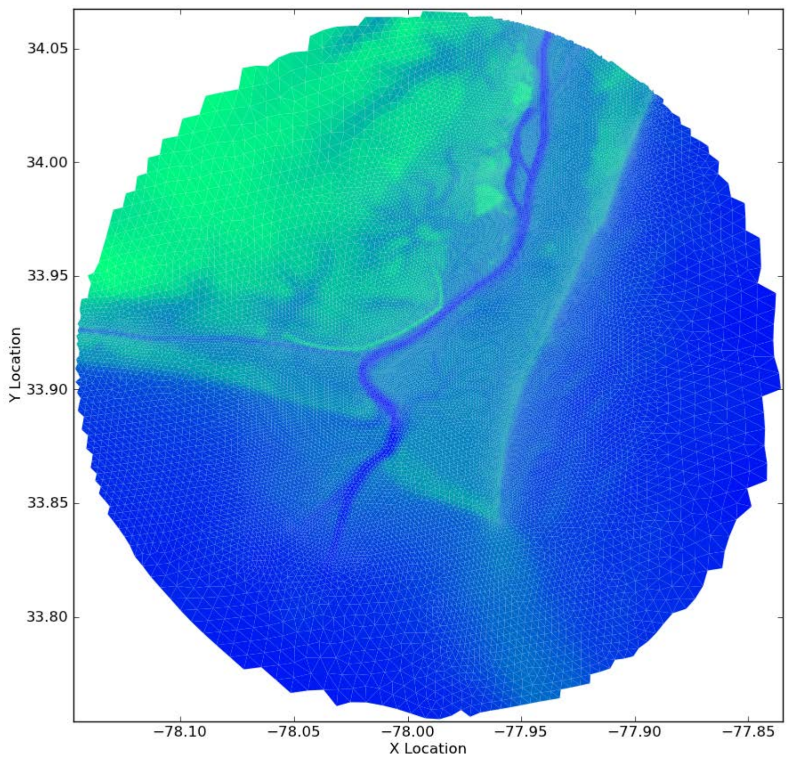


Figure 4.4: Modified subdomain grid of Test Case - Levee 2

Because the elevations of the levee nodes are changed and some of the wet nodes are made dry, modified ADCIRC Hotstart Algorithm calculates the surface elevations of levee nodes as if the simulation is cold-started. This prevents the model from erroneously determining the water column heights of the levee nodes. In addition, the output data obtained from the cold started run is omitted to accurately determine the maximum values of the data of the grid.

An initial conditions file recorded before the hurricane storm surge event (at timestep 400.000) is used to hot-start the simulation. A cold-started model of modified grid is also performed to evaluate the accuracy of the hot-started modified grid. The maximum elevations of the runs are compared and it is seen that the largest maximum elevation error occurring in a node is less than 2.5 cm.

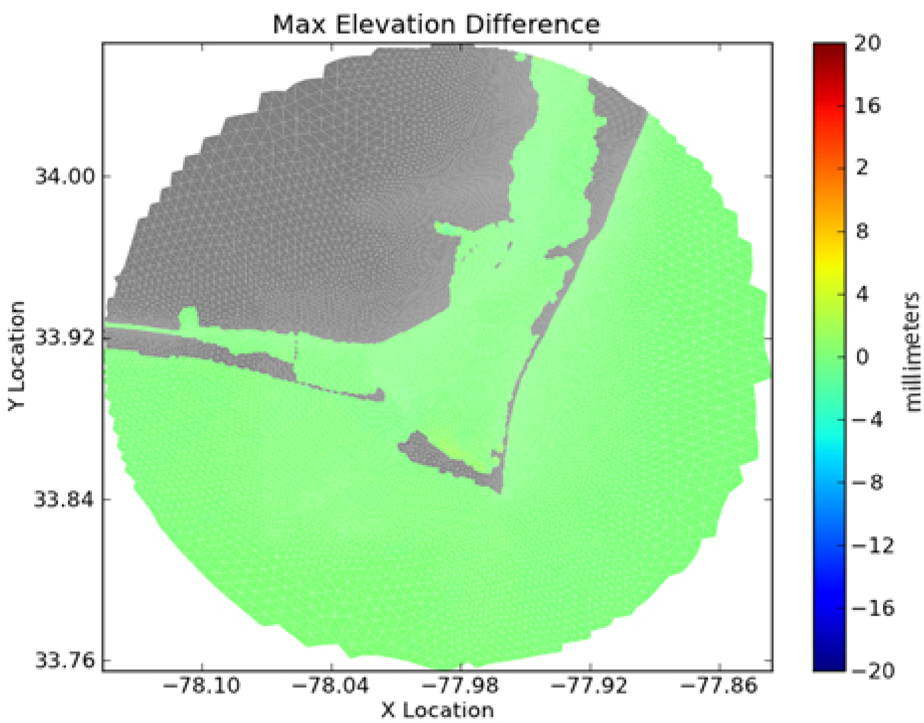


Figure 4.5: Maximum Elevation Comparison between hot-started and cold-started runs of Test Case – Levee 2

Example problems provided in this chapter is performed using both subdomain and subduration methods. Comparisons of the data show that different flooding scenarios can be simulated accurately and efficiently. Therefore, it is concluded that subdomain and subduration methods allow engineers to make changes to the model and analyze various test case scenarios on the same grid in a much less time.

Chapter 5 – Conclusions

The characteristics of storm surge require an extensive modeling process to fully assess the destructive effects of hurricanes on coastal communities. Subdomain and subduration modeling approaches implemented in ADCIRC are evaluated in an effort to maintain the efficiency of computational models of storm surge when various inundation scenarios are required to be considered.

First, the accuracy of subdomain modeling is examined. ADCIRC's wetting and drying algorithm is modeled in LTSA, a model-checking tool used to analyze concurrent software systems. Then, wet/dry forcing of boundary nodes, increasing the frequency of boundary forcing and packaging is implemented to increase the reliability and accessibility of the subdomain modeling approach. Subduration modeling is implemented to reduce the total runtime of a series of hurricane simulations in the same location with slight modifications to the grid. Several test cases are presented to evaluate the accuracy of the approaches. It is concluded that both approaches perform well for engineering purposes in a considerably shorter runtime.

Directions for future work include the incorporation of wave models like SWAN (Booij et al. 1999) in the subdomain approach.

REFERENCES

Booij, N., Ris, R.C., and Holthuijsen, L.H. (1999). "A third-generation wave model for coastal regions, Part I, model description and validation." Journal of Geophysical Research, 104, 7649–7666.

Dietrich, J.C., Kolar, R.L., and Luettich, R. A. Jr. (2004). "Assessment of ADCIRC's Wetting and Drying Algorithm." *Proceedings of the 15th International Conference on Computational Methods in Water Resources*, Chapel Hill, NC, Vol. 2, C.T. Miller, M.W. Farthing, W.G. Gray, and G.F. Pinder, eds., Elsevier, 1767–1778.

Karypis, G., and Kumar, V. (1998). "Multilevel k-way partitioning scheme for irregular graphs." J. Parallel Distrib. Comput., 48(1), 96–129.

Luettich, R. A. Jr., Westerink, J. J., and Scheffner, N. W. (1992). "ADCIRC: An Advanced Three-dimensional Circulation Model for Shelves Coasts and Estuaries, Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL." Dredging Research Program, Technical Report DRP-92-6, Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, MS.

Luettich, R. A. Jr., and Westerink, J. J. (1995). "Implementation and Testing of Elemental Flooding and Drying in the ADCIRC Hydrodynamic Model." Final Contractors Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Luettich, R. A. Jr., and Westerink, J. J. (2004). "Formulation and Numerical Implementation of the 2D/3D ADCIRC Finite Element Model Version 44.XX."
<http://www.adcirc.org/adcirc_theory_2004_12_08.pdf > (Jul. 11, 2012).

Lynch, D. R., and Gray, W. G. (1978). "Analytical solutions for computer flow model testing," *ASCE Journal of the Hydraulics Division*, 104, 1409–28.

Magee, J., and Kramer, J. (2006). *Concurrency: State Models and Java Programs*, 2nd Edition, Wiley, New York.

Simon, J.S. (2011). “A Computational Approach for Local Storm Surge Modeling.” M.S. thesis, North Carolina State University, Raleigh, NC

Simon, J.S., and Baugh, J.W. (2011). “A nested mesh approach for local storm surge modeling.” Technical report CE-431-11, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Raleigh, NC.

Tanaka, S., Bunya, S., Westerink, J.J., Dawson, C., and Luettich, R. A. Jr. (2010). “Scalability of an Unstructured Grid Continuous Galerkin Based Hurricane Storm Surge Model” *J. Sci. Comput.*, DOI: 10.1007/s10915-010-9402-1.

Westerink, J. J., Luettich, R. A. Jr., and Scheffner, N. W. (1994). “ADCIRC: An Advanced Three-dimensional Circulation Model for Shelves Coasts and Estuaries, Report 2: User’s Manual for ADCIRC-2DDI.” Technical Report DRP-92-6, Department of the Army, Waterways Experiment Station, Vicksburg, MS.

APPENDICES

Appendix A – Subdomain User's Guide

A.1 Work Flow of Subdomain Modeling

Table A.1: Work Flow of Subdomain Modeling Approach

	Grid	Description
1a)	**subdomain**	**Generate Subdomain** *python script:* gensub.py *requires:* full fort.13*, full fort.14, shape file *generates:* fort.13*, fort.14, fort.015, py.140, py.141
1b)	**full domain**	**Generate Full domain Control File** *python script:* python genfull.py *requires:* sub-fort.14*, sub-py.140* *generates:* fort.015
2)	**full domain**	**Run ADCIRC on the full domain** *requires:* fort.14, fort.15, fort.015, additional input files* *generates:* fort.063, fort.064, fort.065
3)	**subdomain**	**Extract Subdomain Boundary Conditions** *python script:* python genbcs.py *requires:* full-fort.063, fort.064, fort.065 *generates:* fort.019
4)	**subdomain**	**Run ADCIRC on the subdomain** *requires:* fort.14, fort.15, fort.015, fort.019, additional input files*

* conditional

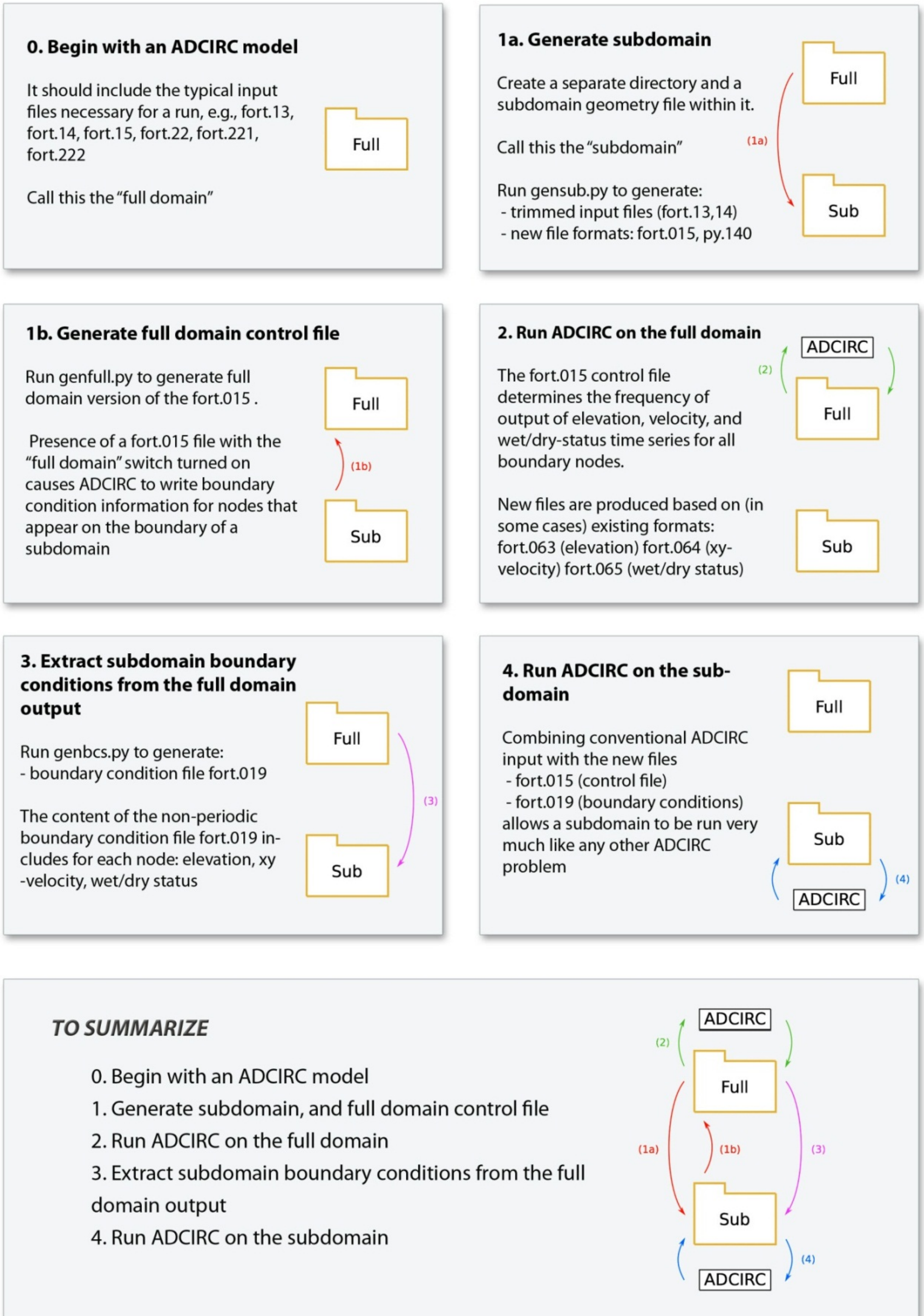


Figure A.1: Summary of the work flow of Subdomain Modeling Approach

A.2 Descriptions of Subdomain Modeling files and parameters

Subdomain Modeling Files:

- fort.015: Control Parameters
- fort.019: Subdomain boundary conditions file
- fort.063: Full-domain elevation output.
- fort.064: Full-domain velocity output.
- fort.065: Full-domain wet/dry output.

Subdomain Modeling parameters:

- NOUTGS: if NOUTGS is set to 1, Subdomain output files (fort.063-065) are recorded during a full run. (This variable must be set to 1 for a full run.)
- NSPOOLGS: The number of timesteps at which information is written to subdomain output files (fort.063-065).
- ncsu_bound_ele: Elevations of subdomain boundary nodes are forced if ncsu_bound_ele is set to 1. (This variable must be set to 0 for a full run.)
- ncsu_bound_vel: Velocities of subdomain boundary nodes are forced if ncsu_bound_vel is set to 1. (This variable must be set to 0 for a full run.)
- ncsu_bound_wd: Wetting and drying of subdomain boundary nodes are forced if ncsu_bound_wd is set to 1. (This variable must be set to 0 for a full run.)
- subdomainOn: : logical variable used to determine whether subdomain approach is active or not.
- num_nodes_out: number of write-nodes. (Only the data of write-nodes are provided in subdomain output files to reduce file sizes.)
- write_nodes: integer array storing write-nodes.
- read_u(i): forced x velocity of boundary node i. (read from fort.019)
- read_ v(i): forced y velocity of boundary node i. (read from fort.019)
- read_ wd(i): forced wet/dry status of boundary node i. (read from fort.019)

A.3 Subdomain Modeling User's Guide

1a) Generate Subdomain

python script: gensub.py
directory: subdomain
requires: full fort.13*, full fort.14, shape file(shape.c14 or shape.e14)
generates: fort.13*, fort.14, py.140, py.14, fort.015

The first step is to generate the subdomain. Create a separate subdomain directory and write a shape file which will be used to generate the subdomain geometry file within this directory. Elliptical, circular or user defined shapes can be subtracted from the full domain grid. Formats of the shape files are as follows

- *for an elliptical subdomain, shape.e14:*
  - *line 1* latitude and longitude of focal point 1
  - *line 2* latitude and longitude of focal point 2
  - *line 3* width of ellipse
- *for a circular subdomain, shape.c14:*
  - *line 1* center coordinates
  - *line 2* radius

Use python script *gensub.py* to create subdomain fort.14 and fort.015 files. If the full domain has a fort.13 file (nodal attributes), this script will also produce a fort.13 file for the subdomain. Additionally, script will ask user to enter parameters *ncsu_bound_ele*, *ncsu_bound_vel* and *ncsu_bound_wd*. These parameters control boundary forcing of subdomain. If the full domain has a meteorological forcing file (e.g. fort.22, fort.221, fort.222), symbolically link the file in the sub-domain directory. Copy other required input files from full domain directory to subdomain directory. Make sure to edit copied fort.15 file:

- Set NBFR to 0 (NBFR: Total number of forcing frequencies)
- Delete lines that are related to periodic forcing frequencies on full domain boundaries.
- Delete coordinates of recording stations out of subdomain.
- Update recording stations number

1b) Generate Full domain Control File

python script: genfull.py
directory: full domain
requires: subdomain fort.14*, subdomain py.140*
generates: fort.015

In order to activate subdomain modeling, generate fort.015 file for the full run using genfull.py. This script will ask user to input subdomain modeling parameters. User can specify either all the nodes of a full-domain or only the boundary nodes of subdomains as write-nodes. (Only the write-nodes will be provided in additional output files fort.063, fort.064, fort.065)

Note: If fort.015 file does not exist in a full domain or a subdomain directory, original ADCIRC run (without subdomain modeling) will be performed.

genfull.py: This script automatically generates a fort.015 file (subdomain modeling control parameters file). There are two options to create a fort.015 file:

1. The first option is to assign all the full domain nodes as write-nodes. This option may lead to excessive usage of disk space for a large domain, especially when the recording frequency is high. However, any subdomain can be generated after a full run using this option, since the data is recorded for all the nodes of the full domain. Usage:

   genfull.py -a [Full Domain Path]

2. Second option is to assign only the boundary nodes of previously created sub-domains as write-nodes. This option requires much less storage, while it only provides the output data for

sub-domain boundary nodes generated before the full run. Boundary node numbers of sub-domains are automatically mapped to full domain node numbering and written to fort.015 file in the working directory. Any number of sub-domains can be specified. Usage:

genfull.py -s [Full Domain Path] [Number of Sub-domains]

Finally, the script asks for the parameters which determine the forcing configuration: NOUTGS, NSPOOLGS, and directories of subdomains

2) Run ADCIRC on the full domain

directory: full domain
requires: fort.14, fort.15, fort.015, additional input files*
generates: fort.063, fort.064, fort.065

Perform the preprocessing if the run is parallel. Then, run ADCIRC on the full domain. New output files fort.063 (elevation), fort.064 (velocity), and fort.065 (wet/dry) are produced during the run. Note that ADCIRC subdomain modeling is activated only if fort.015 exists in the directory.

3) Extract Subdomain Boundary Conditions

python script: python genbcs.py
directory: subdomain
requires: full fort.063, fort.064, fort.065,
generates: fort.019

Use genbcs.py script to create boundary conditions file which contains time varying elevation, velocity and wet/dry boundary conditions for boundary nodes of a sub-domain. The runtime of the script may take a while depending on the size of the grid and the sampling rate.

genbcs.py: This script reads fort.063, fort.064 and fort.065 files of full domain run, and then generates a fort.019 file for the specified sub-domain. Type of full domain run (serial or parallel), full domain path, sub-domain path, forcing frequency, DT, and NSPOOLGS should be specified as arguments.

forcing-freq: Number of time steps at which information will be written to fort.019 file.
NSPOOLGS: Number of time steps at which information is written to output files. (.06*)
DT: One time step in seconds.
H0: Minimum water depth for a node to be wet.

Note: forcing-freq must be a multiple of NSPOOLGS.

- Usage of genbcs.py:

genbcs.py [type][OriginalPath][ScaledPath][forcing-freq][DT][NSPOOLGE][H0]
(type: -p for parallel full domain run, -s for serial full domain run)

- *fort.019 file* format*:*

```
etiminc
for k=1,neta
        esbin(k), read_u(k), read_v(k)
        read_wd(k)
end k loop
```

- *Parameter definitions:*

etiminc: Time increment (secs) between consecutive sets of b.c. values contained in fort.019.
neta: Total Number of boundary nodes
esbin(k): Forced elevation at node k.
read_u(k): Forced x velocity at node k.
read_v(k): Forced y velocity at node k.
read_wd(k): Forced wet/dry flag at node k.

4) Run ADCIRC on the subdomain

directory: subdomain

requires: fort.14, fort.15, fort.015, fort.019, additional input files*

Perform the preprocessing if the run is parallel. Then, run ADCIRC on the subdomain. Note that ADCIRC subdomain modeling is activated only if fort.015 exists in the directory.

Example: Implementation of Sub-domain Approach on Quarter Annular Test Problem

In this section, sub-domain approach is implemented on quarter annular test case, a simple example problem available from the ADCIRC Development Group. Quarter annular grid shown in the Figure A.2 consists of 63 nodes and 96 elements. Outside arc is an open ocean boundary which is subject to tidal forces, while the other three sides are closed land boundaries.

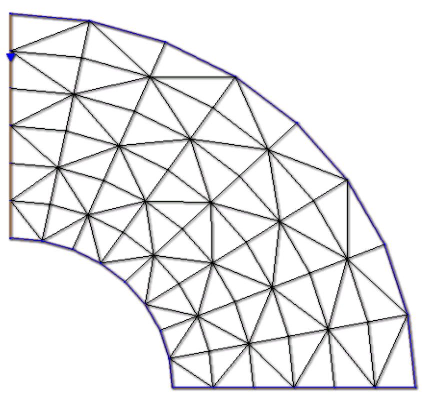


Figure A.2: Quarter Annular Test Grid

1a) Generate Subdomain

python script: gensub.py

directory: subdomain

requires: full fort.13*, full fort.14, shape file(shape.c14 or shape.e14)

generates: fort.13*, fort.14, py.140, py.14, fort.015

Create a subdomain directory

Create a shape file in the subdomain directory. *shape.e14 :*

```
40824.6 98559.5  ! focal point 1
98559.5 40824.6  ! focal point 2
60000            ! width
```

- Run gensub.py to generate subdomain fort.14, fort.015, py.140, py.141 files

```
$ python ../gensub.py [full fort.14 dir] 0 fort.14
...
fort.015 file for subdomain run will be generated
Please enter following parameters:
Enter the parameter 'ncsu_bound_ele': ( 0 or 1)
1
Enter the parameter 'ncsu_bound_vel': ( 0 or 1)
1
Enter the parameter 'ncsu_bound_wd':  ( 0 or 1)
1
```

A fort.14 file consisting of 16 nodes and 18 elements, a fort.015 file and mapping files are created in the sub-domain directory. Now, copy fort.15 from full domain and make the following changes:

- Set NBFR to 0 (NBFR: Total number of forcing frequencies)
- Delete lines that are related to periodic forcing frequencies on boundaries
- Set elevation and velocity recording station numbers to zero
- Delete coordinates of recording stations

1b) Generate Full domain Control File

python script: python genfull.py

directory: full domain

requires: subdomain fort.14*, subdomain py.140*

generates: fort.015

- Move to full run directory.
- Generate fort.015 file for the full run using genfull.py. Usage:

Print all nodes:	genfull.py -a [Path]
Print subd.boundary-nodes:	genfull.py -s [FullDomain Path] [Number of Subdomains]

- Although this example does not require a large disk space, only the boundary nodes of subdomain will be written to full domain fort.015 file:

```
$ python ../genfull.py -s ./ 1
This script creates fort.015 file for Subdomain Modeling.
Enter the parameter 'NOUTGS':
1
Enter the parameter 'NSPOOLGS':
1
Enter the directory of subdomain - 1 of 1 :
../qa-subdomain/
reading fort.14 at  ../qa-subdomain/
reading new to old nodes at  ../qa-subdomain/
Subdomain 1 is done.
fort.015 file is created.
```

2) Run ADCIRC on the full domain

directory: full domain

requires: fort.14, fort.15, fort.015, additional input files*

generates: fort.063, fort.064, fort.065

- Symbolically link adcirc, padcirc and adcprep files in work directory of ADCIRC.
- Run ADCIRC. (preprocess if run is parallel)

3) Extract Subdomain Boundary Conditions

python script: python genbcs.py

directory: subdomain

requires: full-fort.063, fort.064, fort.065

generates: fort.019

- Move to subdomain directory.
- Generate fort.019 boundary conditions file for the subdomain run using genbcs.py. Usage:

  [for parallel full run: -p | for serial full run: -s]
  [OriginalPath][ScaledPath][forcing-freq][DT][NSPOOLGS][H0]
  NOTE: forcing-freq must be multiple of NSPOOLGS !

- genbcs.py:

```
$ python ../genbcs.py -p ../qa/ ./ 1 174.656 1 1
```

4) Run ADCIRC on the subdomain

directory: subdomain

requires: fort.14, fort.15, fort.015, fort.019, additional input files*

- Symbolically link adcirc, padcirc and adcprep files in work directory of ADCIRC.
- Run ADCIRC. (preprocess if run is parallel)

Conclusion: Maximum elevations files of both runs are compared. It is observed that both full run and subdomain run resulted in the same maximum elevations for all the nodes on subdomain grid. Largest error: 2.8×10^{-6} m.

Appendix B –Subdomain Changes Made in ADCIRC Code

File Name: cstart.F

Directory: adc50_51++/src/

Description: Initialization of cold started ADCIRC run.

cstart.F, change #1

- Check to see if fort.015 (subdomain model parameter file) exists.
- If the file exists, set variable *subdomainOn* to True. This will activate subdomain approach.
- Read the parameters that control subdomain modeling from fort.015 file.
- Finally, read the list of write-nodes stored in fort.015 file.

Added lines 49-99:

```
C-- NCSU SUBDOMAIN - CHANGE:

       subdomainOn = .false.
       INQUIRE(file=trim(globaldir)//'/'//'fort.015', Exist=subdomainOn)
       if (subdomainOn) then

          if (myproc.eq.0) write(*,*) "Subdomain Active"
          open(1015, file=trim(globaldir)//'/'//'fort.015')
          read(1015,*) NOUTGS
          read(1015,*) NSPOOLGS
          read(1015,*) ncsu_bound_ele
          read(1015,*) ncsu_bound_vel
          read(1015,*) ncsu_bound_wd
          ncsu_print_wd = NOUTGS
          if (myproc.eq.0) write(*,*) "NCSU_bound_ele set", ncsu_bound_ele
          if (myproc.eq.0) write(*,*) "NCSU_bound_vel set", ncsu_bound_vel
          if (myproc.eq.0) write(*,*) "NCSU_bound_wd  set", ncsu_bound_wd
          read(1015, *) num_nodes_out
          allocate(write_nodes(num_nodes_out+1))
          do i=1, num_nodes_out
                read(1015, *) write_nodes(i)
          enddo
          write_nodes(num_nodes_out+1) = 0
          close(1015)
        else
```

```
            ncsu_bound_ele = 0
            ncsu_bound_vel = 0
            ncsu_bound_wd = 0
         endif

#ifdef CMPI
        if (subdomainOn) then
            nlwnodes = 0
            DO I=1,NP
               IF (ANY(write_nodes.eq.nodes_lg(I))) then
                  nlwnodes = nlwnodes + 1
               ENDIF
            END DO
            allocate( lwnodes( nlwnodes ) )
            i2=1
            DO i=1,NP
               IF (ANY(write_nodes.eq.nodes_lg(I))) then
                  lwnodes(i2) = I
                  i2 = i2+1
               ENDIF
            END DO
         endif
#endif


C-- NCSU SUBDOMAIN --
```

cstart.F, change #2

Initialization of boundary conditions file in the code is changed: If subdomain approach is activated and *ncsu_bound_ele* is set to 1, open and read fort.019 subdomain boundary conditions file consisting of elevation, velocity and wet/dry flags. Otherwise, open and read fort.19 file as in the original ADCIRC code.

Edited lines 191-215:

```
C-- NCSU SUBDOMAIN - CHANGE:
         if (subdomainON.and.ncsu_bound_ele.eq.1) THEN
                 OPEN(1019,FILE=TRIM(INPUTDIR)//'/'//'fort.019')
                 READ(1019,*) ETIMINC
                 DO J=1,NETA
```

```
                READ(1019,*) ESBIN1(J),read1_u(j),read1_v(j)
                READ(1019,*) read_wd(j)
        END DO
        DO J=1,NETA
                READ(1019,*) ESBIN2(J),read2_u(j),read2_v(j)
                READ(1019,*) read_wd(j)
        END DO

    else

        OPEN(19,FILE=TRIM(INPUTDIR)//'/'//'fort.19')
        READ(19,*) ETIMINC
        DO J=1,NETA
                READ(19,*) ESBIN1(J)
        END DO
        DO J=1,NETA
                READ(19,*) ESBIN2(J)
        END DO
    endif
C-- NCSU SUBDOMAIN --
```

cstart.F, change #3

Additional full-domain output files, which will later be used to generate subdomain boundary conditions file, are written if *NOUTGS* in fort.015 file is set to 1. Following code opens additional output files fort.063 and fort.064.

Added lines 872-883:

```
C-- NCSU SUBDOMAIN - CHANGE:

      IF(subdomainON.and.NOUTGS.eq.1) THEN
         CALL OPEN_GBL_FILE(1063, TRIM(GLOBALDIR)//'/'//'fort.063',
     $    NP_G, NP, HEADER63)
      ENDIF

      IF(subdomainON.and.NOUTGS.eq.1) THEN
         CALL OPEN_GBL_FILE(1064, TRIM(GLOBALDIR)//'/'//'fort.064',
     $    NP_G, NP, HEADER64)
      ENDIF
C-- NCSU SUBDOMAIN
```

File Name: hstart.F

Directory: adc50_51++/src/

Description: Initialization of hot started ADCIRC run.

hstart.F, change #1

Added lines 145-196:

same as change #1 in cstart.F

hstart.F, change #2

Edited lines 884-910:

same as change #2 in cstart.F

hstart.F, change #3

Read the elevation, velocity, and wet/dry boundary conditions of a subdomain run from fort.019. If subdomain modeling is not active, read only elevation from fort.19 file.

Edited lines 919-926:

```
C-- NCSU SUBDOMAIN - CHANGE:
            if (subdomainON.and.ncsu_bound_ele.eq.1) THEN
                    READ(1019,*) ESBIN2(J),read2_u(j),read2_v(j)
                    READ(1019,*) read_wd(j)
            else
                    READ(19,*) ESBIN2(J)
            endif
C-- NCSU SUBDOMAIN --
```

hstart.F, change #4

Edited lines 936-943:

same as change #3 in hstart.F

File Name: timestep.F

Directory: adc50_51++/src/

Description: calculation of elevations, wetting/drying algorithm, calculation of velocities.

timestep.F, change #1

Declare integer i_sd, array index

Added line 174:

```
      integer i_sd      ! NCSU SUBDOMAIN
```

timestep.F, change #2

Force wet/dry status of boundary nodes right after wetting and drying algorithm.

Added lines 2528-2536:

```
C-- NCSU SUBDOMAIN - CHANGE :
        if (ncsu_bound_wd.eq.1) then
           DO I=1,NETA
              NNODECODE ( NBDV(I) ) = read_wd(i)
              NODECODE ( NBDV(I) ) = read_wd(i)
           END DO
        endif
C-- NCSU SUBDOMAIN --
```

timestep.F, change #3

Write wet/dry flags of write-nodes to output file fort.065 during a full run.

Note: If run is parallel, separate fort.065 files will be generated for each processor.

Added lines 2726-2766:

```
C-- NCSU SUBDOMAIN - CHANGE :
C-- write wet/dry flags to fort.065
      IF(subdomainON.and.NOUTGS.eq.1) THEN
#ifdef CMPI
         if(it.eq.1) then
                 WRITE(TEMPDIRNAME,'(A2,I4.4)') 'PE',MYPROC
                 OPEN(1065,FILE=TEMPDIRNAME//'/'//'fort.065',
     &               STATUS='REPLACE')
                 write(1065,*) nlwnodes
```

```
                close(1065)
        endif
#else
        if(it.eq.1) then
                OPEN(1065,FILE='fort.065',STATUS='REPLACE')
                write(1065,*) num_nodes_out
                close(1065)
        endif
#endif
        IF(mod(IT,NSPOOLGS).eq.0) THEN
#ifdef CMPI
             WRITE(TEMPDIRNAME,'(A2,I4.4)') 'PE',MYPROC
             OPEN(1065,FILE=TEMPDIRNAME//'/'//'fort.065',
     &          ACCESS='SEQUENTIAL',POSITION='APPEND')
             do i=1,nlwnodes
               write(1065,*) nodes_lg(lwnodes(i)), nodecode(lwnodes(i))
             END DO
#else
             OPEN(1065,FILE='fort.065',
     &          ACCESS='SEQUENTIAL',POSITION='APPEND')
             DO I=1,num_nodes_out
               WRITE(1065,*) write_nodes(i),NODECODE(int(write_nodes(I)))
             END DO
#endif
             CLOSE(1065)
        ENDIF
      ENDIF
C-- NCSU SUBDOMAIN --
```

timestep.F, change #4

- If time increment between consecutive sets of boundary conditions in fort.019 has passed, read new sets of boundary conditions.
- Interpolate boundary elevations and velocities at intermediate timesteps.
- Note: If subdomainOn is false, the code reads fort.19 as in the original ADCIRC.

Edited lines 3928-3966 (inside the subroutine gwce_new):

```
C-- NCSU SUBDOMAIN - CHANGE :
      IF((NBFR.EQ.0).AND.(NOPE.GT.0)) THEN
         IF(TimeLoc.GT.ETIME2) THEN
            ETIME1=ETIME2
            ETIME2=ETIME1+ETIMINC
            if (subdomainOn.and.ncsu_bound_ele.eq.1) then
```

```
               DO J=1,NETA

                  ESBIN1(J)=ESBIN2(J)
                              read1_u(j) = read2_u(j)
                              read1_v(j) = read2_v(j)
                  READ(1019,*) ESBIN2(J),read2_u(j),read2_v(j)
                  READ(1019,*) read_wd(j)
               END DO

             else
                DO J=1,NETA
                   ESBIN1(J)=ESBIN2(J)
                   READ(19,*) ESBIN2(J)
                END DO
             endif
         ENDIF

         ETRATIO=(TimeLoc-ETIME1)/ETIMINC
         if (subdomainOn.and.ncsu_bound_ele.eq.1) then
            DO I=1,NETA
               NBDI=NBD(I)

               eltemp(i) = (esbin1(i) + etratio*(esbin2(i) - esbin1(i)))
                    uutemp(i)= (read1_u(i)+etratio*(read2_u(i)-
read1_u(i)))

                    vvtemp(i)= (read1_v(i)+etratio*(read2_v(i)-
read1_v(i)))

                    eta2(nbdi)=eltemp(i)
            END DO

         else
            DO I=1,NETA
               NBDI=NBD(I)
               Eta2(NBDI)=RampElev
     &           *(ESBIN1(I)+ETRATIO*(ESBIN2(I)-ESBIN1(I)))
            END DO
         endif
      ENDIF

C-- NCSU SUBDOMAIN --
```

timestep.F, change #5

Added line 4889:

same as change #1 in timestep.F

timestep.F, change #6

- If boundary velocity forcing is turned on, set x and y velocities of boundary nodes to interpolated values.
- If boundary wet/dry forcing is turned on, set wet/dry flags of boundary nodes to values read from fort.019.

Added line 5515-5527:

```
C-- NCSU SUBDOMAIN - CHANGE:
         if(ncsu_bound_vel.eq.1) then
                DO i_sd=1,NETA
                        uu2(nbd(i_sd)) = uutemp(i_sd)
                        vv2(nbd(i_sd)) = vvtemp(i_sd)
                END DO
         endif
         if(ncsu_bound_wd.eq.1) then
                DO i_sd=1,NETA
                    wd2(nbd(i_sd)) = read_wd(i_sd)
                END DO
         endif
C-- NCSU SUBDOMAIN --
```

timestep.F, change #7

Edited lines 3928-3966 (inside the subroutine gwce_new_pc):

same as change #4 in timestep.F

File Name: write_output.F

Directory: adc50_51++/src/

Description: Subroutines to write the data to the output files.

write_output.F, change #1

Declare logical variables that will be used to control additional output files.

Added lines 112,113:

```
      LOGICAL s_packed63 ! NCSU SUBDOMAIN
      LOGICAL s_packed64 ! NCSU SUBDOMAIN
```

write_output.F, change #2

Set logical s_packed63 to True. This will prevent subroutine writeOutArray_trim() from calling subroutine collectFullDomainArray twice in a timestep.

Added line 740:

```
      s_packed63 = .true.     ! NCSU SUBDOMAIN
```

write_output.F, change #3

Set logical s_packed64 to True. This will prevent subroutine writeOutArray_trim() from calling subroutine collectFullDomainArray twice in a timestep.

Added line 832:

```
      s_packed64 = .true.     ! NCSU SUBDOMAIN
```

write_output.F, change #4

If time to write additional output data (fort.063, fort.064), call appropriate subroutines to write elevations and velocities of the write-nodes.

Added lines 888-924:

```
C...  NCSU SUBDOMAIN - CHANGE:
C.... write elev. & vel. for subd. b.c.
C...
      IF(subdomainON.and.NOUTGS.eq.1) THEN
         IF(mod(IT,NSPOOLGS).eq.0) THEN
#ifdef CMPI

                  IF(MNWPROC.GT.0) THEN

                     CALL WRITE_GBL_FILE_THROUGH_WRITER
     $
(TRIM(GLOBALDIR)//'/'//'fort.063',ElevDescript,TimeLoc,it,
     $                 writer_store63, -99999.D0)

                     CALL WRITE_GBL_FILE_THROUGH_WRITER
     $
(TRIM(GLOBALDIR)//'/'//'fort.064',VelDescript,TimeLoc,it,
     $                 writer_storeTwo, 0.D0)
                  ELSE
                     CALL writeOutArray_trim(1063, TimeLoc, IT,
```

```
ElevDescript,
     &                            pack63, unpackOne, IGEP,
     &                            'fort.063        ',s_packed63)

                     CALL writeOutArray_trim(1064, TimeLoc, IT,
VelDescript,
     &                         packTwo, unpackTwo, IGVP,
     &                         'fort.064        ',s_packed64)
                  ENDIF
#else
                  CALL writeOutArray_trim(1063, TimeLoc, IT, ElevDescript,
     &                            pack63, unpackOne, IGEP,
     &                            'fort.063        ',s_packed63)

                  CALL writeOutArray_trim(1064, TimeLoc, IT, VelDescript,
     &                         packTwo, unpackTwo, IGVP,
     &                         'fort.064        ' ,s_packed64)
#endif
         ENDIF
      ENDIF
C...  NCSU SUBDOMAIN
```

write_output.F, change #5

A new subroutine writeOutArray_trim() is created based on the subroutine writeOutArray() in the original ADCIRC code. This new subroutine is used to write fort.06* output files containing only the data of write-nodes.

Edited lines :

```
subroutine writeOutArray_trim(...):
...(+30 lines)

      IF ((MNPROC.gt.1).and.(WRITE_LOCAL_FILES.eqv..false.)) THEN

  C...  NCSU SUBDOMAIN - CHANGE:
               if (s_packed) then
                  continue
               else
                  CALL collectFullDomainArray(descript, pack_cmd,
unpack_cmd)
               endif
  C...  NCSU SUBDOMAIN --

      ENDIF
```

```
      SELECT CASE (ABS(descript % specifier))
      CASE(1) !ascii text
         IF ( (MNPROC.gt.1).and.(MyProc.eq.0)
.and.(.not.WRITE_LOCAL_FILES)) THEN
            OPEN(lun,FILE=TRIM(GLOBALDIR)//'/'//fn,
     &           ACCESS='SEQUENTIAL',POSITION='APPEND')
            WRITE(lun,2120) TimeLoc,IT
            IF (descript % num_items_per_record .eq. 1) THEN
               DO j=1, num_nodes_out            ! NCSU SUBDOMAIN
                    I = write_nodes(j)          ! NCSU SUBDOMAIN
                  WRITE(lun,2453) I, descript % array_g(I)
               ENDDO
            ENDIF
            IF (descript % num_items_per_record .eq. 2) THEN
               DO j=1, num_nodes_out             ! NCSU SUBDOMAIN
                  I = write_nodes(j)             ! NCSU SUBDOMAIN
                  WRITE(lun,2454) I, descript % array_g(I),
     &                            descript % array2_g(I)
               ENDDO
            ENDIF
            CLOSE(lun)
         ENDIF
         IF ((MNPROC.eq.1).or.(WRITE_LOCAL_FILES)) THEN
            OPEN(lun,FILE=TRIM(LOCALDIR)//'/'//fn,
     &           ACCESS='SEQUENTIAL',POSITION='APPEND')
            WRITE(lun,2120) TimeLoc,IT
            IF (descript % num_items_per_record .eq. 1) THEN
               IF ((trim(descript % field_name) .eq. 'Elev').and.
     &             (descript % ConsiderWetDry .EQV. .TRUE.)) THEN
                  DO j=1, num_nodes_out         ! NCSU SUBDOMAIN
                     I = write_nodes(j)         ! NCSU SUBDOMAIN
                     if(NODECODE(I).EQ.1) THEN
                        WRITE(lun,2453) I, descript % array(I)
                     ELSE
                        WRITE(lun,2453) I, descript % alternate_value
                     ENDIF
                  END DO
               ELSE
                  DO j=1, num_nodes_out         ! NCSU SUBDOMAIN
                     I = write_nodes(j)         ! NCSU SUBDOMAIN
                     WRITE(lun,2453) I, descript % array(I)
                  END DO
               ENDIF
            ENDIF
            IF (descript % num_items_per_record .eq. 2) THEN
               DO j=1, num_nodes_out            ! NCSU SUBDOMAIN
                  I = write_nodes(j)            ! NCSU SUBDOMAIN
                  WRITE(lun,2454) I, descript % array(I),
     &                            descript % array2(I)
               END DO
            ENDIF

         ENDIF
```

```
          filepos = filepos+1+descript % num_records_this

...(+79 lines)
end subroutine writeOutArray_trim(...)
```

File Name: adcprep.F

Directory: adc50_51++/prep/

Description: Pre-processing of parallel ADCIRC run.

adcprep.F, change #1

If fort.015 file exists, call prep019() instead of prep19()

Edited lines 534-543:

```
C--NCSU SUBDOMAIN - CHANGE:
            subdomainOnPrep = .false.
            INQUIRE(file='fort.015', Exist=subdomainOnPrep)

            if (subdomainOnPrep) then
               CALL PREP019()
            else
               CALL PREP19()
            endif
C--NCSU SUBDOMAIN --
```

File Name: prep.F

Directory: adc50_51++/prep/

Description: Subroutines used for pre-processing of parallel ADCIRC run.

New subroutine called PREP019() is created based on PREP19() to pre-process new boundary conditions file fort.019. Following changes from #1 to #7 are the differences between these two subroutines:

prep.F, change #1

Declare additional variables and arrays that will be used during pre-processing.

Added lines 2100-2107:

```
C--NCSU SUBDOMAIN CHANGE:
C      CHARACTER*40  ETIMINC,ESBINP
C      CHARACTER*40,ALLOCATABLE :: ESBIN(:)
      double precision  ETIMINC,ESBINP, ESBINP2, ESBINP3        !
      double precision,ALLOCATABLE :: ESBIN(:), ESBIN2(:), ESBIN3(:)
      integer,allocatable :: ESBIN4(:)
      integer ESBINP4
C--NCSU SUBDOMAIN--
```

prep.F, change #2

Call Openprep019() instead of OpenPrepFiles()

Edited lines 2114-2115:

```
    CALL OpenPrep019(19, 'aperiodic elevation boundary  ', !NCSU SUBDOMAIN
     &     1, nproc, SDU, Success)
```

prep.F, change #1

Allocate additional arrays that will be used during pre-processing.

Added lines 2124-2128:

```
C--NCSU SUBDOMAIN - CHANGE:
      allocate ( ESBIN2(MNETA) )
      allocate ( ESBIN3(MNETA) )
      allocate ( ESBIN4(MNETA) )
C--NCSU SUBDOMAIN--
```

prep.F, change #4

Convert read & write type of ETIMINC appropriately.

Edited lines 2133-2142:

```
C--NCSU SUBDOMAIN - CHANGE:
C      READ(19,40) ETIMINC
       READ(19,*) ETIMINC
C--NCSU SUBDOMAIN--

      DO IPROC = 1,NPROC
C--NCSU SUBDOMAIN - CHANGE:
C        WRITE(SDU(IPROC),40)  ETIMINC
         WRITE(SDU(IPROC),*)  ETIMINC
C--NCSU SUBDOMAIN--
```

prep.F, change #5

This code reads global boundary conditions file (fort.019). Read format is changed from fort.19 to fort.019 .

Edited lines 2150-2155:

```
C--NCSU SUBDOMAIN - CHANGE:
C        READ(19,40,END=9999)  ESBIN(I)   ! old format
         read(19,*,end=9999)  ESBIN(I), ESBIN2(I), ESBIN3(I)
         read(19,*,end=9999)  ESBIN4(I)
      ENDDO
C--NCSU SUBDOMAIN--
```

prep.F, change #6

This code writes localized boundary conditions for each processor of a parallel run. Write format is changed from fort.19 to fort.019 .

Edited lines 2162-2169:

```
C--NCSU SUBDOMAIN - CHANGE:
C           WRITE(SDU(IPROC),40) ESBINP   ! old format
            ESBINP2 = ESBIN2(OBNODE_LG(I,IPROC))
            ESBINP3 = ESBIN3(OBNODE_LG(I,IPROC))
            ESBINP4 = ESBIN4(OBNODE_LG(I,IPROC))
            WRITE(SDU(IPROC),*) ESBINP, ESBINP2, ESBINP3
            WRITE(SDU(IPROC),*) ESBINP4
C--NCSU SUBDOMAIN--
```

prep.F, change #7

Deallocate additional arrays used for pre-processing of fort.019

Added lines 2185-2189:

```
C--NCSU SUBDOMAIN - CHANGE:
      deallocate( ESBIN2 )
      deallocate( ESBIN3 )
      deallocate( ESBIN4 )
C--NCSU SUBDOMAIN--
```

prep.F, change #8

New subroutine called Openprep019() is created based on OpenPrepFiles(). To be able to handle pre-processing of fort.019 boundary conditions files, length of character variables has been changed. Following changes indicate the differences between these two subroutines:

Edited line 5741:

```
      CHARACTER(len=8) DefaultName  !NCSU SUBDOMAIN

      CHARACTER(len=15) sdFileName  !NCSU SUBDOMAIN
```

Added lines 5750-5751:

```
      DefaultName= 'fort.019'    !NCSU SUBDOMAIN
      FileName = 'fort.019'      !NCSU SUBDOMAIN
```

Edited line 5741:

```
      sdFileName(8:15) = DefaultName   !NCSU SUBDOMAIN
```

Edited lines 5791-5792:

```
 1010 FORMAT('File ',A8,/,' WAS NOT FOUND! Try again or type "skip"',/)
 1011 FORMAT('File ',A8,/,' WAS FOUND!  Opening & Processing file.',/)
```

File Name: global.F

Directory: adc50_51++/src/

Description: Global Variables used in ADCIRC code.

Additional variables declared in global.F

```
integer :: ncsu_print_wd          ! NCSU SUBDOMAIN
integer :: ncsu_bound_ele         ! NCSU SUBDOMAIN
integer :: ncsu_bound_vel         ! NCSU SUBDOMAIN
integer :: ncsu_bound_wd          ! NCSU SUBDOMAIN
logical subdomainOn               ! NCSU SUBDOMAIN
integer,allocatable,target :: WD2(:)
real(sz),allocatable :: read1_u(:),read2_u(:)  ! NCSU SUBDOMAIN
real(sz),allocatable :: read1_v(:),read2_v(:)  ! NCSU SUBDOMAIN
integer,allocatable  :: read_wd(:)             ! NCSU SUBDOMAIN
integer,allocatable  :: read_nc(:), read_ni(:) ! NCSU SUBDOMAIN
real(sz),allocatable :: eltemp(:),uutemp(:),vvtemp(:)     ! NCSU
INTEGER  NOUTGS, NSPOOLGS
integer :: num_nodes_out  ! NCSU SUBDOMAIN
integer, allocatable :: write_nodes(:)    !NCSU SUBDOMAIN
```

Additional allocations in global.F

```
allocate ( WD2(MNP))
ALLOCATE ( read1_u(MNETA),read2_u(MNETA) )        ! NCSU SUBDOMAIN
ALLOCATE ( read_wd(MNETA) )                       ! NCSU SUBDOMAIN
ALLOCATE ( read1_v(MNETA),read2_v(MNETA) )        ! NCSU SUBDOMAIN
ALLOCATE (eltemp(MNETA),uutemp(MNETA),vvtemp(MNETA))! NCSU SUBDOMAIN
```

File Name: pre_global.F

Directory: adc50_51++/src/

Description: Global Variables used in pre-processing.

Additional variable declared in pre_global.F

```
LOGICAL subdomainOnPrep       !NCSU SUBDOMAIN
```

Appendix C – Additional LTSA Diagrams

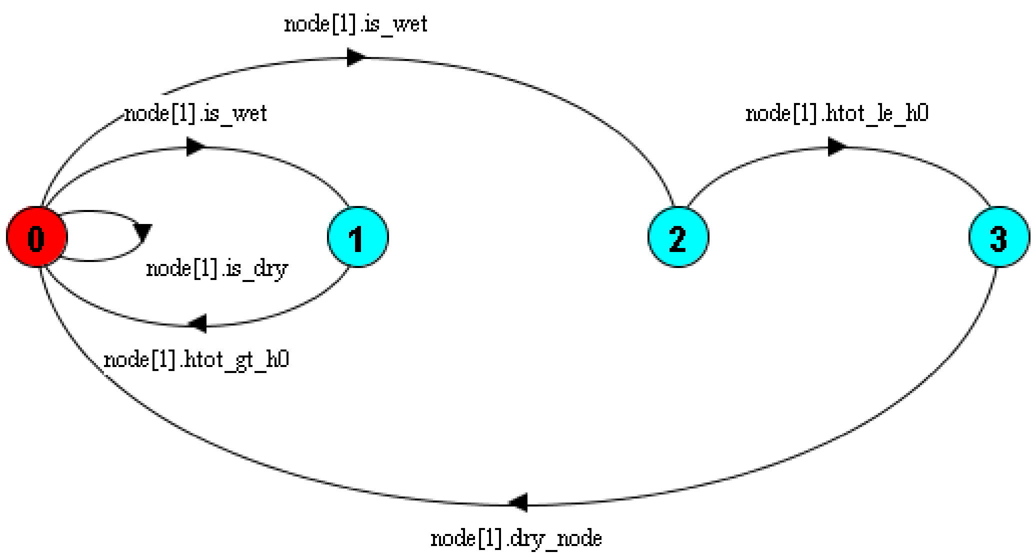


Figure C.1: LTSA Diagram of the process PART1: If the water level of the wet node is greater than H0, the node stays wet (trace: 0, 1, 0). If the water level is less than H0, node is dried (trace: 0, 2, 3, 0). Hidden actions: part1.start, part1.end, node[1].update_nc

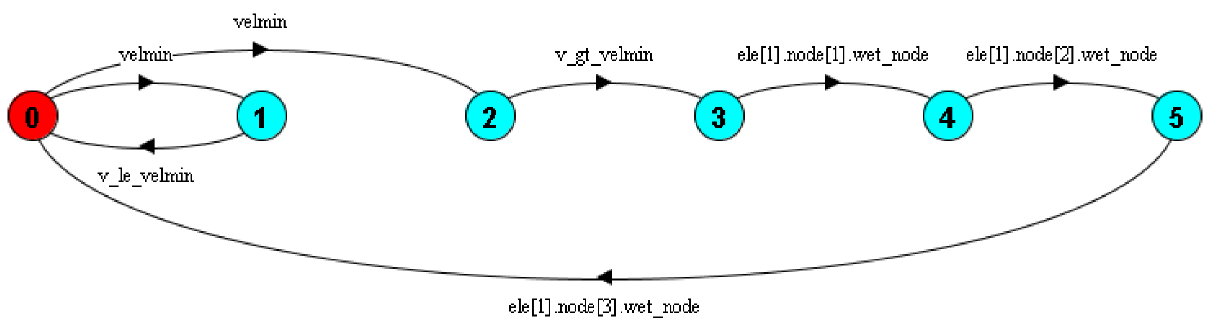


Figure C.2: LTSA Diagram of the process PART2. If the velocity is greater than Vmin, nodes in the element are made wet (trace 0, 2, 3, 4, 5, 0). Minimization Operator: PART2@{ele[1].evaluate,ele[1].node[i:1..3].wet_node,velmin,v_gt_velmin,v_le_velmin}

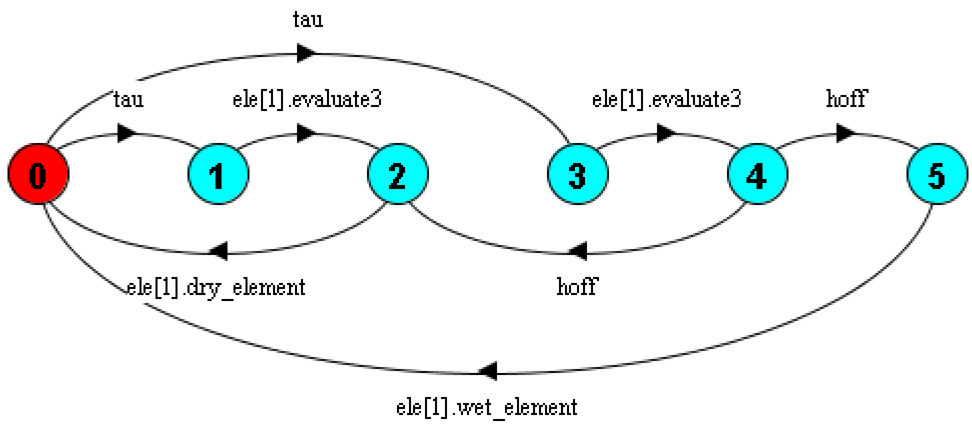


Figure C.3: LTSA Diagram of the process PART3. (Trace 0, 1, 2, 0: Element has less than two wet nodes, element is dried. Trace 0, 3, 4, 2, 0: Element has at least two wet nodes, $h < H_{off}$. Element is dried. Trace 0, 3, 4, 5, 0: Element has at least two wet nodes, $h \geq H_{off}$. Element is wetted. Minimization operator: PART3@{ele[1].{evaluate3,dry_element,wet_element},hoff})

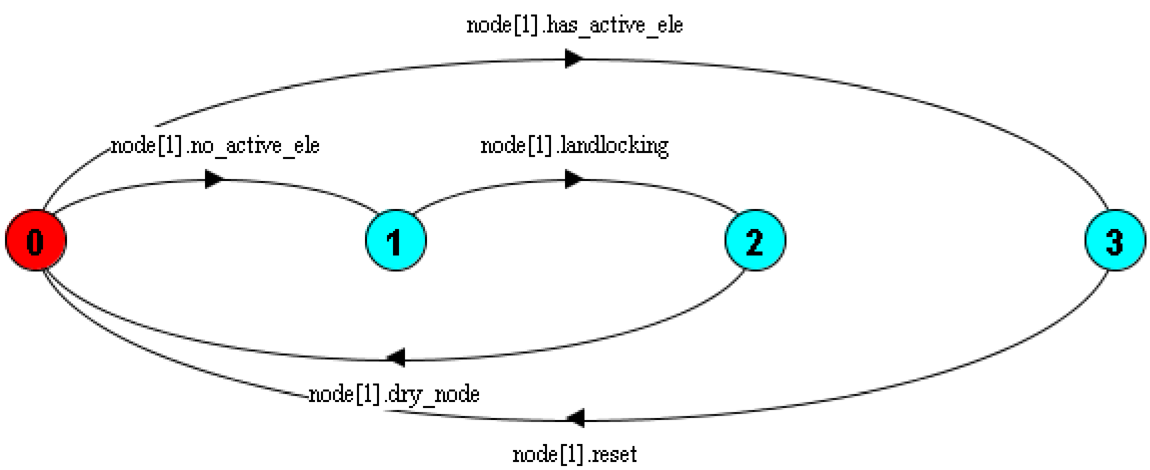


Figure C.4: LTSA Diagram of the process PART4. (Trace 0, 3, 0: Node has active element, no landlocking occurs. Trace 0, 1, 2, 0: No active element, landlocking occurs. Minimization operator: PART4@{node[1].{has_active_ele,no_active_ele,reset,landlocking,dry_node})

Appendix D – Trace-to-violations of LTSA Model properties

D.1 Trace to property violation in Subdomain1

```
node.1.wet_node
node.1.update_nc
node.2.wet_node
node.2.update_nc
node.3.dry_node
node.3.update_nc
node.4.dry_node
node.4.update_nc
node.5.dry_node
node.5.update_nc
node.6.dry_node
node.6.update_nc
end.initialization
part0.start
ele.1.wet_element
ele.2.wet_element
ele.3.wet_element
ele.4.wet_element
ele.5.wet_element
part0.end
part1.start
node.1.is_wet
node.1.htot_gt_h0
node.2.is_wet
node.2.htot_gt_h0
node.3.is_dry
node.4.is_dry
node.5.is_dry
node.6.is_dry
part1.end
part2.start
node.1.is_wet
node.4.is_dry
node.2.is_wet
ele.1.evaluate2
velmin
v_le_velmin
node.3.is_dry
node.1.is_wet
node.2.is_wet
ele.2.evaluate2
velmin
v_le_velmin
node.5.is_dry
node.1.is_wet
ele.3.evaluate2
pass2
node.5.is_dry
node.4.is_dry
node.1.is_wet
ele.4.evaluate2
pass2
node.2.is_wet
node.4.is_dry
node.6.is_dry
ele.5.evaluate2
pass2
part2.end
part3.start
node.1.is_wet
node.4.is_dry
node.2.is_wet
ele.1.evaluate3
hoff
ele.1.dry_element
node.3.is_dry
node.1.is_wet
node.2.is_wet
ele.2.evaluate3
hoff
ele.2.wet_element
node.3.is_dry
node.5.is_dry
node.1.is_wet
ele.3.evaluate3
ele.3.dry_element
node.5.is_dry
node.4.is_dry
node.1.is_wet
ele.4.evaluate3
ele.4.dry_element
node.2.is_wet
node.4.is_dry
node.6.is_dry
ele.5.evaluate3
ele.5.dry_element
part3.end
part4.start
ele.1.is_dry_ele
ele.2.is_wet_ele
node.3.active_ele
node.1.active_ele
node.2.active_ele
ele.3.is_dry_ele
ele.4.is_dry_ele
ele.5.is_dry_ele
end_main
node.1.has_active_ele
node.1.reset
node.2.has_active_ele
node.2.reset
node.3.has_active_ele
node.3.reset
node.4.no_active_ele
node.4.landlocking
node.4.dry_node
node.5.no_active_ele
node.5.landlocking
node.5.dry_node
node.6.no_active_ele
node.6.landlocking
node.6.dry_node
part4.end
update.start
node.1.update_nc
node.2.update_nc
node.3.update_nc
node.4.update_nc
node.5.update_nc
node.6.update_nc
update.end
report.start
node.1.is_wet
node.1.report_wet
node.2.is_wet
node.2.report_wet
node.3.is_dry
node.3.report_dry
node.4.is_dry
node.4.report_dry
node.5.is_dry
node.5.report_dry
node.6.is_dry
node.6.report_dry
```

D.2 Trace to property violation in Subdomain2

```
node.1.dry_node
node.1.update_nc
node.2.wet_node
node.2.update_nc
node.3.dry_node
node.3.update_nc
node.4.dry_node
node.4.update_nc
node.5.dry_node
node.5.update_nc
node.6.wet_node
node.6.update_nc
end.initialization
part0.start
ele.1.wet_element
ele.2.wet_element
ele.3.wet_element
ele.4.wet_element
ele.5.wet_element
part0.end
part1.start
node.1.is_dry
node.2.is_wet
node.2.htot_gt_h0
node.3.is_dry
node.4.is_dry
node.5.is_dry
node.6.is_wet
node.6.htot_gt_h0
part1.end
part2.start
node.1.is_dry
node.4.is_dry
node.2.is_wet
ele.1.evaluate2
pass2
node.3.is_dry
node.1.is_dry
node.2.is_wet
ele.2.evaluate2
pass2
node.3.is_dry
node.5.is_dry
node.1.is_dry
ele.3.evaluate2
pass2
node.5.is_dry
node.4.is_dry
node.1.is_dry
ele.4.evaluate2
pass2
node.2.is_wet
node.4.is_dry
node.6.is_wet
ele.5.evaluate2
velmin
v_le_velmin
part2.end
part3.start
node.1.is_dry
node.4.is_dry
node.2.is_wet
ele.1.evaluate3
ele.1.dry_element
node.3.is_dry
node.1.is_dry
node.2.is_wet
ele.2.evaluate3
ele.2.dry_element
node.3.is_dry
node.5.is_dry
node.1.is_dry
ele.3.evaluate3
ele.3.dry_element
node.5.is_dry
node.4.is_dry
node.1.is_dry
ele.4.evaluate3
ele.4.dry_element
node.2.is_wet
node.4.is_dry
node.6.is_wet
ele.5.evaluate3
hoff
ele.5.wet_element
part3.end
part4.start
ele.1.is_dry_ele
ele.2.is_dry_ele
ele.3.is_dry_ele
ele.4.is_dry_ele
ele.5.is_wet_ele
node.2.active_ele
node.4.active_ele
node.6.active_ele
end_main
node.1.no_active_ele
node.1.landlocking
node.1.dry_node
node.2.has_active_ele
node.2.reset
node.3.no_active_ele
node.3.landlocking
node.3.dry_node
node.4.has_active_ele
node.4.reset
node.5.no_active_ele
node.5.landlocking
node.5.dry_node
node.6.has_active_ele
node.6.reset
part4.end
update.start
node.1.update_nc
node.2.update_nc
node.3.update_nc
node.4.update_nc
node.5.update_nc
node.6.update_nc
update.end
report.start
node.1.is_dry
node.1.report_dry
node.2.is_wet
node.2.report_wet
node.3.is_dry
node.3.report_dry
node.4.is_dry
node.4.report_dry
node.5.is_dry
node.5.report_dry
node.6.is_wet
node.6.report_wet
```

Appendix E – Model Parameter and Boundary Condition Files (fort.15)

E.1 Hurricane Fran Subdomain Runs

```
nc_v20_subdomain msl fran     ! 32 CHARACTER ALPHANUMERIC RUN DESCRIPTION
 padcirc <ADCVER>      ! 24 CHARACTER ALPANUMERIC RUN IDENTIFICATION
 1                     ! NFOVER - NONFATAL ERROR OVERRIDE OPTION
 1                     ! NABOUT - ABREVIATED OUTPUT OPTION PARAMETER
 -10                     ! NSCREEN - UNIT 6 OUTPUT OPTION PARAMETER
 0                     ! IHOT - HOT START PARAMETER
 2                     ! ICS - COORDINATE SYSTEM SELECTION PARAMETER
 0                     ! IM - MODEL SELECTION PARAMETER
 1                     ! NOLIBF - BOTTOM FRICTION TERM SELECTION PARAMETER
 2                     ! NOLIFA - FINITE AMPLITUDE TERM SELECTION PARAMETER
 1                     ! NOLICA - SPATIAL DERIVATIVE CONVECTIVE SELECTION PARAMETER
 1                     ! NOLICAT
 4                     ! NWP
surface_directional_effective_roughness_length
mannings_n_at_sea_floor
surface_canopy_coefficient
primitive_weighting_in_continuity_equation
 1                     ! NCOR - VARIABLE CORIOLIS IN SPACE OPTION PARAMETER
 0                     ! NTIP - TIDAL POTENTIAL OPTION PARAMETER
 12                    ! NWS - WIND STRESS AND BAROMETRIC PRESSURE OPTION PARAMETER
 1                     ! NRAMP - RAMP FUNCTION OPTION
 9.81                  ! G - ACCELERATION DUE TO GRAVITY - DETERMINES UNITS
 -3.0                  ! TAU0 - WEIGHTING FACTOR IN GWCE
  0.5                  ! DT - TIME STEP (IN SECONDS)
 0.00                  ! STATIM - STARTING TIME (IN DAYS)
 0.00                  ! REFTIM - REFERENCE TIME (IN DAYS)
 1800.0   ! Wind and (if needed) RadStress Time  Increment
 3.875                 ! RNDAY - TOTAL LENGTH OF SIMULATION (IN DAYS)
 1.                    ! DRAMP - DURATION OF RAMP FUNCTION (IN DAYS)
 0.35 0.30 0.35        ! TIME WEIGHTING FACTORS FOR THE GWCE EQUATION
 0.10 0 0 0.01         ! H0, NODEDRYMIN, NODEWETMIN, VELMIN
 -79.0 35.0            ! SLAM0,SFEA0 - CENTER OF CPP PROJECTION
 0.0030 1.0 10. 0.33333 ! FFACTOR,HBREAK,FTHETA,FGAMMA
 10.0                  ! ESL - LATERAL EDDY VISCOSITY COEFFICIENT
 0.0                   ! CORI - CORIOLIS PARAMETER - IGNORED IF NCOR = 1
 0                     ! NTIF - TOTAL NUMBER OF TIDAL POTENTIAL CONSTITUENTS BE
 0                     ! NBFR - TOTAL NUMBER OF FORCING FREQUENCIES ON OPEN BOU
100.0                  ! ANGINN : INNER ANGLE THRESHOLD
 0 0.0 100.0  300      ! NOUTE,TOUTSE,TOUTFE,NSPOOLE:ELEV STATION OUTPUT INFO
 0                     ! TOTAL NUMBER OF ELEVATION RECORDING STATIONS
 0 0.0 100.0  3600     ! NOUTV,TOUTSV,TOUTFV,NSPOOLV:VEL STATION OUTPUT INFO (
0                      ! NSTAV - NUMBER OF ELEVATION RECORDING STATIONS
 0 0.0 24.0  90
 0
 1 0.0 100. 3600       ! NOUTGE,TOUTSGE,TOUTFGE,NSPOOLGE : GLOBAL ELEVATION OUTPUT
INFO (UNIT  63)
 1 0.0 100. 3600       ! NOUTGV,TOUTSGV,TOUTFGV,NSPOOLGV : GLOBAL VELOCITY
 1 0.0 100. 3600       ! NOUTGM,TOUTSGM,TOUTFGM,NSPOOLGM : GLOBAL MET  OUTPUT
 0                     ! NHARFR - NUMBER OF CONSTITUENTS TO BE INCLUDED
 40.0  50.0  5  0.0    ! THAS,THAF,NHAINC,FMV - HARMONIC ANALYSIS PARAMETERS
 1 1 1 1               ! NHASE,NHASV,NHAGE,NHAGV - CONTROL HARMONIC ANALYSIS
 1 21600 1             ! NHSTAR,NHSINC,NHSLAB  - HOT START FILE GENERATION
 1  0  1.E-7  25 0     ! ITITER, ISLDIA, CONVCR, ITMAX & ILUMP
```

E.2 Hurricane Isabel Subdomain Runs

```
nc_inundation_v9                    ! 30 CHARACTER ALPHANUM RUN DESCRIPTION
adcsubd                     ! 20 CHARACTER ALPANUMERIC RUN IDENTIFICATION
1                           ! NFOVER - NONFATAL ERROR OVERRIDE OPTION
1                           ! NABOUT - ABREVIATED OUTPUT OPTION PARAMETER
-10                         ! NSCREEN - UNIT 6 OUTPUT OPTION PARAMETER
0                           ! IHOT - HOT START PARAMETER
2                           ! ICS - COORDINATE SYSTEM SELECTION PARAMETER
0                           ! IM - MODEL TYPE (0 INDICATES STANDARD DI MODEL)
1                           ! NOLIBF - BOTTOM FRICTION TERM SELECTION PARAMETER
2                           ! NOLIFA - FINITE AMPLITUDE TERM SELECTION PARAMETER
1                           ! NOLICA
1                           ! NOLICAT
4                           ! NWP
surface_directional_effective_roughness_length
mannings_n_at_sea_floor
surface_canopy_coefficient
primitive_weighting_in_continuity_equation
1                           ! NCOR - VARIABLE CORIOLIS IN SPACE OPTION PARAMETER
0                           ! NTIP - TIDAL POTENTIAL OPTION PARAMETER
12                          ! NWS
1                           ! NRAMP - RAMP FUNCTION OPTION
9.81                        ! G - ACCELERATION DUE TO GRAVITY - DETERMINES UNITS
-3                          ! TAU0 - WEIGHTING FACTOR IN GWCE
1                           ! DT - TIME STEP (IN SECONDS)
0.0                         ! STATIM - STARTING TIME (IN DAYS)
0.0                         ! REFTIM - REFERENCE TIME (IN DAYS)
1800                        !wind and red stress time increment
5.495                       ! RNDAY - TOTAL LENGTH OF SIMULATION (IN DAYS)
1                           ! DRAMP - DURATION OF RAMP FUNCTION (IN DAYS)
0.35 0.30 0.35              ! TIME WEIGHTING FACTORS FOR THE GWCE EQUATION
0.10 10 10 .01              ! H0 - MINIMUM CUTOFF DEPTH
-79.0 35.0                  ! SLAM0,SFEA0 - CENTER OF CPP PROJECTION
0.003  1. 10. 0.33333       !  FFACTOR - BOTTOM FRICTION COEFFICIENT
10.0                        ! ESL - LATERAL EDDY VISCOSITY COEFFICIENT
0.0                         ! CORI - CORIOLIS PARAMETER - IGNORED IF NCOR = 1
0                           ! NTIF - TOTAL NUMBER OF TIDAL POTENTIAL CONSTITUENTS
0                           ! NBFR - TOTAL NUMBER OF FORCING FREQUENCIES ON OPEN B.
100.0                       ! ANGINN : INNER ANGLE THRESHOLD
0  0.  100.  600            ! NOUTE,TOUTSE,TOUTFE,NSPOOLE:ELEV STATION OUTPUT INFO
0                           ! TOTAL NUMBER OF ELEVATION RECORDING STATIONS
0    0.0  100.0 3600        ! NOUTV,TOUTSV,TOUTFV,NSPOOLV:VEL STATION OUTPUT
0                           ! TOTAL NUMBER OF VELOCITY RECORDING STATIONS
0 0.0 24.0  90
0
1    0.0  100.0 100         ! NOUTGE,TOUTSGE,TOUTFGE,NSPOOLGE : GLOBAL ELEV
1    0.0  100.0 100         ! NOUTGV,TOUTSGV,TOUTFGV,NSPOOLGV : GLOBAL VEL
0 0.0 100. 3600             ! NOUTGM,TOUTSGM,TOUTFGM,NSPOOLGM : GLOBAL MET  OUTPUT
0                           ! NHARF
30  120   720  0.0000000    ! THAS, THAF, NHAINC,FMV
0 0 0 0                     ! NHASE,NHASV,NHAGE,NHAGV
0 86400                     ! NHSTAR,NHSINC
1  0  1e-10  25             ! ITITER,ISLDIA,CONVCR,ITMAX
```