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Simulation of Coastal Inundation Instigated by Storm Surge and River Discharge in the Chesapeake Bay Using Sub-grid Modeling Coupled with Lidar Data

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INTRODUCTION

Coastal flooding initiated by storm surge and river discharge during hurricanes and Nor'easters along the U.S. East Coast is a substantial threat to residential properties, community infrastructure, and human life. Very high-resolution, accurate flooding prediction at the street-level is highly desirable. The traditional methods for universally decreasing the size of a model grid to achieve street-level resolution is constrained by the computational limitations. As an ideal alternative, the sub-grid modeling approach enables the model to cover a large domain with reasonable resolution while simultaneously allowing the sub-grid to resolve sub-scale features efficiently. Key elements involved in this study are outlined below:

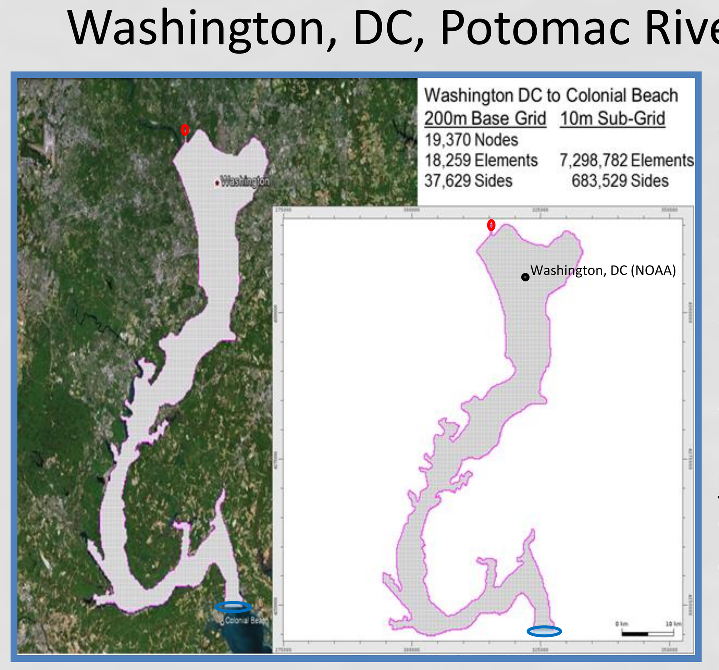
- Coupling with high-resolution Lidar-derived digital topography into the sub-grid of the model will increase accuracy of inundation simulations.
- Developing a general purpose wetting-and-drying scheme using an innovative nonlinear solver (Casulli, 2009; Casulli and Stelling, 2011).
- Sub-grid modeling is an efficient method based on the formulation by which velocities on the sub-grid level can be obtained through combination of velocities calculated at the coarse computational grid, the discretized bathymetric depths, and local friction parameters without resorting to solve the full set of equations for model outputs.
- This salient feature enables coastal flooding to be addressed in a single cross-scale model from the ocean to the upstream river channel without overly refining the grid resolution.

HYPOTHESES

- Embedding Lidar topography into the model sub-grid via Geographic Information Systems (GIS) will increase resolution and resolve small creeks and streams ≥ 2nd order.
- The partial wetting and drying inundation scheme utilized in the model inundation algorithm will be verified as both accurate and robust upon comparison with observations.
- Sub-grid modeling will replicate the results of a likewise-resolution true grid model, indicating that there is minimal loss of quantitative accuracy in the sub-grid approach.

STUDY SITES

Washington, DC, Potomac River Estuary, VA



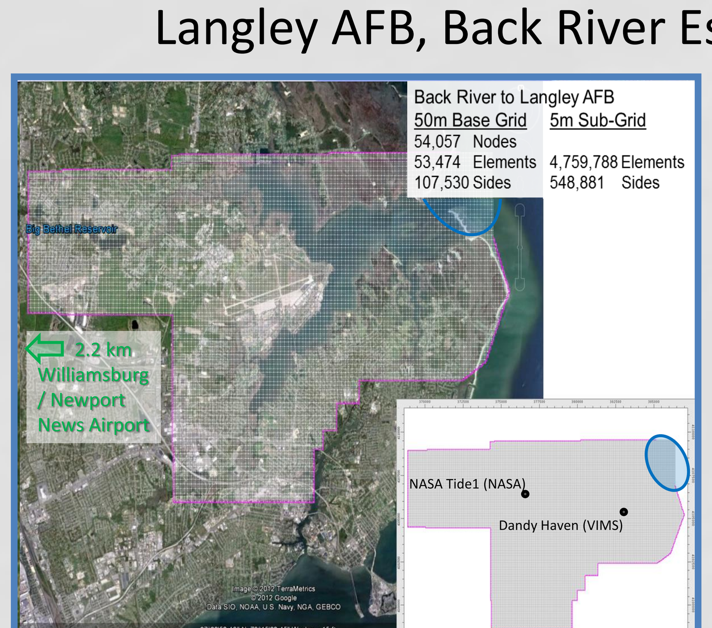
Open Boundary Condition at Colonial Beach (NOAA)

Flux Boundary Condition at Little Falls, MD for River Discharge (USGS)

Wind and Atmospheric Pressure Inputs from Washington DC (NOAA)

Great Flood of 1936
03/01/1936 00:00 GMT - 03/30/1936 00:00 GMT

Langley AFB, Back River Estuary, VA



Open Boundary Condition at Back River Dandy Haven (VIMS Tide Watch)

Precipitation Input from Williamsburg / Newport News Airport (NWS)

Wind and Atmospheric Pressure Inputs from Sewells Point (NOAA)

2011 Hurricane Irene
08/20/2011 00:00 GMT - 08/30/2011 00:00 GMT

ABSTRACT

Sub-grid modeling is a novel method by which water level elevations on the sub-grid level can be obtained through the combination of water levels and velocities efficiently calculated at the coarse computational grid, the discretized bathymetric depths, and local friction parameters without resorting to solve the full set of equations. Sub-grid technology essentially allows velocity to be determined rationally and efficiently at the sub-grid level. This salient feature enables coastal flooding to be addressed in a single cross-scale model from the ocean to the upstream river channel without overly refining the grid resolution. To this end, high-resolution DEMs will be developed using GIS from Lidar-derived topography for incorporation into a sub-grid model, for research into two case studies related to inundation: (1) The Great Flood of 1936 was utilized as a test for sub-grid modeling in Washington, DC. It demonstrated that the sub-grid model can achieve accurate results upon comparison with NOAA observation data and replicate the results of a likewise-resolution true grid model, indicating that there is minimal loss of quantitative accuracy in the sub-grid approach (R^2 = 99.98). (2) Spatial comparison of GPS wrack line data with model results for 2011 Hurricane Irene demonstrated that sub-grid model results accurately predicted the water level observed at Langley Research Center.

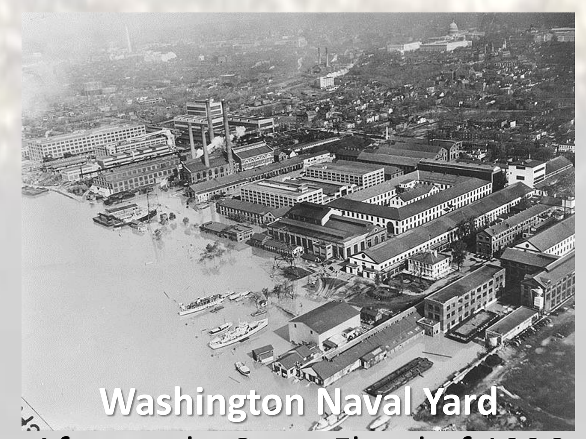
METHODS AND MATERIALS

The sub-grid modeling approach was applied to the Chesapeake Bay for simulating two flooding cases (Table 1):

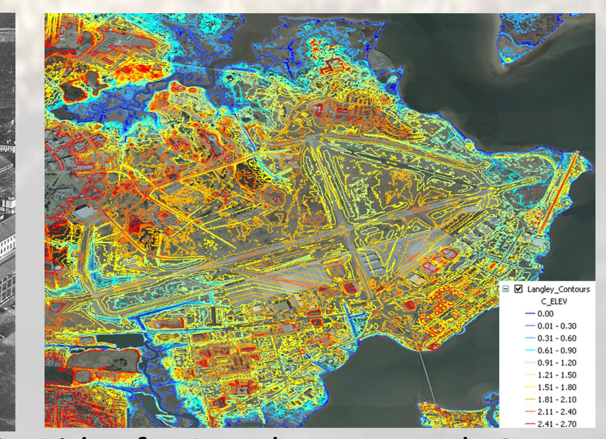
1. The Great Flood of 1936, which occurred in Washington, DC, was caused by the sudden increase of spring fresh water flow derived from heavy snowmelt in the upper Potomac River, resulting in a flood stage of 9 feet and widespread inundation of the entire capital mall area.
2. The second case is for Back River in Poquoson near Langley Air Force Base for Hurricane Irene where heavy precipitation initiated a flash flooding event in 2011 for a large area of Poquoson.

	Scenarios	Location	Grid Resolution		Research Applications
			Base Grid	Sub-Grid	
1	Great Flood of 1936	Washington, DC	200m	10m	River Discharge, Storm Surge, Urban Flooding
2	2011 Hurricane Irene	Langley AFB, VA	50m	5m	Precipitation, Storm Surge

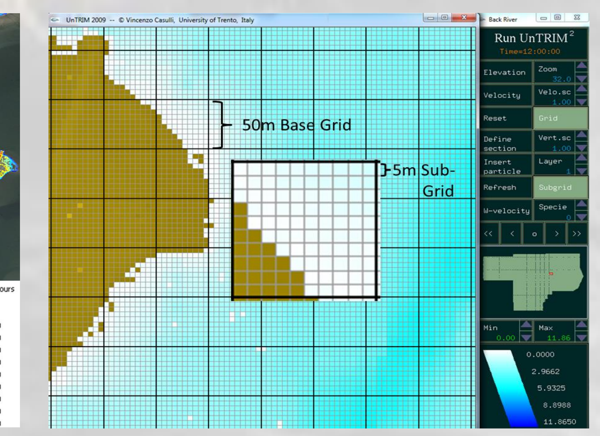
Table 1. Scenarios associated with Washington, DC, and Langley Research Center with grid resolutions



Aftermath: Great Flood of 1936



Lidar for Langley Research Center



Sub-Grid for Langley in UnTRIM²

RESULTS

The Great Potomac River Flood of 1936 in Washington, DC

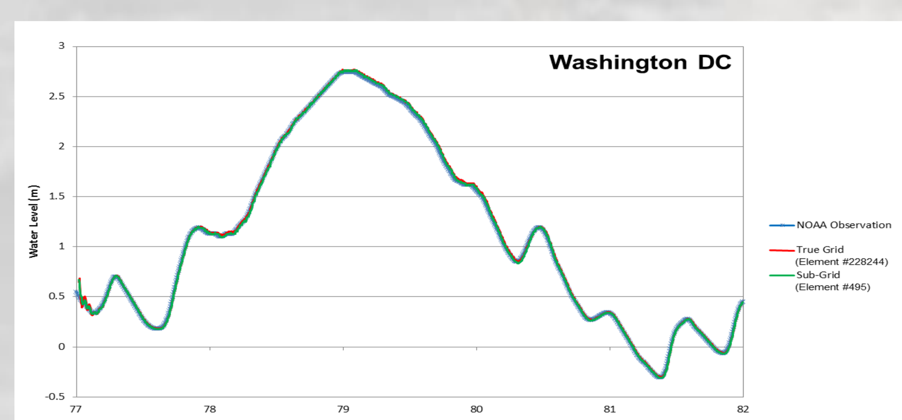


Figure 1. Great Flood of 1936 comparison of Sub-Grid and True Grid with observation data depicting quantitatively similar results; R^2=99.98

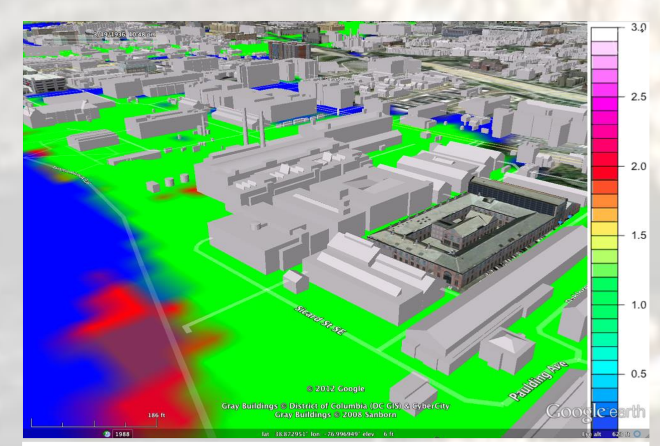


Figure 5. UnTRIM² result for the Great Flood of 1936 at Washington Naval Shipyard in Google Earth

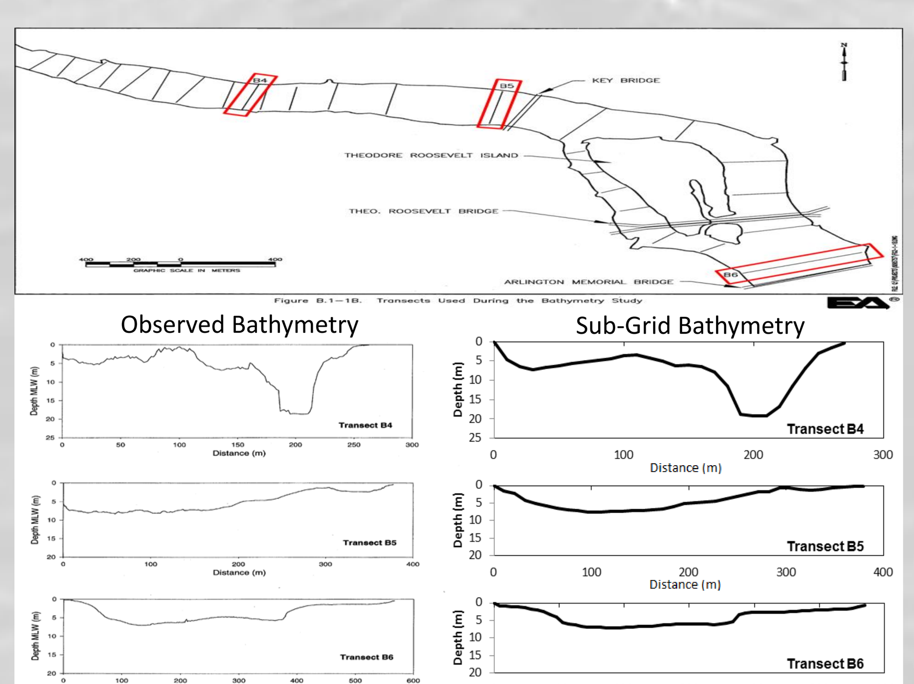


Figure 2. Three example bathymetric transects used for verification of bathymetry interpolation in Washington, DC (map on top), with corresponding sounding data published in U.S. Army Corps. of Engineers Report (bottom left), and UnTRIM² sub-grid bathymetry (bottom right) in the vicinity of the Washington aqueduct (USACE 2001)

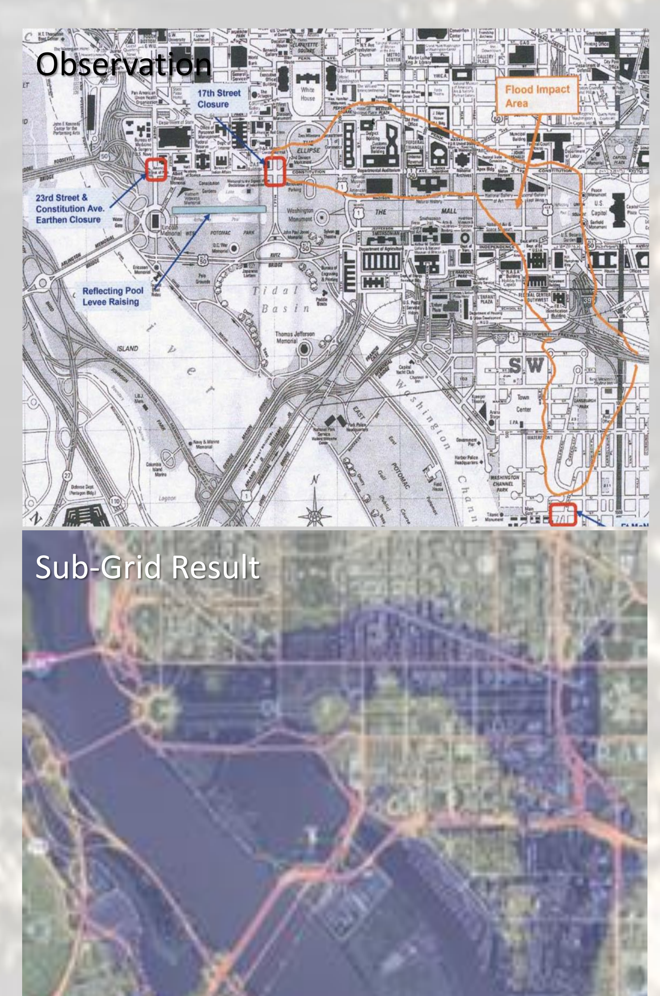


Figure 6. Peak inundation for the Great Flood of 1936 shown flooding the capital mall area of Washington, DC. Historic U.S. Army Corps of Engineers 1936 flood map at left used for verification of the model's inundation algorithm for the partial wetting and drying scheme, UnTRIM² model results at right (NCPC Report, 2008)

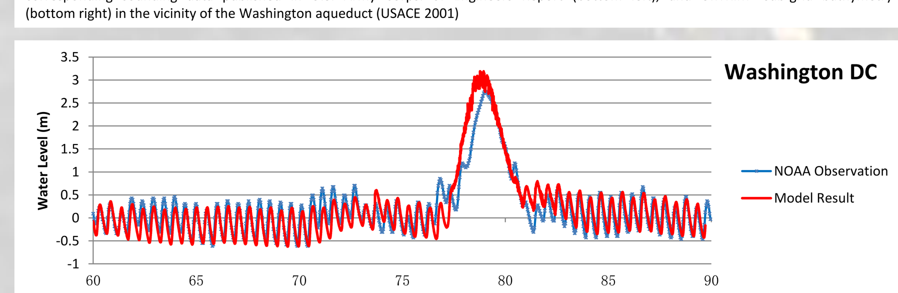


Figure 3. Great Flood of 1936 30-day calibration comparison of NOAA observation at Washington, DC, with Sub-Grid results; R^2=92.76

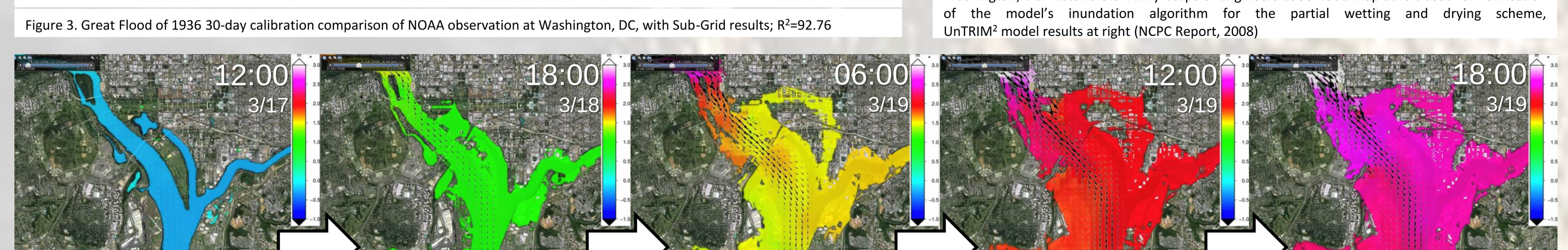


Figure 4. Great Flood of 1936 inundation displayed in Google Earth with depth-averaged velocities at 5 different times leading up to the peak of maximum inundation (12:00 on 3/17, 18:00 on 3/18, 06:00 on 3/19, 12:00 on 3/19, and 18:00 on 3/19)

2011 Hurricane Irene in NASA Langley

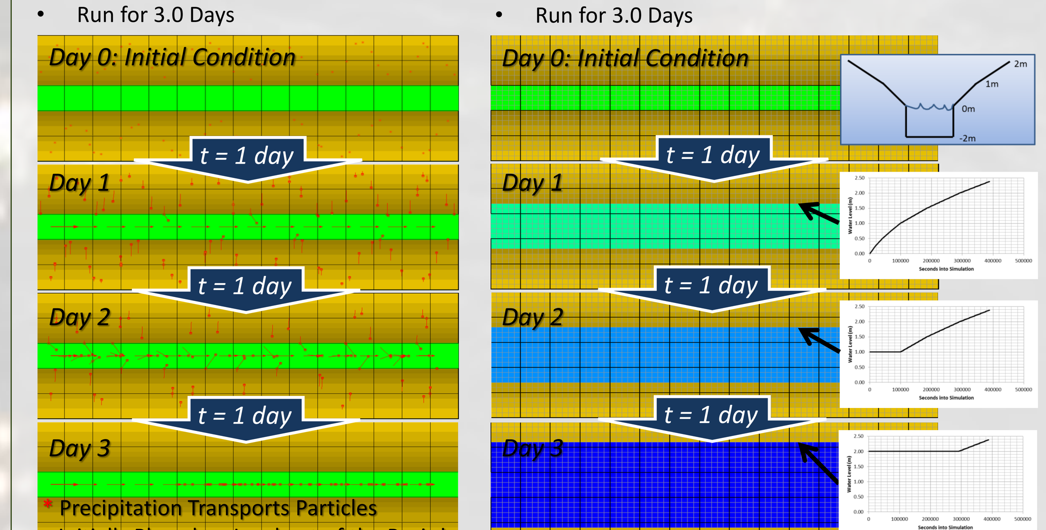
Ideal Test Cases for Precipitation Input

Open Flow Basin with Rainfall

- Flux Boundary Input: 0.5 m/sec at left
- No Open Boundary Forcing at right
- Input Rainfall at constant 25 mm/hr
- Run for 3.0 Days

Closed Flow Basin with Rainfall

- No Flux Boundary Forcing at left
- No Open Boundary Forcing at right
- Input Rainfall at constant 25 mm/hr
- Run for 3.0 Days



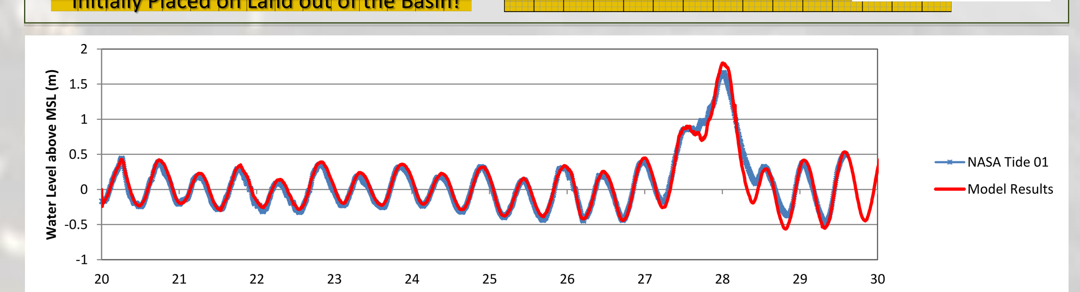


Figure 7. 2011 Hurricane Irene temporal comparison in GMT of observed results (NASA Tide 01) and sub-grid results (R^2 = 89.43) with an observed peak of 1.71m

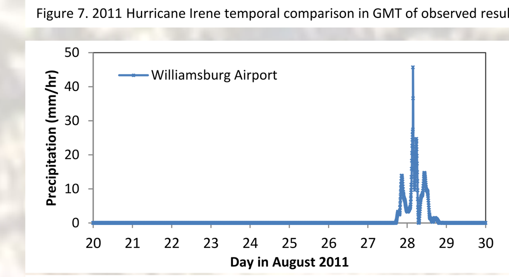


Figure 8. Precipitation input data from Williamsburg/Newport News Airport shown for 2011 Hurricane Irene with a peak of 46 mm/hr

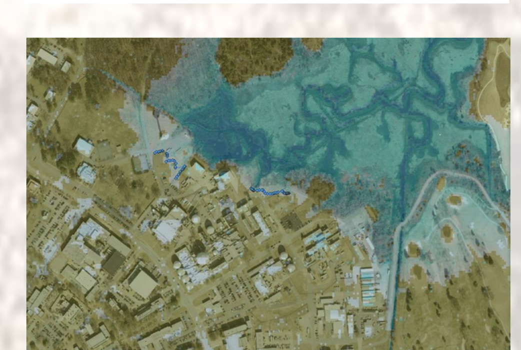


Figure 9. Maximum extent of 2011 Hurricane Irene flooding at Langley Research Center with GPS-recorded wrack line (blue dots) for comparison

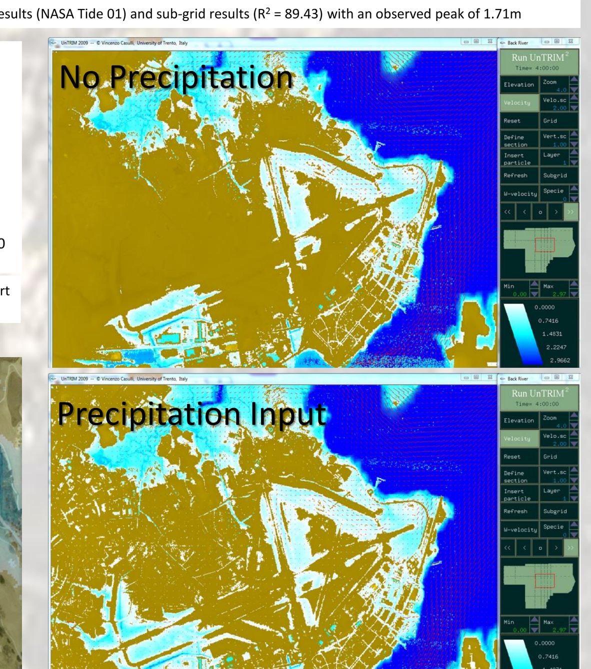


Figure 10. Comparison of with and without precipitation shown at bottom and on top, respectively, for 2011 Hurricane Irene at Langley Research Center in Hampton

DISCUSSION

Great Flood of 1936 in Washington, DC

- The sub-grid modeling approach readily replicated the results of a likewise-resolution true grid model (R^2 = 99.98), indicating:
  1) minimal loss of quantitative accuracy in the sub-grid approach, and
  2) both methods match the observation at Washington, DC (Figures 1&3)
- All runs were conducted on a Dell T3500 PC Workstation with Windows XP Professional (64-bit edition); an Intel Xeon Quad Core X5570 Processor (2.93GHz); with 6 GB RAM running UnTRIM² (Table 2 below)

Sub-Grid (200m Base Grid with 10m Sub-Grid)	True Grid (10m Resolution Grid)
1,294 Elements	451,500 Elements
1,466 Nodes	454,967 Nodes
2,759 Sides	906,466 Sides
3 hours to run	22.5 days to run
30 day simulation	30 day simulation

- Bathymetry data were verified with 2001 USACE published transect data near Roosevelt Island and the Arlington Mem. Bridge (Figure 2)
- UnTRIM² result at Washington Naval Yard in Google Earth 3D (Figure 5)
- Spatial extent of flood damage was verified from historic records, and is consistent with observations from USACE shown in Figures 4 & 6.

2011 Hurricane Irene at Langley Research Center, VA

- Good time series comparison for observed results vs. sub-grid results yields R^2 = 89.43; slightly over-predicting the peak at 1.71m (Figure 7)
- Comparison of with and without precipitation inputs (Figure 8) specifies that rainfall (46 mm/hr) is critical for modeling inland flooding (Figure 10)
- Favorable spatial comparison for maximum extent of inundation using GPS-recorded wrack line data at Langley Research Center (Figure 9)

CONCLUSION

- Comparison between with and without the use of the sub-grid method demonstrated that the sub-grid approach yields very similar results to that of the true grid-- especially for water level calculation, making the sub-grid approach ideal for inundation modeling.
- Inclusion of river discharge and precipitation as inputs is vital in the continuing effort to determine flooding extent and duration of major storm events in hind cast and forecast.
- Sub-grid modeling has great potential to be utilized for accurately simulating coastal flooding, which is concurrently subjected to large-scale storm surge and due to precipitation.
- Hydrodynamic modeling of major inundation events is vital to improving preventative measures that can potentially mitigate the loss of property and loss of human life.

ACKNOWLEDGEMENTS

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