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Title: Transition of the Coastal and Estuarine Storm Tide Model to an Operational Model for Forecasting Storm Surges

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Report Term or Frequency: Semi-annual

Final Annual Report: No

1. ACCOMPLISHMENTS

We continued to conduct experimental forecasts during 2016 hurricane season and convert CEST into a fully operational model by working with NHC's Storm Surge Unit through the JHT program. The major objectives of this project include (1) testing CEST with existing and recently developed SLOSH basins with track files from NHC, (2) developing CEST P-Surge through collaboration with Meteorological Development Laboratory (MDL), (3) conducting real-time surge forecasting during hurricane seasons, and (4) porting CEST to the Linux operating system used by NHC, preparing documents and training staff members at NHC to use CEST. The status of four major tasks at the end of this period is presented in the Table 1.

Table 1. Status of proposed tasks and deliverables.

Tasks	Proposed Timeline	Actual Status
Task 1: Testing CEST on existing and recently developed SLOSH basins	2016 Q2	Completed
Task 2: Developing CEST P-Surge	2017 Q2	Ongoing
Task 3: Conducting real-time surge forecasting during hurricane seasons	2015 Q3 & Q4 2016 Q3 & Q4	completed
Task 4: Porting CEST to NHC forecast environment	2017 Q2	Delivered the CEST code to NHC and ongoing

During this period, we investigated the difference in inundation patterns produced by CEST and SLOSH using Hurricane Rita (2005). In the previous progress report (Zhang et al., 2016b), we found that the CEST model produced comparable maximum MOM heights, but less inundation areas than SLOSH in most cases among thirty basins by comparison of storm surge magnitudes and inundation areas. For example, the inundation area of the category 3 SLOSH MOM is 50% larger than the inundation area of the category 3 CEST MOM in Apalachicola Bay Basin, and 70% larger in the Sabine Lake basin. This difference can have a significant impact on delineating the evacuation zones. Execution of evacuation from hurricane impact zones is expensive operation. Therefore, it is necessary to examine what factors cause the difference, even though such a study was not planned in the original proposal.

Tasks 1, 3, and 4 are on schedule, but Task 2 is delayed because of the investigation of the SLOSH and CEST difference and a prolonged illness of the principal investigator. The percentage of proposed tasks and deliverables are presented in Table 2.

The proposed project fits the NHC-6/JTWC11 priority "Advanced coastal inundation modeling and/or applications, visualization, or dissemination technology that enhances operational storm surge forecast accuracy or delivery". The project deliverables are the CEST forecast system and associated documents and training materials.

Table 2. Completion percentage of proposed tasks and deliverables.

Tasks	Cumulative percent toward Completion
Task 1: Testing CEST on existing and recently developed SLOSH basins	100%
Task 2: Developing CEST P-Surge	30%
Task 3: Conducting real-time surge forecasting during hurricane seasons	100%
Task 4: Porting CEST to NHC forecast environment	65%

We have discussed the principles of P-Surge with the developers of Meteorological Development Laboratory. For the next reporting period, we will develop a CEST P-Surge prototype.

2. PRODUCTS

The large difference between SLOSH and CEST MOMs occurs in the basins with large areas of coastal plain with almost flat topography. We speculated that the difference in the treatment of the effect of the overland bottom friction on the water flow was the major reason to cause the different MOMs between SLOSH and CEST in the previous report (Zhang et al., 2016b).

Numerical experiments conducting on the Apalachicola Bay basin seemed to verify our speculation. However, this is not sufficient, the best way to examine the difference is to use a historical hurricane event with detailed field observations to determine how well the overland flooding patterns from CEST and SLOSH fit observations. After discussing with the Storm Unit at NHC, we selected the new Texas Basin (TX3) and Hurricane Rita to conduct a comparison. The TX3 basin was developed by NHC in 2016, the basin was not thoroughly tested using hypothetical set of hurricanes, and the final MOEWs and MOMs had not been generated when the comparison test was performed. By doing so, CEST directly participated in the basin development, verification, and generation of MOEWs and MOMs and could provide additional help to NHC for the development of storm surge products.

The TX3 basin was converted into the CEST grid by following the procedure listed in the first progress report (Zhang et al., 2016a). The TX3 basin with semi-circle domain covers the coastal area of Texas with a minimum grid cell resolution about 120 meters along the coastal area (Table 3).

Table 3. Statistics of the TX3 Basin

Basin Name	TX3
Dimension	817*704
Minimum grid size	120 meters
Total number cell in SLOSH	575,168
Total number cell in CEST	578,214
Time Step In CEST	10 second
Initial water elevation	0 meter
Computational time for 4 days simulation*	2.4 hours

Note: * Computation time was derived by recording the simulation time using a single processor in a Dell PC workstation with four 2.5 GHZ Intel Xeon processors and 16GB of RAM.

2.1 Calculation of Manning’s Coefficient

Manning’s coefficients for grid cells over the land were estimated using the 2011 national land cover datasets (NLCD) created by the U.S. Geological Survey (USGS). A table of Manning’s coefficients (Table 4) corresponding to different land cover categories (Zhang et al., 2013) was employed in this study. Since the spatial resolution of NLCD is 30 m which is usually smaller than the cell size of a CEST grid, an average Manning’s coefficient (n_a) for a grid cell was calculated using

$$n_a = \frac{\sum_{i=1}^N (n_i \alpha) + n_w \beta}{N\alpha + \beta} \quad (1)$$

where n_i is the Manning’s coefficient value of a NLCD pixel within a model grid cell, α is the area of a NLCD pixel, N is the total number of NLCD pixels within a model cell, n_w is the Manning’s coefficient for the oceanic area β that are not covered by NLCD pixels.

Table 4. Manning’s coefficients for various categories of land cover.

NLCD Class Number	NLCD Class Name	Manning Coefficient
11	Open Water	0.020
12	Perennial Ice/Snow	0.010
21	Developed Open Space	0.020
22	Developed Low Intensity	0.050
23	Developed Medium Intensity	0.100
24	Developed High Intensity	0.130
31	Barren Land (Rock/Sand/Clay)	0.090
32	Unconsolidated Shore	0.040
41	Deciduous Forest	0.100
42	Evergreen Forest	0.110
43	Mixed Forest	0.100
51	Dwarf Scrub	0.040
52	Shrub/Scrub	0.050
71	Grassland/Herbaceous	0.034
72	Sedge/Herbaceous	0.030
73	Lichens	0.027
74	Moss	0.025
81	Pasture/Hay	0.033
82	Cultivated Crops	0.037
90	Woody Wetlands	0.140

91	Palustrine Forested Wetland	0.100
92	Palustrine Scrub/Shrub Wetland	0.048
93	Estuarine Forested Wetland	0.100
94	Estuarine Scrub/Shrub Wetland	0.048
95	Emergent Herbaceous Wetlands	0.045
96	Palustrine Emergent Wetland (Persistent)	0.045
97	Estuarine Emergent Wetland	0.045
98	Palustrine Aquatic Bed	0.015
99	Estuarine Aquatic Bed	0.015

Fig. 1 shows that large Manning’s coefficients occur along the east-north coastal area of the TX3 basin, especially at the coastal zone in Louisiana with forest, while the west-south coastal area has smaller Manning’s coefficients. The Manning’s coefficient of the ocean bottom was set to be a constant value of 0.015.

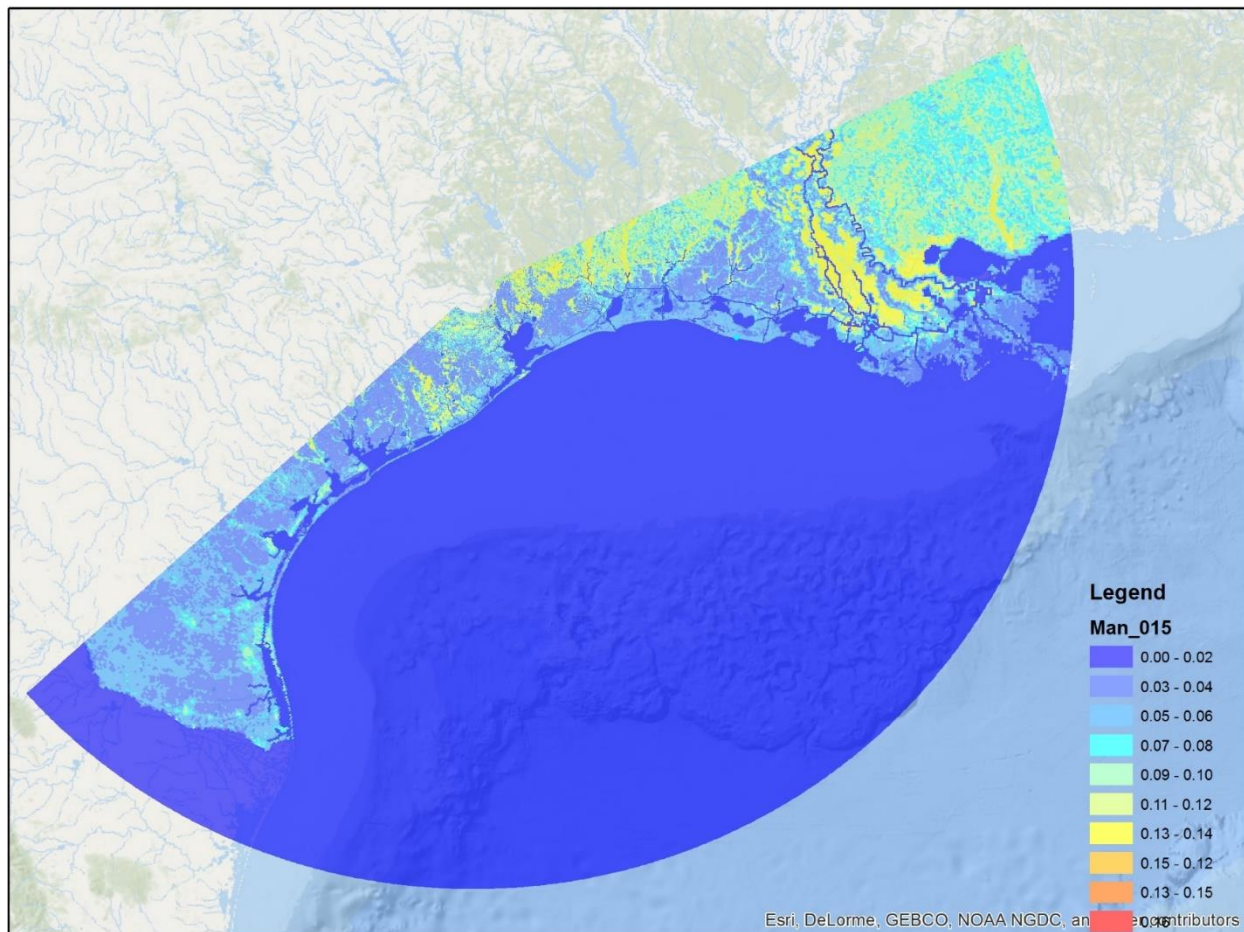


Fig. 1. Manning’s coefficients calculated based on the 2011 national landcover dataset at TX3 Basin.

2.2 Results for Hurricane Rita

The Storm Surge Unit at NHC and the CEST group at FIU independently conducted SLOSH and CEST storm surge simulations on the TX3 basin. The initial water level was set to be 0 m above the NAVD88 model for both SLOSH and CEST and the same storm track provided by NHC was used to drive the surge models. For CEST, the storm tide simulation for Hurricane Rita started at 0000 coordinated universal time (UTC) on September 22 and ending at 0000 UTC on September 26, 2005, continuing for 96 hours. The time step was set to be 10 seconds. The water level elevation at the open boundary was generated using seven tidal constituents M2, S2, N2, K1, O1, K2, and Q1. These constituents were obtained from the U.S. Army Corps of Engineers' (USACE) East Coast 2001 database of tidal constituents (ref). Fig. 2 represents the peak storm tide heights caused by Hurricane Rita above the NAVD 88 at the TX3 basin. The maximum peak storm tide height is about 15 feet around the location Rita made landfall.

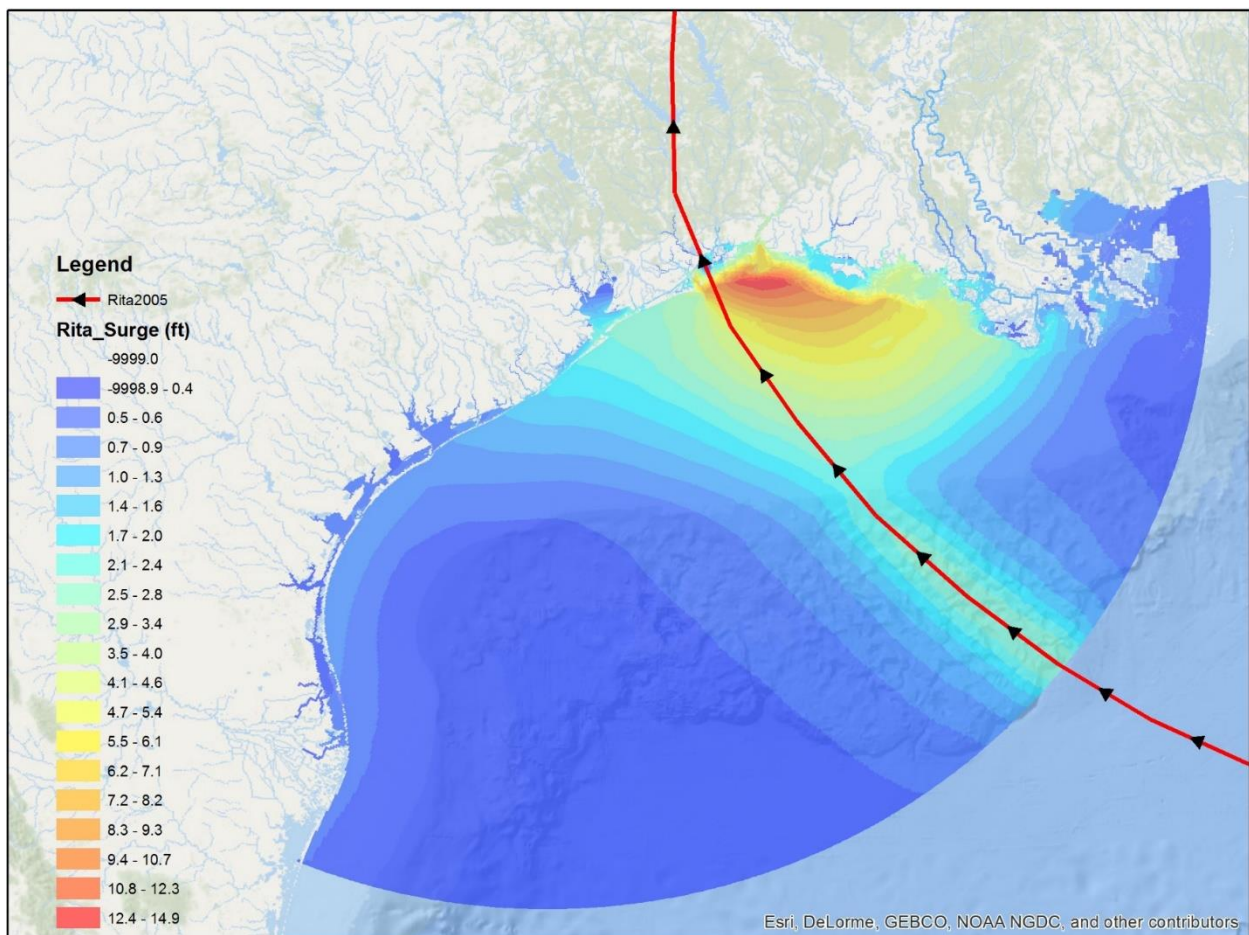


Fig. 2. Computed peak storm surge heights for Hurricane Rita.

NOAA tide gauges and USGS mobile gauges deployed during the storm provide valuable data for comparing computed storm surges both in the coastal water and on the land. Twelve NOAA tide stations and sixteen USGS stations were selected to compare the time series of the storm tide during Hurricane Rita (Fig. 3).

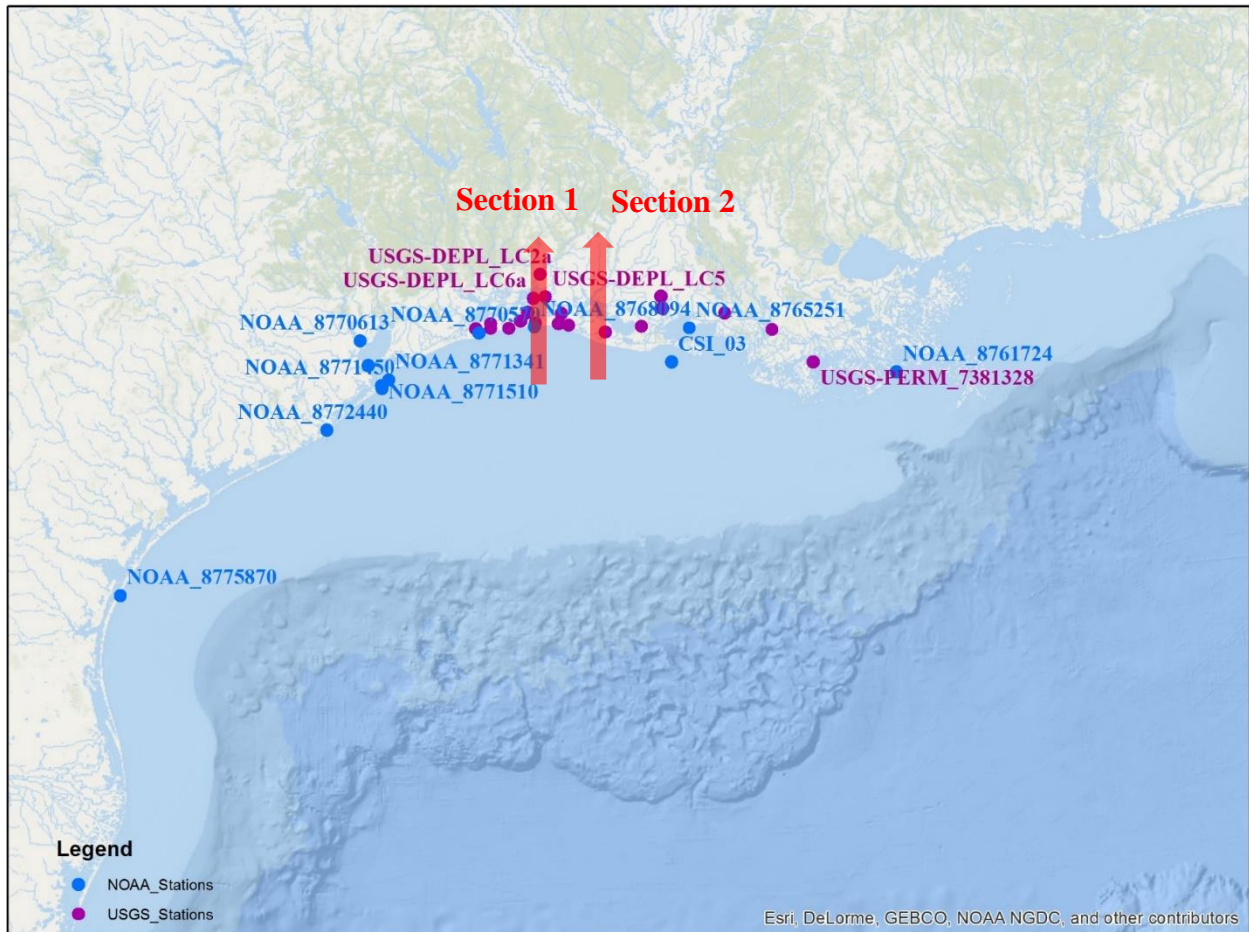
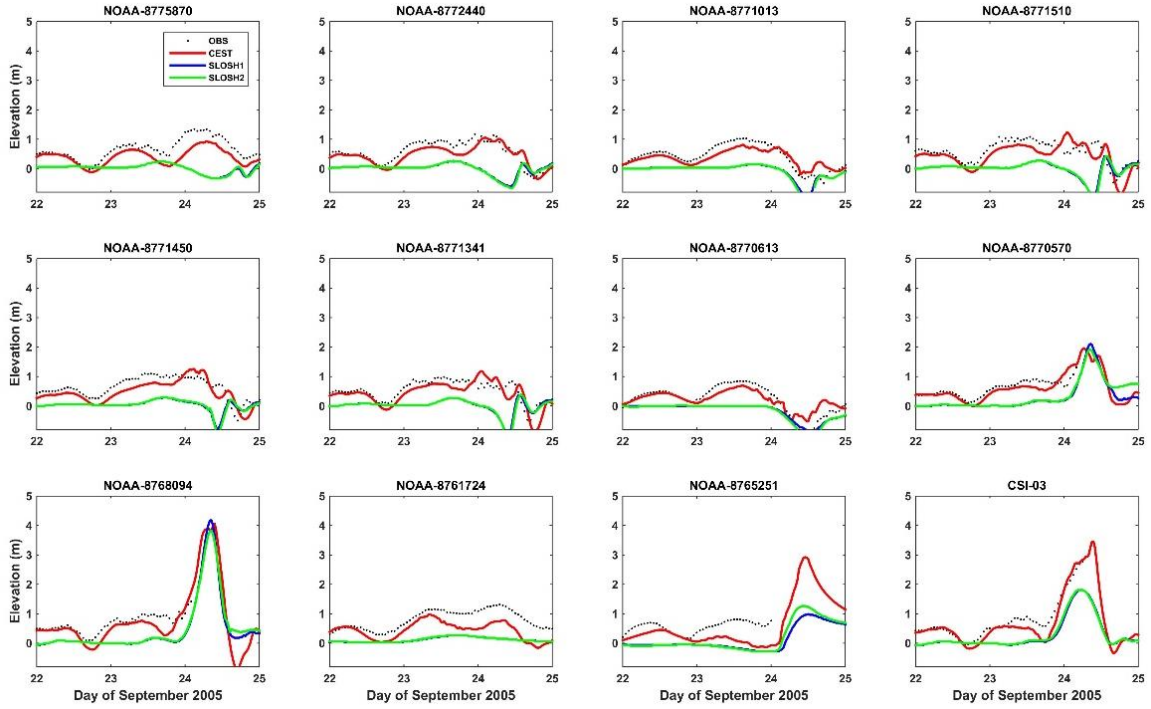
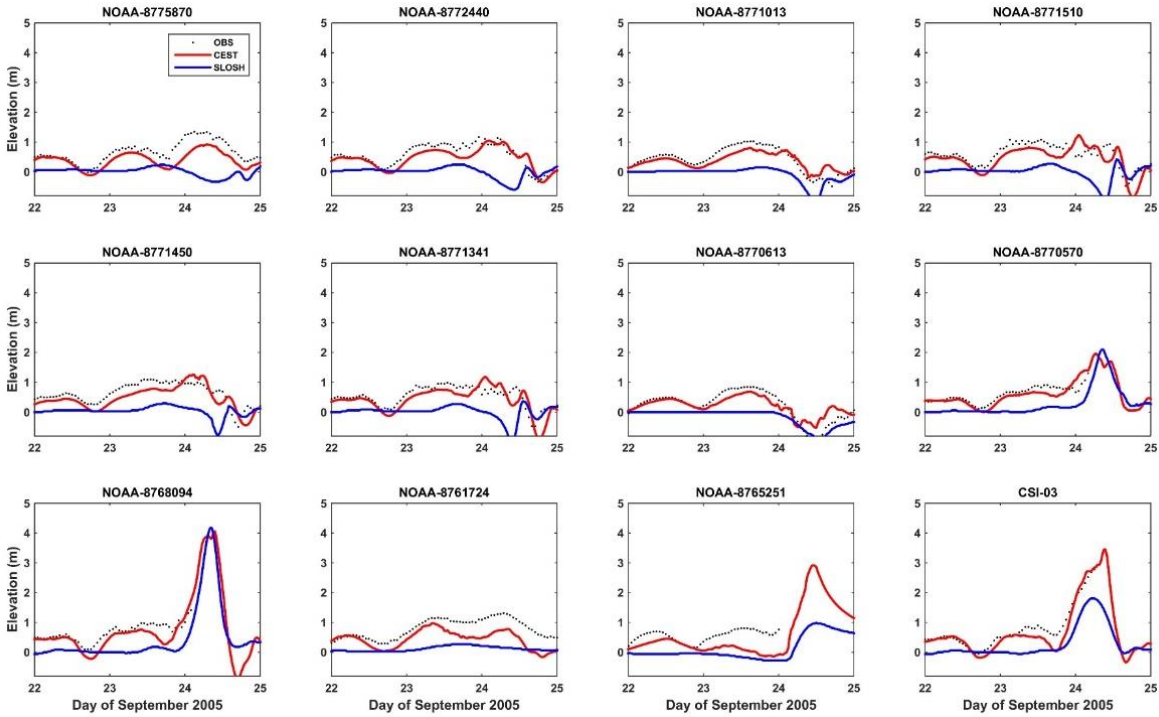


Fig. 3. Locations of 12 NOAA tide gauges, 16 USGS tide gauges, and cross sections 1 and 2.

The time series of computed storm tides indicates that CEST reproduced the patterns of measured storm tides well at all stations (Fig. 4a). The phases and amplitudes of the computed storm tides agreed with the measured ones. The computed storm surges by SLOSH (green line) did not match with observed ones at the stations with small storm surges such as stations 8775870 and 8772440 because the SLOSH simulation did not include the tidal component. Both CEST and SLOSH generated surges (green line) well at the four stations, 8770570, 8768094, 8765251, and CSI-03, where high storm surges occurred. SLOSH underestimated the peak surges at stations CSI-03, partially due to exclusion of the tidal component.

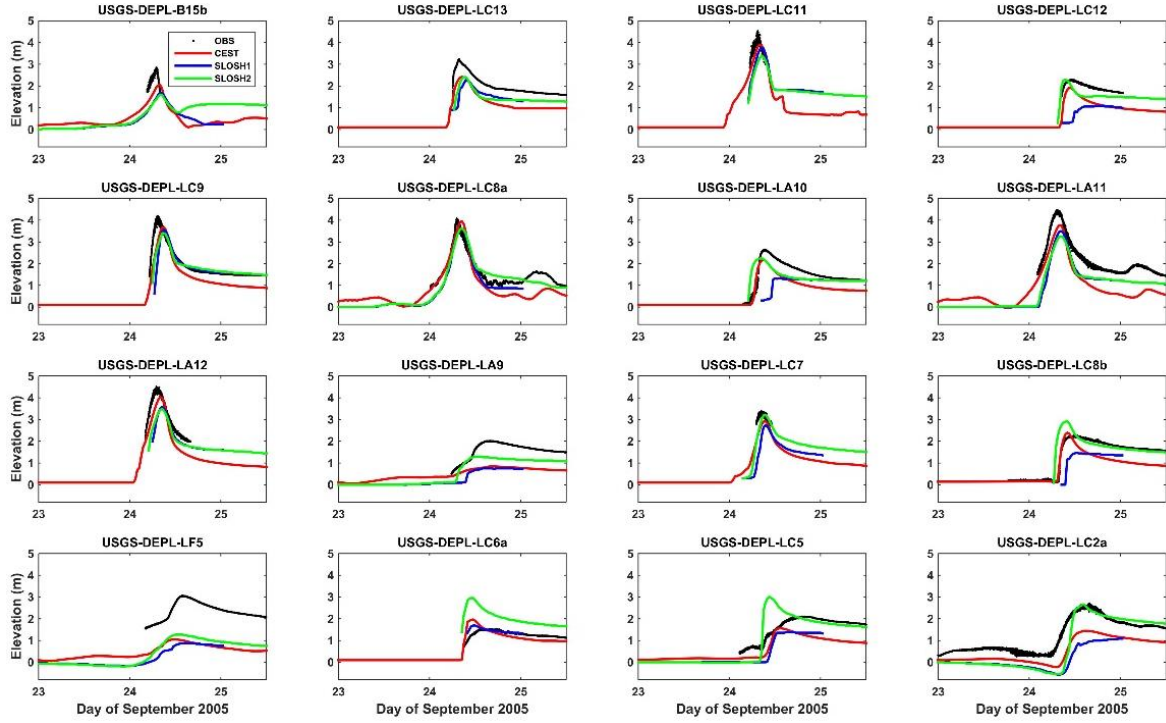


(a)

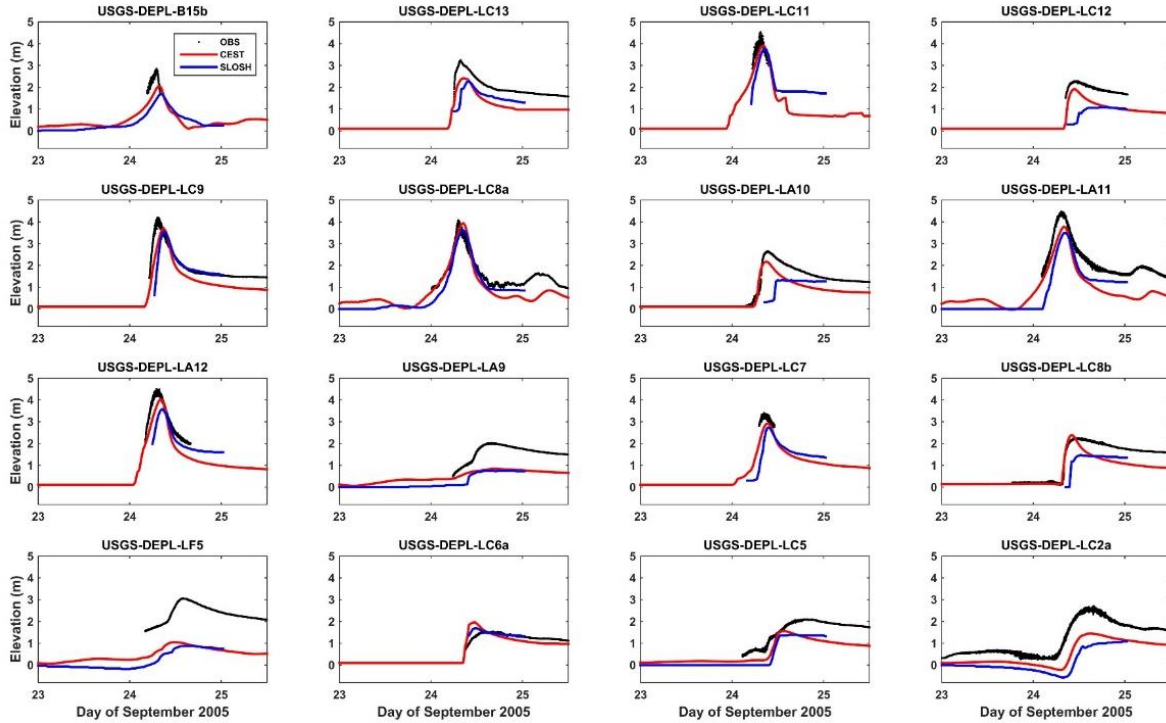


(b)

Fig. 4. (a) Computed storm surges by CEST (red), by SLOSH with the original slip coefficient (green), by SLOSH with the adjusted slip coefficient (blue), and measured water levels (black dots) at 12 NOAA stations during Hurricane Rita. (b) Comparison of computed storm surges by CEST (red), by SLOSH with the adjusted slip coefficient (blue), and measured water levels (black dots) for a sake of clarity.



(a)



(b)

Fig. 5. (a) Computed storm surges by CEST (red), by SLOSH with the original slip coefficient (green), by SLOSH with the adjusted slip coefficient (blue), and measured water levels (black dots) at 16 USGS stations during Hurricane Rita. (b) Comparison of computed storm surges by CEST (red), by SLOSH with the adjusted slip coefficient (blue), and measured water levels (black dots) for a sake of clarity.

The comparison of the storm tides for the stations on the land is also presented in Fig. 5a. The overall inundation processes were successfully simulated in terms of the time and amplitude, at most stations except two stations, USGS-DEPL-LA9 and USGS-DEPL-LF5. Both CEST and SLOSH (green line) underestimated surges at these two stations. SLOSH produced reasonable storm tides on the land, even the tide component was not considered in the simulation. SLOSH produced large overestimates at stations USGS-DEPL-LC6a and USGS-DEPL-LC5. This overestimate pattern is more obvious when the change of storm surge from the shore to inland is examined in the next section.

2.3 Comparison of Inundation Patterns of SLOSH and CEST

The computed maximum storm surges by SLOSH (green line) and CEST along two cross sections perpendicular to the shoreline and next to the landfall location were selected to compare the inundation pattern (Figs. 6 and 7). The CEST maximum storm surges reached largest at the shore and decayed landward gradually along cross section 1, while SLOSH maximum storm surge stayed almost constant inland from the shore (Fig. 6). The SLOSH maximum storm surge was slightly lower than CEST at the shore and much higher than CEST at the location from 25 to 60 km. At cross section 2, the similar pattern occurred for CEST and SLOSH (green line) simulations. The measured maximum storm surges from Hurricane Rita close to cross section 1 decayed distinctively inland from the shore (Fig. 8), matching the change pattern generated

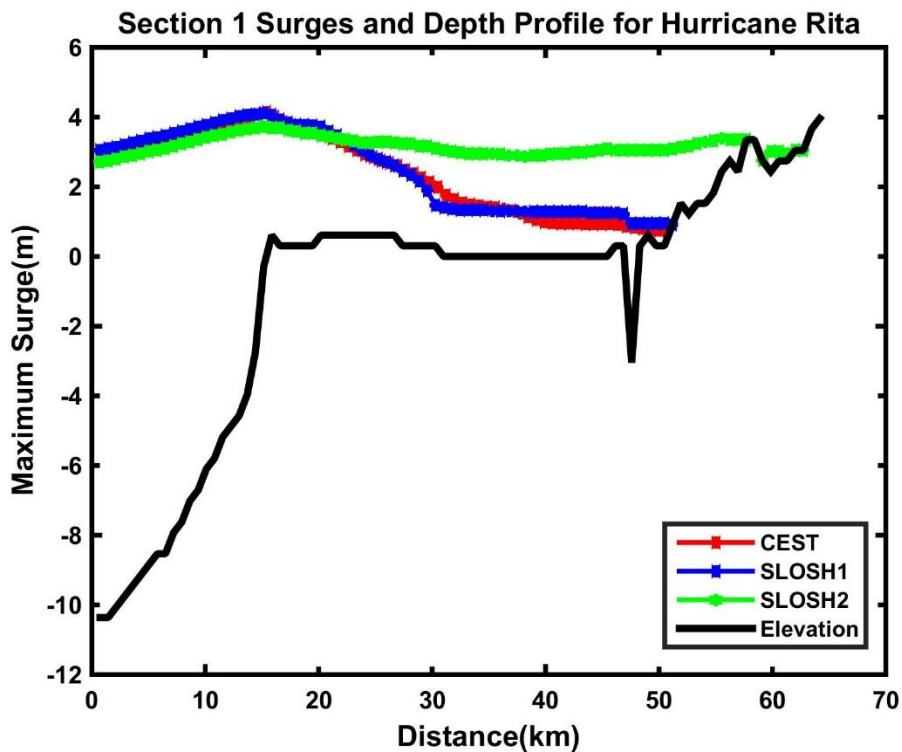


Fig. 6. The maximum surges by CEST, SLOSH with the original slip coefficient (green line), and SLOSH with the adjusted slip coefficient (blue) for Hurricane Rita along cross section 1.

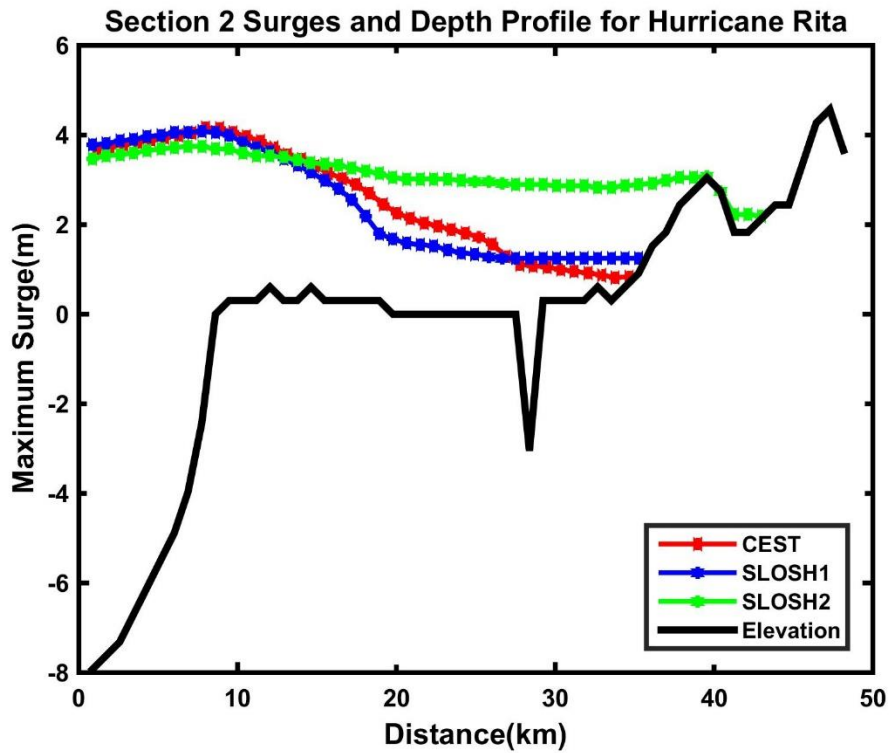


Fig. 7. The maximum surges by CEST, SLOSH with the original slip coefficient (green line), and SLOSH with the adjusted slip coefficient (blue) for Hurricane Rita along cross section 2.

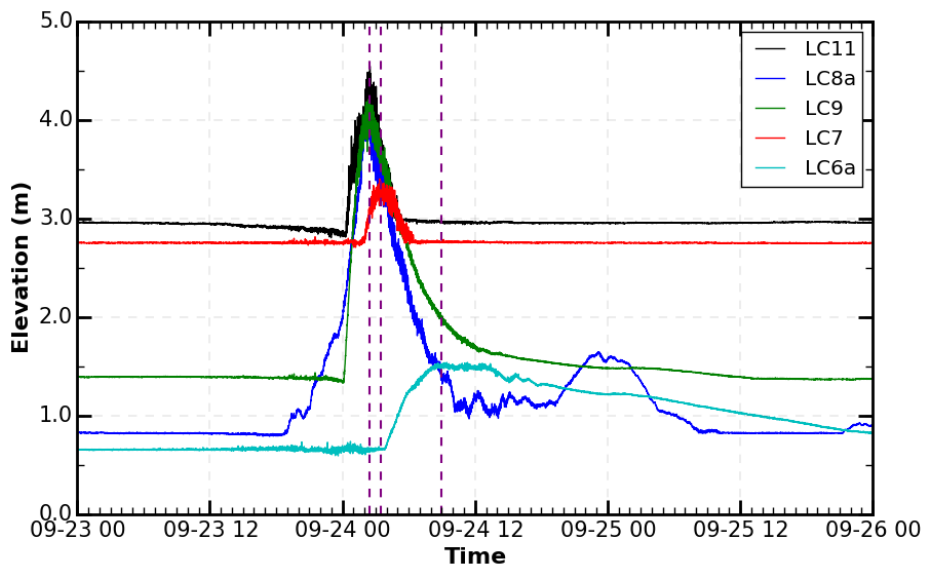


Fig. 8. The measured maximum storm surges from the USGS mobile gauges close to the cross section 1. The locations of the gauges are displayed in Fig. 3. The gauges are arranged inland (LC6a) from the shore (LC11).

by CEST. This indicates that SLOSH overestimated maximum storm surges over the flat land area by using the default slip coefficient which controls the magnitude of the bottom friction force. A constant SLOSH slip coefficient was employed for all SLOSH basins without considering the difference in bottom friction forces from various types of land cover because no land cover data were available when the SLOSH model was developed (Jelesnianski, 1992). The slip coefficient in SLOSH needs to be modified to reproduce the correct landward decay pattern of maximum storm surges in the near flat coastal areas. Thus, the Storm Surge Unit at NHC modified the slip coefficient for the TX3 basin based on the maximum storm surge map and water level time series generated by CEST. The maximum storm surges along cross sections 1 and 2 matching with CEST surges were successfully generated by SLOSH by using the adjusted slip coefficient (blue lines in Figs. 6 and 7). The time series of SLOSH storm surges at 16 USGS stations on the land also agreed with CEST better (Fig. 5b), while the time series of SLOSH storm surges with the adjusted slip coefficient did not differentiate much from the SLOSH time series with the original slip coefficient in the coastal water (Fig. 4a).

To further examine the effect of the slip coefficient on storm surges from SLOSH, the time series of computed storm surges at 20 grid cells along the cross section 1 were compared (Fig. 9). SLOSH with the original slip coefficient produced higher surge than SLOSH with the adjusted slip coefficient and CEST. The CEST and SLOSH with adjusted slip coefficient agreed well both in the magnitude and occurrence of time of the maximum surge. The surge heights from CEST and SLOSH with original slip coefficient decreased after the peak, in contrast, the surge heights from SLOSH with the adjusted slip coefficient did not reduce and are almost flat.

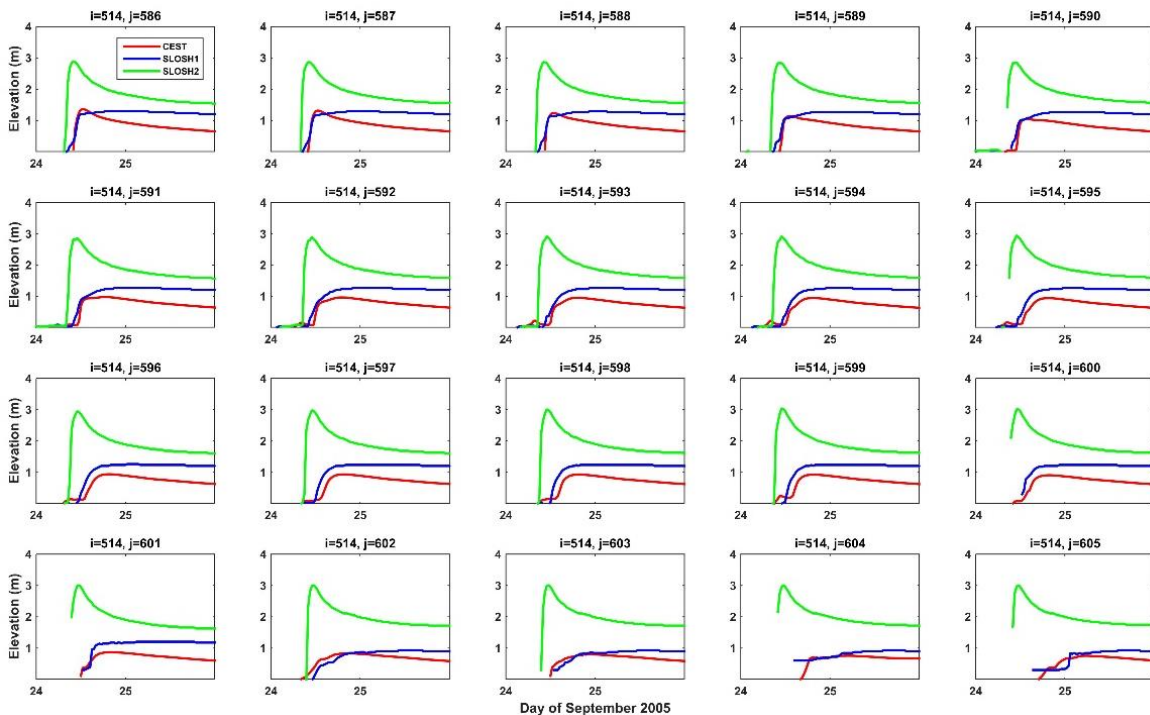


Fig. 9. Computed storm surges for Hurricane Rita by CEST (red), SLOSH with original slip coefficient (green), and SLOSH with adjusted slip coefficient (blue) along cross section 1. The index i is approximately in west-east (small to large) direction and j is in south-north (small to large) direction, respectively.

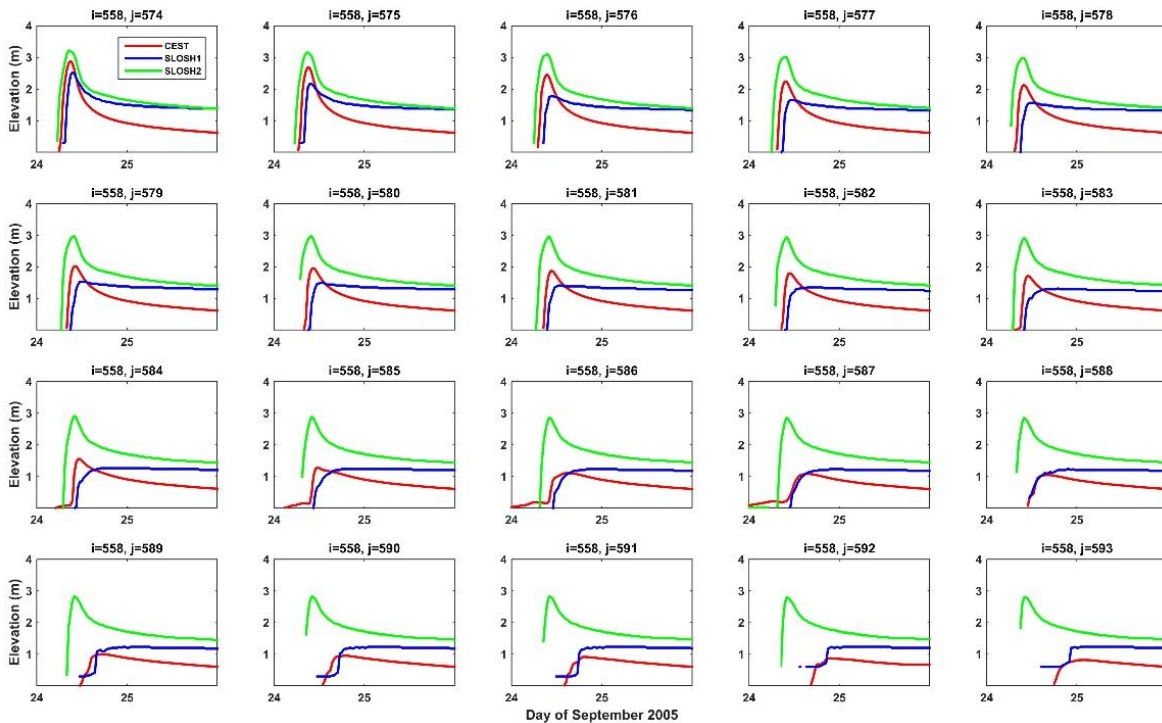


Fig. 10. Computed storm surges for Hurricane Rita by CEST (red), SLOSH with original slip coefficient (green), and SLOSH with adjusted slip coefficient (blue) along cross section 2. The index i is approximately in west-east (small to large) direction and j is in south-north (small to large) direction, respectively.

Fig. 10. Compares the time series of three simulations at 20 grid cells selected from the cross section 2. Similar to what occurred along the cross section 1, SLOSH with the original coefficient produced higher surge than SLOSH with the adjusted slip coefficient and CEST. The pattern of the gradual reduction of water level heights after the peaks showed in all CEST and SLOSH surges with the original slip coefficient, while only occurred in SLOSH surges with the adjusted slip coefficient from $j=574$ to $j=578$. Theoretically, storm surge heights should reduce gradually after reaching peak values typically associated with a maximum onshore wind as a hurricane passes by. The temporal surge pattern of SLOSH with the adjusted slip coefficient deserves a further study.

In summary, the landward decay pattern of maximum storm surges was verified by comparing computed storm surges with field measurements from Hurricane Rita in 2005. SLOSH with the original slip coefficient overestimates the magnitude and extent of overland flooding in the near flat coastal areas, while CEST reproduces the pattern matching with field observations. The SLOSH with the adjusted slip coefficient successfully generated an inland inundation envelope similar to CEST, but with a slower water receding process after the passage of the hurricane. Since storm surge products including MOEWs, MOMs, and P-Surges are all based on maximum storm surges, the adjustment of the slip coefficient for each basin by comparing SLOSH and CEST simulations provides a feasible way to reduce the overestimate of overland inundation in a

near flat coastal area by SLOSH that does not consider the effect of land cover on bottom friction against water flows. Therefore, in addition to real-time forecast, the direct utilization of CEST in the basin development and verification stage helps NHC develop better storm surge products. Even though this part of the research was not planned within the original proposal, the consequence and impact of the results demonstrate that it is well worth effort.

2.4 References

Jelesnianski, C. P., J. Chen, and W. A. Shaffer, 1992: SLOSH: Sea, lake and overland surges from hurricanes. Technical Report NWS 48, 71 pp.

Zhang, K., Y. Li, H. Liu, J. Rhome, and C. Forbes, 2013: Transition of the Coastal and Estuarine Storm Tide Model into an operational storm surge forecast model: A case study of the Florida Coast. *Weather and Forecasting*, 28, 1019-1037.

Zhang, K., Y., Li, and Y.C., Teng, 2016a. Progress Report of the Project “Transition of the Coastal and Estuarine Storm Tide Model to an Operational Model for Forecasting Storm Surges”, 09/01/2015-03/31/2016.

Zhang, K., Y., Li, and Y.C., Teng, 2016b. Progress Report of the Project “Transition of the Coastal and Estuarine Storm Tide Model to an Operational Model for Forecasting Storm Surges”, 04/01/2016-09/30/2016.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Drs. Keqi Zhang and Yuepeng Li at International Hurricane Research Center (IHRC) of FIU have worked on this project. Dr. Yi-cheng Teng resigned from this project on January 2017. The FIU team met the storm surge team of National Hurricane Center 5 times to discuss the project, deliver the product, and exchange the files and documents for the work of this stage. The FIU team also had conversations about the project including progress of the P-Surge with staff members of the Meteorological Development Laboratory twice through phone call and an in-person information exchange.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?

We conducted independent simulations of Hurricane Rita, participated in the verification of the new Texas basin (TX3), and presented the results on the effect of bottom friction on overland storm surge flooding to the Storm Surge Unit in NHC. The NHC surge team is generating MOEWs and MOMs for the TX3 basin using the adjusted slip coefficient in SLOSH.

What was the impact on other disciplines?

The integration of storm surge simulations with GIS improves our capability to process big spatial data such as high-resolution light detection and ranging (LiDAR) DEMs when we are building a geodatabase for developing the basin for Hurricane Rita.

What was the impact on the development of human resources?

Both junior scientists Drs. Yuepeng Li and Yi-Cheng Teng derived more experiences on storm surge modeling and data analysis.

What was the impact on teaching and educational experiences?

NA

What was the impact on physical, institutional, and information resources that form infrastructure?

NA

What was the impact on technology transfer?

NOAA will receive the CEST storm surge model for forecasting storm surges at the end of this project. Currently, SLOSH is the only real-time storm surge forecast model used by NHC. The CEST model will add an alternative model for cross-validation of SLOSH's forecasts and set a basis for producing ensemble surge forecasts using multiple models

What was the impact on society beyond science and technology?

An additional forecast model will help validate the NHC's storm surge inundation prediction affecting evacuation strategies and coastal flooding warnings.

What percentage of the award's budget was spent in a foreign country(ies)?

No budget was spent in a foreign country.

5. CHANGES/PROBLEMS

The task 2 "Developing CEST P-Surge" was delayed because of the investigation of the SLOSH and CEST difference in this period and the prolonged illness of the principal investigator.

6. SPECIAL REPORTING REQUIREMENTS

The Readiness Level for this project is assessed at RL4-RI5. All other items are covered in previous sections of this report.

7. BUDGETARY INFORMATION

The quantitative budget information is submitted separately in the Federal Financial Report. There are no major budget anomalies or deviations from the original planned budget.

8. PROJECT OUTCOMES

The CEST storm surge forecasting system will be transferred to NHC and operated within the organization after the completion of this project