Hydrodynamic response to bathymetric changes in Tampa Bay, Florida

Jing Chen[a,*], Yonggang Liu[a], Robert H. Weisberg[a], Steven A. Murawski[a], Sherryl Gilbert[a], David F. Naar[a], Lianyuan Zheng[a], Matthew Hommeyer[a], Catherine Dietrick[a], Mark E Luther[a], Cheryl Hapke[a], Edward Myers[b], Saeed Moghimi[b], Corey Allen[b], Liujuan Tang[b], Bahram Khazaei[b], Shachak Pe'eri[c], Ping Wang[d]

[a]*College of Marine Science, University of South Florida, St. Petersburg, FL 33701*

[b]*Coast Survey Development Laboratory, Office of Coast Survey, National Ocean Service, NOAA*

[c]*Geosciences Research Division, National Geodetic Survey, National Ocean Service, NOAA*

[d]*School of Geosciences, University of South Florida, Tampa, FL 33620*

*Corresponding author.

E-mail address: jchen15@usf.edu (J. Chen).

Highlights

- The Hydrodynamic response to bathymetric changes is investigated for Tampa Bay.
- Numerical experiments are conducted using original and synthetic bathymetry.
- Local changes in tides and currents are found due to bathymetric changes.
- These local changes can propagate throughout the bay.
- Accurate bathymetry is essential for coastal ocean modeling applications.

ABSTRACT

Bathymetric changes within estuarine and coastal waters can alter the hydrodynamic evolution of sea level and currents, which in turn can influence the ecosystem by altering material property distributions. Here we apply the Tampa Bay Coastal Ocean Model (TBCOM), with an unstructured, high-resolution grid to investigate the hydrodynamic response to bathymetric changes at the periphery of the Tampa Bay mouth over a relatively small area when compared to the whole model domain. Two separate numerical experiments are conducted with the same forcing, one using the original bathymetry and the other employing a revised synthetic bathymetry. The simulated sea level, amplitude and phase of the M2 tide, and associated currents are compared for the two experiments. Significant changes in water level (up to +/-10 cm) and current velocities (up to 20 cm/s) are found in the shallow peripheral area with the two different bathymetric data sets. These bathymetric influences are not limited to the locations where the bathymetric changes occur; they also extend remotely to areas of the bay. Since Tampa Bay bathymetry varies with storm-induced sediment redistributions and human actives such as shipping channel dredging and beach nourishment, these findings emphasize the need for accurate and updated bathymetry for coastal ocean modeling and applications.

Keywords   Numerical Model, Water level, Coastal ocean circulation, Sensitivity study, Bathymetry

1. Introduction

Coastal areas have rapidly growing populations, with approximately 3 billion people already living within 200 kilometers of the coastline (Creel 2023). As of 2014, United States coastal counties housed 127 million people, which is as much as the entire population of Japan (NOAA's National Coastal Population Report: Population Trends from 1970 to 2020, https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/facts/coastal-population-report.pdf). While containing nearly 40% of the United States population, coastal counties account for less than 10% of the total continental United States land mass. With economies fueled by tourism and recreation, marine commerce, aquaculture and offshore energy, coastal communities face challenges from sea level rise, high-tide flooding, beach erosion, waste disposal and hurricanes, all of which require adequate modeling systems for assessing environmental impacts of both natural and human-induced changes (e.g. Amoudry and Souza,2011).

Essential to any coastal ocean or estuary model is accurate underlying bathymetry. Local bathymetric changes may produce changes in tide and wind-driven response magnitudes (Talke et al., 2014; Orton et al., 2015). The bathymetry of the continental shelf can affect the coastal and estuarine processes through the complex linkage between the small-scale processes and the large-scale dynamics from the deep ocean (e.g. Ezer, 2013; Weisberg et al., 2014).

The impacts due to bathymetric changes are difficult to estimate analytically given the geometric complexity of most coastal and estuarine regions; hence the need for numerical circulation models. Examples for Tampa Bay include Weisberg and Zheng (2006) and Meyers et al. (2008). Infrastructure effects such as causeways were investigated by Meyers et al. (2013, 2017) and Zhu et al. (2015) using a much higher resolution model to assess the effects of channel deepening and widening on the Tampa Bay hydrodynamics. Elsewhere, Familkhalili and Talke (2016) showed the amplification of both tides and storm surge, which is influenced by reduced hydraulic drag caused by greater mean depths. Using smoothed bathymetry, Ye et al. (2018) highlighted the central role played by bathymetry in the hydrodynamic variables of the Chesapeake Bay estuarine system. Ralston et al. (2019) discovered that the deepening and straightening of channels causes a reduction in friction and reduces the overall risk of flooding in certain parts of Hudson River estuary. Zhang et al. (2021) found that the changes in the bathymetry at the mouth of the Changjiang Estuary can affect the circulation patterns throughout the estuary.

Tampa Bay (Fig. 1) is an active area of sediment transport, erosion, and sedimentation caused both by natural processes (e.g. Berman et al., 2005; Westfall et al., 2018; Rodgers et al., 2018) and human activities (e.g. Wang et al., 2009, Wang et al., 2011, Roberts and Wang, 2012). A newly formed Center for Ocean Mapping and Innovative Technologies (COMIT) at University of South Florida is developing new approaches to effectively map the coastal zones, leading to improved high-resolution modeling, to help build resilient coastal ecosystems, communities, and economies.

As part of COMIT, the Tampa Bay Coastal Ocean Model (TBCOM) (Chen et al., 2018, 2023b) serves as a hydrodynamic application tool. TBCOM employs the unstructured grid (Fig. 2) Finite Volume Community Ocean Model (FVCOM, Chen et al., 2003) with a resolution high enough to include Tampa Bay, Sarasota Bay, the Intra-Coastal Waterway and all of the interconnected inlets that provide access to the adjacent Gulf of Mexico. To include the effects from the Gulf of Mexico, TBCOM is nested in the West Florida Coastal Ocean Model (WFCOM; Zheng and Weisberg, 2012; Weisberg et al., 2014), which FVCOM-based gets its open boundary values from the Global Hybrid Coordinate Ocean model (HYCOM). Previous and recent applications of FVCOM to estuaries and lakes are extensive (e.g. Chen et al., 2009; Huang et al., 2011; Mao et al., 2020; Chen, 2021; Sahoo et al., 2021; Li et al., 2022; Mou et al., 2022; Ge et al., 2022; Zhou et al., 2023).

Here we employ TBCOM to investigate the effects of bathymetric changes near the mouth of Tampa Bay on the circulation throughout the entire Tampa Bay. The remainder of the paper is organized as follows: Section 2 describes the data and methods, including general information of study area, TBCOM, and the experimental design. Section 3 provides the experimental results. Section 4 then discusses the results and summarizes the findings.

2. Data and methods

2.1 Bathymetric data

The original topographic (elevation and bathymetry) data set used by TBCOM was compiled by National Oceanic and Atmospheric Administration (NOAA) and United States Geological Survey (USGS, Hess, 2001) with a resolution of 30 m (Fig. 1). The vertical reference frame, tidal datum field of this data set was generated by a combination of a circulation model and spatial interpolation. The datum field was then interpolated to a uniform grid and referenced to mean lower low water (MLLW).

In order to investigate the sensitivity of TBCOM to bathymetric changes, a new bathymetric grid was used in place of the original NOAA-USGS data in this area. The new grid includes newly collected bathymetric data for Boca Ciega Bay, two inlets to the Gulf, and a portion of lower Tampa Bay (courtesy of Dr. Ping Wang and students) (Fig. 3). These data were collected using a narrow single-beam shallow water Odem echo sounder and DGPS during high tides, using a mean sea level (MSL) vertical chart datum. These newly collected data were then supplemented with surrounding bathymetric data of unknown source, to form a new grid for comparison. The chart datum(s) for the remaining portions of the new grid is uncertain. Thus, with the discrepancy of data sources for the new grid, one must view these data as “synthetic” data that were used for a sensitivity test. Some of the differences in bathymetric data between the original and the synthetic bathymetry maps may be real, but others may be artifacts, to be corrected as new, datum controlled data become available.

2.2. Tampa Bay Coastal Ocean Model

Numerical circulation models for Tampa Bay started with two-dimensional barotropic applications (e.g. Goodwin, 1980, 1987, 1989; Ross, 1973; Ross et al., 1984). Galperin et al. (1991, 1992) were the first to investigate fully three-dimensional, time, and density dependent circulation utilizing the Princeton Ocean Model (POM) of Blumberg and Mellor (1987). This was followed by further applications of slightly modified POM versions by Vincent et al. (2000), Meyers et al. (2007), Meyers and Luther (2008), followed by a Regional Ocean Model System (ROMS, Haidvogel et al., 2008) by Zhang and Wei (2010). All of these initial, baroclinic applications derived their open boundary values at or near the bay mouth and therefore, with the exception of tides, lacked interactions with the adjacent Gulf of Mexico.

To include the effects of the adjacent Gulf of Mexico, Weisberg and Zheng (2006) applied FVCOM with horizontal resolution as fine as 300 m to include the various connecting inlets, adjacent Sarasota Bay, and the Intra-Coastal Waterway. This model was further refined (to have resolution as fine as 20 m) to resolve all of the inlets connecting these water bodies with the Gulf of Mexico and the main shipping channel (Zhu et al., 2015a, 2015b, 2015c; Chen et al., 2019).

Estuaries are heavily influenced both by terrestrial-based water bodies and the open ocean (e.g. Raimonet and Cloern, 2016). Freshwater inflows from rivers and land runoff establish the salinity gradient that drives the estuarine circulation (e.g. Hansen and Rattray, 1965; Geyer and MacCready, 2014), create nutrient distributions (e.g. Damme et al., 2005) and support ecological diversity (e.g. Feyrer et al., 2015). Across-shelf transport via upwelling and downwelling circulations, caused either by local winds or deeper ocean interactions, connect the estuary with the continental shelf and the deeper ocean (e.g. Weisberg, 1976; Wang and Elliot, 1978; Weisberg and He, 2003; Weisberg and Liu 2022).

TBCOM is designed to include influences from both the land and the ocean. The estuary and adjacent Gulf of Mexico portion of the TBCOM is based in the Zhu et al. (2015a, b, c) and the Chen et al. (2019) model applications. For the land component, daily river discharges are downloaded from the USGS (https://waterdata.usgs.gov/nwis) and input to the model. By nesting into WFCOM, TBCOM includes the continental shelf and the deeper ocean connections. Thus, TBCOM downscales from the deep ocean, across the continental shelf and into the estuaries. The astronomical tides are included in the open boundary forcing of WFCOM. Other local forcing includes surface winds and heat fluxes provided by the NOAA NCEP NAM (National Oceanic and Atmospheric Administration's National Centers for Environmental Prediction North American Mesoscale Forecast System) with spatial and temporal resolutions of 12 km and 3 hr, respectively. Data assimilation presently includes nudging of the sea surface temperature (SST) to the satellite derived Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA, Donlon et al., 2012) daily SST product to correct for possible systematic temperature drifts caused by the net surface heat flux biases (e.g. Virmani and Weisberg, 2005). Nudging is a form of data assimilation method used in ocean modelling, whereby the model is gently pushed towards a known state over time. This method has been widely used in ocean data assimilation (e.g. Holland and Malanotte-Rizzoli, 1989; Malanotte-Rizzoli and Young, 1992; Abbasi et al., 2018). The nudging scheme of FVCOM is described in Chen et al. (2006). Finally, after implementing daily, automated nowcasts, and 3.5 day forecasts, TBCOM was established in September 2017 and has run unabated ever since. The veracity of TBCOM has been tested using comprehensive in situ observations (Chen et al. 2018, 2023b). TBCOM is used to assess the responses of the Tampa Bay estuary to either naturally occurring (e.g. Beck et al., 2022; Chen et al. 2018b, 2020, 2022; Liu et al., 2017, 2022, 2023) or anthropogenic (Liu et al., 2021; Chen et al. 2023a) perturbations. The TBCOM hindcast products also have been used to support the studies of an anchored spar-buoy seafloor geodetic system at the mouth of Tampa Bay (Xie et al. 2019, 2021).

2.3. Experimental design (sensitivity study)

The coastal regions are subject to high energy events that transport sediment and quickly change the depth structure of navigable waterways. The objective of this research is to determine how the coastal and estuary circulation near and within Tampa Bay may react to bathymetric changes. Thus, two numerical experiments conducted over a two month duration (February 1, 2018 to March 31, 2018) were run: one with the original bathymetry data supplied by USGS and NOAA and the other using synthetic bathymetry data for the relatively shallow region near Boca

Ciega Bay and Fort DeSoto Park, FL on the northern side of the Tampa Bay mouth (Fig. 3). The initial conditions are a restart file saved from the TBCOM hindcast results on January 31, 2018. To allow for an adjustment to the synthetic bathymetry, we discarded the first month of simulation (February 1, 2018 to February 28, 2018) by which time the flow field was fully adjusted. The model results for the following month (March 1, 2018 to March 31, 2018) were used to diagnose the results.

3. Results

This section compares model results from the two experimental runs, each with a different bathymetry for the region shown in Figure 3. The comparisons include both water level and currents.

3.1. Water *L*evel

Due to its generally shallow depths and low land elevations, the Tampa Bay region is highly sensitive to both sea level and depth changes. Figure 4 shows the differences of the simulated water level for the two experiments instantaneously sampled at 1:00 UTC Mar 1st, 2018. Obvious changes (-10 to 10 cm) are noted in areas where the bathymetry data are significantly different. In the momentum equation, the friction term can be linearized to be proportional to Cd/H (e.g. Jay, 1991; Friedrichs and Aubrey, 1994; Familkhalili and Talke, 2016), where Cd is the linearized drag coefficient and H is the depth. The change in water depth alters bottom friction, affecting both water level amplitude and phase propagation. Despite the localization of the changes in bathymetry, differences in sea level, albeit small at about 1 cm, occur throughout the bay due to propagation away from the region where the bathymetry changes were made.

Being that tides are the dominant contributor to water level and currents within Tampa Bay, we assess how the localized bathymetric changes affected the M2 tidal constituent throughout the bay. This was done by calculating the amplitude and phase for the M2 tide at all of the 115369 node points within the model domain using the least squares harmonic analysis method of Foreman (1977).

Figure 5 compares the amplitude and phase of the M2 tide with the two different bathymetries over the region where they changed. The amplitude of M2 tide is generally between 20 to 25 cm (Fig. 5a and 5b). Within the shallow region of Fort DeSoto Park, we see a decrease in amplitude where the synthetic bathymetry is shallower (Fig. 3). Farther to the north, the V-shaped region of Long Bayou (Fig. 1), where the bathymetry did not change, also shows a decrease in the M2 amplitude. This is attributed to shallower water depths within the Intra-Coastal Waterway to the south of Long Bayou. Thus, upstream bathymetric changes can affect downstream tidal variations. Along with amplitude changes, phase changes are also evident, as shown for the M2 tide (with the original and the synthetic bathymetry data) in Figures 5d, and 5e, respectively. The phase differences (Fig. 5f) are as large as 30°owing to location-dependent changes in propagation speeds. This finding is consistent with both theoretical and realistic studies in other estuaries (e.g. Friedrichs and Aubrey, 1994; Friedrichs, 2010; Chant et al., 2018). The change in the bottom friction can cause the change the tidal energy flux (Ralston et al., 2018). The convergence or divergence of tidal energy flux will end up with the change in tidal amplitude and phase.

Given these localized changes Figure 6 extrapolates these over the entirety of Tampa Bay. While not large, the M2 tide amplitude and phase changes are not insignificant either. The increased drag by decreased depth even over a relatively small portion of the bay near its mouth imposes an amplitude change of around 0.5 cm over most of the bay. The phase also changes by a few degrees.

The differences between the two sets of harmonic constants including amplitude and phase for two experiments are also calculated as complex distance (or complex error) in the complex plane (Foreman et al. 1993; Huang et al. 2022); that is,

$$Complexdistance = \sqrt{\frac{\left(\left(A_1 cosP_1 - A_2 cosP_2\right)^2 + \left(A_1 sinP_1 - A_2 sinP_2\right)^2\right)}{2}}$$

where A_1 and A_2 are modeled tidal amplitudes with synthetic and original bathymetry, respectively, and P_1 and P_2 are modeled tidal phases with synthetic and original bathymetry, respectively. We can also see the complex distances of M2 tide between the two experiments are larger in the area with synthetic bathymetry data. Inside Tampa Bay, the distances range from 0.5 to 0.6 cm (Fig. 7).

Figure 8 compares the amplitude and phase of the K1 tide with the two different bathymetries over the region where they had changed. The K1 tide amplitude is generally smaller than M2 tide (Fig. 8a). Similar to M2 tide, K1 tidal amplitude and phase changes throughout the bay due to the difference in the bathymetry. Amplitudes and phases of other tidal constituents will also be altered by changes of bathymetry. Further investigations will eventually be conducted using new (versus synthetic) data being collected by COMIT.

3.2. Currents

Figure 9 presents the one-month average of depth-averaged velocities in the area with synthetic bathymetry (Fig. 9a), the difference in time and depth-averaged current velocities (Fig.

9b) between the two experiments, and the magnitude of these differences (Fig. 9c) near Fort DeSoto Park. We can see that the magnitude of time and depth-averaged currents are generally less than 10 cm/s (Fig. 9a). The depth-averaged currents are stronger at the locations with complex constrictions such as tidal inlets, narrow areas of intra-coastal waterways, and shipping channels. In these regions, the magnitude can be as large as about 20 cm/s. The change of the current velocities and their magnitudes (Fig. 9b and 9c) are larger in the area with synthetic bathymetry, especially near narrow channels such as those at tidal inlets. At some locations within a narrow channel, the magnitudes of the velocity changes may be larger than the original magnitude of velocity itself.

Figure 10 shows the same variables as Figure 9 over the entire Tampa Bay region of interest. The changes in currents inside Tampa Bay are not as significant as areas with the synthetic bathymetry data. But we can still see a relatively large change of current magnitude in the area (Fig. 10c) following the shipping channel and constrictions form a complex geometry as shown in Figure 1. This is mainly because the area with synthetic bathymetry data is near the shipping channel and the stronger current in the channel and the area with complex geometry (Chen et al., 2019) when compared with the other areas. This again demonstrates the importance of the accurate bathymetry in coastal ocean modeling.

Recognizing that instantaneous and averaged current velocities may differ, the instantaneous surface currents with synthetic bathymetry data and the vector of difference between the two experiments near the area with new data and the entire Tampa Bay region at 1:00 UTC Mar 1st, 2018, are shown in Figures 11 and 12, respectively. Figure 13 provides the magnitude of the difference in surface currents between the two experiments at the same time. There are significant differences in simulated current velocities due to bathymetric changes near the area with synthetic bathymetry data. The differences of currents between two experiments can be as large as the currents, and sometimes even larger than the currents because of small tidal phase differences. The maximum velocity difference exceeds 50 cm/s. Since the synthetic bathymetric data covers a part of the shipping channel, the bathymetry changes in that part of the shipping channel could cause differences in ocean currents locally (between the two numerical experiments). Any changes of currents in the shipping channel may propagate along the deep channel network and spread to the upper Tampa Bay area.

4. Discussion and conclusions

We used the Tampa Bay Coastal Ocean Model (TBCOM) to investigate the sensitivity of a very high resolution, estuarine hydrodynamic model to variations in localized bottom bathymetry. This is important because relatively shallow regions frequently lack high resolution bathymetry, and even where such data may exist, sedimentation and dredging may alter the bathymetry on short and episodic time scales. Understanding and accurately quantifying estuarine circulation and water levels are critical for maritime transportation and commerce, coastal flooding and risk, and ecosystem services. Therefore, it is prudent to assess how prone these variables may be to alterations in bathymetry.

With horizontal resolution as fine as 20 m, TBCOM derives its open boundary values from the West Florida Coastal Ocean Model (WFCOM), which in turn derives its open boundary values from the Hybrid Coordinate Ocean Model (HYCOM), thereby downscaling from the deep ocean, across the continental shelf and into Tampa Bay. The original bathymetry for TBCOM harkens back to a joint NOAA-USGS product compiled in 2001. More recent, localized bathymetry data merged into a synthetic data grid provided an opportunity to assess the sensitivity of Tampa Bay sea level and currents to localized variations in bathymetry, especially over relatively shallow areas near the bay mouth. This was completed by running two separate simulations, one with the original bathymetry, the other with the synthetic bathymetry, thereby focusing on how these two different simulations express the M2 tide constituent amplitude and phase, both locally and throughout the bay.

Local differences were found to be significant, especially where the water depths are shallowest. By altering the relative importance of bottom drag, both the amplitude and phase of the M2 tide are altered. Being that the bathymetric changes occur near the mouth of Tampa Bay, the modifications to the M2 amplitude and phase also propagated throughout the bay, albeit at relatively small magnitudes (less than a 1 cm in amplitude and only a few degrees in phase). Nonetheless, for shallow estuaries synthetic bathymetry data (with well constrained uncertainties in depth, position, and vertical datum used) may be significantly different and improved with respect to previous bathymetry data of unknown origin, unknown uncertainties, and unknown vertical datum used at the time of the original collection. The results of our sensitivity test confirm that it is important to have these model-underpinning bathymetry data as accurate as possible. Not only is this important for water level and currents, but also for any scalar variables, if mixed over the water column, as usually occurs in shallow water, that will be diluted based on water depth. Thus, it is not possible to accurately assess salinity, or anything else of ecological importance if the underlying water depth itself is not accurately known. Moreover, since all water properties, including sediments, pollutants, nutrients, fish larvae, etc., are affected by the circulation, the hydrodynamic response to bathymetric change has ramifications beyond the estuarine hydrodynamics themselves. For these reasons, accurate updates of estuarine bathymetry are a necessary part of any estuarine environmental support program, especially in areas prone to erosion or redeposition, or anthropogenic activities such as dredging or beach nourishment.

Acknowledgments:

This project was supported by NOAA Office of Coast Survey through the Center for Ocean Mapping and Innovative Technologies (COMIT, award NA20NOS4000227), NOAA/IOOS through the Southeast Coastal Ocean Observing Regional Association (SECOORA, award NA21NOS0120097), State of Florida Department of Environmental Protection (agreement # AT007), and State of Florida through FWC/FWRI (agreement # 20035). This work used Stampede2 at TACC through allocation OCE170007 from the Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS) program, which is supported by National Science Foundation grants #2138259, #2138286, #2138307, #2137603, and #2138296 (Boerner et al., 2023). All of the data used in the analyses are available through the sources cited in the text.

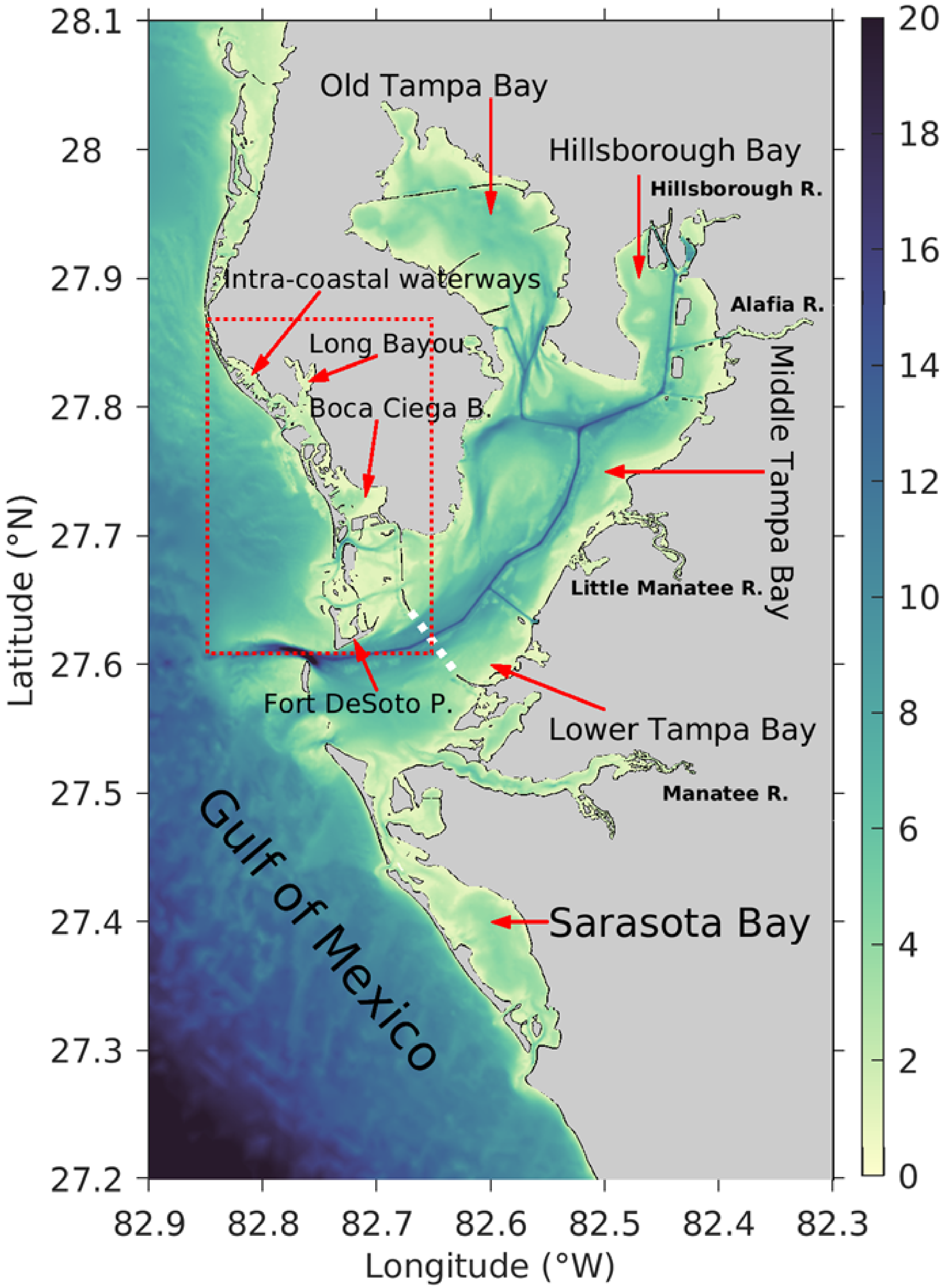

Fig. 1. The major structural features and subregions of Tampa Bay, with color-coded bathymetry (units in m). The area with updated bathymetry data is indicated by the red box.

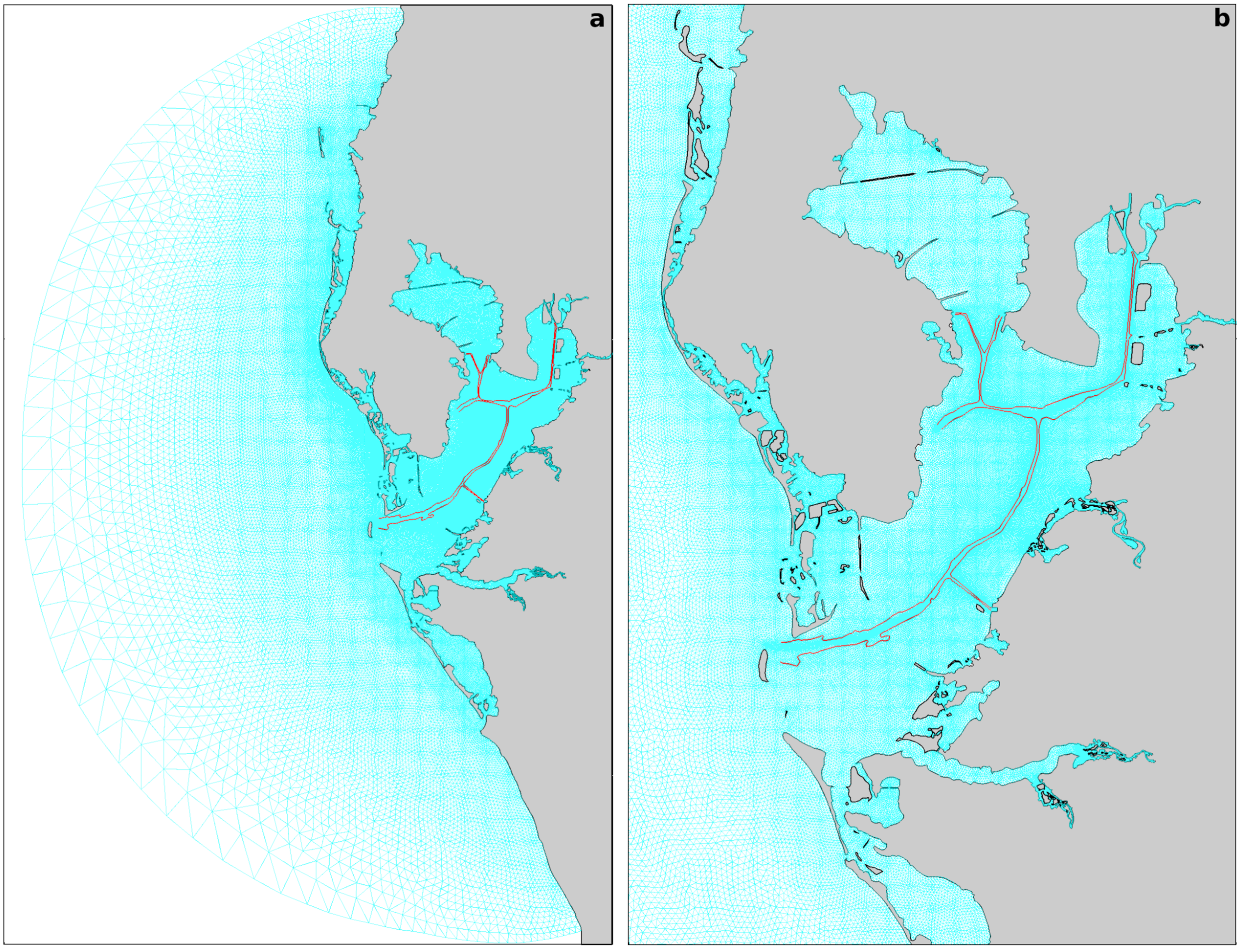

Fig. 2. The TBCOM grid (a) and zoomed views of Tampa Bay regions (b). The red lines indicate the shipping channel.

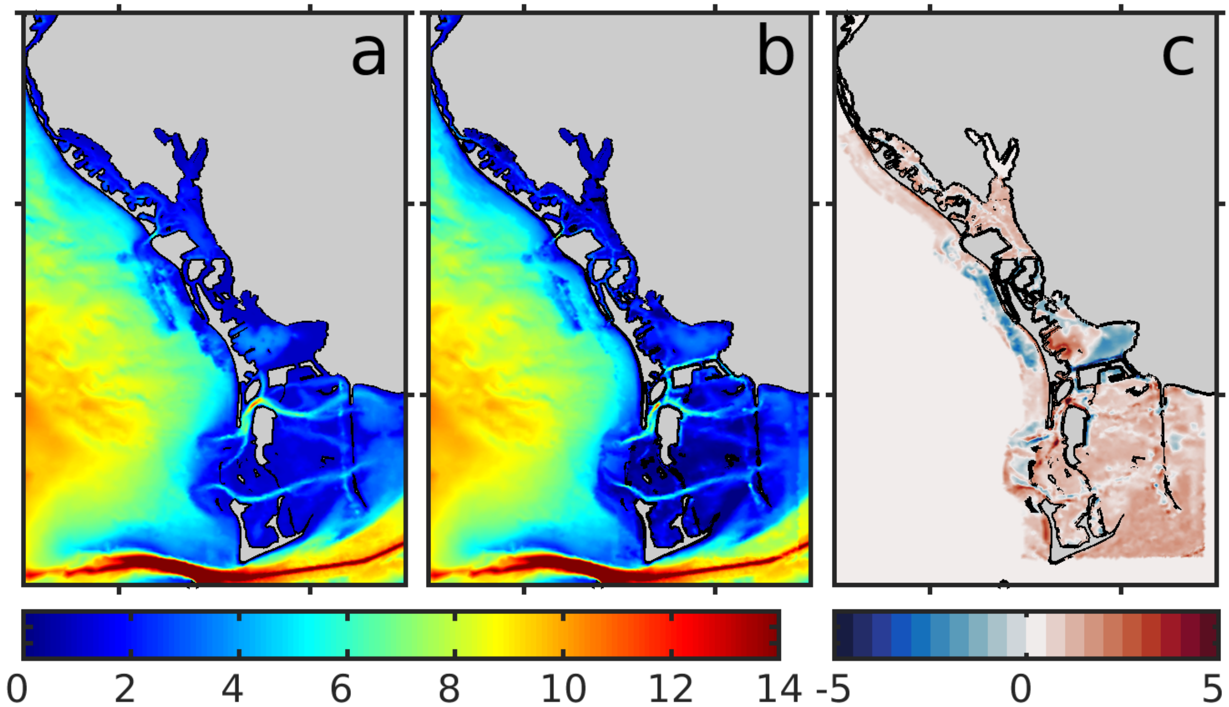

Fig. 3. Original bathymetry from USGS and NOAA(a), synthetic bathymetry (b), and the difference between two bathymetric data (c) (units in m).

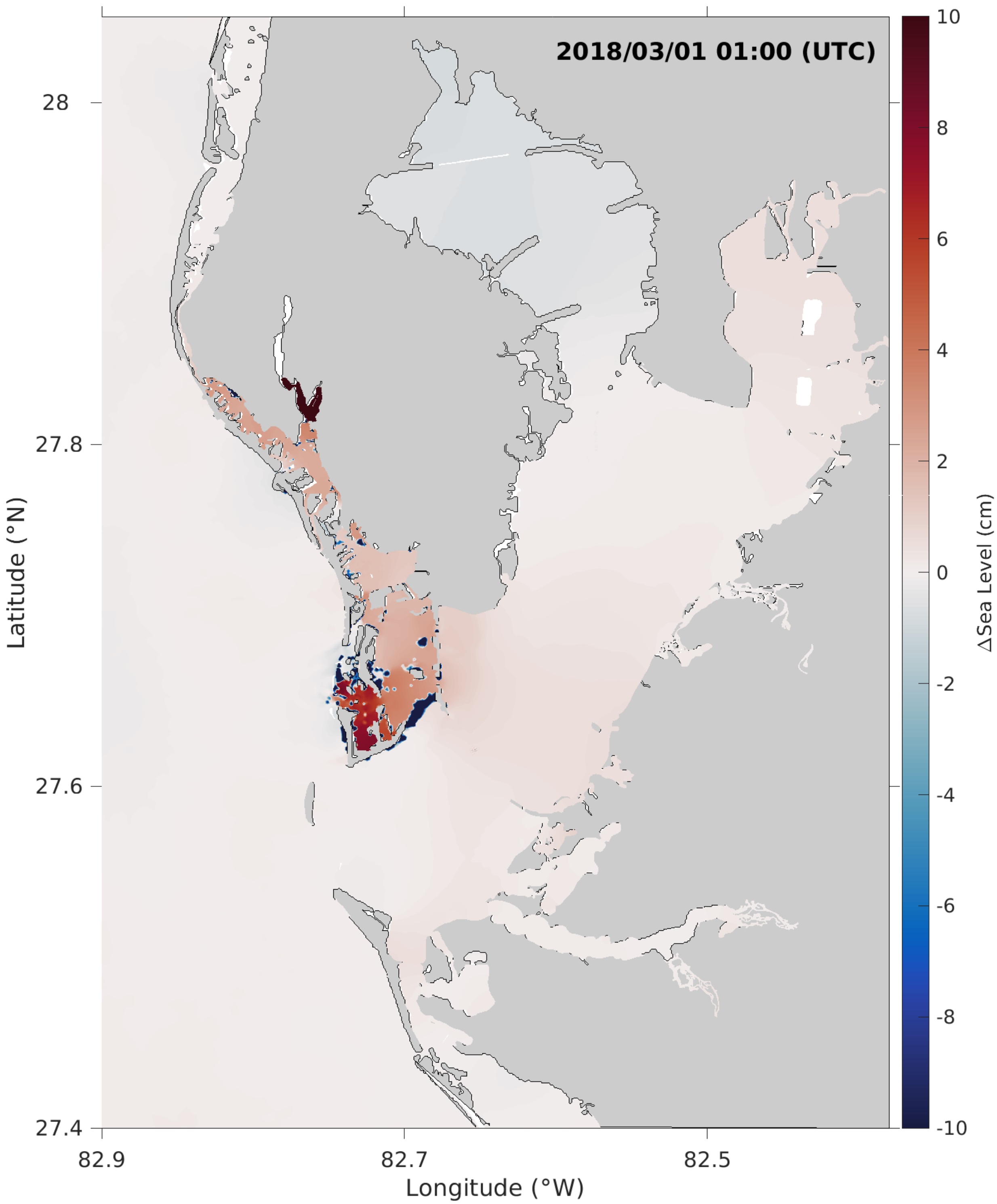

Fig. 4. The water level difference between two experiments at 1:00 Mar 1st 2018.

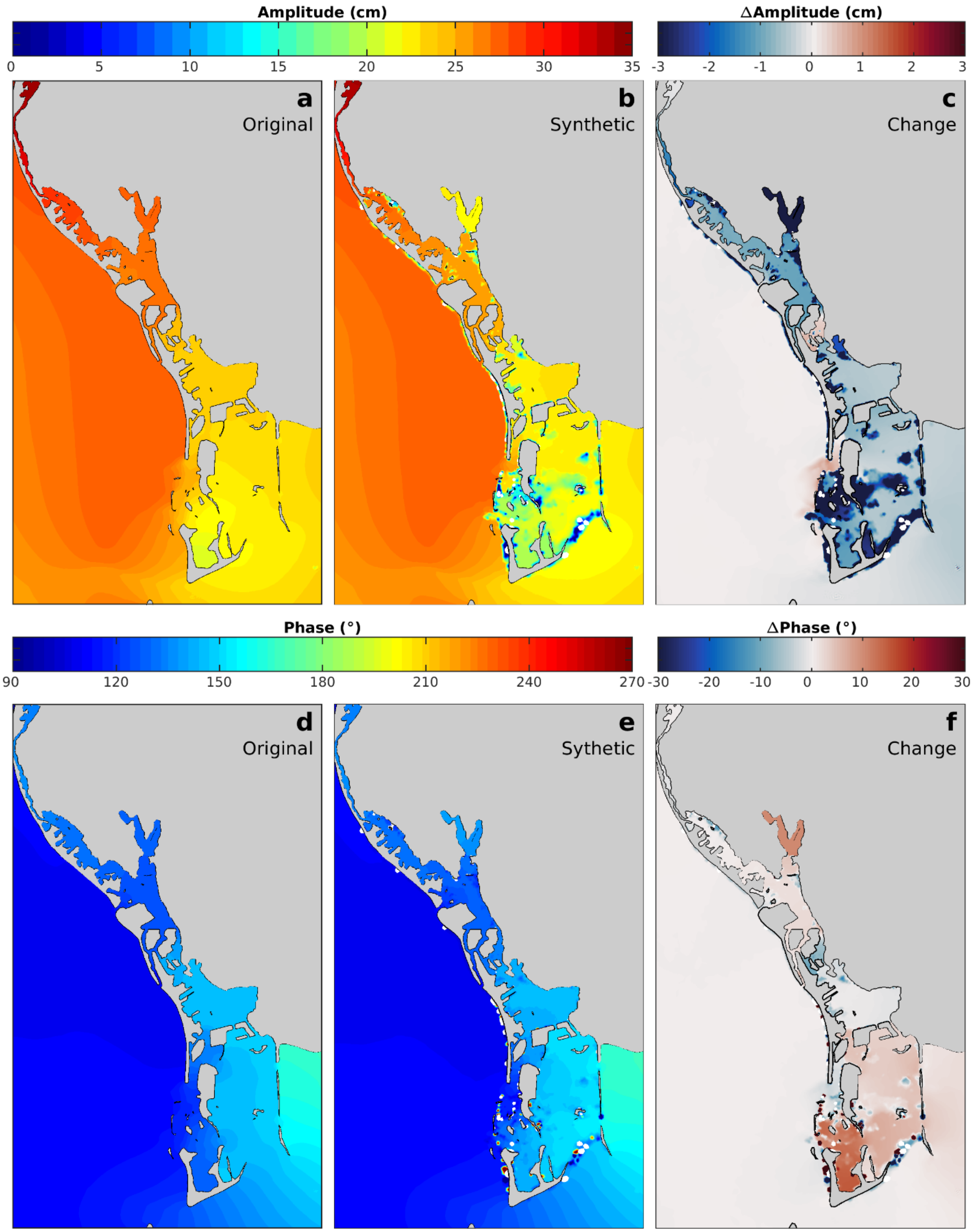

Fig. 5. TBCOM simulated M2 tide amplitude with the different bathymetries (a and b), and the difference between two experiments (c). TBCOM simulated M2 tide phase with the different bathymetries (d and e), and the difference between two experiments (f).

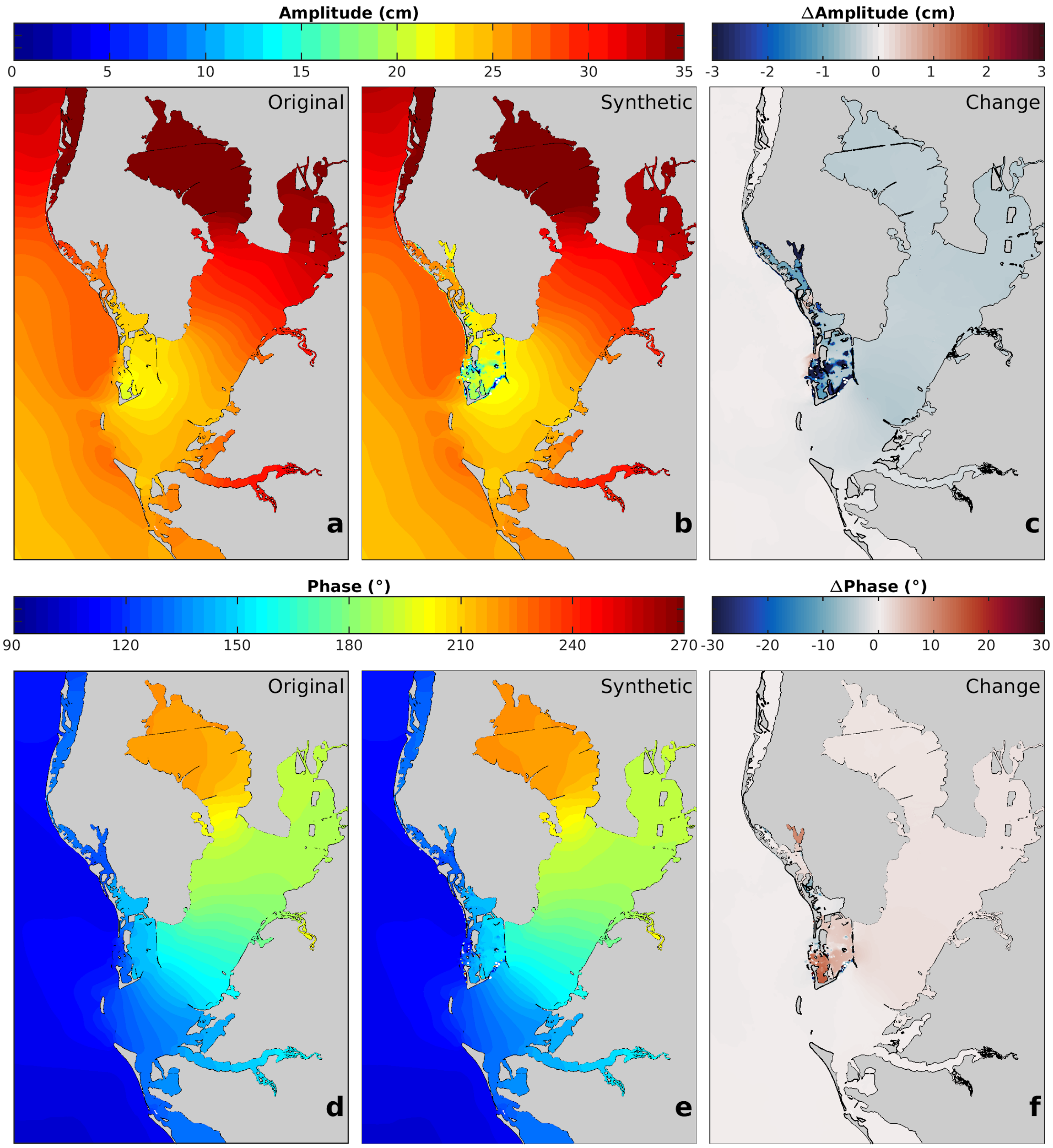

Fig. 6. TBCOM simulated M2 tide amplitude with the different bathymetries (a and b), and the difference between two experiments (c) for the whole Tampa Bay. TBCOM simulated M2 tide phase with the different bathymetries (d and e), and the difference between two experiments (f) for the whole Tampa Bay.

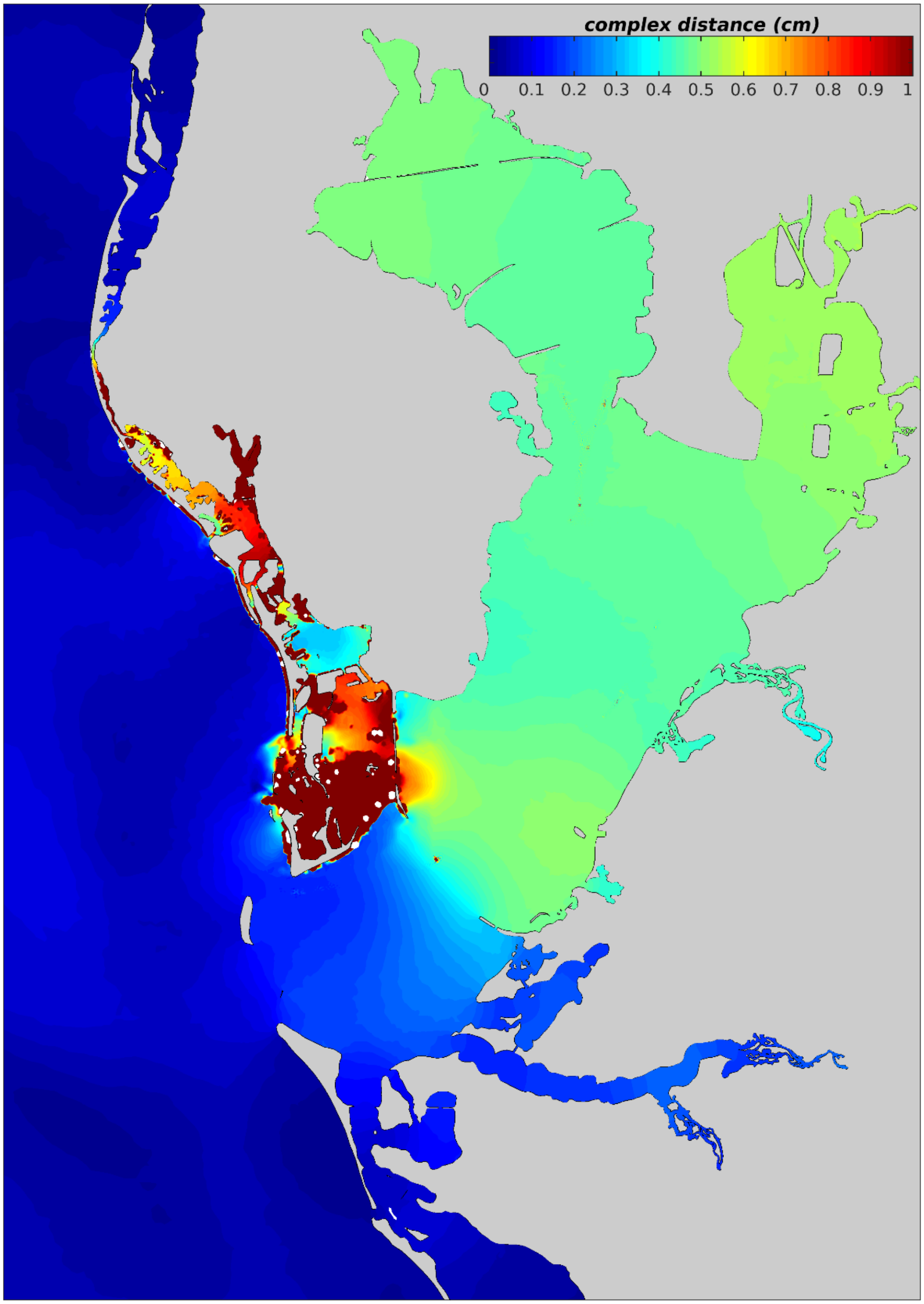

Fig. 7. Complex distances of the M2 tide changes.

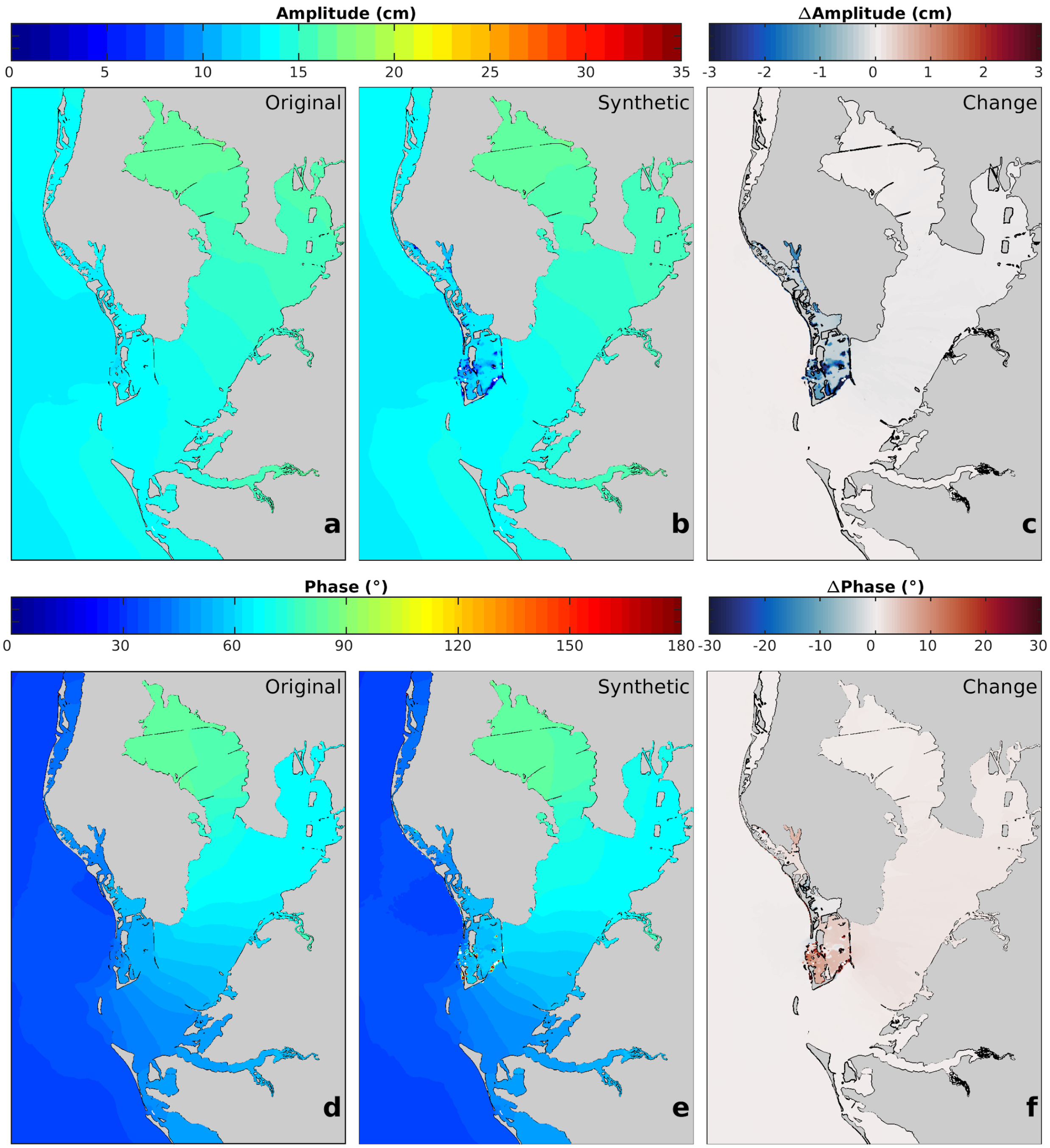

Fig. 8. TBCOM simulated K1 tide amplitude with the different bathymetries (a and b), and the difference between two experiments (c) for the whole Tampa Bay. TBCOM simulated M2 tide phase with the different bathymetries (d and e), and the difference between two experiments (f) for the whole Tampa Bay.

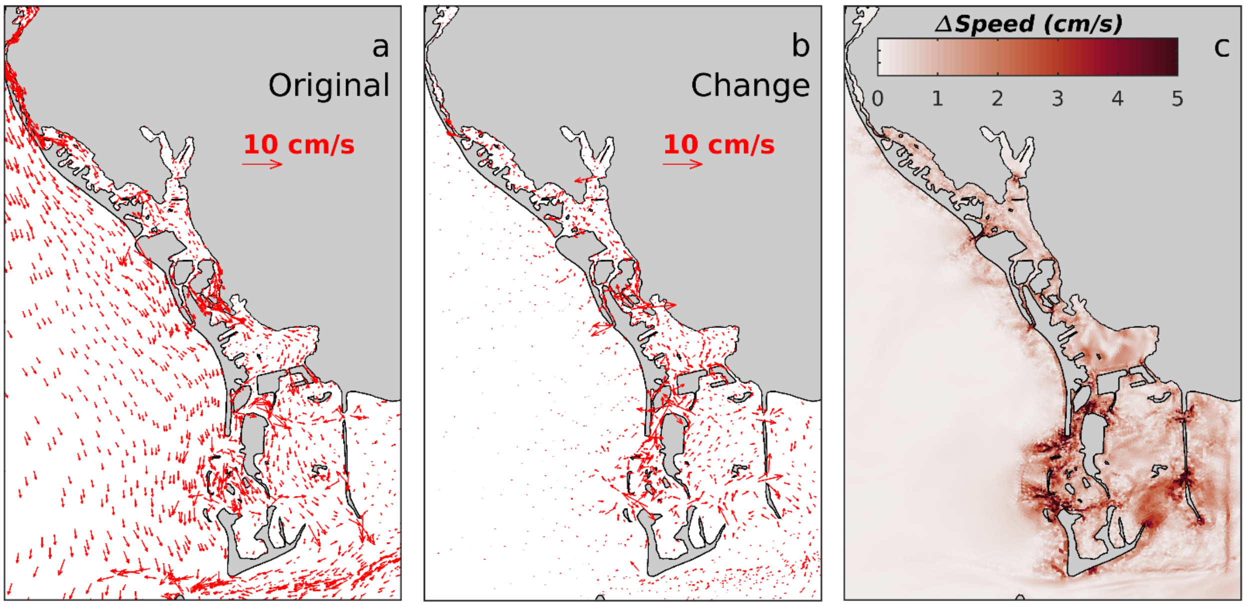

Fig. 9. One month averaged of deep averaged velocities in the area with original bathymetry (a). The difference of one month averaged of deep averaged velocities between two experiments (b). The magnitude of difference of one month averaged of deep averaged velocities between two experiments (c).

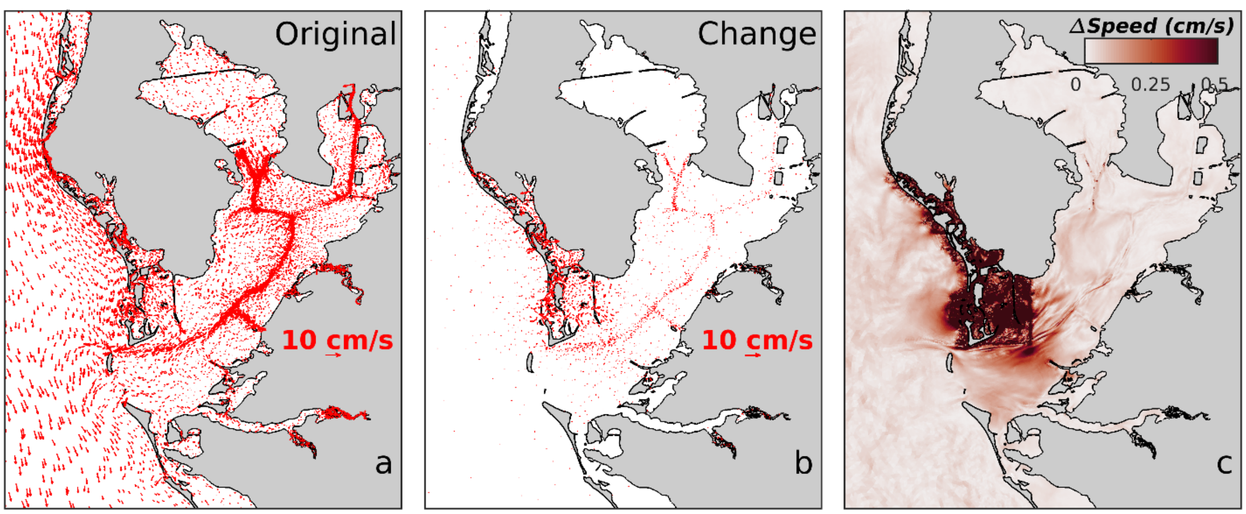

Fig. 10. One month averaged of deep averaged velocities in the area with original bathymetry (a) for the whole Tampa Bay. The difference of one month averaged of deep averaged velocities between two experiments (b) for the whole Tampa Bay. The magnitude of difference of one month averaged of deep averaged velocities between two experiments (c) for the whole Tampa Bay.

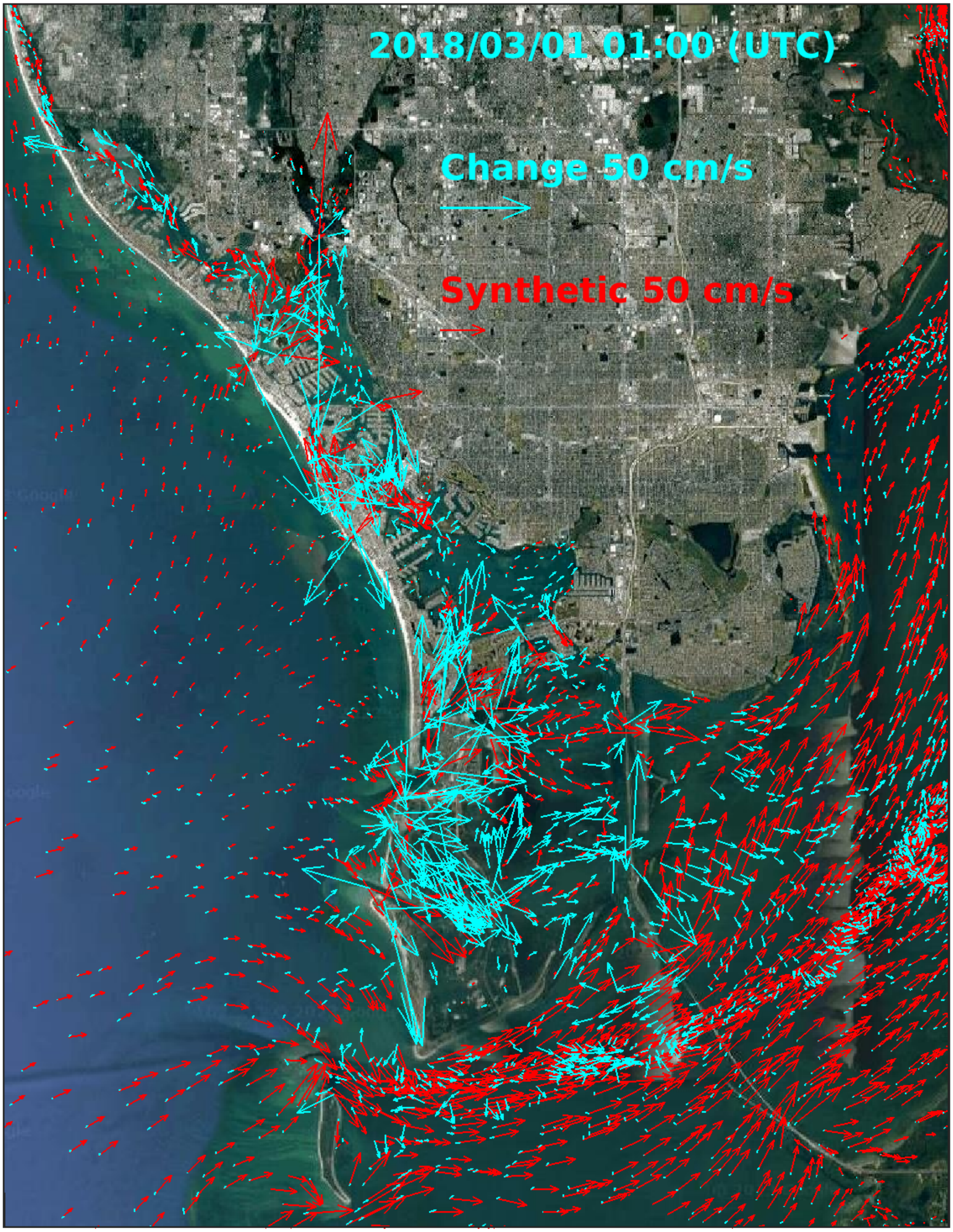

Fig. 11. TBCOM simulated currents (red arrows) and velocity difference between two experiments.

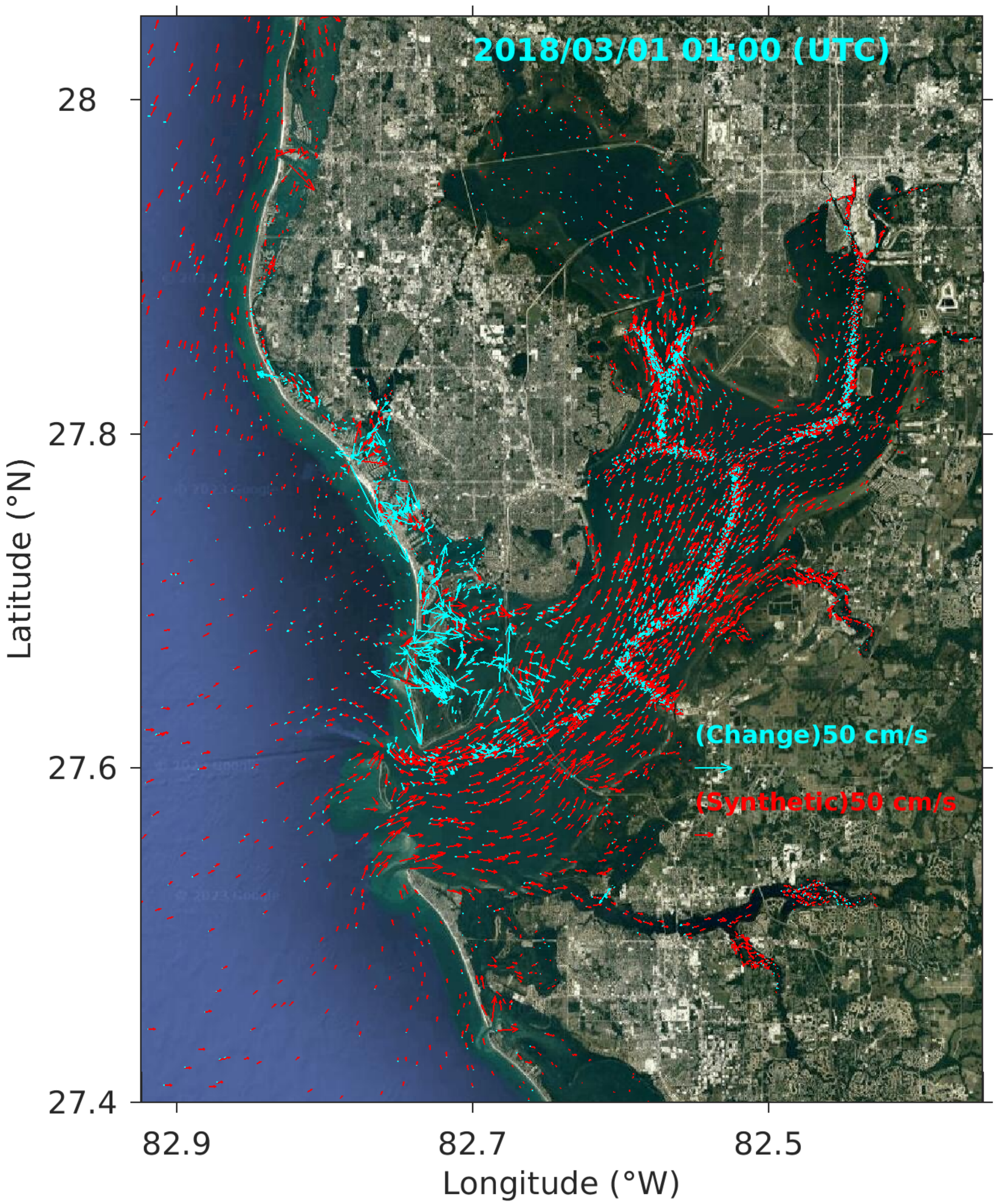

Fig. 12. TBCOM simulated currents (red arrows) and velocity difference between two experiments for the whole Tampa Bay.

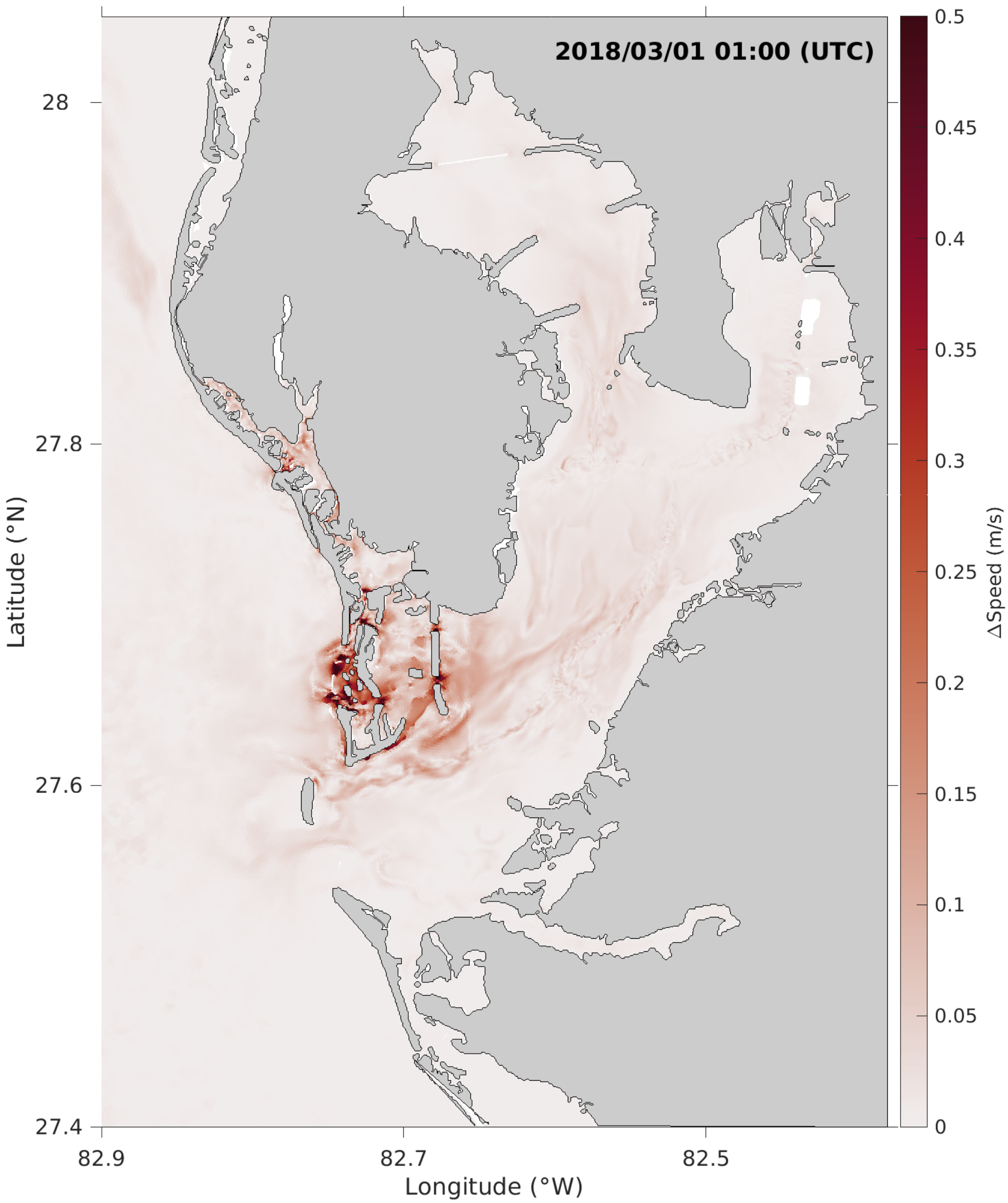

Fig. 13. The magnitude of velocity difference between two experiments at 1pm Mar 1st 2018.

References

Abbasi, M. R., Chegini, V., Sadrinasab, M., Siadatmousavi, S. M., 2019. Correcting the sea surface temperature by data assimilation over the Persian Gulf. Iran. J. Sci. Technol. Trans. A: Sci. 43, 141-149.

Amoudry, L. O., Souza, A. J., 2011. Deterministic coastal morphological and sediment transport modeling: A review and discussion. Rev. Geophys. 49,2.

Beck, M., Altieri, A., Angelini, C., Burke, M.C., Chen, J., Chin, D.W., Gardiner, J., Hu, C., Hubbard, K.A., Liu, Y., Lopez, C., Medina, M., Morrison, E., Philips, E.J., Raulerson, G.E., Scolaro, S., Sherwood., E.T., Tomasko, D., Weisberg, R.H., Whalen, J., 2022. Initial estuarine response to inorganic nutrient inputs from a legacy mining facility adjacent to Tampa Bay, Florida. Mar. Pollut. Bull. 178, 113598. https://doi.org/10.1016/j.marpolbul.2022.113598.

Berman, G., Naar, D. F., Hine, A. C., Brooks, G., Tebbens, S. F., Donahue, B. T., Wilson, R., 2005. Geologic structure and hydrodynamics of Egmont Channel: An anomalous inlet at the mouth of Tampa Bay, Florida. J. Coast. Res. 21(2), 331-357, https://doi.org/10.2112/03-0015.1

Blumberg, A.F., Mellor, G.L., 1987. A description of a three-dimensional coastal ocean circulation model, in: Heaps, N.S. (Ed.), Three -Dimensional Coastal Ocean Models. Coastal and Estuarine Sci., vol. 4. AGU, Washington, D. C, pp. 1–16.

Boerner, T.J., Deems, S., Furlani, T.R., Knuth, S.L., Towns, J., 2023. ACCESS: Advancing Innovation: NSF’s Advanced Cyberinfrastructure Coordination Ecosystem: Services &

Support. In: Practice and Experience in Advanced Research Computing 2023, July, 2023. Portland, Oregon.

Chant, R. J., Sommerfield, C. K., Talke, S. A., 2018. Impact of channel deepening on tidal and gravitational circulation in a highly engineered estuarine basin. Estuaries Coast., 41, 1587-1600.

Chassignet, E. P., Hurlburt, H. E., Metzger, E. J., Smedstad, O. M., Cummings, J. A., Halliwell, G. R., Bleck, R., Baraille, R., Wallcraft, A.J., Lozano, C., Tolman, H.L., Srinivasan, A.A., Hankin, S., Cornillon, P., Weisberg, R., Barth, A., He, R., Werner, F., Wilkin, J., 2009. US GODAE: global ocean prediction with the HYbrid Coordinate Ocean Model (HYCOM). Oceanography 22(2), 64-75.

Chen, C., Beardsley, R.C., Cowles, G., 2006. An Unstructured Grid, Finite-Volume Coastal Ocean Model-FVCOM User Manual. New Bedford, Massachusetts.

Chen, C., Gao, G., Qi, J., Proshutinsky, A., Beardsley, R. C., Kowalik, Z., Lin, H., Cowles, G., 2009. A new high‐resolution unstructured grid finite volume Arctic Ocean model (AO‐FVCOM): An application for tidal studies. J. Geophys. Res. Oceans., 114, C8.

Chen, C., Liu, H., Beardsley, R. C., 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries. J. Atmos. Oceanic Technol. 20(1), 159-186.

Chen, J., Weisberg, R. H., Liu, Y., Zheng, L., 2018a. The Tampa Bay Coastal Ocean Model Performance for Hurricane Irma. Mar Technol Soc J. 52(3), 33-42. https://doi.org/10.4031/MTSJ.52.3.6.

Chen, J., Weisberg, R. H., Liu, Y., Zheng, L., 2018b. Tampa Bay Response to Hurricane Irma. In: Abstract Presented at Ocean Sciences Meeting, February, 2018. Portland, Oregon.

Chen, J., Weisberg, R.H., Liu, Y., Zheng, L., Zhu J., 2019. On the Momentum Balance of Tampa Bay. J. Geophys. Res. Oceans. 124, 4492-4510. https://doi.org/10.1029/2018JC014890.

Chen, J., Weisberg, R. H., Liu, Y., Zheng, L., Law, J., 2020. The Tampa Bay Coastal Ocean Model Nowcast/Forecast System with Ecological Applications. In: Abstract Presented at Ocean Sciences Meeting, February, 2020. San Diego, California.

Chen, J., Liu, Y., Weisberg, R. H., Sun, Y., Zheng, L., Law, J., 2022. Storm surge simulations based on an Ian-like Hurricane over Tampa Bay. In: Abstract (NH45G-2542) Presented at AGU Fall Meeting, December, 2022. Chicago, Illinois.

Chen, J., Weisberg, R. H., Liu, Y., Zheng, L., 2023a. Hillsborough Bay inflow modification study: An application of the Tampa Bay Coastal Ocean Model. Estuar. Coast. Shelf Sci. 281, 108213. https://doi.org/10.1016/j.ecss.2023.108213.

Chen, J., Weisberg, R. H., Liu, Y., Zheng, L., Law, J., Gilbert, S., Murawski, S.A., 2023b. A Tampa Bay coastal ocean model (TBCOM) nowcast/forecast system. Deep-Sea Res. Part II 211, 105322. https://doi.org/10.1016/j.dsr2.2023.105322

Creel, L., 2003. Ripple effects: population and coastal regions. Washington, DC: Population reference bureau.

Damme, S. V., Struyf, E., Maris, T., Ysebaert, T., Dehairs, F., Tackx, M., Heip, C., Meire, P., 2005. Spatial and temporal patterns of water quality along the estuarine salinity gradient of the Scheldt estuary (Belgium and The Netherlands): results of an integrated monitoring approach. Hydrobiologia. 540, 29-45.

Donlon, C.J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E., Wimmer, W., 2012. The operational sea surface temperature and sea ice analysis (OSTIA) system. Remote Sens. Environ. 116, 140-158.

Ezer, T., 2013. Sea level rise, spatially uneven and temporally unsteady: Why the US East Coast, the global tide gauge record, and the global altimeter data show different trends. Geophys. Res. Lett. 40(20), 5439-5444.

Familkhalili, R., Talke, S. A., 2016. The effect of channel deepening on tides and storm surge: A case study of Wilmington, NC. Geophys. Res. Lett. 43(17), 9138-9147.

Feyrer, F., Cloern, J. E., Brown, L. R., Fish, M. A., Hieb, K. A., Baxter, R. D., 2015. Estuarine fish communities respond to climate variability over both river and ocean basins. Glob. Chang. Biol. 21(10), 3608-3619.

Foreman, M. G. G., 1977. Manual for tidal heights analysis and prediction (Pacific Marine Science Report. Patricia Bay: Institute of Ocean Sciences.

Foreman, M. G. G., Henry, R. F. 1989. The harmonic analysis of tidal model time series. Adv. Water Resour. 12(3), 109-120.

Friedrichs, C. T., Aubrey, D. G., 1994. Tidal propagation in strongly convergent channels. J. Geophys. Res. Oceans 99(C2), 3321-3336.

Friedrichs, C. T., 2010. Barotropic tides in channelized estuaries, in: Valle-Levinson, A. (Ed.), Contemporary issues in estuarine physics. Cambridge University Press, New York, pp. 27-61.

Galperin, B., Blumberg, A. F., Weisberg, R. H., 1991. A time-dependent three-dimensional model of circulation in Tampa Bay. In Proceedings of the Tampa Bay Area Scientific Information Symposium. Florida: Tampa, Vol. 2, pp. 77-97.

Galperin, B., Blumberg, A. F., Weisberg, R. H., 1992. The importance of density driven circulation in well mixed estuaries: The Tampa Bay experience, in: Spaulding, M. L., Blumberg, A. (Eds.), Estuarine and Coastal Modeling. American Society of Civil Engineers, Tampa, pp. 332–343.

Ge, J., Lu, J., Zhang, J., Chen, C., Liu, A., Ding, P., 2022. Saltwater Intrusion‐Induced Flow Reversal in the Changjiang Estuary. J. Geophys. Res. Oceans 127(11), e2021JC018270.

Geyer, W. R., MacCready, P., 2014. The estuarine circulation. Annu. Rev. Fluid Mech. 46, 175-197.

Haidvogel, D.B., Arango, H., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C., Wilkin, J., 2008. Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. J. Comput. Phys. 227(7), 3595-3624.

Hansen, D. V., Rattray, M., 1965. Gravitational circulation in straits and estuaries. J. Mar. Res. 23, 104– 122.

He, R., Weisberg, R. H., 2003. A Loop Current intrusion case study on the West Florida Shelf. J. Phys. Oceanogr. 33(2), 465-477.

Hess, K., 2001. Generation of tidal datum fields for Tampa Bay and the New York bight. NOAA Technical Report NOS CS 11, Silver Spring.

Hetland, R. D., Hsueh, Y., Leben, R. R., Niiler, P. P., 1999. A loop current‐induced jet along the edge of the West Florida Shelf. Geophys. Res. Lett. 26(15), 2239-2242.

Holland, W. R., Malanotte-Rizzoli, P., 1989. Assimilation of altimeter data into an ocean circulation model: Space versus time resolution studies. J. Phys. Oceanogr. 19(10), 1507-1534.

Huang, H., Justic, D., Lane, R. R., Day, J. W., Cable, J. E., 2011. Hydrodynamic response of the Breton Sound estuary to pulsed Mississippi River inputs. Estuar., Coast. Shelf Sci. 95(1), 216-231.

Huang, W., Zhang, Y. J., Wang, Z., Ye, F., Moghimi, S., Myers, E., Yu, H., 2022. Tidal simulation revisited. Ocean Dyn. 72(3-4),187-205.

Jay, D. A., 1991. Green's law revisited: Tidal long‐wave propagation in channels with strong topography. J. Geophys. Res. Oceans 96(C11), 20585-20598.

Li, S., Chen, C., 2022. Air-sea interaction processes during hurricane Sandy: Coupled WRF-FVCOM model simulations. Prog. Oceanogr. 206, 102855.

Liu, Y., Weisberg, R. H., Chen, J., Merz, C. R., Law, J., Zheng, L., 2017. West Florida Shelf Response to Hurricane Irma. In: Abstract (NH23E-2804) Presented at AGU Fall Meeting, December, 2017. New Orleans, Louisiana.

Liu, Y., Weisberg, R.H., Zheng, L., Sun, Y., Chen, J., 2021. Nowcast/forecast of the Tampa Bay, Piney Point effluent plume: a rapid response. In: Abstract (Os35b-1036) Presented at AGU Fall Meeting, December, 2021. New Orleans, Louisiana.

Liu, Y., Weisberg, R. H., Zheng, L., Chen, J., Hu, C., Law, J., Sun, Y., 2022. Coastal Ocean Response to Hurricane Ian as Simulated by the WFCOM and TBCOM Nowcast/Forecast Systems. In: Abstract (NH43C-05) Presented at AGU Fall Meeting, December, 2022. Chicago, Illinois.

Liu, Y., Weisberg, R.H., Zheng, L., Hubbard, K.A., Muhlbach, E.G. Garrett, M.J., Hu, C., Cannizzaro, J.P., Xie, Y., Chen, J., John, S., Liu, L. Y., 2023. Short-term forecast of Karenia brevis trajectory on the West Florida Shelf. Deep-Sea Res. Part II 211, 105335. https://doi.org/10.1016/j.dsr2.2023.105335

Malanotte-Rizzoli, P., Young, R. E., 1992. How useful are localized clusters of traditional oceanographic measurements for data assimilation? Dyn. Atmos. Oceans 17(1), 23-61.

Mao, M., Xia, M., 2020. Particle dynamics in the nearshore of Lake Michigan revealed by an observation‐modeling system. J. Geophys. Res. Oceans 125(8), e2019JC015765.

Meyers, S.D., Luther, M. E., Wilson, M., Holm, H.E., Linville, A., Sopkin, K., 2007. A numerical simulation of residual circulation in Tampa Bay. Part I: Low-frequency temporal variations. Estuaries Coast. 30, 679–697. https://doi.org/10.1007/BF02841965

Meyers, S.D., Luther, M. E., 2008. A numerical simulation of residual circulation in Tampa Bay. Part II: Lagrangian residence time. Estuaries Coast. 31, 815-827. https://doi.org/10.1007/s12237-008-9085-0

Meyers, S. D., Linville, A. J., Luther, M. E., 2014. Alteration of residual circulation due to large-scale infrastructure in a coastal plain estuary. Estuaries Coast. 37, 493-507. https://doi.org/10.1007/s12237-013-9691-3

Meyers, S. D., Moss, A. J., Luther, M. E., 2017. Changes in residence time due to large-scale infrastructure in a coastal plain estuary. J. Coast. Res. 33(4), 815-828.

Mou, L., Niu, Q., Xia, M., 2022. The roles of wind and baroclinic processes in cross-isobath water exchange within the Bohai Sea. Estuar. Coast. Shelf Sci. 274, 107944.

Oey, L. Y., Zhang, H. C., 2004. The generation of subsurface cyclones and jets through eddy–slope interaction. Cont. Shelf Res. 24(18), 2109-2131.

Orton, P.M., Talke, S.A., Jay, D.A., Yin, L., Blumberg, A.F., Georgas, N., Zhao, H., Roberts, H.J., MacManus, K., 2015. Channel shallowing as mitigation of coastal flooding. J. Mar. Sci. Eng. 3(3), 654-673.

Raimonet, M., Cloern, J. E., 2017. Estuary–ocean connectivity: fast physics, slow biology. Glob. Chang. Biol. 23(6), 2345-2357.

Ralston, D. K., Geyer, W. R., 2019. Response to channel deepening of the salinity intrusion, estuarine circulation, and stratification in an urbanized estuary. J. Geophys. Res. Oceans 124(7), 4784-4802.

Roberts, T. M., Wang, P., 2012. Four-year performance and associated controlling factors of several beach nourishment projects along three adjacent barrier islands, west-central Florida, USA. Coast. Eng. 70, 21-39.

Rodgers, M., Vallee, M., Wang, P., Cheng, J., 2019. Measuring complex beach-dune morphology and nearshore processes using UAVs. In: Coastal Sediments 2019: Proceedings of the 9th International Conference, May, 2019. Tampa/St. Petersburg, Florida

Talke, S. A., Orton, P., Jay, D. A., 2014. Increasing storm tides in New York harbor, 1844–2013. Geophys. Res. Lett. 41(9), 3149-3155.

Sahoo, B., Mao, M., Xia, M., 2021. Projected changes of water currents and circulation in Lake Michigan under Representative Concentration Pathways scenarios. J. Geophys. Res. Oceans 126(5), e2020JC016651.

Vincent, M., Burwell, D., Luther, M., 2000. The Tampa Bay Nowcast-Forecast System, in: Spaulding, M.L., Butler, H.L. (Eds.), Estuarine and Coastal Modeling. American Society of Civil Engineers, Reston, pp. 765–780.

Virmani, J. I., Weisberg, R. H., 2005. Relative humidity over the West Florida continental shelf. Mon. Weather Rev. 133(6), 1671-1686. https://doi.org/10.1175/MWR2944.1.

Wang, D.P., Elliot, A.J., 1978. Non-tidal variability in the Chesapeake Bay and Potomac River; evidence for non-local forcing. J Phys Oceanogr. 8, 225-232.

Wang, P., Elko, N. A., Roberts, T. M., 2009. Profile equilibration and longshore spreading associated with beach nourishment: a case study along west-central Florida coast. In: Proceedings of Coastal Dynamics 2009: Impacts of Human Activities on Dynamic Coastal Processes. August, 2009. Tokyo, Japan.

Wang, P., Roberts, T. M., Dabees, M., Horwitz, M. H., 2011. Beach changes associated with active 2009-2010 El Nino winter along the west-central Florida barrier islands. In: The Proceedings of the Coastal Sediments 2011. May, 2011. Miami, Florida.

Warner, J. C., Geyer, W. R., Lerczak, J. A., 2005. Numerical modeling of an estuary: A comprehensive skill assessment. J. Geophys. Res. Oceans 110, C5.

Weisberg, R.H., 1976. The nontidal flow in the Providence River of Narragansett Bay: a stochastic approach to estuarine circulation. J. Phys. Oceanogr. 6, 721-734

Weisberg, R.H., He, R., 2003. Local and deep-ocean forcing contributions to anomalous water properties on the West Florida Shelf. J. Geophys. Res. 108, C6. https://doi.org/10.1029/2002JC001407

Weisberg, R.H., Liu, Y., 2022. Local and deep-ocean forcing effects on the West Florida Shelf circulation and ecology. Front. Mar. Sci. 9, 863227, https://doi.org/10.3389/fmars.2022.863227

Weisberg, R.H., Zheng, L., 2006. Hurricane storm surge simulations for Tampa Bay. Estuaries Coasts. 29, 899-913.

Weisberg, R. H., Zheng, L., Peebles, E., 2014. Gag grouper larvae pathways on the West Florida Shelf. Continent. Shelf Res. 88, 11-23.

Weisberg, R. H., Zheng, L., Liu, Y., 2016. West Florida shelf upwelling: Origins and pathways. J. Geophys. Res. Oceans 121(8), 5672-5681. https://doi.org/10.1002/2015JC011384

Westfall, Z. J., 2018. Morphodynamics of Shell key and Mullet Key barrier islands: their origin and development. PhD dissertation. University of South Florida, Tampa

Ye, F., Zhang, Y.J., Wang, H.V., Friedrichs, M.A., Irby, I.D., Alteljevich, E., Valle-Levinson, A., Wang, Z., Huang, H., Shen, J., Du, J., 2018. A 3D unstructured-grid model for Chesapeake Bay: Importance of bathymetry. Ocean Model. 127, 16-39.

Xie, S., Law, J., Russell, R., Dixon, T.H., Lembke, C., Malservisi, R., Rodgers, M, Iannaccone, G., Guardato, S., Naar, D.F., Calore, D., Fraticelli, N., Brizzolara, J., Gray, J.W., Hommeyer, M., Chen, J., 2019. Seafloor geodesy in shallow water with GPS on an anchored spar buoy. J. Geophys. Res. Solid Earth 124(11), 12116-12140. https://doi.org/10.1029/2019JB018242

Xie, S., Chen, J., Dixon, T. H., Weisberg, R. H., Zumberge, M. A., 2021. Offshore Sea Levels Measured With an Anchored Spar‐Buoy System Using GPS Interferometric Reflectometry. J. Geophys. Res. Oceans 126(11), e2021JC017734. https://doi.org/10.1029/2021JC017734

Zhang, A., Wei, E., 2010. Development of NOAA's Tampa Bay operational forecast system. In: Spaulding, M.L. (Ed.), Estuarine and Coastal Modeling. American Society of Civil Engineers, Reston,VA, pp. 686–703

Zhang, L., Yang, Z., Zhang, F., Li, Z., Wang, Y., Gao, S. (2021). Longitudinal residual circulation in the South Passage of Yangtze Estuary: Combined influences from runoff, tide and bathymetry. Sci. China Earth Sci. 64, 2129-2143.

Zheng, L., Weisberg, R.H., 2012. Modeling the west Florida coastal ocean by downscaling from the deep ocean, across the continental shelf and into the estuaries. Ocean Model. 48, 10-29. https://doi.org/10.1016/j.ocemod.2012.02.002.

Zhou, X., Rowe, M., Liu, Q., Xue, P., 2023. Comparison of Eulerian and Lagrangian transport models for harmful algal bloom forecasts in Lake Erie. Environ. Model. Softw. 162, 105641.

Zhu, J., Weisberg, R. H., Zheng, L., Han, S., 2015a. Influences of channel deepening and widening on the tidal and nontidal circulations of Tampa Bay. Estuaries Coast. 38(1), 132-150. https://doi.org/10.1007/s12237-014-9815-4.

Zhu, J., Weisberg, R. H., Zheng, L., Han, S., 2015b. On the flushing of Tampa Bay. Estuaries Coast. 38, 118-131. https://doi.org/10.1007/s12237-014-9793-6.

Zhu, J., Weisberg, R. H., Zheng, L., Qi, H., 2015c. On the salt balance of Tampa Bay. Cont. Shelf Res. 107, 115-131, https://doi.org.10.1016/j.csr.2015.07.001.