

OPERATIONAL HYDRODYNAMIC SEDIMENT TRANSPORT AND WATER QUALITY MODEL FOR BISCAYNE BAY, FLORIDA

FINAL TECHNICAL REPORT

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1 Summary

This report summarizes the results of the activities performed by FIU Institute of Environment during the execution of the project: *Operational Hydrodynamic Sediment Transport and Water Quality Model for Biscayne Bay, Florida (BBOM: Biscayne Bay Operational Model)*. The main project objective was the implementation of the model and the subsequent calibration and validation with field data. To achieve the project goals FIU designed and executed a set of data collection campaigns that provided high frequency depth, velocities and water quality data. During the project we also gather data from sources including NOAA, SFWMD and others, that allowed us to complement the data sets used for the model verification.

The model development was divided into several stages that included the hydrodynamic model implementation, with subsidiary calibration and validation to make sure that the model was able to reproduce the Biscayne Bay velocity fields. Once the hydrodynamic component was validated, we implemented the water quality component focusing on the salinity dynamics. The idea was that, having a model capable of reproducing both the bay hydrodynamics together with the salinity dynamics, is a solid platform over which we can add other pollutants to the model.

The results presented in this report show that the BBOM was capable of representing data throughout the bay including water depths and salinities in 42 SFWMD stations throughout the bay provided that adequate boundary conditions are imposed both on the oceanic and land boundaries. These conditions should include the tidal elevations and salinities on the ocean boundaries and inflow discharges and salinities from the canals and inland groundwater flow.

The Biscayne Bay Operational Model develop in this project is a solid computational platform open to all researchers, agencies, and interested stakeholders, that can be used to study a variety of environmental management scenarios in the Bay. This is contribution #1537 from the Institute of Environment at Florida International University

2 Introduction

The well-being of South Florida's economy is closely tied to the ecosystem health of coastal water bodies, especially of Biscayne Bay, whose estuarine waters have experienced the impact of anthropogenic interventions since the early 1900's, including major disruptions of its hydrology and sustained urban and agricultural development.

Biscayne Bay contributes to a multibillion-dollar tourist, recreation, and fishing industry centered on Biscayne National Park and the Aquatic Preserve. Furthermore, a multibillion-dollar real estate industry flourishes along its shorelines. All of that wealth and job creation power rests on the good water quality (WQ) of the Bay. For many years, these bay ecosystems have remained very productive, despite the significant impact caused on its natural resources by human settlements, but Biscayne is showing warning signs of water quality decay: algal blooms, fish-kills, seagrass die-offs are all alarming signs. Phosphorous enrichment and Chlorophyll increase since 2013, seagrass beds in North BB are disappearing, macro algae blooms persist in South-central inshore, blue-green algae and diatom bloom are becoming more frequent and prolonged, red-algae blooms seem to be moving from SW Florida to SE Florida coasts, fish kills are becoming the norm, while sport fishing is collapsing. Meanwhile, monitoring efforts had declined significantly since 2008, to the point that today it is difficult to explain the causes of decay, and even worse, to advise on what to do to protect bay waters and its ecosystems.

Facing dwindling funds and the need to improve monitoring WQ, the scientific community, together with federal, local and state government, and citizens have engaged in diverse programs to face the crisis. In this context, our main objective has been to implement an operational physically-based hydrodynamic, sediment transport, and water quality model, to support the design and testing of an optimized WQ monitoring program for Biscayne Bay. The current version of the model, developed under this project, provides high-resolution dynamics including velocities, water depths, and salinities for Biscayne Bay. This modeling tool would find practical applications "getting the water right" for Biscayne Bay to restore estuarine conditions as envisioned by the Everglades Restoration Project.

This project has been a partnership between a public university (FIU), the private sector (Hydronia LLC), the local government (Miami-Dade County), funded by the Federal government through the Environmental Protection Agency (EPA; Subcontract X7-01D00520) to tackle a community challenge. This proposal aligns with the Core Mission of EPA Strategic Plan, by focusing on delivering real results to provide Floridians with clean bay water, while rebalancing the power between Washington and the states (local government) to create tangible environmental results for the American people.

3 Purpose and Scope

The initial objective of this project was to implement an operational physically-based hydrodynamic, sediment transport and water quality model to support research and management of natural resources by providing statistically robust evidences of water-linked issues for stakeholders and policy makers. This model would be a cornerstone in the design of an optimized WQ monitoring program for Biscayne Bay. In practice, the model would provide high-resolution dynamics, including velocities, water depths, erosion/deposition patterns, and concentrations of pollutants in the bay. The calibrated and validated model would help. Logistical and technical inconveniences cascading from COVID19 pandemics hindered full development of all modeling modules. Nevertheless, we were able to fully develop two of the fundamental components of BBOM, the hydrodynamic and the salinity modules.

The hydrodynamic and salinity modules, calibrated and validated with available and new data generated in this project, would help forging the foundations of a future Coastal Information System to serve agencies and the community to evaluate environmental conditions of Biscayne Bay under diverse scenarios, and to assess the effectiveness of management actions.

In this report we present the development of BBOM, describing first the implementation, calibration and validation of the hydrodynamic component, and second, the calibrations and validation of the salinity module of the BBOM model using independent data sets. Data were provided by the South Florida Water Management District (SFWMD), Biscayne National Park (BNP), Miami-Dade County (MDCo), and the National Oceanic and Atmospheric Administration (NOAA).

4 Site Description

Biscayne Bay is a semi-enclosed coastal lagoon), located on the Atlantic coast of South East Florida, United States that is approximately 35 miles (56 km) long and up to 8 miles (13 km) wide, spanning 428 square miles (1,110 km²)(Figure 1). Biscayne Bay is defined by its geology. Specifically, the surface expression is a shallow depression in bedrock produced by erosion and sedimentation through one or more major changes in sea level acting on a suite of marine and fresh water deposits dominated by limestone. Biscayne Bay includes two aquatic preserves and Biscayne Bay National Park. The Bay was historically connected to the Everglades by streams (glades) cutting through the Atlantic Coastal Ridge, a ridge of limestone parallel to the shoreline. Additionally, freshwater entered the bay as springs and as a diffuse surficial sheet extending from coastal wetlands to the shoreline. Ground-water discharge to Biscayne Bay is restricted to within 100-1000 meters of the shoreline.

Besides the Biscayne Bay basin itself, three major physiographic provinces define the sub-regional geomorphology, the Atlantic Coastal Ridge developed on the resistant Miami Limestone to the west; the southern slope, locus of Holocene sedimentation; and the High Coral Keys developed on the wave-resistant Key Largo Limestone to the east. Bedrock in all provinces has been subjected to severe weathering leading to the development of mature karst topography where epikarst features are abundant (sinkholes, caves, microkarst, etc), and relief is controlled by differential resistance to erosion processes. This fundamental setting is responsible for subsequent development and distribution of habitats.

Biscayne Bay, in general, is pretty shallow with natural depths ranging from a few centimeters to about 6 m deep. The average depth is around 2 m (6.5 ft), except in dredged channels (Comp and Seaman 1985). Extremely shallow areas may become dry during low tidal stages. Around the port of Miami, depths may be as high as 15 m. along the channel and ship maneuver areas that were dredged to allow for large ships.

Biscayne Bay is connected on the south to Card and Barnes Sounds that are two smaller embayments. The drainage basin covers 938 square miles (2,430 km²). Biscayne Bay has several ocean connections, some of which are narrow such as the Haulover inlet and the entrance to the Port of Miami, and wide openings such as the so-called Safety Valve along the central part of the Bay. The Safety Valve is a series of shallow mud/sand flats separated by tidal flow channels, stretching about 8 miles (13 km) from the south end of Key Biscayne to the Ragged Keys at the north end of the Florida Keys archipelago.

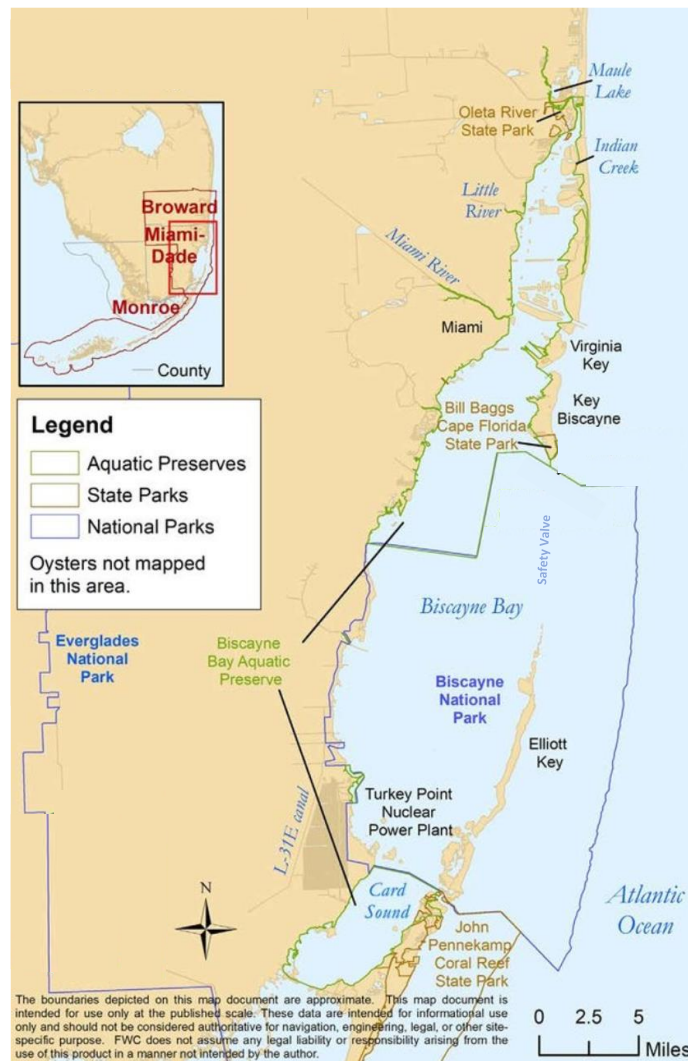


Figure 1 Biscayne Bay, bordering the Great Miami, South Florida (After Radabaugh et al, 2019)

5 Previous Studies

Wang & Kreeke (1986) developed a tidal circulation model for North Biscayne Bay. The limited computational resources available at that time required a nested numerical modeling approach using one- and two-dimensional models. The model was able to determine that the tidal forcing is the dominant flow-generating mechanism in North Biscayne Bay.

Langevin (2001) modeled the rates and patterns of submarine ground-water discharge to Biscayne Bay using the SEAWAT code, a combined version of MODFLOW and MT3D models to simulate variable-density Flow. Results from his regional-scale model suggest that the average rate of fresh ground-water discharge to Biscayne Bay for the 10-year period (1989-1998) is about 10^5 cubic meters per day for the 100 km of coastline. This discharge rate is about 6% of the measured surface water discharge to the Bay for the same period. Furthermore, the model also suggests that about 100% of the fresh groundwater discharge occurs north of the Cutler Drain Canal.

Wang et al. (2003) developed a 2D model describing the currents, residence times, salinity patterns, and larval transport for Southern Biscayne Bay. Model forcing included tides, wind, and freshwater inflows prescribed from 4 years of recorded observations. Physical and biological performance tests were applied to two hindcasts. Computed tidal currents and salinities agreed with observations, except in the nearshore zone. To improve model predictions in these areas, Wang et al. indicated that additional and more accurate model boundary conditions and linkages to better hydrologic and atmospheric models are needed, and that the offshore shelf and coral reef tract should be included.

Brown et al. (2003) developed a 2D numerical model of the hydrodynamics and salinity of Biscayne Bay, FL. Based on RMA10-WES computer code. The model was calibrated and verified against an extensive set of hydrodynamic and salinity field data collected in a previous effort performed by the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, in conjunction with the Biscayne National Park. Brown et al. model successfully reproduced observed tidal signals in the Central and North Bay, with respect to both the tidal and subtidal (i.e., wind-driven) response. The tidal signal is well represented in the South Bay, but the wind-driven response is excessive in the model. The model successfully reproduces the observed velocity signal and found that the entire water column generally responds in the same direction, which justifies the validity of a 2-D depth-integrated model for Biscayne Bay. Brown et al. model ran in high-end workstations to run, and despite that, it required long runtimes mostly due to the high numerical overload of the Finite Element Method used in RMA10. For instance, a 10-month simulation required approximately 6.5 days to complete the run.

Zhu et al. (2011) applied the BBSM model Finite Element hydrodynamic and transport model, to understand the influence of non-point sources including bather shedding, animal fecal sources, and nearshore sand, as well as the impact of the environmental conditions at a recreational marine beach in South Florida.

Stabenau and Renshaw (2011, 2015) applied an improved version of the BBSM mainly to simulate the effect of groundwater inflow to the Bay's surface water salinity. The model was calibrated

with a data set that included salinity measurements, tidal stages, and velocities, but lacked “the groundwater component due to uncertainty in its quantity”. That resulted in the impossibility of reproducing mean salinity and salinity variability along the shoreline. After some adjustments in friction in nearshore areas for their BBSM version 4, salinity in the nearshore region improved. An important finding of this Project is that groundwater and other freshwater sources along the coast, must be included to properly model salinity in Biscayne Bay.

All of the modeling efforts summarized above focus on either the north or the south Bay exclusively. They indicate that due to areas that dry due to low tidal elevations, the model results show numerical instabilities. This is attributed to the difficulties of the Finite Element Method in accurately conserving mass at the elements scale. Also, the numerical codes are not optimized for high-resolution meshes as required to capture detailed hydrodynamic patterns and pollutant transport pathways, which result in exceedingly long runtimes.

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6 Approach

The general modeling approach for BBOM was to implement first the hydrodynamic component that accounts for tidal boundary conditions at the open ocean boundaries, point inflow discharges coming from inland, and wind over the model domain. Our general strategy was to use as much measured data as possible for calibration and validation of the hydrodynamic module. Most water depth data came from NOAA, and wind data was either from NOAA or Weather Flow (Figure 2; Table 1). Likewise, current data are inexistent or unavailable for the bay. Therefore, we collected simultaneous readings of these parameters in up to 18 selected stations in Biscayne Bay. The idea was to have precise information as to how water moves in Biscayne Bay. Once the hydrodynamic model was calibrated and validated, we moved into the water quality module of RiverFlow2D, with salinity for the central and southern portions of Biscayne Bay.

7 Data Collection Campaigns

Under a NASA-funded research project (Award: 5616-FIU-NASA-H03G), FIU collected current, depth and water quality data in four stations in four separate campaigns from 2017 to 2019 (Table 2). In those campaigns, we deployed four platforms, which consisted of a TCM-1[®] tilt current meter (Lowell Instruments LLC) to log current speed, azimuth, velocities, and temperature, and an EXO2 multiprobe sonde to measure water quality parameters. In 2020 and 2021, campaigns of data collection were performed in Biscayne Bay under the current EPA-funded project.

The 2020 campaign included the deployment of five instrumented platforms in North Biscayne Bay and six platforms in Central and Southern Biscayne Bay to log currents with a TCM-1, and additionally, each platform had an Arduino-based system for measuring water pressure and temperature. Instruments were deployed on a concrete slab on the bay bottom. Data logging was programmed every minute. Deployments were planned to be maintained and/or retrieved every week, but logistic complications due to COVID19 extended unattended deployment for over a

month. Out of five platforms deployed in Northern Biscayne Bay, two were lost from areas of heavy boat traffic; and two pressure sensors were heavily fouled by barnacle growth. A similar scenario was faced in South Central Biscayne Bay. Out of six instrumented platforms, two were stolen, and some pressure sensors were damaged. All of this resulted in data and instrumental losses.

An additional field campaign was done in early 2021 (campaign 6; Table 2). Instrumental payloads included new TCM-1[®] and HOBO[®] pressure and conductivity meters. Deployment included 19 stations (Figure 3). Again, some instruments were lost and finally we retrieve data from five stations in North Biscayne Bay, five stations in Central Biscayne Bay and three stations in South Biscayne Bay.

Table 1. Monitoring stations used for the hydrodynamic simulations. C1 to c6 are field campaigns. D: Depth. WSE: Water Surface Elevation. V: Water velocity. W: Wind velocity. D: Water depth; C: Conductivity; NA: Not applicable.

No.	code	Name	Source	Latitude	Longitude	C1	C2	C3	C4	C5	C6
1	8723080	HAULOVER PIER	NOAA	25.9033	-80.12	D	D	D	D	D	D
2	8723165	MIAMI	NOAA	25.7783	-80.185	D	D	D	D	D	D
3	8723170	MIAMI BEACH	NOAA	25.7683	-80.1317	D	D	D	D	D	D
4	8723178	GOVERNMENT CUT	NOAA	25.7633	-80.13	D	D	D	D	D	D
5	8723214	Virginia Key	NOAA	25.7317	-80.1617	D	D	D	D	D	D
6	8723289	CUTLER, BISCAYNE BAY	NOAA	25.615	-80.305	D	D	D	D	D	D
7	8723355	RAGGED KEY NO. 5	NOAA	25.5233	-80.175	D	D	D	D	D	D
8	8723409	ELLIOTT KEY HARBOR	NOAA	25.4533	-80.1967	D	D	D	D	D	D
9	8723423	TURKEY POINT	NOAA	25.4367	-80.33	D	D	D	D	D	D
10	8723465	ARSENICKER, CARD SOUND	NOAA	25.3733	-80.29	D	D	D	D	D	D
11	8723506	PUMPKIN KEY, CARD SOUND	NOAA	25.325	-80.2933	D	D	D	D	D	D
12	8723534	CARD SOUND BRIDGE	NOAA	25.2883	-80.37	D	D	D	D	D	D
13	FWYF1	Fowey Rock	NOAA	25.5906	-80.0967	W	W	W	W	W	W
14	VAKF1	Virginia Key	NOAA	25.7314	-80.1619	W	W	W	W	W	W
15	MLRF1	Molasses Reef	NOAA	25.0117	-80.3764	W	W	W	W	W	W
16	PVGF1	Port Everglades Channel	NOAA	26.0925	-80.1089	W	W	W	W	W	W
17	XCFL	Carysfort Reef Light	Weather Flow	25.2269	-80.2092	W	W	W	NA	NA	NA
18	XCRN	Crandon	Weather Flow	25.7158	-80.1497	NA	W	W	NA	NA	NA
19	XDGE	Biscayne Bay Harbor Pilots	Weather Flow	25.7669	-80.1453	W	W	W	NA	NA	NA
20	XDIN	Dinner Key Light 1	Weather Flow	25.7133	-80.2106	NA	W	W	NA	NA	NA
21	XGVT	Government Cut	Weather Flow	25.7495	-80.0995	W	NA	W	NA	NA	NA
22	XKBS	Biscayne Bay Light 20	Weather Flow	25.6566	-80.1853	W	W	W	NA	NA	NA

23	XMSP	Morningside Park	Weather Flow	25.8228	-80.1782	W	W	W	NA	NA	NA
24	XNMI	North Miami	Weather Flow	25.9092	-80.1605	W	W	W	NA	NA	NA
25	XSKL	South Key Largo	Weather Flow	25.1001	-80.4318	W	W	W	NA	NA	NA
26	XSOM	South Miami	Weather Flow	25.6328	-80.2979	W	W	W	NA	NA	NA
27	XTKY	Turkey Point	Weather Flow	25.4339	-80.3454	W	W	W	NA	NA	NA
28	St#3	--	FIU	25.8359	-80.1487	NA	NA	NA	NA	V	NA
29	St#5	--	FIU	25.81137	-80.1489	NA	NA	NA	NA	V	NA
30	St#15	--	FIU	25.46294	-80.2711	NA	NA	NA	NA	D	NA
31	St#16	--	FIU	25.43628	-80.2383	NA	NA	NA	NA	V	NA
32	BB1	--	FIU	25.69539	-80.2077	V	V	V	V	V D	V D
33	BB2	--	FIU	25.61403	-80.2418	V	V	V	V	NA	V D
34	BB3	--	FIU	25.33283	-80.317	V	V	V	V	NA	V D C
35	BB4	--	FIU	25.22361	-80.3896	V	V	V	V	V D	D
36	BB5	--	FIU	25.90062	80.12379	NA	NA	NA	NA	NA	V D
37	BB6	--	FIU	25.86688	80.15826	NA	NA	NA	NA	NA	V D C
38	BB7	--	FIU	25.83686	80.17246	NA	NA	NA	NA	NA	V D C
39	BB8	--	FIU	25.8359	80.14874	NA	NA	NA	NA	NA	V D
40	BB9	--	FIU	25.81868	80.17476	NA	NA	NA	NA	NA	V D
41	BB10	--	FIU	25.8026	80.15328	NA	NA	NA	NA	NA	V D
42	BB11	--	FIU	25.75558	80.17673	NA	NA	NA	NA	NA	V D
43	BB12	--	FIU	25.07701	80.13404	NA	NA	NA	NA	NA	V D
44	BB13	--	FIU	25.65745	80.14964	NA	NA	NA	NA	NA	V D C
45	BB14	--	FIU	25.53563	80.27485	NA	NA	NA	NA	NA	V D
46	BB15	--	FIU	25.53654	80.16138	NA	NA	NA	NA	NA	V D
47	BB16	--	FIU	25.46947	80.30647	NA	NA	NA	NA	NA	V D
48	BB17	--	FIU	25.45717	80.23734	NA	NA	NA	NA	NA	V D
49	BB18	--	FIU	25.36194	80.22554	NA	NA	NA	NA	NA	V D
50	BB19	--	FIU	25.12182	80.03419	NA	NA	NA	NA	NA	V D C

Table 2 FIU data collection campaigns used in this Project.

Campaign	Start date and time	End date and time
1	10/10/2017 11:50	10/17/2017 14:39
2	6/20/2018 15:57	6/28/2018 9:27
3	4/1/2019 16:25	4/16/2019 14:07
4	10/29/2019 15:02	11/13/2019 13:32
5	8/19/2020 12:11	10/14/2020 9:57
6	1/5/2021 10:05	1/21/2021 17:12

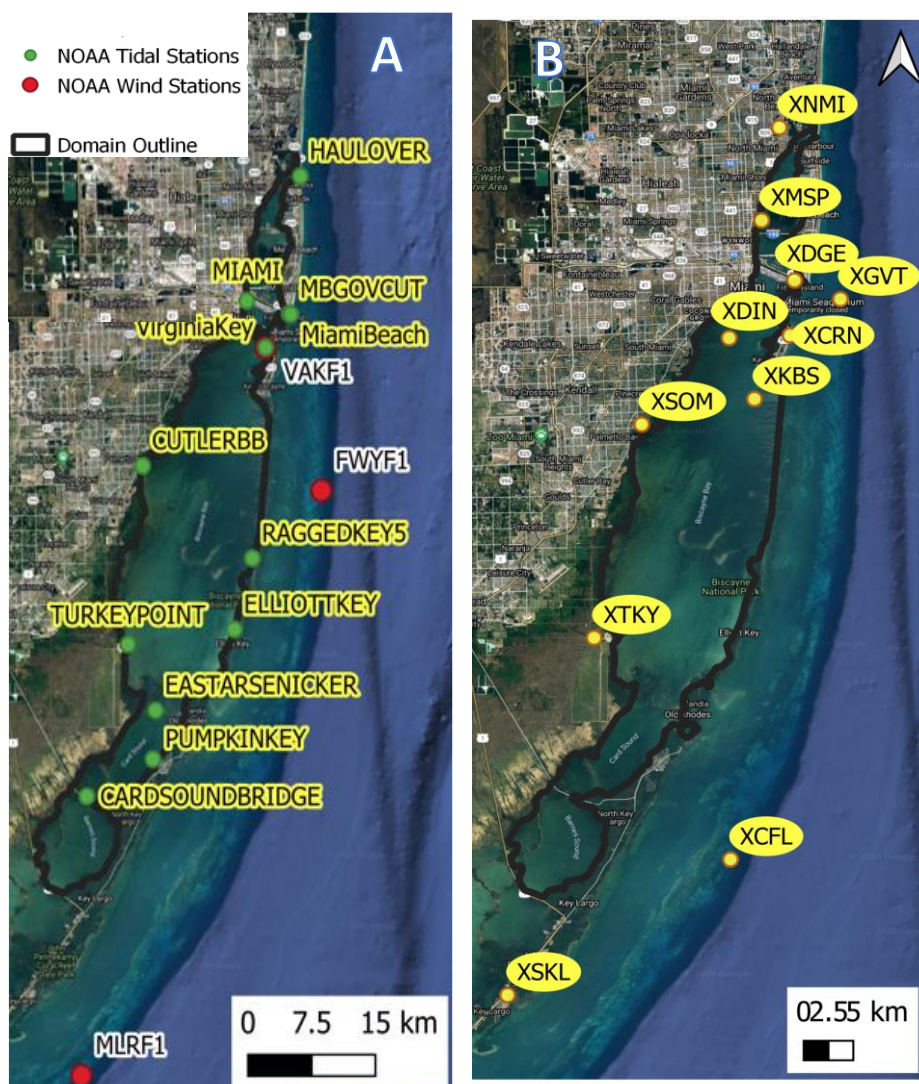


Figure 2 A:NOAA tide and wind stations; B: Weather Flow wind stations



Figure 3 FIU Monitoring Stations.

8 Computer Model

The computer model used in this project is based on RiverFlow2D (Hydronia, 2020), a combined two-dimensional (2D) hydrologic and hydraulic, sediment transport, and water quality flexible mesh model for rivers, floodplains, estuaries, and coastal areas. RiverFlow2D is capable of computing velocities, depths, sediment, and pollutant concentrations in unstructured triangular-cell meshes that can be adapted to irregular boundaries and accurately represent bathymetric gradients. The model allows achieving stable and accurate finite-volume solutions with virtually exact local and global mass conservation at the triangular-cell level without requiring artificial terms to stabilize the numerical solution (Hydronia, 2020, Valera et al., 2016). In addition, the computation engine can run in advanced GPUs (Graphics Processing Units) that significantly reduces run times for high-resolution applications. This represents a considerable improvement over previous Biscayne Bay models, since the high-performance computing version of RiverFlow2D is capable of significantly reducing runtimes, bringing opportunities to simulate high-resolution hydrodynamics and water quality assessments.

The model has been extensively used in hundreds of projects worldwide to assess hydrodynamics and pollutant transport in rivers and coastal areas (Valera et al., 2016; Mahmoudi et al., 2017). The use of unstructured flexible meshes based on triangles of user-selected size allows for obtaining detailed general circulation patterns over complex bathymetry and contour geometries such as those typical of Biscayne Bay. This flexibility allows high-resolution results over the areas of interest while using large cells on areas away from the canals. The model computes at each triangular cell the water velocity vector, depth, and the concentration of suspended sediments and chemical constituents. The velocities and depths are a function of the time-dependent wind field and tidal forcing. The model also accounts for solute concentration for each pollutant, reaction rates for the transport, and reaction processes for the following parameters: Dissolved Oxygen (DO), Temperature (Tem), Salinity (Sal), Carbonaceous biological Oxygen demand, Phytoplankton, Total organic carbon (TOC), Total coliforms, Ammonium, Nitrate, Organic Nitrogen, Inorganic, and Organic Phosphorus.

In addition to the numerical capabilities, RiverFlow2D includes a Graphical User Interface (GUI) based upon a plugin developed by Hydronia for the Open Source Geographical Information System QGIS (www.qgis.org). The GUI offers a comprehensive set of visualization tools, including map rendering, animations, and exporting graphs in shapefile format and Google Earth. This means that future users of BBOM will be able to make changes, simulations, and visualizations in a friendly, easy to use software environment.

9 Hydrodynamic and Salinity Transport Equations

The BBOM hydrodynamic and salinity transport equations can be expressed in vector form as follows:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} + \frac{\partial \mathbf{G}(\mathbf{U})}{\partial y} = \mathbf{H}(\mathbf{U}) + \mathbf{R}(\mathbf{U}) + \mathbf{D}(\mathbf{U})$$

Where x and y are the horizontal spatial coordinates, t is time, and the state vectors are written as follows:

$$\begin{aligned}\mathbf{U} &= (h, q_x, q_y, h\phi)^T \\ \mathbf{F} &= \left(q_x, \frac{q_x^2}{h} + \frac{1}{2}gh^2, \frac{q_x q_y}{h}, h\phi u \right)^T \\ \mathbf{G} &= \left(q_y, \frac{q_x q_y}{h}, \frac{q_y^2}{h} + \frac{1}{2}gh^2, h\phi v \right)^T \\ \mathbf{H} &= (0, gh(S_{0x} - S_{fx}), gh(S_{0y} - S_{fy}), 0)^T\end{aligned}$$

Where $q_x = uh$, $q_y = vh$, u and v are the depth-integrated velocity components in x and y directions respectively, h is the water depth, and ϕ is the depth-integrated salinity, g is the gravitational acceleration S_{0x} , S_{0y} are bed slopes and S_{fx} , S_{fy} are the friction slopes. The sources terms associated to the salinity transport equation are expressed as follows:

$$\begin{aligned}\mathbf{R} &= (0, 0, 0, -Kh\phi)^T \\ \mathbf{D} &= (0, 0, 0, \nabla(Dh\nabla\phi))^T\end{aligned}$$

Where K is an uptake parameter not used for now in the salinity model, and D is an empirical dispersion matrix.

10 Bathymetric Data

The bathymetric data used throughout the project for the Biscayne Bay Operational Model was obtained from the NOAA website¹ and corresponds to the Continuously Updated Digital Elevation Model (CUDEM) - 1/9 Arc-Second Resolution Bathymetric-Topographic Tiles, National Centers for Environmental Information, NESDIS, NOAA, U.S. Department of Commerce. The data was last updated on 2019-09-03. This data will be referred to as *Topo-bathymetric* since it does not only include the underwater elevations, but it covers part of the land coast that confines Biscayne Bay.

The dataset belongs to a suite of Digital Elevation Models (DEMs) for the U.S. coast to support a variety of NOAA missions, including improved inundation modeling and mapping, habitat characterization, and visualization of Earth's surface. The DEMs were developed according to a 0.25-degree tiling scheme. The spatial resolution of the tiles "telescopes" from the coastal zone to the deep ocean floor at 1/9, 1/3, and 3 arc-second grid resolution. Only the 1/9 arc-second DEM tiles integrate both bathymetric and topographic data; all other resolutions map bathymetry only. The tiling of the DEMs facilitates targeted, rapid updates as new coastal and marine elevation data are acquired and become available. Bathymetric and topographic data utilized for DEM creation originate from a variety of sources, including (but not limited to) the NOAA Office of Coast Survey, NOAA National Geodetic Survey, NOAA Office for Coastal Management, U.S. Geological Survey, and the U.S. Army Corps of Engineers. The DEMs are referenced vertically to the North American Vertical Datum of 1988. The vertical units of the DEMs are meters. The DEMs are referenced horizontally to the North American Datum of 1983. The horizontal units of the data are decimal degrees. This data set is a raster file with 14457 columns and 28411 rows and may have been mosaiced, re-projected, and clipped from the original tiles. The data set was generated from a larger data set and includes all valid data within the requested geographic bounds.

10.1 Horizontal Positional Accuracy

The horizontal accuracy of the DEM is dependent upon the accuracy of the source datasets used in its creation in conjunction with the spatial resolution of the DEM. The horizontal accuracy of the source data collected using modern surveying techniques and equipment (e.g. Global Navigation Satellite Systems) is assumed to be 1 meter or better. Data acquired before the advent and widespread adoption of modern surveying techniques are likely less accurate. No quantitative horizontal accuracy analyses have been performed on the DEM tiles.

10.2 Vertical Positional Accuracy Report

The vertical accuracy of the DEM is dependent upon the accuracy of the source datasets used in its creation in conjunction with the spatial resolution of the DEM. The vertical accuracy of topographic data collected using modern surveying techniques and equipment (e.g., lidar) is assumed to be, at worst, better than 0.5 meters RMSE. The vertical accuracy of bathymetric data is dependent on a variety of factors, including acquisition sensor/platform, post-processing,

1 <https://coast.noaa.gov/dataviewer/#/lidar/search/where:id=8483>

environmental conditions, and surveyed depth range. No quantitative vertical accuracy analyses have been performed on the DEM tiles. Figure 3 presents a general view of the topo-bathymetric data set.

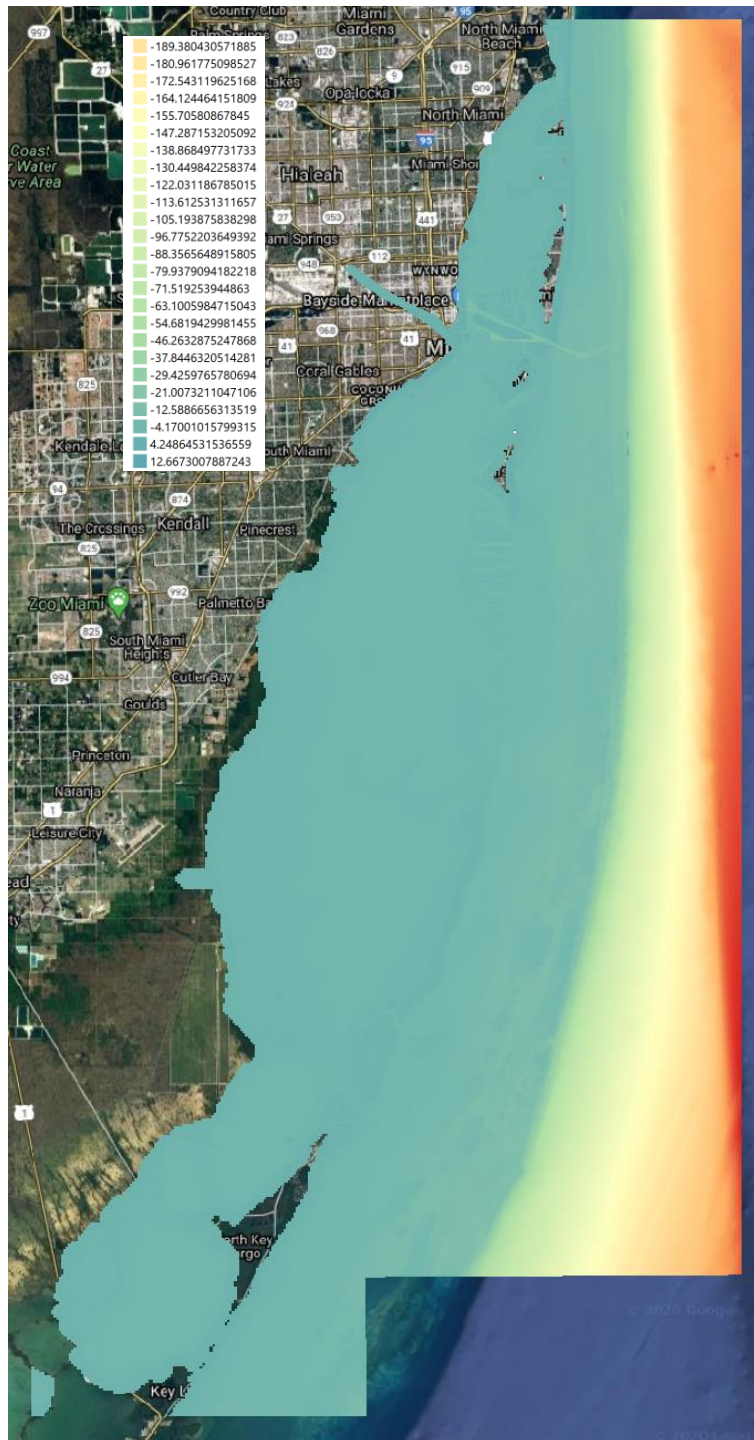


Figure 3 Topo-bathymetric data set used for the Biscayne Bay Operational Model. Colors and numbers in the legend indicate elevation in meters.

11 Hydrodynamic Model Calibration

This section presents the results of the calibration of the BBOM hydrodynamic. The purpose of this calibration is to ensure that adjusting bed roughness Manning's n parameters the model can reproduce the bay hydrodynamics represented by dynamic velocity fields and water elevations. In order to assess the quality of the calibration the model results were compared with available data and data gathered in the measurement campaigns performed in the project.

11.1 Tidal Data

There are 12 NOAA stations with 6-minute interval tidal data in the Biscayne Bay that were initially considered for this study, and they are listed in Table 2.

Figure 4 shows a map with the station locations. We downloaded the data needed for modeling at 6 min intervals from the NOAA website. Observed data are only available for Virginia Key stations. Other stations only provide predicted water surface elevations. Since in the first phase of this study there were no measurements that could be used as boundary conditions, predicted values from NOAA station were used in to initiate the study. The stations near boundaries were used as boundary conditions (Haulover, Miami Beach Government Cut, Virginia Key, Ragged Key No. 5, and Elliot Key). Other stations re used for calibration and evaluation of the model results.

The NOAA site did not allow the option to select the desired tidal datum NAVD 88 for stations 8723178, 8723355, 8723409, 8723465, and 8723506. Therefore, raw data were downloaded from NOAA website by selecting MLLW datum, and later, they were converted to NAVD 88 using NOAA vertical datum transformation online tools (<https://vdatum.noaa.gov/vdatumweb/>).

Table 2 NOAA tidal stations used in the Project.

No.	Name	code	Longitude	Latitude	Original Datum	Datum	Correction
1	HAULOVER PIER, N. MIAMI BEACH	8723080	-80.12	25.90333333	NAVD	NAVD	0
2	MIAMI, BISCAYNE BAY	8723165	-80.185	25.77833333	NAVD	NAVD	0
3	Miami Beach	8723170	- 80.13166667	25.76833333	NAVD	NAVD	0
4	MIAMI BEACH, GOVERNMENT CUT	8723178	-80.13	25.76333333	MLLW	NAVD	0.685
5	Virginia Key	8723214	- 80.16166667	25.73166667	NAVD	NAVD	0
6	CUTLER, BISCAYNE BAY	8723289	-80.305	25.615	NAVD	NAVD	
7	RAGGED KEY NO. 5, BISCAYNE BAY	8723355	-80.175	25.52333333	MLLW	NAVD	0.54
8	ELLIOTT KEY HARBOR, ELLIOTT KEY	8723409	- 80.19666667	25.45333333	MLLW	NAVD	0.514
9	TURKEY POINT, BISCAYNE BAY	8723423	-80.33	25.43666667	NAVD	NAVD	0
10	EAST ARSENICKER, CARD SOUND	8723465	-80.29	25.37333333	MLLW	NAVD	0.415
11	PUMPKIN KEY, CARD SOUND	8723506	- 80.29333333	25.325	MLLW	NAVD	0.366
12	CARD SOUND BRIDGE	8723534	-80.37	25.28833333	NAVD	NAVD	0

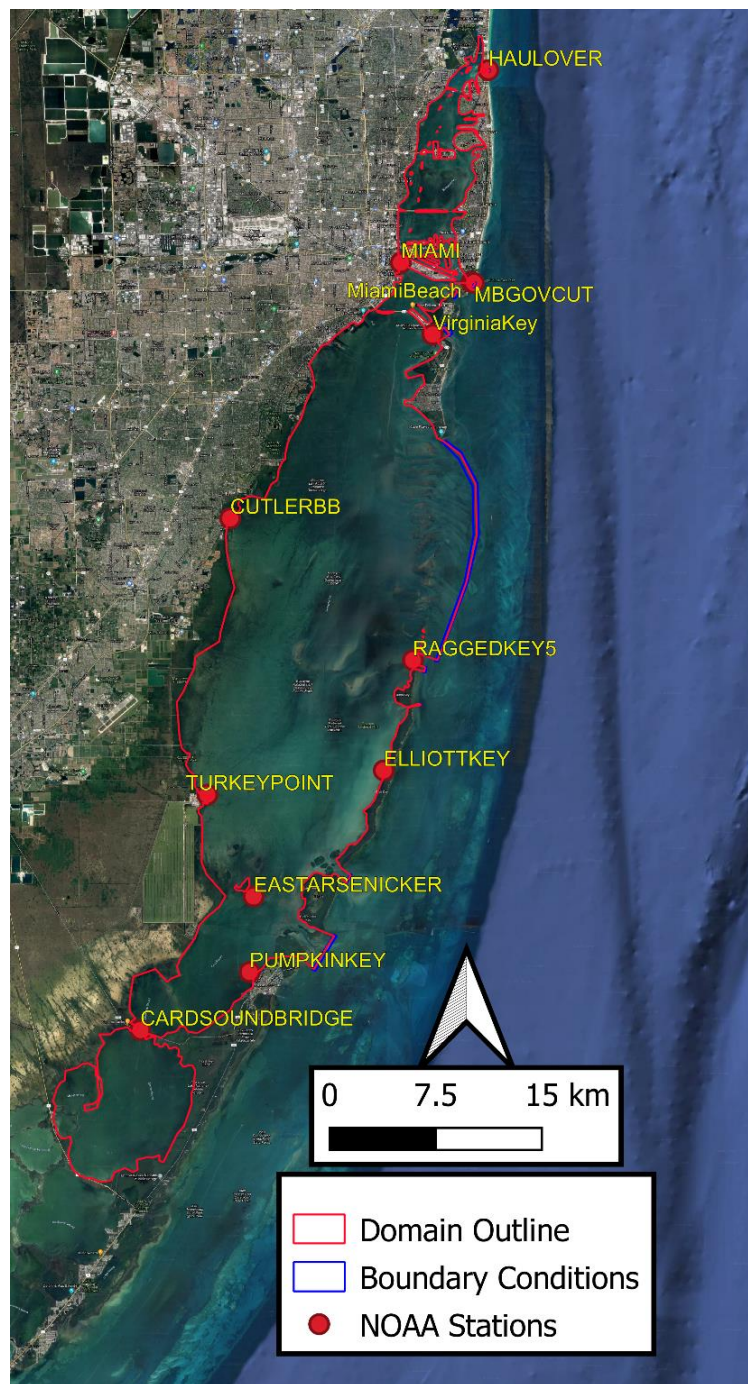


Figure 4 NOAA Tidal Elevation Stations. Virginia Key station has observed tidal elevations. On all other stations, NOAA provides tide elevation predictions.

11.2 Wind Data

Two sources for wind data were in the project. One is from NOAA stations and the second from Weather Flow, a private company that provides weather data service in the region.

Table 3 presents the wind station location and site elevation used. The distributions of the stations in Biscayne Bay is shown in Figure 5. The historical data from NOAA is approximately complete from 2017 till the end of 2019. But station MLRF1 has data until April 2019. However, the data provided by Weather Flow is not complete. The data covers three-time ranges of October 1st-20th 2017, June 15th-30th 2018, and November 1st 2018-June 30th 2019.

We performed a qualitative analysis of the wind data for stations MLRF1, XSKL, XCFL, XTKY, FWYF1, XSOM, XKBS, and VAKF1, and found that the dominant wind direction is relatively homogeneous inside the Bay. This is clear from the wind rose of some stations (Figure 5). Other researchers saw the same trends comparing Fowey Rocks and Convoy Point velocity FWYF1 (Brown et al. 2003; McAdory et al. 2002). Based on this assumption, Brown et al. (2013) used Convoy Point data for the whole Bay. However, for the central Bay, a higher wind velocity is considered with a factor of 1.225, since it was assumed that North Bay, South Bay (Card and Barnes Sounds), and along the western shoreline in Central Bay are relatively sheltered as compared with the main Central Bay area.

Since the height of the sensors is different in each station, the raw velocity data were adjusted to account for differences in magnitude due to the height of data collection. The raw data were corrected to the standard 10-m height above the water using the following equation (Hsu 1988).

$$V = v_{ref} \frac{\ln(z/z_{ref})}{\ln(z_{ref}/z_0)}$$

Where V , is the velocity at elevation z above the water surface, and v_{ref} , is the measured velocity at the elevation of z_{ref} . z_0 , is the roughness height in the wind direction. The roughness and site elevation values are also shown in Table 3. These height corrected data can be used to calculate wind stress on the water surface using the formulation of Wu (1980).

Table 3 List of wind stations.

Source	Name	code	Lat	Lon	Roughness (m)	Site elevation (m)	height above site elevation (m)
NOAA	Fowey Rock	FWYF1	25.5906	-80.0967	0.0002	0	43.9
NOAA	Virginia Key	VAKF1	25.7314	-80.1619	0.02	1.7	10.2
NOAA	Molasses Reef	MLRF1	25.0117	-80.3764	0.0002	0	15.8
NOAA	Port Everglades Channel	PVGF1	26.0925	-80.1089	0.1	3	3.5
NOAA	Port Everglades	PEGF1-8722956	26.0858	-80.1158	0.1	-	-
Everglades NPS	Whipray Basin	WRBF1	25.0722	-80.7353	-	-	-
Weather Flow	Carysfort Reef Light	XCFL	25.2269	-80.2092	0.0002	0	14.5
Weather Flow	Crandon	XCRN	25.7158	-80.1497	0.015	1	7.9
Weather Flow	Biscayne Bay Harbor Pilots	XDGE	25.7669	-80.1453	0.3	4	12.3
Weather Flow	Dinner Key Light 1	XDIN	25.7133	-80.2106	0.0002	0	5.2
Weather Flow	Government Cut	XGVT	25.7495	-80.0995	0.0002	0	22.9
Weather Flow	Biscayne Bay Light 20	XKBS	25.6566	-80.1853	0.0002	0	6.1
Weather Flow	Morningside Park	XMSP	25.8228	-80.1782	0.1	0	10.4
Weather Flow	North Miami	XNMI	25.9092	-80.1605	0.2	3	16.8
Weather Flow	South Key Largo	XSKL	25.1001	-80.4318	0.1	2	18.3
Weather Flow	South Miami	XSOM	25.6328	-80.2979	0.12	4	10.4
Weather Flow	Turkey Point	XTKY	25.4339	-80.3454	0.03	1	19.8

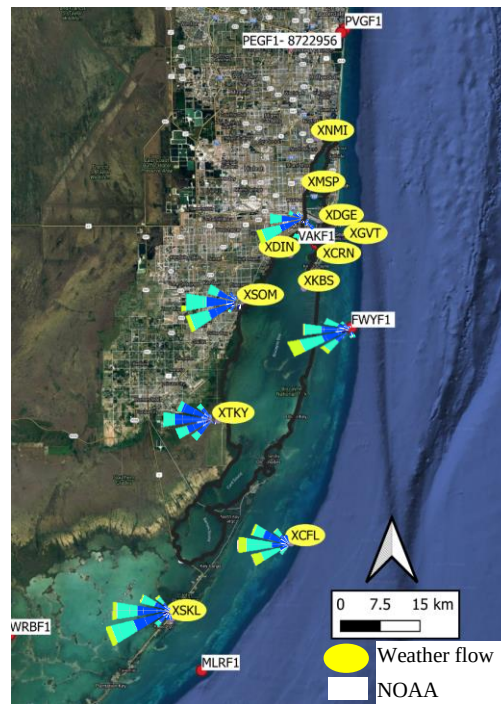


Figure 5 Location of the wind stations, Yellow ellipse and white rectangular are weather flow and NOAA stations.

11.3 Velocity Data

The velocity data were collected during five campaigns since October 2017. The measurement was done using TCM1 tilt current meter sensors produced by Lowell Instrument LLC. The velocity measurement has done at 1 min intervals. The list of the stations and campaigns for the measurements has shown in Table 4. Using the wind rose concept, the dominant velocity directions at BB1, BB2, BB3, and BB4 for the 3rd campaign are shown in the map in Figure 7. There are two dominant flow directions in each station and similarly in Biscayne Bay. Therefore, it can be expected that there are two flow cycles inside the Bay that are shown by red and yellow arrows in Figure 5. To better understand the flow patterns inside Biscayne Bay. The temporal changes in velocity and direction in each station are shown in Figure 7 for April 5th to 9th 2019. In this figure, the direction of the flow is shown by the green line. In all stations, there is two opposite main direction. For example, for BB1 these directions are NE (30°) and SW (200°). A close look at the velocity fluctuations shows that the maximum velocity always occurred in NE or SW direction. The velocity starts to decrease from its maximum in one direction, let's say NE (30°), to reach a minimum and change its direction toward SW. It continues to increase to reach a new maximum in the SW direction. There is a similar trend in other stations. However, the start time of flow direction changes is not the same in all stations. In other words, there is a lag in these fluctuations from BB1 to BB4. This phenomenon is shown by adding three red lines to Figure 7. These three lines are matched to the beginning and end of both cycles at BB1 station. The lag between BB2 and BB1 is very small. However, the lag between BB1 and BB3/BB4 fluctuations is about 50% of the length of each cycle. Therefore, when BB1 reaches 50% of its first cycle (for example, flow in direction 200°), the flow direction would change in BB3 and BB4. BB3 and BB4 follow the same

trend.

Table 4 FIU water velocity stations.

Biscayne Bay Sites	Site description	Latitude	Longitude	Campaign				
				1	2	3	4	5
BB1	Key Biscayne	25 41' 43.4"N	80 12' 27.6"W	*	*	*	*	*
BB2	N. Biscayne Nat'l Park	25 36' 50.5"N	80 14' 30.5"W	*	*	*	*	
BB3	Card Sound	25 19' 58.2"N	80 19' 01.3"W	*	*	*	*	
BB4	Barnes Sound	25 13' 25.0"N	80 23' 22.6"W	*	*	*	*	*
St#3	--	25°50'9.24"N	80° 8'55.48"W	--	--	--	--	*
St#5	--	25°48'40.92"N	80° 8'55.93"W	--	--	--	--	*
St#16	--	25°26'10.6"N	80°14'17.9"W	--	--	--	--	*

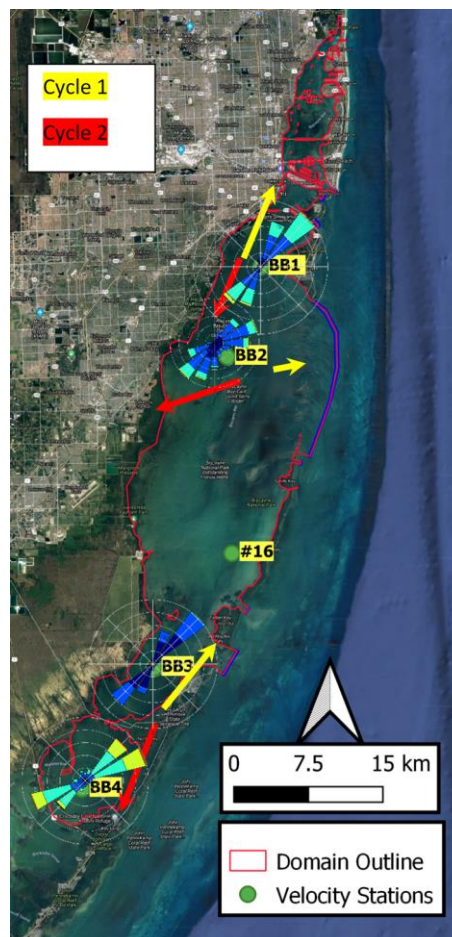


Figure 6 Water velocities observed at FIU Stations.

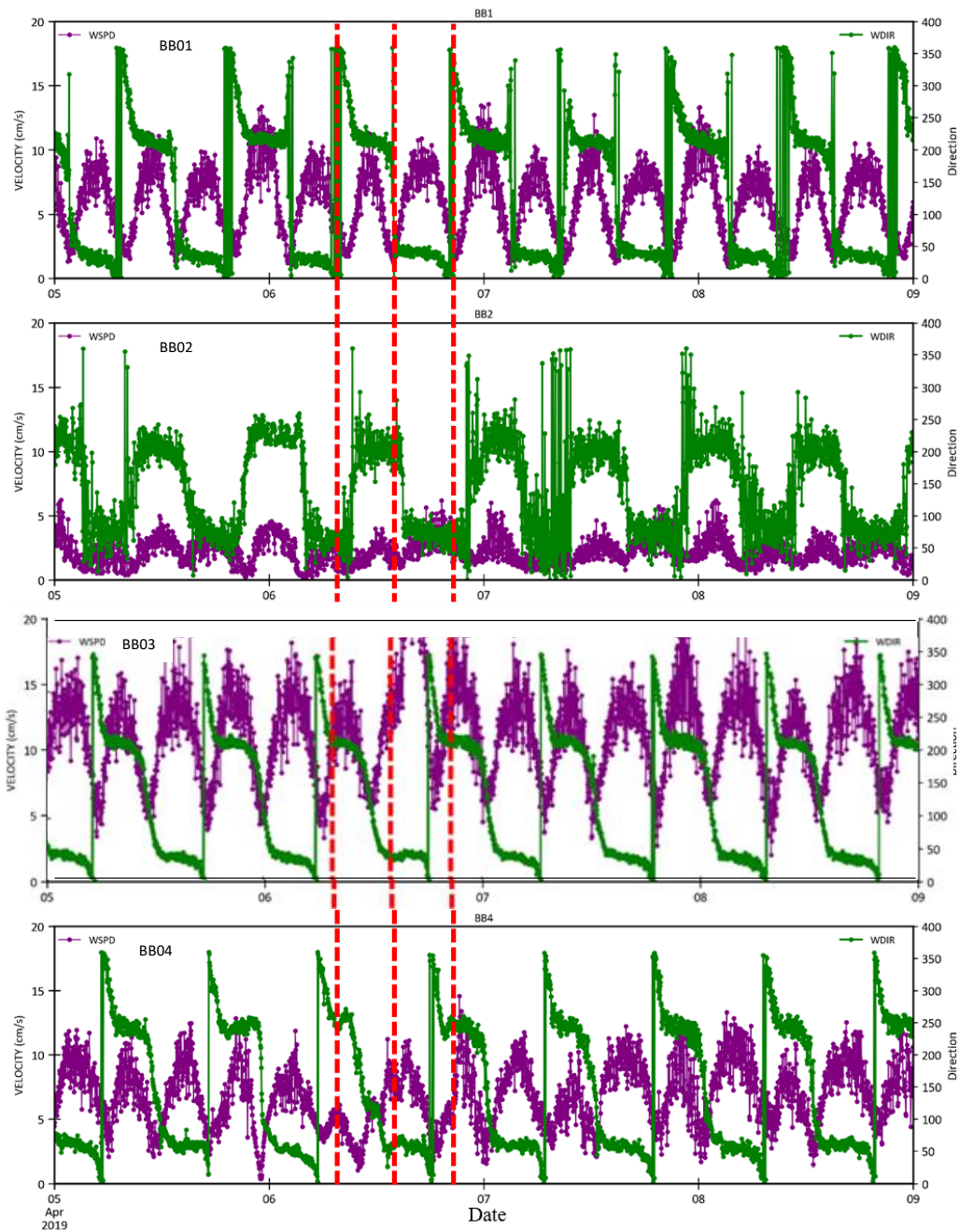


Figure 7 Dominant velocity directions at BB1, BB2, BB3, and BB4 for the 3rd campaign.

11.4 Depth Data

In the 2020 campaign, TCM1 sensors were installed at stations BB1, BB4, St#3, and St#5. In addition, pressure sensors were installed in stations BB1, BB4, and #15. The pressure sensors were designed and installed on a plate that was deployed at Biscayne Bay bed in the desired station, as shown in Figure 8. The sensor records the pressure (=depth) at one-minute intervals.

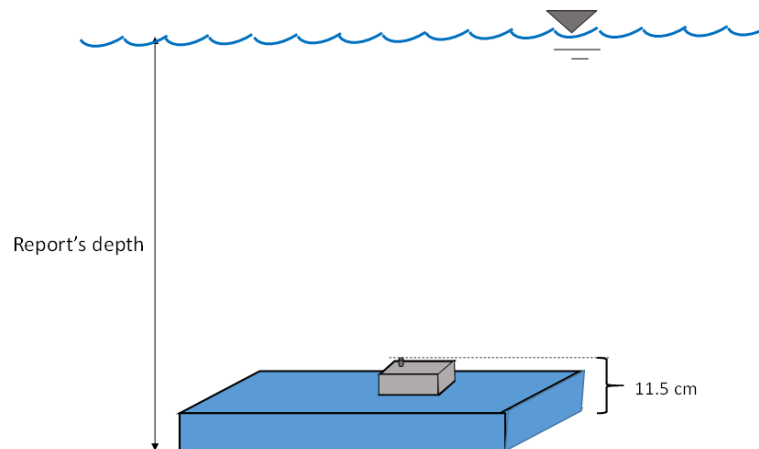


Figure 8 Illustration of pressure sensor deployment.

11.5 Model Implementation

For the hydrodynamic calibration stage, the model domain polygon was designed so it covers both north and south Biscayne Bay, Card and Barnes Sounds, and a part of the oceanic boundary that extends beyond the Safety Valve (see Figure 96). Extending the model domain in this way includes the essential role that the Safety Valve has in Biscayne Bay hydrodynamics while avoiding the potential numerical issues that could occur if we would locate an open boundary along a very shallow area with high velocities and drying zones. For the first phase of the calibration, tidal and wind forces were considered as the main forces controlling the water flow inside the Bay. The effect of groundwater interaction, evaporation, rainfall, and inflow from the canals will be considered in subsequent analysis.

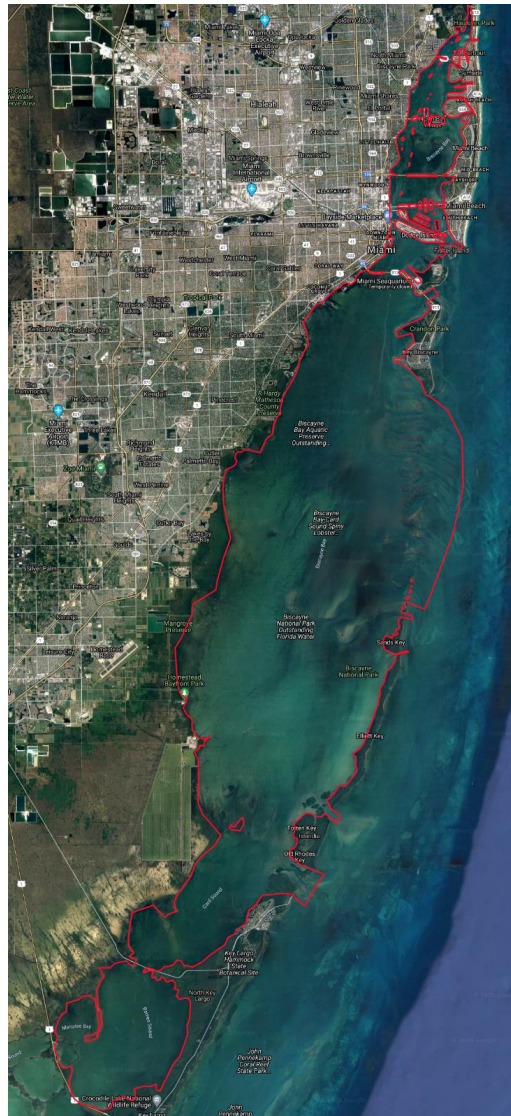


Figure 9 Model domain. The red polygon defines the model extent.

11.5.1 Mesh Geometry and Topology

The mesh developed for the model calibration has 43,872 cells covering an area of 733 km². The cell sizes vary from 24 m to 610 m. Figure 10 depicts the model computational mesh that was generated for BBOM hydrodynamic calibration.

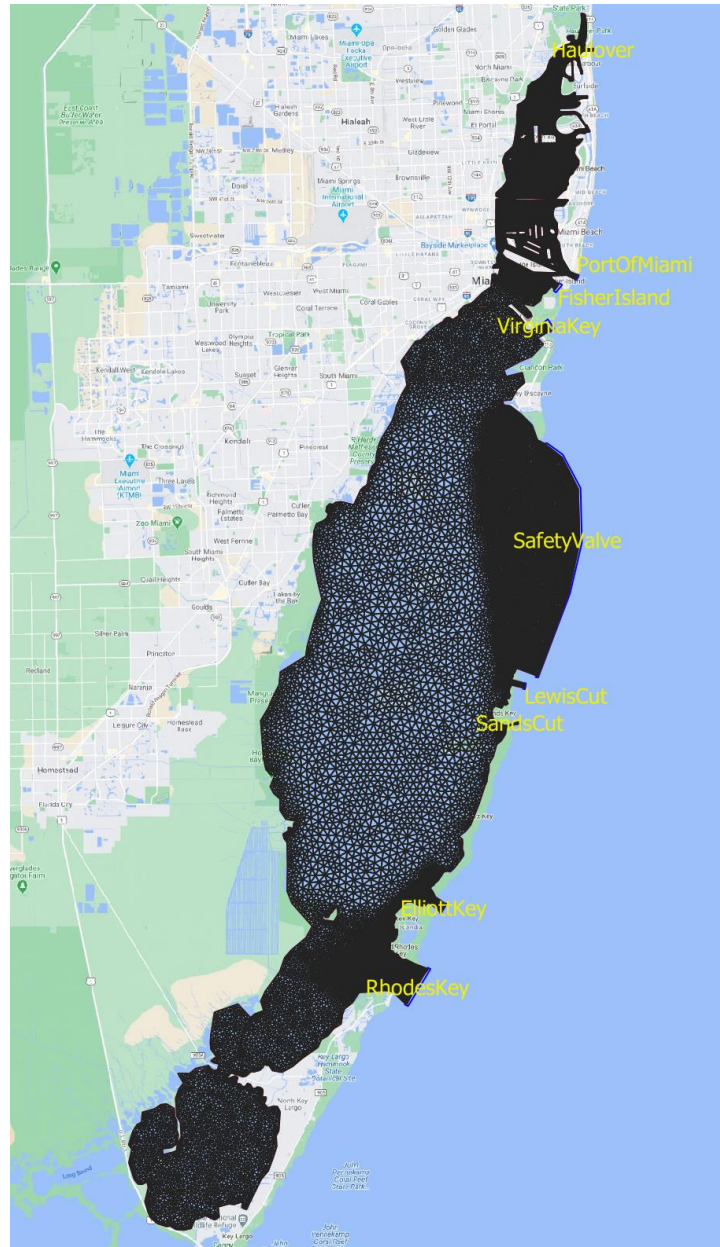


Figure 10 Biscayne Bay Operational Model (BBOM) computation mesh. Darker areas are higher resolution zones with smaller cells to better represent bathymetric and contour gradients.

Table 5 BBOM Flexible Mesh Parameters.

Mesh Parameter	Value
Number of cells (triangles)	43,872
Number of nodes	23,390
Total mesh area	7,333 km ² .
Average cell size (approx.)	182.78 m.
Minimum cell size (approx.)	24.45 m.
Maximum cell size (approx.)	610.81 m.
Maximum cell elevation	19.94 m.
Minimum cell elevation	-52.28 m

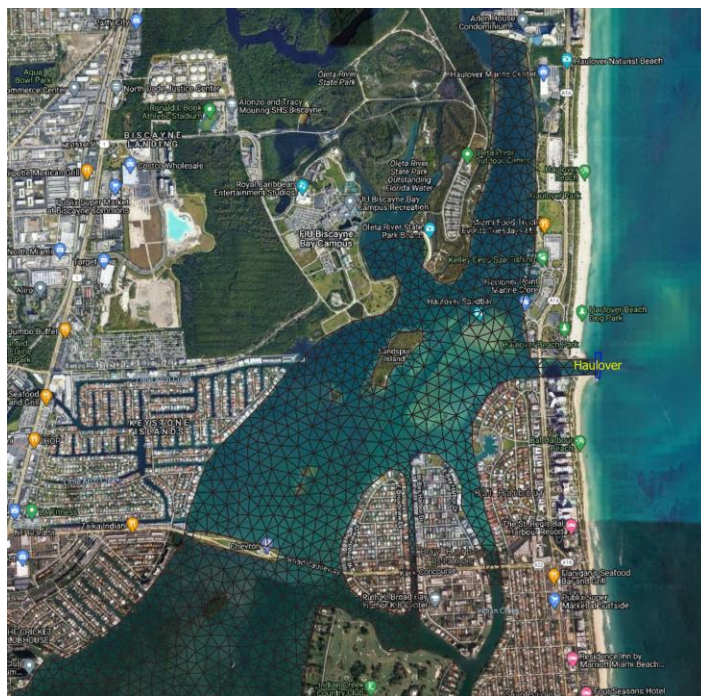


Figure 11 Detail of BBOM mesh on the northern end of Biscayne Bay, showing Haulover tidal open boundary.

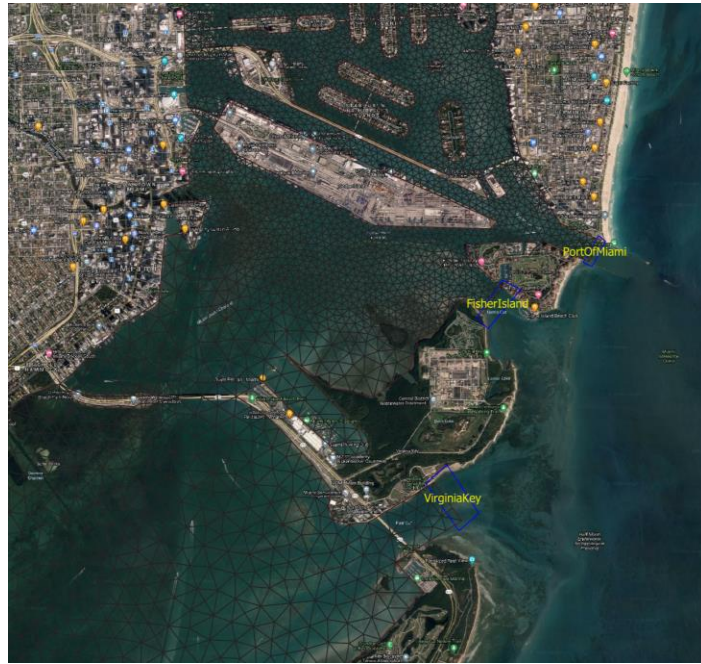


Figure 12 Detail of BBOM mesh around Virginia Key, showing Port of Miami, Fisher Island, and Virginia Key open boundaries.

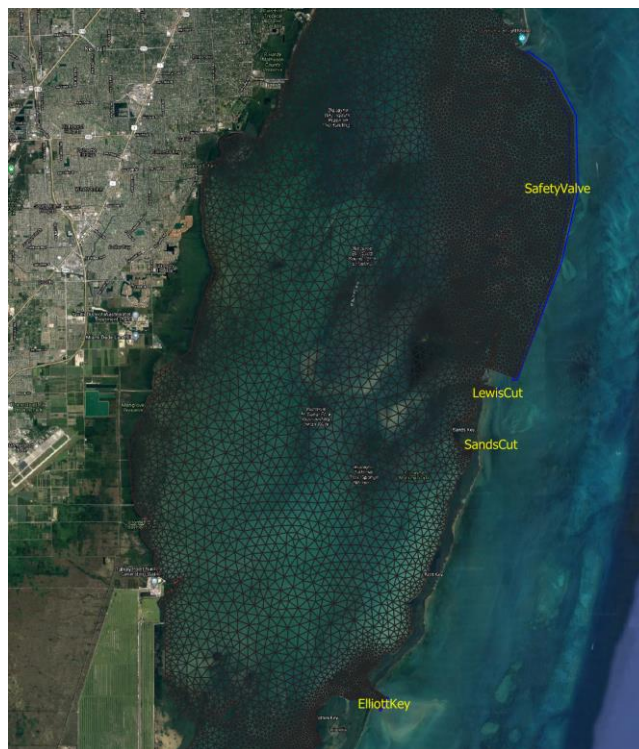


Figure 13 Detail of BBOM mesh in the central region of Biscayne Bay, showing the SafetyValve, LewisCut, SandsCut, and Elliott Key open boundaries.

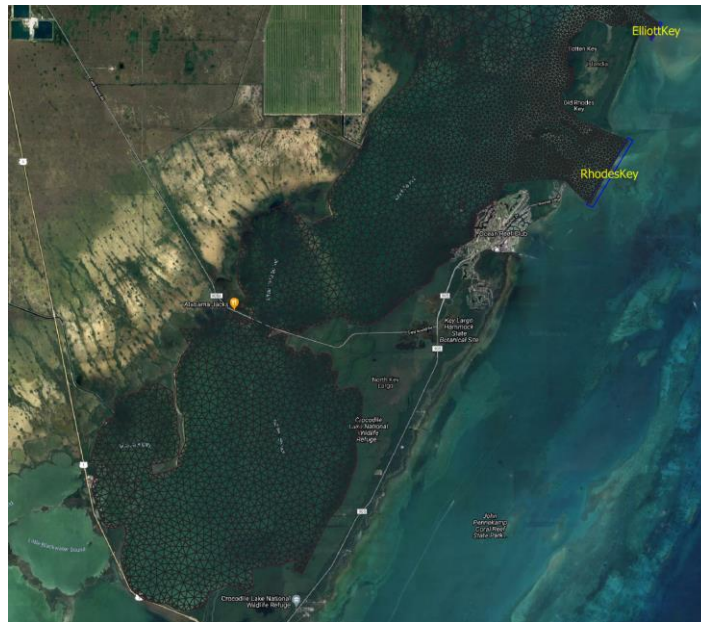


Figure 14 Detail of BBOM mesh in the southern Biscayne Bay, Elliott Key, and Rhodes Key.

11.5.2 *Bed roughness*

The model bed roughness and internal dissipation are represented in the model by a Manning's formula source term. The Manning's formula relates the bed roughness to the flow velocities, depth, and bottom gradient using a non-dimensional coefficient n that can typically vary from 0.012 for smooth surfaces to 0.5 or more for flow over highly vegetated or rough beds. Due to the inherent uncertainty involved in the determination of the n values, these are usually considered as a calibration coefficient that can be adjusted in order to reproduce results such as depths and velocities. The initial distribution of the Manning coefficient was adopted based on Brown et al. (2003) and later adjusted based on the initial calibration process. Figure 15 shows the distribution of n values in 10 areas, that was the starting point for the model calibration. Variation of these values affects the model results, as will be seen in later sections.

11.6 *Model Hydrodynamic Calibration Results*

The model hydrodynamic calibration started by performing a sensitivity analysis varying the tidal boundary conditions, the Manning's n roughness distribution, and the effect of wind stress using data for 1st, 2nd, 3rd, and 5th campaigns. In this process, the observed data, as well as the NOAA tidal predictions, were compared with the model results for the periods indicated in Table 6

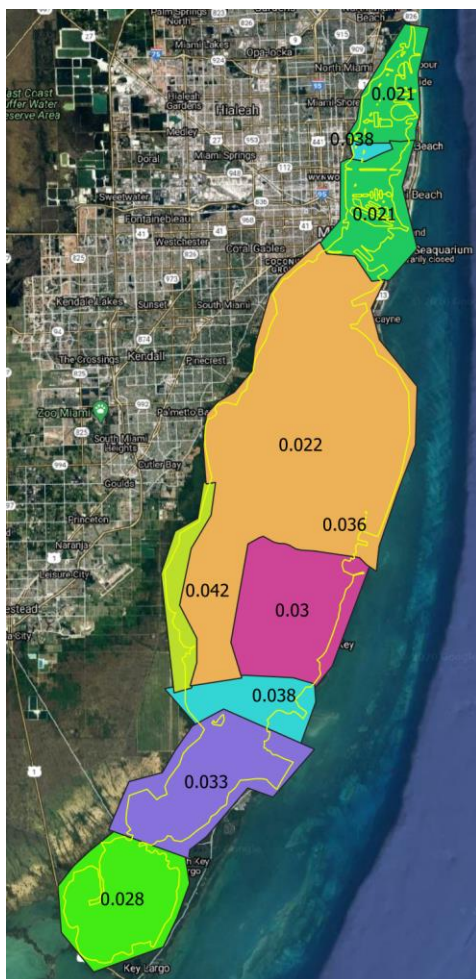
Figure 15 Manning's n roughness coefficient regions.

Table 6 Measurement and simulation periods.

No.	Measurement campaign time period	
	Start	End
1	2017-10-10	2017-10-17
2	2018-06-20	2018-06-28
3	2019-04-01	2019-04-16
4	2019-10-29	2019-11-13
5	2020-08-19	2020-10-14
6	2021-01-07	2021-01-19

For each measurement campaign, the model was run considering four different calibration scenarios to investigate the effect of boundary conditions, Manning's n coefficient, and wind effects. The scenarios were identified as CS1, CS2, CS3, and CS4.

In run CS1, a constant Manning coefficient of 0.014 was considered for the whole of Biscayne Bay the NOAA tidal values from Virginia Key station were assigned to all open boundaries.

In scenario CS2 imposed tidal prediction at each open boundary taken from the nearest NOAA station as it is illustrated in Figure 16.

For the scenario CS3, in addition to imposing the same tidal conditions as CS2, considered distributed Manning's n areas as shown in Figure 15.

Scenario SC4, included the conditions indicated for scenario CS3 and added the effect of wind stress.

Table 7 summarizes the conditions used in each scenario.

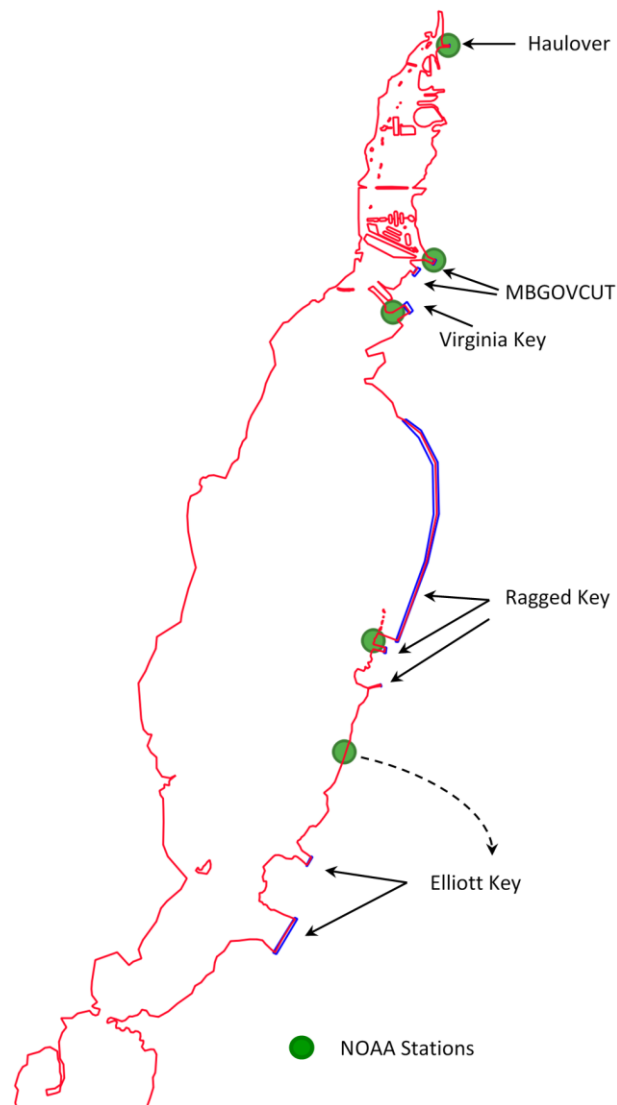


Figure 16 NOAA data and prediction stations used for the model calibration.

Table 7 Calibration scenarios.

Scenario	Tidal condition	Manning's n roughness	Wind
SC1	Virginia key tide for all boundaries.	Constant $n = 0.014$	Not considered.
SC2	Variable from nearest NOAA prediction station.	Distributed according to Figure 15.	Not considered.
SC3	Variable from nearest NOAA prediction station.	Distributed according to Figure 15.	Not considered.
SC4	Variable from nearest NOAA prediction station.	Distributed according to Figure 15.	Distributed.

Note that in all the figures that follow in this section, the “_const Boundary” refer to the case where only Virginia Key tide is used for all open boundary conditions. “_var Boundary” is used to identify results when the nearest NOAA station is used. “_const. n” refers to the case of constant Manning's n, while “_var. n” is used for distributed Manning's n.

Figure 17 to Figure 25 present comparisons of the velocity and water surface elevation predicted by the model for calibration scenarios CE1 and CE2 at all observation points for the 2020 campaign. The measured velocities at stations St#3, St#5, and St#16, BB1, and BB4 are also shown. Since the measured water elevations were limited to stations St#15, BB1, and BB4, we used other locations where NOAA tidal predictions are available.

Figure 26 to Figure 34 show the results of calibration scenarios CE2, CE3, and CE4 show the model comparison of the model results with predictions and measurements to assess the model sensitivity to boundary conditions, Manning's n distribution, and wind.

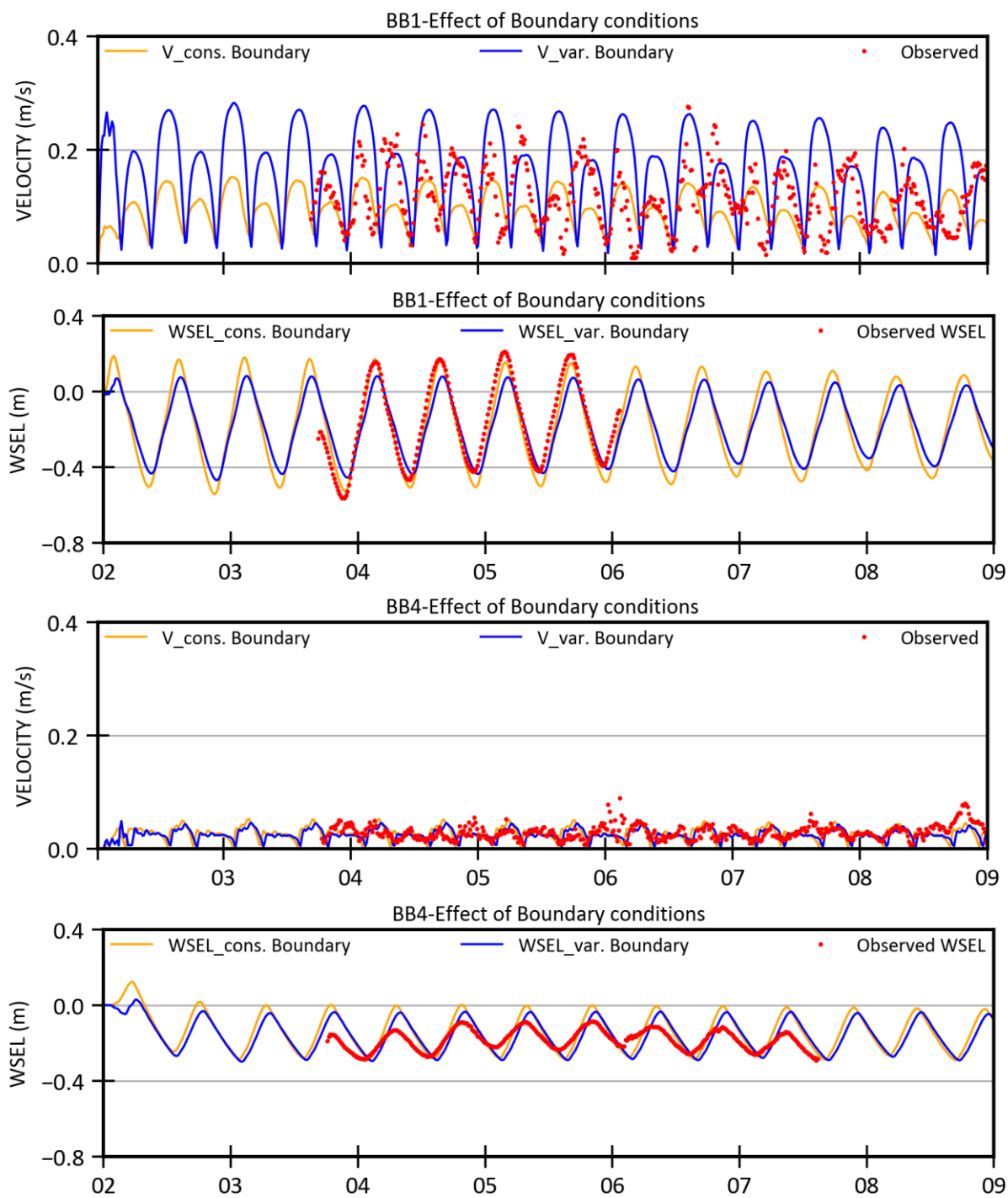


Figure 17 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations BB1 and BB4.

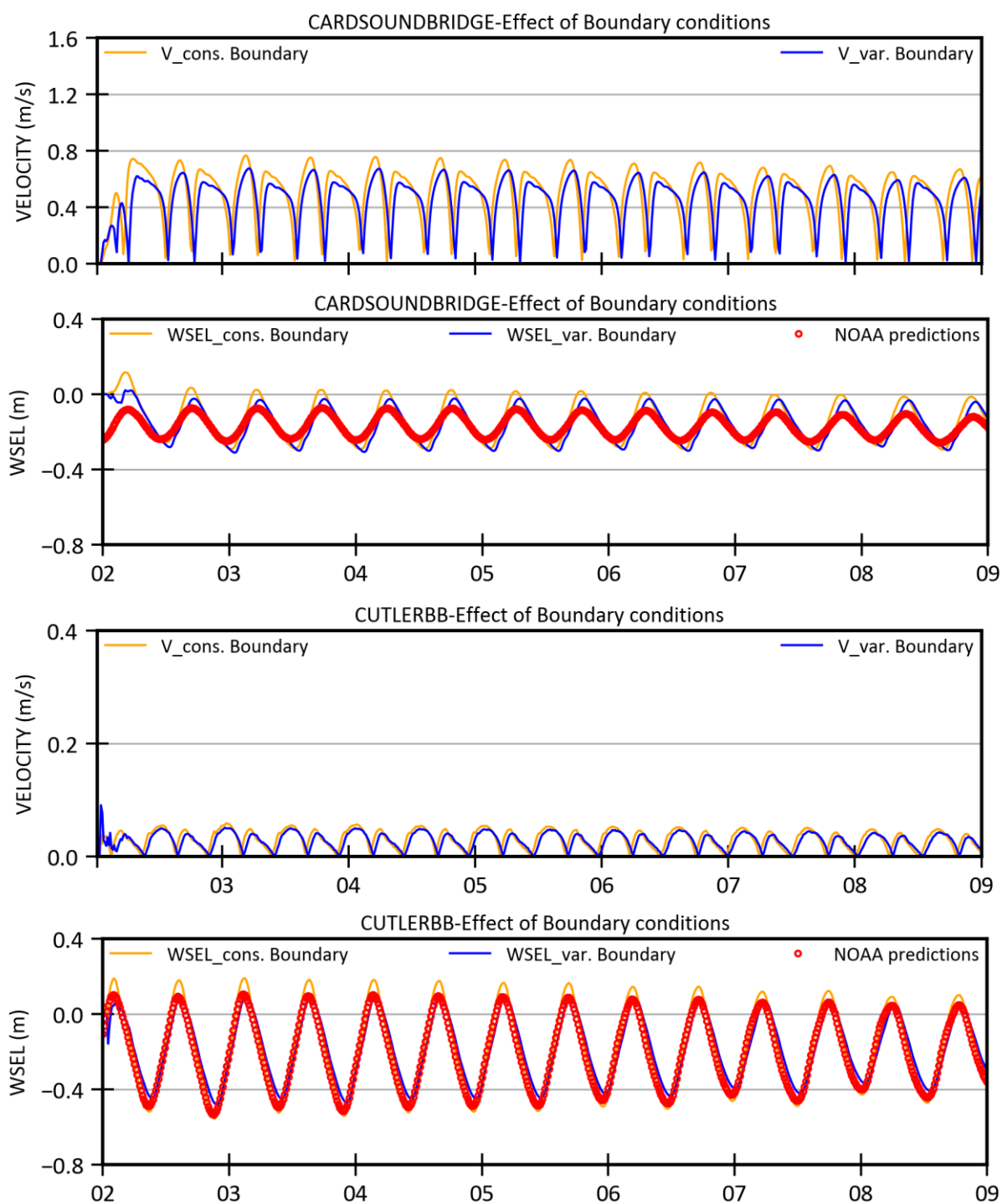


Figure 18 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations CardSoundBridge and CutlerBB and BB4.

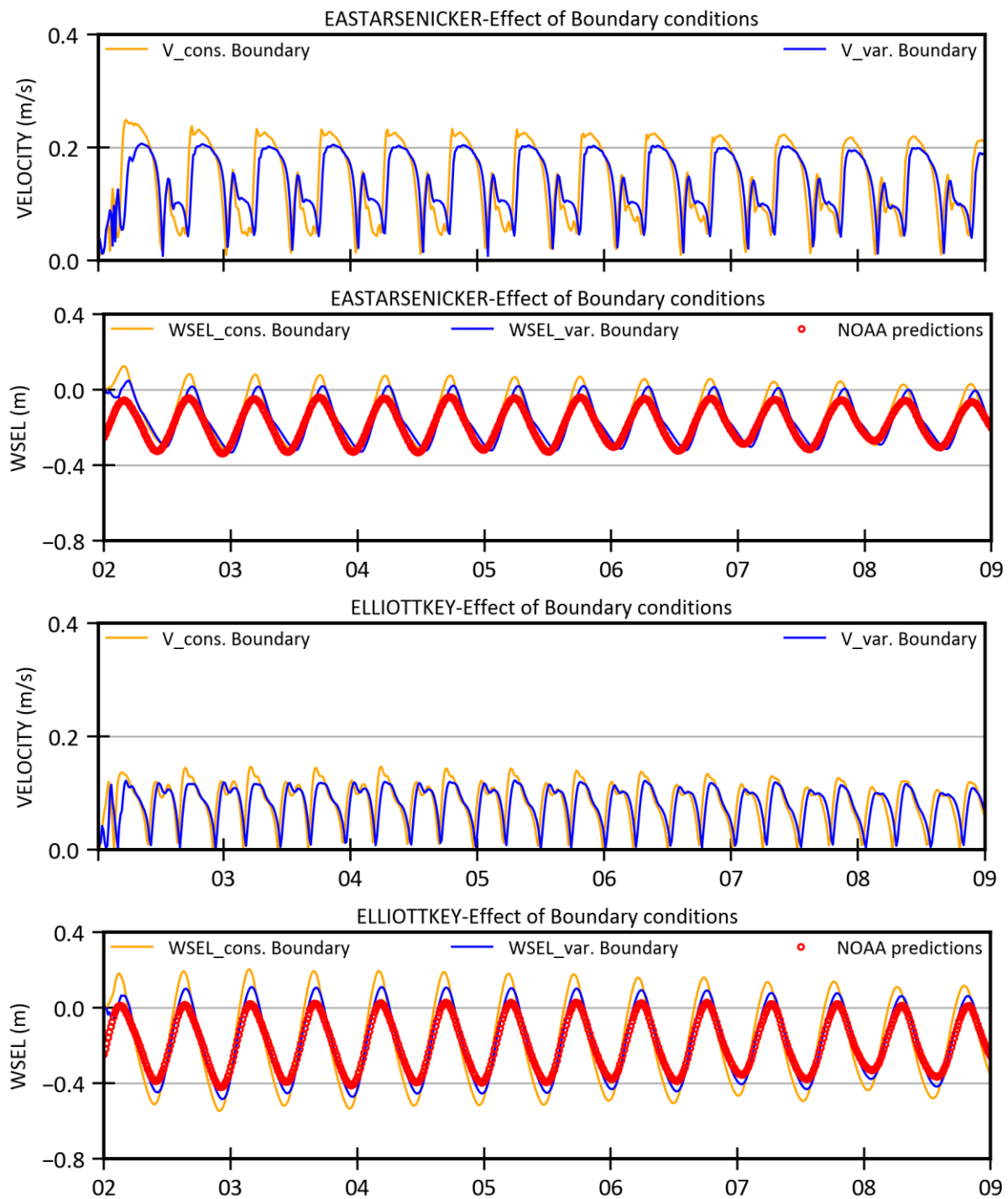


Figure 19 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations EASTARSENICKER and ELLIOTTKEY.

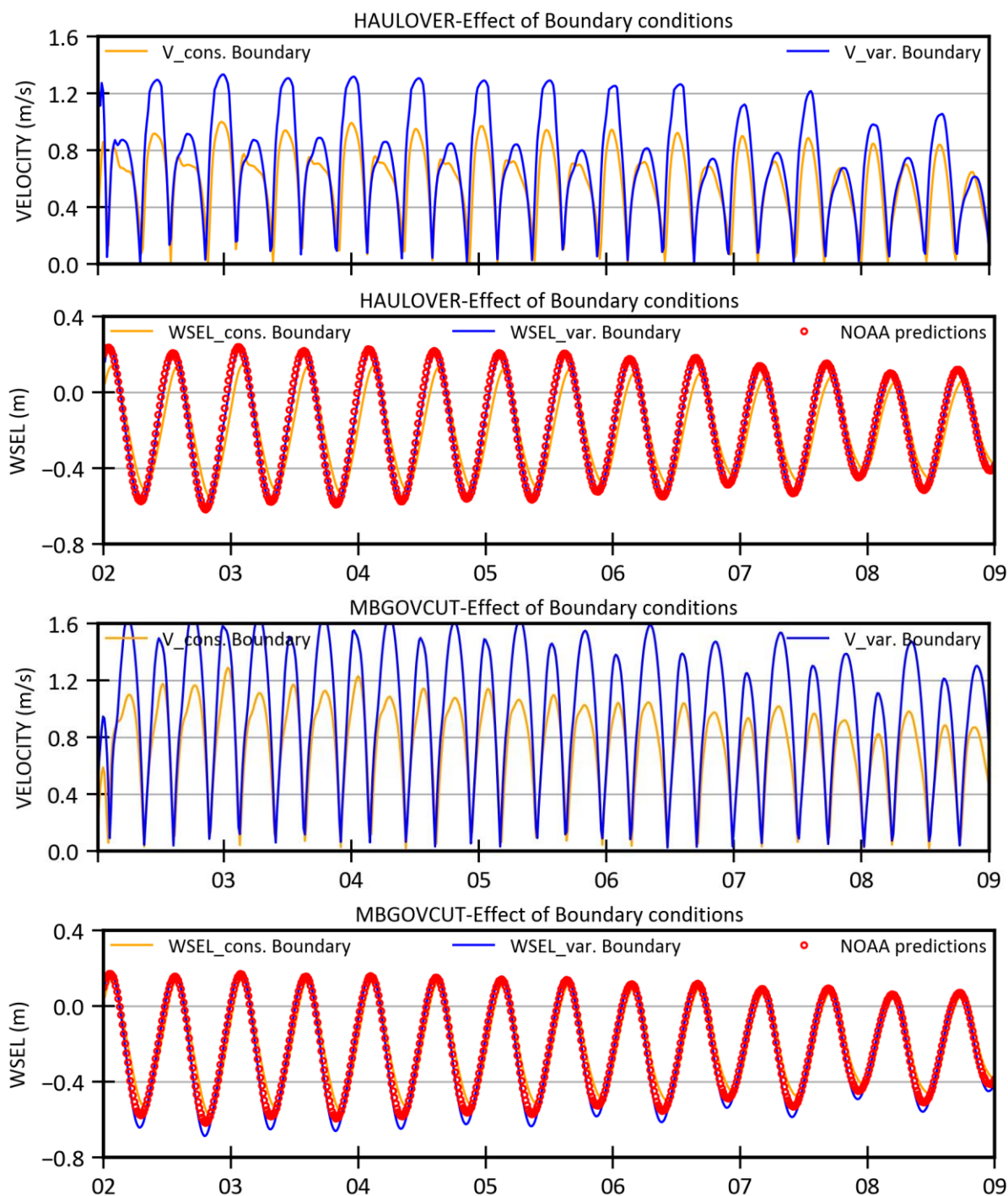


Figure 20 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations HAULOVER and MGGOV CUT.

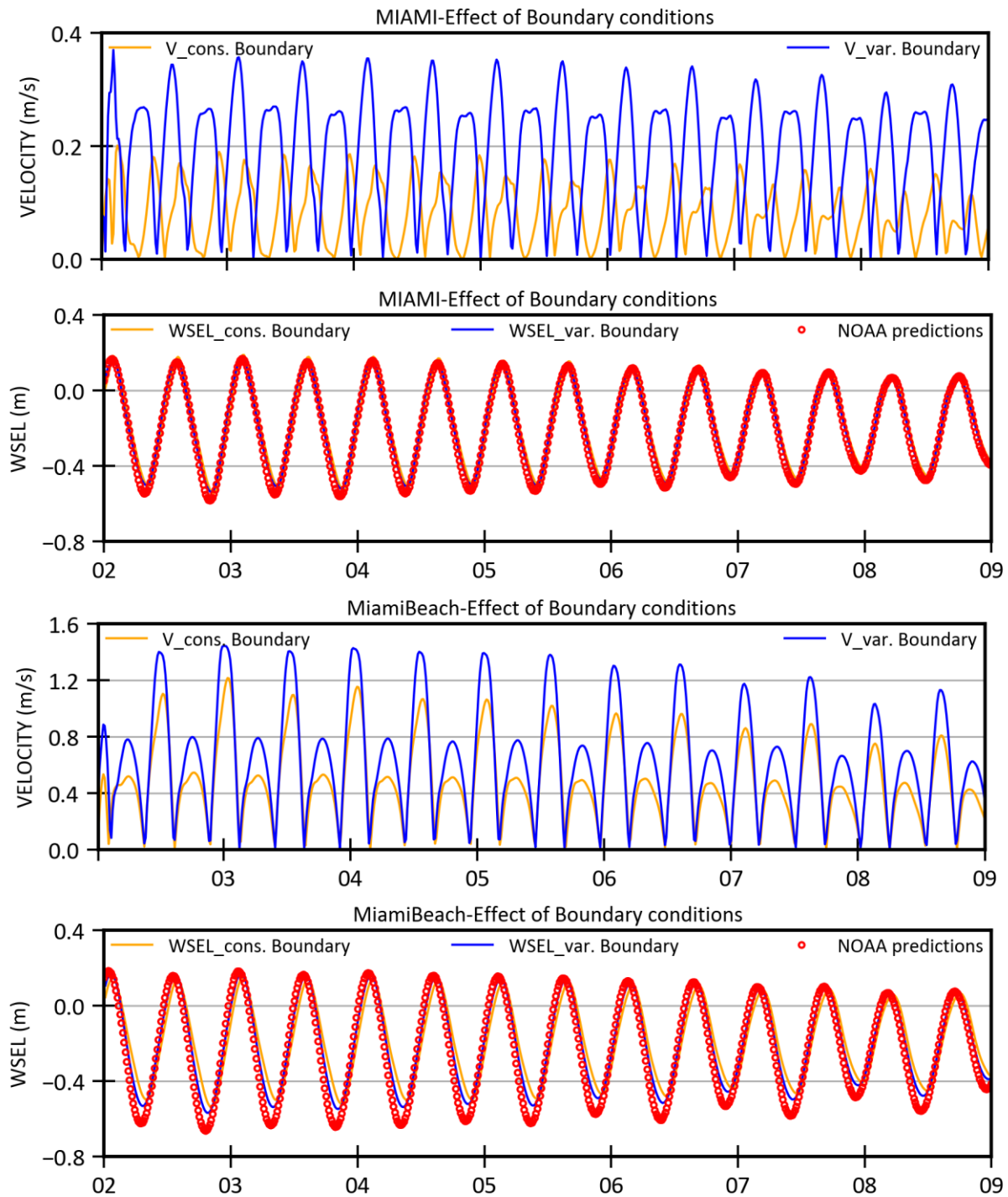


Figure 21 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations Miami and MiamiBeach.

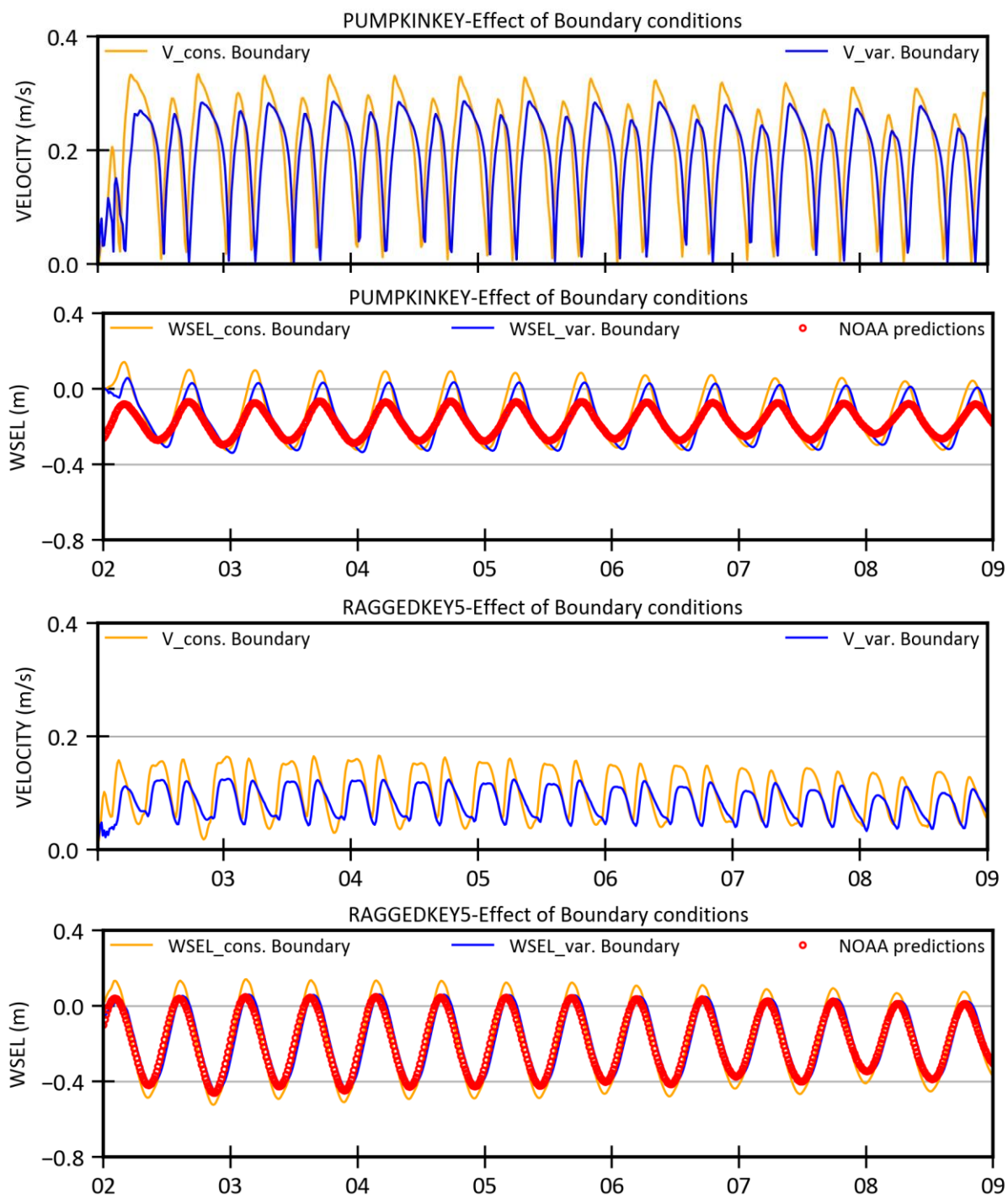


Figure 22 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations PUMKINKEY and RAGGEDKEY.

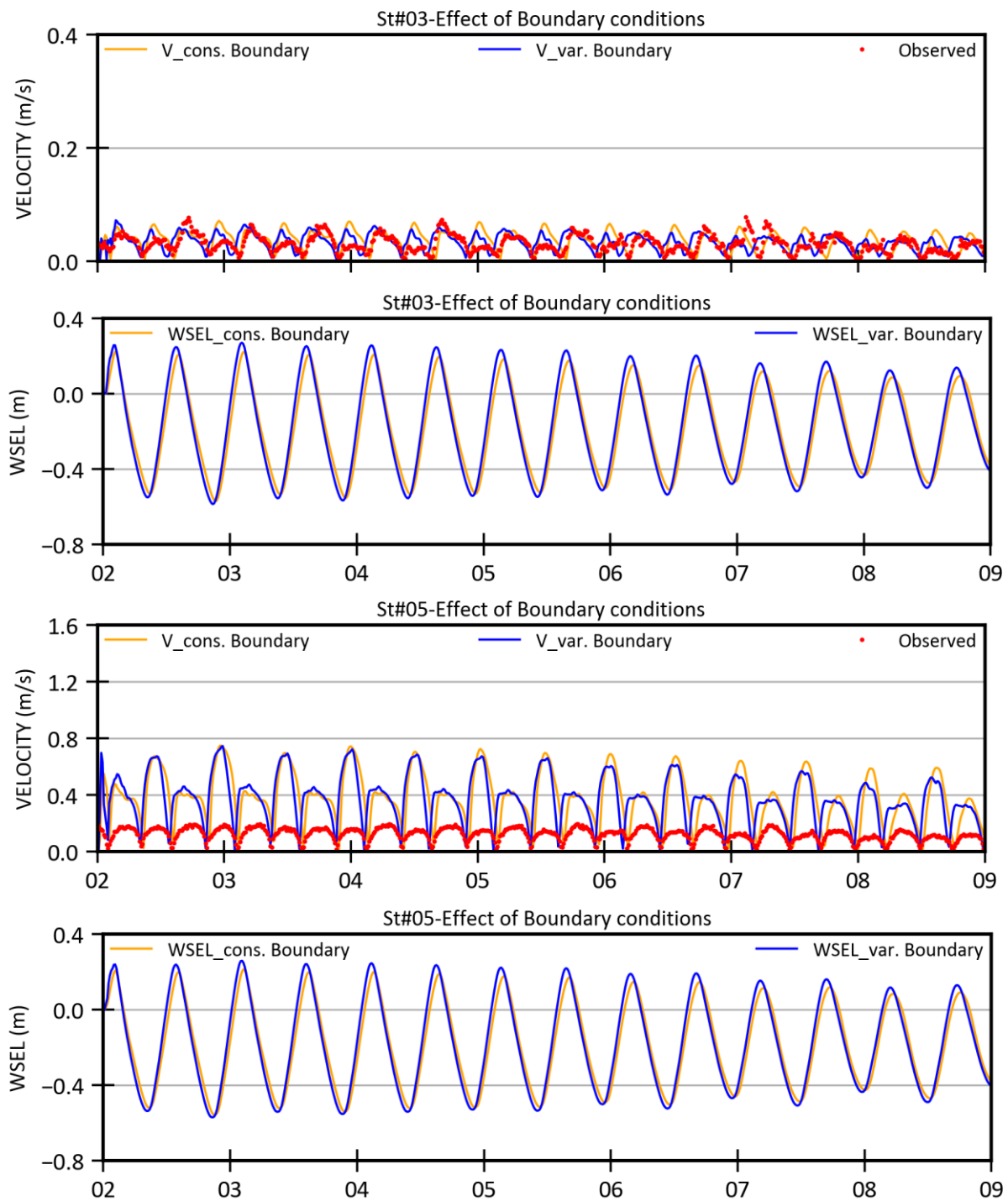


Figure 23 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations St#3 and St#5.

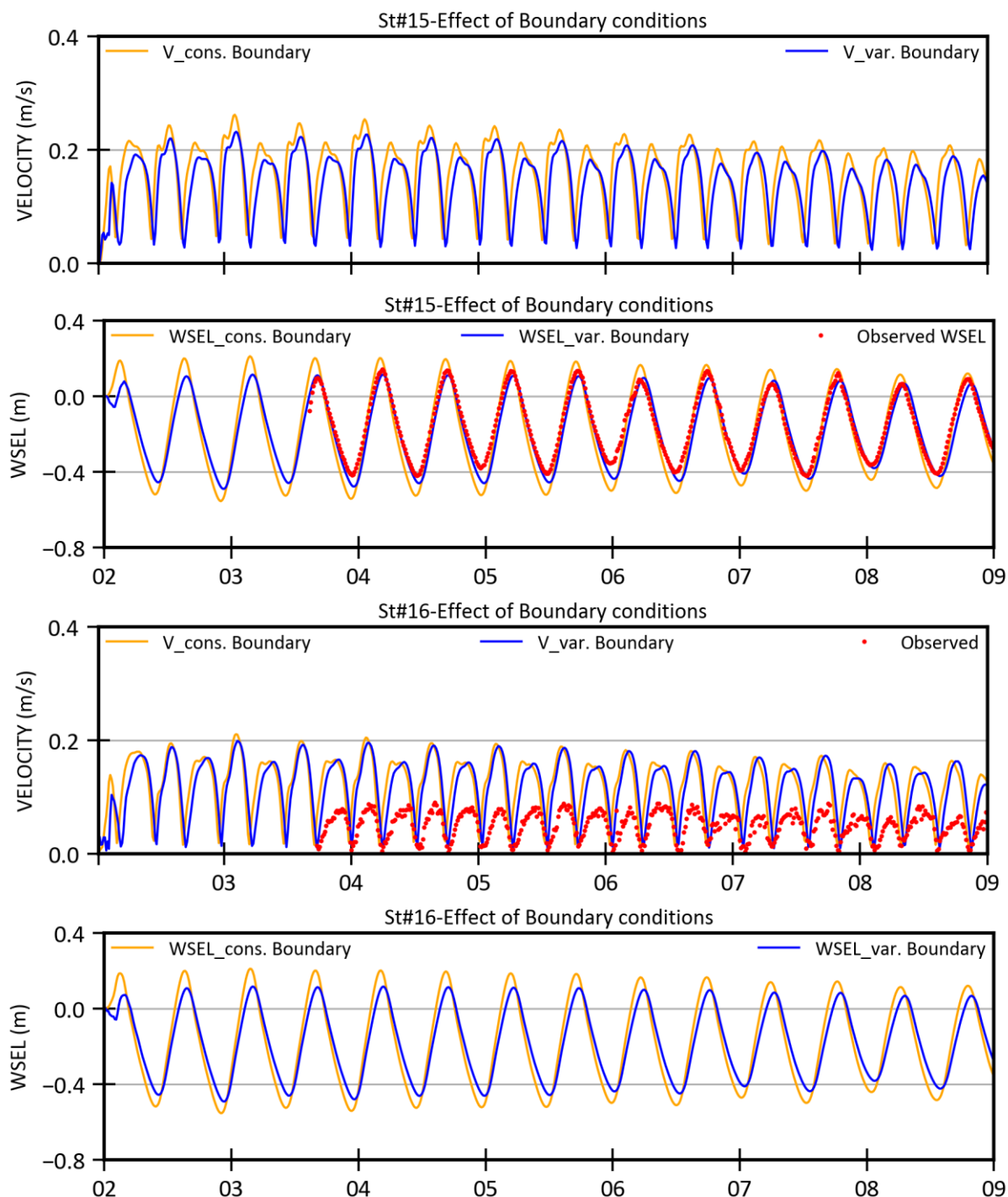


Figure 24 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations St#15 and St#16.

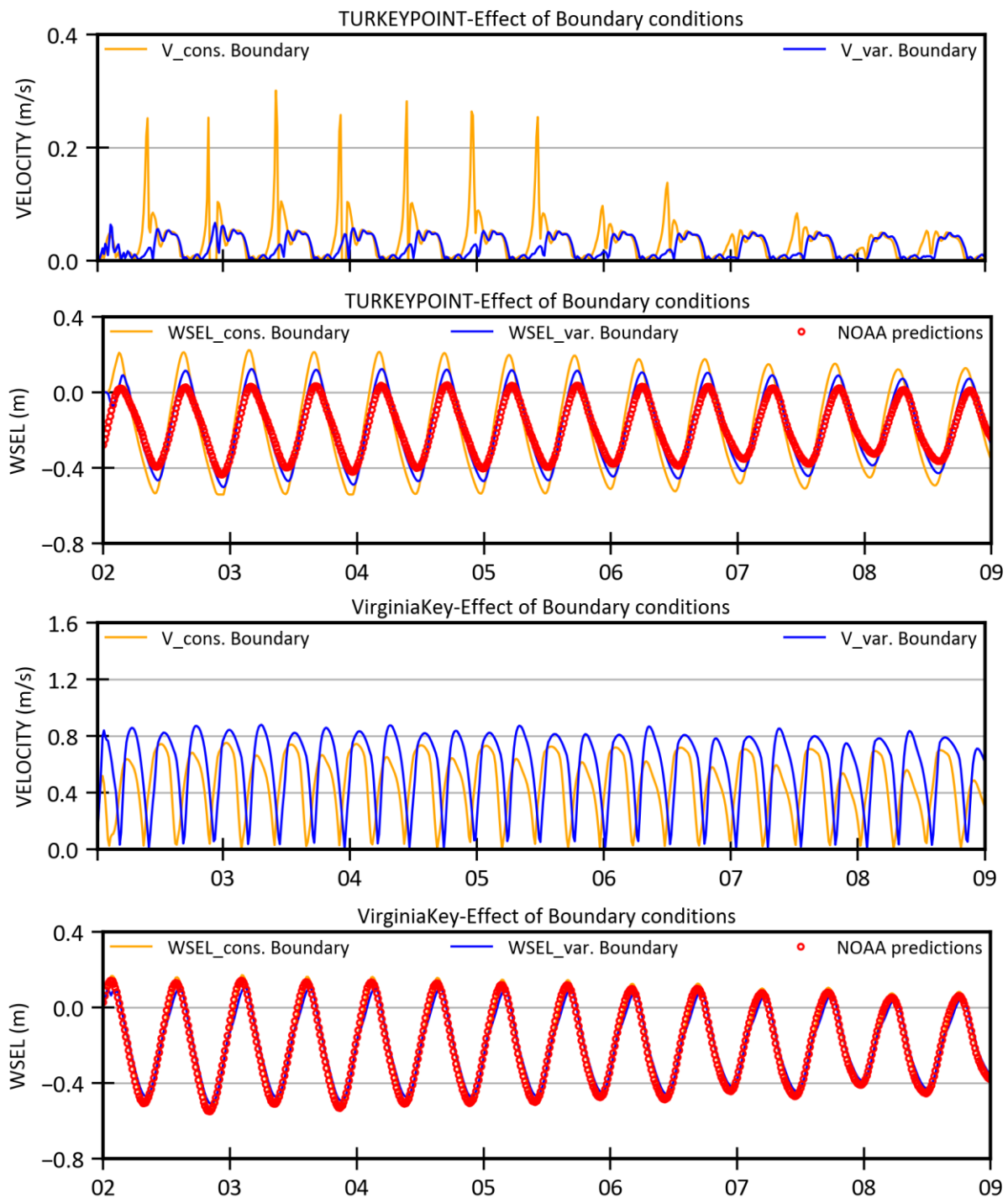


Figure 25 Sensitivity to boundary conditions. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations TURKEYPOINT and VirginiaKey.

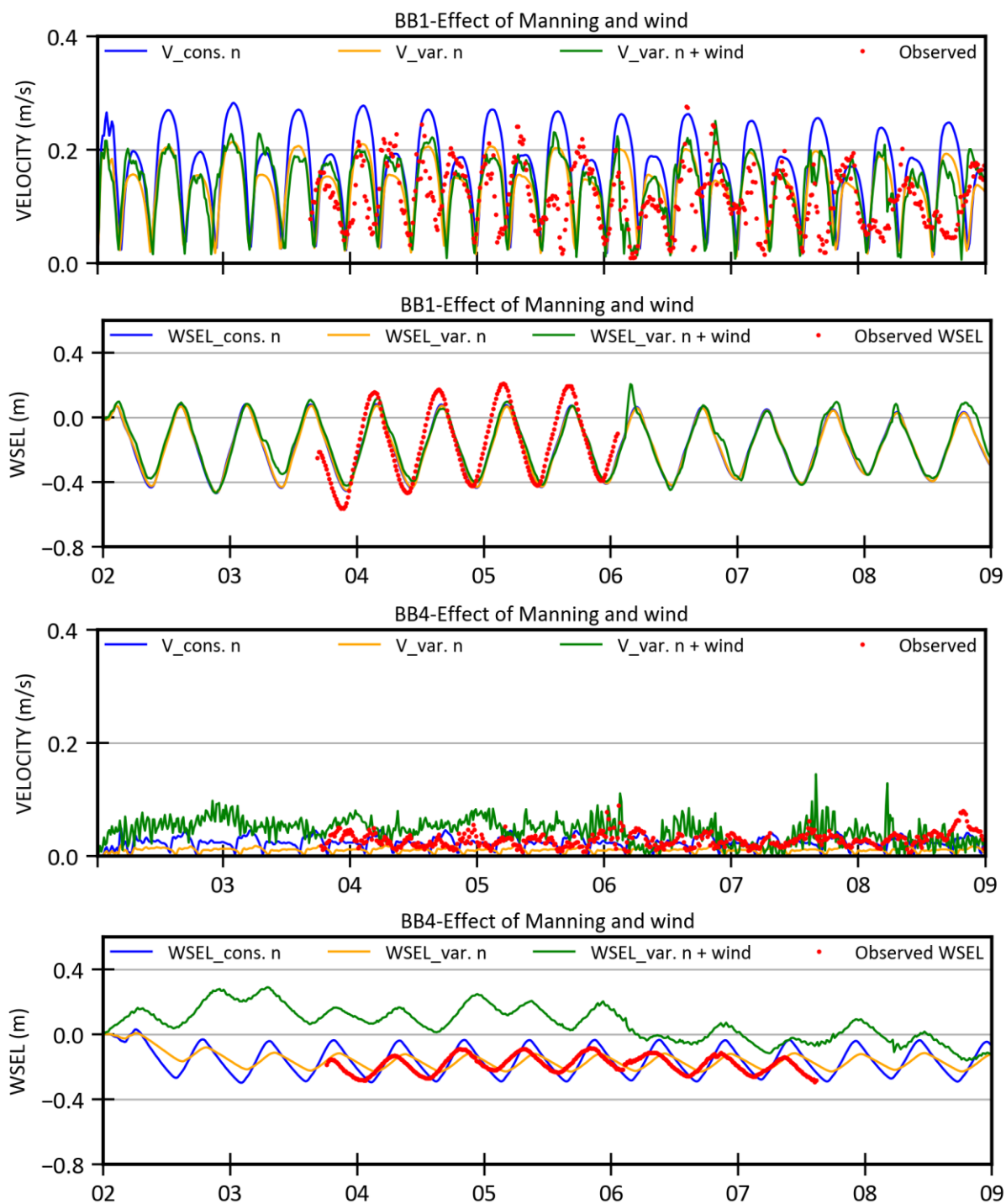


Figure 26 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations BB1 and BB4.

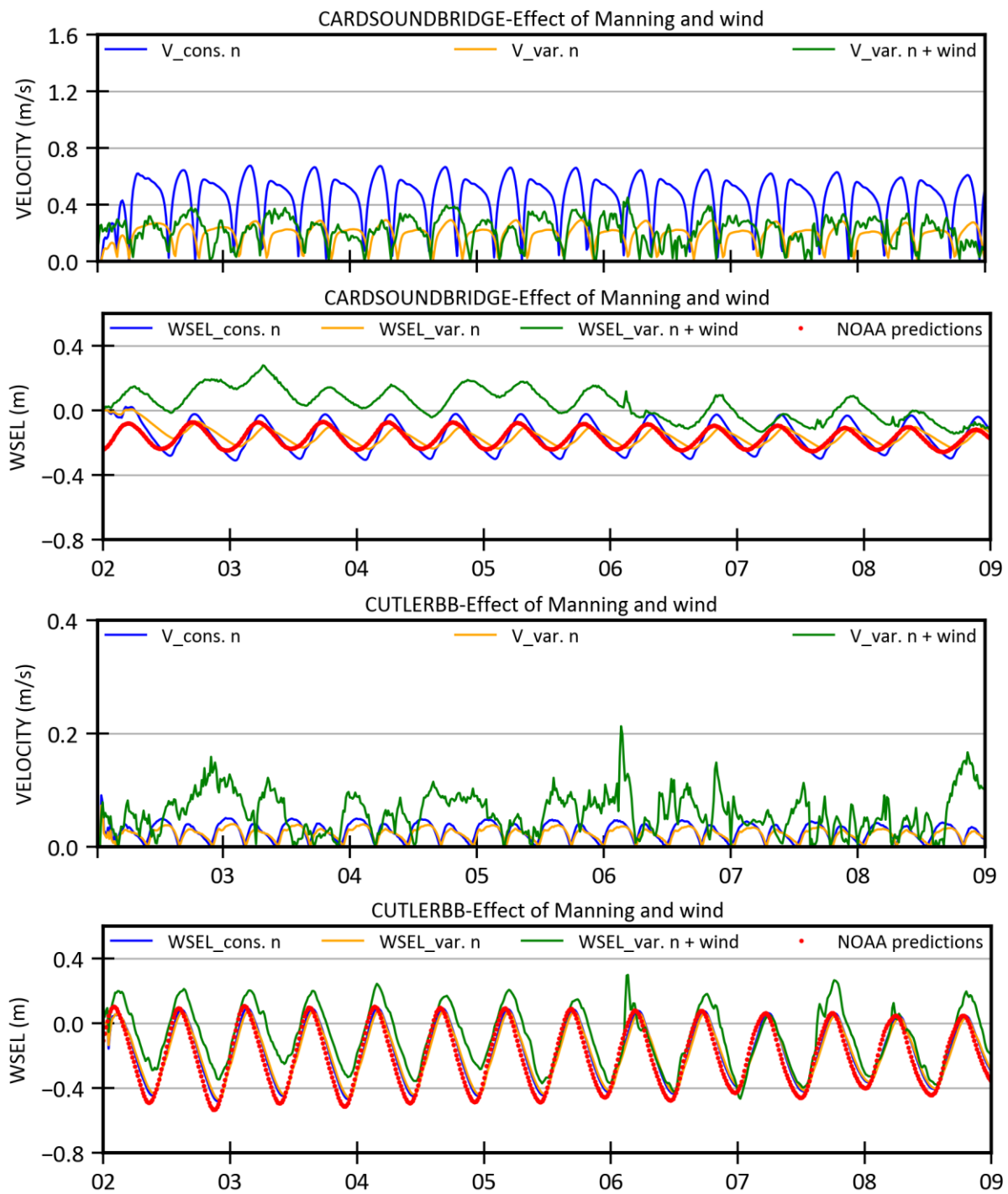


Figure 27 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations CARDSOUNDBRIDGE and CUTLERBB.

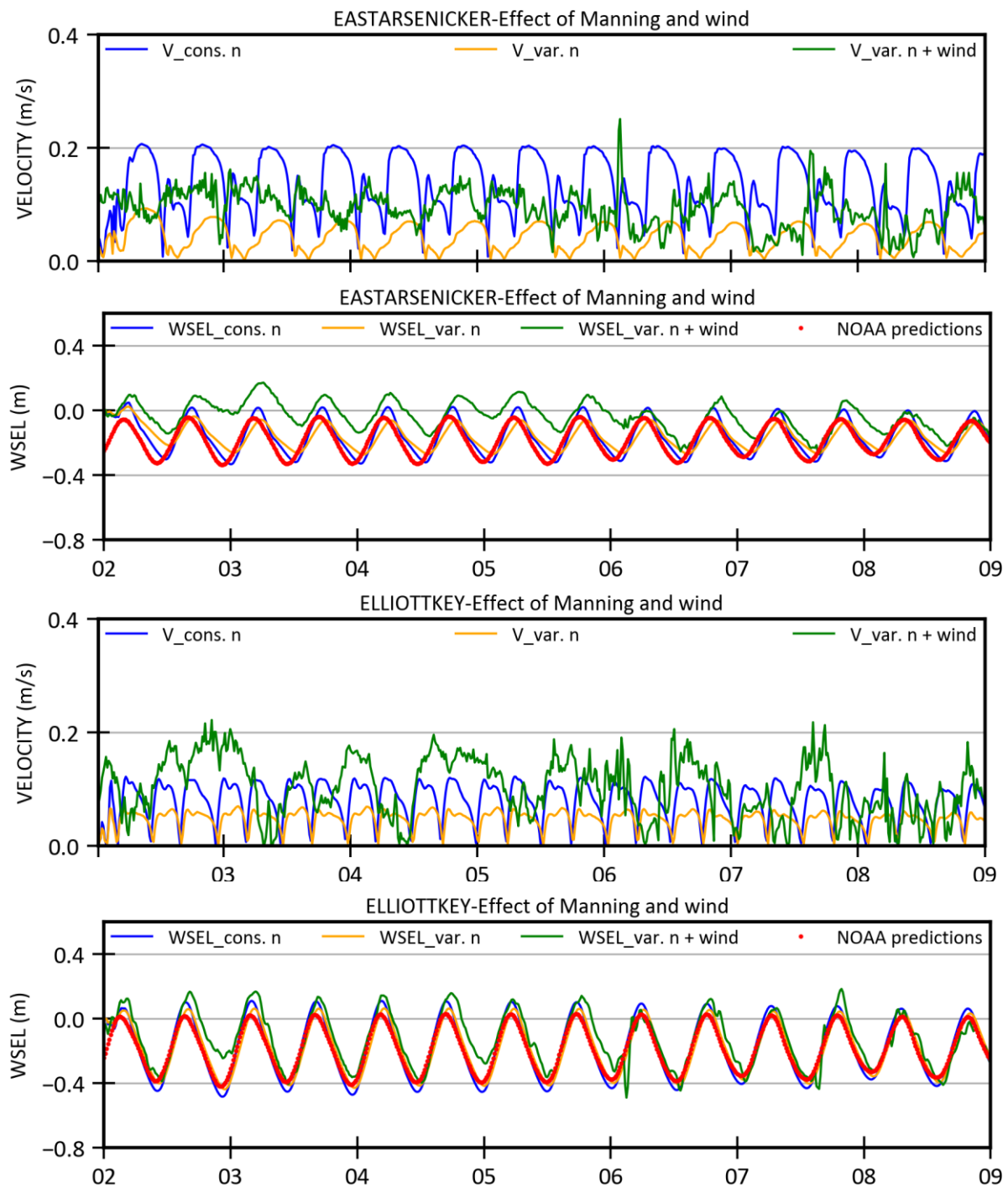


Figure 28 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations EASTARSENICKER and ELLIOTTKEY.

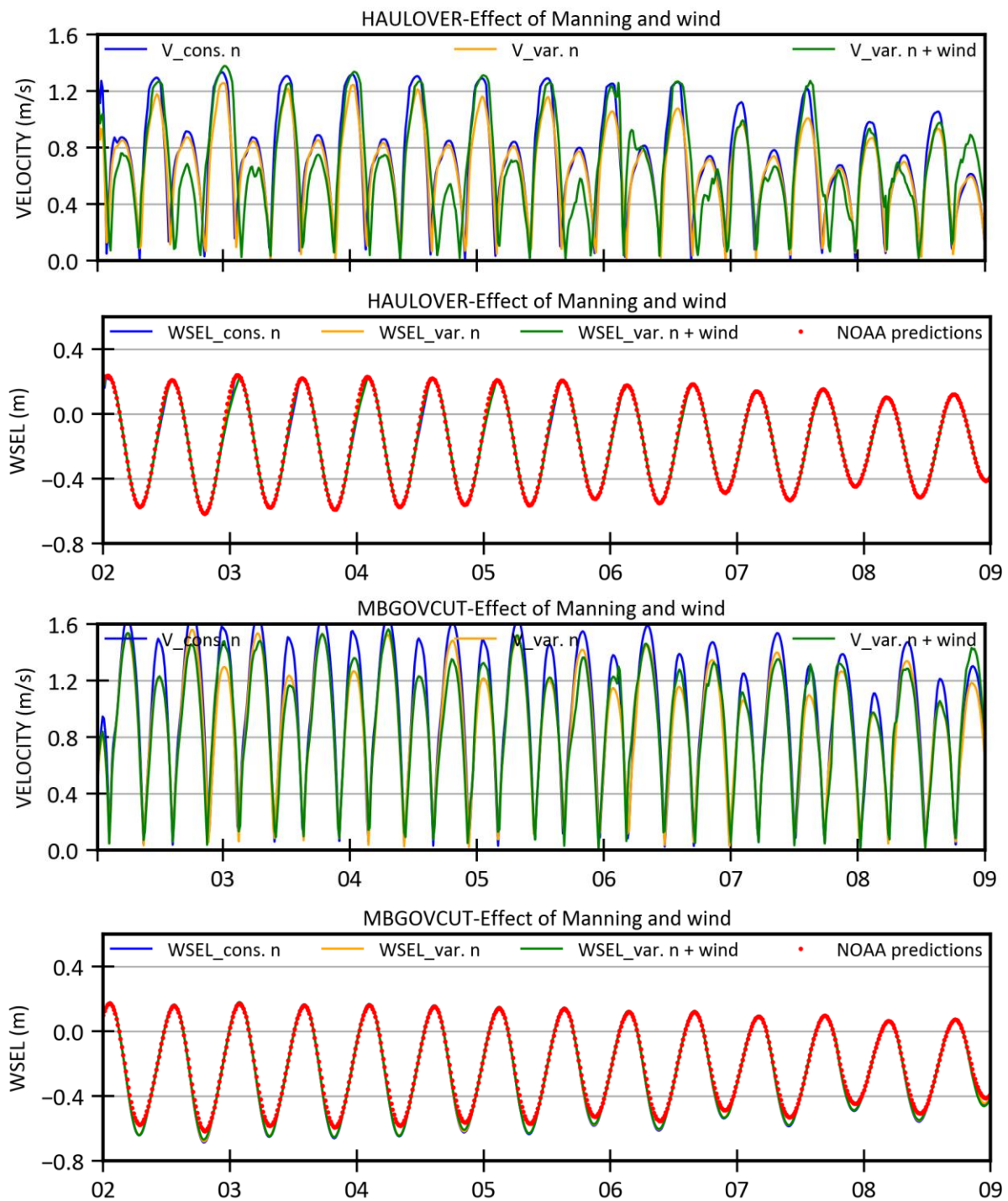


Figure 29 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations HAULOVER and MBGOVCUT.

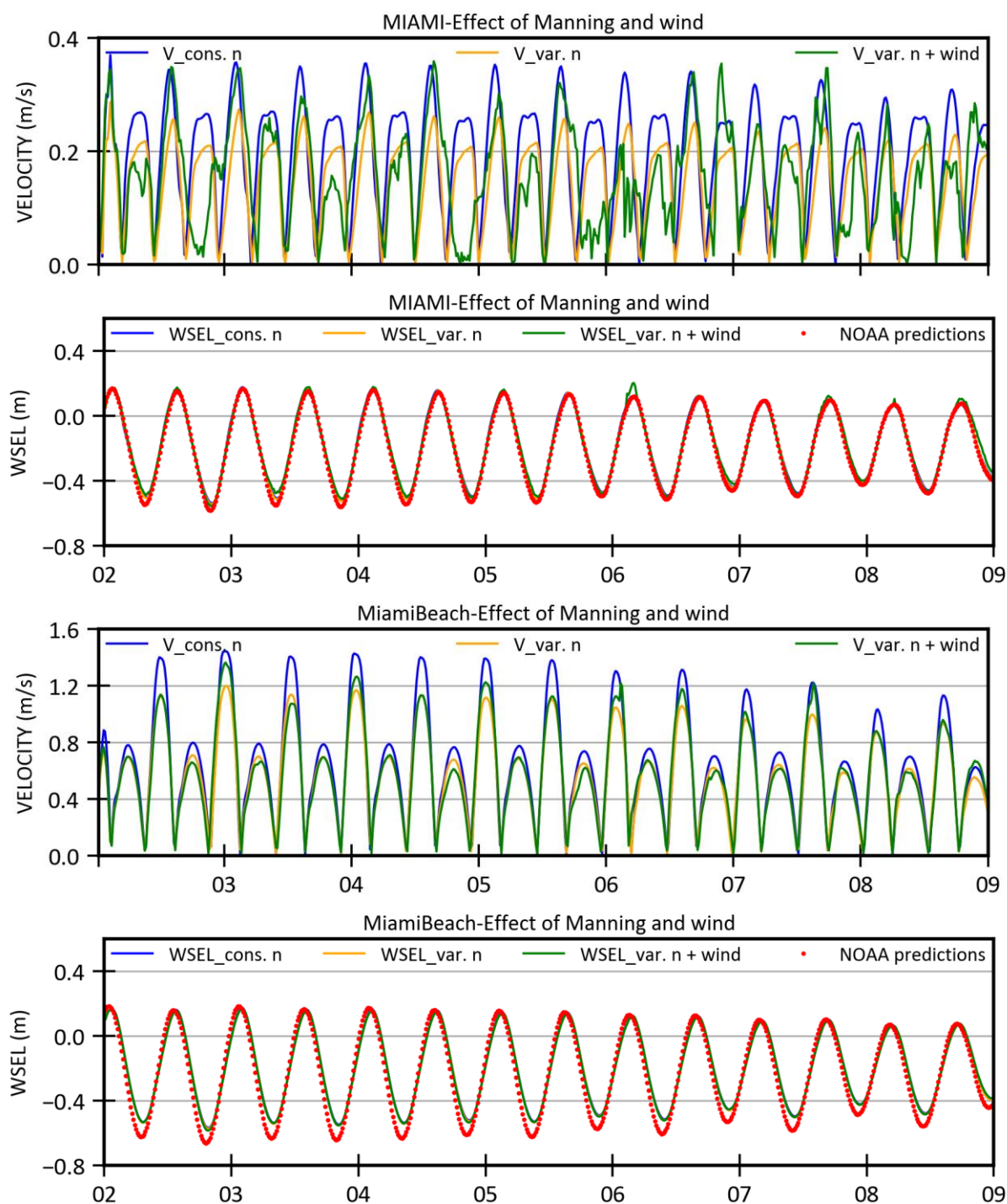


Figure 30 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations MIAMI and MiamiBeach.

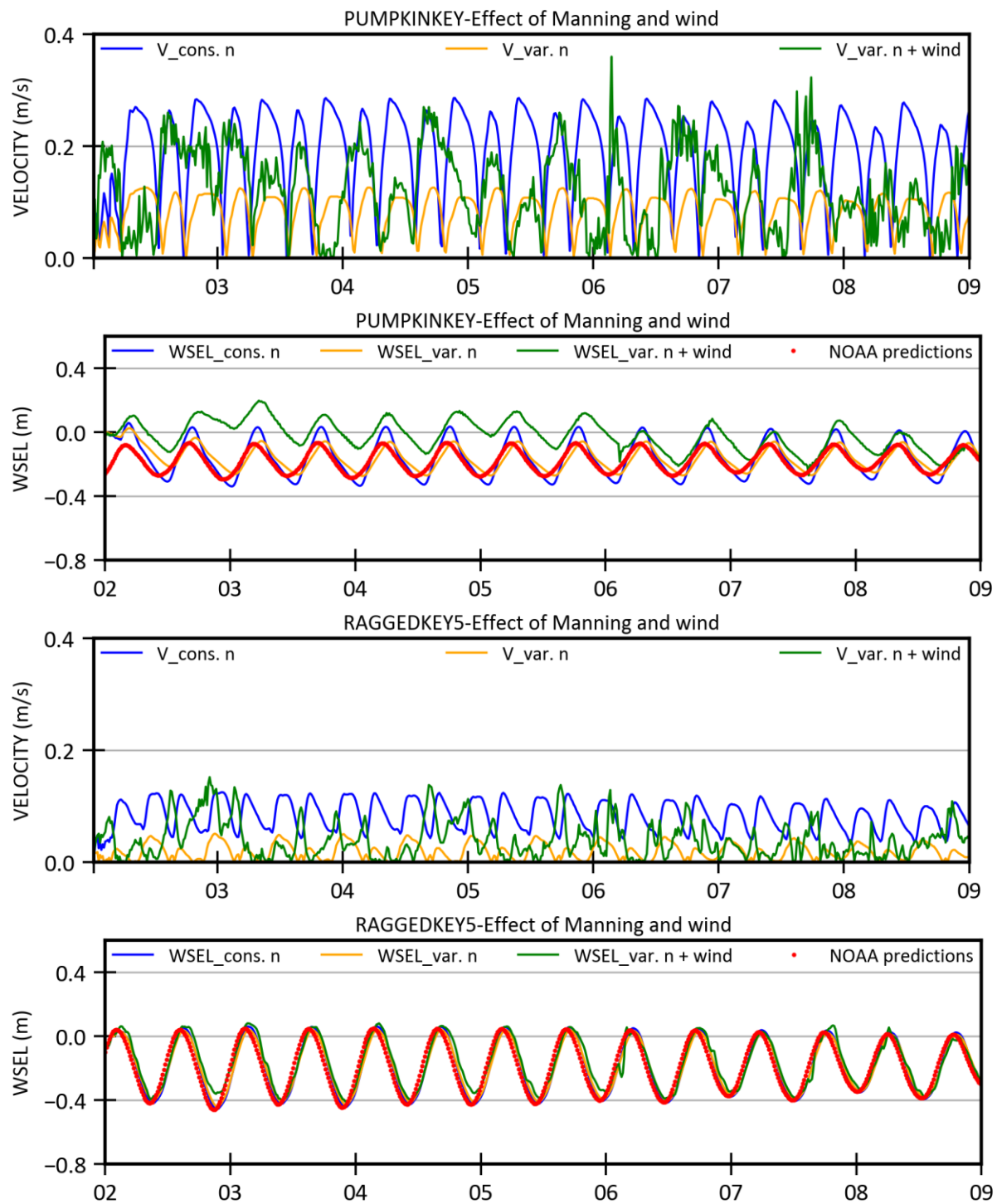


Figure 31 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations PUMPKINKEY and RAGGEDKEY.

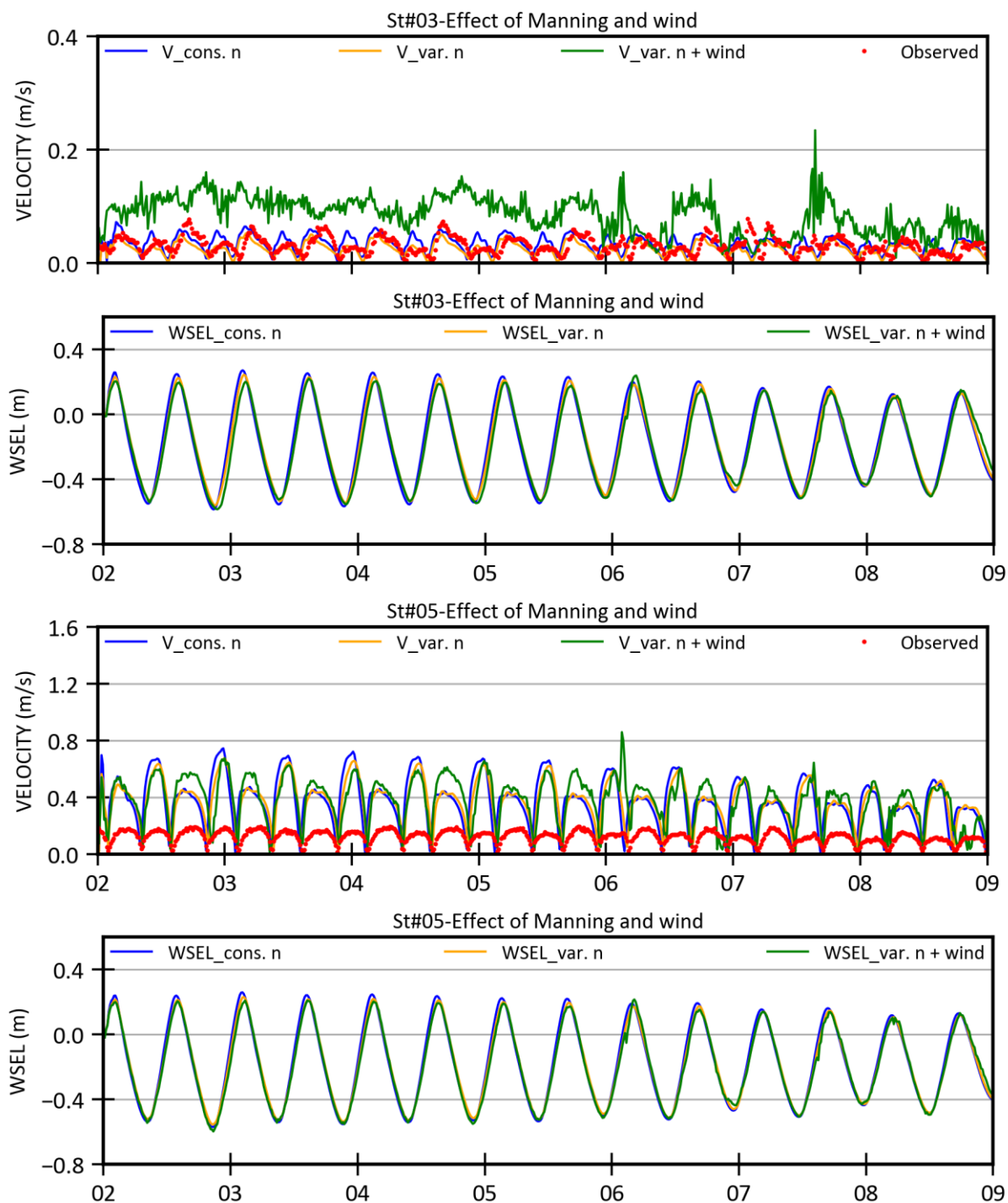


Figure 32 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations St#3 and St#5.

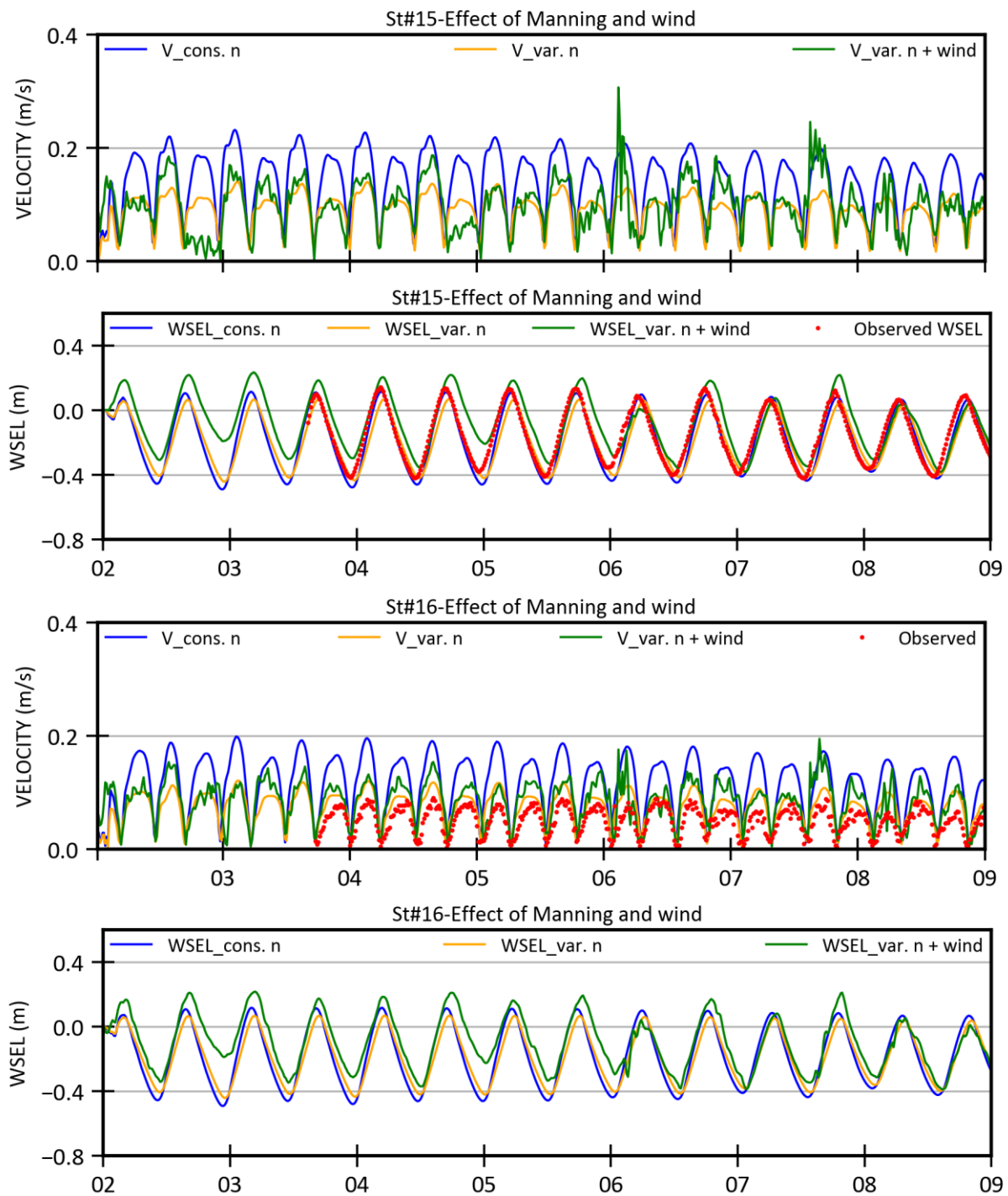


Figure 33 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations St#15 and St#16.

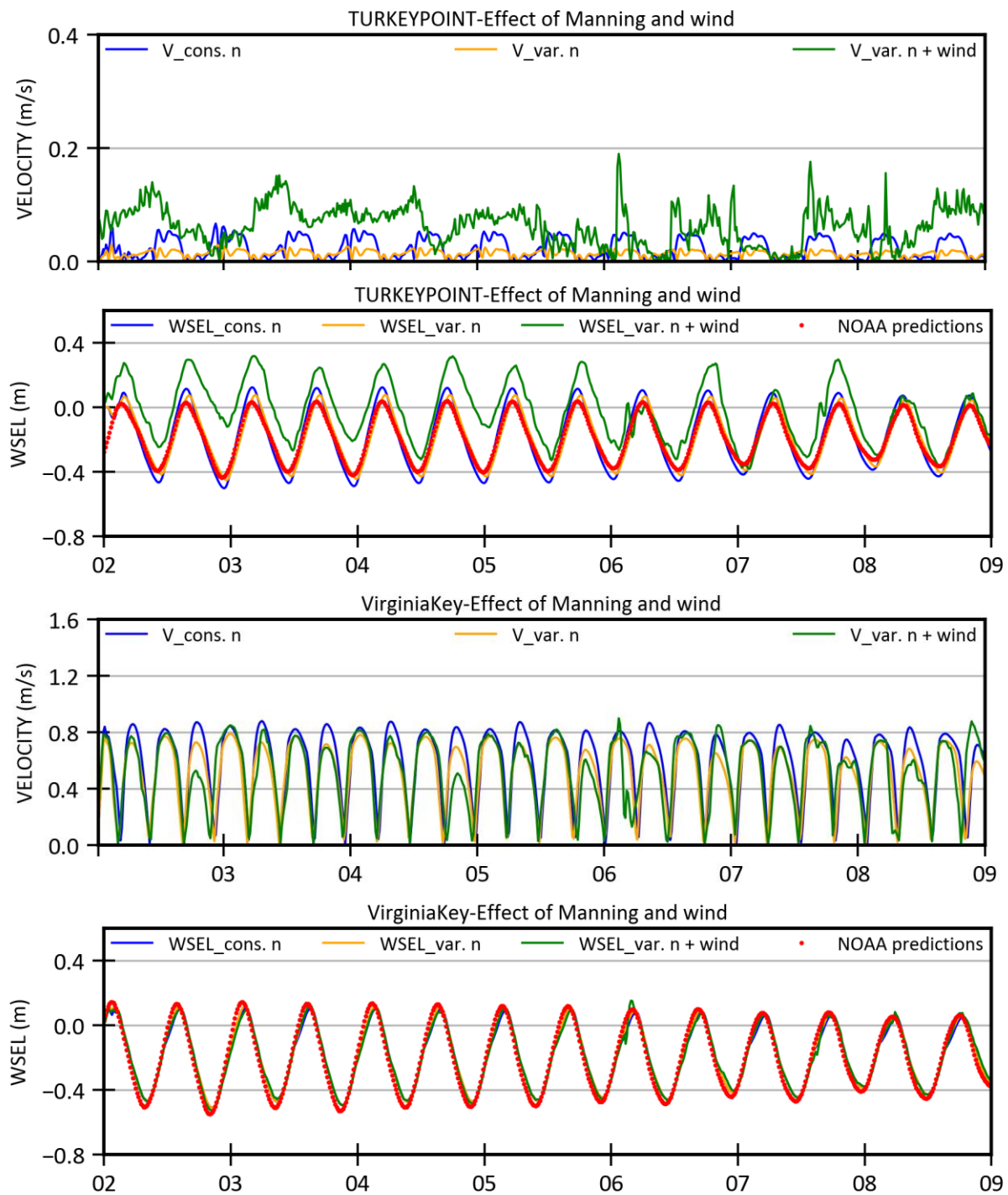


Figure 34 Sensitivity to Manning's n and wind. Comparison of Water Surface Elevations (WSE) and Velocity with observations at stations TURKEYPOINT and VirginiaKey.

11.7 Velocity fields

As an illustration of the model graphical output, the following figures depict the velocity fields that occur throughout Biscayne Bay. Figure 37 shows two sub-basins with contrasting velocity fields, first, the one from Haulover Inlet to Broad Causeway displaying high velocities, and second, from Broward Causeway to NE79th St Causeway with significantly lower velocities. This suggests high flooding/flushing rates and mixing for the northern sub-basin and more stagnation in the southern one. This circulation pattern is of special relevance because the polluted Biscayne Canal drains to the southern sub-basin, where quieter waters have longer residence times, increasing the exposure time of its ecosystems to incoming pollutants.

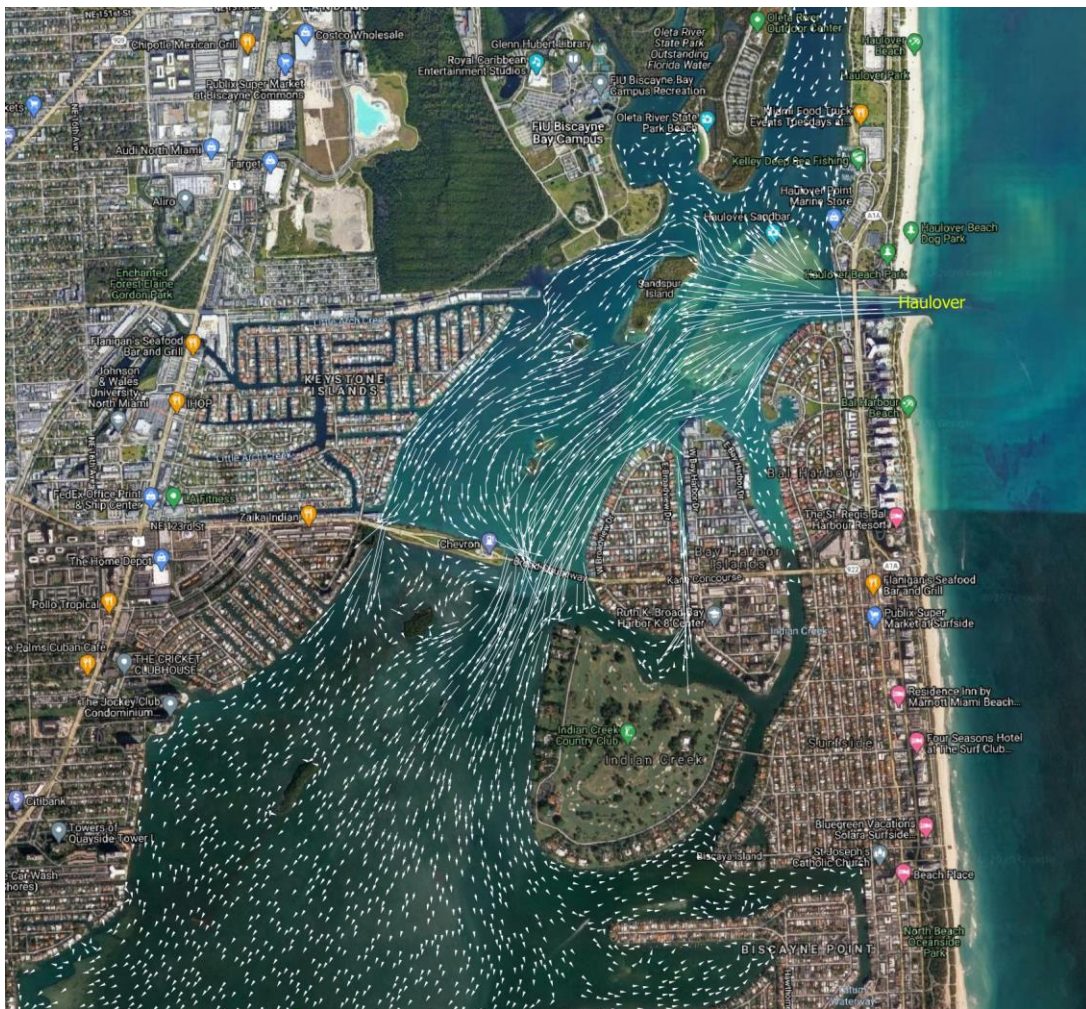


Figure 35 Velocity field near the northern end of Biscayne Bay. Haulover is the northern open boundary in the model.

Figure 38 suggests that the Julia Tuttle sub-basin is diagonally subdivided into two triangular-shaped areas, a low-velocity compartment towards the northwest, and a higher velocity domain towards the southeast. The northwest slow-moving, eddy/prone area receives waters from the polluted Little River, and it is where the largest seagrass die-off has occurred in North Biscayne.

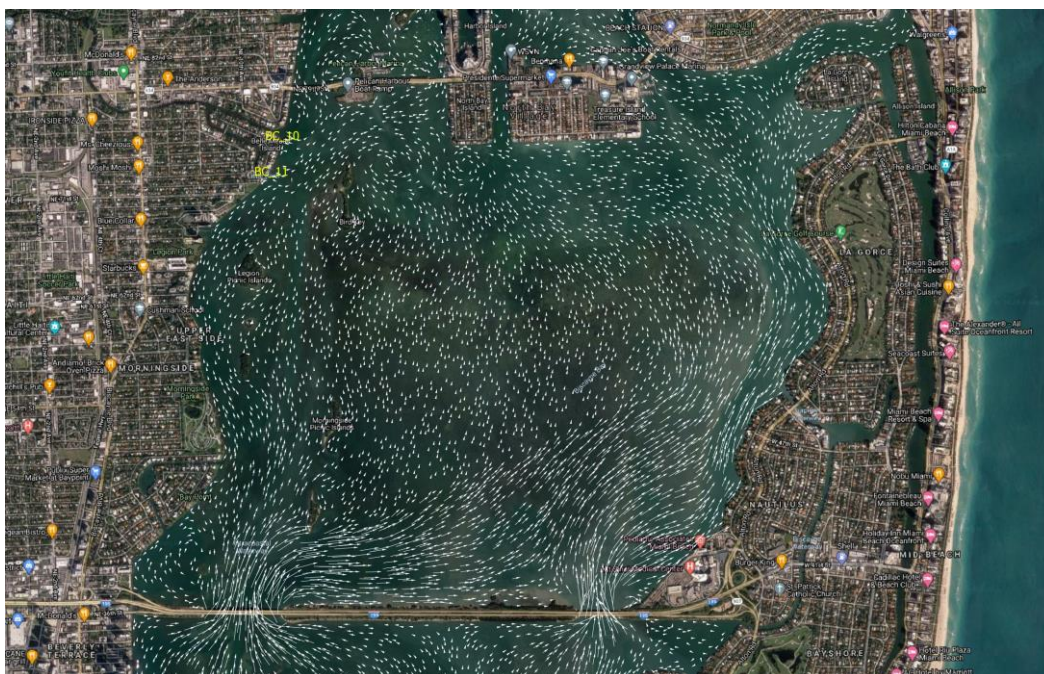


Figure 36 Velocity field in the area limited by the 195 highway to the south and SR 934 to the north. Note the higher velocities through the 195 bridges and the circulation patterns with large eddies.

Figure 39 shows two major inlets, Government Cut and Fisher Island. During flood tides, water from the Government Cut moves in three directions. First, straight northwest along the Main Channel to turn north under the MacArthur Causeway; second, northwards to the Venetian Island sub-basin; and third, along the Fisherman's Channel, in between the Port of Miami and Fisher Island. Fisher Island's incoming waters move to the Virginia Key-Miami River sub basin, on the northern portion of Central Biscayne Bay. Waters from this sub-basin move under the Rickenbacker Causeway toward the northern portion of Central Biscayne Bay. Waters coming in from these two inlets move at high velocity to the west.

Virginia Key inlet flooding waters (Figure 40) join waters coming south from the Virginia Key-Miami River sub basin to Central Biscayne Bay. Currents in this northern portion of the bay are relatively slow, especially to the west and to the south of the área.

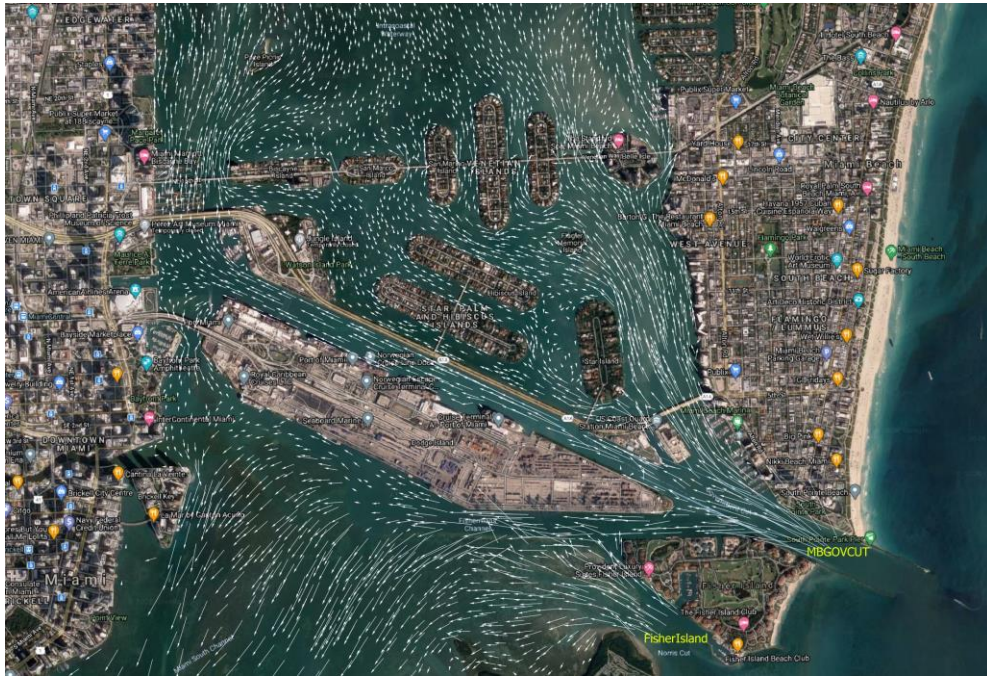


Figure 37 Velocity filed in the Port of Miami zone. There are two important open boundaries in this area, Miami Beach (MBGOVCUT) and Fisher Island.

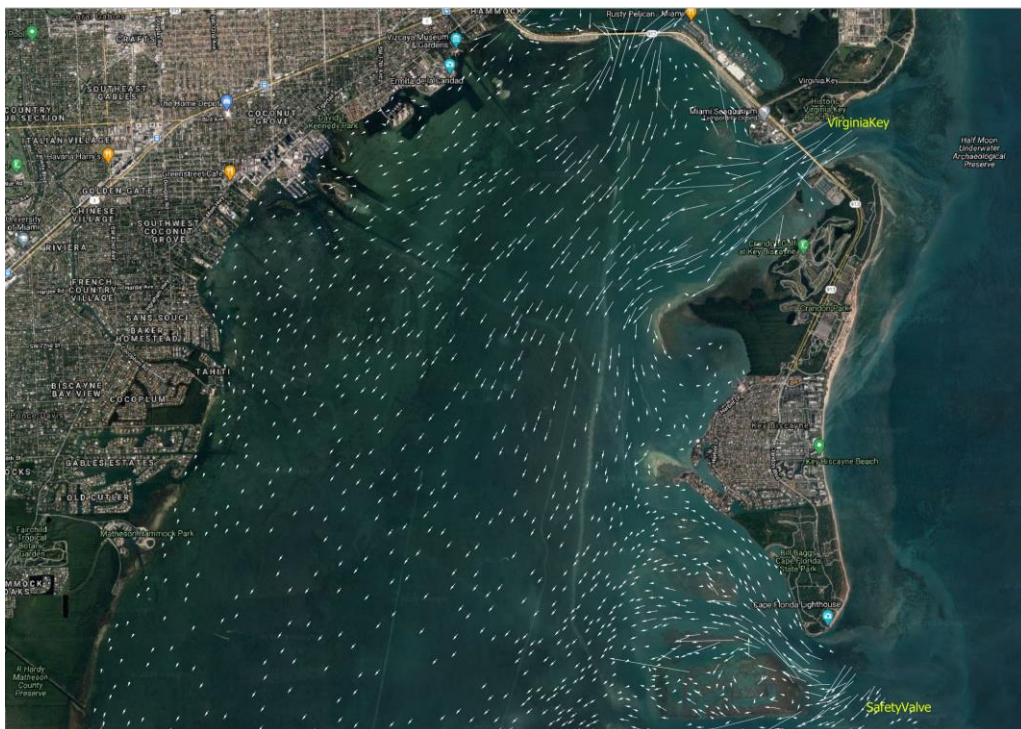


Figure 38 Velocity field around the area of Virginia Key.

The Safety Valve area (Figure 41) controls the main water entrance to Central Biscayne Bay. Waters move swiftly westwards over the shallows and then turn southwest, and south upon

approaching the shoreline.

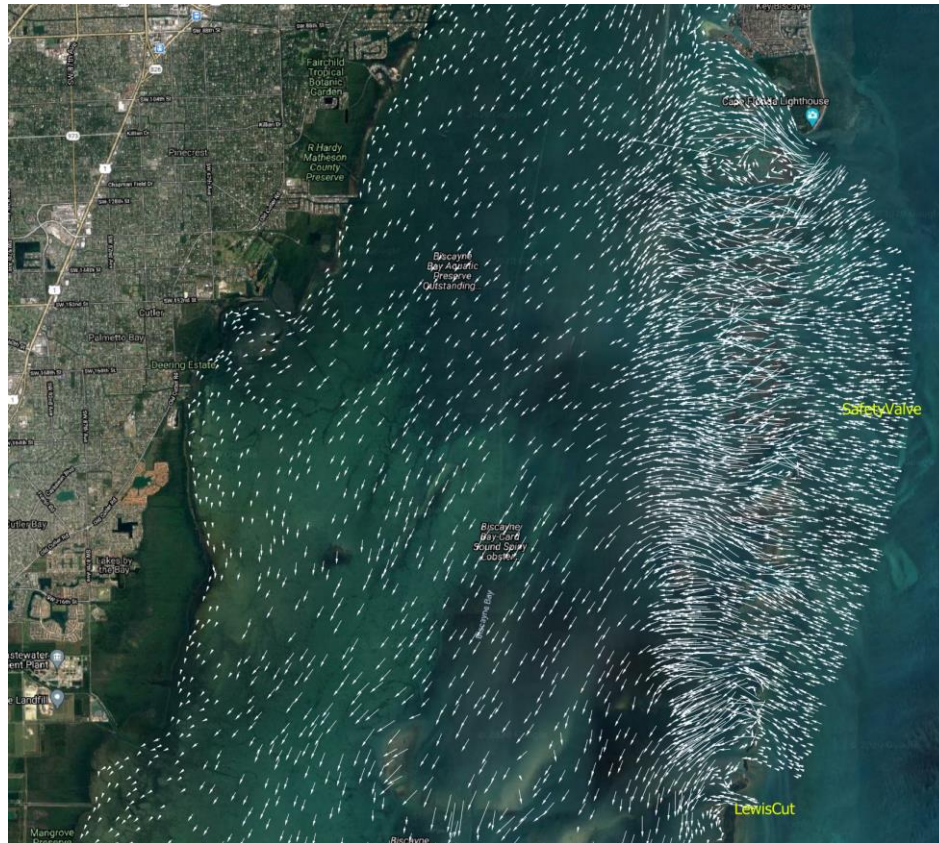
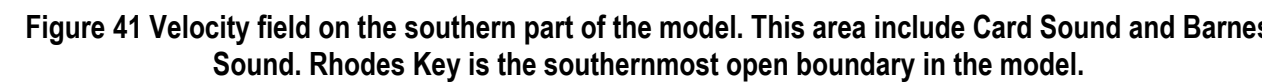
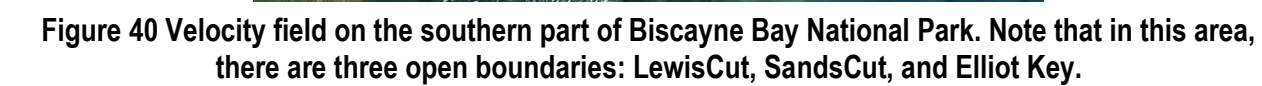


Figure 39 Velocity field on the Safety Valve area. Note the higher velocities over the shallows.

Incoming waters through the Lewis Cut, Sands Cut, Cesar's Creek and Rhodes Channel (Figure 42) seem to have only local influence in the overall circulation pattern of Biscayne Bay. Finally, waters in the southernmost portion of Biscayne Bay (Card and Barnes Sound, and Manatee Bay) show very low velocity (Figure 43), and flow is mostly outwards, even during incoming tides. Those characteristics suggest that most of the properties of the water column in that area are the result of local processes.



11.8 Conclusions about the Hydrodynamic Calibration

- The results of the calibration scenarios performed so far show that the model is able to reproduce measured and predicted water elevations and velocities in several Biscayne Bay locations with acceptable precision.
- As it was expected, using a distributed boundary condition from NOAA tidal prediction provides a much better comparison than using a single tidal record for all open boundaries.
- Manning's n coefficient affected the velocities and water surface elevations, and literature values were adjusted in order to improve the model comparison with measured data.
- The wind has a significant effect, particularly toward the southern parts of Biscayne Bay. In the calibration scenarios presented, it was observed that considering the wind led to an increase in the differences between model and measurements or predictions. This is probably due to the wind stress coefficient used
- There are clear differences in velocity field among sub-basins and even within individual sub-basins in Biscayne Bay. Those patterns may be related to well known water quality differences in the bay, and will surely help future interpretations of water quality data. The examples shown in figures 38 and 30 are worth mentioning. When peak tidal flooding occurs, water moves inside and south from Haulover inlet, while it also moves inside and north from Government Cut. The water masses meet each other in the Julia Tuttle Basin and the southern portion of the basin north of North BayVillage. There, eddies and low velocity zones prevail where two of the more polluted tributaries to the Bay converge.

12 Hydrodynamic Model Validation

This section presents the results of the BBOM hydrodynamics model validation. The purpose of the validation is to verify that the model can reproduce measured velocity and depths from an independent data set as the ones used in the calibration phase without adjusting the bed roughness Manning's n parameters obtained in the calibration phase.

The mesh developed for the model validation, as well as the bed roughness distribution was identical as that used in the calibration phase.

The model validation involves simulating the bay hydrodynamics for a period of time different from those used in the calibration phase. To that end, we used the period from 1/12/2021-1/19/2021 that corresponds to the most recent FIU monitoring campaign where all of the stations were collecting data simultaneously.

12.1 Tidal Data

In this phase, we imposed boundary conditions using tidal data near the model open boundaries collected during the January 2021 campaign. In the northern part of the Bay we used data from the BB05 FIU station for the Haulover inlet and data from the BB12 FIU station for the Port of Miami, Virginia Key, and Key Biscayne inlets, as shown in Figure 42.



Figure 42 Boundary Condition Data Used in the Northern part of Biscayne Bay Model.

Data from station BB13 was used as the tidal condition for the Safety Valve open boundary, as shown in Figure 43. Unfortunately, the instruments installed during the January 2021 campaign to measure pressure at stations BB15 and BB18 did not provide accurate data, and we had to use the tidal elevations from station BB13 for the southern (see Figure 43)

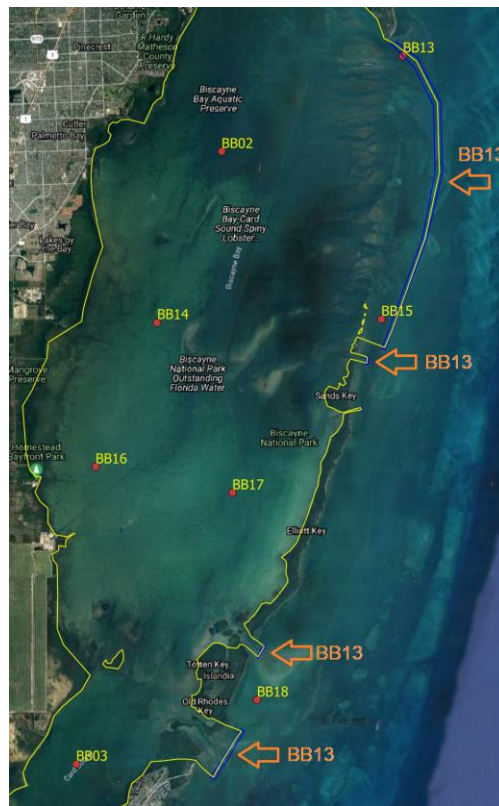


Figure 43 Boundary Condition Data Used in the Central and Southern parts of Biscayne Bay Model.

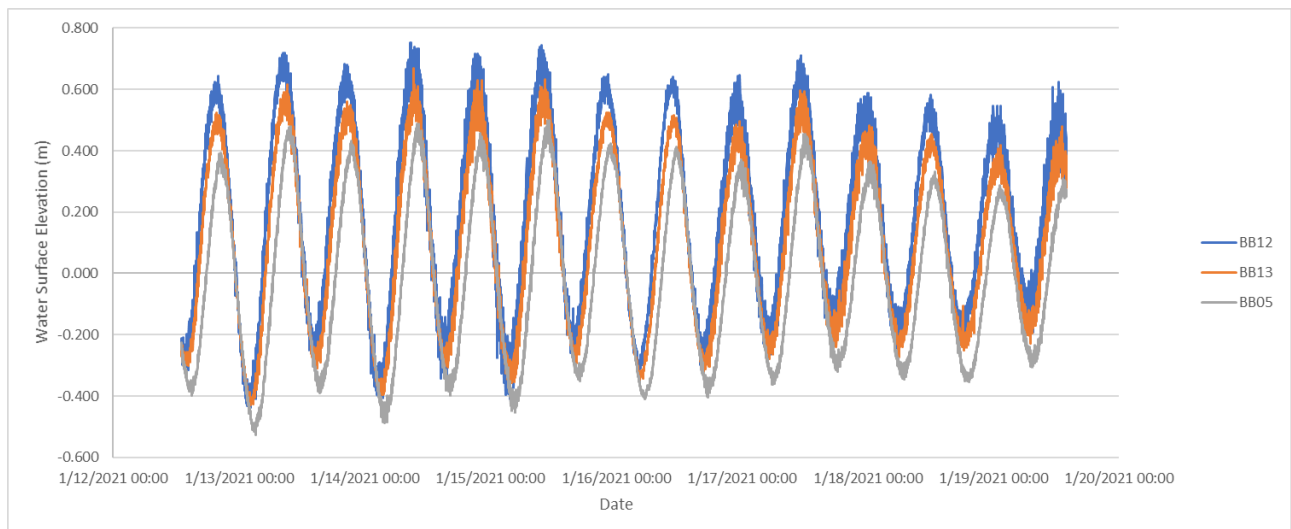


Figure 44 Measured water elevations a BB05, BB12, and BB13 stations from 1/12/2021 and 1/19/2021.

12.2 Wind Data

The wind data used for the model validation was obtained from the NOAA Virginia Key station and correspond to the period /01/2021 to 1/31/2021. During this period, the average wind speed was around 2.5 m/s, with gust reaching 12 m/s for short periods (see Figure 45). The wind velocity components in East and North directions were provided to the model at 6-minute intervals.

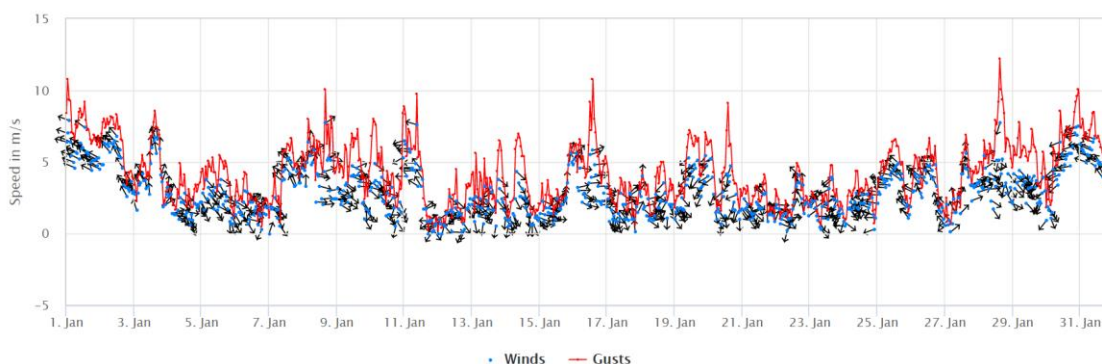


Figure 45 Wind speed at NOAA Virginia Key station 8723214 from 1/01/2021 to 1/31/2021. Source: NOAA/NOS/Center for Operational Oceanographic Products and Services.

<https://tidesandcurrents.noaa.gov/met.html?bdate=20210101&edate=20210131&units=metric&timezone=LST%2FLDT&id=8723214&interval=h>.

12.3 Model Validation Results

The model was run for that period using the same Manning's n roughness parameters previously determined in the calibration phase (Figure 15). The figures in this section depict comparisons of the model results with measurements for water surface elevations and velocities for 12 stations BB02, BB04, BB05, BB07, BB09, BB10, BB11, BB13, BB14, BB15, BB17, and BB19.

After a comprehensive analysis of these results, our preliminary assessment of this validation indicates that the model represents the water surface elevations very closely at all the locations evaluated. The velocity comparison shows that the model can replicate the measured velocities closely, although there are a few locations where the differences are relatively high. We need to look into these results in more detail to understand the source of these discrepancies.

12.3.1 Results on the Northern Bay

The following Figure 47 to Figure 54 compare water elevations and velocities for stations in the northern part of the Bay shown in Figure 46. Note that the TCM1 anemometer at station BB05 did measure velocities during the validation period. Given that station BB06 was lost and BB08 presented data capturing inconsistencies those sites were not included.

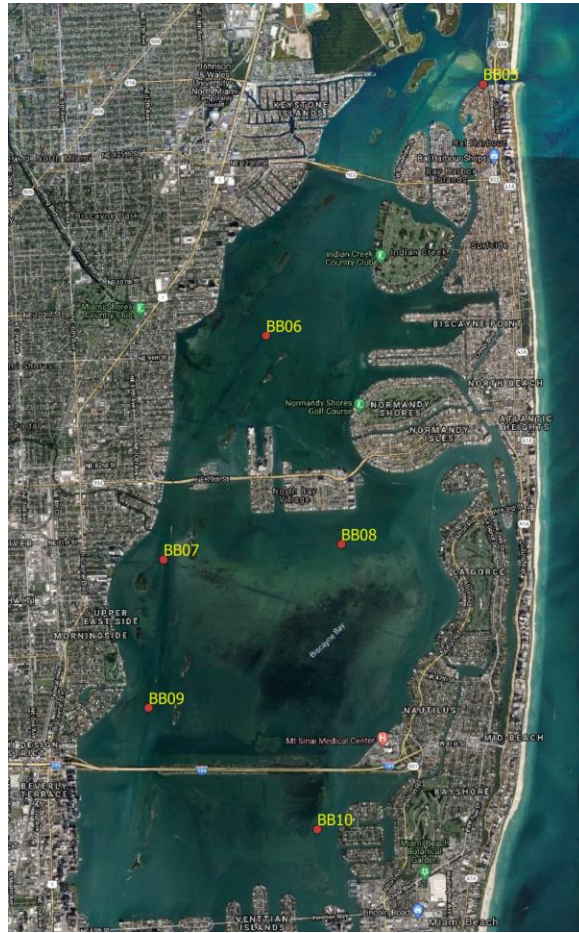


Figure 46 Model validation stations in the Northern Bay.

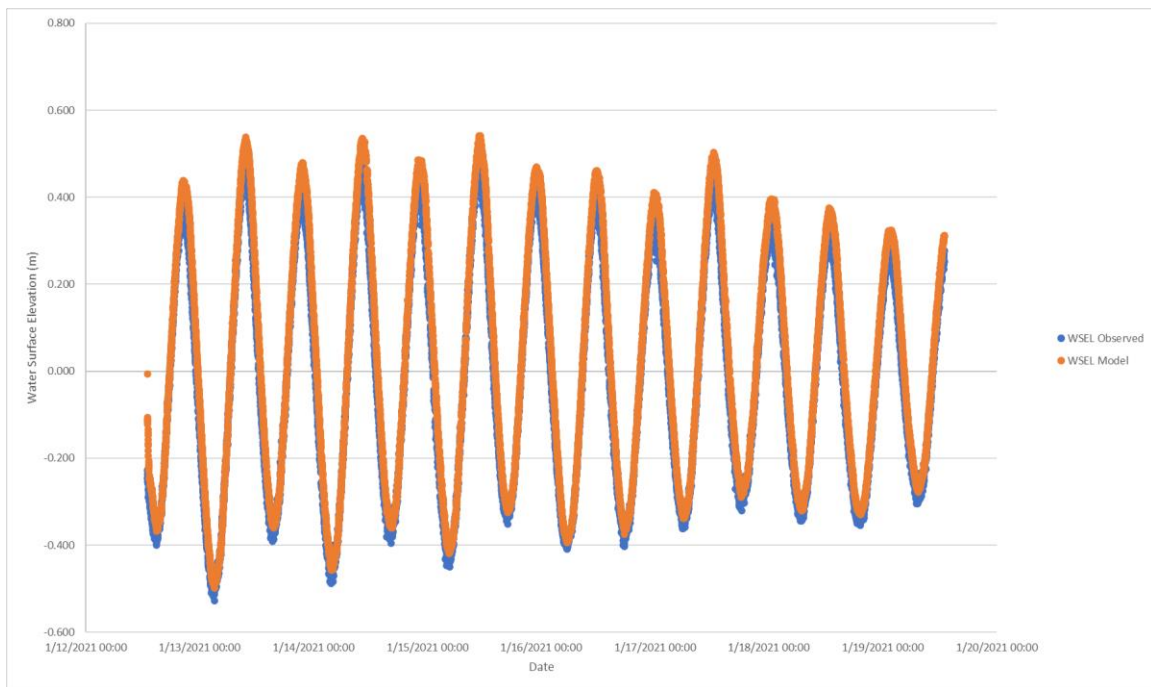


Figure 47 Water elevations calculated by the model (orange) and measured (blue) at station BB05.

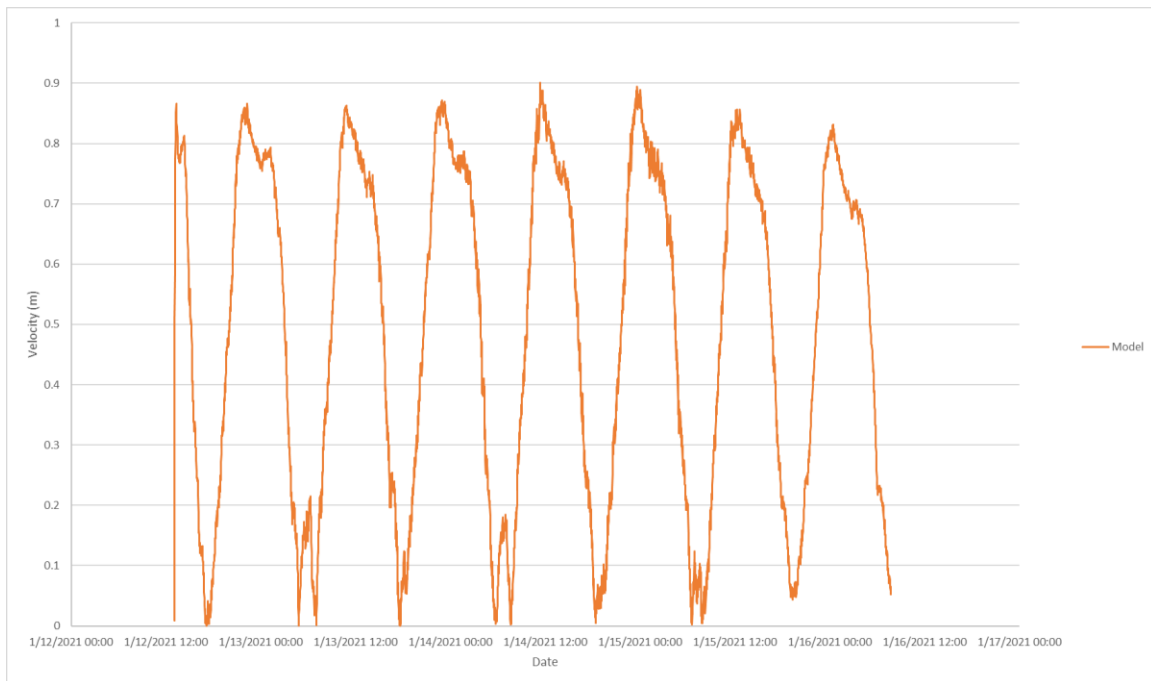


Figure 48 Velocities calculated by the model (orange) at station BB05.

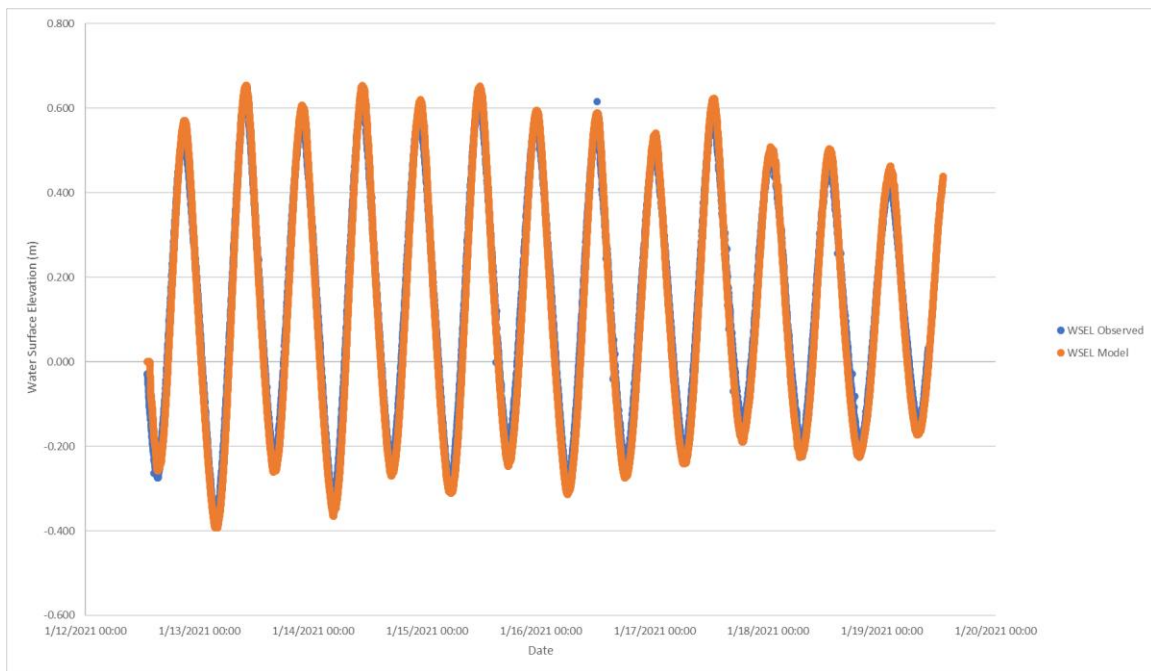


Figure 49 Water elevations calculated by the model (orange) and measured (blue) at station BB07.

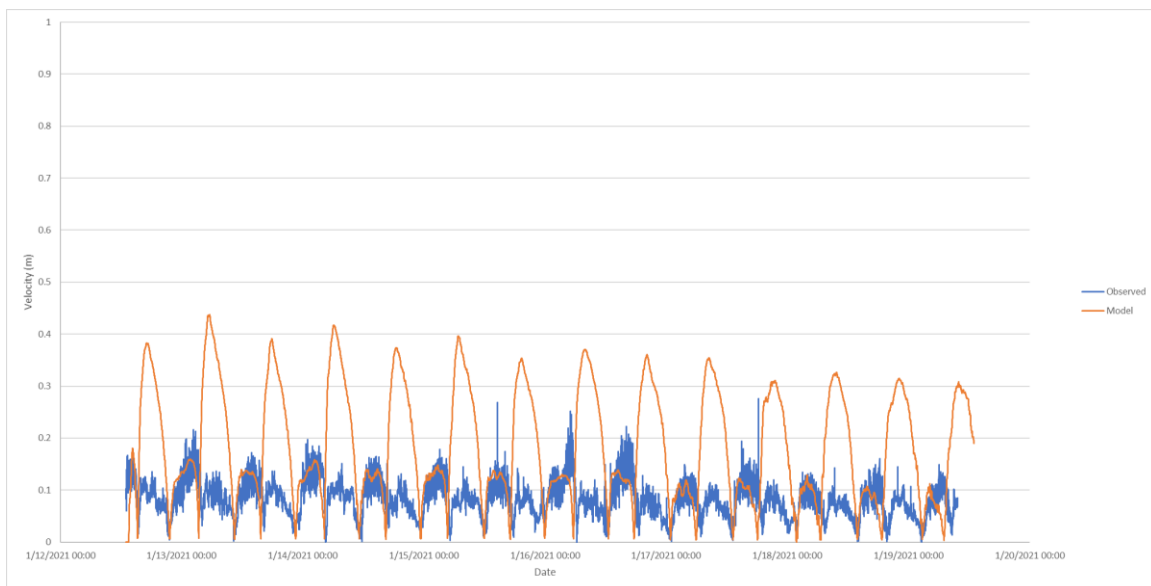


Figure 50 Velocities calculated by the model (orange) and measured (blue) at station BB07.

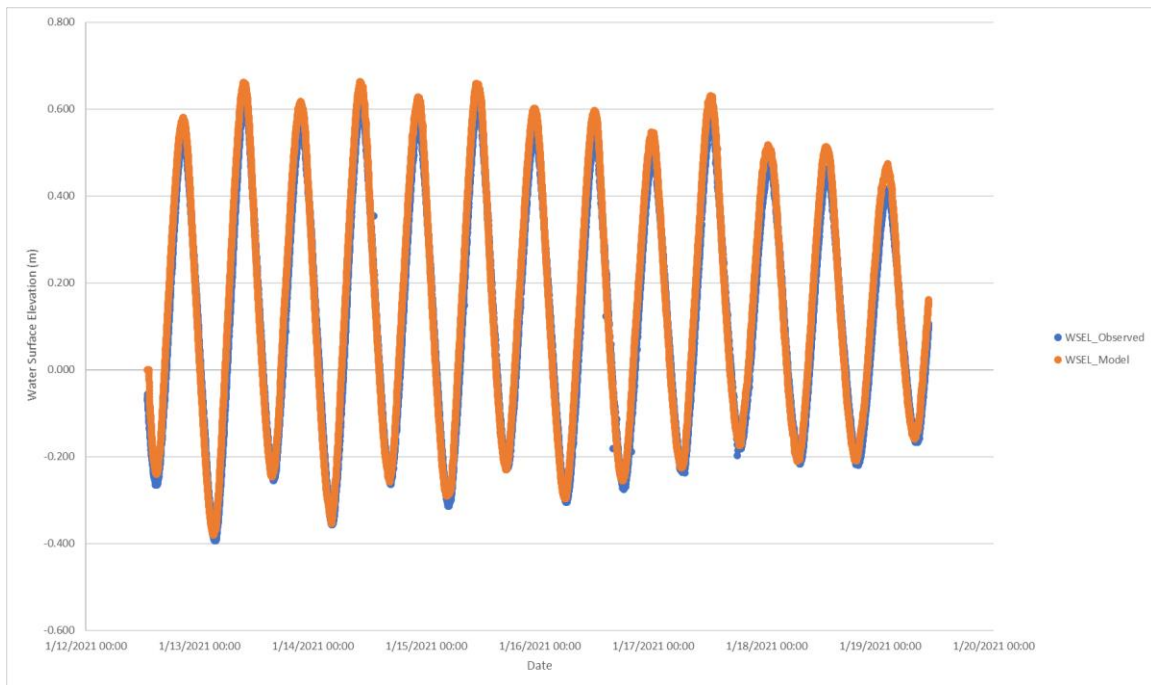


Figure 51 Water elevations calculated by the model (orange) and measured (blue) at station BB09.

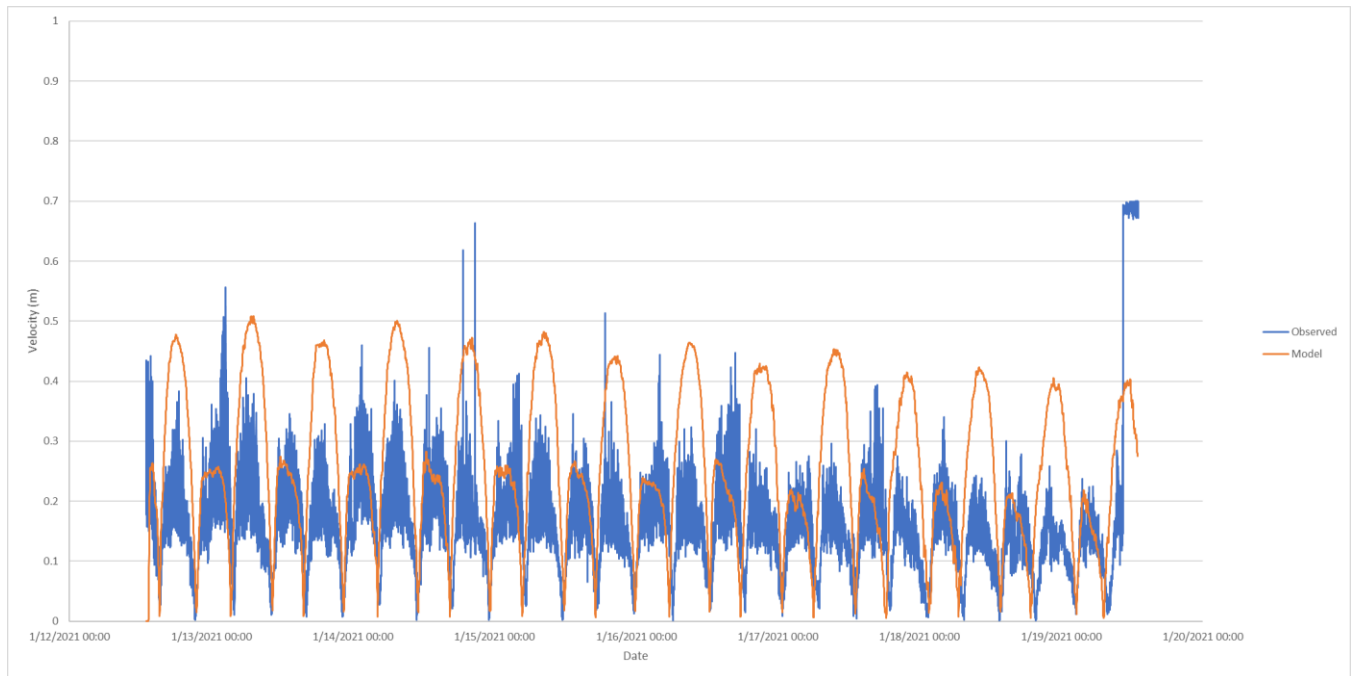


Figure 52 Velocities calculated by the model (orange) and measured (blue) at station BB09.

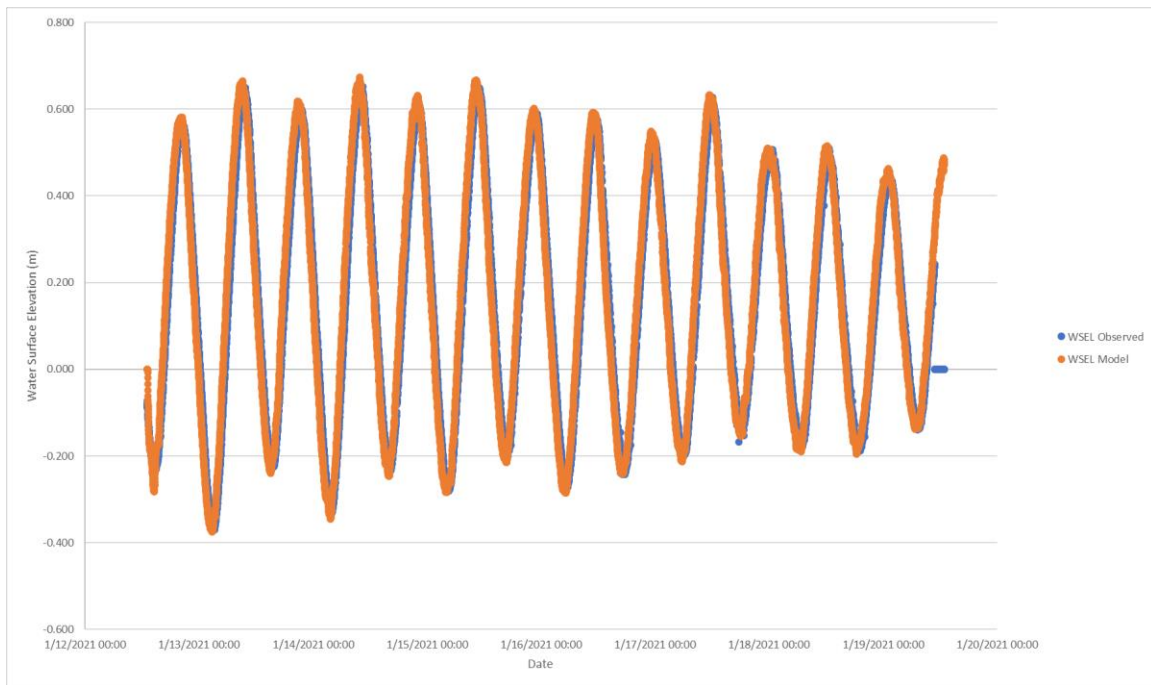


Figure 53 Water elevations calculated by the model (orange) and measured (blue) at station BB10.

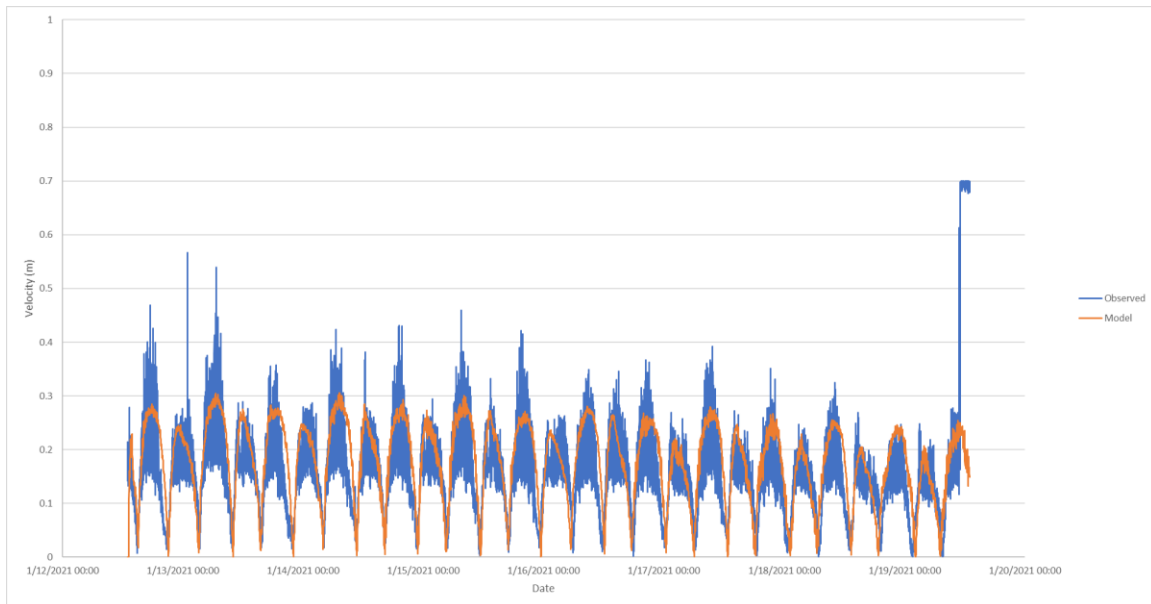


Figure 54 Velocities calculated by the model (orange) and measured (blue) at station BB10.

12.3.2 Results on the Central Bay

Figure 56 to Figure 66 compare water elevations and velocities for stations in the central part of the Bay shown in Figure 55. Stations BB01 and BB16, had data capturing inconsistencies and were not included.

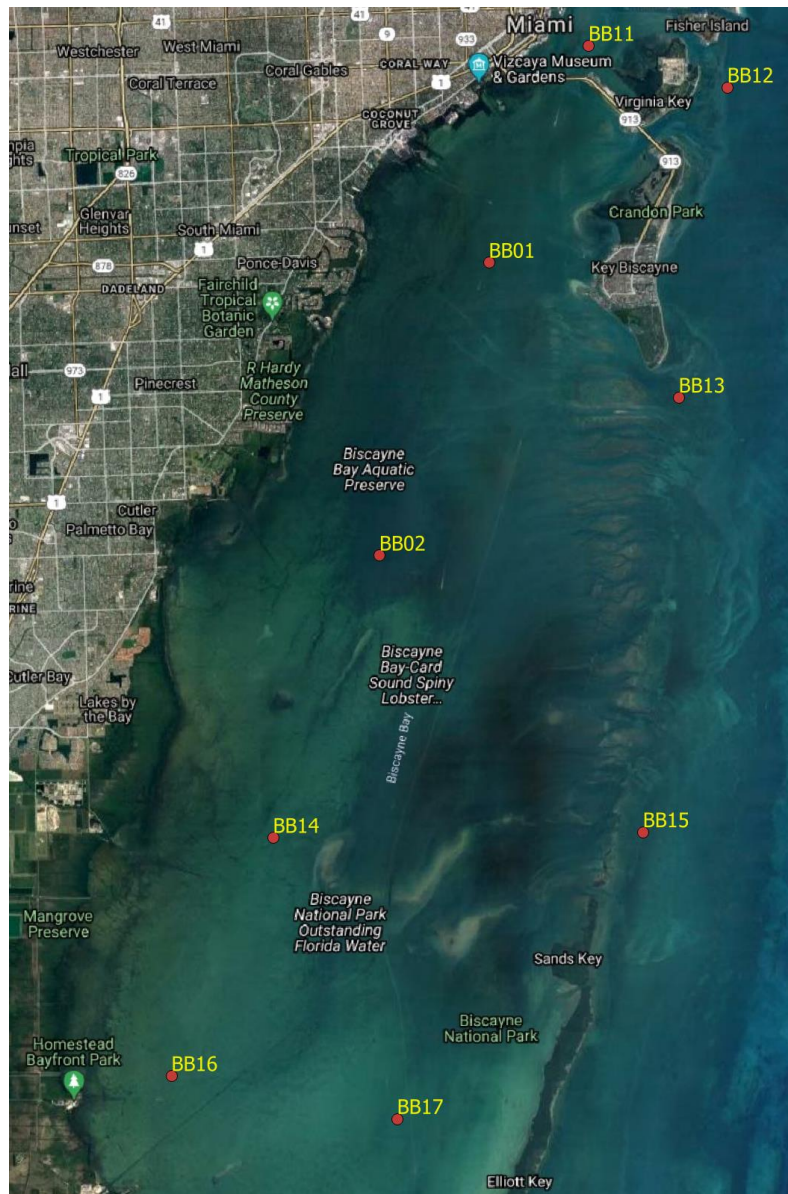


Figure 55 Model validation stations in the Central Bay.

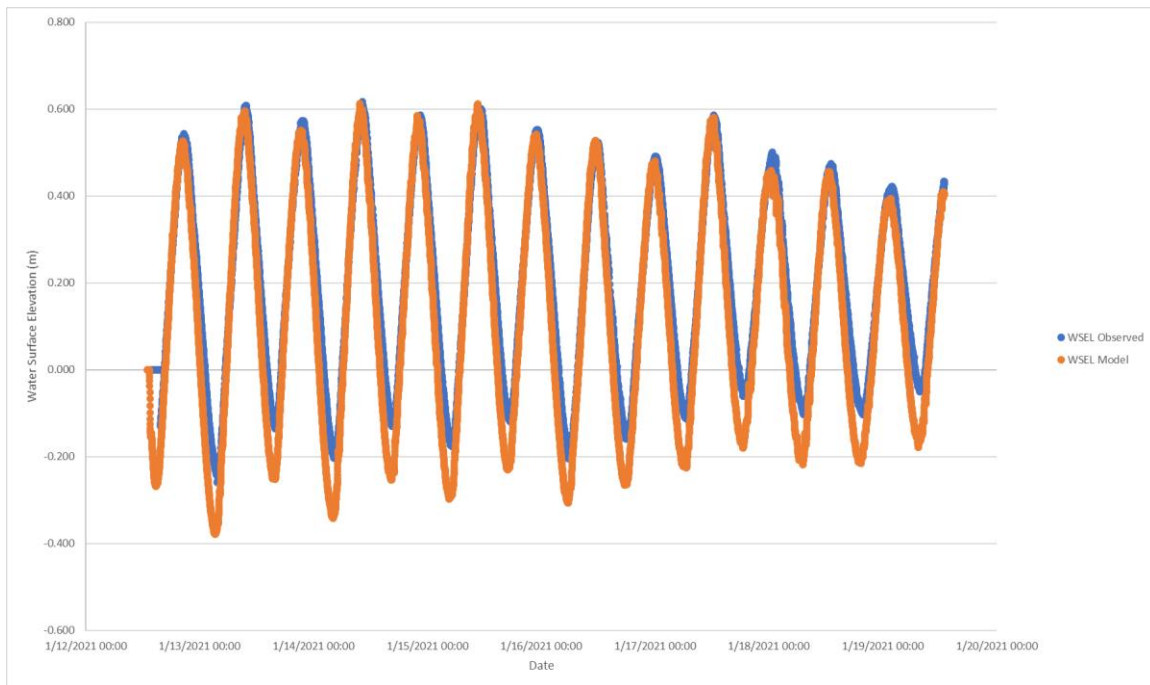


Figure 56 Water elevations calculated by the model (orange) and measured (blue) at station BB02.

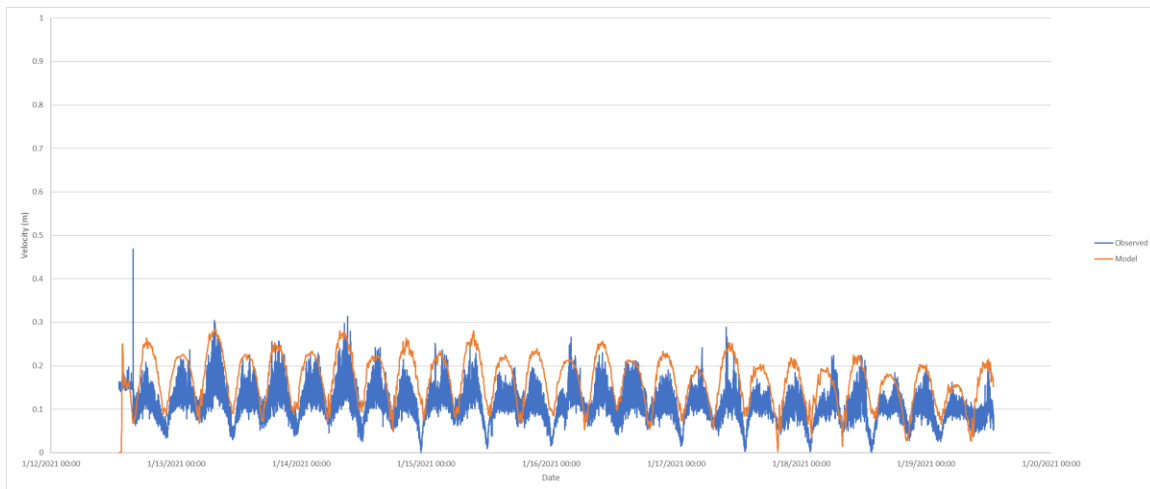


Figure 57 Velocities calculated by the model (orange) and measured (blue) at station BB02.

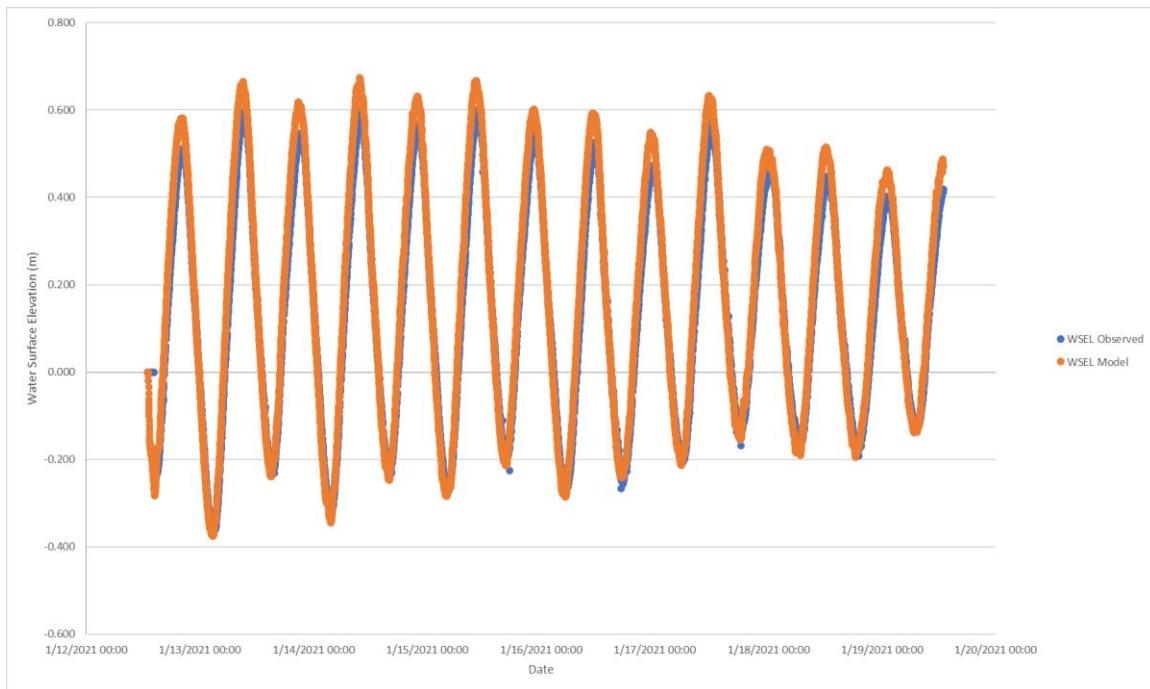


Figure 58 Water elevations calculated by the model (orange) and measured (blue) at station BB11.

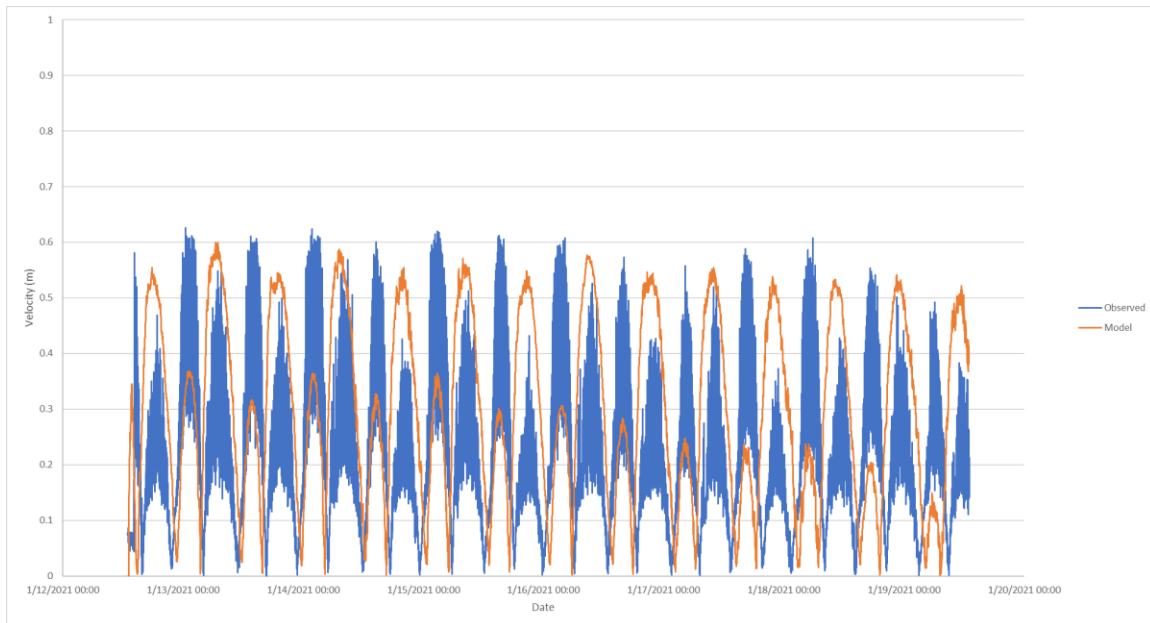


Figure 59 Velocities calculated by the model (orange) and measured (blue) at station BB11.

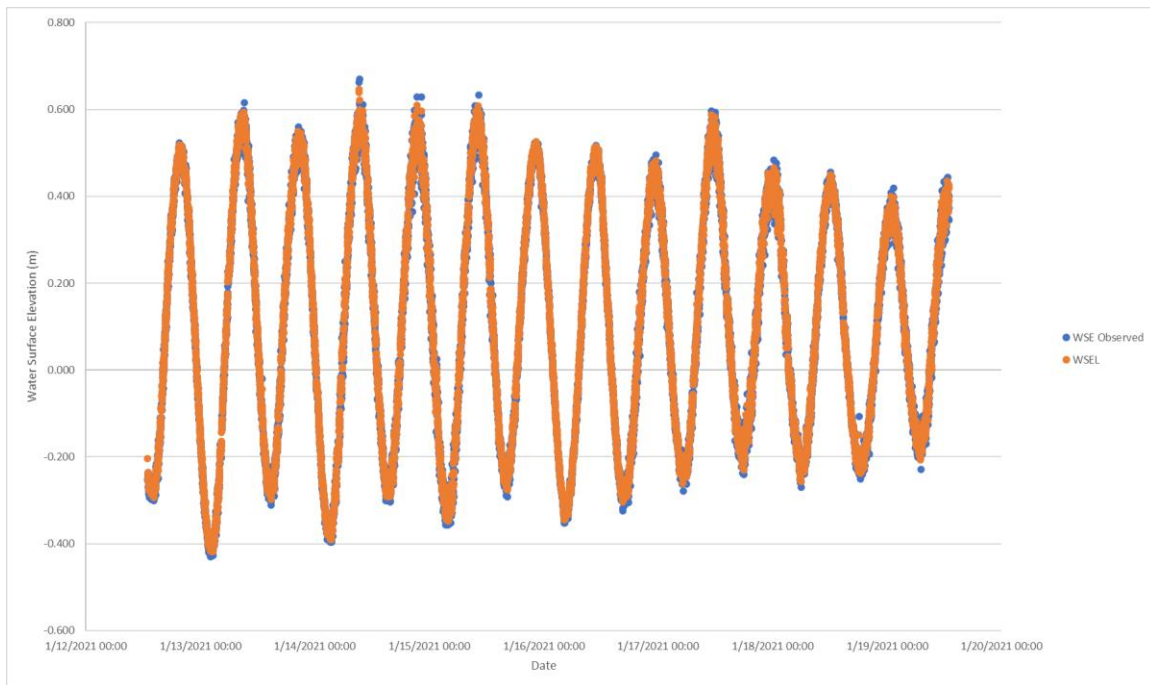


Figure 60 Water elevations calculated by the model (orange) and measured (blue) at station BB13.

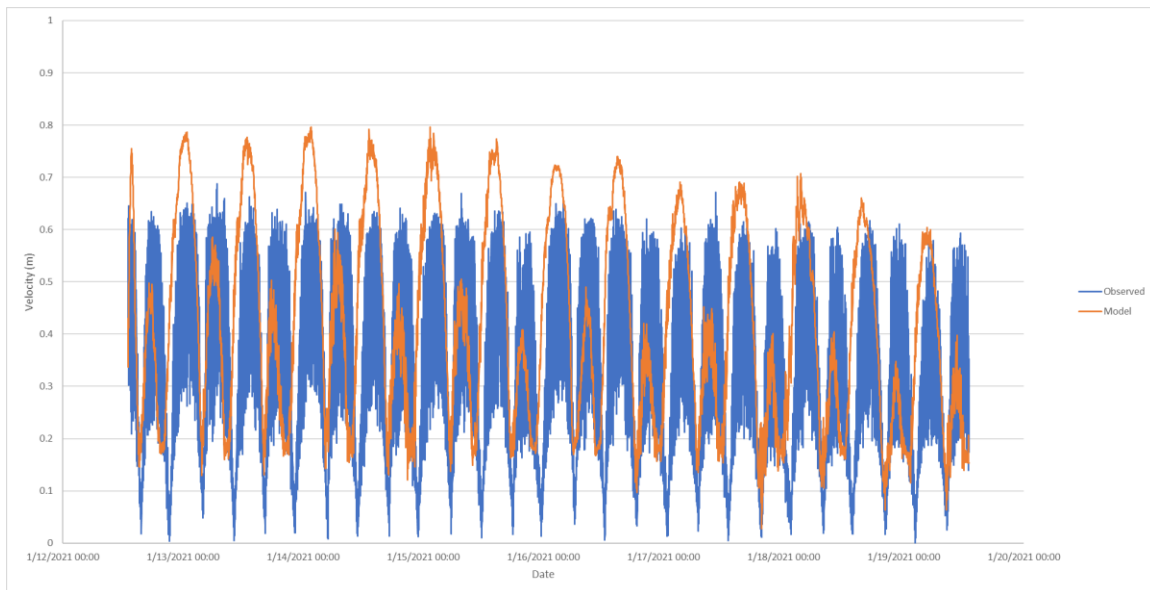


Figure 61 Velocities calculated by the model (orange) and measured (blue) at station BB13.

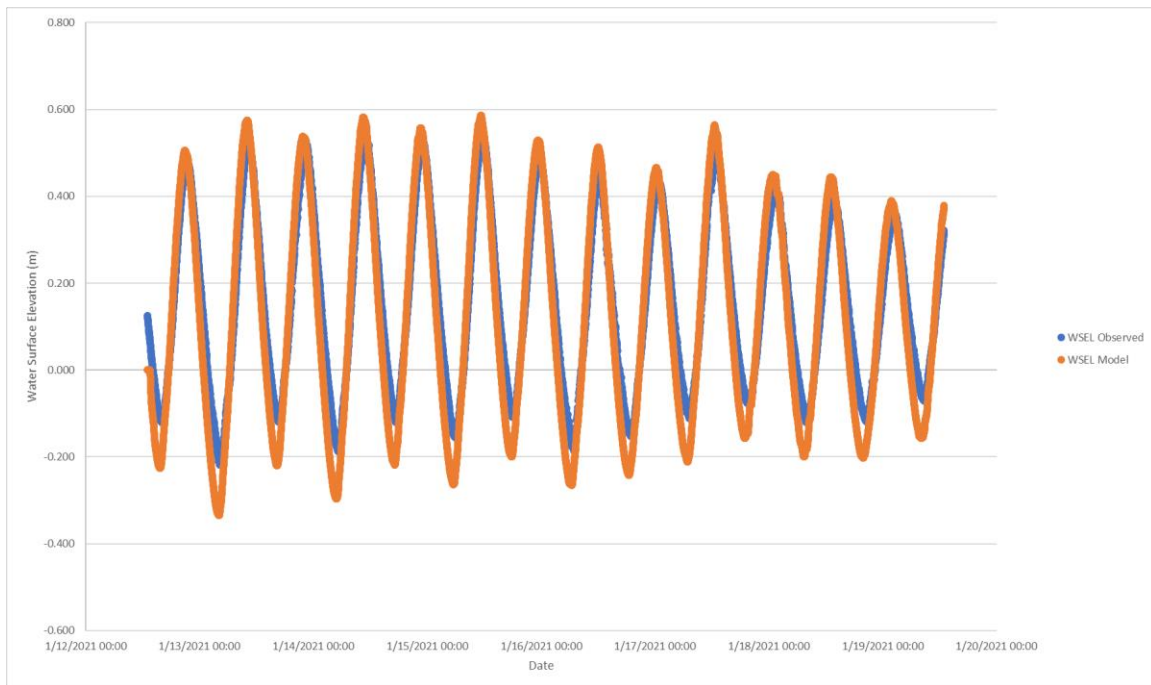


Figure 62 Water elevations calculated by the model (orange) and measured (blue) at station BB14.

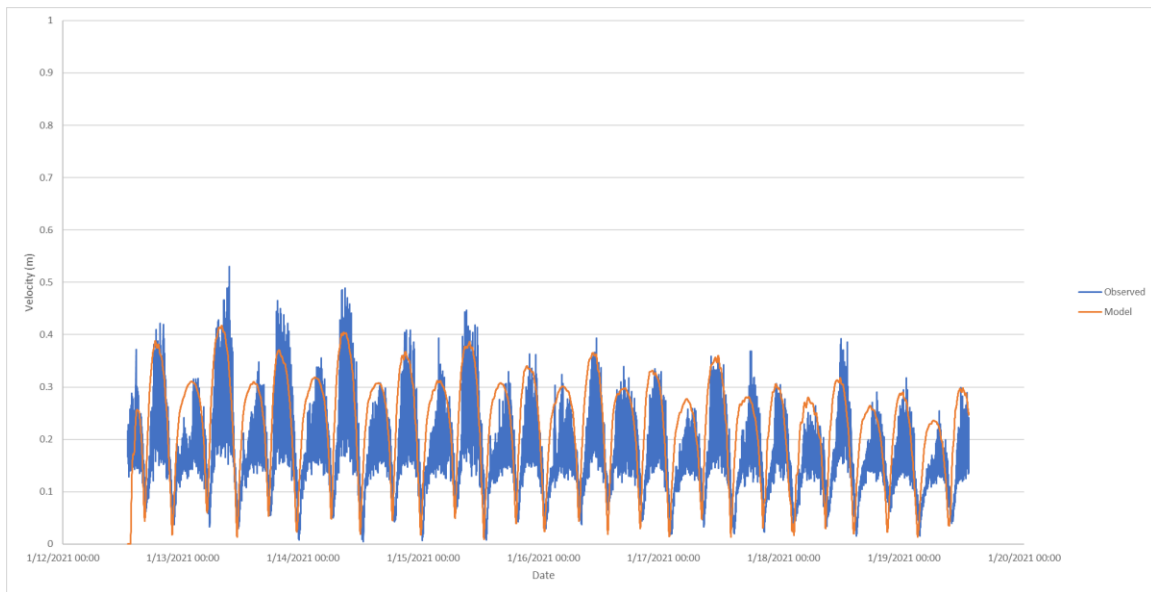


Figure 63 Velocities calculated by the model (orange) and measured (blue) at station BB14.

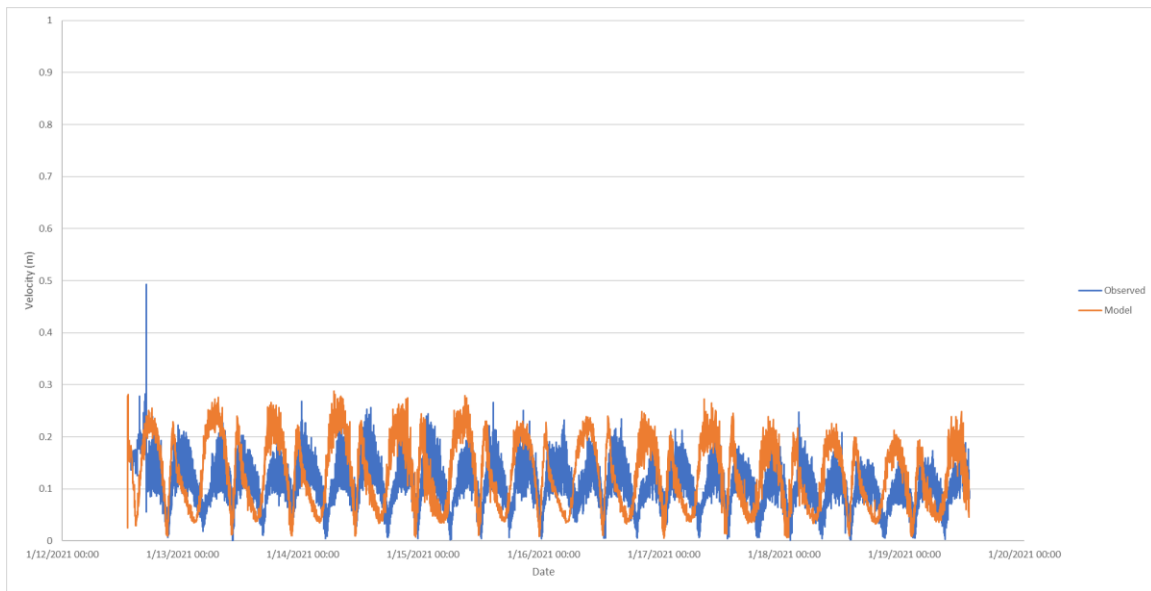


Figure 64 Velocities calculated by the model (orange) and measured (blue) at station BB15.

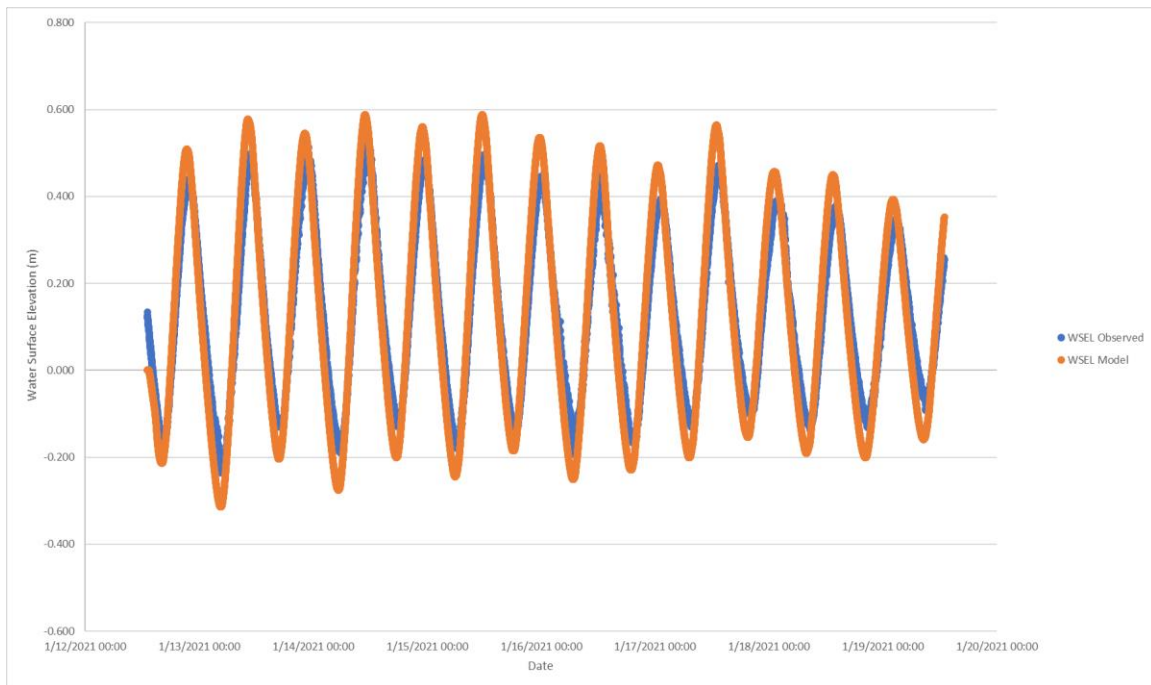


Figure 65 Water elevations calculated by the model (orange) and measured (blue) at station BB17.

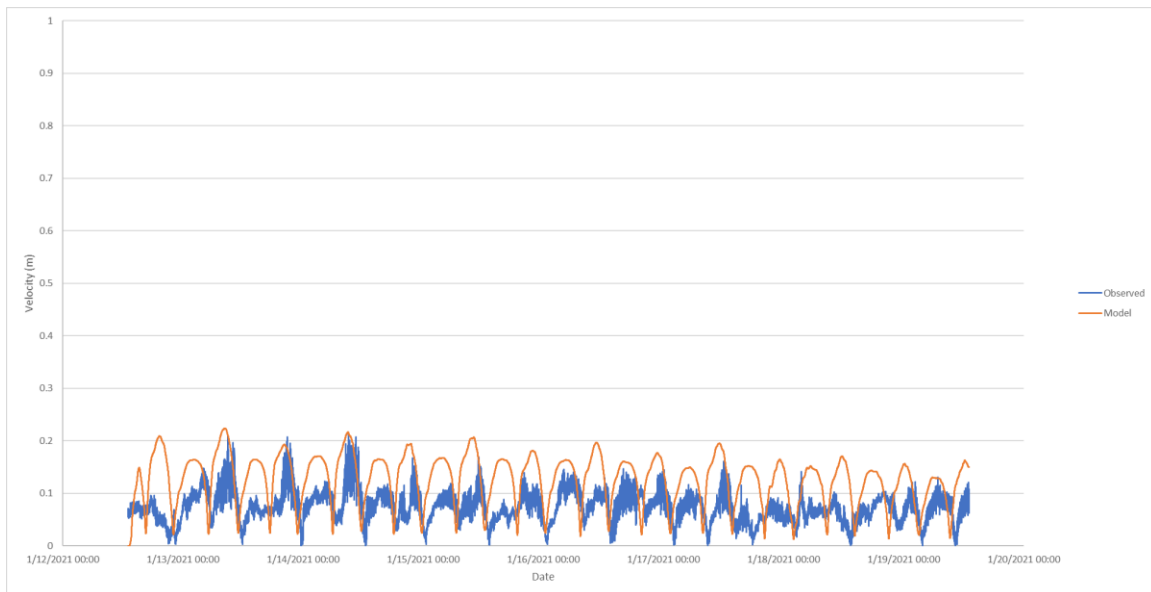


Figure 66 Velocities calculated by the model (orange) and measured (blue) at station BB17.

12.3.3 Results on the Southern Bay

The following Figure 68 to Figure 71 compare water elevations and velocities for stations in the southern part of the Bay shown in Figure 67. Station BB03 presented incorrect measurements and was not included.

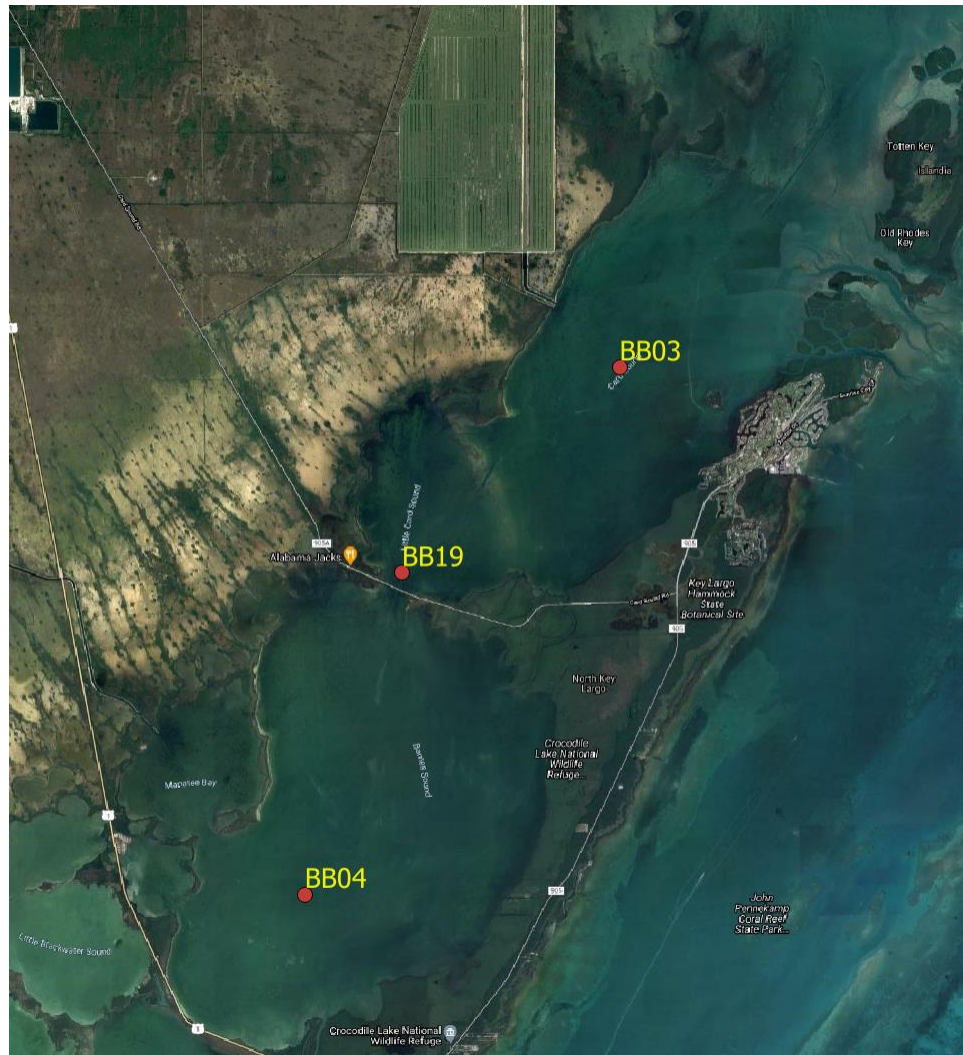


Figure 67 Model validation stations in the Central Bay.

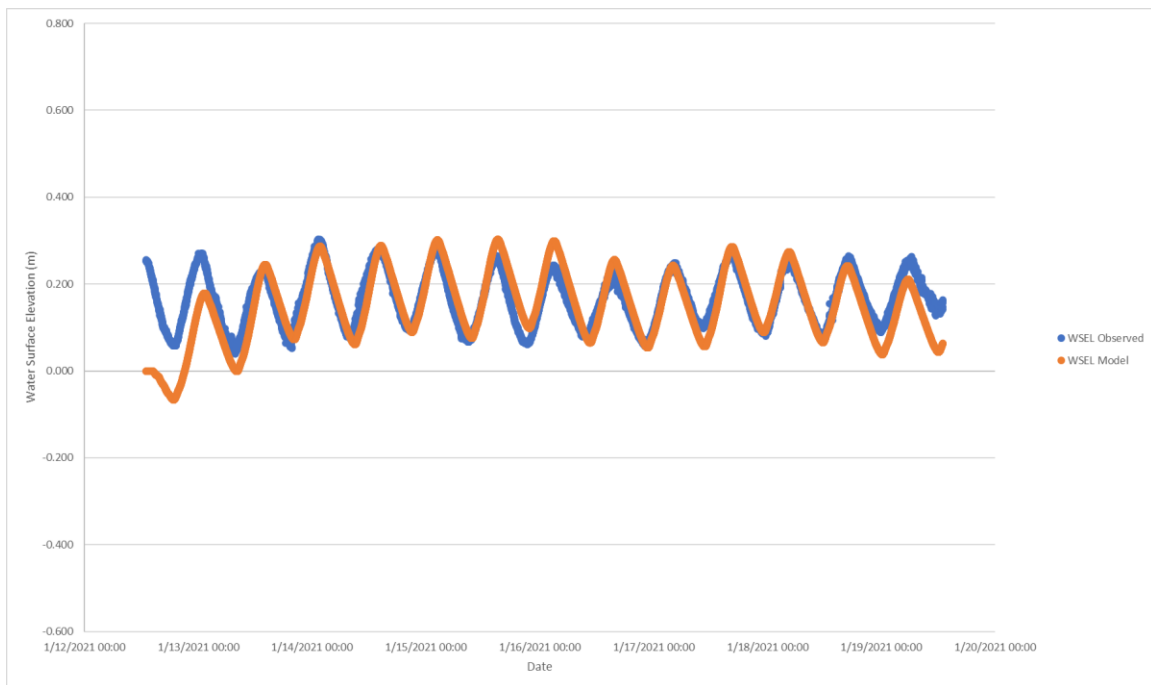


Figure 68 Water elevations calculated by the model (orange) and measured (blue) at station BB04.

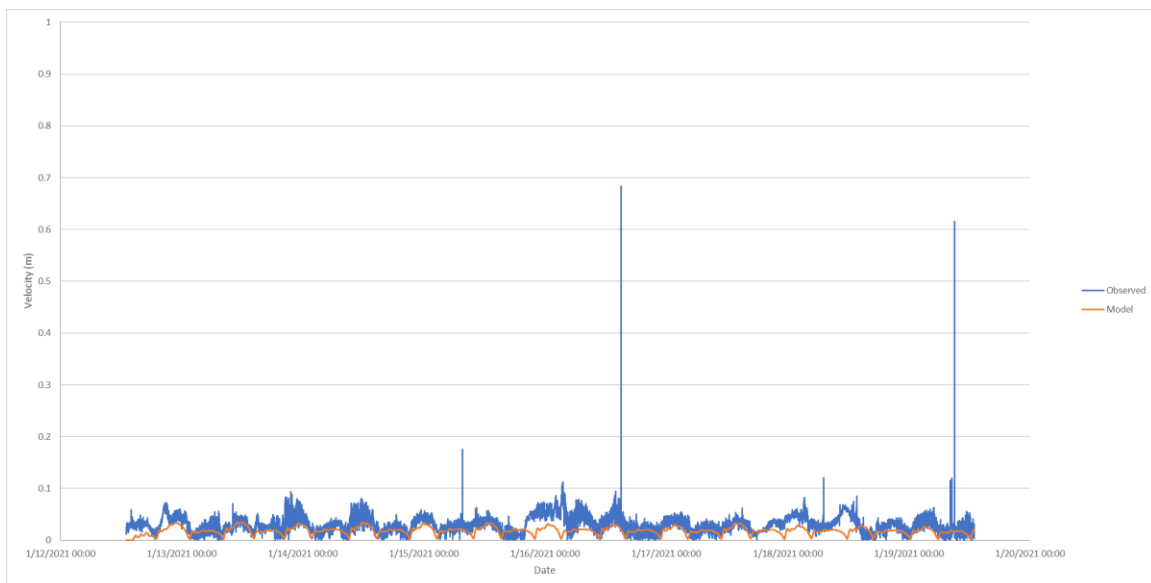


Figure 69 Velocities calculated by the model (orange) and measured (blue) at station BB04.

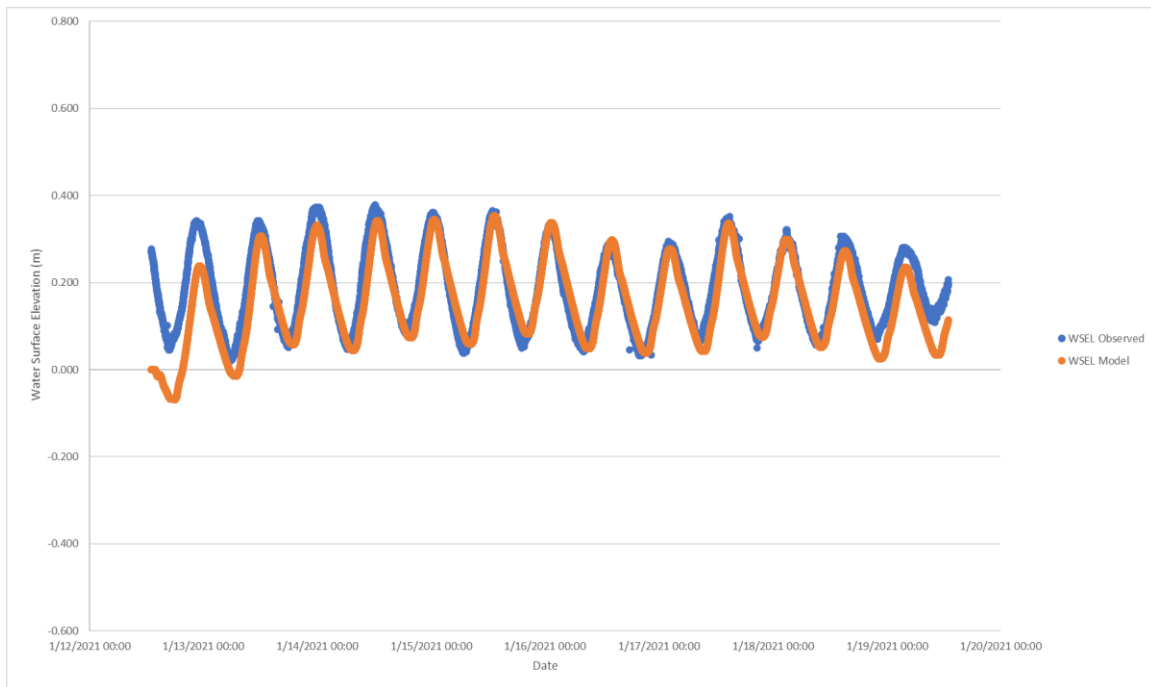


Figure 70 Water elevations calculated by the model (orange) and measured (blue) at station BB19.

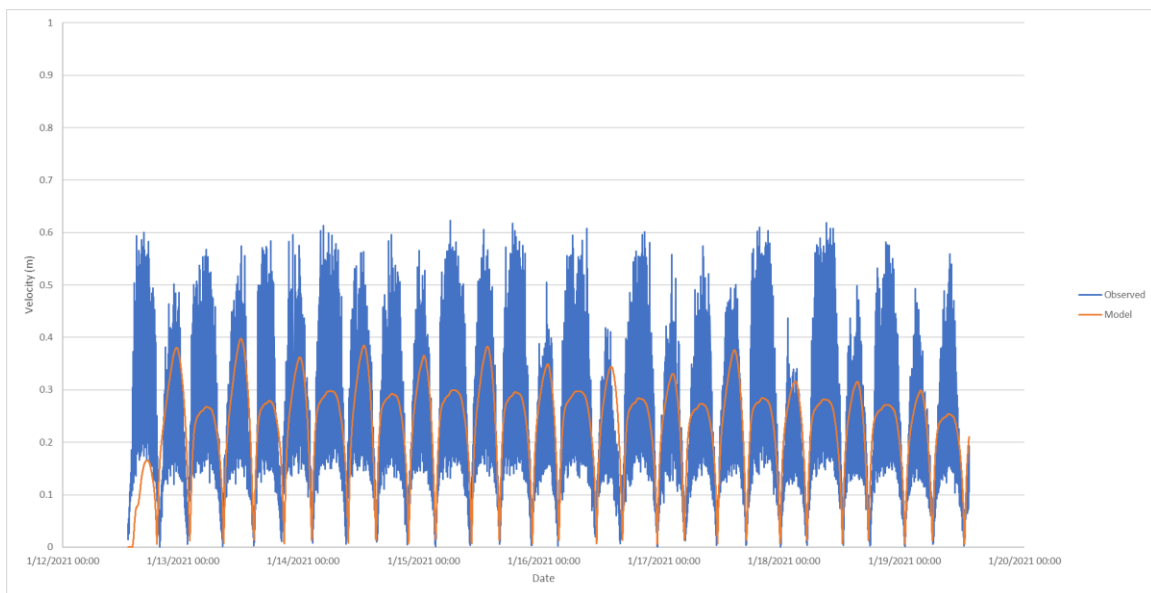


Figure 71 Velocities calculated by the model (orange) and measured (blue) at station BB19.

12.4 Velocity Fields

As an illustration of the model graphical output for the calibration period of 1/12/2021-1/19/2021, The following figures depict the velocity fields that occur throughout Biscayne Bay for times during the validation period 1/12/2021-1/19/2021. The general patterns resembles those of the initial calibration, but there are significant improvements



Figure 72 Velocity field near the northern end of Biscayne Bay. Haulover is the northern open boundary in the model.



Figure 73 Velocity field in the area limited by the 195 highway to the south and SR 934 to the north. Note the higher velocities through the 195 bridges and the circulation patterns with large eddies.

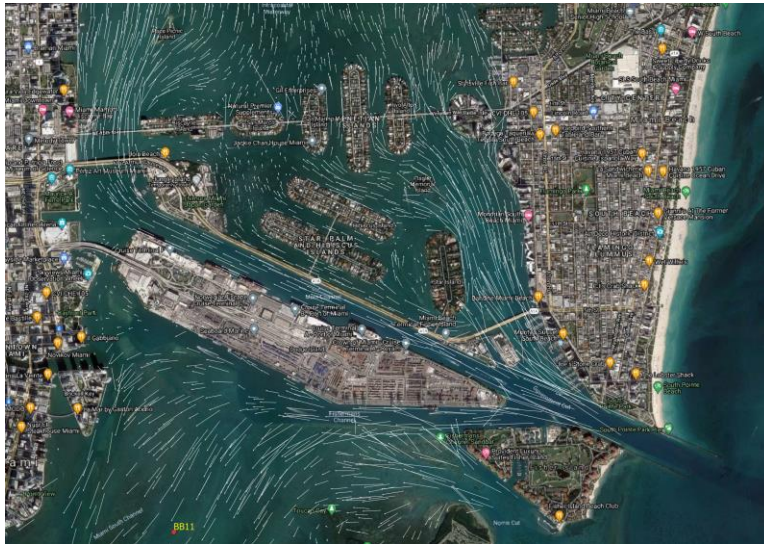


Figure 74 Velocity field in the Port of Miami zone. There are two important open boundaries in this area, Miami Beach (MBGOVCUT) and Fisher Island.

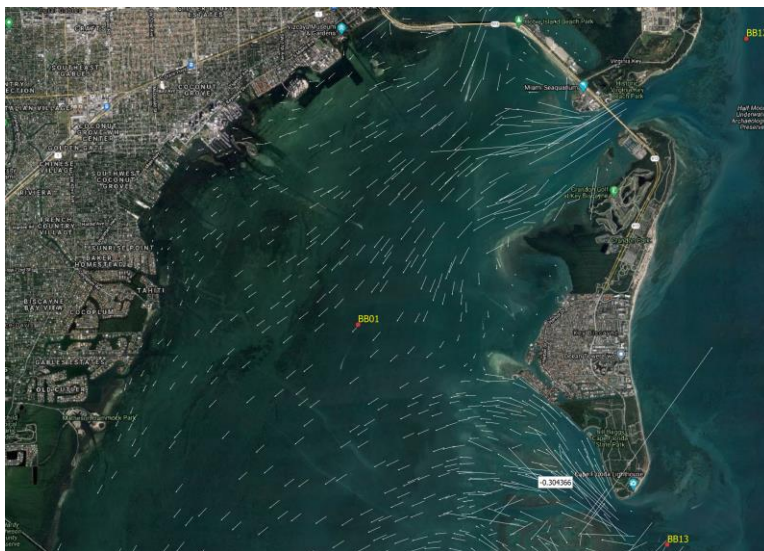


Figure 75 Velocity field around the area of Virginia Key.

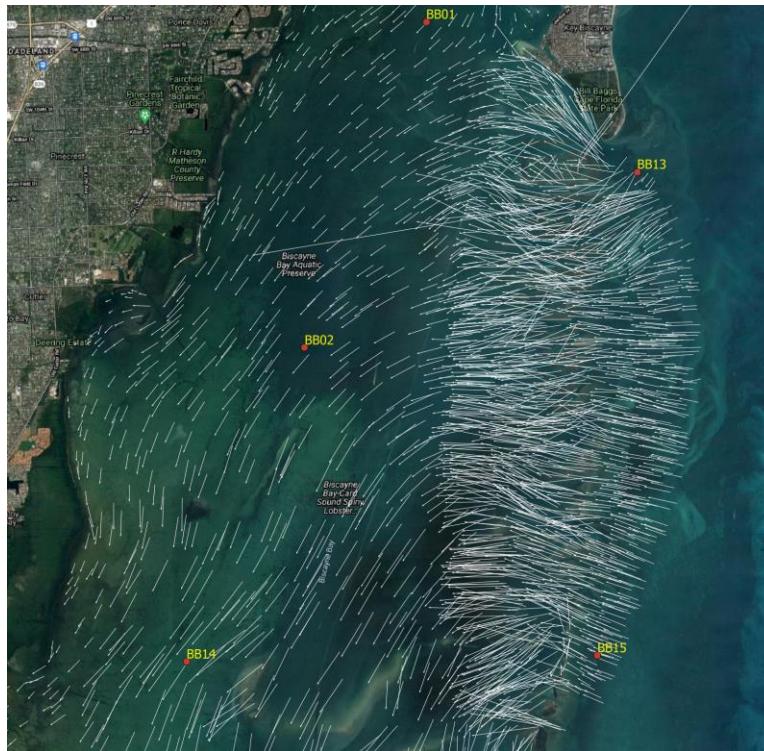


Figure 76 Velocity field on the Safety Valve area. Note the higher velocities over the shallows.



Figure 77 Velocity field on the southern part of Biscayne Bay National Park. Note that in this area, there are three open boundaries: LewisCut, SandsCut, and Elliot Key.



Figure 78 Velocity field on the southern part of the model. This area includes Card Sound and Barnes Sound. Rhodes Key is the southernmost open boundary in the model.

12.5 Conclusions about the Model Validation

This section presented the results for the validation of the hydrodynamic component of the Biscayne Bay Operational Model BBOM. The results of the hydrodynamic validation show that the model can predict measured water elevations and velocities in several locations throughout Biscayne Bay. For the validation, we used the period from 1/12/2021-1/19/2021 that corresponds to the most recent FIU monitoring campaign where all of the stations were collecting data simultaneously.

- In the northern bay, measured and modeled water elevations coincide extremely well. At some sites (BB07), modeled velocity, shows an asymmetric tidal cycle, whose high level component does not match measured data completely. In other instances, the coincidence between modeled and measured velocities is very good (BB10)
- In the Central Bay all modeled water elevations coincide very well with measured data. Modeled velocities in four stations (BB02, BB14, BB15 and BB17) agree with measured data, but two stations (BB11 and BB13) have some discrepancies due to the asymmetry of their modeled pattern.
- In the Southern Bay we deployed instruments in three stations, but those in station BB03 were stolen. Water elevation agreement between modeled and measured is good. Modeled velocities were lower than measured velocities in all instances. We should keep

in mind that velocities are very low in this area, from about 0.05 m/sec in Barnes Sound (BB04) to about 0.3 m/sec close to the Card Sound bridge (BB19).

- The velocity fields in Northern North Bay indicate the existence of two sub-basins with contrasting velocity fields, first, the one from Haulover Inlet to Broad Causeway displaying high velocities, and second, from Broward Causeway to NE79th St Causeway with significantly lower velocities. This suggests high flooding/flushing rates and mixing for the northern sub-basin and more stagnation in the southern one.
- We refined the subdivision of the Julia Tuttle into two clearly distinguished areas, a low-velocity compartment in the center of the basin, bordered toward the west, east and south shorelines by high velocity zones (Figure 74). The central slow-moving, eddy/prone area, receiving waters from the polluted Little River, is where the largest seagrass die-off has occurred in North Biscayne since 2013.
- During high tide cycles, water entering the bay at Government Cut moves fast in three directions. First, straight northwest along the Main Channel to turn north under the MacArthur Causeway; second, northwards to the Venetian Island sub-basin; and third, along the Fisherman's Channel. Fisher Island's fast incoming waters move to the Virginia Key-Miami River sub basin, on the northern portion of Central Biscayne Bay. Waters from this sub-basin move under the Rickenbacker Causeway toward the northern portion of Central Biscayne Bay.
- Virginia Key inlet flooding waters (Figure 76) drain towards the northern portion of Central Biscayne Bay, west of Key Biscayne. Currents in this northern portion of the bay are relatively slow, especially to the west and to the south of the area. Velocity declines progressively as it moves westward, to the coast.
- The Safety Valve area (Figure 41) controls the main water entrance to Central Biscayne Bay. Waters move swiftly westwards over the shallows and then turn southwest, and south as they approach the shoreline. This is a very dynamic system where not only tides, but winds help moving the water into the bay.
- This validation reconfirms that waters through the Lewis Cut, Sands Cut, Cesar's Creek and Rhodes Channel (Figure 42) have only local influence in the overall circulation pattern of Biscayne Bay.
- Finally, waters in the southernmost portion of Biscayne Bay (Card and Barnes Sound, and Manatee Bay) show very low velocity (Figure 79), and flow is mostly outwards, even during incoming tides. Those characteristics suggest that most of the properties of the water column in that area are the result of local processes and sources from the Everglades

13 Salinity Transport Component

In this section we describe the incorporation of the Salinity Transport Component of the Biscayne Bay Operation Model.

13.1 Salinity Transport Model Implementation

The model domain polygon was designed so that it covers both north and south Biscayne Bay, Card and Barnes Sounds, and a part of the oceanic boundary that extends beyond the Safety Valve (see Figure 96). Extending the model domain in this way includes the essential role that the Safety Valve has in Biscayne Bay hydrodynamics while avoiding the potential numerical issues that can occur if we would locate an open boundary along a very shallow area with high velocities and drying zones. For the first phase of the calibration, tidal and wind forces were considered as the main forces controlling the water flow inside the Bay. At the present stage we are considering the combined effects of freshwater inflows from canals and groundwater, and tidal forcing on the ocean boundaries and wind stress on the water surface.

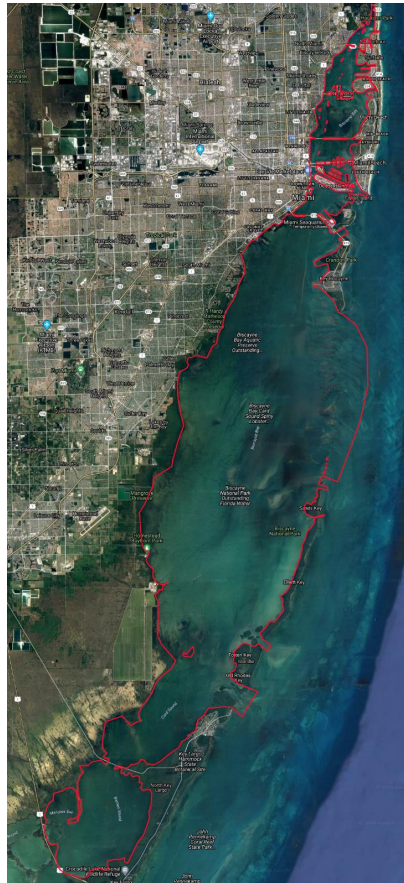


Figure 79 Model domain. Red polygons define the model extent.

13.1.1 Mesh Geometry and Topology

The mesh developed for the model calibration has 43,872 cells covering an area of 733 km². The cell sizes vary from 24 m to 610 m. Figure 97 depicts the model computational mesh that has been generated for BBOM.

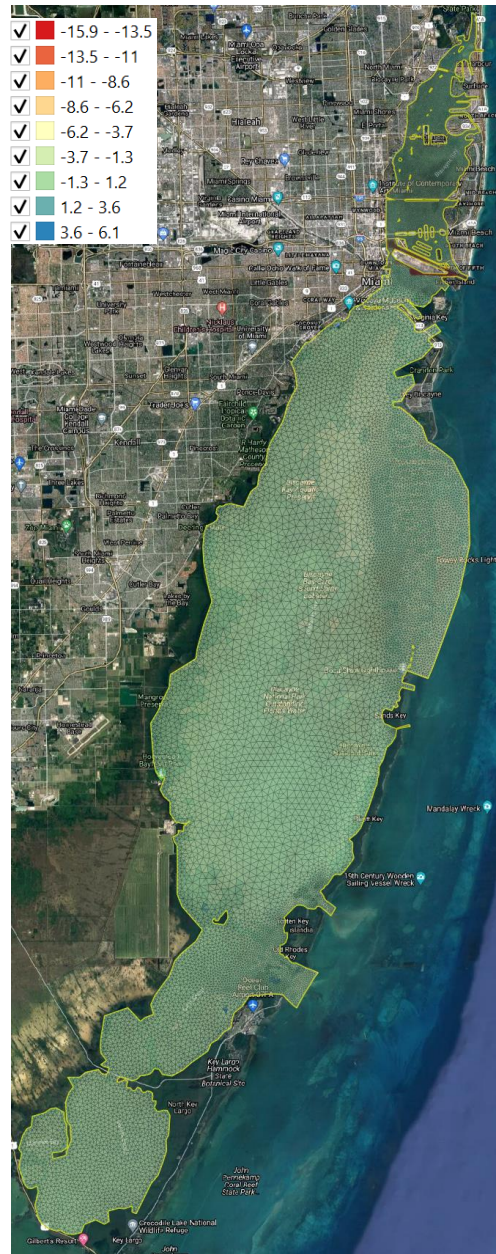


Figure 80 Biscayne Bay Operational Model (BBOM) computation mesh. Darker areas are higher resolution zones with smaller cells to better represent bathymetric and contour gradients. Legend indicates the bed elevations in meters.

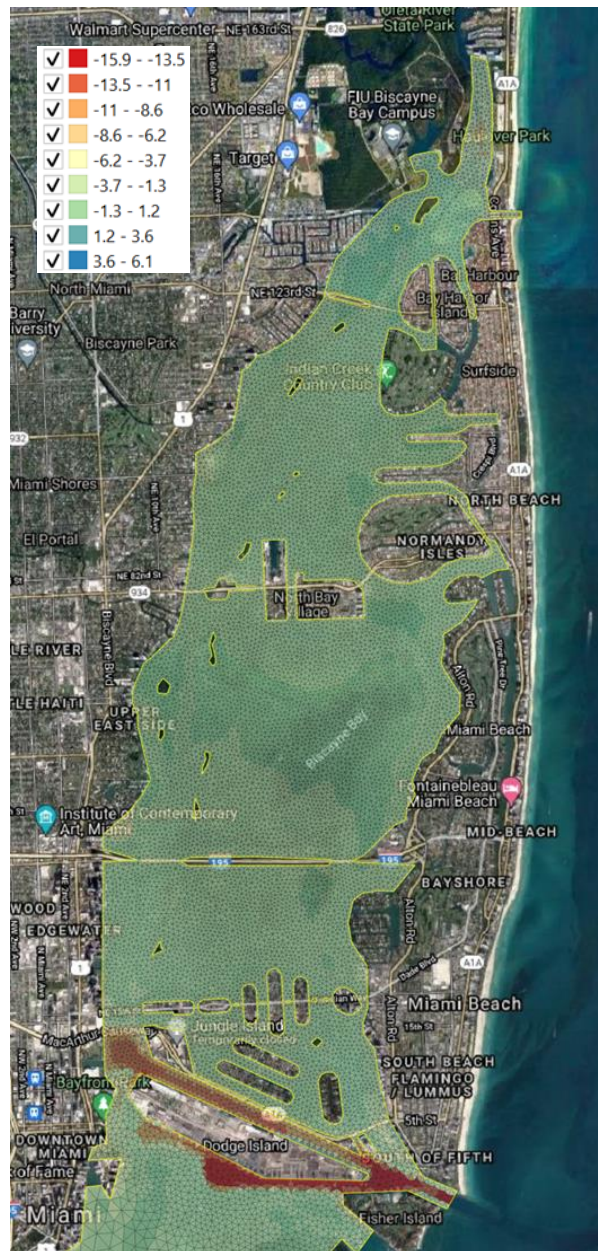


Figure 81 Detail of BBOM mesh on the northern end of Biscayne Bay, showing Haulover tidal open boundary. Legend indicates the bed elevations in meters.

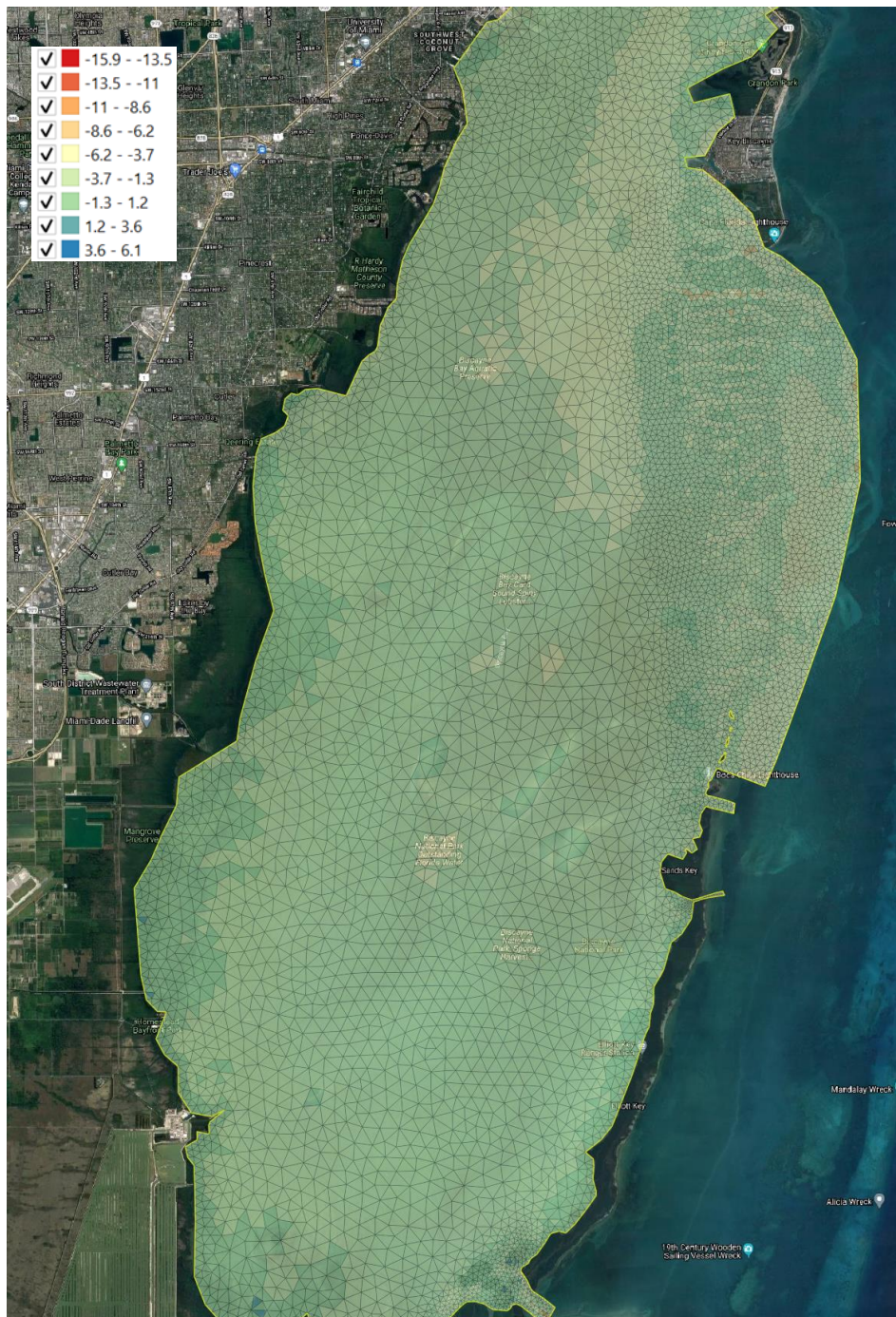


Figure 82 Detail of BBOM mesh on the central Biscayne Bay. Legend indicates the bed elevations in meters.

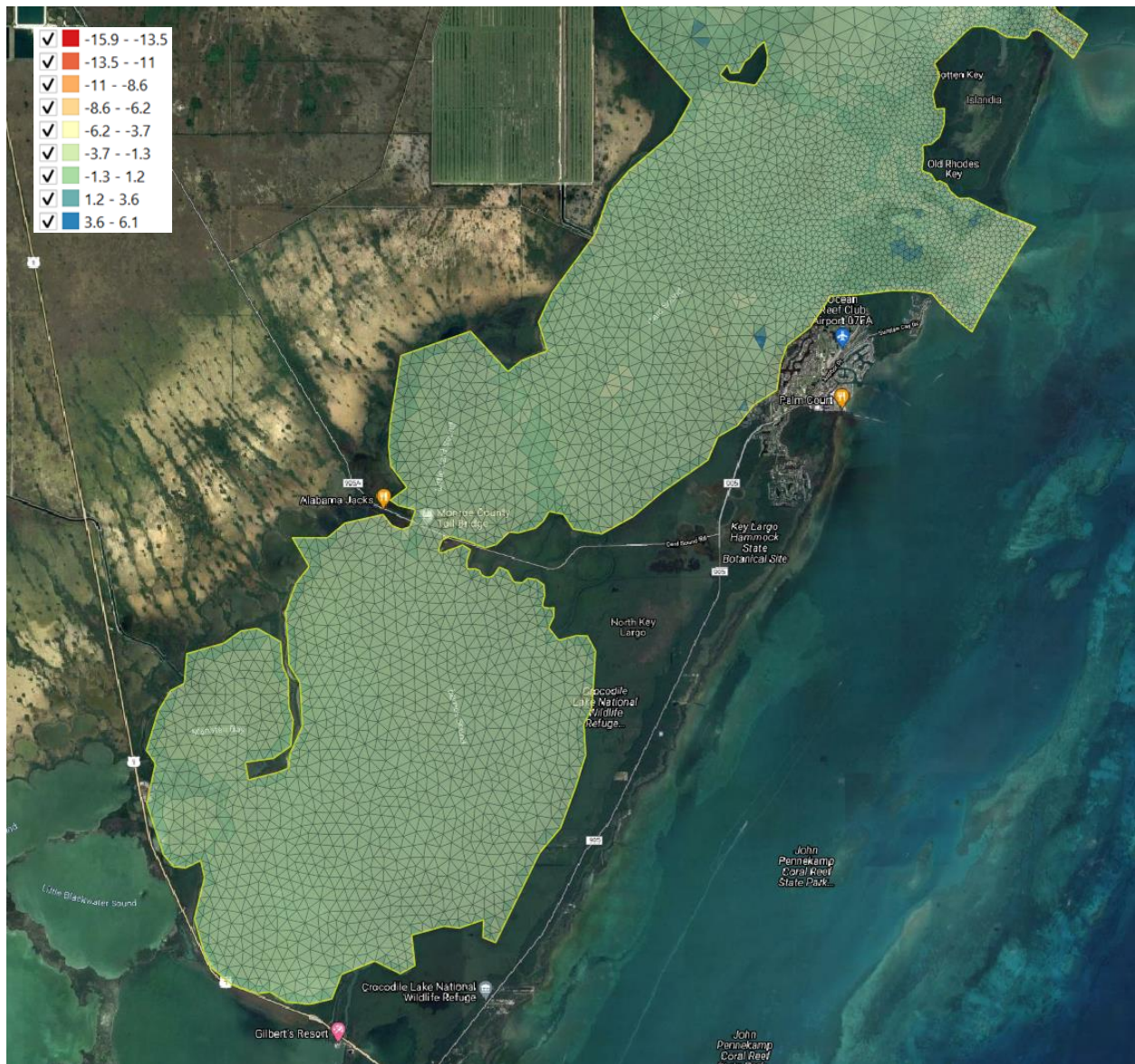


Figure 83 Detail of BBOM mesh on the southern end of Biscayne Bay. Legend indicates the bed elevations in meters.

13.1.2 Boundary Conditions

The Salinity Transport Model requires two types of boundary conditions. On the ocean inlets, time series of the tidal elevations and water salinity are specified. The model uses the tidal elevation for both inflow and outflow, and salinity is only used when the flow direction is toward the bay interior. At all canals that enter the bay, the boundary condition includes the water discharge (m^3/s) and the salinity. Also, the model can incorporate conditions representing the ground water inflow that occur along the interface between the bay and the land. Along those areas the model requires the groundwater discharge and the salinity. Table 8 summarizes the 33 inflow and outflow conditions that were used for the BBOM Salinity Transport Component implementation. Figure 87 to Figure 89 show the boundary conditions as specified on the northern, central, and southern portions of the bay.

Table 8 Boundary conditions used in the BBOM Salinity Transport Component.

No.	Inflow/outflow Boundary	Boundary Type	Boundary Condition File Name	Inflow Salinity (o/oo)
1	Haulover	Tide elevation + Salinity	BB05_TIDE.TXT	36
2	VirginiaKey	Tide elevation + Salinity	BB12_TIDE.TXT	36
3	FisherIsland	Tide elevation + Salinity	BB12_TIDE.TXT	36
4	MBGOVCUT	Tide elevation + Salinity	BB12_TIDE.TXT	36
5	LewisCut	Tide elevation + Salinity	BB13_TIDE.TXT	36
6	SafetyValve	Tide elevation + Salinity	BB13_TIDE.TXT	36
7	SandsCut	Tide elevation + Salinity	BB13_TIDE.TXT	36
8	ElliottKey	Tide elevation + Salinity	BB13_TIDE.TXT	36
9	RhodesKey	Tide elevation + Salinity	BB13_TIDE.TXT	36
10	InterCostalN	Water discharge + Salinity	InterCostalN.txt	0
11	InterCostalMid	Water discharge + Salinity	InterCostalSMid.txt	0
12	InterCostalS	Water discharge + Salinity	InterCostalS.txt	0
13	BC_30	Water discharge + Salinity	BBCentral4.txt	0
14	BBCentral3	Water discharge + Salinity	BBCentral3y.txt	0
15	BBCentral2	Water discharge + Salinity	BBCentral2.txt	0
16	BBCentral.txt	Water discharge + Salinity	BBCentral.txt	0
17	MangrovePreserve	Water discharge + Salinity	Mangrovepreserve.txt	0
18	BTurkeyPoint	Water discharge + Salinity	Turkey2.txt	0
19	Cardsound	Water discharge + Salinity	CarlSound.txt	0
20	BarnesSound	Water discharge + Salinity	BarnesSound.txt	0
21	Manatee	Water discharge + Salinity	Manatee.txt	0
22	S197	Water discharge + Salinity	S197C.txt	0
23	S20F	Water discharge + Salinity	S20F.txt	0
24	S20G	Water discharge + Salinity	S20G.txt	0
25	S21A	Water discharge + Salinity	S21A.txt	0

26	S21S	Water discharge + Salinity	S21S.txt	0
27	S123S	Water discharge + Salinity	S123S.txt	0
28	S700P	Water discharge + Salinity	S700P.txt	0
29	S22S	Water discharge + Salinity	S22S.txt	0
30	G93	Water discharge + Salinity	G93.txt	0
31	S25S	Water discharge + Salinity	S25S.txt	0
32	S27S	Water discharge + Salinity	S27S.txt	0
33	S28_S	Water discharge + Salinity	S28S.txt	0

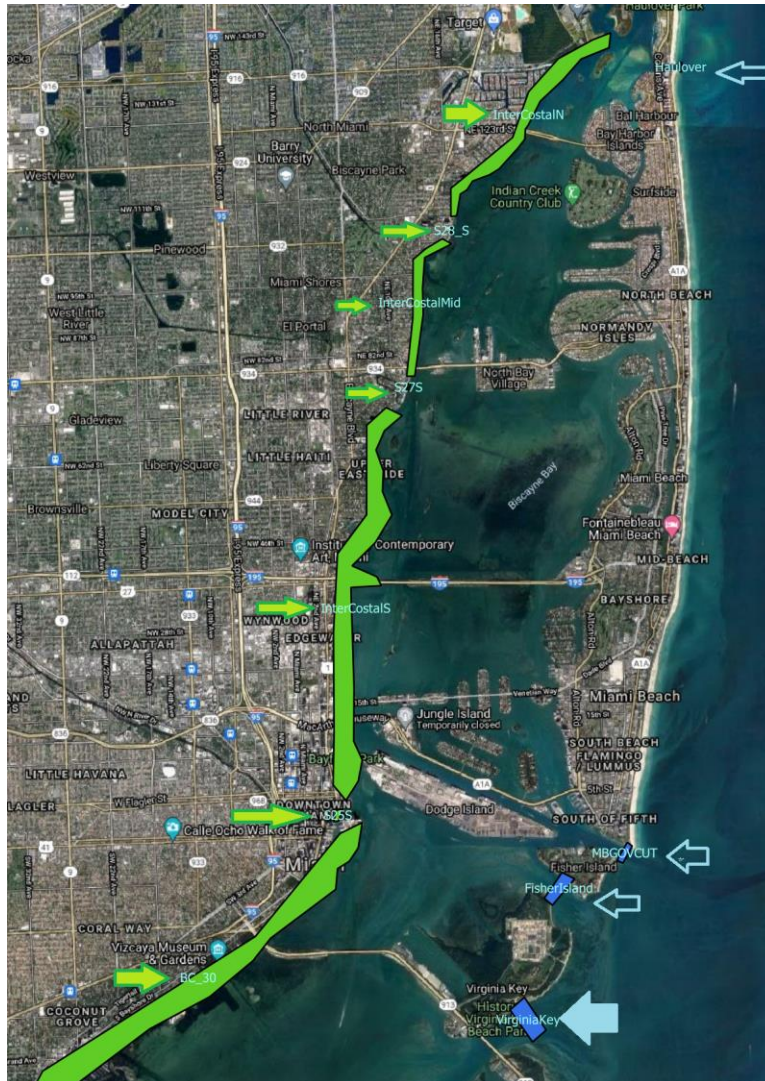


Figure 84 Boundary Conditions for the Salinity Transport Model. Northern Biscayne Bay.

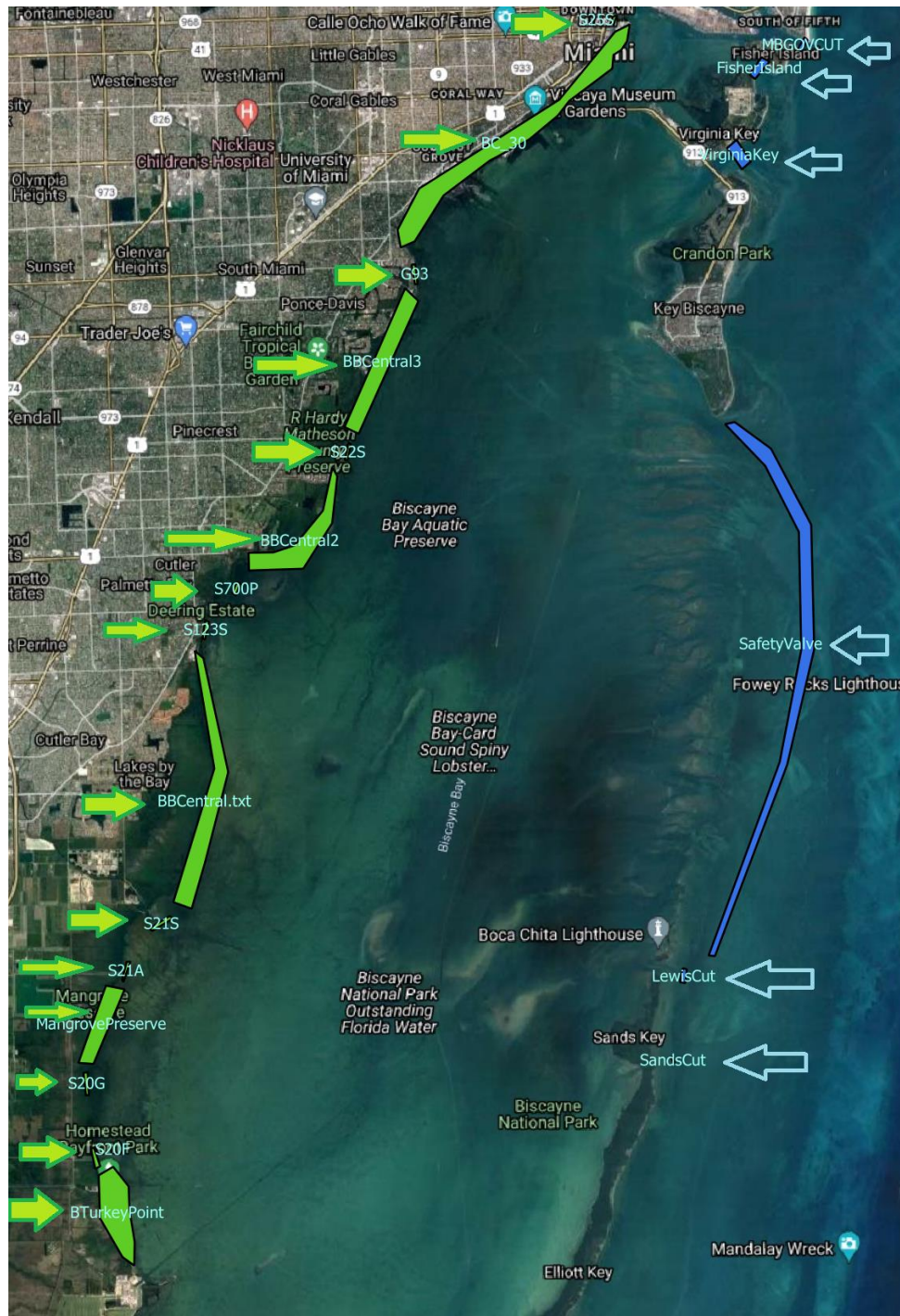


Figure 85 Boundary Conditions for the Salinity Transport Model. Central Biscayne Bay.

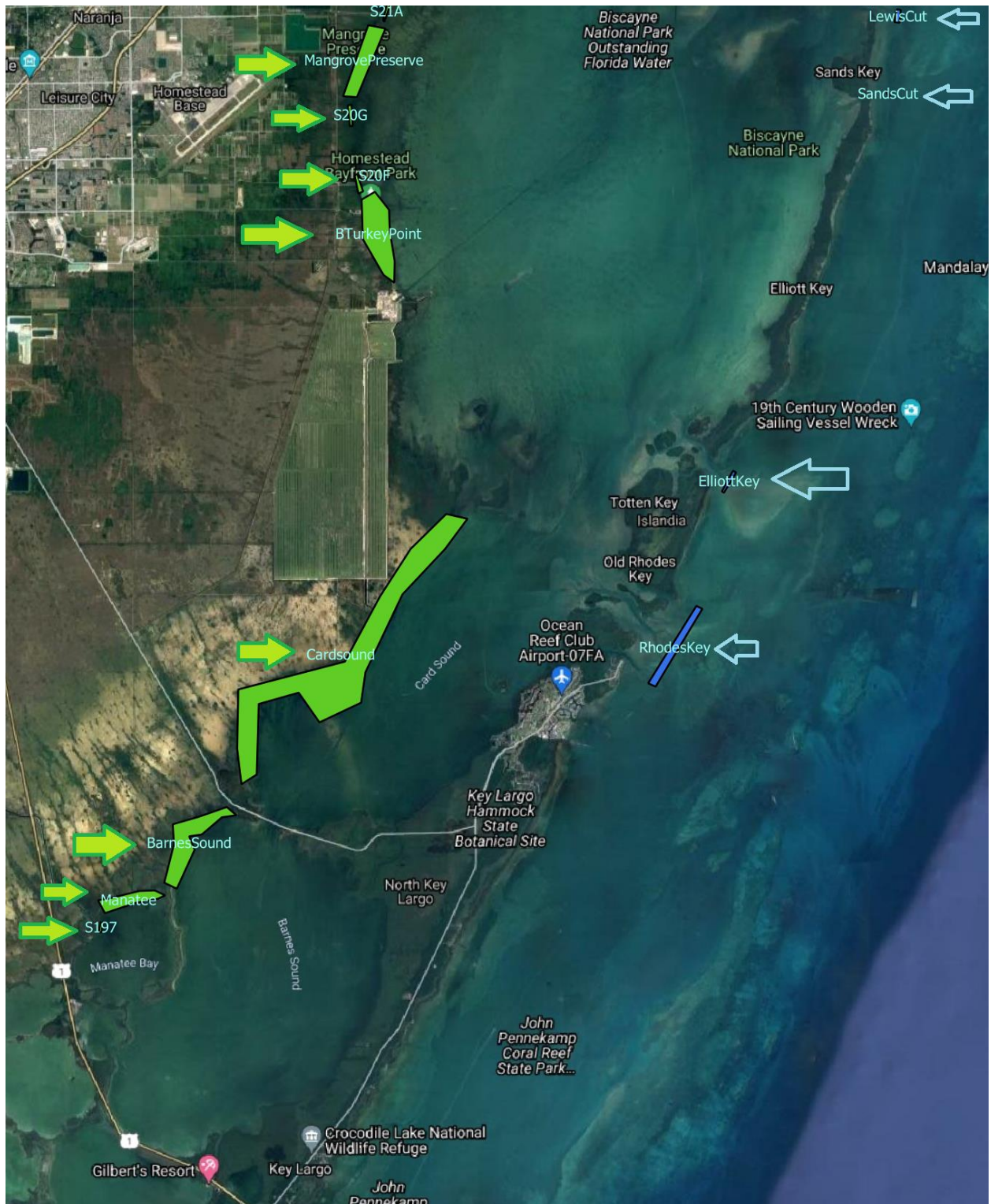


Figure 86 Boundary Conditions for the Salinity Transport Model. Southern Biscayne Bay.

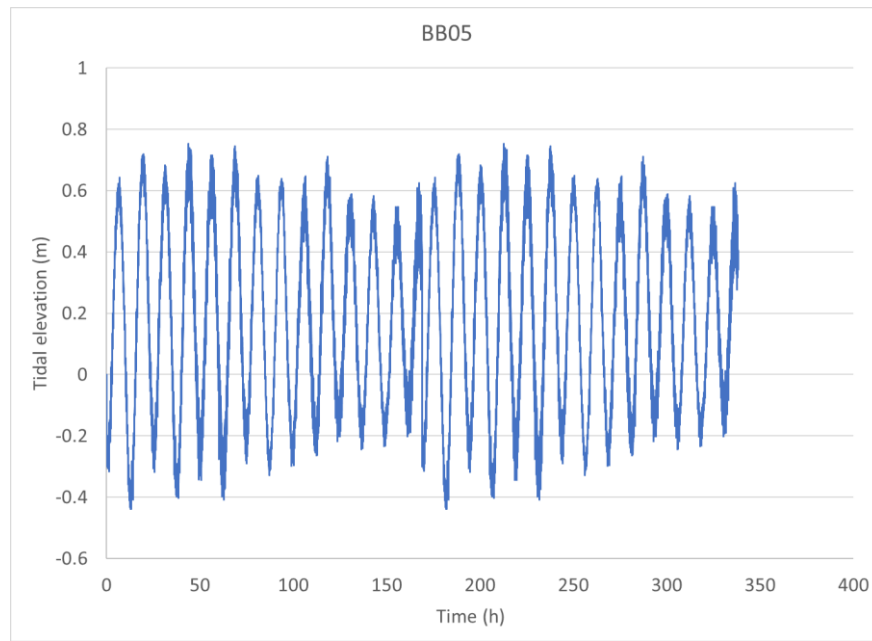


Figure 87 Tidal elevations measured at station BB05 used as boundary conditions at Haulover inlet.

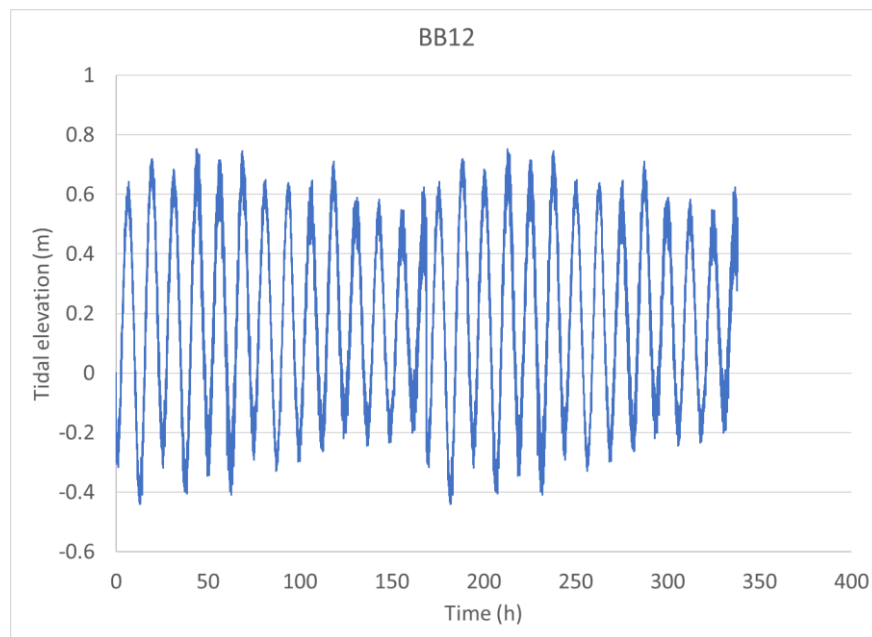


Figure 88 Tidal elevations measured at station BB12 used as boundary conditions at Virginia Key Fisher Island and Government Cut inlets.

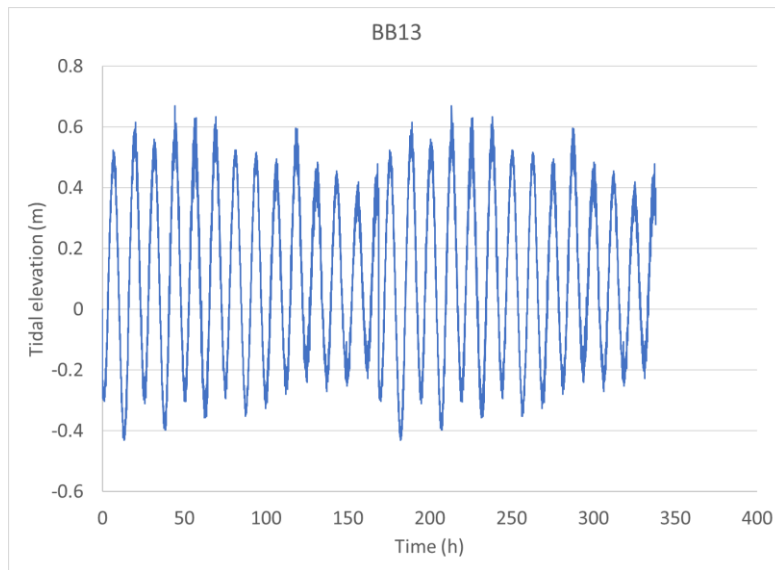


Figure 89 Tidal elevations measured at station BB13 used as boundary conditions at Lewis Cut, Safety Valve, Sands Cut, Elliott Key, and Rhodes Key.

13.2 Results for Salinity

The model calibration for salinity started by performing a sensitivity analysis varying the tidal boundary conditions, the Manning's n roughness distribution obtained during the hydrodynamic calibration, and the effect of wind stress using data for the January 2021 data collection campaign.

13.2.1 Salinity Maps

As an illustration of the initial BBOM results, the following figures depict the salinity distribution of Biscayne Bay at various times during the January 7-day simulations.



Figure 90 Salinity distribution on northern Biscayne Bay at time 8h, 14.5 h and 6 days.

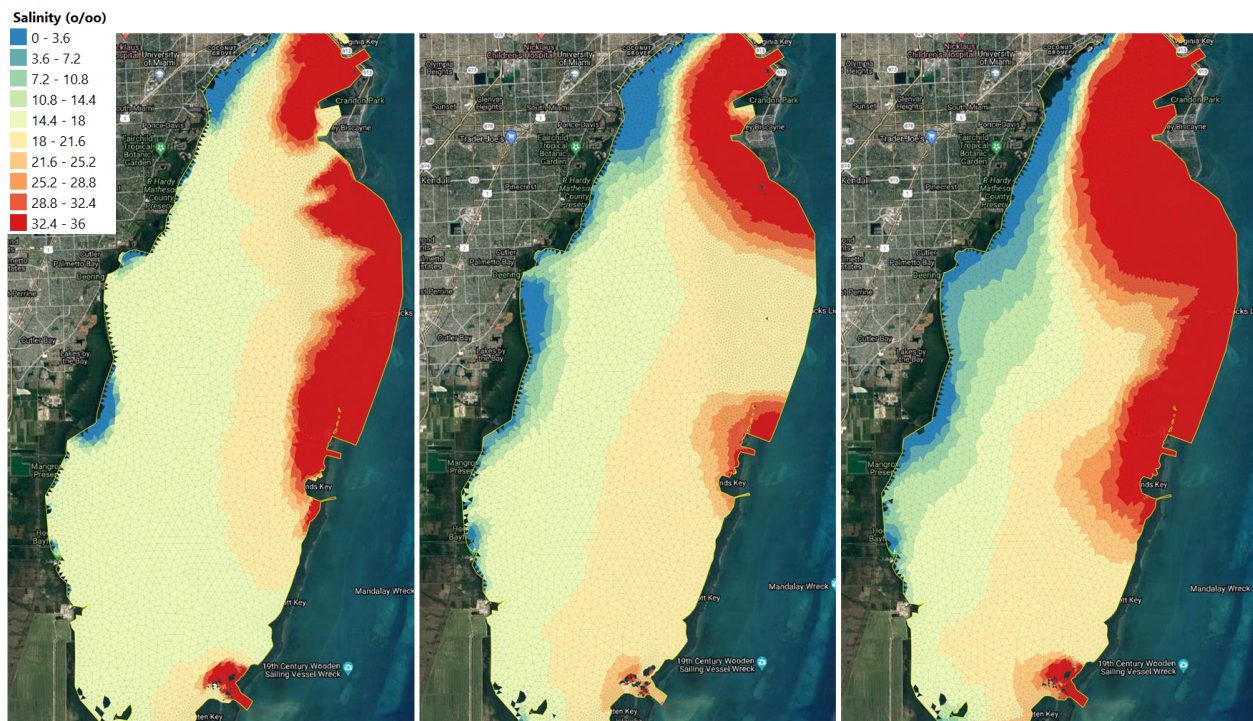


Figure 91 Salinity distribution on central Biscayne Bay at time 8h, 14.5 h and 6 days.

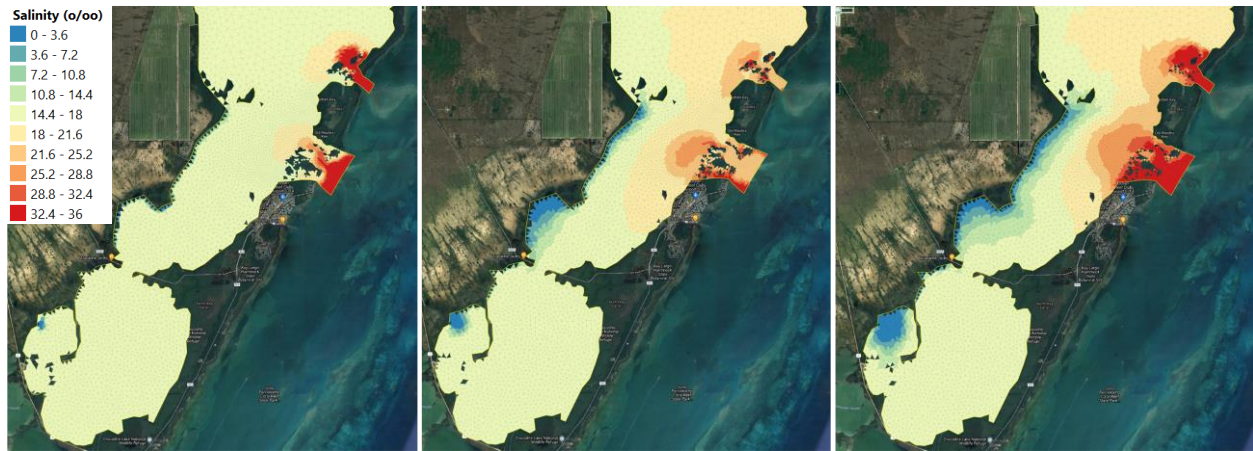


Figure 92 Salinity distribution on southern Biscayne Bay at time 8h, 14.5 h and 6 days.

13.2.2 Salinity Animations



Salinity_GW1_North3.avi

Figure 93 Salinity distribution animation in northern Biscayne Bay.



Salinity_GW1_South3.avi

Figure 94 Salinity distribution animation in southern Biscayne Bay.

13.3 Conclusions about the BBOM Salinity Transport Component Implementation

This section presented the BBOM Salinity Transport Component implementation. Results show that BBOM can provide dynamic salinity patterns through Biscayne Bay. The following sections will report on the model calibration and validation.

Design and construction of bands of boundary condition and point sources at the mouth of canals and rivers, rendered a highly dynamic system, where water movements and patterns follow very closely the tidal cycles and the contribution of large tributaries.

There are interesting circulation patterns in the Bay (Figure 91 to 93). During high tide marine waters generate a damming effect, which keeps freshwaters from the Little River and Biscayne canal ponding close to their mouths, while little freshwater comes out of the Miami River. At low tide freshwater from the Oleta River, Arch Creek, Little River and the Miami River are driven off. Water from Biscayne Canal moves north to join water flushed from Arch Creek and Oleta River exit through Haulover Inlet. Water from Little River moves preferentially south to finally exit through Government Cut, together with some of the Miami River inflows.

Further south, some water from the Miami River remains close to shore where together with other freshwater masses coming from land are progressively mixed with marine waters from Virginia Key and Fisher Island inlets, as well as from the Safety Valve. The largest tidal flooding comes from the Safety Valve, especially along Cape Florida Channel, just south of Key Biscayne.

14 Hydrodynamic and Salinity Model Calibration

This section presents the results of the calibration of the BBOM hydrodynamics and salinity. The purpose of this calibration is to ensure that model can reproduce the bay hydrodynamics and salinity distribution represented by water elevation and salinity throughout the bay. In order to assess the quality of the calibration the model results were compared with available data from SFWMD stations.

14.1 Salinity Transport Model Calibration Dataset

For the purpose of validating the salinity component we use a data set provided by the South Florida Water Management District (SFWMD). The data include depths and salinities collected at 37 stations mostly concentrated in the middle section of Biscayne Bay for a period of two months between December 2021 and January 2022. Figure 95 shows a map with the station locations, and Table 9 presents the names and coordinates of the 37 stations.

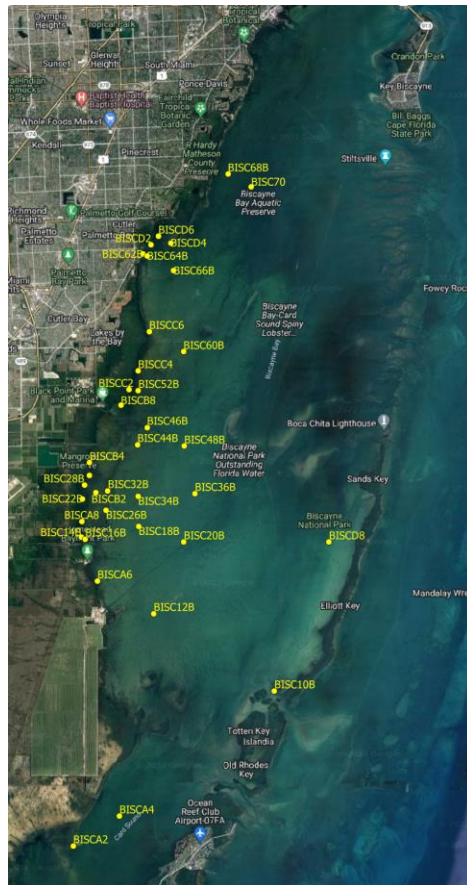


Figure 95 SFWMD data stations used in the BBOM Hydrodynamic and Salinity and Calibration.

Table 9 List of SFWMD Stations used in BBOM Salinity and Hydrodynamic Validation.

No.	Name	Latitude	Longitude
1	BISC10B	25°23'51.7"	80°14'9.5"
2	BISC12B	25°26'9.58"	80°18'3.59"
3	BISC14B	25°28'25"	80°20'24.09"
4	BISC16B	25°28'21.5"	80°20'15.98"
5	BISC18B	25°28'43.6"	80°18'31.9"
6	BISC20B	25°28'15.7"	80°17'4.3"
7	BISC22B	25°29'32.7"	80°20'20.78"
8	BISC26B	25°29'12.5"	80°19'35.4"
9	BISC28B	25°29'54.39"	80°20'19.49"
10	BISC32B	25°29'46.79"	80°19'31.71"
11	BISC34B	25°29'36.7"	80°18'32.69"
12	BISC36B	25°29'41"	80°16'42.1"
13	BISC40B	25°30'19.2"	80°20'8.78"
14	BISC44B	25°31'7.89"	80°18'33.69"
15	BISC46B	25°31'38.2"	80°18'14.59"
16	BISC48B	25°31'4.79"	80°17'2.39"
17	BISC52B	25°32'43.39"	80°18'31.3"
18	BISC60B	25°33'51.39"	80°17'2.99"
19	BISC62B	25°36'44.1"	80°18'21"
20	BISC64B	25°36'40.89"	80°18'12.69"
21	BISC66B	25°36'14.7"	80°17'21.19"
22	BISC68B	25°39'4.6"	80°15'34.5"
23	BISC70	25°38'42"	80°14'49.19"
24	BISCA2	25°19'20.1"	80°20'42.35"
25	BISCA4	25°20'12.44"	80°19'12.28"
26	BISCA6	25°27'7.58"	80°19'52.68"
27	BISCA8	25°28'52.6"	80°20'22.92"
28	BISCB2	25°29'43.69"	80°19'55.19"
29	BISCB4	25°30'36.39"	80°20'7.07"
30	BISCB8	25°32'18.7"	80°19'4.07"
31	BISCC2	25°32'45.08"	80°18'49.31"
32	BISCC4	25°33'18.2"	80°18'31.68"
33	BISCC6	25°34'27.29"	80°18'9.35"
34	BISCD2	25°37'0.39"	80°18'4.68"
35	BISCD4	25°37'3.6"	80°17'26.88"
36	BISCD6	25°37'15.48"	80°17'50.64"
37	BISCD8	25°28'14.19"	80°12'21.59"

14.2 Model Implementation

The BBOM applications presented in previous sections included the northern, central and southern

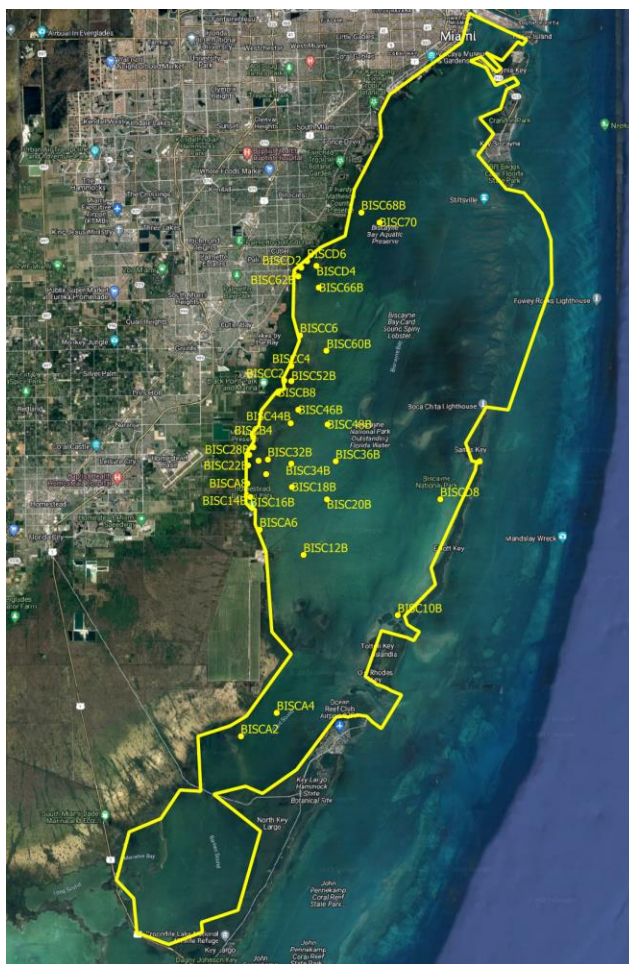


Figure 96 Model domain. The yellow polygon defines the model extent.

The mesh developed for the model calibration has 19,494 cells covering an area of 683 km². The cell sizes vary from 26 m to 1,163 m.

Table 10 BBOM Flexible Mesh Parameters.

Mesh Parameter	Value
Number of cells (triangles)	19,494
Number of nodes	10,079
Total mesh area	683 km ² .
Average cell size (approx.)	264.75 m.
Minimum cell size (approx.)	26.49 m.
Maximum cell size (approx.)	1,163 m.
Maximum cell elevation	15.51 m.
Minimum cell elevation	-15.83 m

Figure 97 depicts the model computational mesh that has been generated for BBOM for Central and South Biscayne Bay. Figure 98 show details of the Central portion, especially of the Safety Valve area. Figure 99, on the other hand, details the mesh geometry for southern Biscayne Bay, including offshore Turkey Point, Barnes and Card Sound

14.2.2 *Boundary Conditions*

The salinity transport model requires two types of boundary conditions. On the ocean inlets, time series of the tidal elevations and water salinity are specified. The model uses the tidal elevation for both inflow and outflow, and salinity is only used when the flow direction is toward the bay interior.

At all canals that enter the bay from the land side, the boundary conditions include the water discharge (m³/s) and the salinity (o/oo). Also, the model incorporates conditions representing the ground water inflow that occur along the interface between the bay and the land. Along those areas the model requires the groundwater discharge and the salinity. Table 11 summarizes the 33 inflow and outflow conditions used in BBOM.

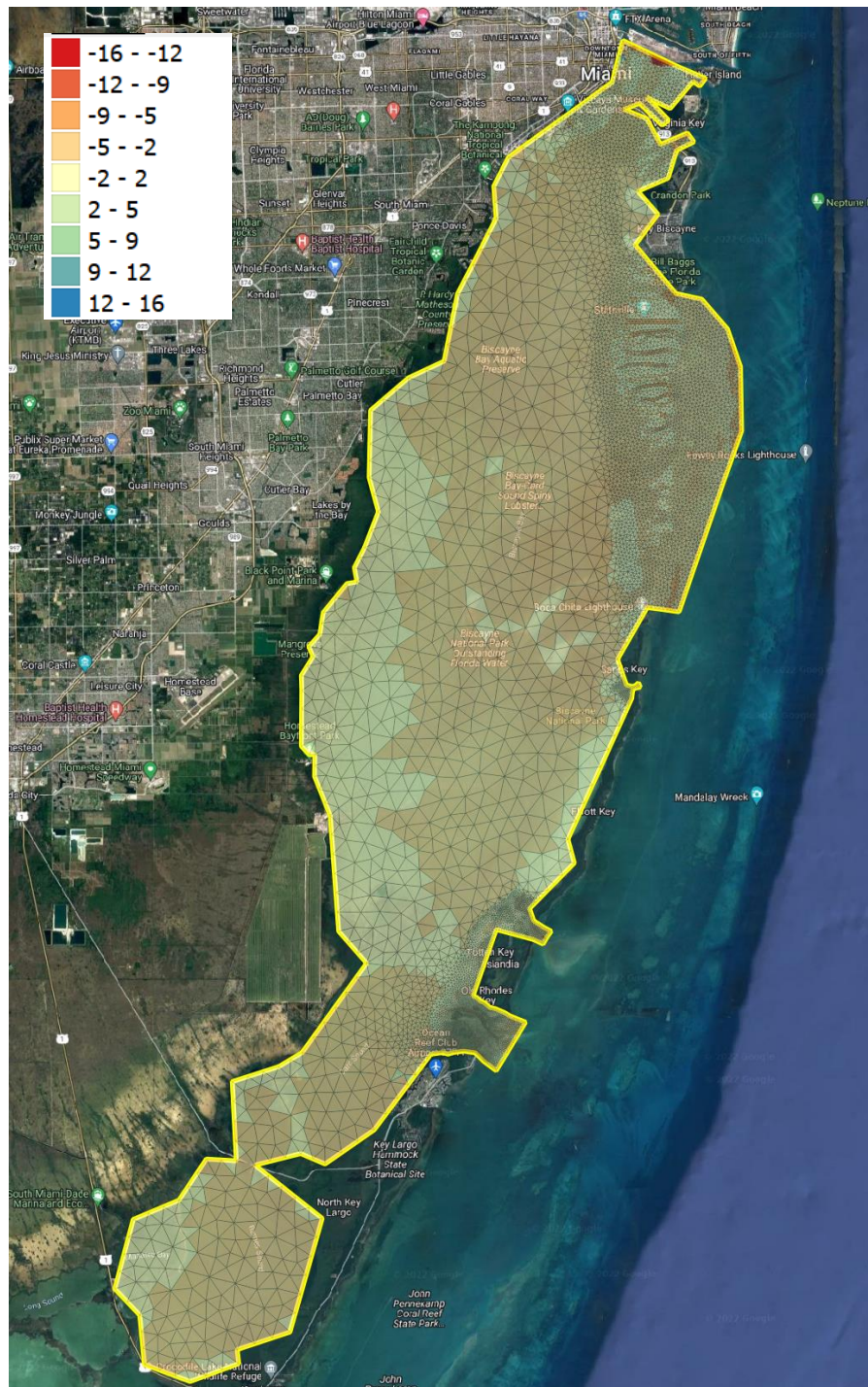


Figure 97 Biscayne Bay Operational Model (BBOM) computation mesh. Darker areas are higher resolution zones with smaller cells to better represent bathymetric and contour gradients. Legend indicates the bed elevations in meters.

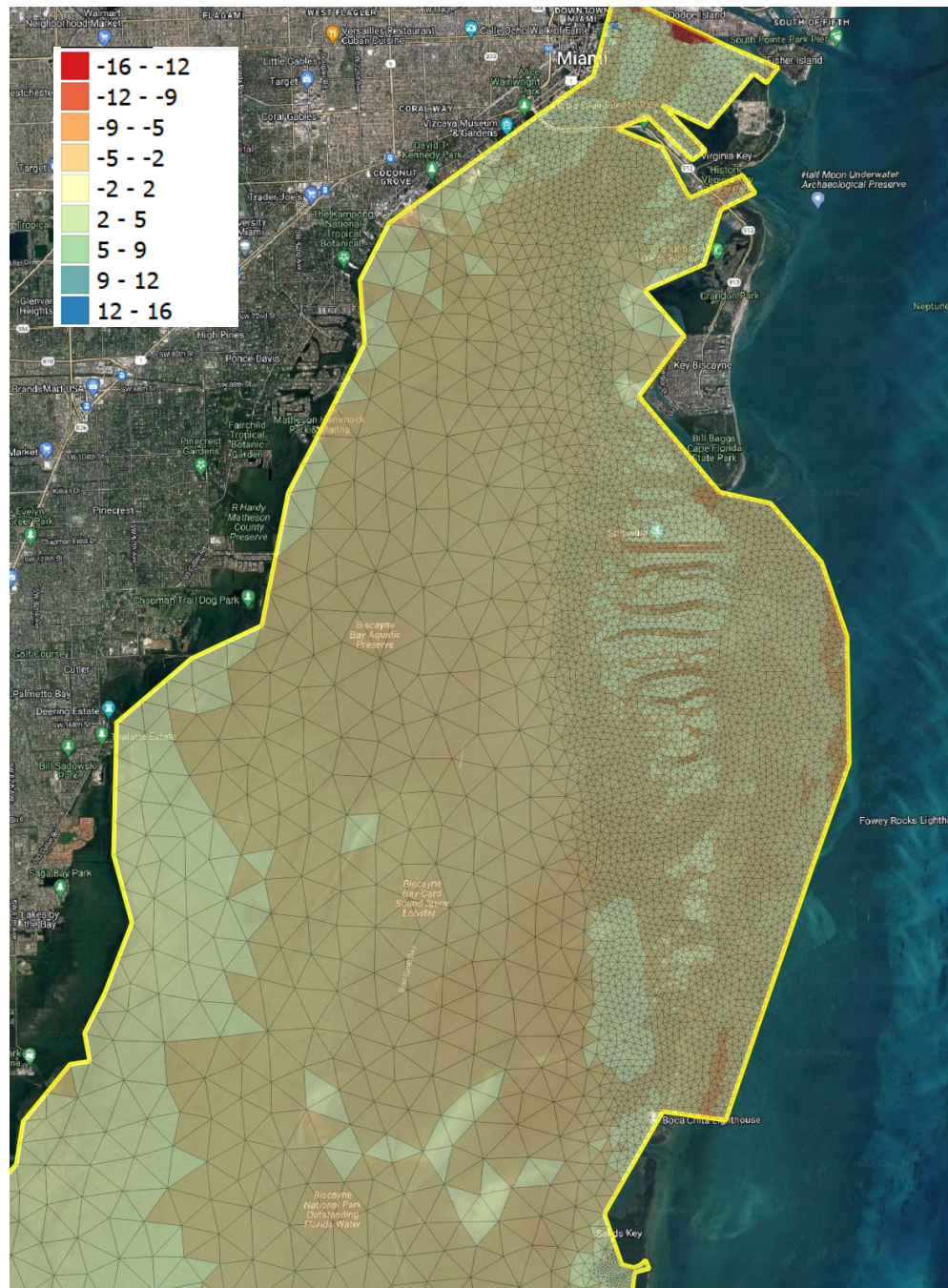


Figure 98 Detail of BBOM mesh on the central Biscayne Bay, showing the Safety Valve tidal open boundary. Legend indicates the bed elevations in meters.

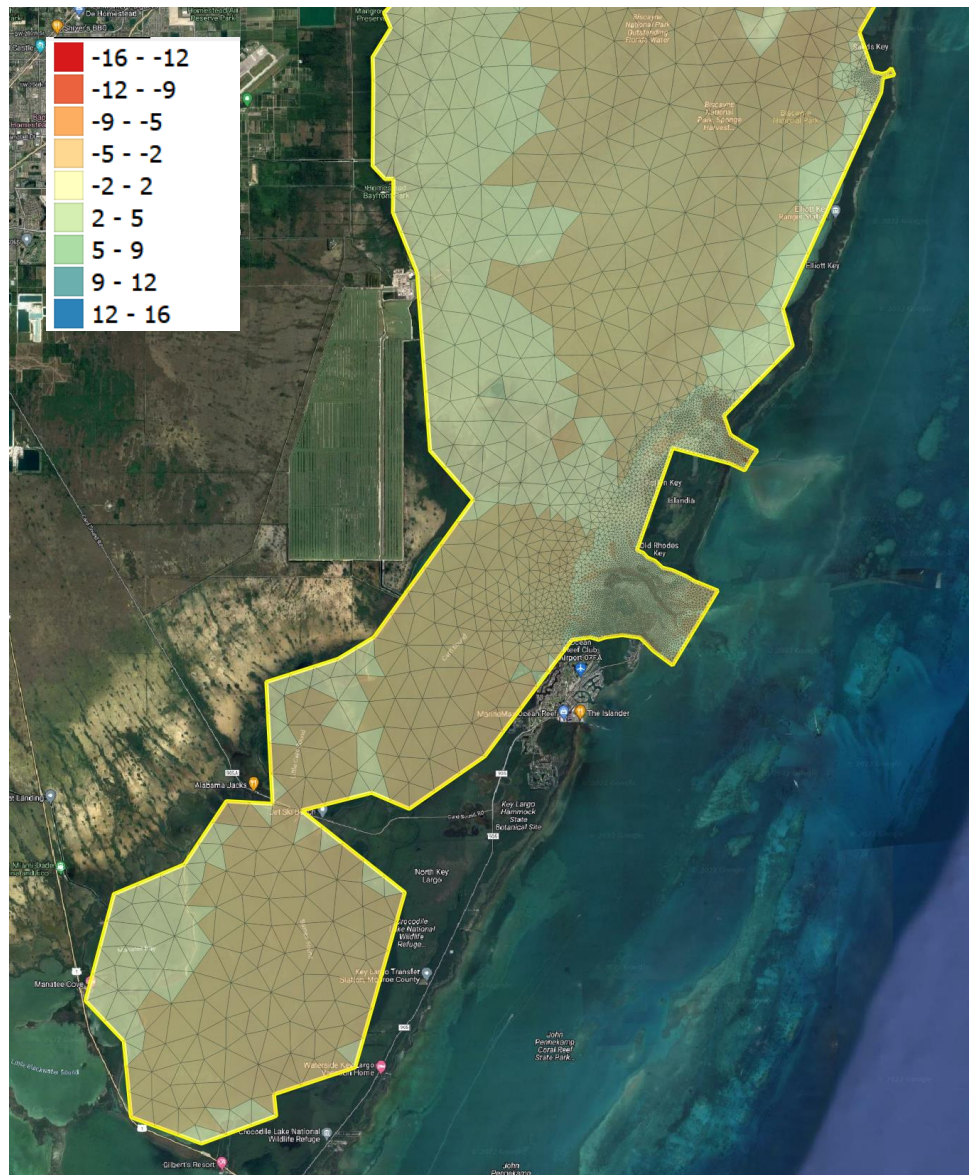


Figure 99 Detail of BBOM mesh on the southern end of Biscayne Bay. Legend indicates the bed elevations in meters.

Table 11 Boundary Conditions used in the Salinity Transport Component Calibration.

Inflow/outflow Boundary	Boundary Type	Boundary Condition File Name
VirginiaKey	Tide elevation + Salinity	BB12_TIDE.TXT
FisherIsland	Tide elevation + Salinity	BB12_TIDE.TXT
MBGOVCUT	Tide elevation + Salinity	BB12_TIDE.TXT
LewisCut	Tide elevation + Salinity	BB13_TIDE.TXT
SafetyValve	Tide elevation + Salinity	BB13_TIDE.TXT
SandsCut	Tide elevation + Salinity	BB13_TIDE.TXT
ElliottKey	Tide elevation + Salinity	BB13_TIDE.TXT
RhodesKey	Tide elevation + Salinity	BB13_TIDE.TXT
InterCostalN	Water discharge + Salinity	InterCostalN.txt
InterCostalMid	Water discharge + Salinity	InterCostalSMid.txt
InterCostalS	Water discharge + Salinity	InterCostalS.txt
BC_30	Water discharge + Salinity	BBCentral4.txt
BBCentral3	Water discharge + Salinity	BBCentral3y.txt
BBCentral2	Water discharge + Salinity	BBCentral2.txt
BBCentral.txt	Water discharge + Salinity	BBCentral.txt
MangrovePreserve	Water discharge + Salinity	Mangrovepreserve.txt
BTurkeyPoint	Water discharge + Salinity	Turkey2.txt
Cardsound	Water discharge + Salinity	CarlSound.txt
BarnesSound	Water discharge + Salinity	BarnesSound.txt
Manatee	Water discharge + Salinity	Manatee.txt
S197	Water discharge + Salinity	S197C.txt
S20F	Water discharge + Salinity	S20F.txt
S20G	Water discharge + Salinity	S20G.txt
S21A	Water discharge + Salinity	S21A.txt
S21S	Water discharge + Salinity	S21S.txt
S123S	Water discharge + Salinity	S123S.txt
S700P	Water discharge + Salinity	S700P.txt
S22S	Water discharge + Salinity	S22S.txt
G93	Water discharge + Salinity	G93.txt
S25S	Water discharge + Salinity	S25S.txt
S27S	Water discharge + Salinity	S27S.txt
S28_S	Water discharge + Salinity	S28S.txt

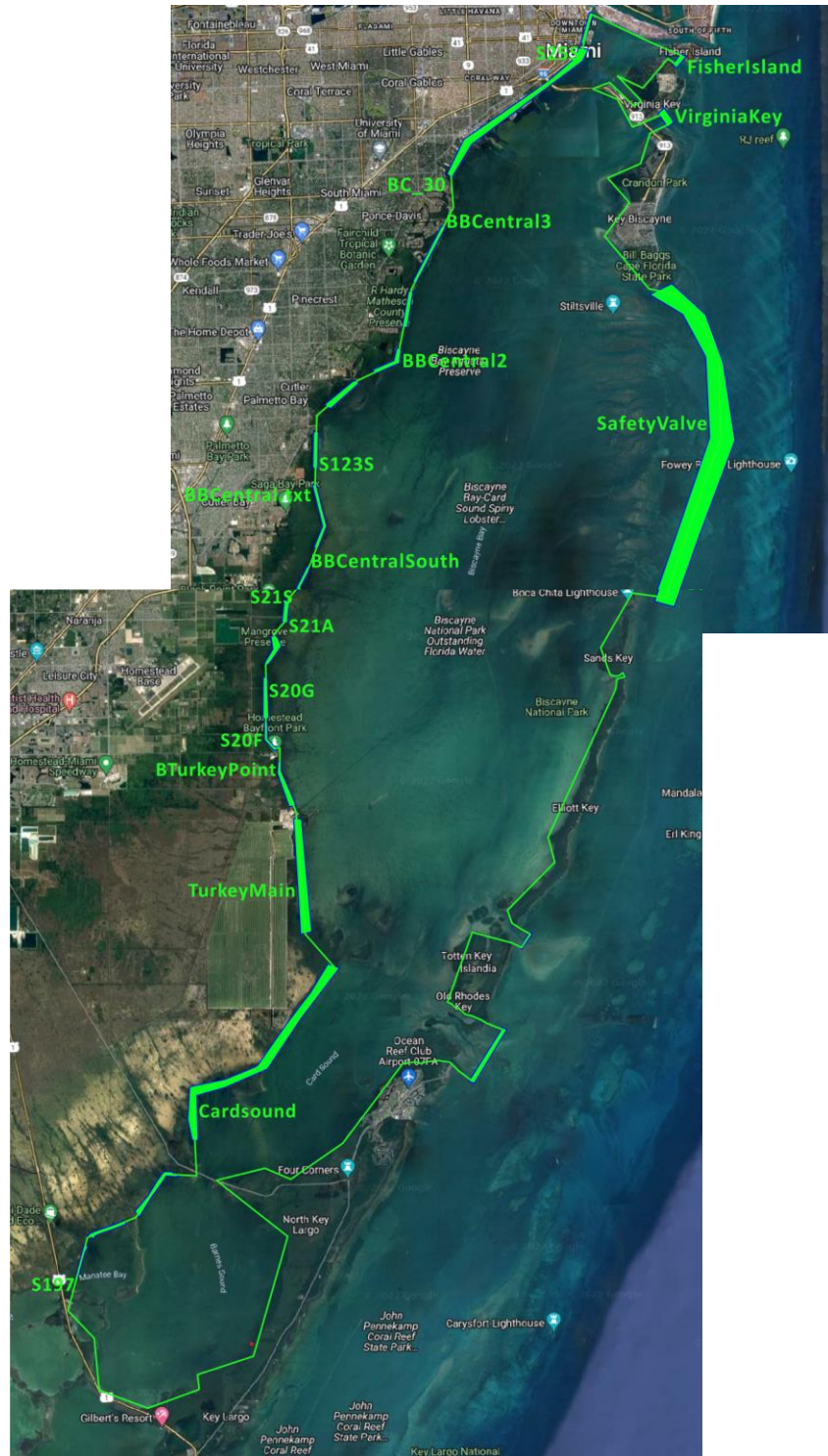


Figure 100 Boundary Conditions for the Salinity Transport Model of Biscayne Bay.

14.3 Hydrodynamics and Salinity Results

The model calibration for salinity kept the same Manning's n roughness parameter distribution obtained during the hydrodynamic calibration and the same dispersion coefficients. The wind time series was updated to represent the wind velocity for the period of December 2020-January 2021. In order to calibrate the model, the salinity and the groundwater inflows had to be adjusted based on the data from the SFWMD stations that were close to the land-bay boundary.

14.3.1 Comparison of Water Elevations

Measured and modeled surface water elevations were compared using statistical quality indexes and plots, as shown in Figure 101 to Figure 104.

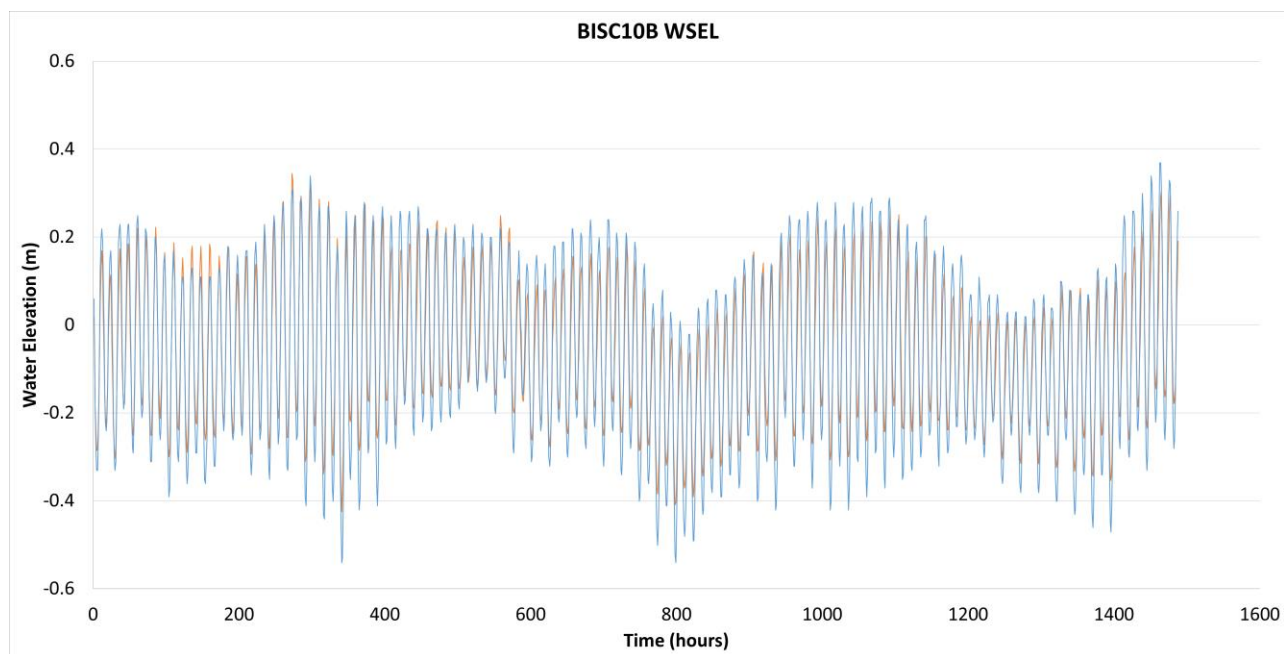


Figure 101 Comparison of water elevations at station BISC10B. Blue lines are model results, Orange line are observations.

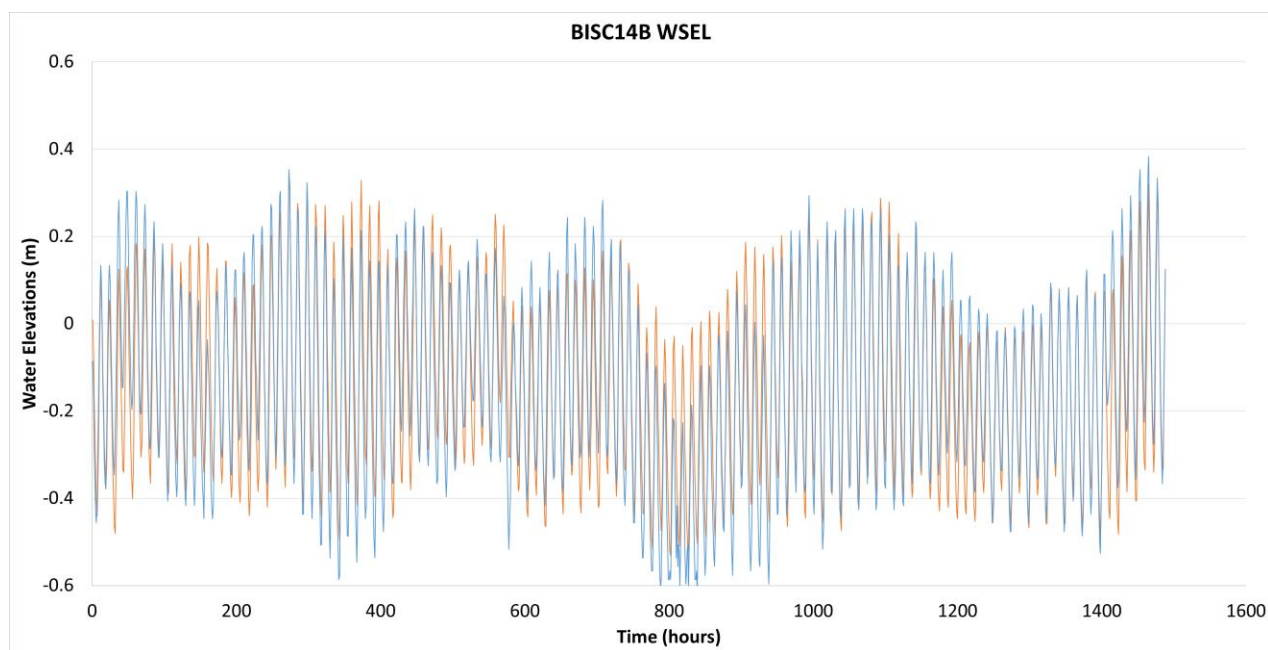


Figure 102 Comparison of water elevations at station BISC14B. Blue lines are model results, Orange line are observations.

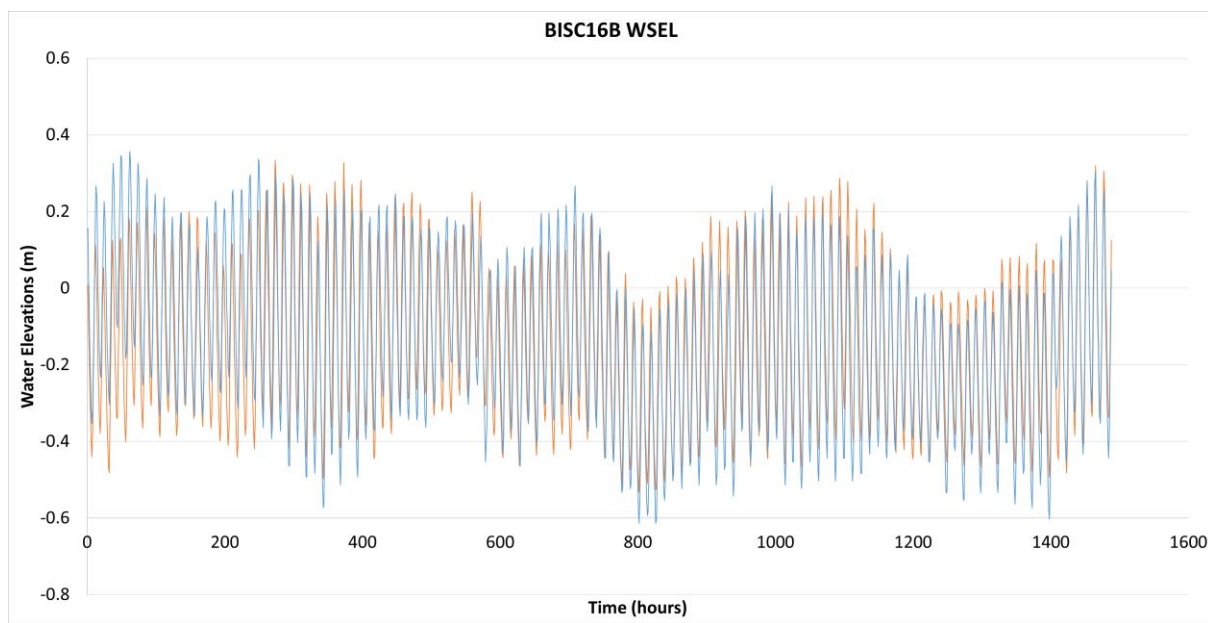


Figure 103 Comparison of water elevations at station BISC16B. Blue lines are model results, Orange line are observations.

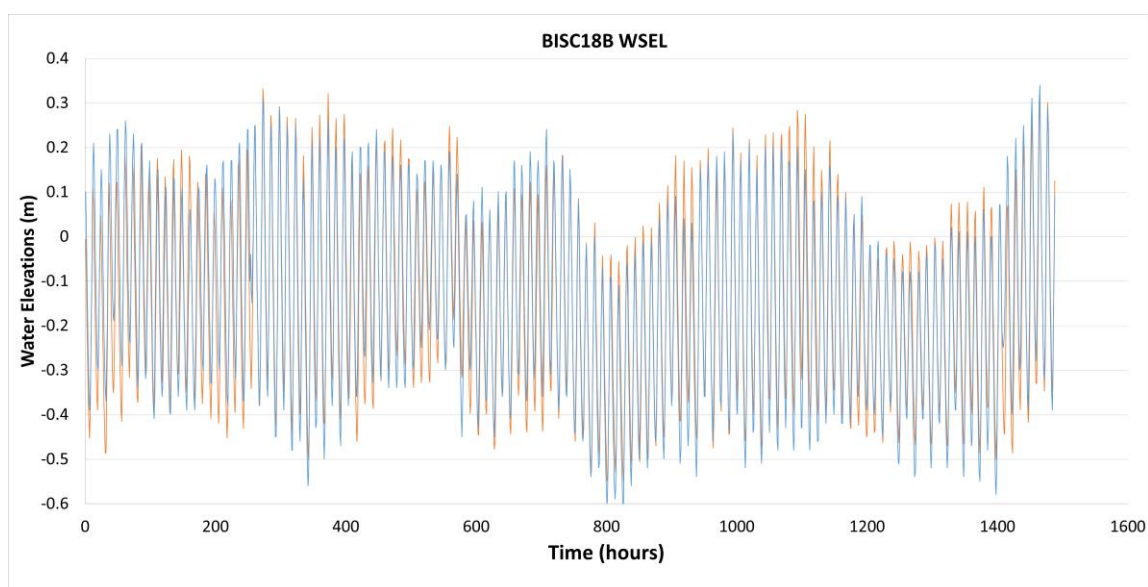


Figure 104 Comparison of water elevations at station BISC18B. Blue lines are model results, Orange line are observations.

14.3.2 *Comparison of Salinities*

Measured and modeled salinities were compared using statistical quality indexes and plots, as shown in the examples of Figure 105 to Figure 119. We have been able to replicate very closely the measured time series with the model.

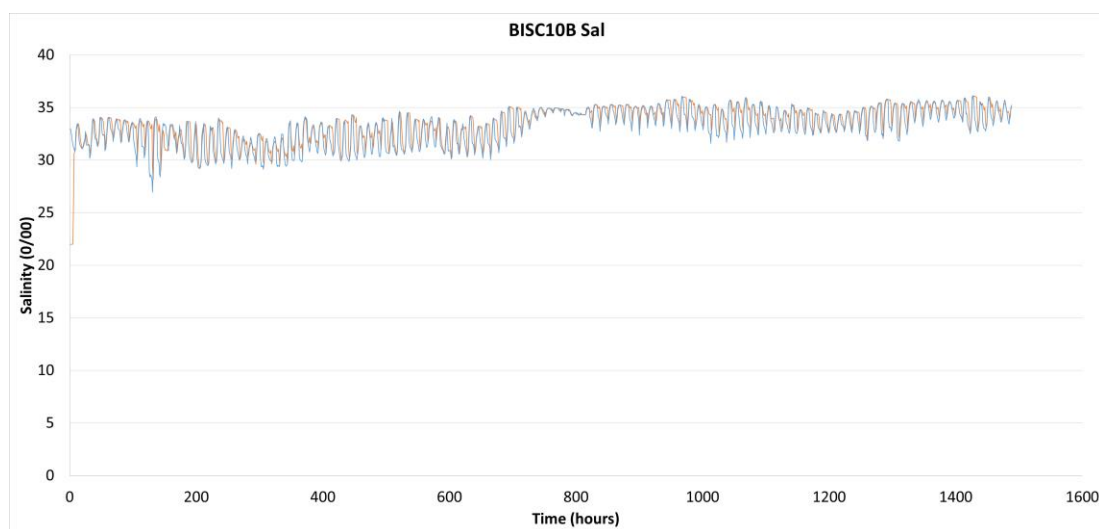


Figure 105 Comparison of salinities at station BISC10B. Blue lines are model results, Orange line are observations.

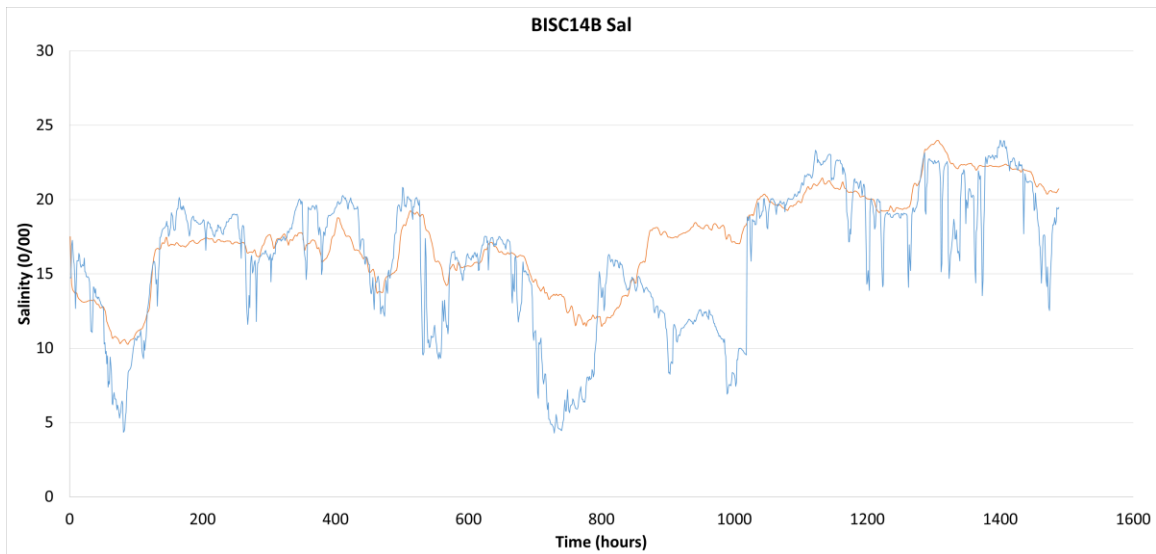


Figure 106 Comparison of salinities at station BISC14B. Blue lines are model results, Orange line are observations.

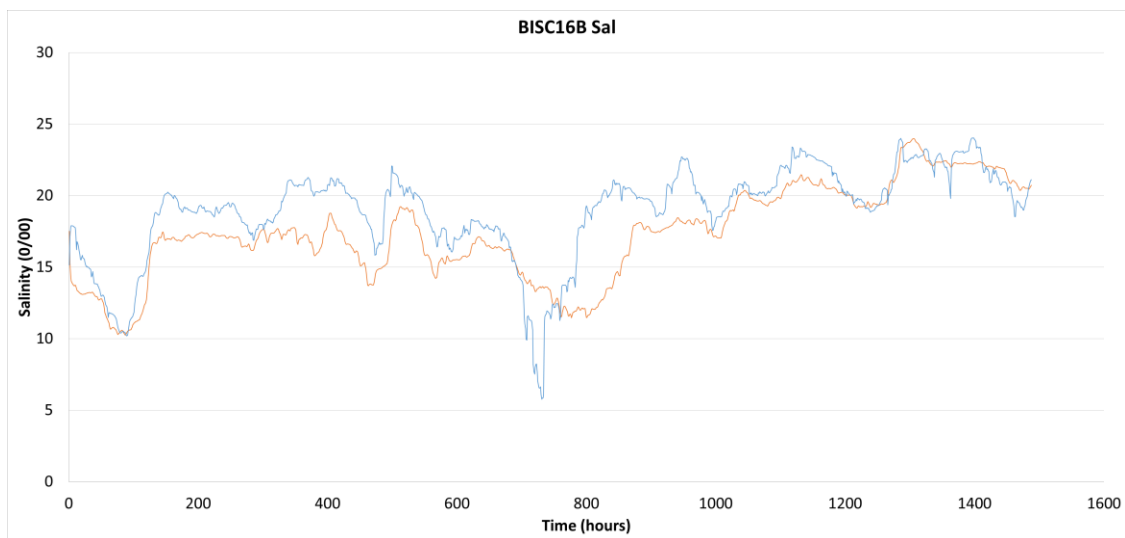


Figure 107 Comparison of salinities at station BISC16B. Blue lines are model results, Orange line are observations.

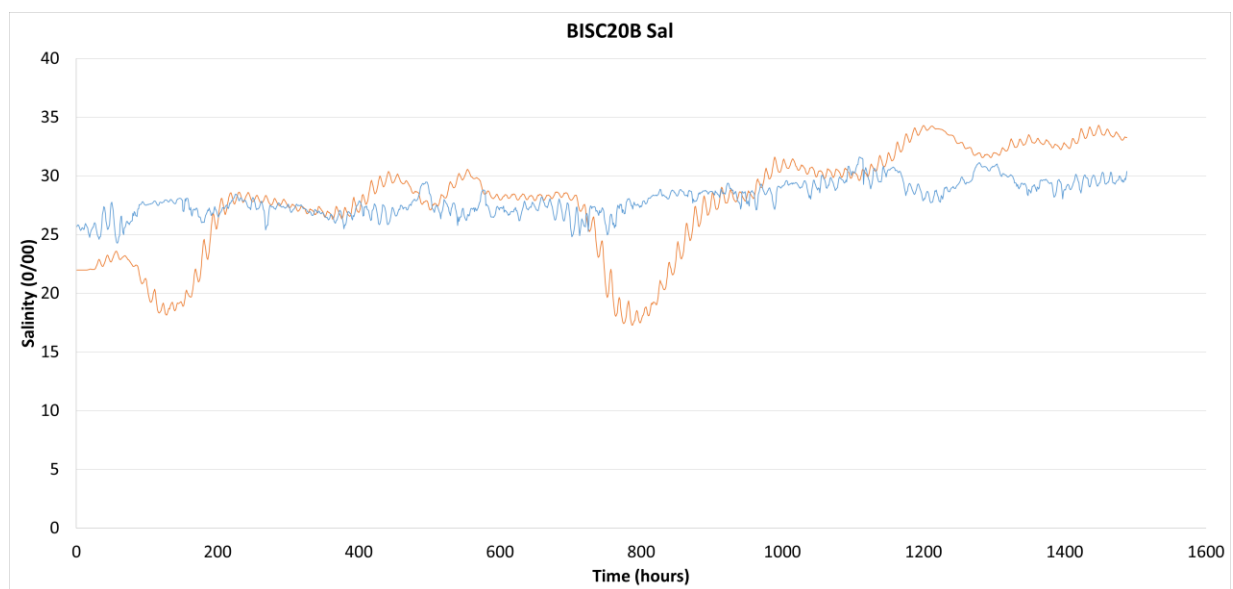


Figure 108 Comparison of salinities at station BISC20B. Blue lines are model results, Orange line are observations.

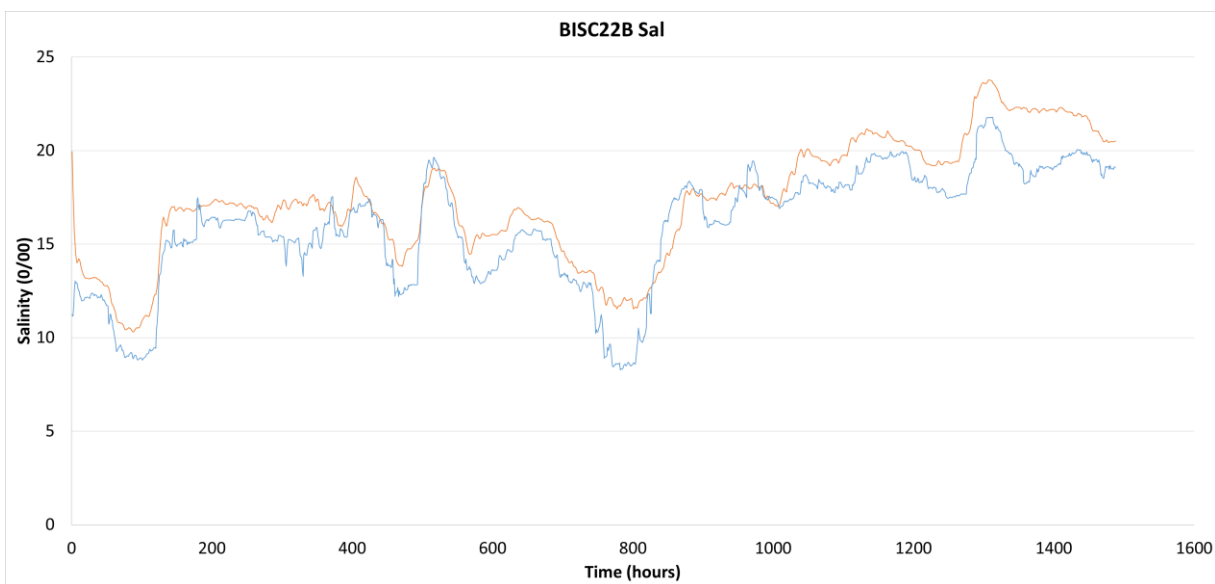


Figure 109 Comparison of salinities at station BISC22B. Blue lines are model results, Orange line are observations.

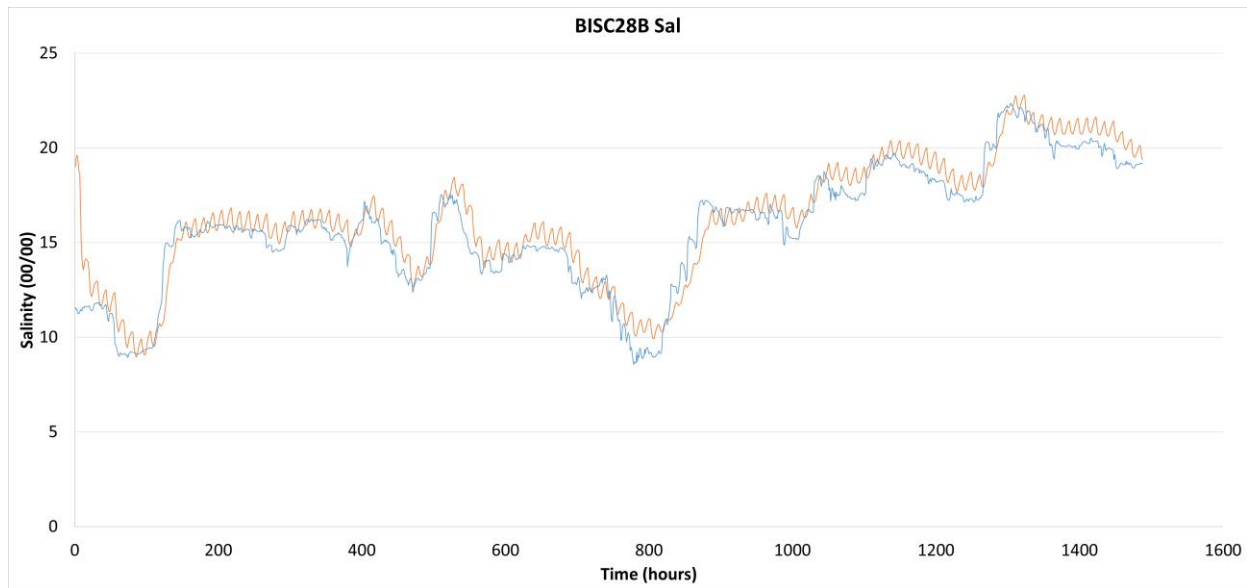


Figure 110 Comparison of salinities at station BISC28B. Blue lines are model results, Orange line are observations.



Figure 111 Comparison of salinities at station BISC32B. Blue lines are model results, Orange line are observations.

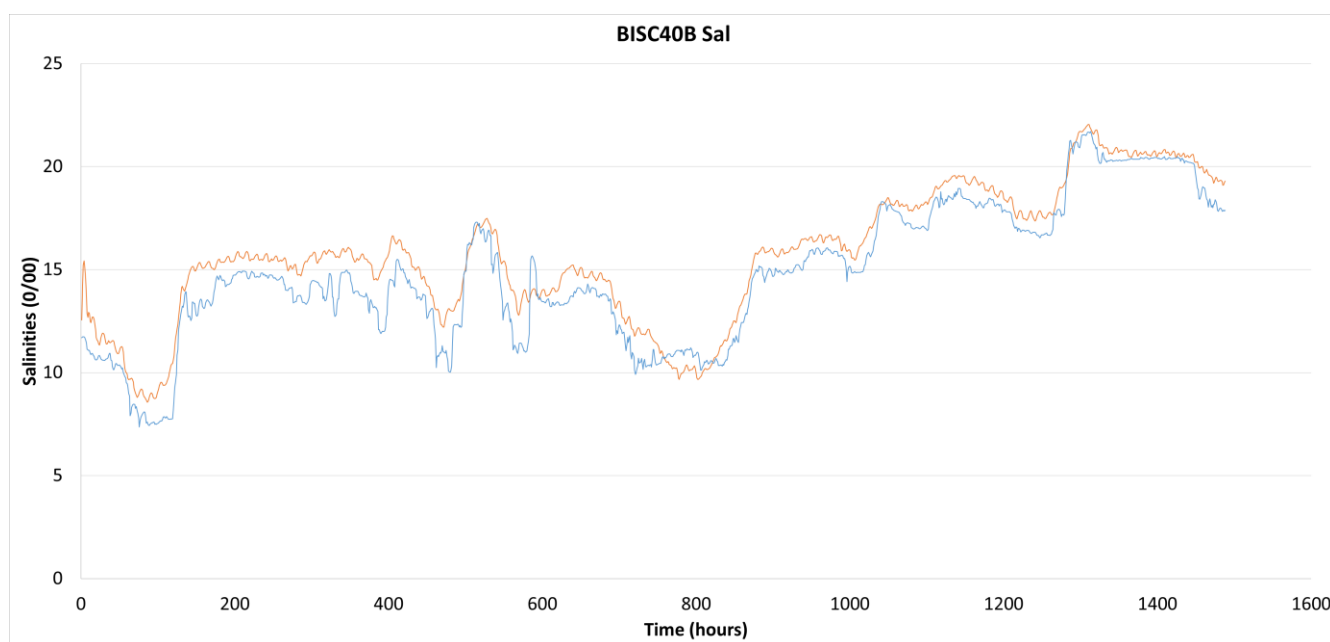


Figure 112 Comparison of salinities at station BISC40B. Blue lines are model results, Orange line are observations.

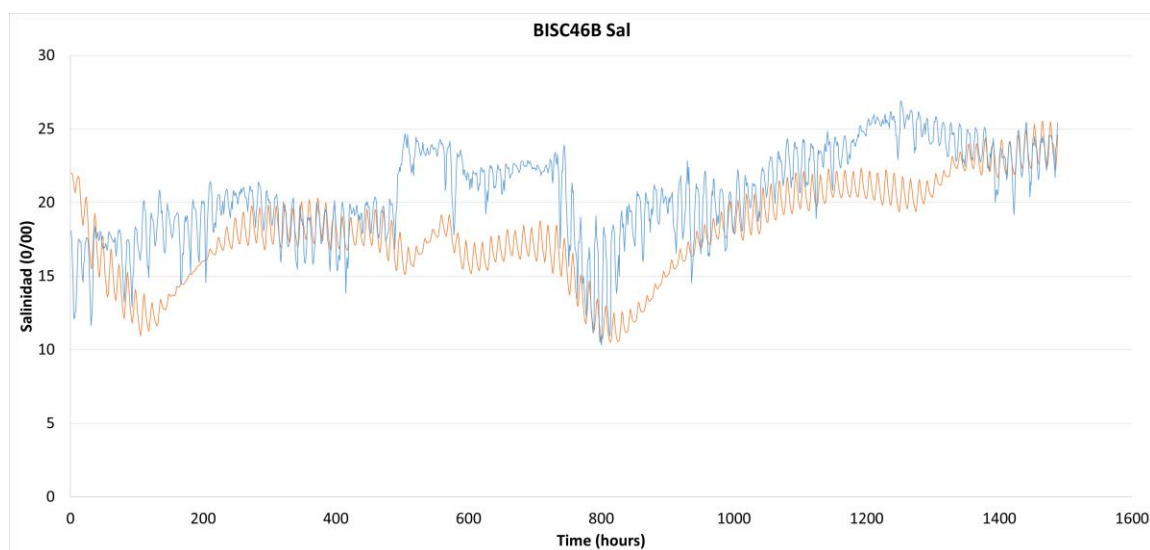


Figure 113 Comparison of salinities at station BISC46B. Blue lines are model results, Orange line are observations.

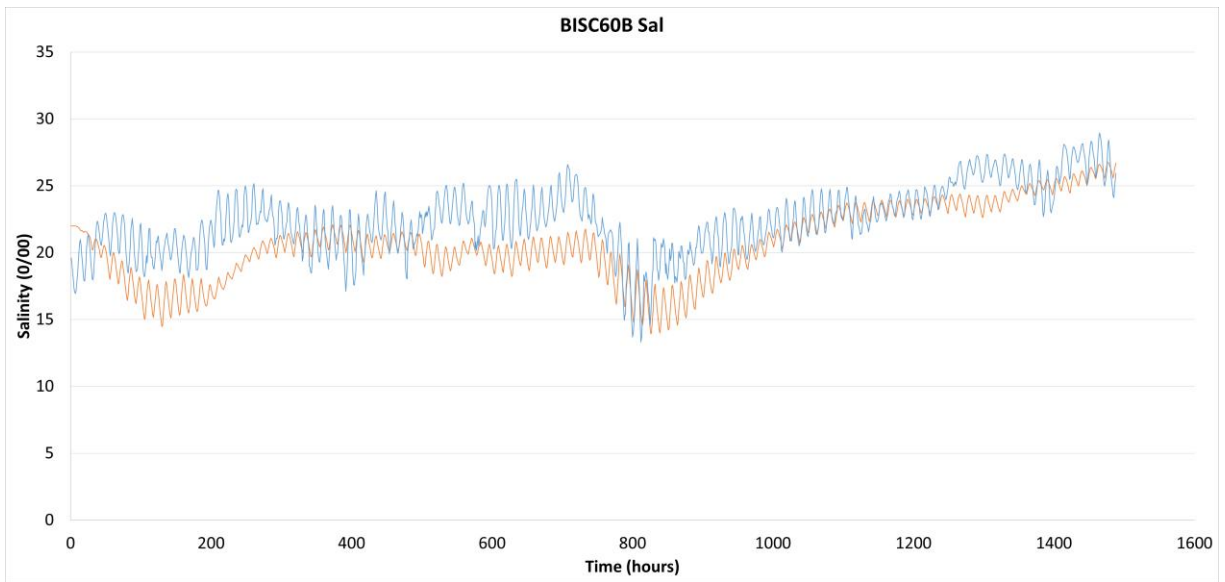


Figure 114 Comparison of salinities at station BISC60B. Blue lines are model results, Orange line are observations.

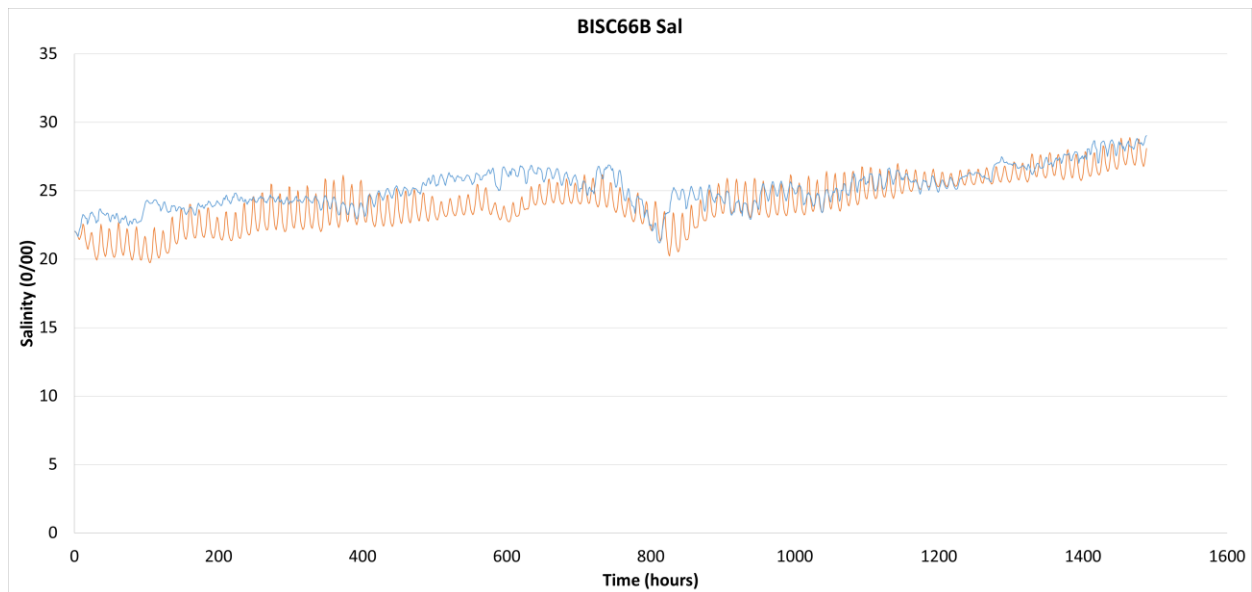


Figure 115 Comparison of salinities at station BISC66B. Blue lines are model results, Orange line are observations.

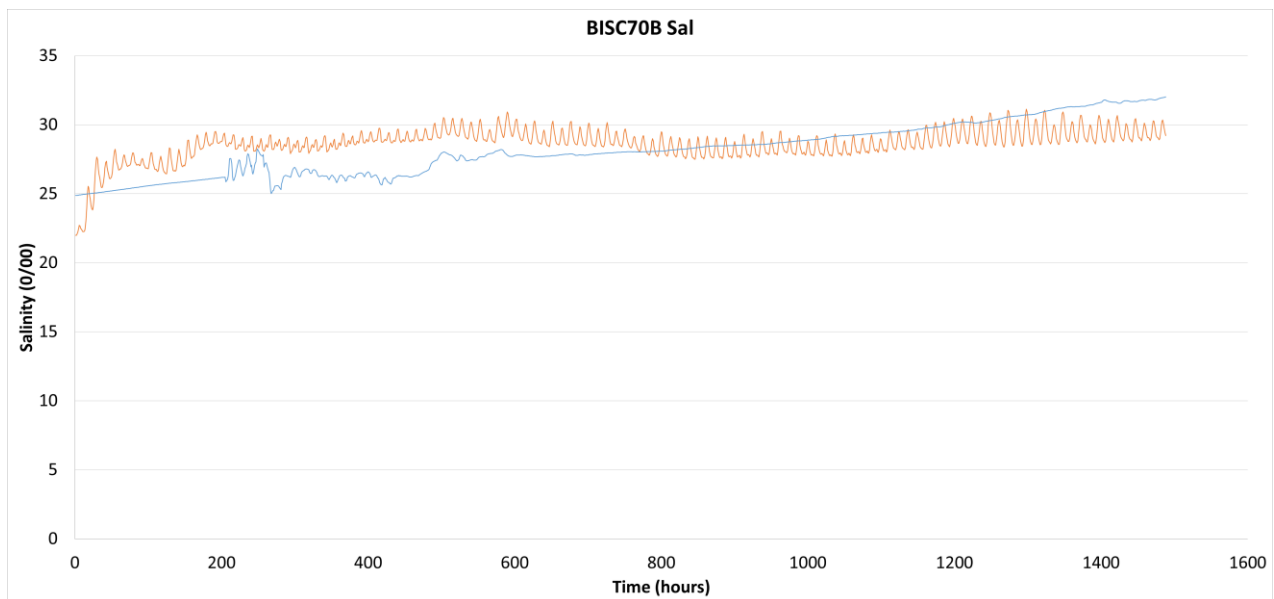


Figure 116 Comparison of salinities at station BISC70B. Blue lines are model results, Orange line are observations.

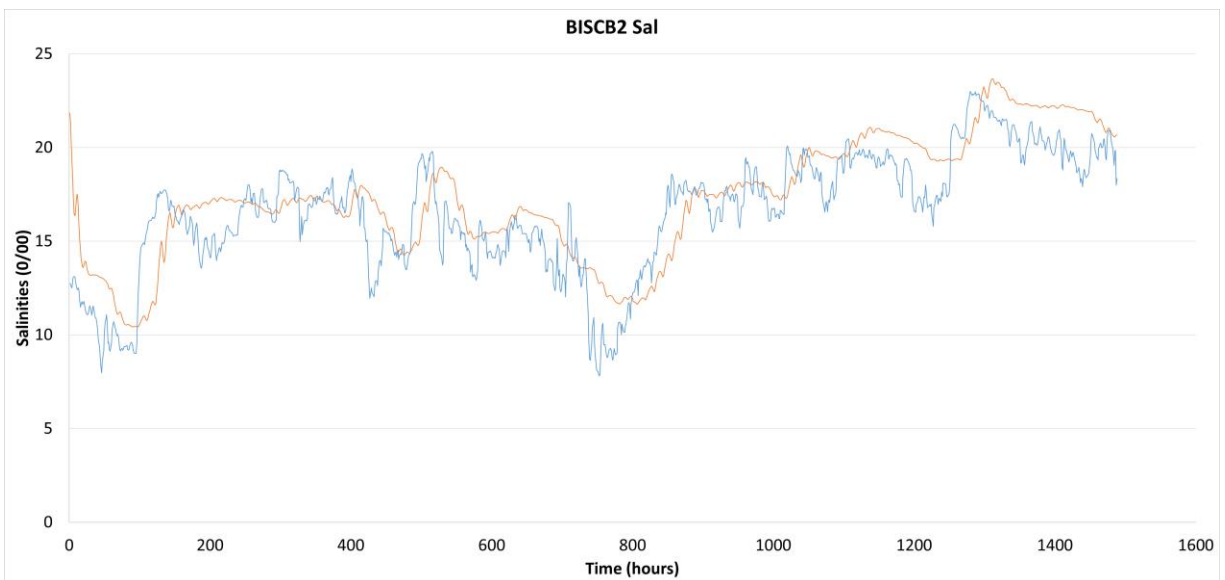


Figure 117 Comparison of salinities at station BISCB2. Blue lines are model results, Orange line are

observations.

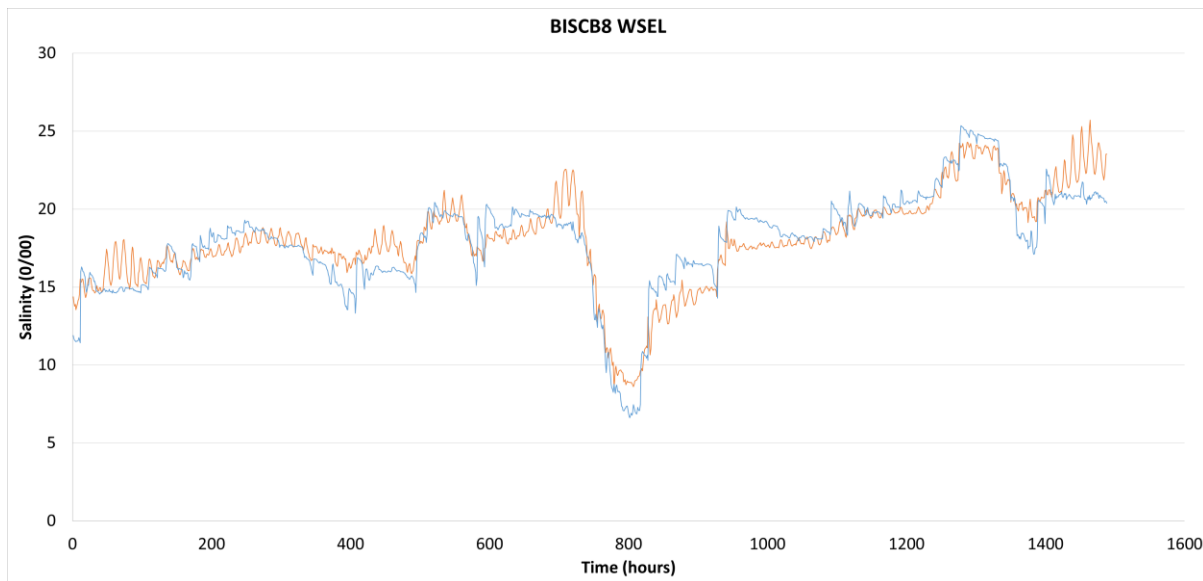


Figure 118 Comparison of salinities at station BISC8. Blue lines are model results, Orange line are observations.

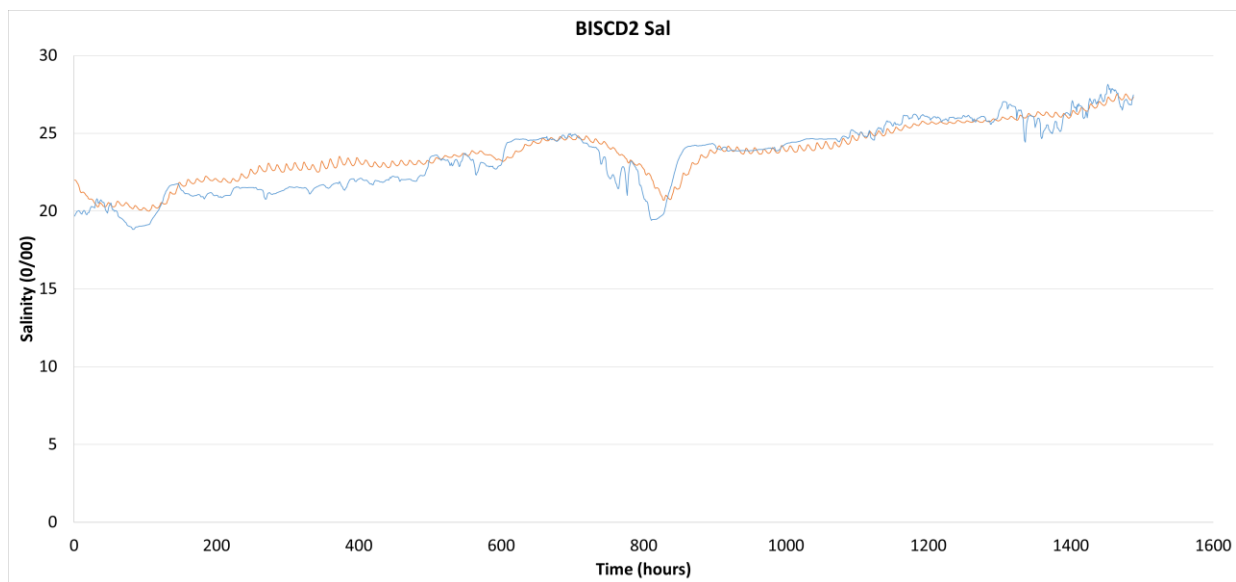


Figure 119 Comparison of salinities at station BISCD2. Blue lines are model results, Orange line are observations.

14.3.3 Error Correlations

The following table summarizes the errors based on the Correlation Quality Index.

Table 4 Correlation Quality Indexes obtained during validation of Water Surface Elevation and Salinity for the Salinity Transport Component.

Station	Water Surface Elevation Correlation Index	Salinity Correlation Index
BISC10B	97%	76%
BISC12B	93%	30%
BISC14B	90%	73%
BISC16B	89%	80%
BISC18B	94%	66%
BISC20B	92%	54%
BISC22B	93%	94%
BISC26B	93%	76%
BISC28B	55%	95%
BISC32B	93%	72%
BISC34B	94%	71%
BISC36B	94%	45%
BISC40B	93%	98%
BISC44B	95%	66%
BISC46B	95%	67%
BISC48B	95%	76%
BISC52B	89%	63%
BISC60B	96%	78%
BISC62B	87%	92%
BISC64B	88%	72%
BISC66B	96%	80%
BISC68B	96%	-39%
BISC70	96%	49%
BISCA2	86%	91%
BISCA4	86%	87%
BISCA6	94%	82%
BISCA8	75%	80%
BISCB2	94%	82%
BISCB4	73%	78%
BISCB8	90%	90%
BISCC2	89%	73%
BISCC4	88%	55%
BISCC6	90%	64%
BISCD2	97%	94%
BISCD4	88%	59%
BISCD6	92%	97%
BISCD8	94%	65%

14.3.4 Salinity Maps

The following figure illustrate the salinity distribution of Biscayne Bay at selected times during the simulation period.

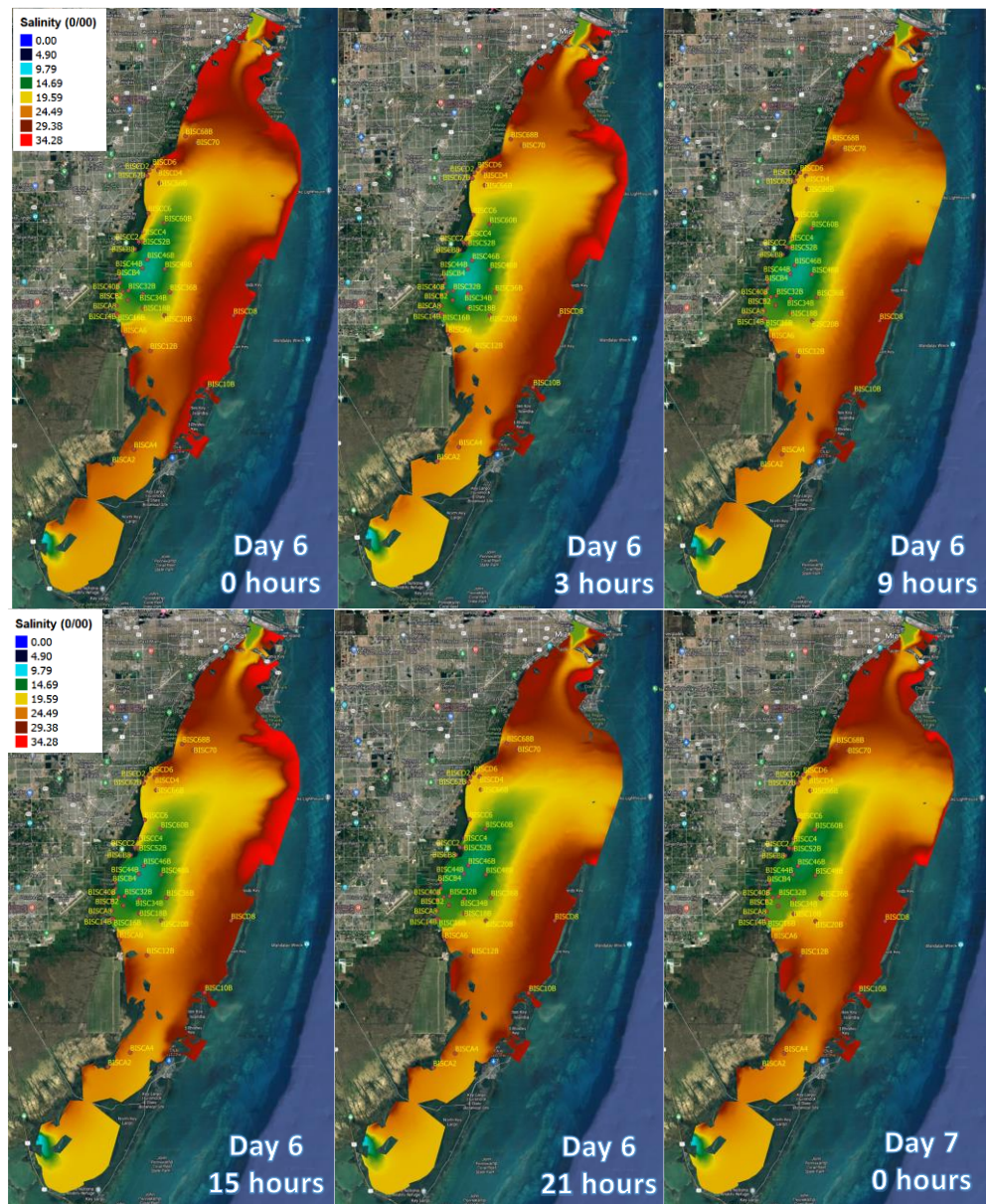


Figure 120 Salinity distribution at time 0, 3, 9, 15, and 21 hours during Day 6 and at 0 hours of day 7.

14.3.5 Salinity Distribution Dynamic Animation

The report includes the salinity dispersion animation for a period of 30 days in the attached SalinityBBOM_30Days.avi file.

14.4 Conclusions about the Calibration of the Hydrodynamics and Salinity Transport Component

This section summarizes the main conclusions from the implementation, calibration and validation of the Hydrodynamics and Salinity Transport Component of the Biscayne Bay Operational Model. The model calibration for salinity kept the same Manning's n roughness parameter distribution obtained during the hydrodynamic calibration and the same dispersion coefficients. The wind time series was updated to represent the wind velocity for the period of December 2020-January 2021. In order to calibrate the model, the salinity and the groundwater inflows had to be adjusted based on the data from the SFWMD stations that were close to the land-bay boundary.

The purpose of this calibration is to ensure that model can reproduce the bay hydrodynamics and salinity distribution represented by water elevation and salinity throughout the bay. We used a good dataset from the SFWMD that included depths and salinities collected at 37 stations, mostly concentrated in the western half of Central Biscayne Bay. Data covered the period of December 2020-January 2021. We had to exclude Northern Biscayne Bay due to the lack of appropriate data for the period of interest.

The model calibration for salinity kept the same Manning's n roughness parameter distribution obtained during the hydrodynamic calibration and the same dispersion coefficients. The wind time series was updated to represent the wind velocity for the period of December 2020-January 2021. In order to calibrate the model, the salinity and the groundwater inflows had to be adjusted based on the data from the SFWMD stations that were close to the land-bay boundary. We considered the combined effects of freshwater inflows from canals and groundwater, and tidal forcing on the ocean boundaries and wind stress on the water surface.

In Summary, what we found is:

- Modeled water elevation and salinity follow very closely the patterns of measured data, as observed for salinity timeseries plots in Figures 112 to 130.
- Correlation Quality Indexes obtained during validation of Water Surface Elevation and Salinity for the Salinity Transport Component were very high for water elevations (average > 90%) and moderated for salinity (average > 71%). That indicates that we have been able to replicate very closely the measured time series with the BBOM model as shown in figures 130 to 116, and the calibration is ready for further validation.
- A patch of fresher waters occurs at the west-central half of Central Biscayne Bay, extending from Black Point, at the mouth of the Black Creek Canal (Canal C-1), south to Mowry Canal (Canal C-103). This is the largest freshwater input to BB, followed by the freshwater plume out of the Miami River. Slightly saltier waters surround the fresher water patch and extend offshore towards the Safety Valve, where they meet the marine water wedge (Figure 131)
- Freshwater from the Miami River seems to move preferentially south, to the Rickenbacker Causeway, where significant mixing occur and the intermediate salinity plume moves southward at the Bay axis.

- A medium-high salinity zone (24-34‰) occurs along the coast, from Rickenbacker causeway to the Hardy Matheson County Preserve, west of the fresher Miami River plume

Table 12 List of SFWMD Stations used in BBOM Salinity and Hydrodynamic Validation.

No.	Name	Latitude	Longitude
1	BISC10B	25°23'51.7"	80°14'9.5"
2	BISC12B	25°26'9.58"	80°18'3.59"
3	BISC14B	25°28'25"	80°20'24.09"
4	BISC16B	25°28'21.5"	80°20'15.98"
5	BISC18B	25°28'43.6"	80°18'31.9"
6	BISC20B	25°28'15.7"	80°17'4.3"
7	BISC22B	25°29'32.7"	80°20'20.78"
8	BISC26B	25°29'12.5"	80°19'35.4"
9	BISC28B	25°29'54.39"	80°20'19.49"
10	BISC32B	25°29'46.79"	80°19'31.71"
11	BISC34B	25°29'36.7"	80°18'32.69"
12	BISC36B	25°29'41"	80°16'42.1"
13	BISC40B	25°30'19.2"	80°20'8.78"
14	BISC44B	25°31'7.89"	80°18'33.69"
15	BISC46B	25°31'38.2"	80°18'14.59"
16	BISC48B	25°31'4.79"	80°17'2.39"
17	BISC52B	25°32'43.39"	80°18'31.3"
18	BISC60B	25°33'51.39"	80°17'2.99"
19	BISC62B	25°36'44.1"	80°18'21"
20	BISC64B	25°36'40.89"	80°18'12.69"
21	BISC66B	25°36'14.7"	80°17'21.19"
22	BISC68B	25°39'4.6"	80°15'34.5"
23	BISC70	25°38'42"	80°14'49.19"
24	BISCA2	25°19'20.1"	80°20'42.35"
25	BISCA4	25°20'12.44"	80°19'12.28"
26	BISCA6	25°27'7.58"	80°19'52.68"
27	BISCA8	25°28'52.6"	80°20'22.92"
28	BISCB2	25°29'43.69"	80°19'55.19"
29	BISCB4	25°30'36.39"	80°20'7.07"
30	BISCB8	25°32'18.7"	80°19'4.07"
31	BISCC2	25°32'45.08"	80°18'49.31"
32	BISCC4	25°33'18.2"	80°18'31.68"
33	BISCC6	25°34'27.29"	80°18'9.35"
34	BISCD2	25°37'0.39"	80°18'4.68"
35	BISCD4	25°37'3.6"	80°17'26.88"
36	BISCD6	25°37'15.48"	80°17'50.64"
37	BISCD8	25°28'14.19"	80°12'21.59"
38	BISC54B	25°32'42.00"	80°17'24.00"
39	BISC56B	25°33'52"	80°18'19.09"
40	BISCB6	25°31'38.2"	80°19'47.64"
41	BISCC8	25°35'20.29"	80°18'25.19"

15.2 Model Implementation

For the validation of the hydrodynamic and salinity transport component, the northern part was not included since the dataset available from the SFWMD only had stations on the central and southern sections. Therefore, similarly to the calibration phase, the model domain polygon covers from the Port of Miami, south to Barnes Sound. The oceanic boundary extends beyond the Safety Valve (see Figure 122). Extending the model domain in this way includes the essential role that the Safety Valve has in Biscayne Bay hydrodynamics while avoiding the potential numerical issues that can occur if we would locate an open boundary along a very shallow area with high velocities and drying zones. For the validation phase, tidal and wind forces were considered as the main forces controlling the water flow inside the Bay establishing boundary conditions at the ocean boundaries and wind stress on the water surface. However, as in the calibration phase, we found essential to consider the combined effects of freshwater inflows from canals and groundwater, and tidal forcing on the ocean boundaries and wind stress on the water surface.

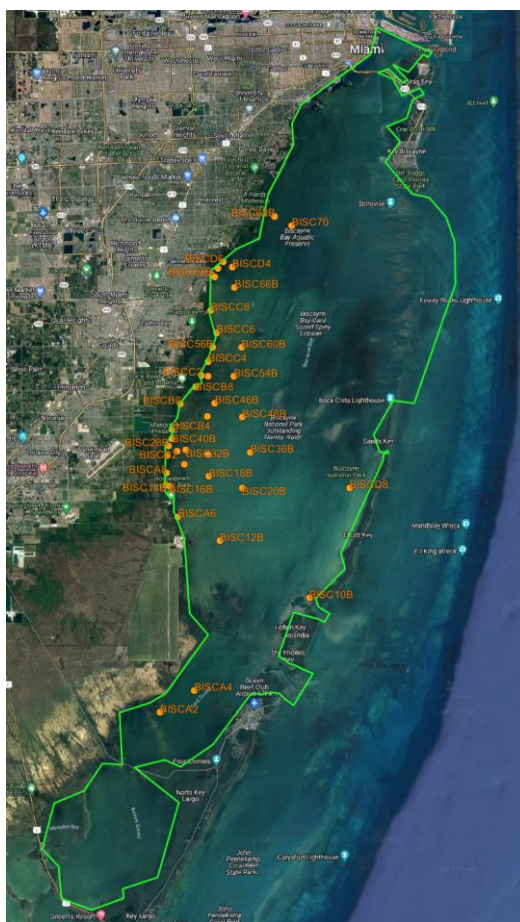


Figure 122 Model domain used for the hydrodynamic and salinity transport validation. The green polygon defines the model extent. The figure also shows the SWFMD stations used to compare measured water elevations and salinities with the model results.

15.2.1 *Mesh Geometry and Topology*

The mesh used for the model validation was the same as that used in the calibration phase. It has 19,494 cells covering an area of 683 km², and the triangular cell sizes vary from 26 m to 1163 m.

15.2.2 *Manning's n roughness and Dispersion Coefficients*

The model validation for salinity kept the same dispersion coefficients and the Manning's n roughness distribution that were obtained during the hydrodynamic calibration.

15.2.3 *Wind Data*

The wind data used for the model validation was obtained from the NOAA Virginia Key station and corresponds to the period January 2019 -December 2019. During this period, the average wind speed was around 4 m/s, with gust reaching 14 m/s for short periods (see Figure 45). The wind velocity components in East and North directions were provided to the model at 6-minute intervals.

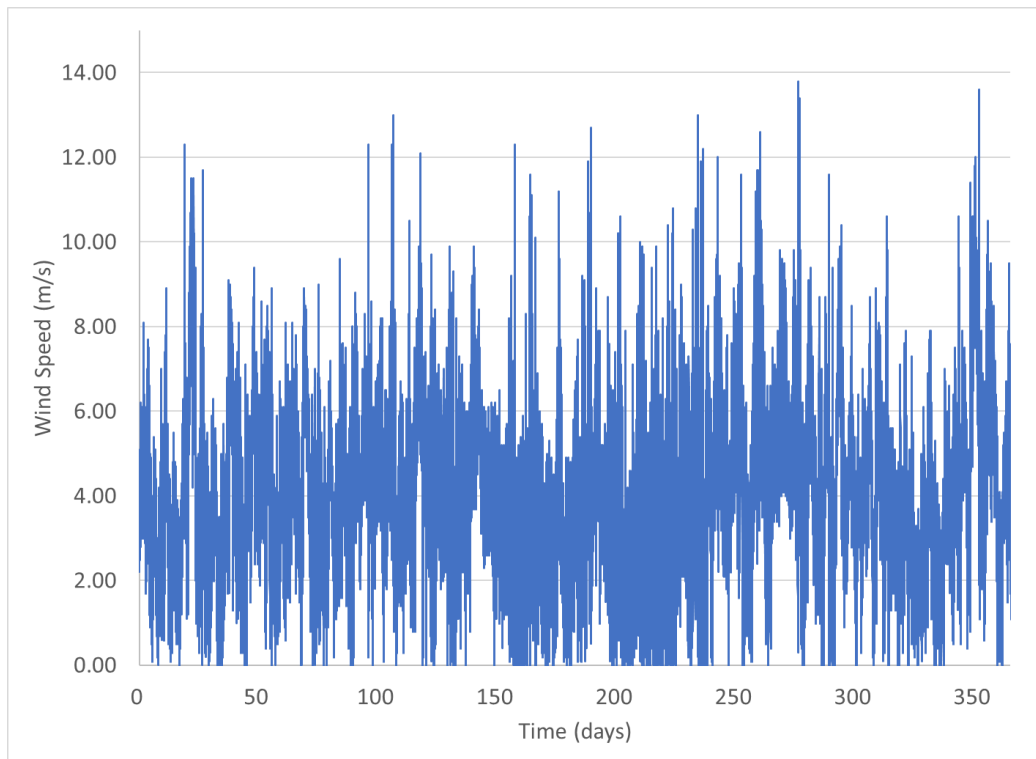


Figure 123 Wind Speed for the period January 2019 -December 2019 from NOAA Virginia Key station 8723214. Source: NOAA/NOS/Center for Operational Oceanographic Products and Services.

15.2.4 Boundary Conditions

The Biscayne Bay Operation Model when applied to simulate the bay hydrodynamics and the salinity distribution, requires two types of boundary conditions at the model inflow and outflow areas. On the ocean inlets, time series of the tidal elevations and water salinity (o/oo) are specified. The model uses the tidal elevation for both inflow and outflow, and salinity is only imposed when the flow direction is toward the bay interior. When the flow is coming out of the bay through the open boundary, the model only imposes the water elevation, and the salinity is taken from the mesh interior. At all canals that enter the bay on the land side, the boundary condition includes the water discharge (m^3/s) and the salinity. Also, the model incorporates conditions representing the ground water inflow that occur along the interface between the bay and the land (Figure 124). Along those areas the model requires the groundwater discharge (m^3/s) and the salinity (o/oo) as described below.

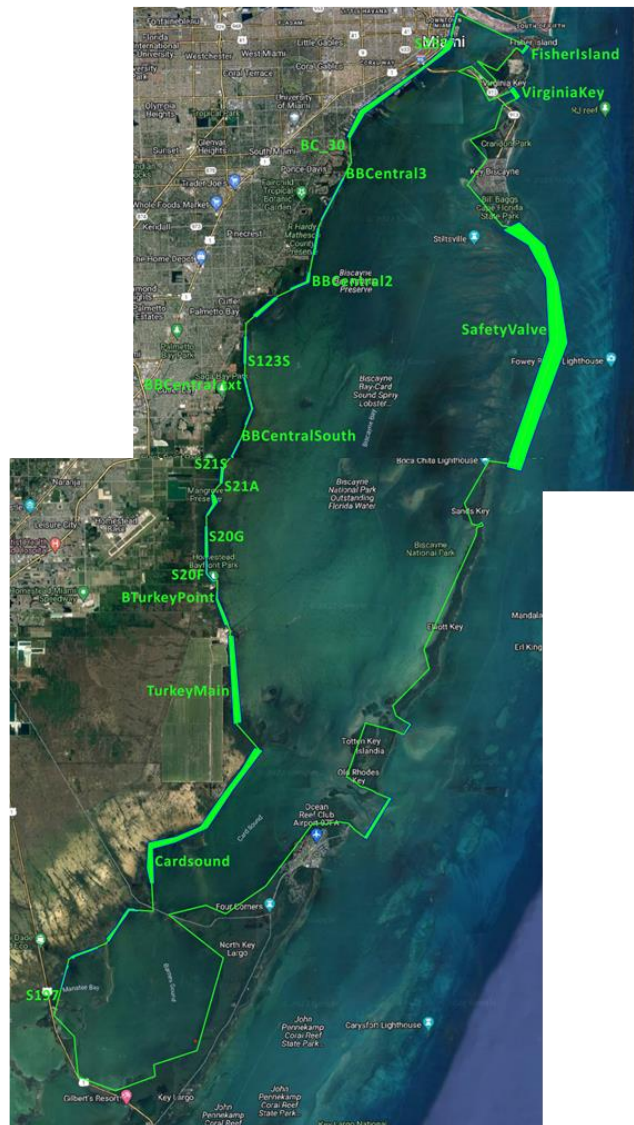


Figure 124 Boundary Conditions for the model validation of Biscayne Bay.

Table 13 summarizes the 26 open boundary conditions used in the BBOM validation.

Table 13 Boundary conditions used in the Hydrodynamic and Salinity Transport Model Validation.

No. Hyd	Inflow/outflow Boundary	Boundary Type	Boundary Condition File Name
1	S25S	Discharge + Salinity vs Time	S25S.txt
2	S22S	Discharge + Salinity vs Time	S22S.txt
3	S700P	Discharge + Salinity vs Time	S700P.txt
4	S123S	Discharge + Salinity vs Time	S123S.txt
5	S21S	Discharge + Salinity vs Time	S21S.txt
6	S21A	Discharge + Salinity vs Time	S21A.txt
7	S20G	Discharge + Salinity vs Time	S20G.txt
8	S20F	Discharge + Salinity vs Time	S20F.txt
9	S197	Discharge + Salinity vs Time	S197C.txt
10	Manatee	Discharge + Salinity vs Time	Manatee.txt
11	BarnesSound	Discharge + Salinity vs Time	BarnesSound.txt
12	Cardsound	Discharge + Salinity vs Time	CarlSound.txt
13	BTurkeyPoint	Discharge + Salinity vs Time	Turkey2.txt
14	MangrovePreserve	Discharge + Salinity vs Time	Mangrovepreserve.txt
15	BBCentral.txt	Discharge + Salinity vs Time	BBCentral.txt
16	BBCentral2	Discharge + Salinity vs Time	BBCentral2.txt
17	BBCentral3	Discharge + Salinity vs Time	BBCentral3y.txt
18	BC_30	Discharge + Salinity vs Time	BBCentral4.txt
19	TurkeyMain	Discharge + Salinity vs Time	TurkeyMain.txt
20	BBCentralSouth	Discharge + Salinity vs Time	BBCentralSouth.txt
21	RhodesKey	Tide Elevation + Salinity vs Time	BISC10B.TXT
22	ElliottKey	Tide Elevation + Salinity vs Time	BISC10B.TXT
23	SafetyValve	Tide Elevation + Salinity vs Time	SafetyValb.TXT
24	FisherIsland	Tide Elevation + Salinity vs Time	SafetyValb.TXT
25	VirginiaKey	Tide Elevation + Salinity vs Time	SafetyValb.TXT
26	BC_26	Tide Elevation + Salinity vs Time	BISC10B.TXT

15.2.4.1 Boundary Conditions at Oceanic Boundaries

Figure 125 depicts the tidal water elevation data from NOAA's Virginia Key Station Figure 126 shows the salinity for the same station. The complete data set is included in the MS-Excel file that accompanies this report.

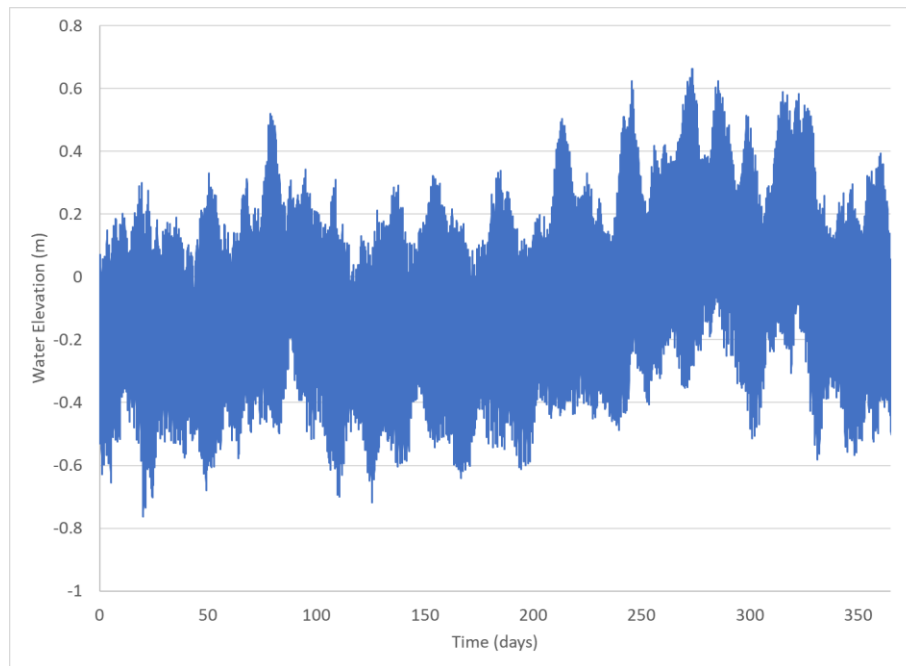


Figure 125 Water elevation time series from Virginia Key NOAA Station used at the Safety Valve open boundary for the period January 2019 -December 2019.

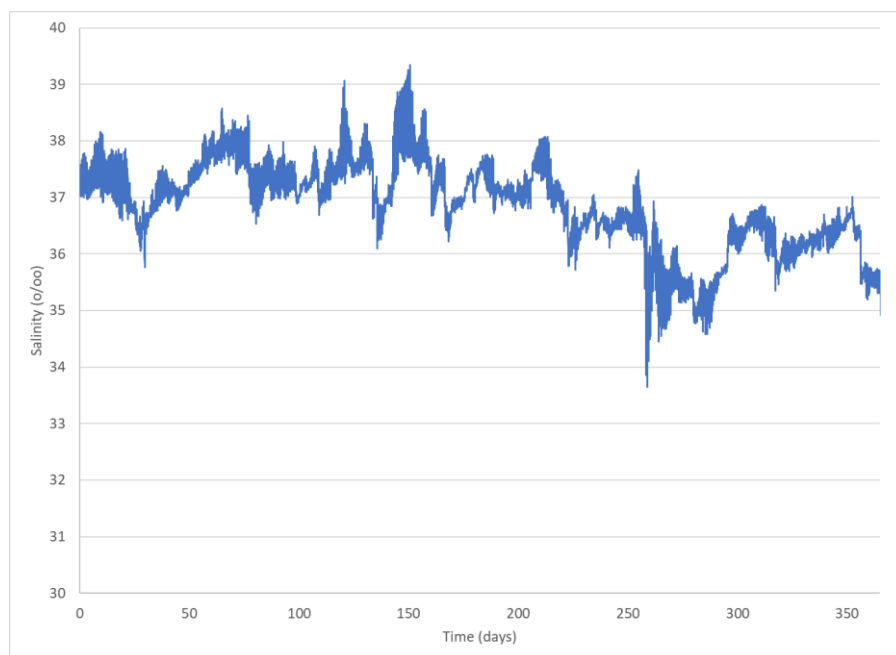


Figure 126 Salinity time series from SFWMD station BISC10B used at open oceanic boundary conditions for the period January 2019 -December 2019.

The boundary conditions for the other inflow and tidal conditions are included in the Excel file included with the report.

15.2.4.2 Boundary Conditions at Continental Bay Boundaries

15.2.4.3 Inflow from Canals

Inflow discharge from 9 canals arriving into the bay were incorporated in the validation phase (see Table 12). As example Figure 127 represents the inflow discharge from S20F canal for the period January 2019-December 2019. In addition salinities were assumed from nearby SFWMD stations as shown in Figure 128.

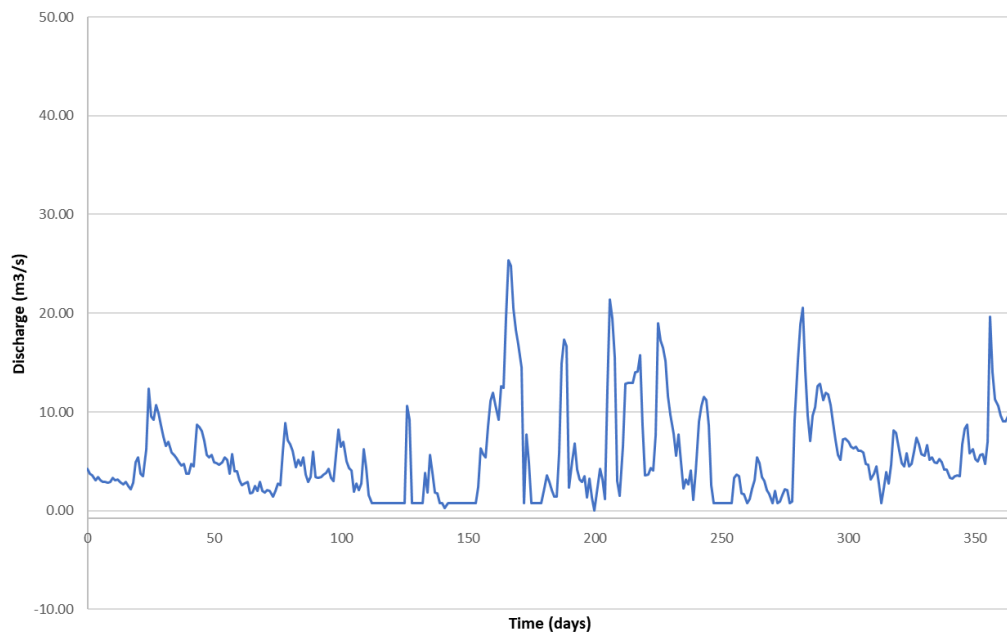


Figure 127 Inflow Discharge from S20F canal for the period January 2019 -December 2019.

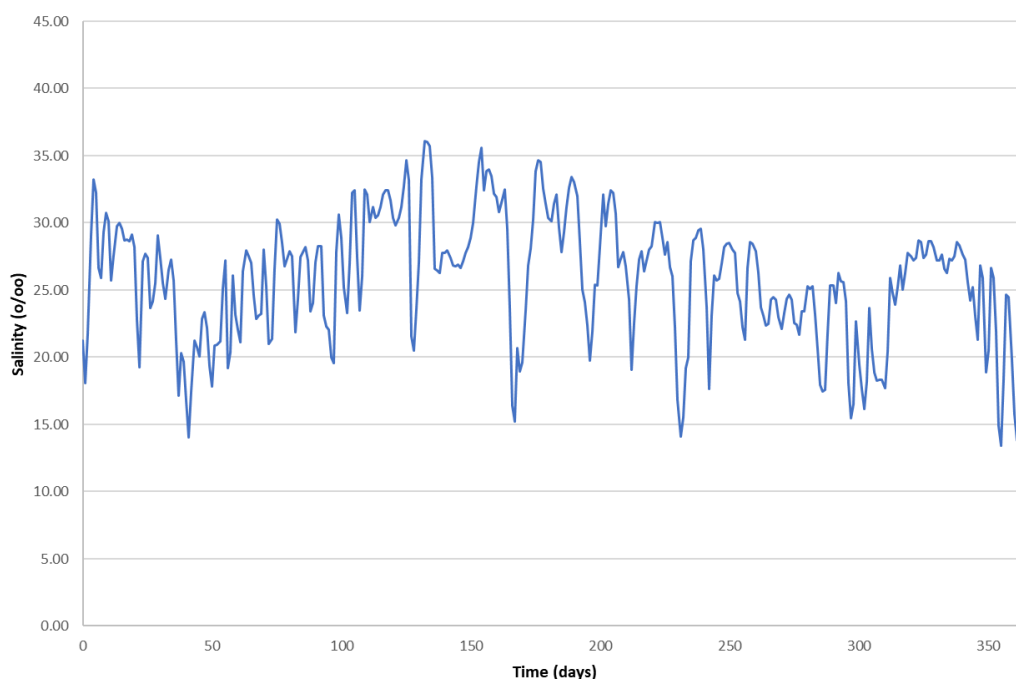


Figure 128 Salinity from S20F canal for the period January 2019 -December 2019.

15.2.4.4 Ground Water Inflow

To obtain adequate salinity comparisons in the bay, we had to impose both the water discharges and the salinity flowing into the bay from the inland groundwater flow. Since we had no groundwater data to establish these inflows, we used salinity data from the SFWMD stations that were closer to each band boundary condition, modified salinity by a reduction factor which made the inflows less salty than the bay. Then, to set the discharge, we calibrated a time series assuming that flowrates varied in magnitude inversely with the salinity. In other words, lower salinities in the close-to shore station lead to high groundwater discharges and vice versa. In order to achieve the final discharge magnitudes, we had to run the model several times, varying the time series factors, which allowed adjusting both the inflow salinity and the groundwater flow at each band.

15.3 Validation Results for Salinity and Hydrodynamics

15.3.1 Comparison of Water Elevations

Results of the model calculated surface water elevations and salinities at each SFWMD station were assessed using direct magnitude comparisons with data, and statistical quality indexes as shown in this section. Figure 129 to Figure 139 present the direct comparison between measured and BBOM calculated water elevations and salinities at the 41 SFWMD stations.

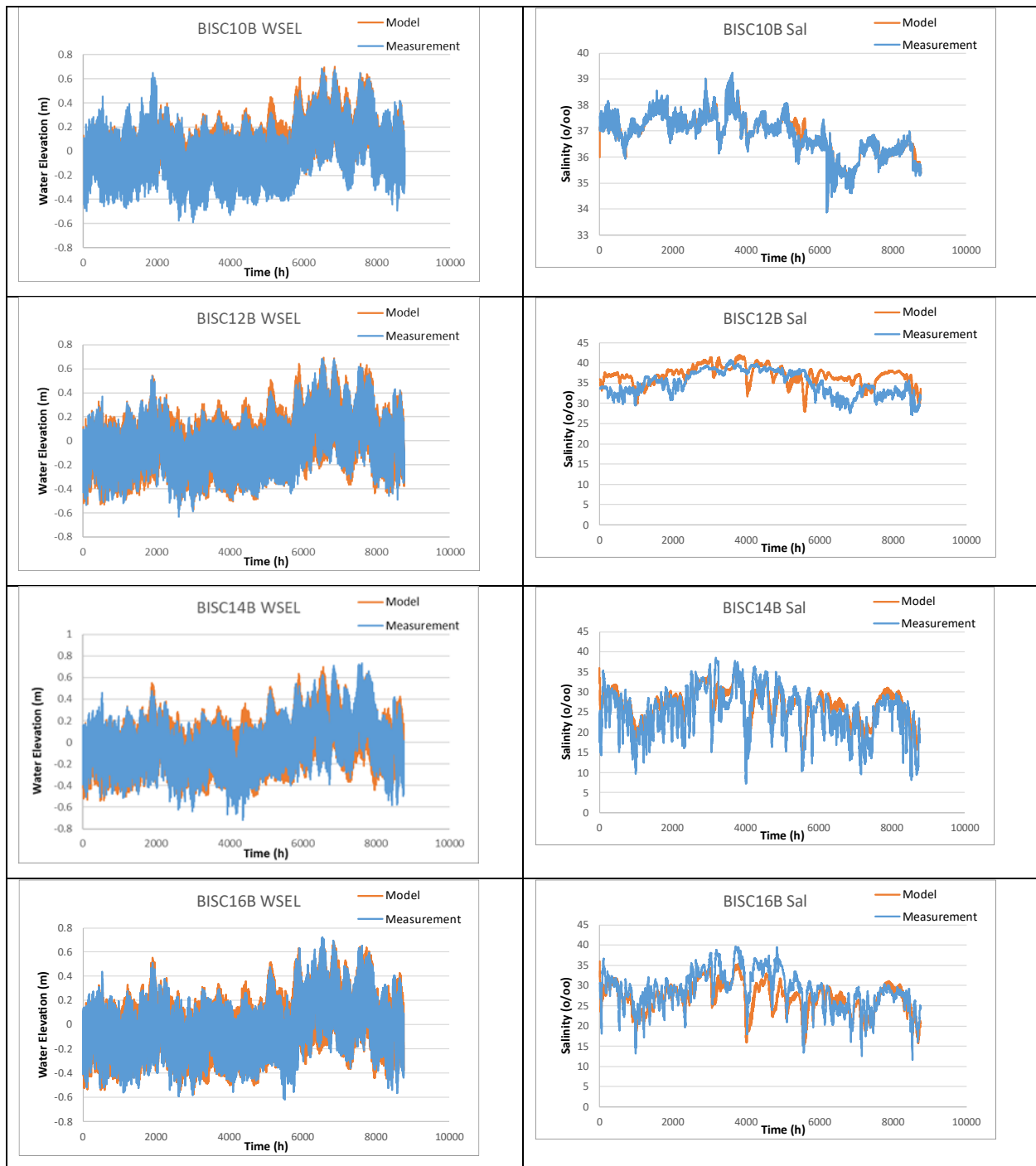


Figure 129 Water Surface elevations and salinities for stations BISC10B, BISC12B, BISC14B, and BISC16B. Comparison of model against measurements.

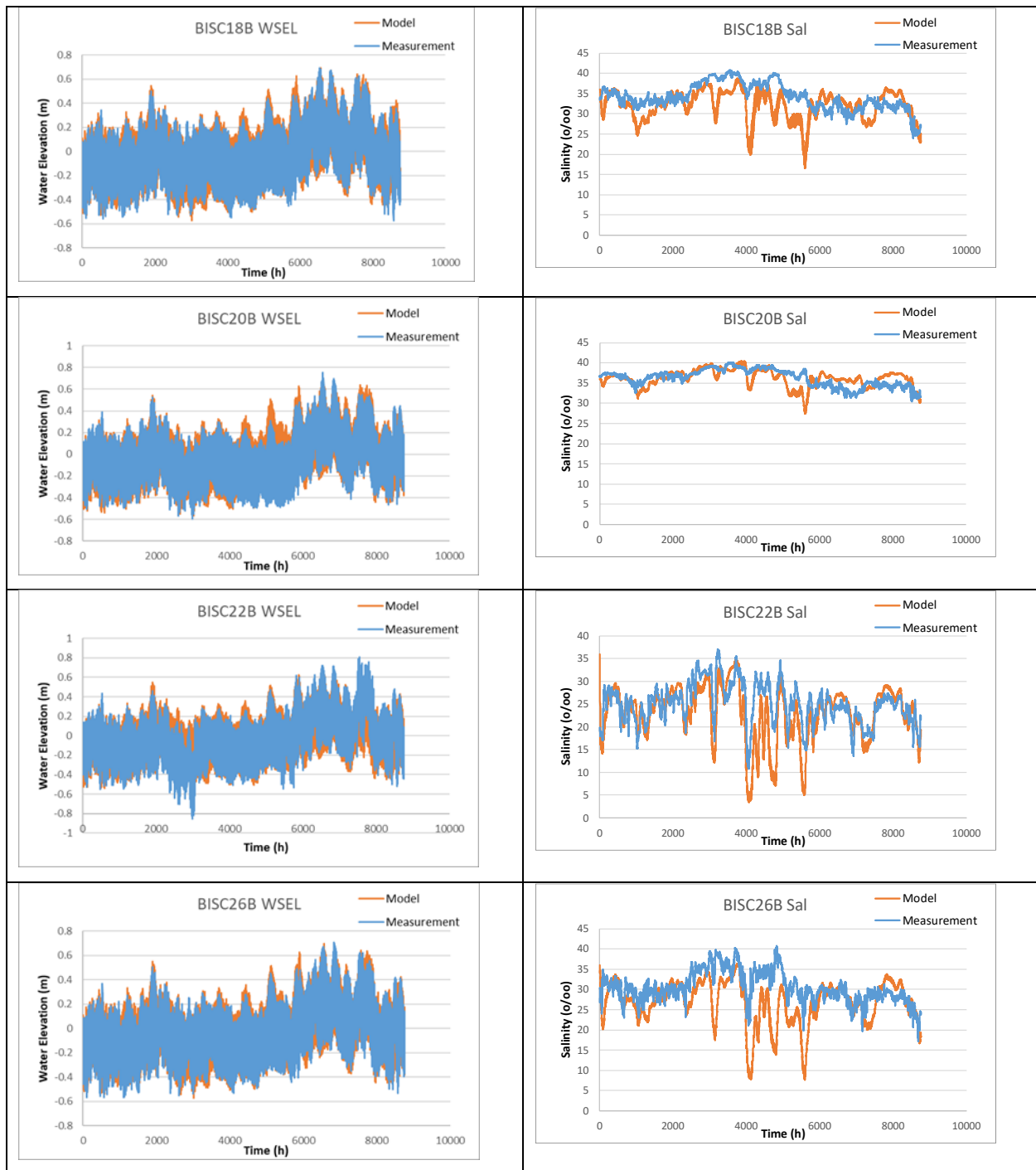


Figure 130 Water Surface elevations and salinities for stations BBISC18B , BISC20B , BISC22B, and BISC26B. Comparison of model against measurements.

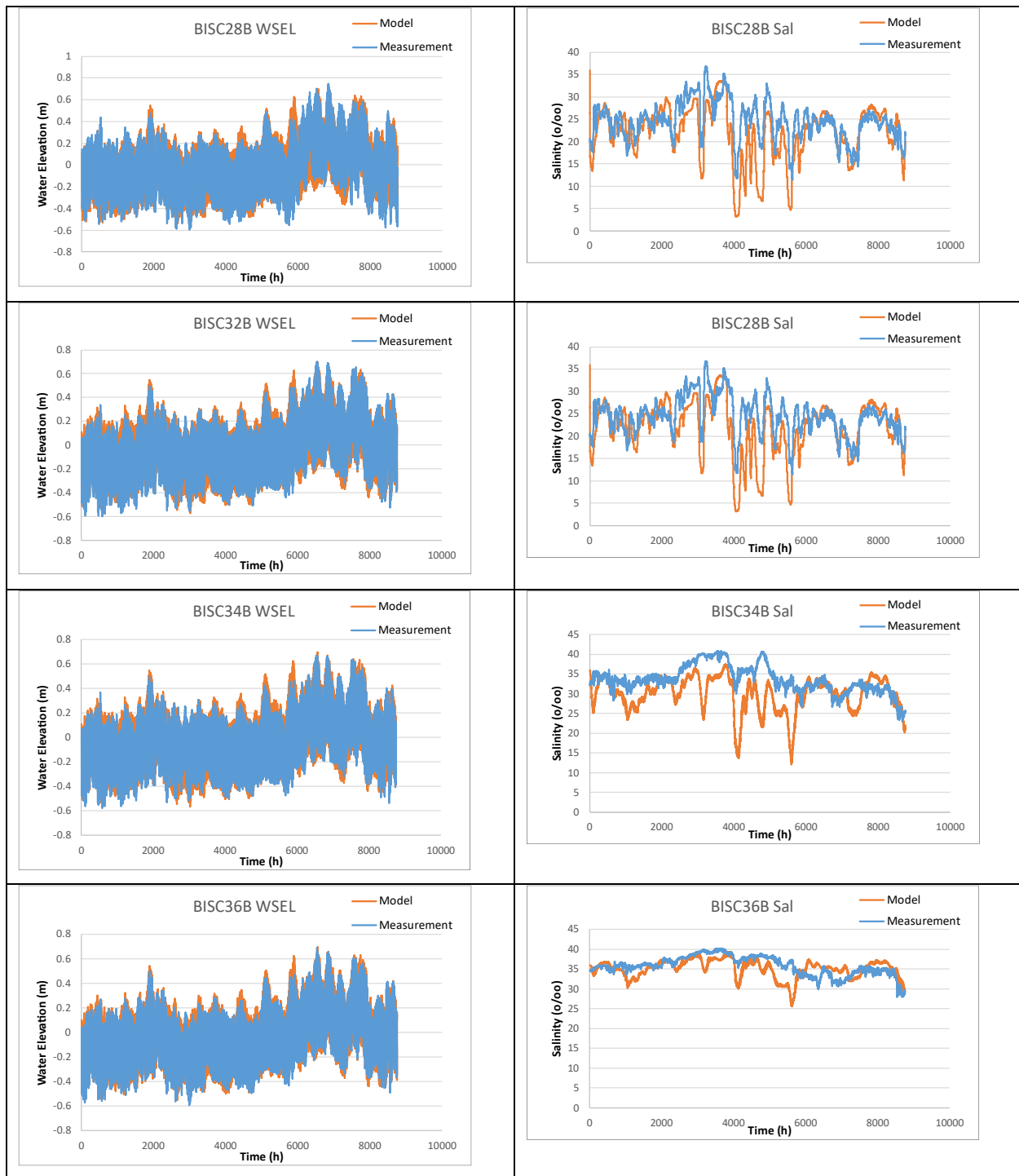


Figure 131 Water Surface elevations and salinities for stations BISC28B, BISC32B, BISC34B, and BISC36B. Comparison of model against measurements.

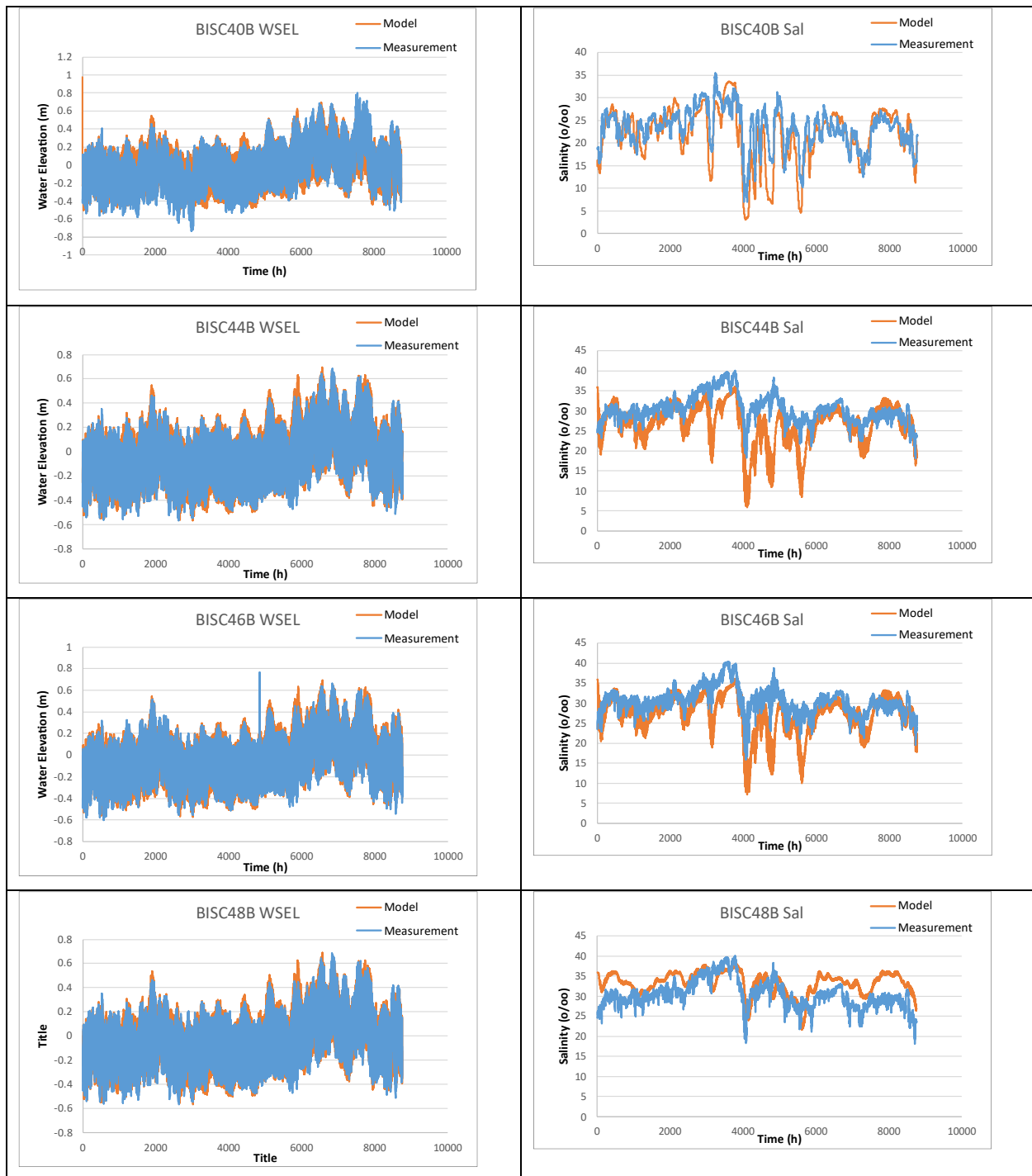


Figure 132 Water Surface elevations and salinities for stations BISC40B, BISC44B, BISC46B, and BISC48B. Comparison of model against measurements.

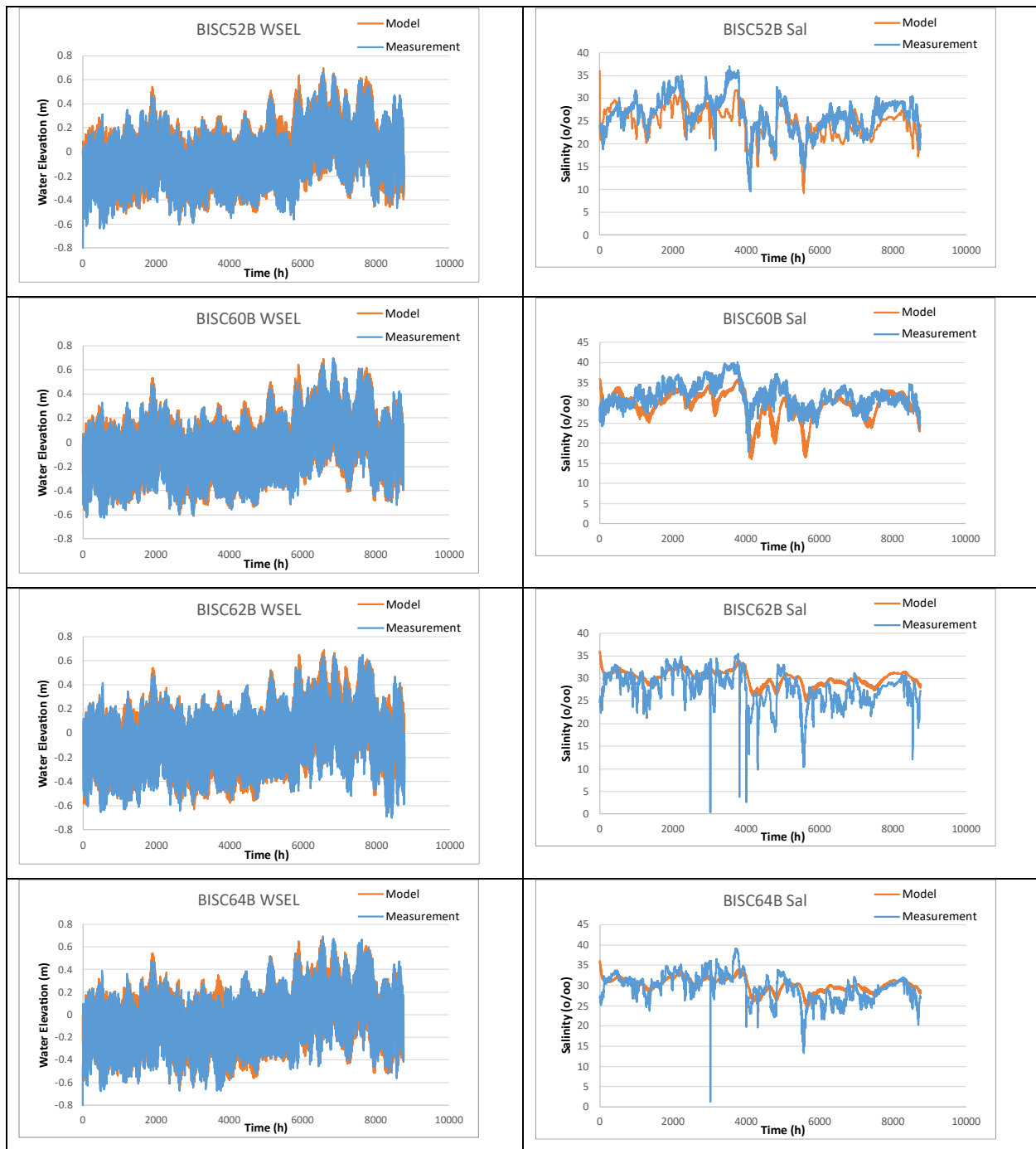


Figure 133 Water Surface elevations and salinities for stations BISC52B, BISC60B, BISC62B, and BISC64B. Comparison of model against measurements.

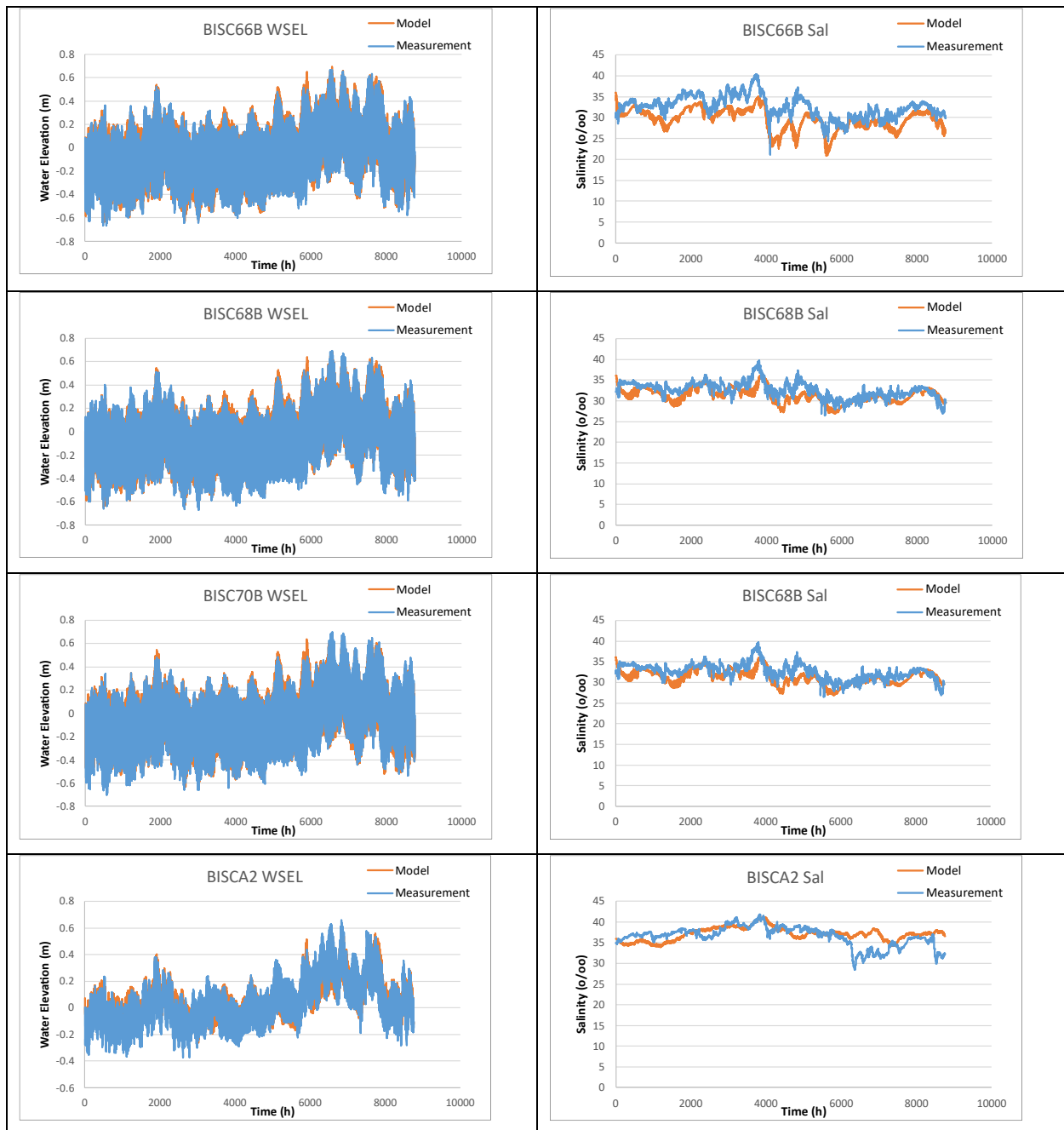


Figure 134 Water Surface elevations and salinities for stations BISC66B, BISC68B, BISC70B, and BISCA2. Comparison of model against measurements.

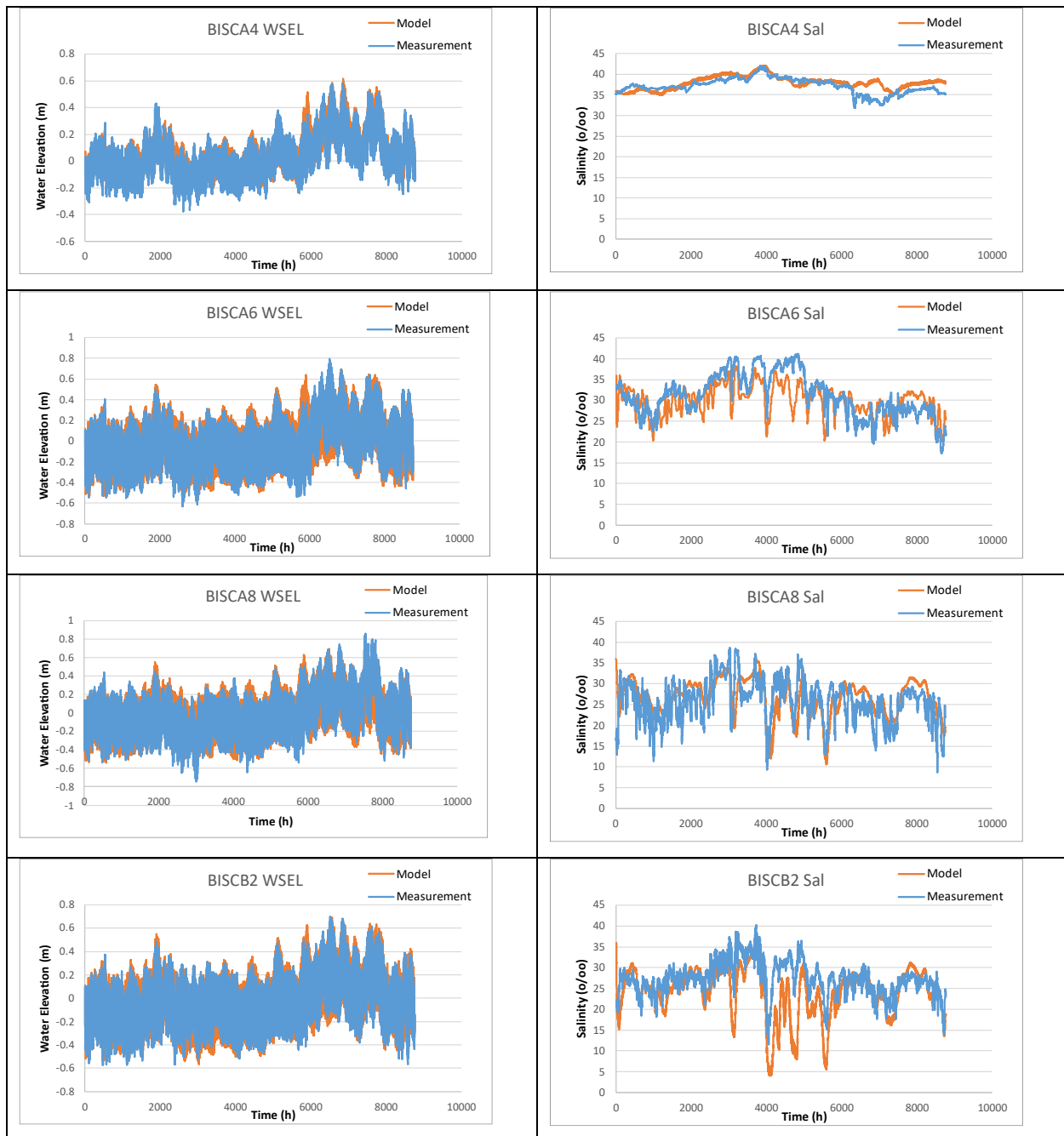


Figure 135 Water Surface elevations and salinities for stations BISCA4, BISCA6, BISCA8, and BISC2. Comparison of model against measurements.

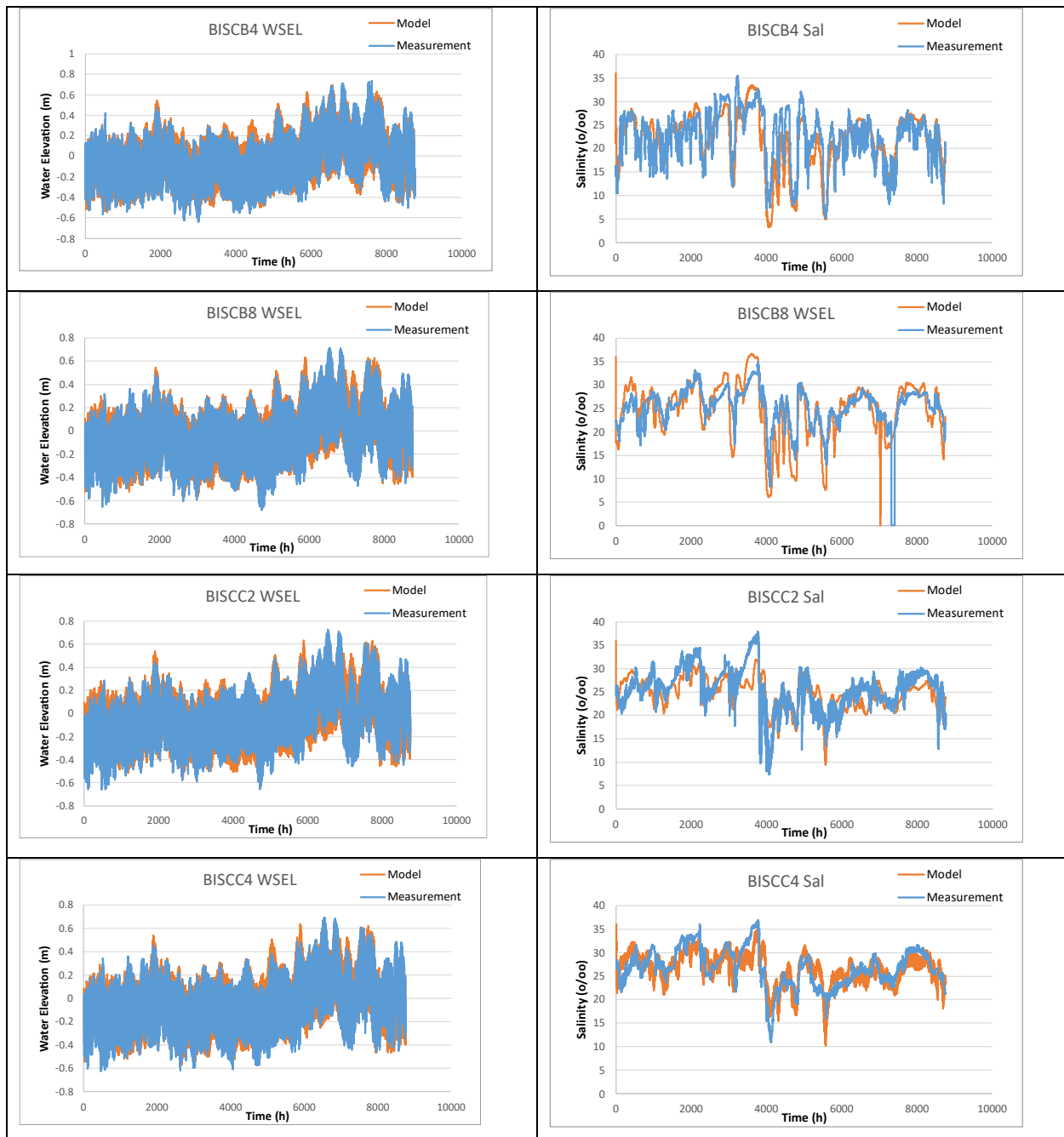


Figure 136 Water Surface elevations and salinities for stations BISC4, BISC8, BISCC2, and BISCC4. Comparison of model against measurements.

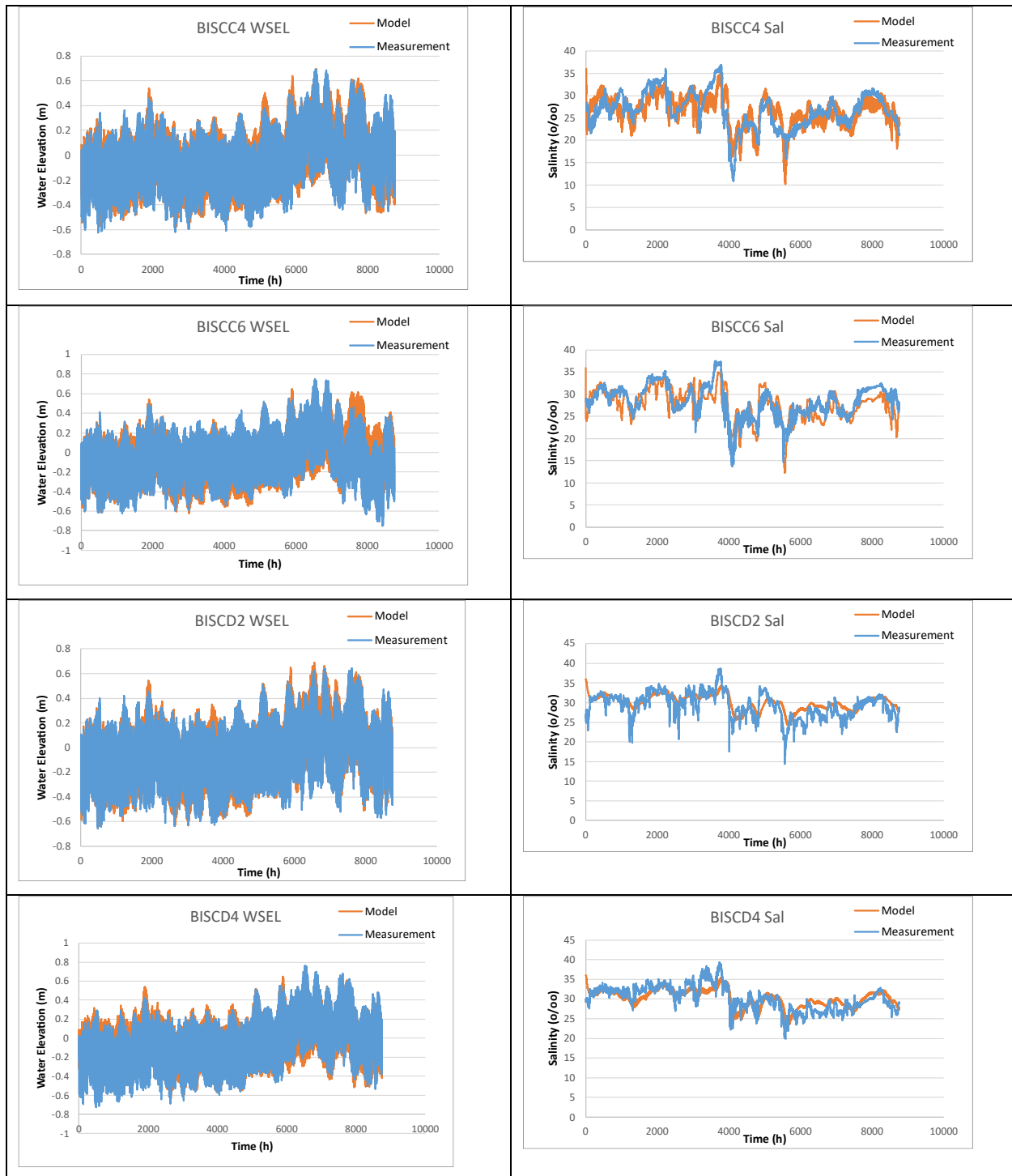


Figure 137 Water Surface elevations and salinities for stations BISCC4, BISCC6, BISCD2, and BISCD4. Comparison of model against measurements.

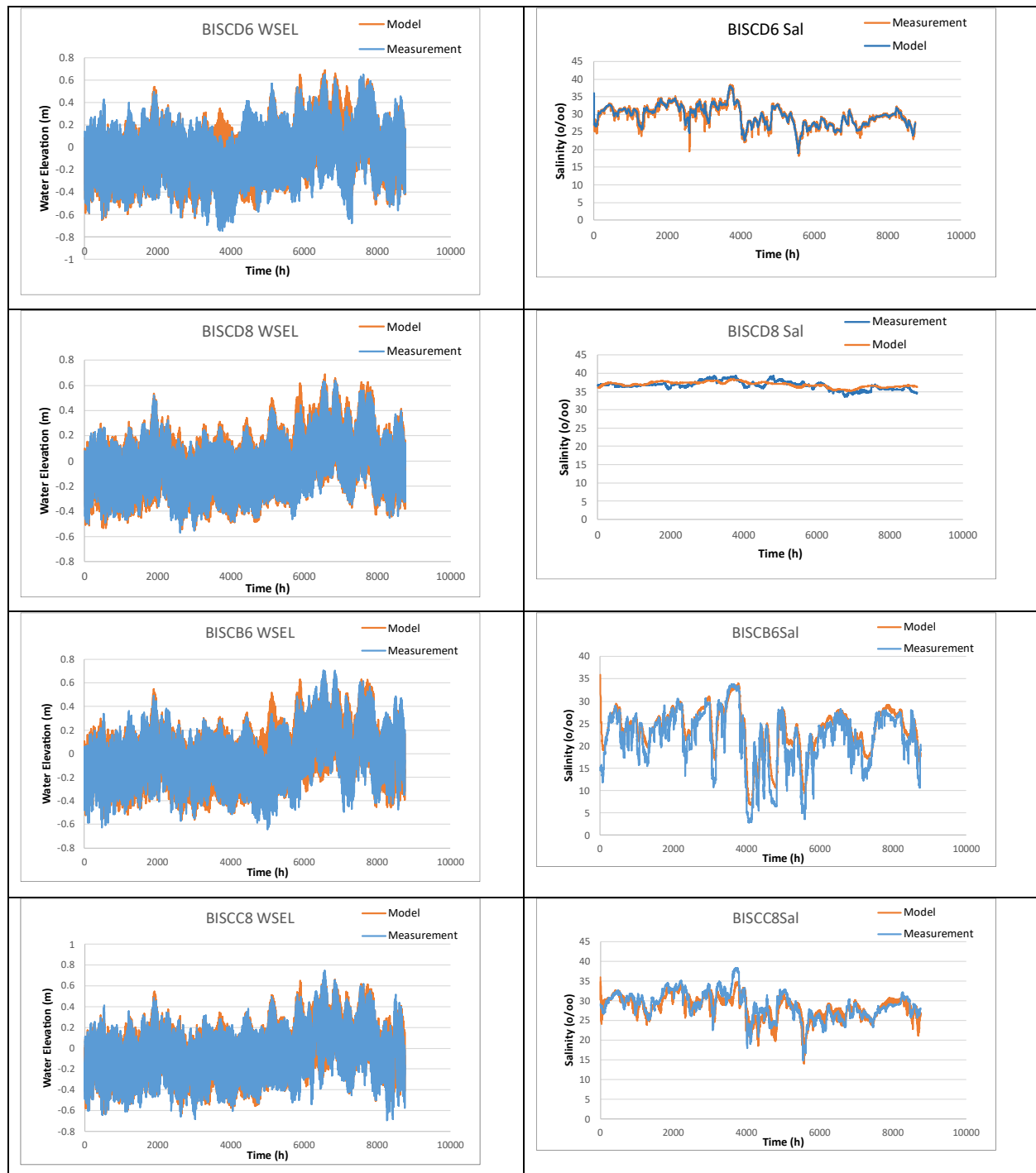


Figure 138 Water Surface elevations and salinities for stations BISCD6, BISCD8, BISC6, and BISCC8. Comparison of model against measurements.

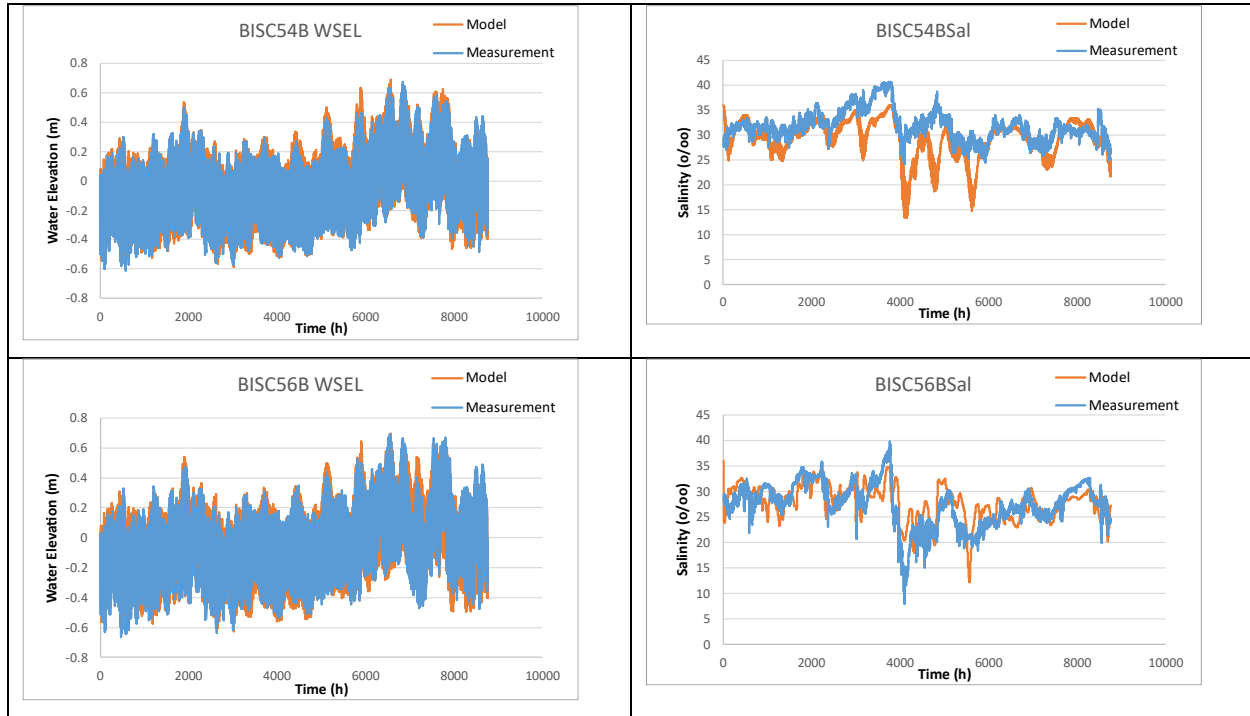


Figure 139 Water Surface elevations and salinities for stations BISC54B, and BISC56B. Comparison of model against measurements.

Figure 140 shows the water surface elevation differences between model and measurements for each station. It can be observed that the average differences are less than 1.1 cm for all stations and less than 2 mm for all but 3 stations.

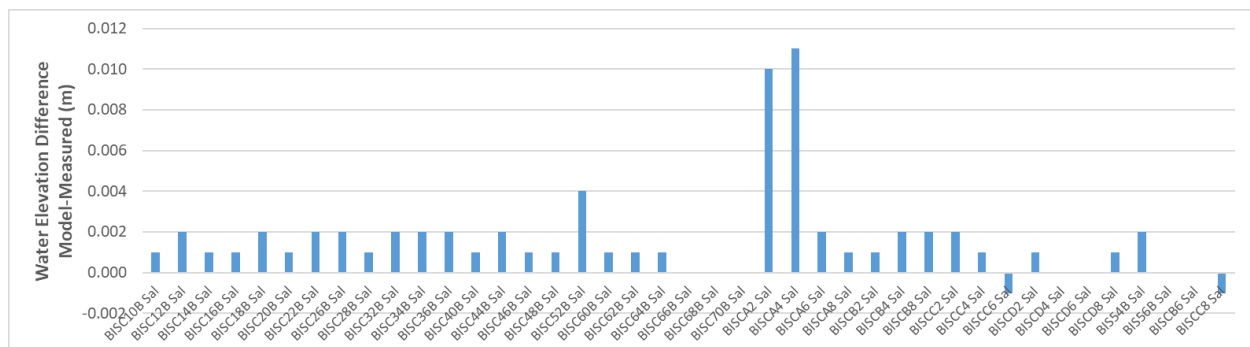


Figure 140 Water Surface Elevation Average Differences (Model-Measured) at the 42 SFWMD stations.

Figure 141 shows the salinity difference between model and measurements for each station. Note that the maximum absolute average differences are less than 4.5 o/oo, and for 30 out of 41 stations

(73%) the difference Model-Measured is less than 2 o/oo.

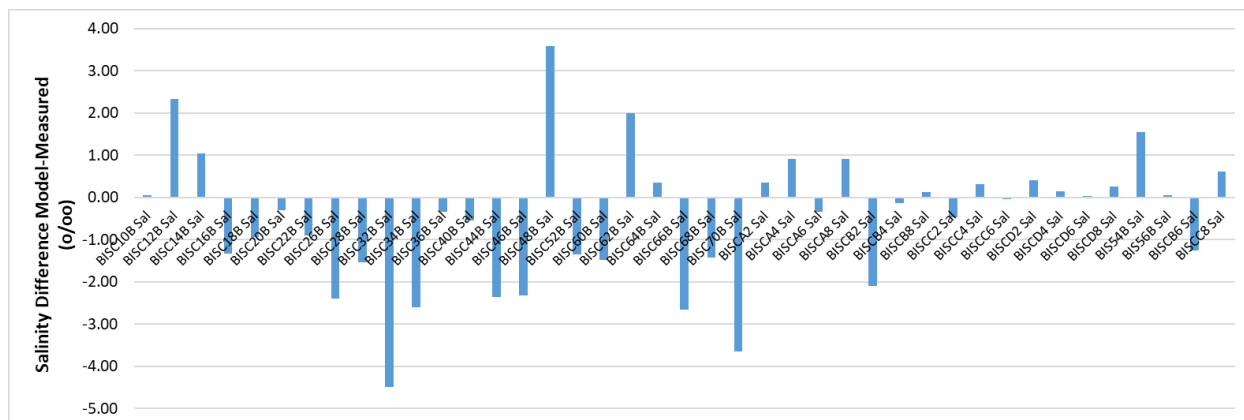


Figure 141 Salinity Average Differences (Model-Measured) at the 42 SFWMD stations.

15.3.2 Error Correlations

The following table summarizes the errors based on the Correlation Quality Index.

Table 4 Correlation Quality Indexes obtained for BBOM validation.

Station	Water Surface Elevation Correlation Index	Salinity Correlation Index
BISC10B	94.46	93.67
BISC12B	92.57	45.16
BISC14B	90.02	82.74
BISC16B	91.31	73.14
BISC18B	92.72	33.53
BISC20B	91.46	40.18
BISC22B	90.16	64.33
BISC26B	92.52	26.14
BISC28B	90.10	65.49
BISC32B	92.11	34.26
BISC34B	92.73	25.24
BISC36B	93.70	37.00
BISC40B	91.29	76.64
BISC44B	92.63	48.76
BISC46B	92.76	57.00
BISC48B	91.96	53.20
BISC52B	91.80	67.97
BISC60B	93.47	54.30
BISC62B	91.06	60.95
BISC64B	91.40	66.45
BISC66B	93.38	64.59
BISC68B	94.49	62.54
BISC70	94.34	61.57
BISCA2	93.55	37.30
BISCA4	92.90	62.99
BISCA6	90.79	66.33
BISCA8	89.68	56.24
BISCB2	92.10	51.30
BISCB4	91.99	76.00
BISCB8	91.06	72.76
BISCC2	89.17	61.45
BISCC4	91.58	72.12
BISCC6	88.59	70.70
BISCD2	91.07	68.96
BISCD4	91.85	75.16
BISCD6	88.70	96.60
BISCD8	93.72	76.81
BISC54B	89.42	91.60
BISC56B	91.31	84.23
BISCB6	92.76	51.06
BISCC8	89.96	64.32

15.3.3 Salinity Maps

The following figure depicts the salinity distribution of Biscayne Bay at selected times during the validation period.

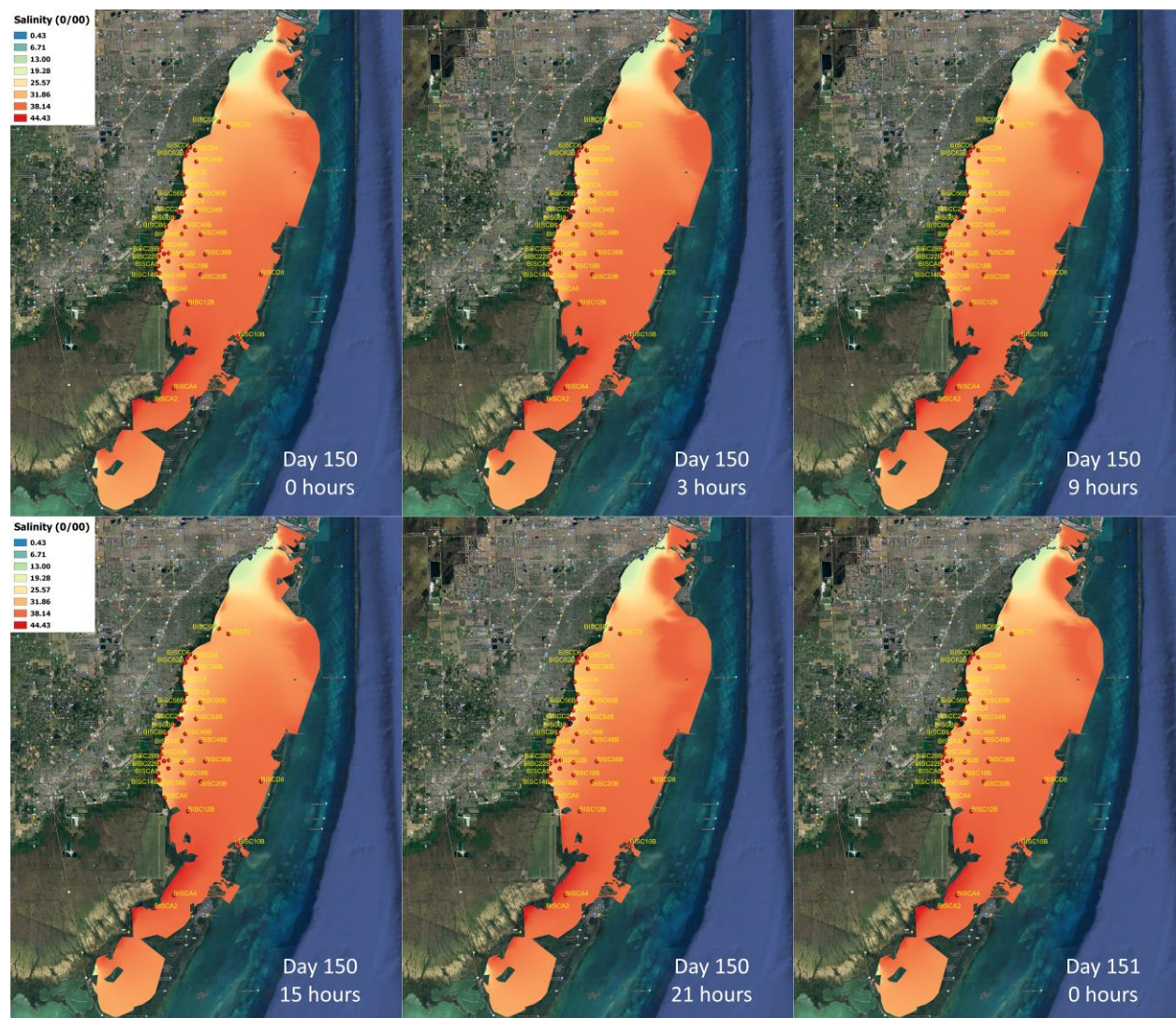


Figure 142 Salinity distribution at time 150 days, and 0, 3, 9, 15, and 21 hours.

15.3.4 Salinity Animations

As part of this report two animations are included. BBOM_Salinity Dynamics_Days_03-33.avi and BBOM_Salinity Dynamics_Days_150-180.avi. The first one shows the salinity dynamics from January 3 to February 2. The second file depicts the salinity dynamics for 30 days starting on day 150.

16 Conclusions

This section summarizes the main conclusions we reached during the construction and testing of the *Operational Hydrodynamic Sediment Transport and Water Quality Model for Biscayne Bay, Florida (BBOM: Biscayne Bay Operational Model)*. Three phases were executed to reach our goals: implementation, calibration and validation. Each one of them entailed different challenges and opportunities to learn, as well as occasions to apply methods, techniques and knowledge to solve the problem facing us.

The following set of conclusions are intended not only to highlight our findings and achievements, but they should also serve as a guide for future researchers or users of BBOM. Conclusions are organized following the order of chapters in the present report.

- Extending the model domain offshore, beyond the shallows of the Safety Valve allows the inclusion of the essential role that the Safety Valve has in Biscayne Bay hydrodynamics while avoiding the potential numerical issues that could occur if we would locate an open boundary along a very shallow area with high velocities and drying zones.
- The application of a model based on unstructured triangular-meshes that can be adapted to irregular boundaries allowed to accurately represent bathymetric gradients and irregular boundaries. BBOM has the capacity to design and quickly generate such meshes, increasing the efficiency and quality of the modeling effort.
- BBOM numerical engine makes use of high performance parallelized computations that run in multiple processor GPU hardware reducing significantly reducing runtimes of long term scenarios.
- Since in the first phase of this study there were no tidal measurements that could be used for all inlet boundary conditions, predicted values from NOAA station were used to initiate the study. Stations near boundaries were used as boundary conditions (Haulover, Miami Beach Government Cut, Virginia Key, Ragged Key No. 5, and Elliot Key). As it was expected, using a distributed boundary condition from NOAA tidal prediction provides a much better comparison than using a single tidal record for all open boundaries.
- Qualitative analysis of the wind data for 8 stations spread over the whole bay suggest a common and uniform wind direction pattern inside the Bay, except in the Central Bay, where wind speed is about 1.5 times higher than areas protected by islands on their eastern side. The wind has a significant effect on water circulation, particularly toward the southern parts of Biscayne Bay.
- The initial spatial distribution of the Manning n bed roughness coefficient was adopted based on Brown et al. (2003) and later adjusted based on the sensitivity analysis of the calibration process. These adjustments underscored the importance of these values, whose variation significantly affects the model results for water elevation and current velocity.

- The model validation involved simulating the bay hydrodynamics for a period of time different from those used in the calibration phase. Results from hydrodynamics validation indicated that BBOM was able to predict with good precision water elevation in the 18 selected stations. Current velocities produced mixed results, some excellent and others with moderate replication of measured data.
- The results of the calibration scenarios show that the model was able to reproduce measured and predicted water elevations and velocities in several Biscayne Bay locations with acceptable precision.
- The definition of velocity fields for each sub-basin within Biscayne Bay highlighted the existence of contrasting velocity fields among and even within sub-basin. This suggests contrasting flooding/flushing rates and mixing leading to coexistence of quieter waters with longer residence times and affected by stagnation, next to water masses moving swiftly and with high flushing/flooding rates.
- Two sub-basins with contrasting velocity fields occur in the northernmost portion of Biscayne Bay. First, the one from Haulover Inlet to Broad Causeway displaying high velocities, and second, from Broward Causeway to NE79th St Causeway with significantly lower velocities. This suggests high flooding/flushing rates and mixing for the northern sub-basin and more stagnation in the southern one. This circulation pattern is of special relevance because the polluted Biscayne Canal drains to the southern sub-basin, where quieter waters have longer residence times, increasing the exposure time of its ecosystems to incoming pollutants.
- The Julia Tuttle Basin may be subdivided into a low-velocity compartment in the center of the basin, bordered toward the west, east and southern shorelines by high water velocity zones. The central slow-moving, eddy/prone area, receive waters from the polluted Little River, and is where the largest seagrass die-off has occurred in North Biscayne since 2013, and fish-kills are becoming the norm.
- Tidal flood waters move fast into the bay across Government Cut to Venetian Islands sub-basin and north to the Julia Tuttle sub basin. Seawater also moves westwards along Fisher Island Channel and Fisherman's Canal to the Miami River mouth and then south, to Central Biscayne Bay. Incoming tidal waters from the Virginia Key Inlet move towards Central Biscayne Bay.
- Most tidal water coming into Biscayne Bay does it across the Safety Valve. An impressive pattern of high velocity currents moving westwards over the shallows turn south and reduce speed when hitting deeper waters.
- Incoming waters through the Lewis Cut, Sands Cut, Cesar's Creek and Rhodes Channel seem to have only local influence in the overall circulation pattern of Biscayne Bay. Finally, waters in the southernmost portion of Biscayne Bay (Card and Barnes Sound, and

Manatee Bay) show very low velocity, and flow seems to be mostly outwards, even during incoming tides.

- Freshwater from the Miami River seems to move preferentially south during flood tide, to the Rickenbacker Causeway, where significant mixing occurs. Likewise, water from Little River gets dammed close to the river mouth during high tides, and then it moves preferentially southwards. Biscayne Canal waters also get dammed in high tide, but moves north when the tides recede. Surface and groundwater from the west coast of Central Bay move north and south parallel to shore, developing a gradual mixing zone.
- The availability of a Graphical User Interface (GUI) for the Open Source Geographical Information System QGIS (www.qgis.org). Provides a comprehensive set of visualization tools, including map rendering, animations, and exporting graphs in shapefile format and Google Earth, which facilitate the analysis of results and accelerates the overall modeling process. Videos of the currents and salinity model runs in this report are good examples of the potential of these visualization tools.
- We found essential to consider the combined effects of freshwater inflows from canals and groundwater, and tidal forcing on the ocean boundaries and wind stress on the water surface to be able to model water levels and salinities. This corroborate similar findings from previous authors
- Correlation Quality Indexes obtained during validation of Water Surface Elevation and Salinity for the Salinity Transport Component were very high for water elevations (average > 90%) and moderated for salinity (average >71%). That indicates that we have been able to replicate very closely the measured time series of water elevation and salinity with the BBOM model.
- To obtain adequate salinity comparisons in the bay, we had to impose both the water discharges and the salinity flowing into the bay from the inland groundwater flow. Since we had no groundwater data to establish these inflows, we used salinity data from the SFWMD stations that were closer to each band boundary condition, modified salinity by a reduction factor which made the inflows less salty than the bay. Then, to set the discharge, we calibrated a time series assuming that flowrates varied in magnitude inversely with the salinity. Future BBOM applications should focus on the integration of the model with an inland groundwater model that could provide more accurate estimations of the inflow discharges and salinities from land to the bay waters.

Finally, the Biscayne Bay Operational Hydrodynamic and Salinity Model developed in this project is a solid computational platform open to all researchers, agencies, and interested stakeholders, that can be used to study a variety of environmental management scenarios in the Bay.

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