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Use of Sediment Tracers to Evaluate Sediment Plume at Cape Fear River Inlet and Adjacent Beaches, North Carolina

Honghai Li, Carter A. Rucker, Lihwa Lin, and Kevin B. Conner

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Use of Sediment Tracers to Evaluate Sediment Plume at Cape Fear River Inlet and Adjacent Beaches, North Carolina

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Abstract

This report documents a numerical modeling investigation on the transport of sediment material placed on designated disposal sites adjacent to Cape Fear River Inlet, North Carolina. Historical and newly collected wave and hydrodynamic data around the inlet are assembled and analyzed. The data sets are used to calibrate and validate a coastal wave, hydrodynamic, and sediment transport model, the Coastal Modeling System. Model alternatives are developed corresponding to different material placement sites. Sediment transport and sediment plume distribution are evaluated within and around the immediate vicinity of Cape Fear River Inlet estuarine system for a representative summer and a winter month. Results of model simulations show that high flows occur along navigation channels and low flows occur outside the inlet in open ocean area. Sand materials placed in disposal sites tend to be trapped in and move along navigation channel and in these offshore placement sites sediment plume shows slow spreading and no significant sand migration from its release locations. Simulations for the summer and winter month present similar distribution patterns of sediments originating from placement sites.

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Preface

This study was conducted for the US Army Corps of Engineers, Wilmington District (SAW), by the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL), funding provided by SAW under MIPR W81EWF13548379.

The field data collection program was completed by the Coastal Engineering Branch of CHL.

The Coastal Inlets Research Program (CIRP) performed the study. The CIRP is administered for Headquarters, US Army Corps of Engineers (HQUSACE), by ERDC-CHL, Vicksburg, Mississippi, under the Navigation Program of HQUSACE. Ms. Tiffany Burroughs is HQUSACE Navigation business line manager. Mr. Charles E. Wiggins, CHL, is ERDC technical director for Navigation. Dr. Tanya M. Beck, CHL, is the CIRP program manager.

This work was conducted under the general administrative supervision of Ms. Lauren M. Dunkin, chief of Coastal Engineering Branch, and Ms. Ashley Frey, chief of the Navigation Division. Mr. Keith W. Flowers and Dr. Ty V. Wamsley were the deputy director and director of CHL during this study period, respectively.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

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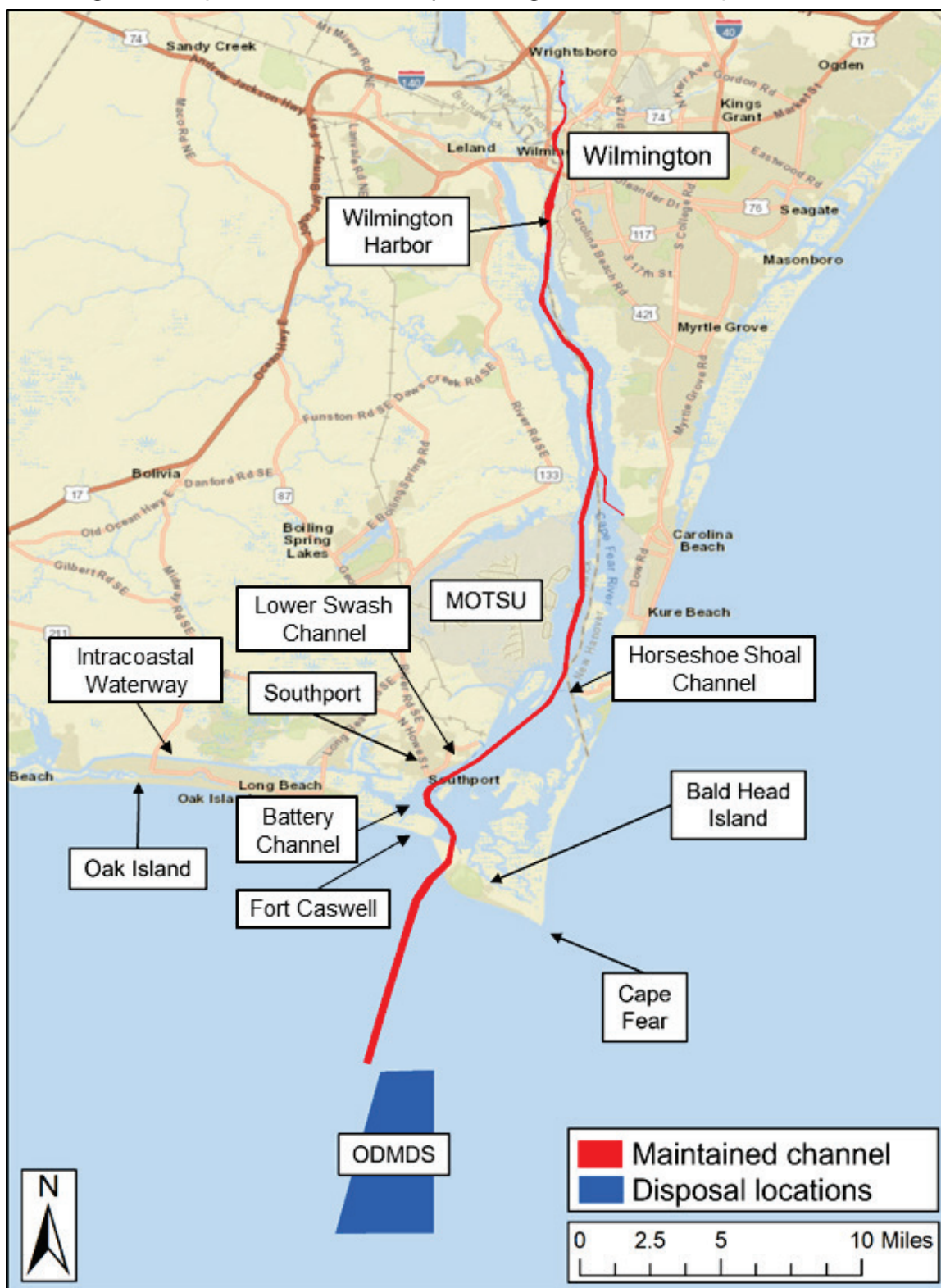
1 Introduction

1.1 Background

Cape Fear River Inlet lies approximately 40 km¹ (25 mi) south of Wilmington Harbor, North Carolina, between Fort Caswell and Bald Head Island. Fort Caswell lies on an island that is approximately 25.2 km (15.7 mi) long and contains Oak Island. The island is bound to the west by Lockwood's Folly Inlet and to the east by Cape Fear River Inlet. Bald Head Island is bound to the west by Cape Fear River Inlet and to the south by Cape Fear. Cape Fear River Inlet is approximately 1.6 km (1 mi) in width, with a maintained channel depth of 13.4 m (44 ft), mean lower low water, from the outer ocean maintenance boundary through the Battery Channel and 12.8 m (42 ft) from Lower Swash Channel through Horseshoe Shoal Channel. Overdepth up to 0.61 m (2 ft) is allowed and the channel width varies, ranging from 121.9–205.7 m (400–675 ft). The dredged channel extends seaward through inlet ebb shoals to the open ocean and connects to the Wilmington Harbor and Atlantic Intracoastal Waterway. Inner Bar Channels are composed of mostly beach quality sand and dredged material from these channels is typically removed by cutter-suction (pipeline dredge) and beneficially placed on the adjacent shorelines of Oak Island or Bald Head Island. During years when there is no beach placement, accumulated material is removed by hopper dredge and taken to the ocean dredged material disposal site (ODMDS). Dredged material from other portions of the river is typically placed on bird islands using a pipeline dredge. Notable adjacent features include Southport, Military Ocean Terminal at Sunny Point, and Cape Fear (Figure 1-1).

1. For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52 and 345–347, respectively. <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

Figure 1-1. Cape Fear River Inlet vicinity with navigation channels and placement sites.



1.2 Objectives

Dredge and placement activities are required for maintaining a navigable depth for vessels passing through Cape Fear River Inlet. The current dredging window is assumed to be 1 December to 15 April (USACE 2021), but the need for risk-based management of dredging has caused interest in exploring year-round dredging rather than operating within these given environmental windows. Eliminating the window of hopper dredging operations would increase efficiency of dredging operations by minimizing issues with dredge availability, thus also reducing cost. Because dredges have typically operated within the environmental window, there is an uncertainty of the environmental effects resulting from operating outside this window. Dredging activities at Cape Fear River Inlet can negatively affect nearby species by changing the suspended sediment concentrations and can cause sediment deposition in atypical locations. The purpose of this study is to evaluate the transport of sediment material placed at designated nearshore and offshore areas and to model activity of suspended sediment with representative summer and winter conditions to determine whether these activities would have negative environmental impacts.

1.3 Approach

A coastal numerical modeling study is conducted to simulate waves, current, tide, and sediment transport within and around the immediate vicinity of Cape Fear River Inlet, Cape Fear River, Wilmington Harbor, and sediment disposal locations. The modeling includes sediment tracing to predict sediment plume spreading emitted from dredged material placement sites. Alternatives on sand placement areas are developed, the effect of forcing conditions (hydrodynamics, waves, and wind) on sediment movement is determined, and alternate placement activities on sediment plume distributions are investigated around Cape Fear River Inlet during typical summer and winter months.

This report is organized as follows. Section 2 introduces historical data that were applied to configure the numerical model and drive the numerical simulations. Section 3 describes the methods for the numerical study. Section 4 presents the results of numerical modeling including the calibration and validation of the calculated waves and hydrodynamics to the field measurements. Section 5 summarizes the results of the study and provides conclusions regarding sediment transport and environmental effects around the Cape Fear River Inlet estuarine system.

2 Data

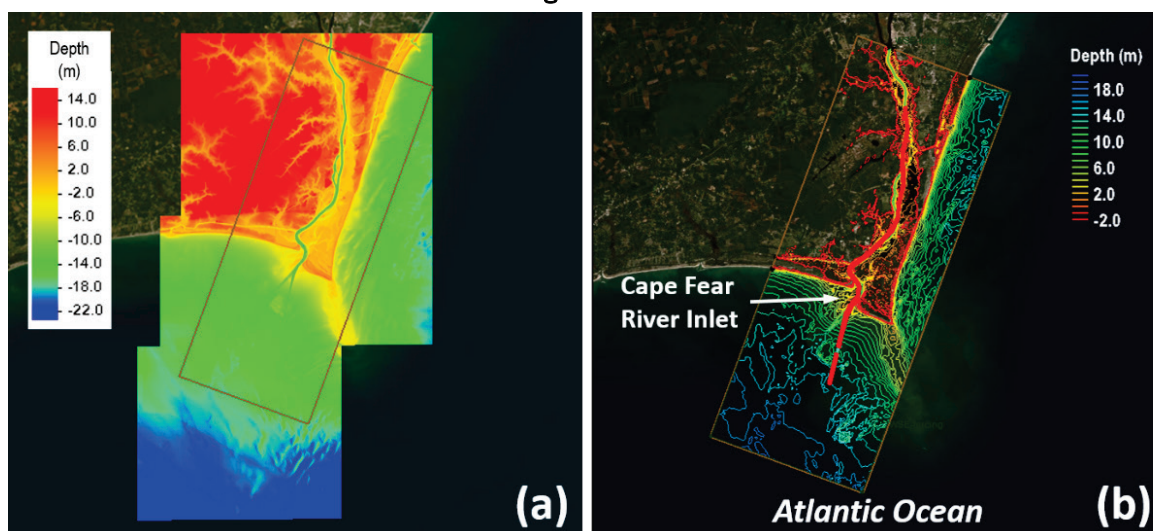
A variety of physical and environmental data for the Cape Fear River Inlet study area are assembled and analyzed in the present study. Historical data available include open ocean, inlet channel and estuarine bathymetry, tidal variations, coastal wind and waves, and sediment composition.

2.1 Bathymetry

The bathymetry and topography data are compiled from a combination of the high-resolution Coastal Digital Elevation Model (DEM) (1/9 arc-second) and the 3 arc-second Coastal Relief Model (CRM) data sets developed at the NOAA National Centers for Environmental Information (NOAA NCEI 2020). Channel conditional surveys and placement area surveys were conducted by the US Army Corps of Engineers, Wilmington District, in 2021 and 2022, which are used to update areas of overlap with the DEM and CRM data sets for the model setup by Surface-water Modeling System (SMS 13.0) (Aquaveo 2020). Shoreline data are used from the latest Google Earth images.

Figure 2-1 shows the spatial coverages and the depth (land elevation) contours of the merged data sets in the study area. The DEM, and CRM data sets have more thorough coverage of land, coastal, and offshore areas with a high spatial resolution. Because of its uniform and dense data distribution, only the extent of the spatial coverage is shown in Figure 2-1. Using the datum information of NOAA tide gauge #8658163 at Wrightsville Beach, North Carolina, (JMPN7) (NOAA 2022), all data sets are converted to local mean sea level (MSL) and incorporated in numerical wave and flow models.

Figure 2-1. (a) NOAA Digital Elevation Model (DEM) / Coastal Relief Model (CRM) bathymetry and (b) conditional survey data coverage with depth and land elevation contours of the merged data set.



2.2 Tide

Water-surface elevation (WSE) data are downloaded from NOAA Wilmington tide gauge #8658120 (WLON7), North Carolina; Wrightsville Beach gauge #8658163 (JMPN7), North Carolina; and Springmaid Pier gauge #8661070 (MROS1), South Carolina (NOAA 2022). Figure 2-2 shows the location of the gauges. A record of WSEs at Wrightsville Beach tide gauge from 11 January to 13 February 2022 is plotted in Figure 2-3, which indicates a mixed, predominantly semidiurnal tidal regime. The mean tidal range (mean high water–mean low water) is 1.21 m (3.98 ft), and the maximum tidal range (mean higher high water–mean lower low water) is 1.37 m (4.49 ft).

Figure 2-2. Locations of (a) NOAA coastal gauges, NOAA National Data Buoy Center (NDBC) and Coastal Data Information Program (CDIP) buoys, and (b) two acoustic wave and current (AWAC) profiler gauges deployed around Cape Fear River Inlet.

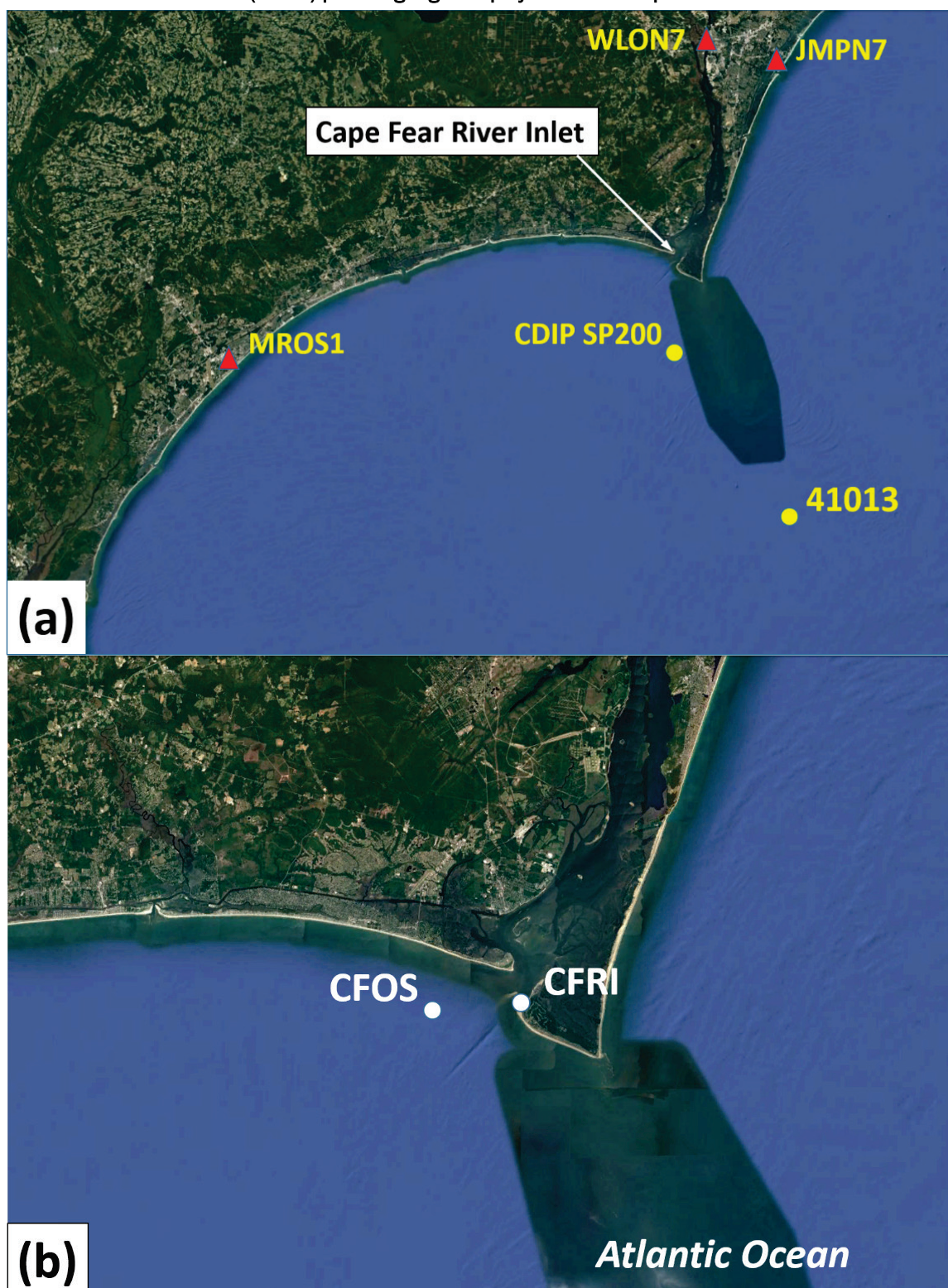
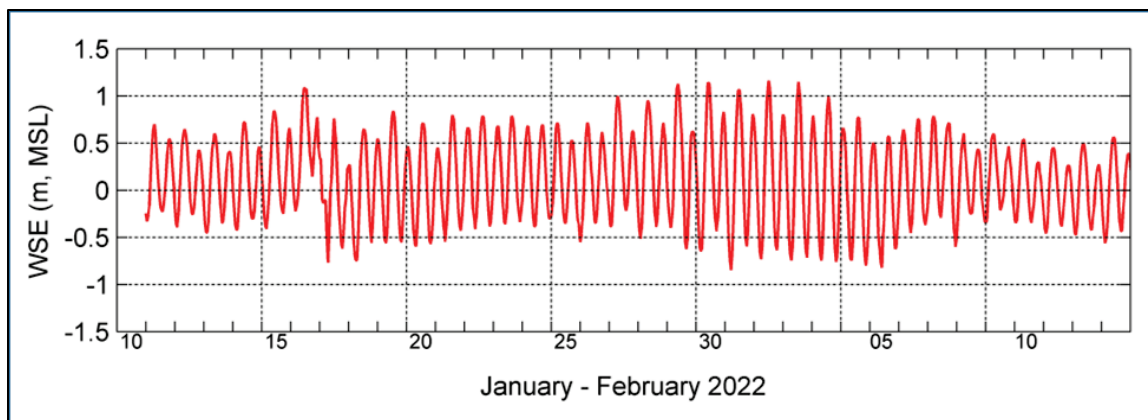


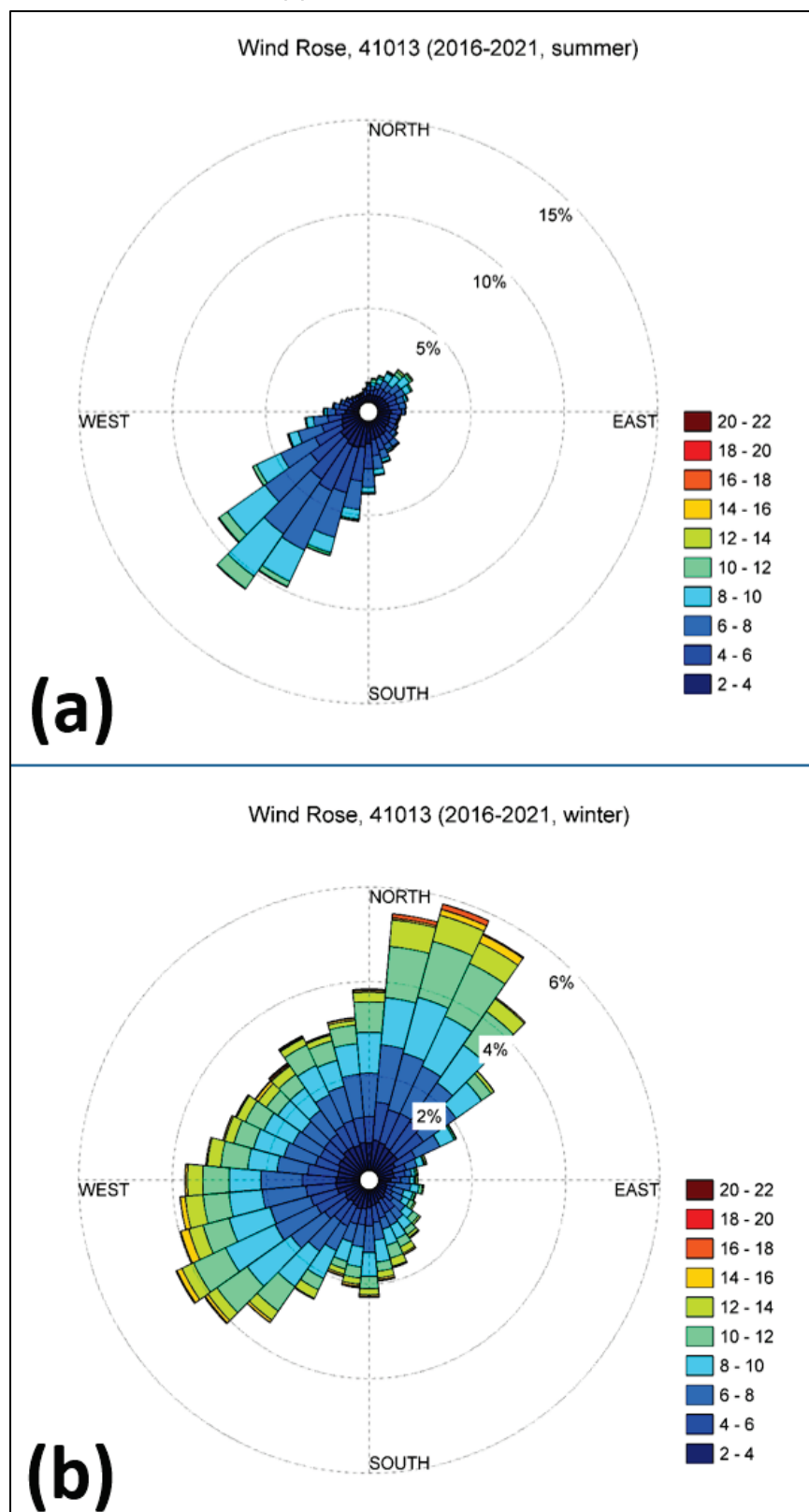
Figure 2-3. Water-surface elevation (WSE) measured at #8658163 from 11 January to 13 February 2022.



2.3 Wind and Waves

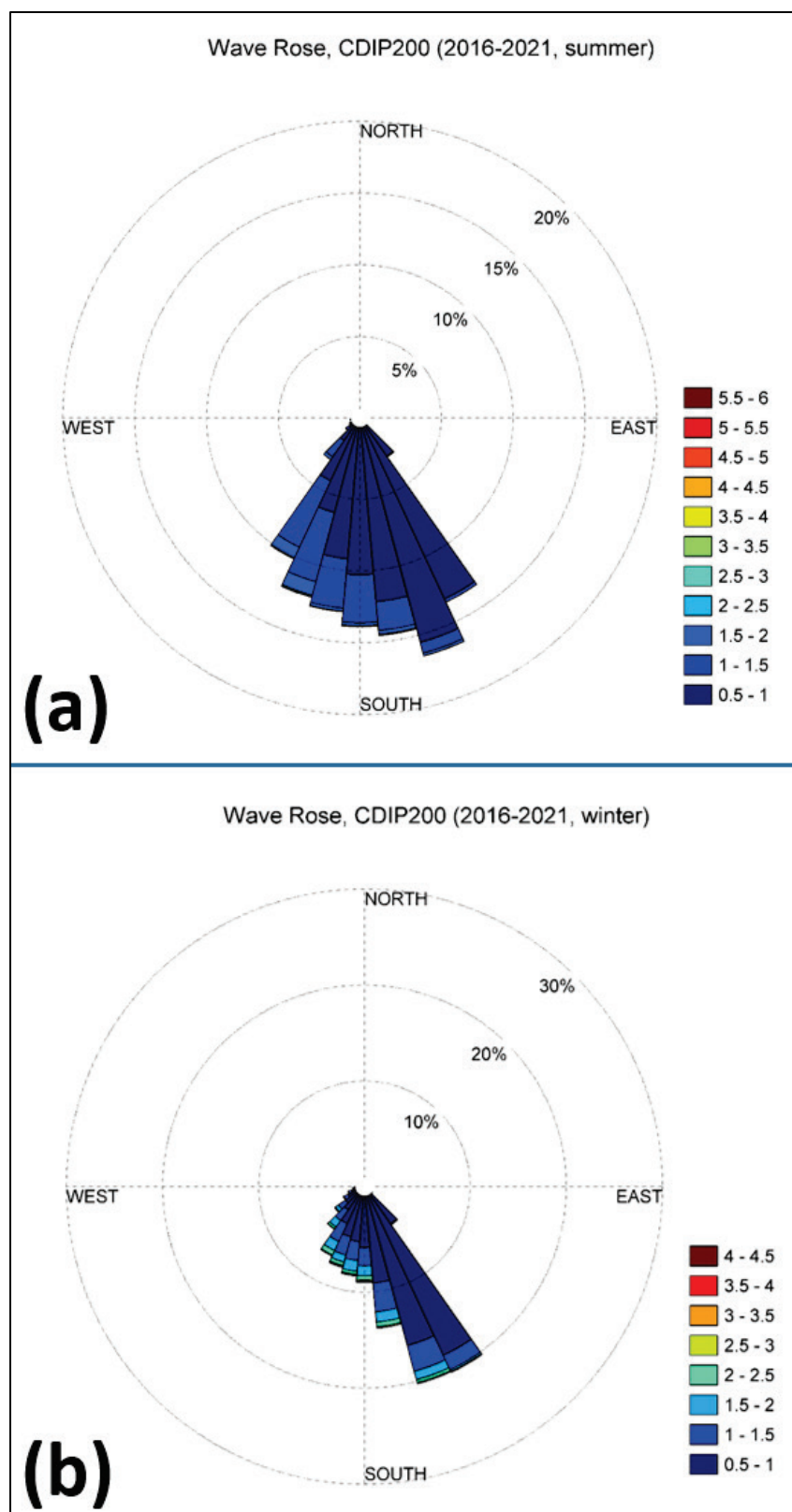
Wind data are obtained from a National Data Buoy Center (NDBC) (NDBC 2022) buoy, 41013, which is located approximately 54 km (33.6 mi) south-southeast of Cape Fear River Inlet (Figure 2-2). Figure 2-4 shows wind roses using the summer (June–August) and winter (December–February) data from 2016 to 2021. The 6 yr data set indicates seasonal changes of wind pattern. A southwesterly wind is dominant during the summer season (more than 50% of the time). A northerly wind (from north-westerly to northeasterly) is dominant during winter season, which occurs more than 40% of the time while southwesterly wind occurs less than 30% of the time. On average, the northerly wind has a stronger speed. From 2016 to 2021, wind vectors with a northerly component that reaches a speed of 10 m/s (22.4 mph) or above occur more than 24% of time. The 6 yr seasonally averaged wind speed is approximately 5.9 m/s (13.2 mph) for summer and 7.6 m/s (17 mph) for winter, respectively.

Figure 2-4. Wind roses at the NDBC buoy 41013 for (a) summer months and (b) winter months from 2016 to 2021.



Spectral wave data are downloaded from one nearshore NOAA buoy and one offshore buoy. The nearshore coastal buoy is Coastal Data Information Program (CDIP) SP 200, Wilmington Harbor, North Carolina, located approximately 18 km (11.2 mi) south-southeast of Cape Fear River Inlet and the offshore buoy is NDBC 41,013 located 54 km (33.6 mi) south-southeast of Cape Fear River Inlet (Figure 2-2). Figure 2-5 shows wave roses at Buoy SP 200 using the summer (June–August) and winter (December–February) data from 2016 to 2021. The measurements indicate that all summer waves propagate from the southwest and southeast sectors, close to the shore-normal direction. The region experiences mild wave conditions during summer months. During winter months, more waves propagate from the south-southeast direction (approximately 60% of the time), and waves propagating from the south-southwest direction occur approximately 30% of the time. Significant wave heights above 2 m (6.56 ft) occur more frequently, and the peak wave height can be above 4 m (13.1 ft) during winter months. High-energy wave conditions usually correspond to the passages of extratropical storms. The 6 yr averaged significant wave height is approximately 0.8 m (2.6 ft) and 0.87 m (2.9 ft) for summer and winter months, respectively.

Figure 2-5. Wave roses at the CDIP buoy SP 200, Wilmington Harbor, for (a) summer months and (b) winter months from 2016 to 2021.



2.4 Sediment

Sediment data are compiled from vibracore samples taken from 2002 to 2019 around the Cape Fear River Inlet. Median grain size, D50, is available at sample locations. Figure 2-6 shows the contour map of the measured median grain sizes at the top layer (Layer 1). Based on those samples, the average D50 is 0.34 mm around the inlet.

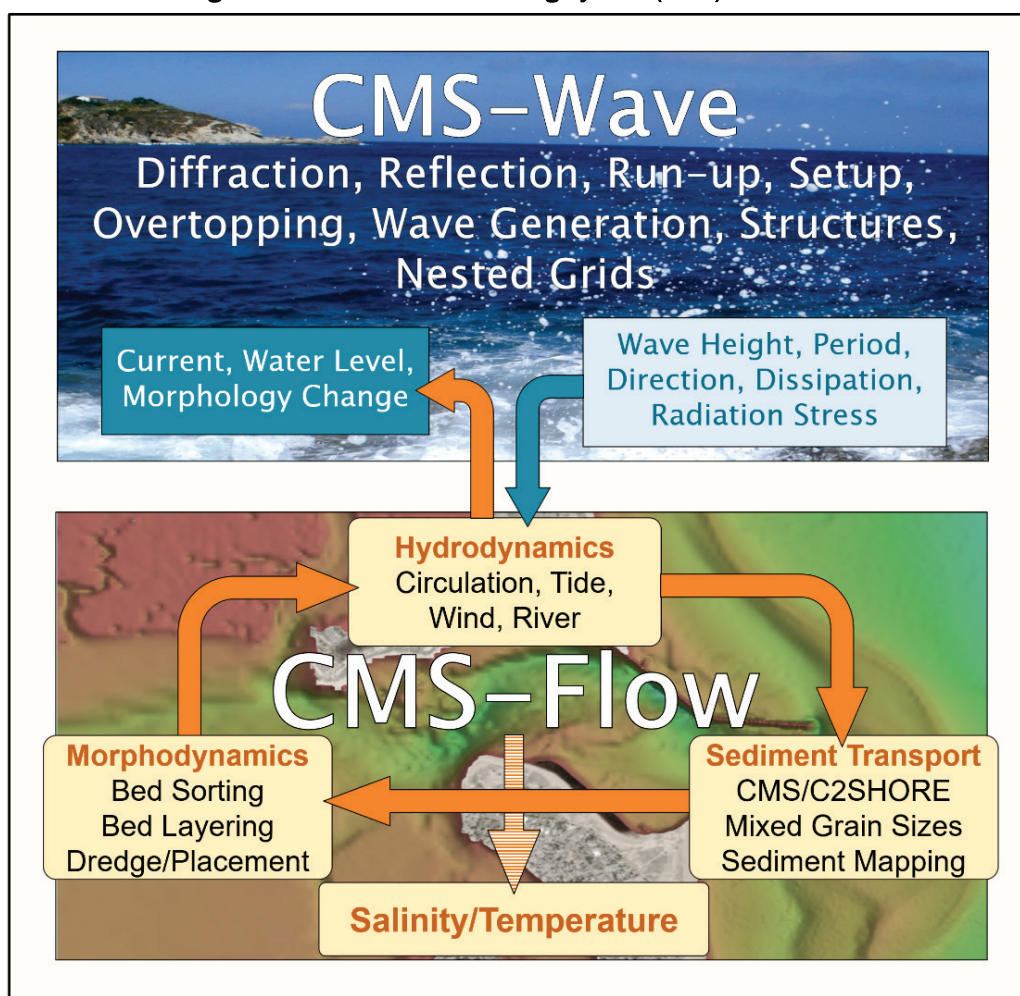
Figure 2-6. Location of sediment grab samples and contours of median grain size, D50 (millimeter).



3 Coastal Modeling System (CMS) Modeling

The Coastal Modeling System (CMS) is an integrated suite of numerical models for waves, flows, sediment transport, and morphology change in coastal and inlet applications. This modeling system includes representation of relevant nearshore processes for practical applications of navigation channel performance and sediment management at coastal inlets and adjacent beaches. The CMS consists of a hydrodynamic and sediment transport model (CMS-Flow) and a spectral wave transformation model (CMS-Wave) (Sanchez et al., “Report 3,” 2011; Sanchez et al., “Report 4,” 2011; Lin et al. 2008). All pre- and postprocessing for these models is performed within the ERDC SMS interface (Aquaveo 2020). The framework of CMS is shown in Figure 3-1.

Figure 3-1. The Coastal Modeling System (CMS) framework.



CMS-Flow is a 2D depth-integrated, finite-volume model that solves the mass conservation and shallow-water momentum equations of water motion on a nonuniform Cartesian grid. CMS-Flow calculates hydrodynamics, sediment transport, and morphology change due to tide, wind, and waves. Wave radiation stresses and other wave parameters are calculated by CMS-Wave and supplied to CMS-Flow for hydrodynamic and sediment transport calculations.

CMS-Wave is a spectral wave transformation model. It solves the steady-state wave-action balance equation on a nonuniform Cartesian grid and is designed to simulate wave processes with ambient currents at coastal inlets and in navigation channels. The model can be used either in half-plane or full-plane mode and includes coastal wave processes, such as wind wave generation and growth, refraction, diffraction, reflection, dissipation due to bottom friction, white-capping and breaking, wave-current interaction, wave runup, wave setup, and wave transmission through structures.

CMS-Flow and CMS-Wave have a dynamic coupling at a certain time interval specified by users. For the Cape Fear River Inlet application, CMS-Wave is run at a 2 hr interval between CMS-Flow simulations.

3.1 Sediment Plume Modeling

To assess sediment migration from dredged material placement sites, the study needs to trace sediment and demonstrate sediment plume spreading originated from those sites. This process can be specified and computed using the CMS feature of sediment tracer simulations (Li et al. 2019).

The sediment transport model in CMS-Flow combines bed load and suspended load as total load. The nonuniform sediment mixture is divided into a suitable number of size classes. In the case of low sediment concentration, the influence among the size classes of moving sediment is assumed negligible.

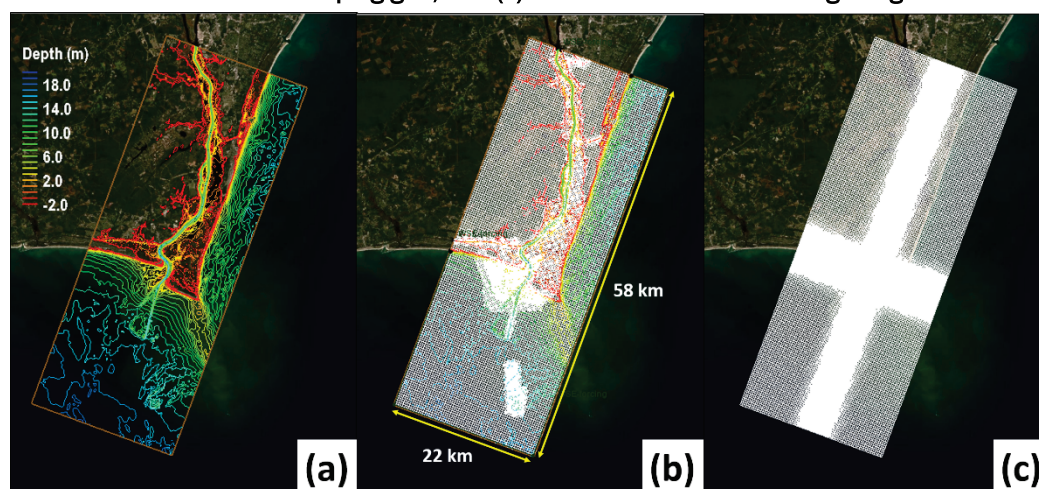
The CMS includes the calculation of multiple-sized sediment transport, bed mixing and multiple bed layering, and bed material gradation (Sanchez et al. 2014). Considering the heterogeneity of bed material size composition, the sediment bed can be divided into multiple layers, and the fraction of each size class can be calculated and stored in each layer. The

sediment in the active or mixing layer, that is, the top layer of the bed, directly exchanges or contacts with the sediment moving in the water column and is buried or assigned to deeper layers as a part of the deposition process. The sediment tracer with a certain grain size can be specified as one class of multiple-size sediment. By tagging the sediment tracer and accounting the history of bed composition within each layer, a multiple-size sediment transport simulation can represent the movement of the sediment tracer with varying grain sizes, perform the tracking of traced volumes (masses) of sediments, and map sediment plume distribution across a model domain (Li et al. 2019).

3.2 Model Domain and Model Setup

A telescoping variable-resolution CMS-Flow grid is developed for the Cape Fear River Inlet and adjacent beaches. The modeling domain is approximately 58 km (36 mi) in cross-shore direction and 22 km (13.7 mi) in longshore direction. The CMS domain consists of 65,000 ocean cells, which covers offshore placement areas and Cape Fear River Inlet and extends along Cape Fear River to Wilmington Harbor (Figure 3-2).

Figure 3-2. The CMS domain: (a) Bathymetry at the inlet entrance channel and the river, (b) CMS-Flow telescoping grid, and (c) CMS-Wave variable rectangular grid.



The water depth ranges from 1 to 2 m (3.28 to 6.56 ft) above MSL at tidal marsh and river areas to 16–17 m (52.5–55.8 ft) below mean sea level at the Cape Fear River Inlet Navigation Channel and the seaward boundary of the CMS domain. The telescoping grid system permits much finer local grid resolution to resolve hydrodynamic and sediment features in areas of high interest. For this study, the cell sizes vary from 20 m (65.6 ft) in front

of nearshore beaches and the navigation channel around the inlet to 320 m (1,050 ft) in offshore open ocean area. The grid cells around ODMDS are also refined for sediment tracing simulation.

The CMS-Wave grid with varying cell sizes is generated for wave modeling, covering the same domain and refined spatial resolutions consistent with refined areas in the CMS-Flow grid (Figure 3-2). Because of the differences in alignment of telescoping grids to variable rectangular grids, CMS-Flow and CMS-Wave grid cells are not aligned but are coupled within the model setup.

3.3 Simulation Periods

The field data are collected from 11 January to 11 April 2022. Corresponding to the survey period, simulations for the CMS calibration and validation are set up to cover the entire data collection period. For the investigation of sediment plume distribution, a representative summer and a winter month are selected, and monthly sediment tracer simulations are set up for transport of dredged material placed at designated disposal sites.

The selection of representative months is based on analysis of wind conditions downloaded from NDBC buoy 41013 (Figure 2-2). Figure 3-3 and Figure 3-4 show the wind roses of three summer (June, July, August) and three winter months (December, January, February) for each year from 2016 to 2021, respectively.

Figure 3-3. Wind roses of summer months at NDBC buoy 41013 from 2016 to 2021.

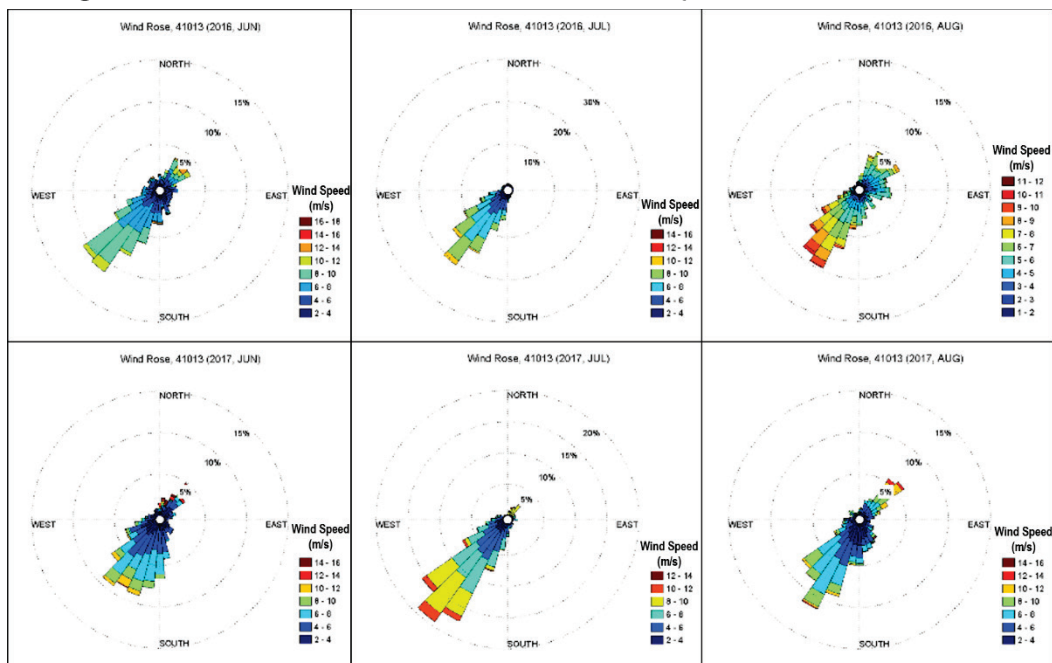


Figure 3-3 (cont.). Wind roses of summer months at NDBC buoy 41013 from 2016 to 2021.

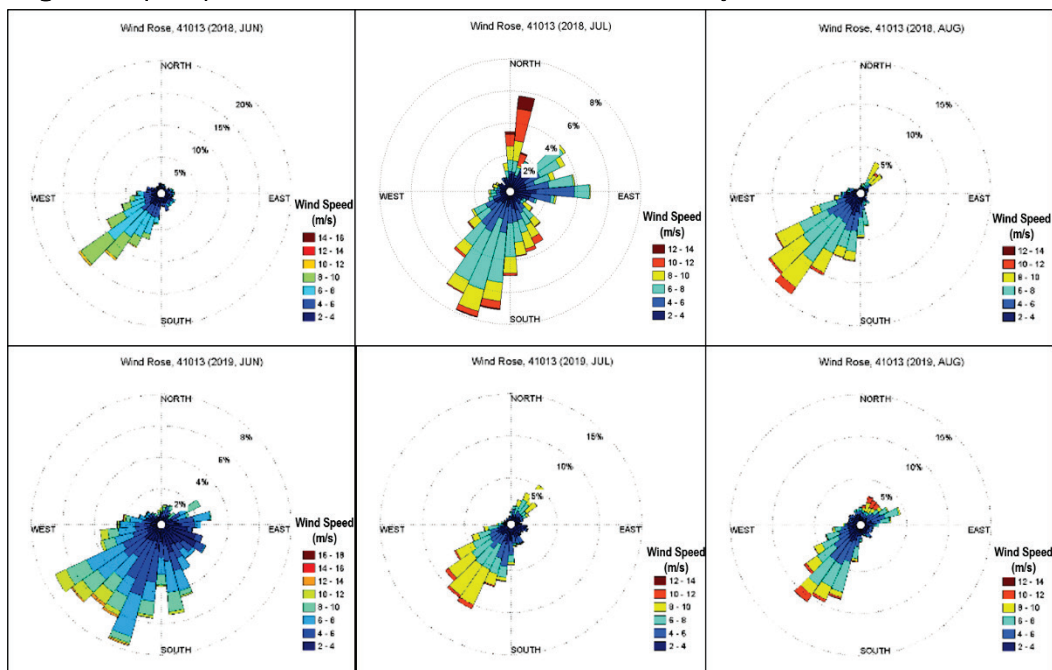


Figure 3-3 (cont.). Wind roses of summer months at NDBC buoy 41013 from 2016 to 2021.

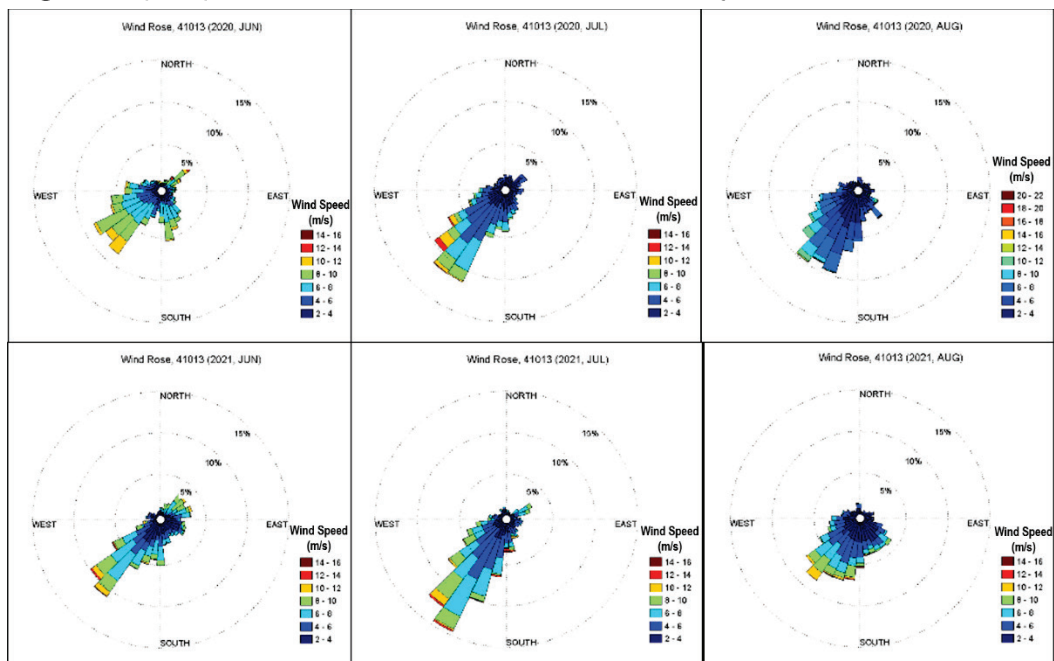


Figure 3-4. Wind roses of winter months at NDBC buoy 41013 from 2016 to 2021.

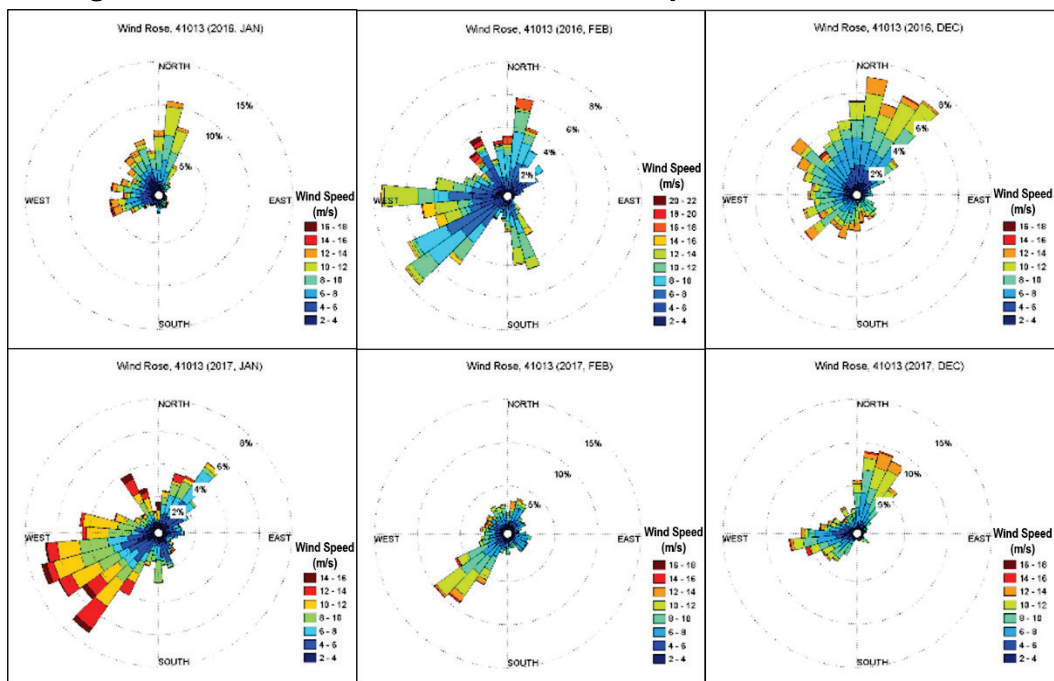


Figure 3-4 (cont.). Wind roses of winter months at NDBC buoy 41013 from 2016 to 2021.

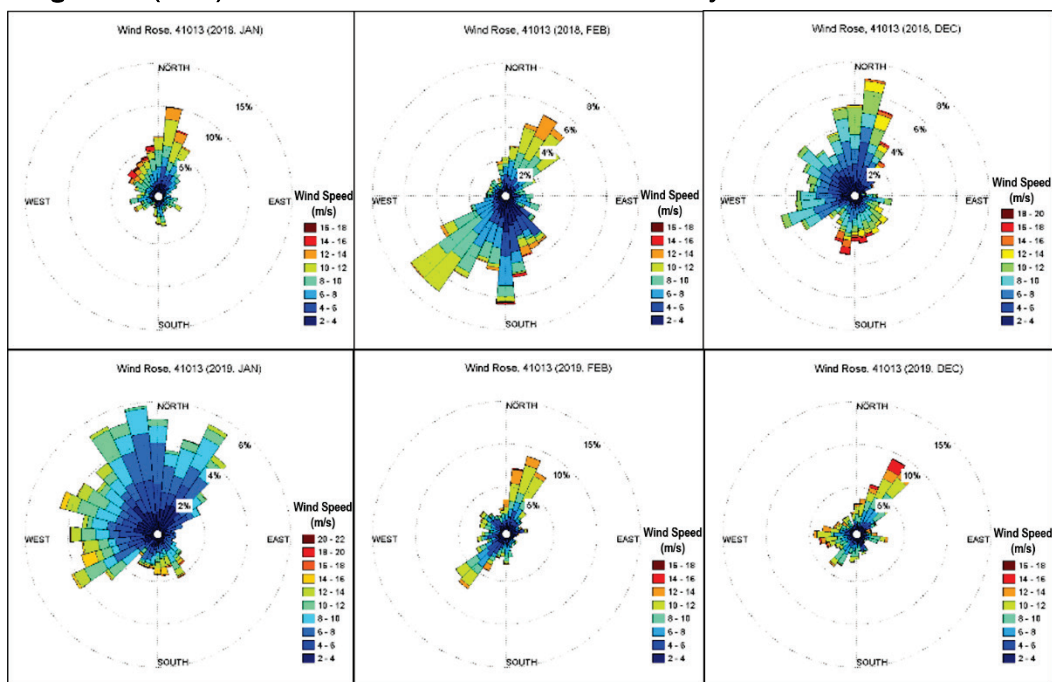
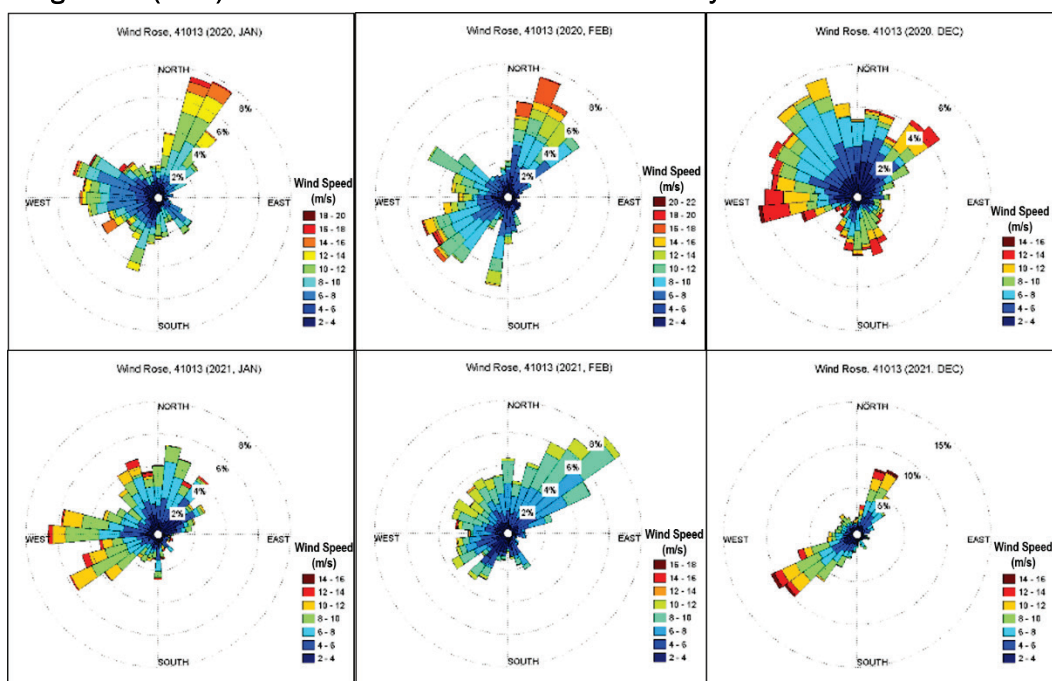


Figure 3-4 (cont.). Wind roses of winter months at NDBC buoy 41013 from 2016 to 2021.



Monthly wind roses in Figure 3-3 and Figure 3-4 are compared with seasonal wind roses as shown in Figure 2-4. Similar to the 2016–2021 summer wind rose, the June 2016 wind rose displays the dominant southwesterly wind directions in the area. Both roses show that the southwesterly wind directions occur more than 50% of the time. The

monthly averaged wind speed of June 2016 is 6.4 m/s (14.3 mph), which is close to the 6 yr averaged wind speed for summer months.

For the winter case, Figure 3-4 shows that the December 2017 wind rose is the closest one to the 2016–2021 wind rose for winter months (Figure 2-4). Both roses demonstrate that northerly wind (from northwesterly to northeasterly) is dominant, and southwesterly wind occurs less than 30% of the time. However, the December 2017 rose shows that the northerly wind occurs more than 50% of the time. Wind vectors with a northerly component and reaching a speed of 10 m/s (22.4 mph) and above occur approximately 35% of the time. The monthly averaged wind speed is approximately 8.1 m/s (18.1 mph) for December 2017. Generally, the wind speed and direction of December 2017 is similar to the 6 yr averaged wind for winter months.

Figure 3-5 and Figure 3-6 show the wave roses of three summer (June, July, August) and three winter months (December, January, February) at CDIP buoy SP 200 for each year from 2016 to 2021, respectively.

Figure 3-5. Wave roses of summer months at CDIP buoy SP200 from 2016 to 2021.

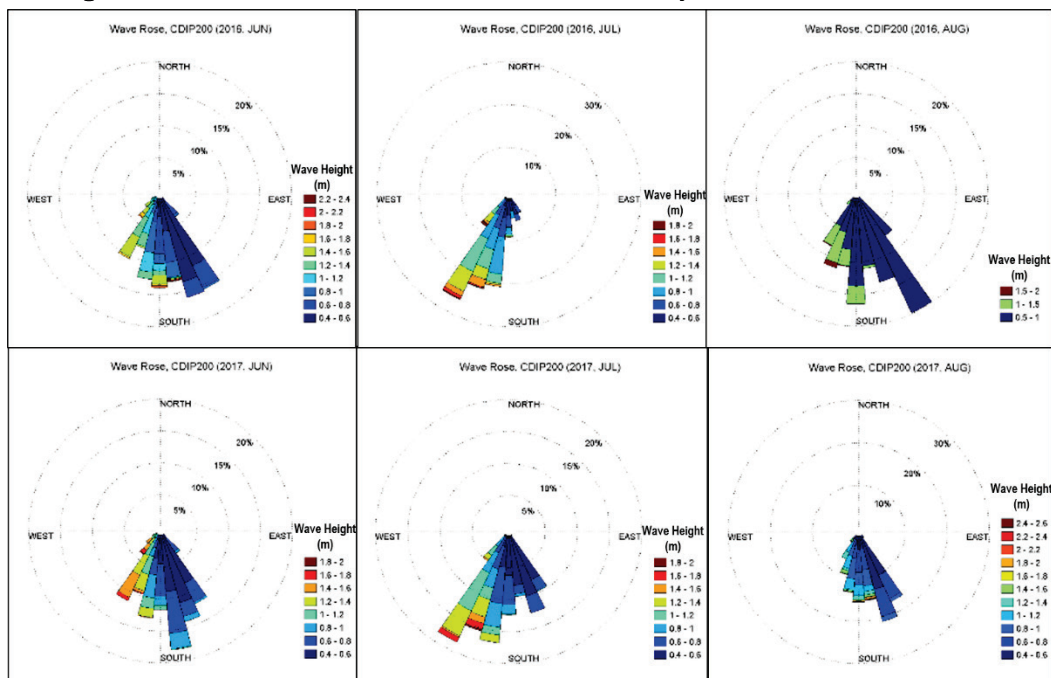


Figure 3-5 (cont.). Wave roses of summer months at CDIP buoy SP200 from 2016 to 2021.

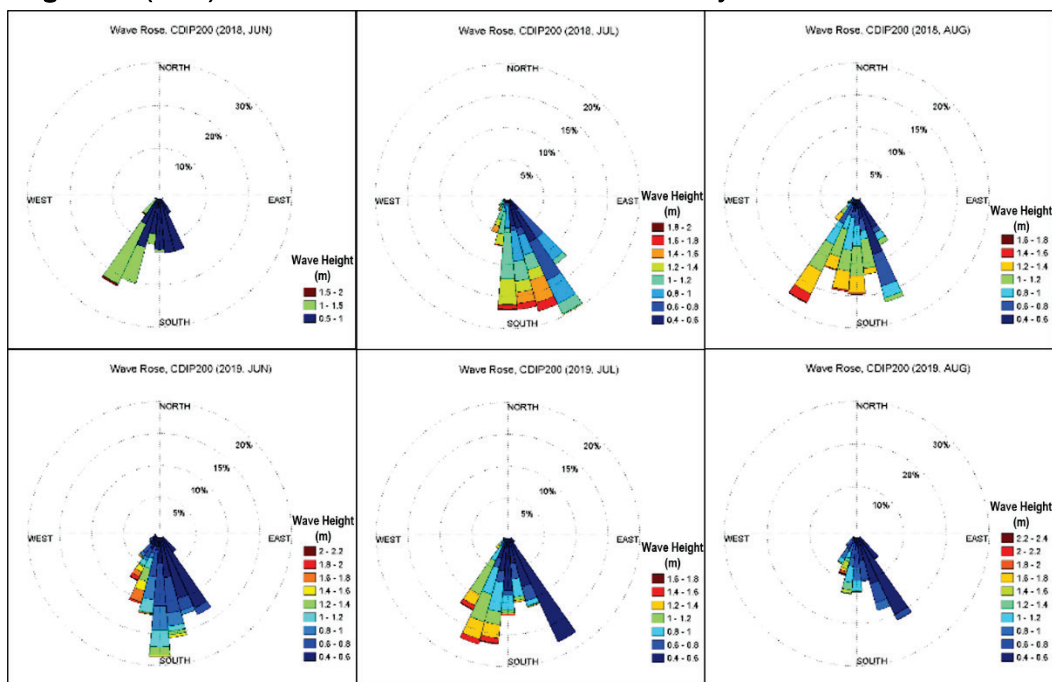


Figure 3-5 (cont.). Wave roses of summer months at CDIP buoy SP200 from 2016 to 2021.

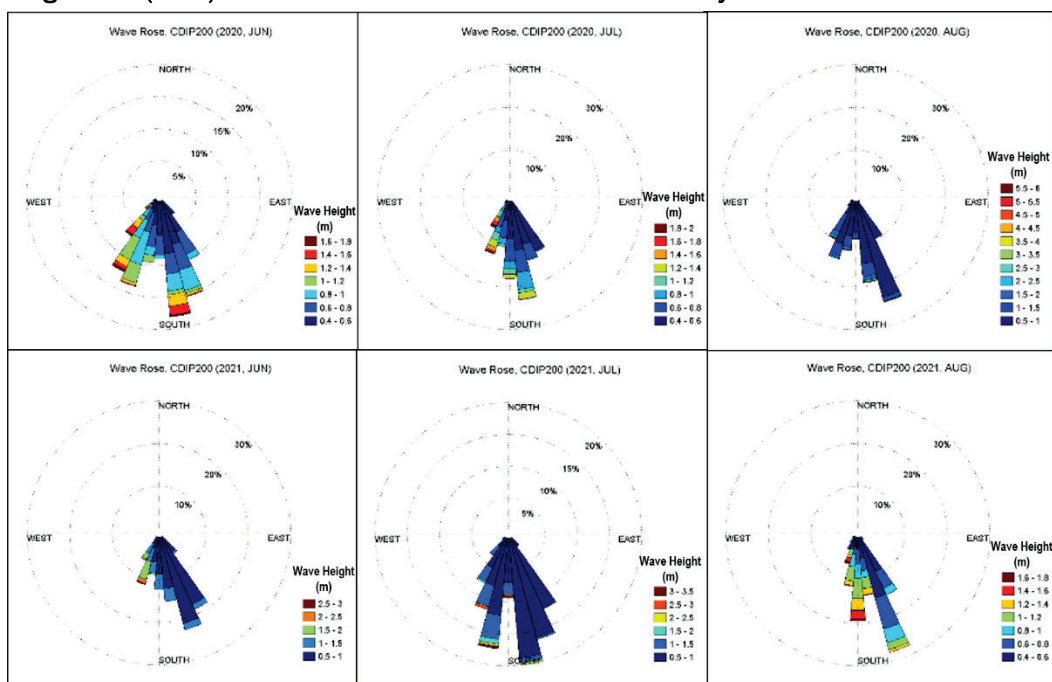


Figure 3-6. Wave roses of winter months at CDIP buoy SP200 from 2016 to 2021.

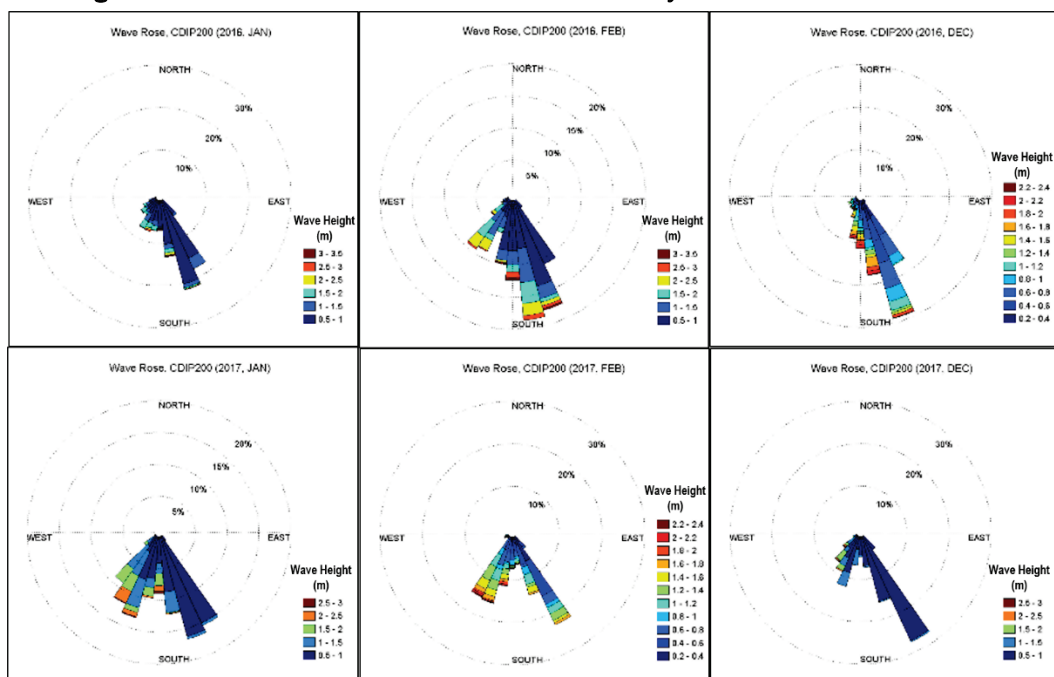


Figure 3-6 (cont.). Wave roses of winter months at CDIP buoy SP200 from 2016 to 2021.

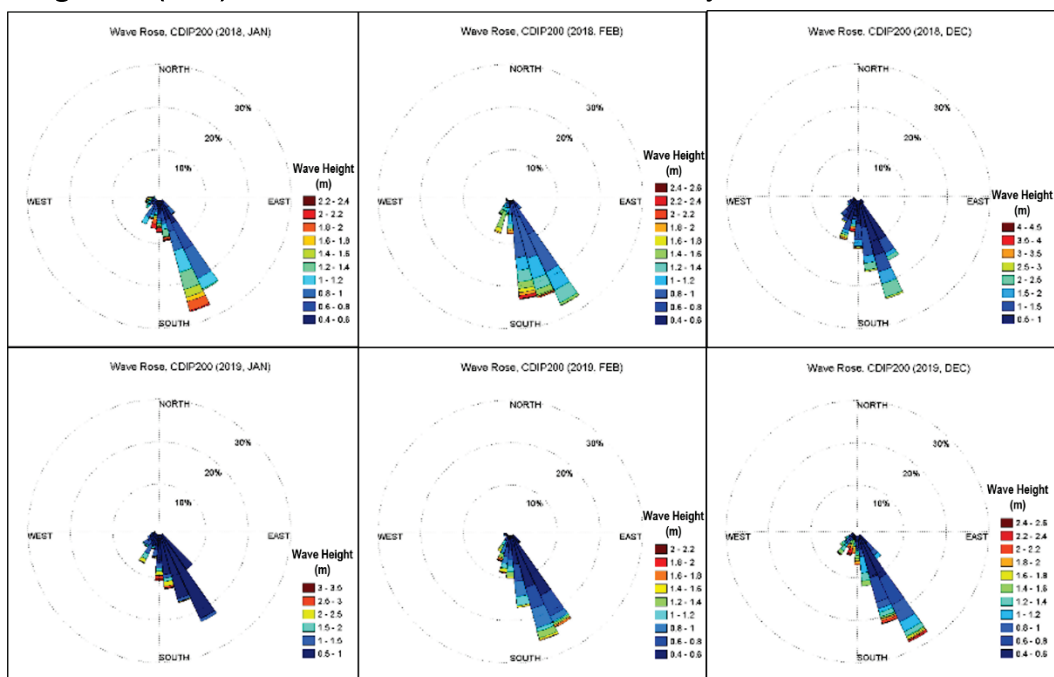
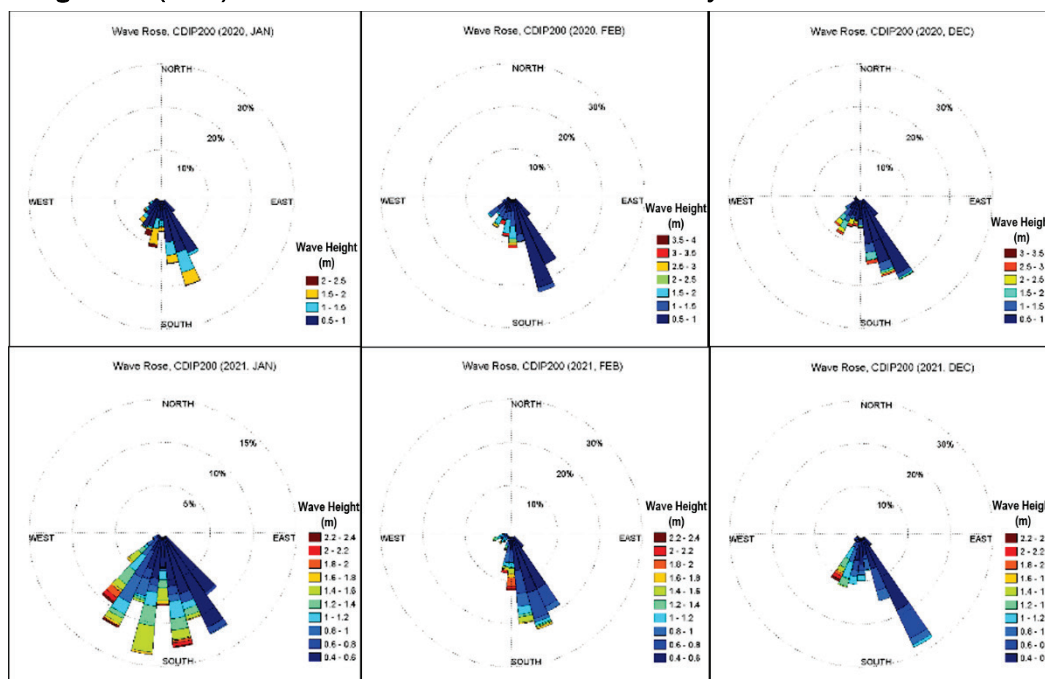


Figure 3-6 (cont.). Wave roses of winter months at CDIP buoy SP200 from 2016 to 2021.



Seasonal and monthly wave roses in Figure 2-5, Figure 3-5, and Figure 3-6 show that all waves measured at CDIP SP 200 propagate from the southwest and southeast sectors. For June 2016 and December 2017, the monthly averaged significant wave heights are 0.82 m (2.7 ft) and 0.72 m (2.4 ft), respectively. The average wave height in June 2016 is slightly higher than the 6 yr averaged wave height for summer months and in December 2017 is lower than that for winter months.

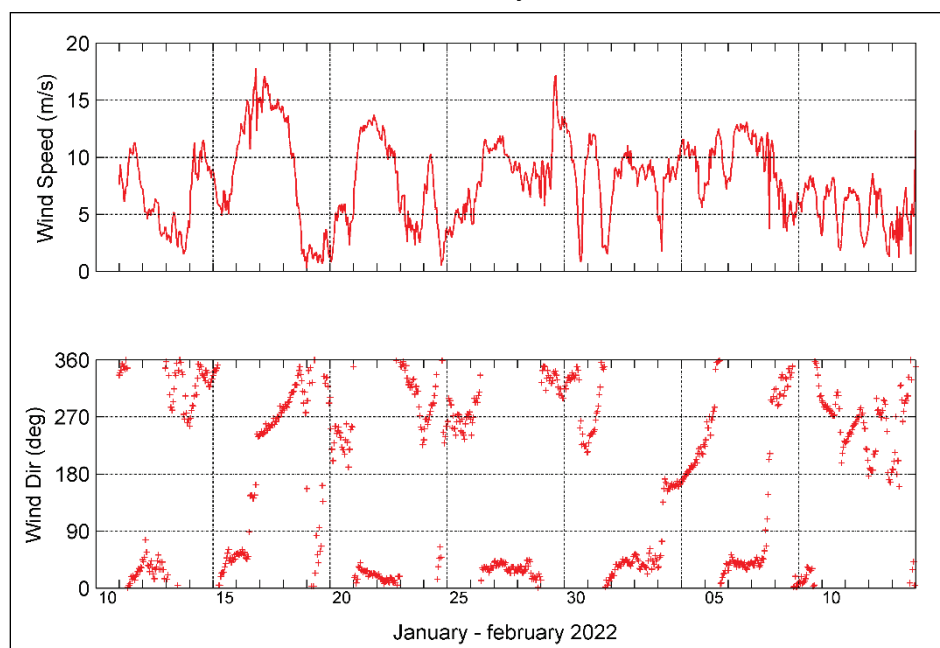
The June 2016 and December 2017 wind and wave data present similar rose patterns and statistical properties as the 2016–2021 data. Therefore, the 2 months are selected as the representative summer and winter month, respectively, to configure production simulations. Thus, three simulation periods are set up for the modeling study: (1) the calibration and validation (January–March 2022), (2) the summer month (June 2016), and (3) the winter month (December 2017).

3.4 Model Forcing

The physical forcing to drive the CMS includes WSE along the open boundaries and wind stress at the surface boundary of CMS-Flow, and wave spectrum at the seaward boundary of CMS-Wave.

NOAA tide gauge (#8661070) at Springmaid Pier, South Carolina, (MROS1) and tide gauge (#8658163) at Wrightsville Beach, North Carolina, (JMPN7) provide the complete water level records for calibration and validation period and for summer and winter month production simulations, respectively. Wind data are downloaded from the NDBC buoy 41,013. Wind speeds and directions for 11 January to 13 February 2022 are shown in Figure 3-7. The time series illustrate wind variations in the study area. During this winter period strong, north-northwesterly wind is dominant. The averaged wind speed is 7.8 m/s (17.5 mph), and the peak wind speed is close to 17.8 m/s (39.8 mph).

Figure 3-7. Wind speeds and directions at NDBC buoy 41013 from 11 January to 13 February 2022.

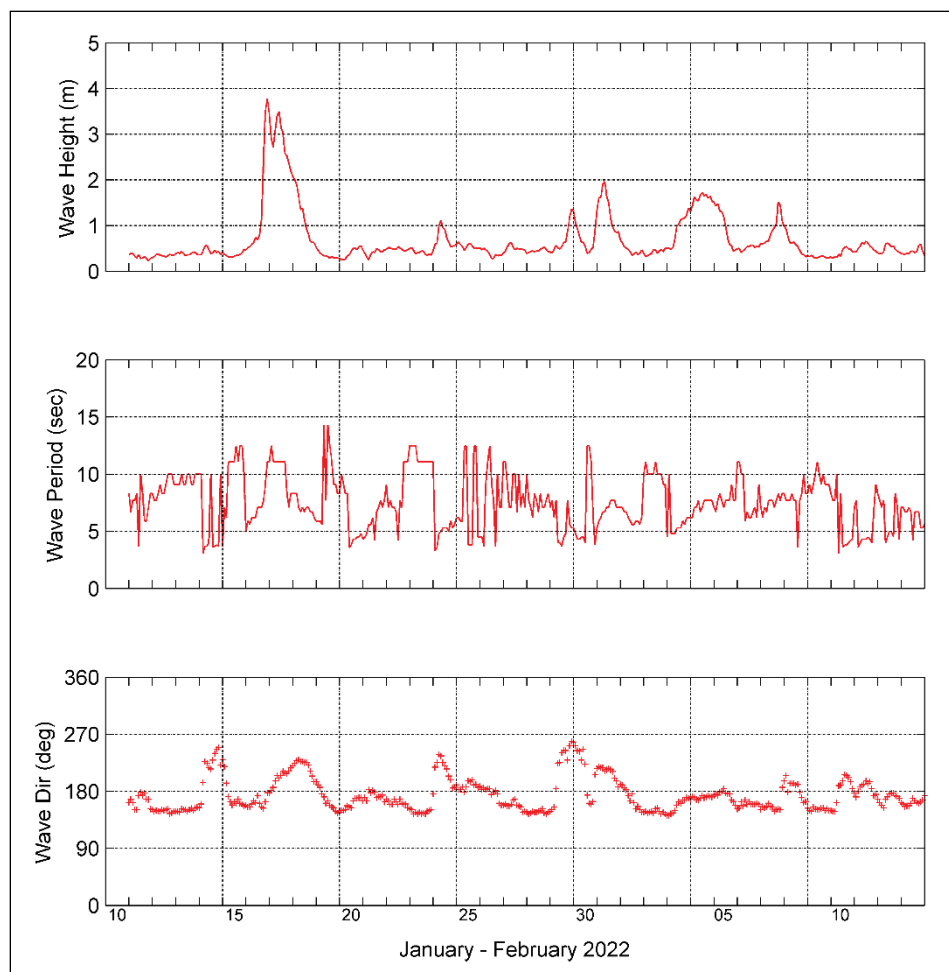


Directional wave spectral data contain total wave energy and are often used to drive a wave model. For model calibration and validation and production simulations during summer and winter months, model incident waves are based on data from CDIP buoy SP 200. The directional wave spectra measured at the coastal buoy are transformed to the seaward open boundary of CMS-Wave.

Time series of wave parameters (significant wave height, peak wave period, and mean wave direction) at CDIP SP 200 are shown in Figure 3-8 from 11 January to 13 February 2022. The dominant wave direction is

from south, southwest, or southeast with an averaged peak wave period of 7.5 s. The mean significant wave height at the buoy site is 0.7 m (2.3 ft).

Figure 3-8. Wave parameters at CDIP buoy SP 200 from 11 January to 13 February 2022.



3.5 Model Alternatives

Sediment materials from regular channel maintenance dredging are placed in designated areas. To investigate spreading of the sediment plume originating from the placement sites, the model alternatives are developed by specifying three sites as selected sediment sources, within which sediment materials in the top bed layer are tagged and tracked as sediment tracers.

Figure 3-9a shows the sketch of three designated offshore placement sites, ODMDS 1, 2, and 3. Table 3-1 lists the physical scales of the placement areas for corresponding model alternatives.

Figure 3-9. Sketch of (a) three designated offshore placement sites and (b) three polygon (sediment trap) areas around the offshore placement sites.

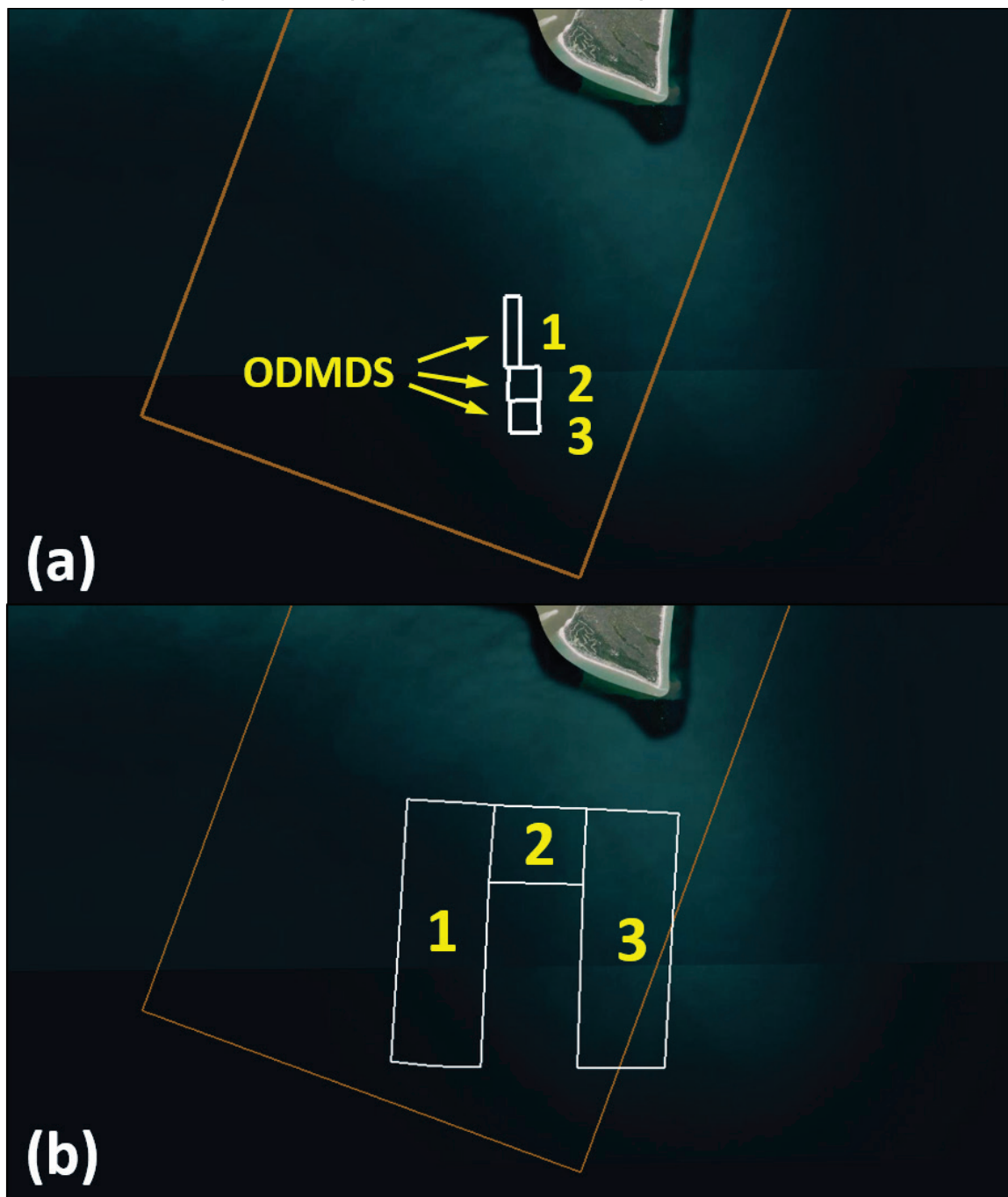


Table 3-1. Model alternatives: physical scales of three placement areas.

Alternative	Placement Site	Area (km ²)	Average Depth (m)	Mass Tracked (10 ³ kg)
1	Northern Area	2.44	14.8	194,360
2	Central Area	2.31	13.1	183,170
3	Southern Area	2.06	13.1	164,340

Based on the information of the latest dredge and placement operations around Cape Fear River Inlet (eHydro 2022), three offshore placement sites are selected for the release and track of sediment materials as alternatives 1, 2, and 3, which cover an area between 2 and 2.5 km² and have an area-averaged water depth between 13 and 15 m (42.7–49.2 ft).

To trace sediment transport and conduct sediment plume analysis around the Cape Fear River estuarine system, three polygons are drawn in Figure 3-9b, which act as sediment traps for counting sediment mass moving into the areas. The polygon areas are specified to catch traced sediment materials originated from the three placement sites and are located west (trap 1), north (trap 2), and east (trap 3) side surrounding those sites.

4 Simulation Results and Analysis

4.1 Model Calibration and Validation

The CMS models are calibrated and validated using water level, current, and wave data collected at Cape Fear River estuarine offshore site (CFOS) and inlet site (CFRI) during January and February 2022. Model incident waves are based on directional wave spectral data from CDIP SP200. The model surface wind input is based on data from NDBC Buoy 41013. The model water level forcing is based on NOAA tide gauge MROS1 at Springmaid Pier, South Carolina, (Figure 2-2).

Figures 4-1 and 4-2 compare the computed wave heights, periods, and directions with the data collected at CFOS and CFRI gauge locations, respectively, for 19 January to 17 February 2022. Table 4-1 Presents the bias, root-mean-square error (RMSE), and correlation coefficients of the calculated wave heights. The statistics of accuracy for model wave period and direction are not calculated as there is too much noise observed in wave period and direction measurements.

Figure 4-1. Model waves and data comparison at Cape Fear River estuarine offshore site (CFOS) gauge location.

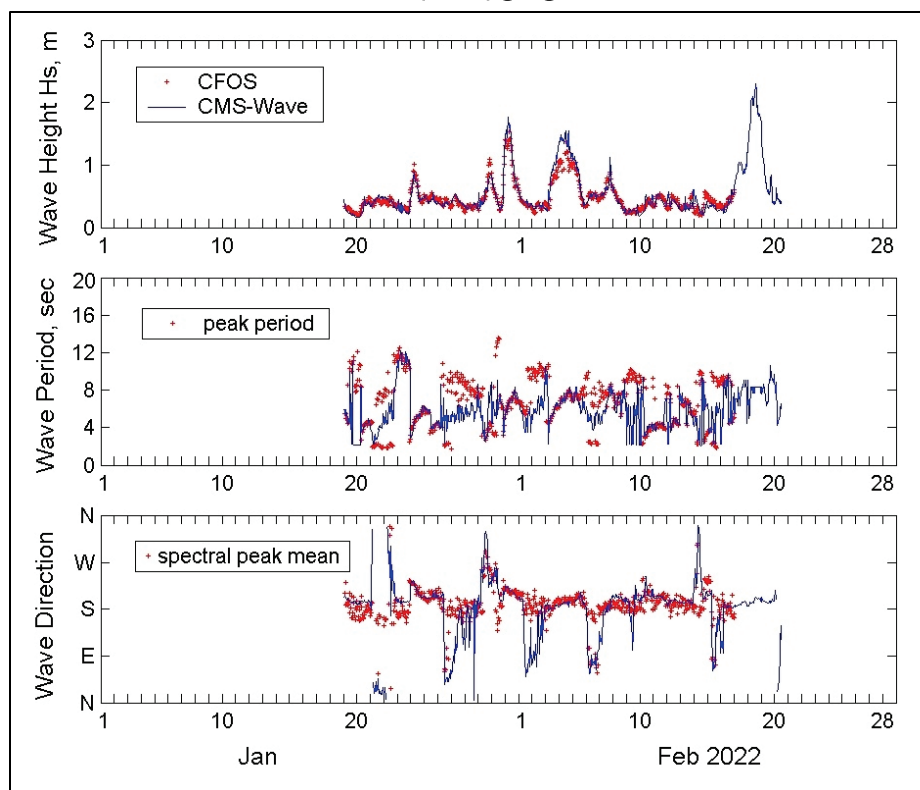


Figure 4-2. Model waves and data comparison at Cape Fear River inlet site (CFRI) gauge location.

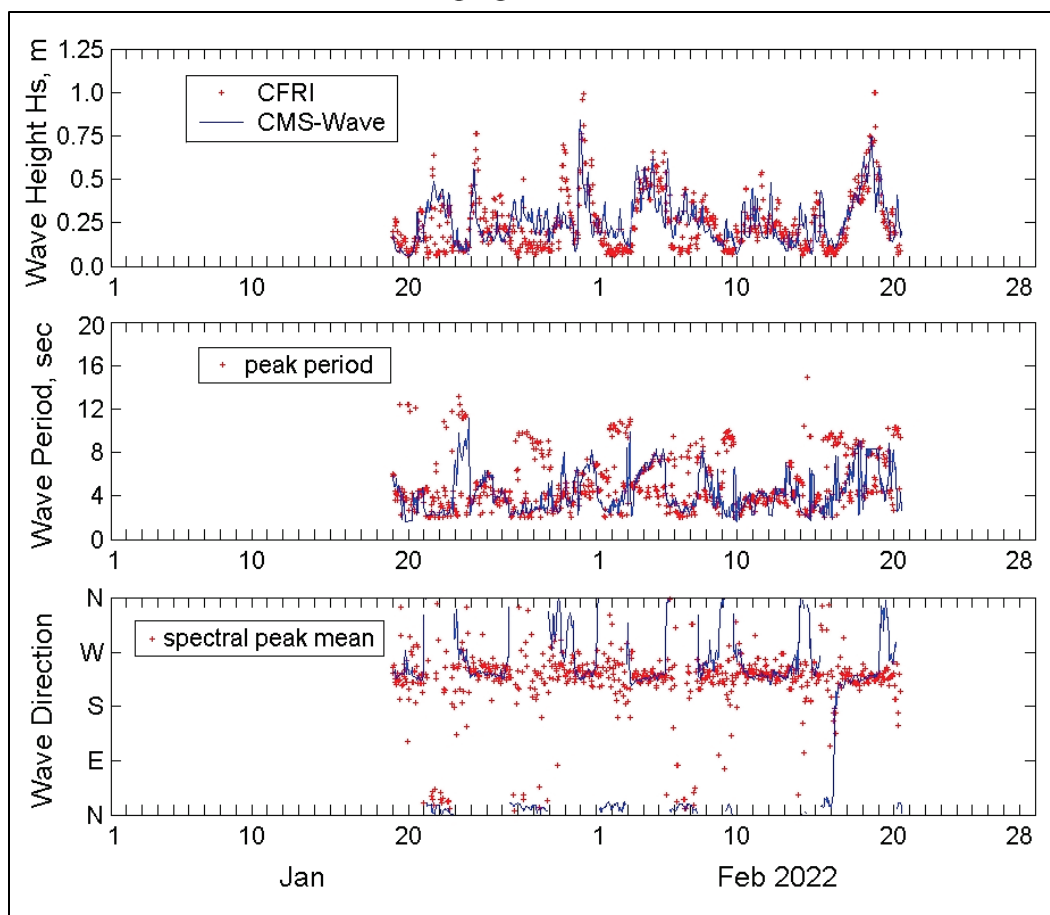


Table 4-1. Statistics of model wave heights at CFOS and CFRI for January–February 2022.

AWAC	Bias (m)	RMSE (m)	Correlation Coefficient
CFOS	0.05	0.17	0.9
CFRI	-0.06	0.17	0.47

Figure 4-3 compares the calculated water levels versus data at CFOS and CFRI locations for January–February 2022. Table 4-2 presents the bias, RMSE, and Correlation Coefficients of the calculated water levels.

Figure 4-3. Model water levels and data comparison at CFOS and CFRI locations for January–February 2022.

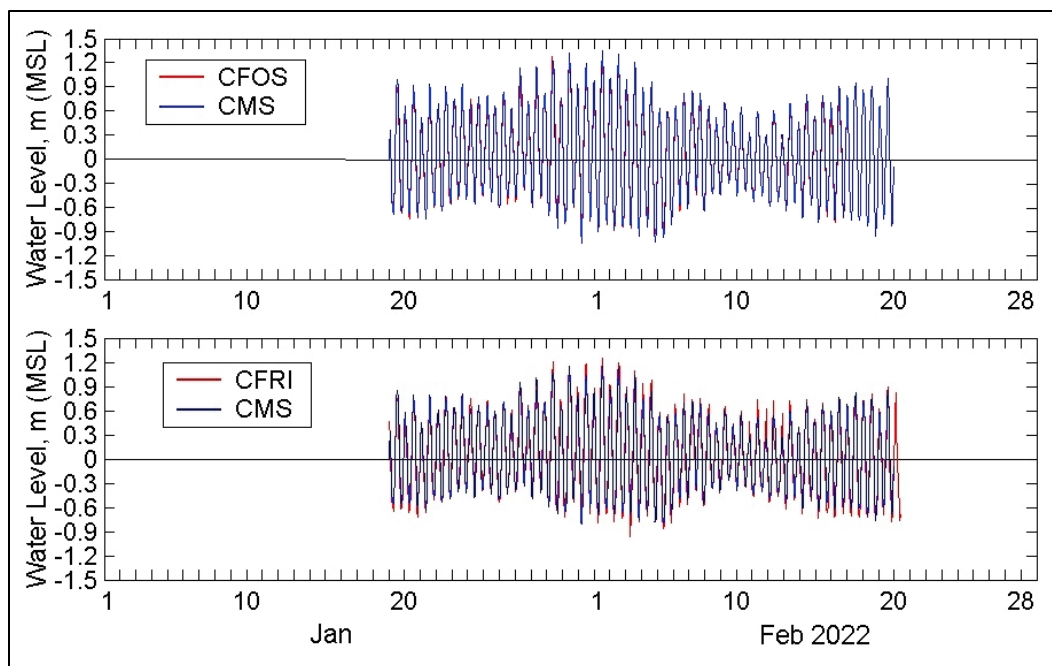


Table 4-2. Statistics of model water levels at CFOS and CFRI for January–February 2022.

AWAC	Bias (m)	RMSE (m)	Correlation Coefficient
CFOS	0.015	0.048	0.99
CFRI	0.003	0.097	0.98

Figures 4-4 and 4-5 compare model current magnitudes and directions versus data at CFOS and CFRI locations for January–February 2022. Table 4-3 presents the bias, RMSE, and correlation coefficients of model current speeds. The statistics of accuracy for model current directions is not calculated as there is too much noise observed in current direction measurements.

Figure 4-4. Model current magnitudes and directions versus data at CFOS for January–February 2022.

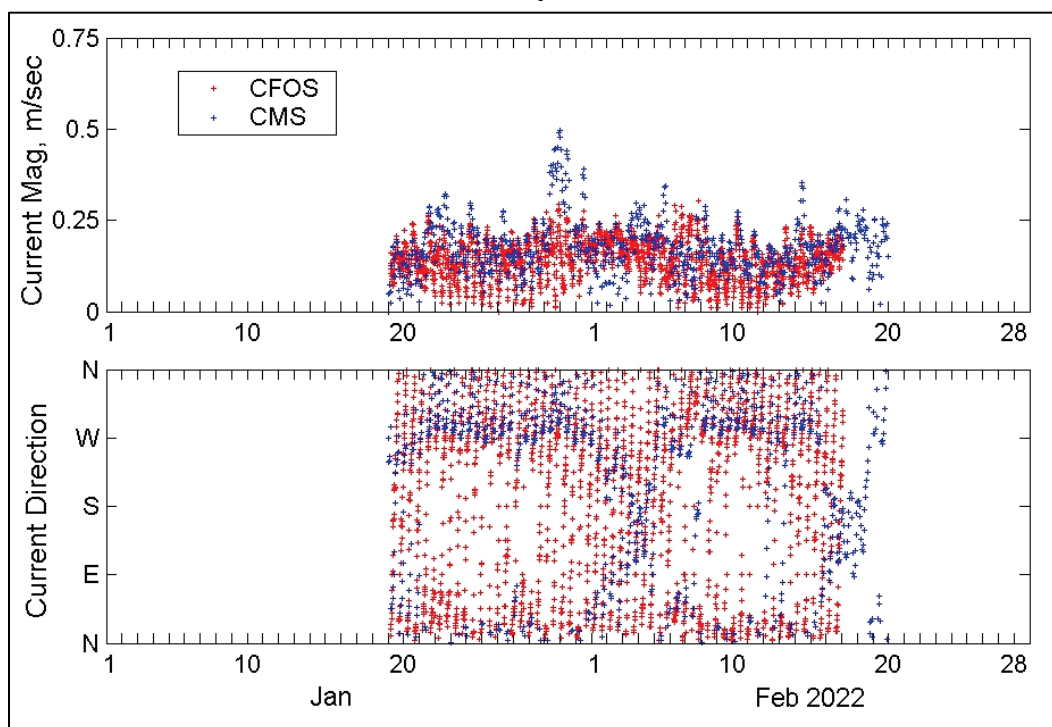


Figure 4-5. Model current magnitudes and directions versus data at CFRI for January–February 2022.

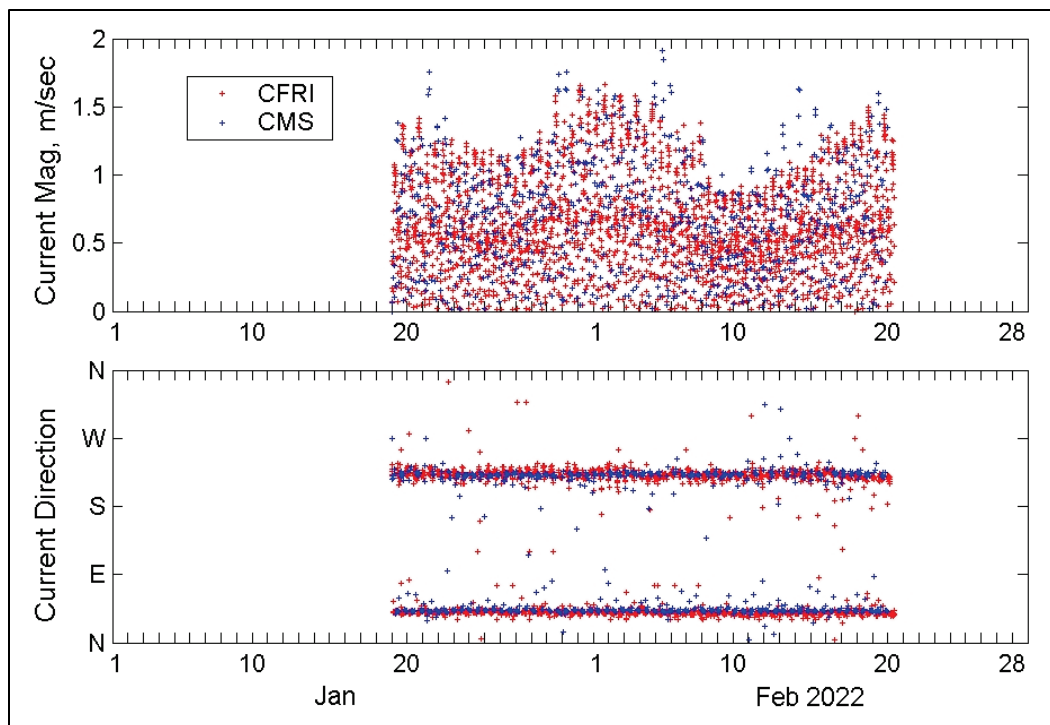


Table 4-3. Statistics of model current speeds at CFOS and CFRI for January–February 2022.

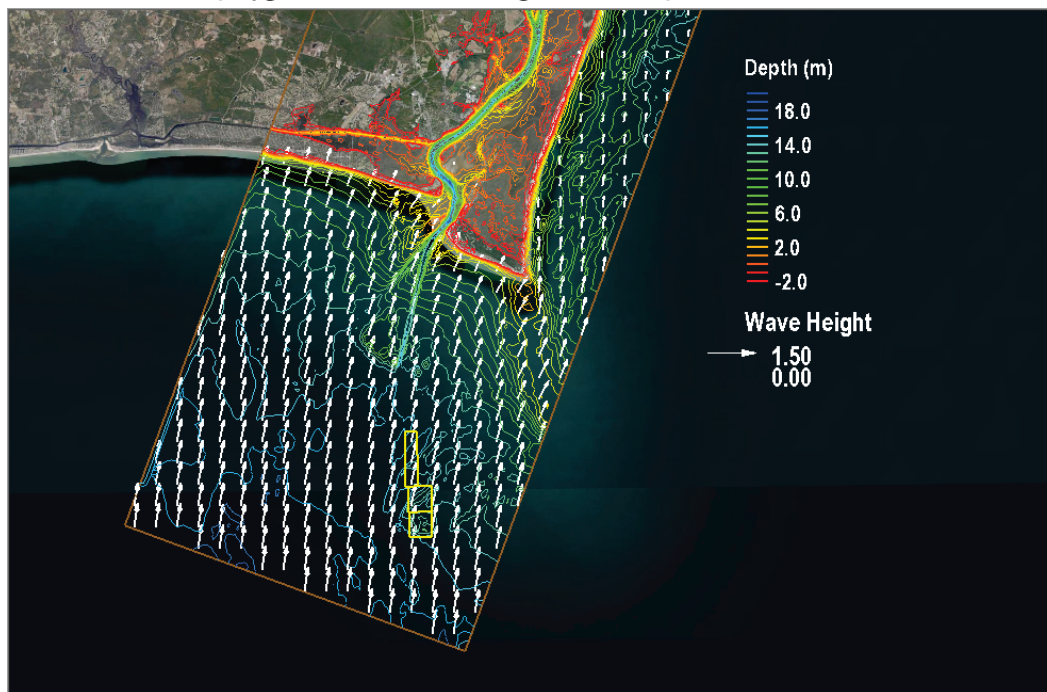
AWAC	Bias (m)	RMSE (m/s)	Correlation Coefficient
CFOS	0.032	0.097	0.18
CFRI	0.057	0.406	0.11

4.2 Summer Month

4.2.1 Waves

Significant wave height vectors are averaged for the summer month (June 2016), and spatial distribution of wave height and directions is shown in Figure 4-6. The figure displays that averaged wave directions are from south and incident waves are refracted approaching to shoreline. Monthly averaged wave heights are approximately 0.77 m (2.5 ft) in the offshore area. In nearshore open area, significant wave heights are between 0.4 to 0.6 m (1.3 to 2.0 ft). Propagating to the inlet entrance channel, wave heights are further reduced to 0.3 m (1.0 ft). On the bay side along Cape Fear River, averaged wave heights have a value of approximately 0.05 m (0.16 ft).

Figure 4-6. Calculated monthly averaged significant wave heights for June 2016. The *yellow polygons* indicate the dredged material placement sites.



4.2.2 Current

The field program deployed two AWACs at the nearshore water (CFOS) and the inlet channel (CFRI) for the period of January to February 2022. The current measurements at these two locations show tidal-dominated signals. The maximum depth-averaged current speed is 0.5 m/s (1.6 ft/s) and above 1.5 m/s (4.9 ft/s) at CFOS and CFRI, respectively (Figures 4-4 and 4-5).

The distribution of model-calculated, depth-averaged flood and ebb currents are illustrated for 6 June 2016 at 00:00 GMT and 06:00 GMT in Figures 4-7 and 4-8, respectively. At the inlet channel, peak current speeds are between 1.3 and 1.5 m/s (3.9 and 4.9 ft/s) and are reduced to between 1.1 and 1.2 m/s (3.6 and 3.9 ft/s) in the bay along the river channel. Open ocean currents are mostly under the influence of winds and waves. Because no storms occur on 6 June 2016 (Figure 4-9), calculated nearshore currents have a small speed between 0.1 and 0.3 m/s (0.3 and 1 ft/s). Around offshore placement areas, model currents speeds are less than 0.05 m/s (0.2 ft/s).

Figure 4-7. Calculated flood currents on 6 June 2016 at 00:00 (GMT). The *yellow polygons* indicate the dredged material placement sites.



Figure 4-8. Calculated ebb currents on 6 June 2016 at 06:00 (GMT). The *yellow polygons* indicate the dredged material placement sites.

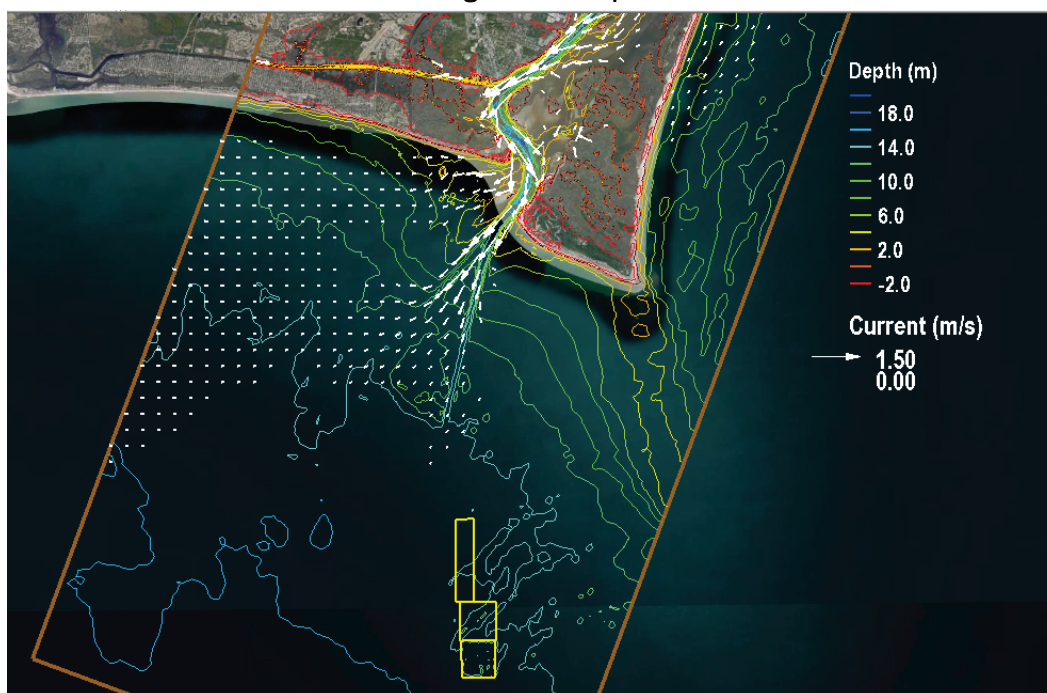
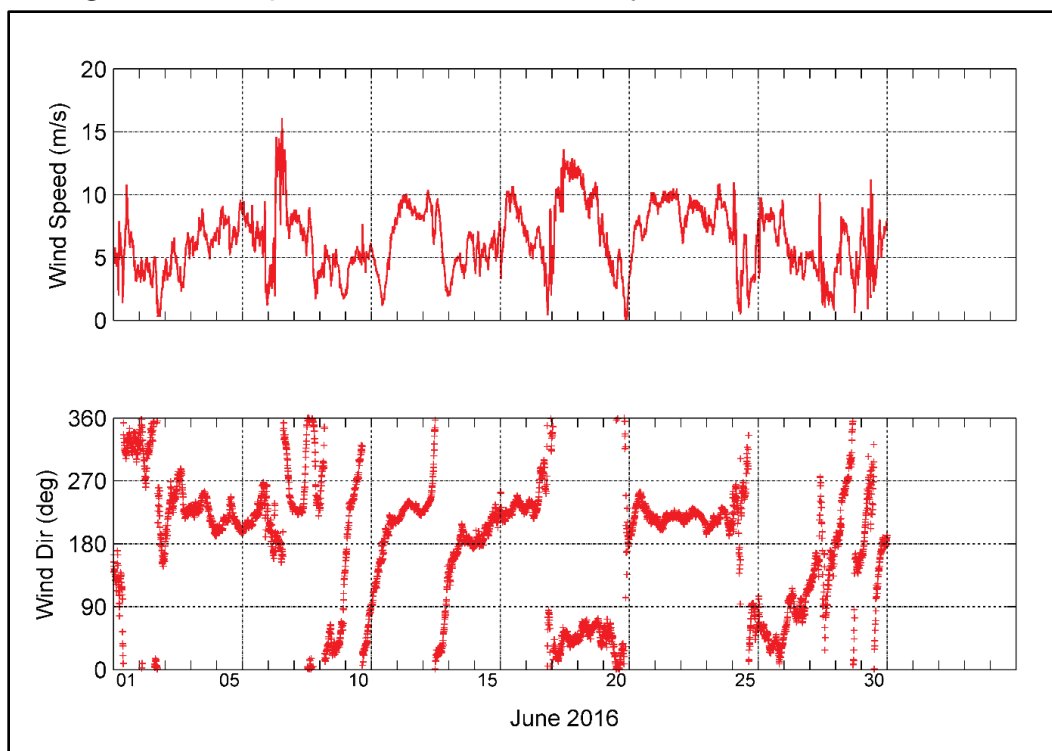


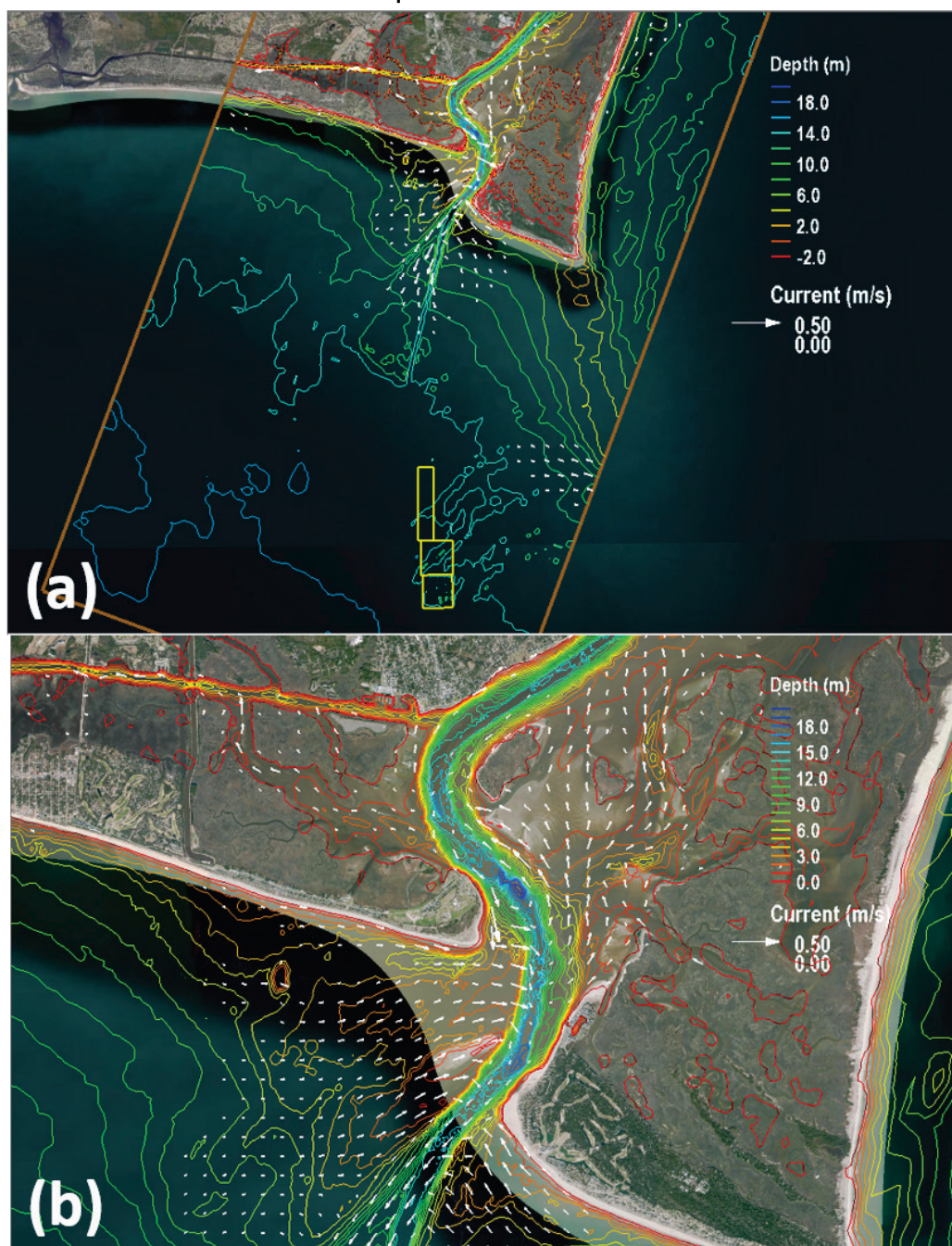
Figure 4-9. Wind speed and direction at NDBC buoy 41013 from 1 to 30 June 2016.



Monthly averaged current pattern is demonstrated by the spatial distribution of model current vectors as shown in Figure 4-10. After filtering out tidal signals, monthly averaged current speeds are much smaller than instantaneous tidal currents. At the inlet channel, peak averaged currents have a speed value between 0.4 and 0.5 m/s (1.3 and 1.6 ft/s) and appear on the flank of the navigation channel around Fort Caswell. The averaged current along the channel in the bay is weak, which indicates a balanced flood and ebb flow along the channel. On the bay side, averaged current speeds are around 0.1 m/s (0.3 ft/s) and the maximum current speeds can be between 0.2 and 0.3 m/s (0.7 and 1 ft/s) over the flanks of the channel and intertidal zone.

Depth-averaged longshore currents also have a small speed of approximately 0.1 m/s (0.3 ft/s) in nearshore areas, and the flow directions are towards the inlet from both sides of the channel along Oak Island and Bald Head Island. In the offshore placement sites, the averaged current speed is less than 0.01 m/s (0.03 ft/s).

Figure 4-10. Calculated monthly averaged currents at (a) inlet and offshore areas and (b) inlet and nearshore areas for June 2016. The *yellow polygons* indicate the dredged material placement sites.



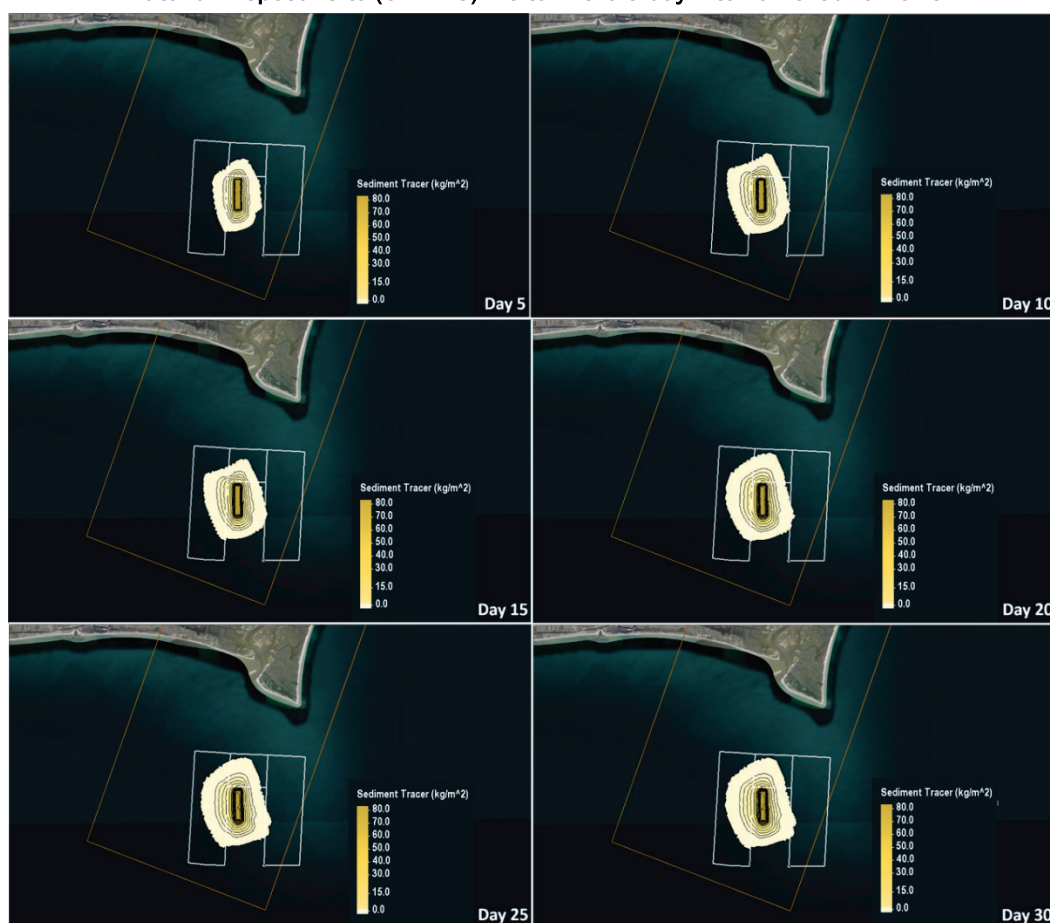
4.2.3 Sediment Plume

Sediment plume simulations are set up for the period of June 2016. Referring to the sediment grab samples (Figure 2-6), transported sediment is assigned a median grain size of 0.3 mm. Five bed layers are specified in the CMS and sediment materials are tracked from the beginning of simulations.

4.2.3.1 Alternative 1: Ocean Dredged Material Disposal Site (ODMDS) 1

Sediment is released at the ODMDS 1 site for Alternative 1. Figure 4-11 shows temporal variations in transport and dissipation of sediment in the top (active) bed layer at a 5-day interval starting at Day 5.

Figure 4-11. Temporal evolution of the sediment plume originating from the Ocean Dredged Material Disposal Site (ODMDS) 1 site in the 5-day interval for June 2016.



At the initial stage of the simulation, the sediment plume is featured by spreading surrounding the releasing site in the open offshore area. The spreading occurs in all directions within a radius of approximately 2.3–2.6 km (1.4–1.6 mi) at Day 5. Corresponding to weak currents in the placement site, the expansion of the plume is dominated by the diffusion process and the advection process plays a minor role. At the end of the summer simulation (Day 30), the plume spreading is extended to 3.4 to 4 km (2.1 to 2.5 mi) in all directions except for south and northeast directions, which implies the influence of tidal and wind-driven currents.

Quantitative movement of sediment is also estimated by counting total mass in all five bed layers within three polygon (trap) areas at the end of the simulation (Figure 4-12). The percentage for each polygon area is the sediment mass originating from the ODMDS 1 site relative to the total sediment mass placed in the top bed layer of the site.

Figure 4-12. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 1 site (*light-brown rectangle*) in June 2016.

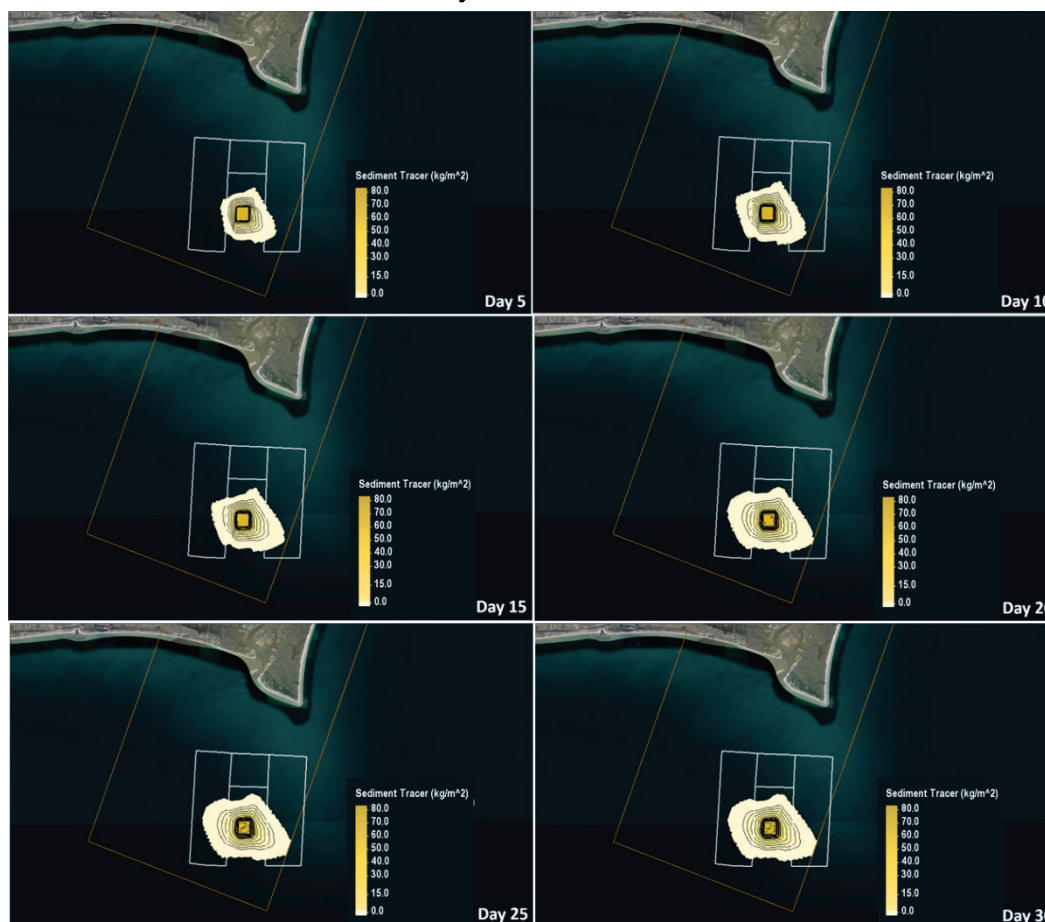


Figures 4-11 and 4-12 indicate that more than 99.9% of sediments stay in the placement site after a 1-month simulation. A total of 0.013% of sediment materials move to the north, and 0.006% of the mass moves to the west. Traps 1 and 3 do not have an equal distance from the ODMDS 1 site. Although Figure 4-11 shows a relatively large plume expansion to the east, only trace of sediment mass is transported into Trap 3 (Figure 4-12).

4.2.3.2 Alternative 2: ODMDS 2

Sediment is released at the ODMDS 2 site for Alternative 2. Figure 4-13 shows temporal variations in transport and dissipation of sediment in the top (active) bed layer at a 5-day interval starting at Day 5.

Figure 4-13. Temporal evolution of the sediment plume originating from the ODMDS 2 site in the 5-day interval for June 2016.



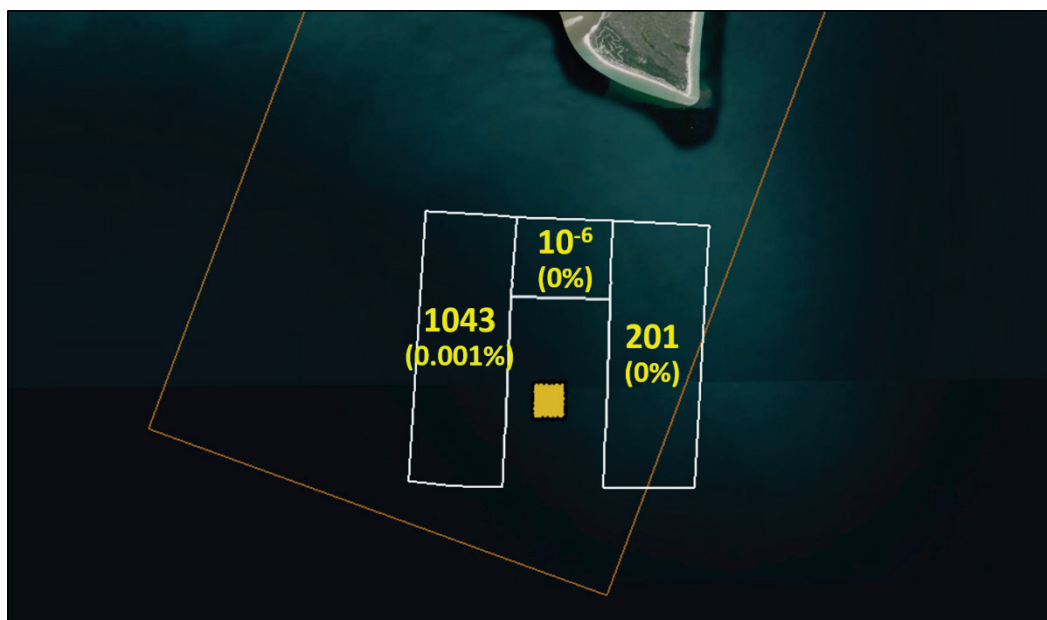
Different from Alternative 1, the model sediment plume in Alternative 2 at the initial stage of sediment tracing shows uneven sediment dissipation surrounding the ODMDS 2 release site. Plume spreading occurs more than 3 km (1.9 mi) towards east-southeast, while the spreading towards other directions is generally less than 2.0 km at Day 5.

From Day 5 to Day 30, the plume grows faster in west-northwest and east-southeast directions. The plume extends west-northwestwards from 1.9 to 4 km (1.2 to 2.5 mi). The ODMDS 2 site is about 4.6 km (2.9 mi) from the model open boundary on the east-southeast side. At the end of the

simulation, the plume expansion in this direction is beyond the boundary limit. Referring to wind conditions shown in Figure 4-9, the pattern of plume expansion can be associated with wind-driven currents over the open ocean domain. Figure 4-13 shows that large plume growth in the north-northeast and south-southwest direction is not as strong as in the west-northwest and east-southeast directions.

Total mass is counted in all five bed layers within three polygon (trap) areas at the end of the simulation (Figure 4-14). The percentage for each polygon area is the sediment mass originating from the ODMDS 2 site relative to the total sediment mass placed in the top bed layer of the site.

Figure 4-14. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 2 site (*light-brown square*) in June 2016.



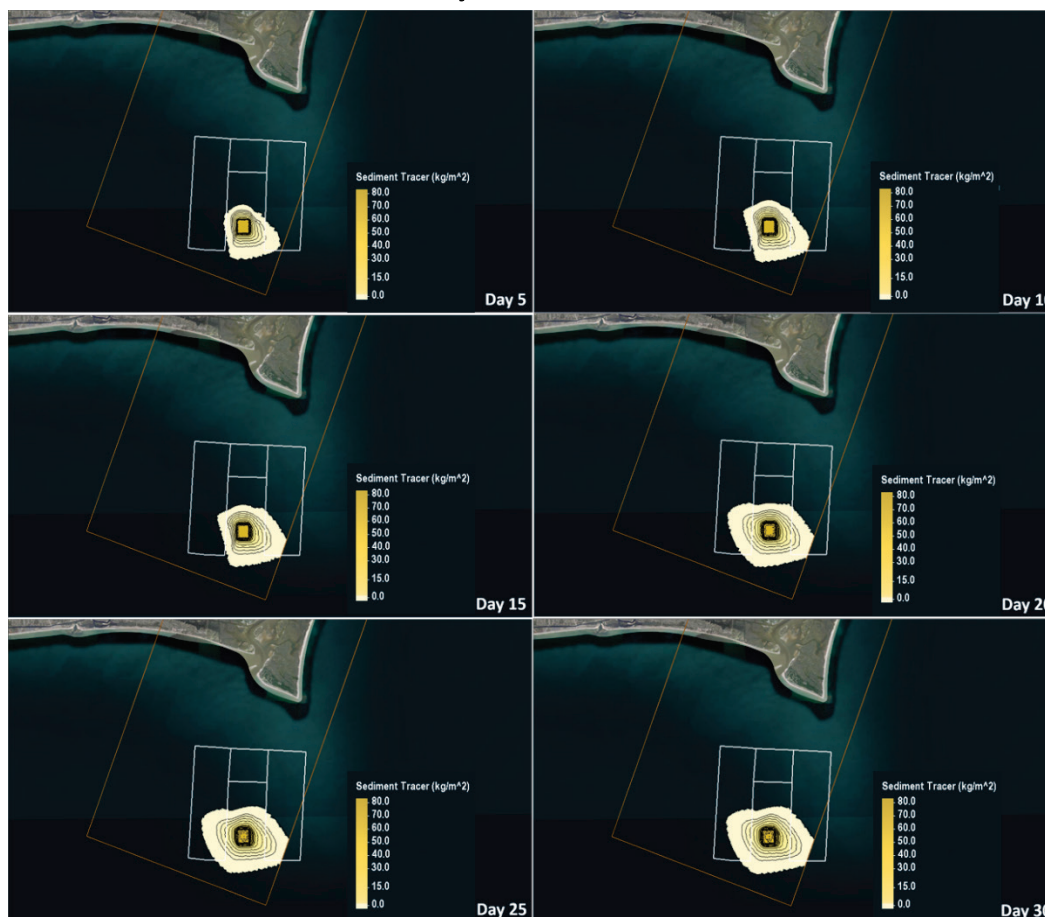
Figures 4-13 and 4-14 indicate that the center of the sediment mass stays around the placement site after 1-month simulation. Sediment materials move to Traps 1 and 3 consistent with the plume pattern as shown in Figure 4-13. Because Trap 3 reaches beyond the open boundary, some materials can move outside the model domain without being counted in the trap.

4.2.3.3 Alternative 3: ODMDS 3

The ODMDS 3 site is next to the south side of the ODMDS 2 site, and the sediment released at it is designated as Alternative 3. Figure 4-15 shows

temporal variations in transport and dissipation of sediment in the top (active) bed layer at a 5-day interval starting at Day 5.

Figure 4-15. Temporal evolution of the sediment plume originating from the ODMDS 3 site in the 5-day interval for June 2016.



Model results indicate similar evolution of sediment plume as for the ODMDS 2 site release. The sediment plume at the initial stage of sediment tracing (Day 5) shows large spreading towards the south and southeast, approximately 3 km (1.9 mi) to the south and 4 km (2.5 mi) to the southeast, and the spreading towards other directions is between 1 and 1.5 km (0.9 mi).

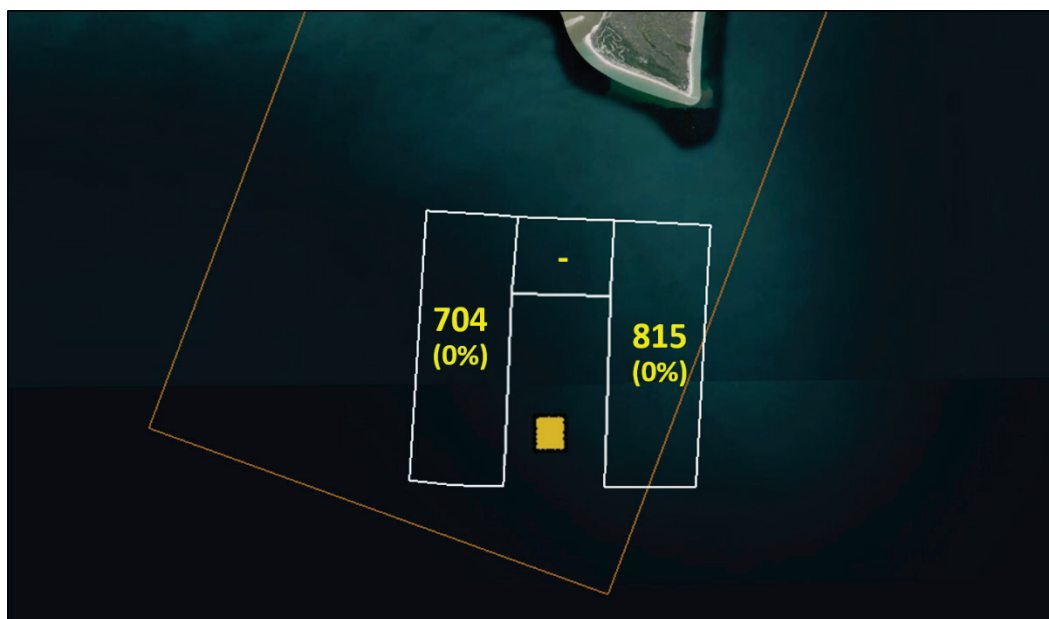
From Day 15 to Day 20, the plume rapidly grows in west-northwest and east-southeast directions, which extends west-northwestwards from 2.6 to 4.3 km (1.6 to 2.7 mi). From Day 20 to Day 30, the plume pattern has only a slight change. Comparing with the ODMDS 2 site, the ODMDS 3 site is closer to the model open boundary on the east-southeast side. The plume expansion has reached the boundary limit at Day 10. Referring to the wind

conditions in Figure 4-9, it can be seen that the changes in wind speed and direction cause the changes in plume distribution.

Total mass is counted in all five bed layers within three polygon (trap) areas at the end of the simulation (Figure 4-16). The percentage for each polygon area is the sediment mass originating from the ODMDS 3 site relative to the total sediment mass placed in the top bed layer of the site.

Figures 4-15 and 4-16 indicate that only trace amounts of tracked sediment moves into Traps 1 and 3 and towards the untagged south side of the ODMDS 3 site. Because Trap 3 intercepts the open boundary, the mass count demonstrates that more sediment materials migrate towards the southeast in the plume's northwest and southeast expansion.

Figure 4-16. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 3 site (*light-brown square*) in June 2016.



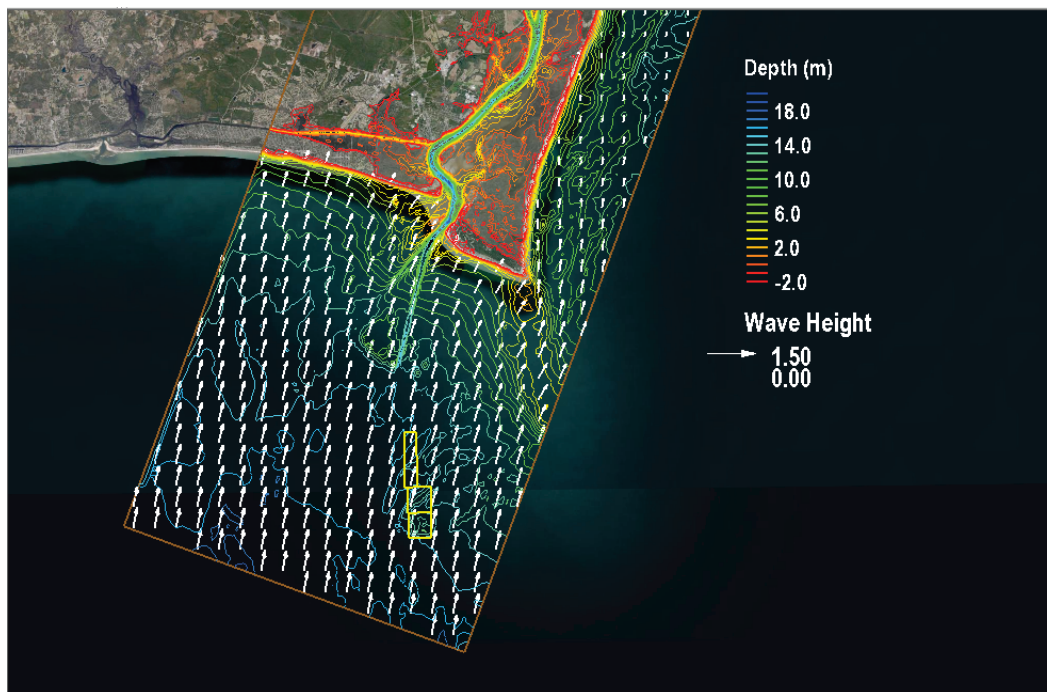
4.3 Winter Month

4.3.1 Waves

Significant wave height vectors are averaged for the winter month (December 2017), and spatial distribution of wave height and direction is shown in Figure 4-17. The figure displays that averaged wave directions are from south-southwest and incident waves are refracted approaching the shoreline. Monthly averaged wave heights are 0.67 m (2.2 ft) in the

offshore area. In nearshore open area significant wave heights are between 0.3 and 0.5 m (1.0–1.6 ft). Propagating to the inlet entrance channel towards the bay, wave heights are further reduced to 0.1 to 0.2 m (0.3 to 0.7 ft). On the bay side along Cape Fear River, averaged wave heights have a value of less than 0.05 m (0.16 ft).

Figure 4-17. Calculated monthly averaged significant wave heights for December 2017. The *yellow polygons* indicate the dredged material placement sites.



4.3.2 Current

Figures 4-18 and 4-19 show the distribution of calculated depth-averaged flood and ebb currents for 3 December 2017 at 23:00 (GMT) and 4 December 2017 at 05:00 GMT, respectively. No strong winter storms occur and tide is the predominant process corresponding to this period (Figure 4-20). During flood and ebb currents, modeled currents in the inlet channel have a speed between 1.1 and 1.2 m/s (3.6 and 3.9 ft/s). Flowing into the bay, tidal currents increase to 1.4 m/s (4.6 ft/s) along the channel. Over the intertidal zone on the bay side, currents are around 0.3 m/s (1 ft/s). Longshore currents outside the inlet in nearshore areas and currents around the offshore material placement sites during the winter month appear stronger than those during the summer month. The current speeds in nearshore and offshore areas are approximately 0.3 m/s (1.0 ft/s) and 0.1 m/s (0.3 ft/s), respectively.

Figure 4-18. Calculated flood currents on 3 December 2017 at 23:00 (GMT). The *yellow polygons* indicate the dredged material placement sites.

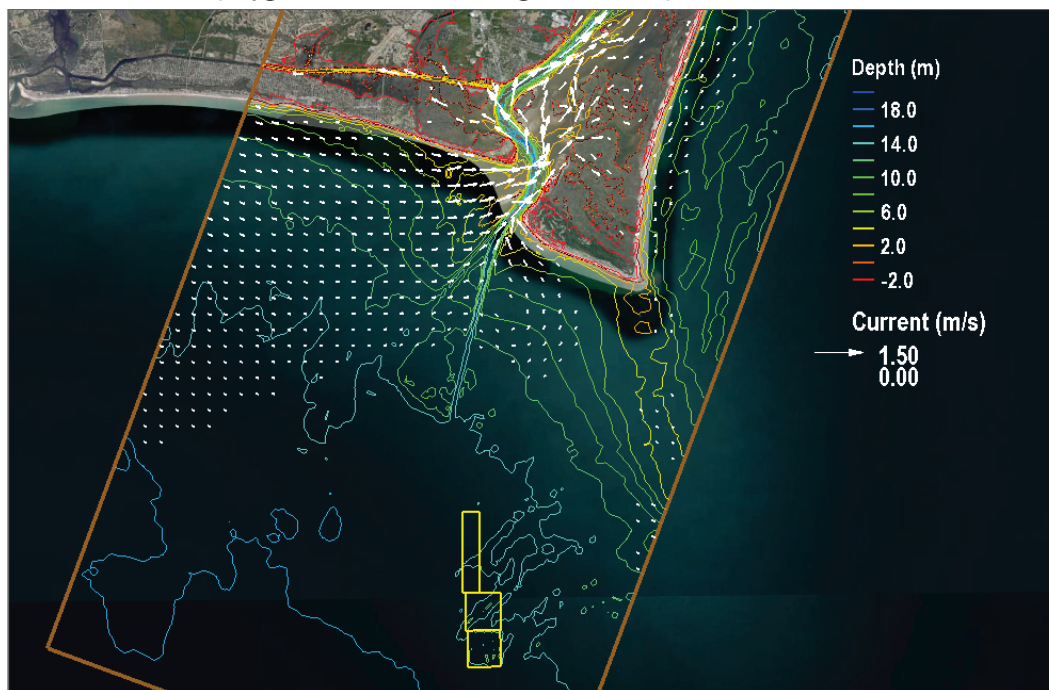


Figure 4-19. Calculated ebb currents on 4 December 2017 at 05:00 (GMT). The *yellow polygons* indicate the dredged material placement sites.

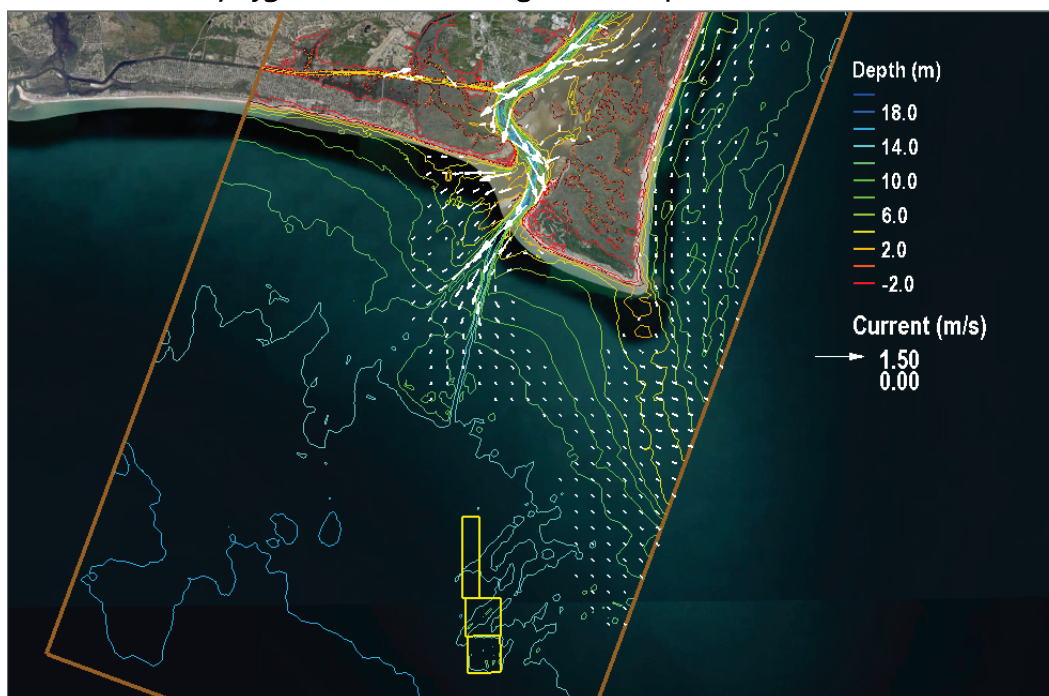
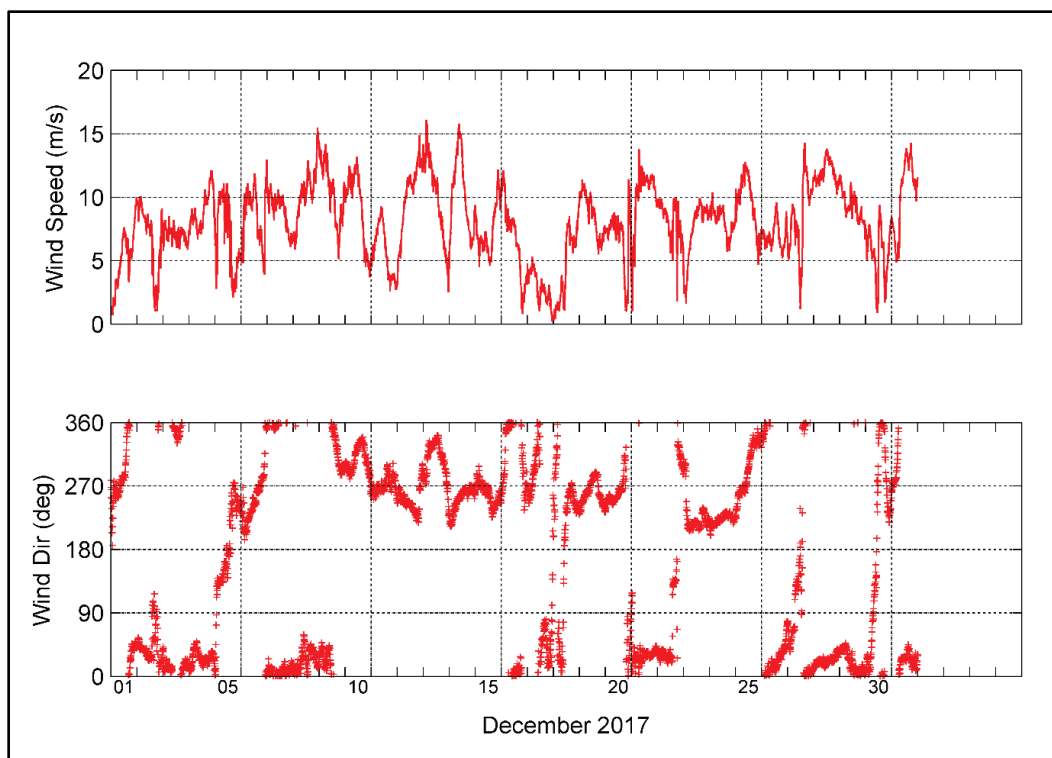


Figure 4-20. Wind speed and direction at NDBC buoy 41013 from 1 to 31 December 2017.

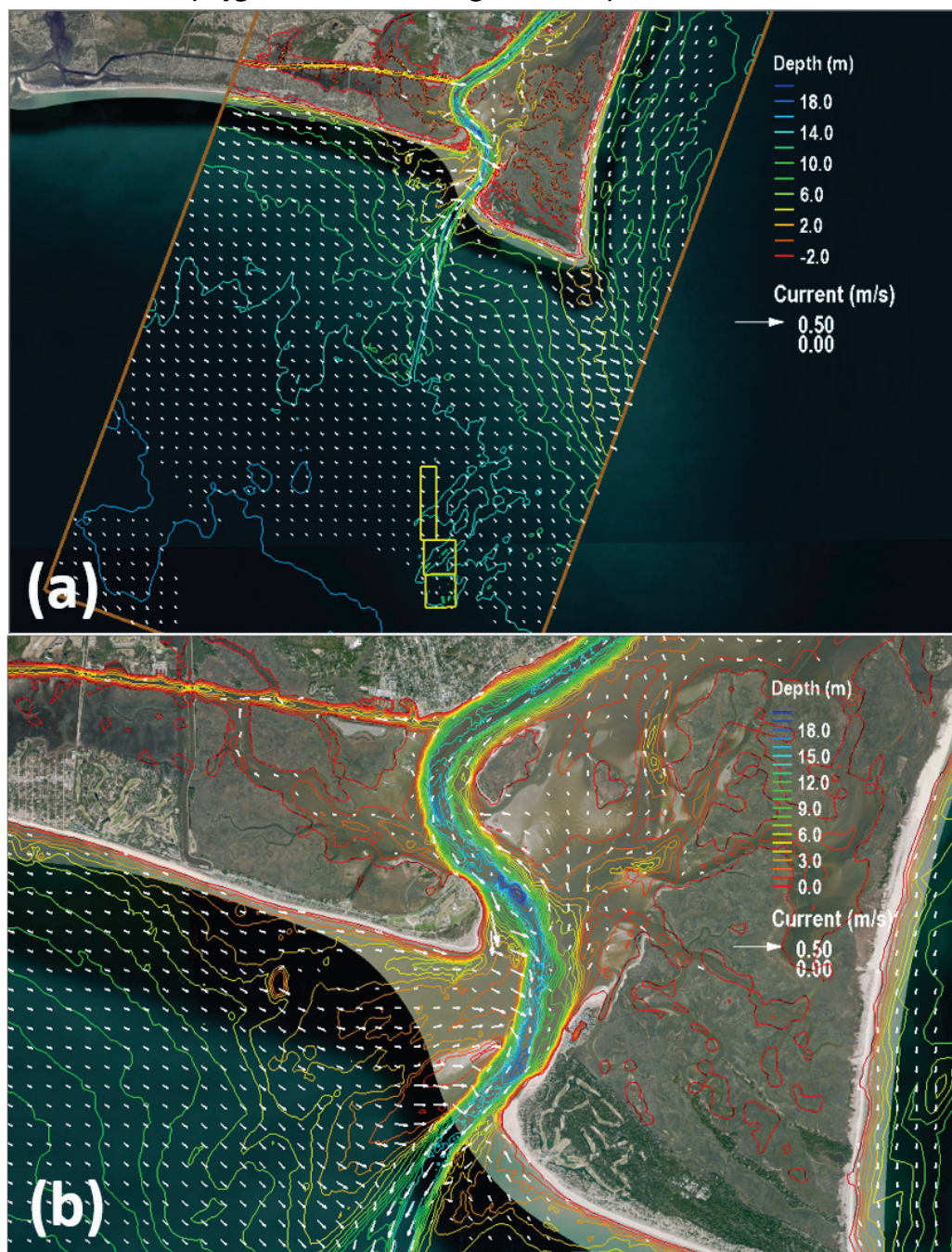


Monthly depth-averaged currents during December 2017 are demonstrated by the spatial distribution of current vectors as shown in Figure 4-21. Like the summer month, the averaged current field indicates balanced flood and ebb flows along the navigation channel. Removing tidal signals from the time-series output, monthly averaged current speeds are much smaller than instantaneous tidal currents. At the inlet channel, peak averaged currents have a speed value greater than 0.4 m/s (1.3 ft/s) on the flank of the channel around Fort Caswell. Inside the bay, averaged current speeds are rather weak, around 0.1 m/s (0.3 ft/s) over the flanks of the channel and intertidal zone.

Depth-averaged nearshore currents have a small speed of approximately 0.1 m/s (0.3 ft/s). Like the summer case, the flow directions are towards the inlet from both sides of the channel along Oak Island and Bald Head Island. The longshore flows meet at the inlet channel and turn to the open ocean side. In the offshore placement sites, the averaged current speed is much larger than that during the summer month, which is around 0.05 m/s (0.2 ft/s). Comparing the monthly averaged flow fields under summer and winter conditions, a distinct difference is the current strength

in the open ocean area. Dominant northerly wind generates relatively stronger eastward currents.

Figure 4-21. Calculated monthly averaged currents for December 2017. The *yellow polygons* indicate the dredged material placement sites.



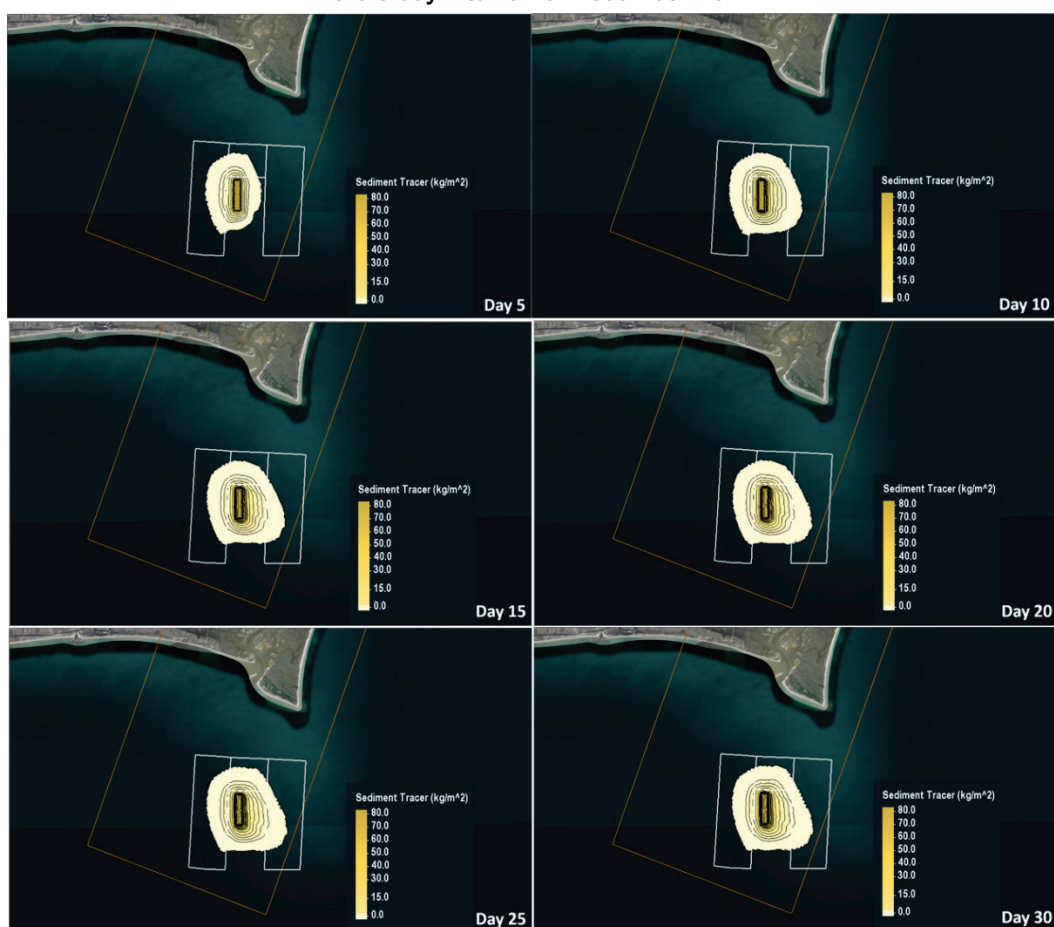
4.3.3 Sediment Plume

Specifying the same mean transport grain size of 0.3 mm, the sediment plume simulation is set up for the period of December 2017. Five bed layers are specified in the CMS, and sediment materials are placed in three dredged material disposal sites and tracked from the beginning of the simulations.

4.3.3.1 Alternative 1: ODMDS 1

Sediment is released at the ODMDS 1 site for Alternative 1. Figure 4-22 shows temporal variations in transport and dissipation of sediment in the top (active) bed layer at a 5-day interval starting at Day 5.

Figure 4-22. Temporal evolution of the sediment plume originating from the ODMDS 1 site in the 5-day interval for December 2017.



In the winter month, the initial sediment plume spreading is primarily towards north and west directions. The northward and westward spreading is approximately 3 to 3.3 km (1.9 to 2.1 mi), and the spreading in other directions is 2 to 2.5 km (1.2 to 1.6 mi) at Day 5. Asymmetric distribution of the plume surrounding the placement site indicates the dominance of the advection process in sediment transport during a winter month.

From Day 5 to Day 15, the sediment plume grows in the southeast direction and it extends from 1.5 to 4.8 km (0.9 to 3 mi) southeastward close to the model open boundary. Consistent strong westerly and northwesterly between Day 9 and Day 15 could be the primary forcing for this rapid plume growth (Figure 4-20). For the next 15 days, there are no significant changes in plume distribution pattern.

Figure 4-23 shows the total sediment mass in all five bed layers within three polygon (trap) areas and the percentage of the total mass within each polygon area relative to the total sediment mass placed in the top bed layer of the site at the end of the simulation.

Figure 4-23. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 1 site (*light-brown rectangle*) in December 2017.

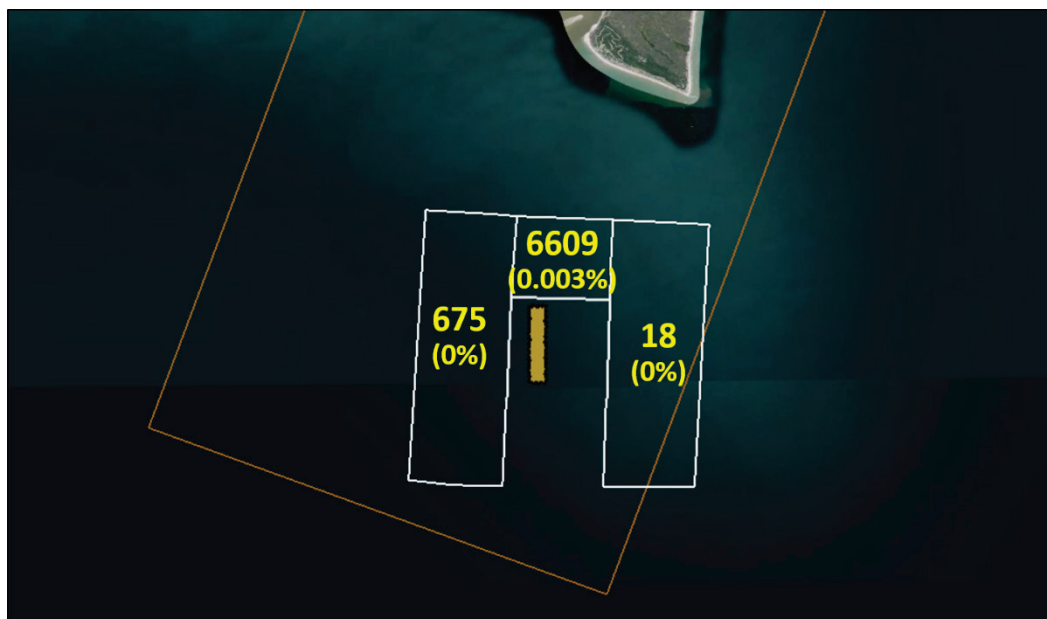


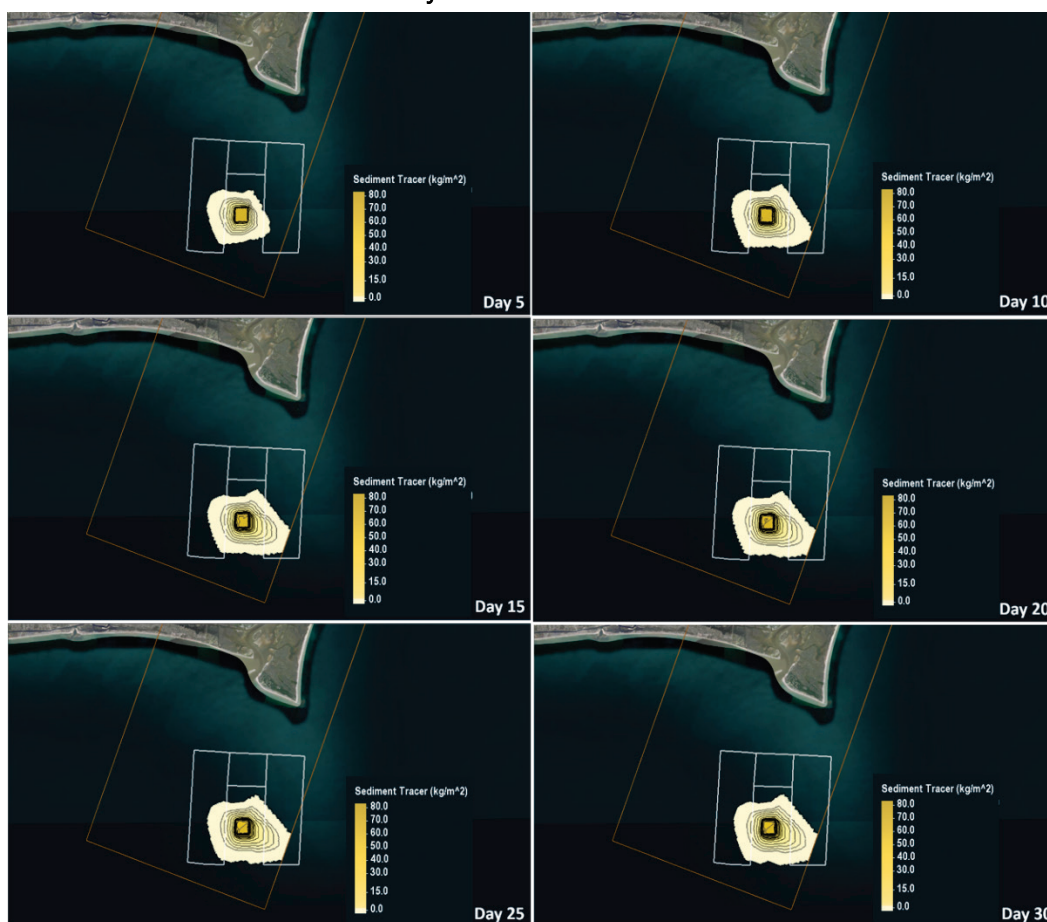
Figure 4-23 indicates that the center of sediment mass is still around the ODMDS 1 placement site after the 1-month simulation. Very small percentages of sediment materials move to the north. Comparing with sediments moving northward, sediment materials moving westward are

one order of magnitude smaller. Traces of materials are detected in Trap 3 on the east side of the ODMDS 1 site.

4.3.3.2 Alternative 2: ODMDS 2

Alternative 2 is to examine the distribution of sediment plume for the materials placed at the ODMDS 2 site during December 2017. Figure 4-24 shows temporal variations in transport and dissipation of sediment in the top (active) bed layer at a 5-day interval starting at Day 5.

Figure 4-24. Temporal evolution of the sediment plume originating from the ODMDS 2 site in the 5-day interval for December 2017.



Like the sediment migration from the ODMDS 1 site, sediments originated from the ODMDS 2 site show primary plume spreading towards the west at Day 5. The maximum plume expansion reaches to a distance between 3 and 3.4 km (1.9 and 2.1 mi) on the northwest, west, and southwest sides of the placement site. Major wind direction changes (Figure 4-20) from the beginning of the simulation to Day 10 result in

plume spreading in the southeast direction towards the model open boundary. During the 5-day period, the edge of the plume grows a distance from 2.8 km to 4.7 km (1.7 to 2.9 mi). From Day 10 to Day 30, the plume grows wider in the southeast direction, but the expansion of the plume is not significant in the other directions.

Figures 4-24 and 4-25 indicate that the center of sediment mass skews towards the southeast of the placement site. Although small percentages of sediment materials move to Trap 3 on the east side of the ODMDS 2 site, the amount of sediment mass counted in Traps 1 and 2 is several orders of magnitude less.

Figure 4-25. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 2 site (*light-brown square*) in December 2017.

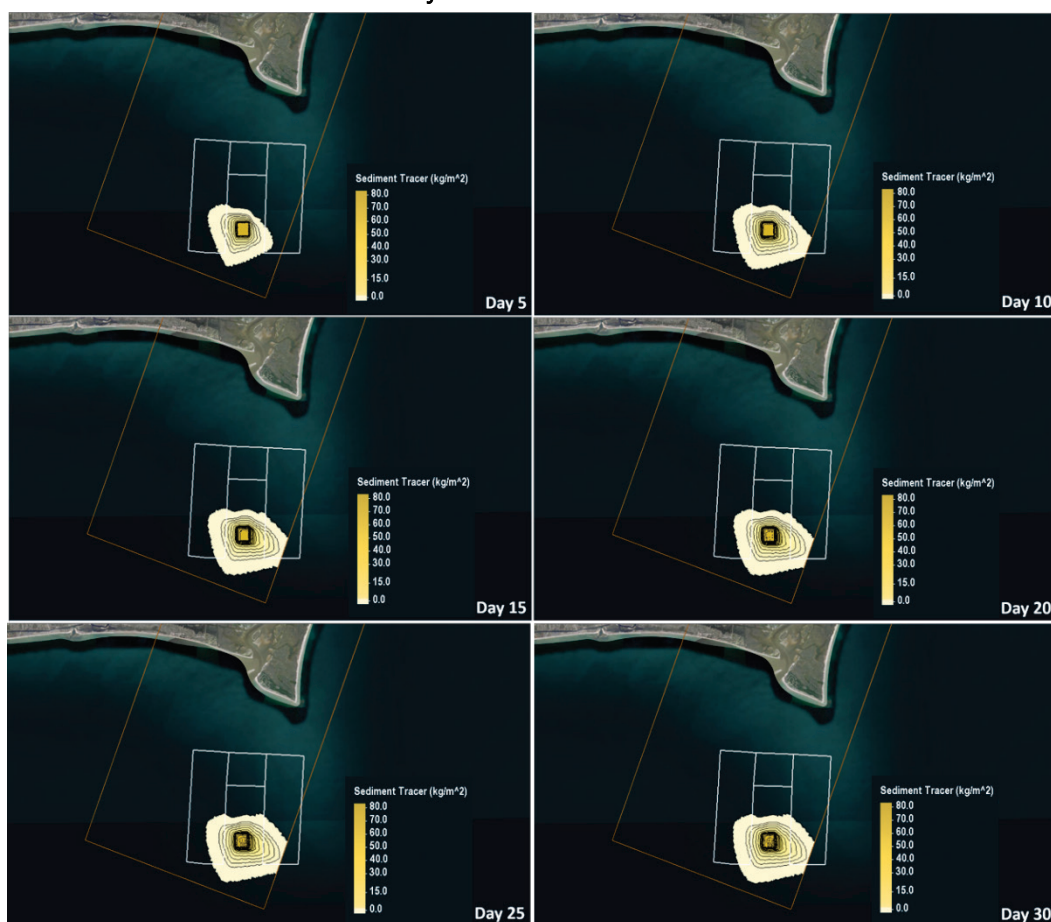


4.3.3.3 Alternative 3: ODMDS 3

Figure 4-26 shows that initial primary sediment spreading around the ODMDS 3 Site is towards the northwest, west, and southwest. The Plume extends a distance between 3.3 and 3.5 km (2.1 and 2.2 mi) to the west of the placement site. The smallest plume expansion is to the north at approximately 1 km (0.6 mi). as analyzed earlier, wind direction changes (Figure 4-20) greatly influence the evolution of sediment plume towards the southeast. The model results show that the expanded plume with a fast moving rate reaches the open boundary to the southeast of the ODMDS 3 site at Day 6.

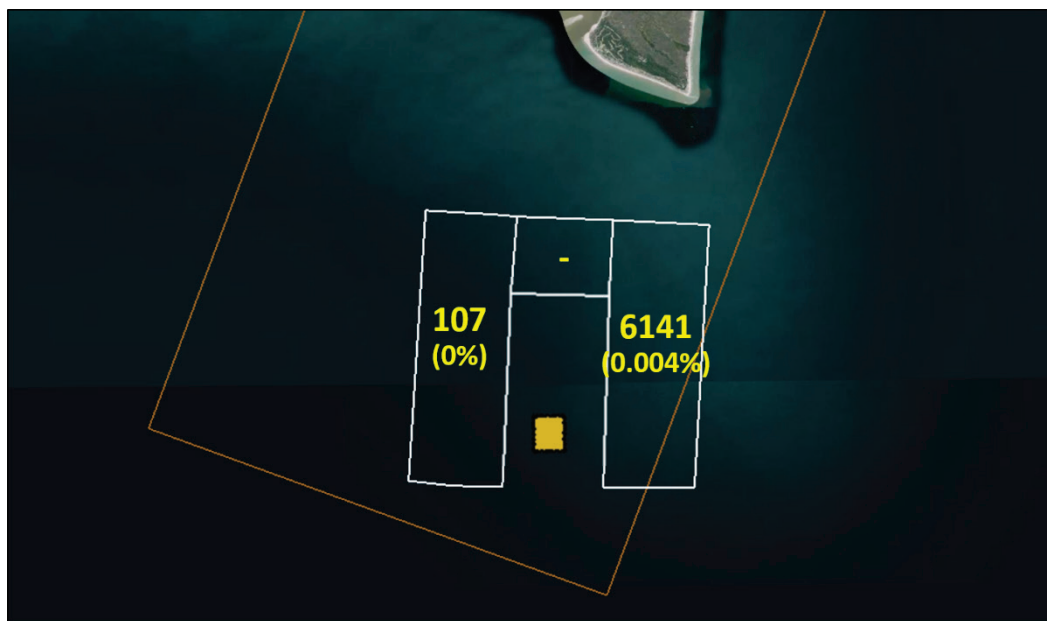
Migration of the sediment plume reflects the importance of the advection process during winter months. From Day 5 to Day 30, the plume expansion rate is different in different directions. The plume grows wider in the southeast direction, and the maximum plume expansion is from less than 1 km (0.6 mi) to more than 3 km (1.9 mi) towards the north and northeast and from 2.5 to 4 km (1.6 to 2.5 mi) towards the south and southeast.

Figure 4-26. Temporal evolution of the sediment plume originating from the ODMDS 3 site in the 5-day interval for December 2017.



Consistent with the plume growth for the sediments originated from the ODMDS 2 site, Figures 4-26 and 4-27 indicate that the center of sediment mass originated from the ODMDS 3 site skews towards the southeast. Most of the moving sediment materials are found in Trap 3 covering the area between the placement site and the open boundary.

Figure 4-27. Sediment total mass (kilogram) within three polygon (trap) areas and percentages relative to materials placed at the ODMDS 3 site (*light-brown square*) in December 2017.



5 Summary

With the implementation of a field survey program, a coupled wave, hydrodynamic, sediment transport model is developed and applied to investigate sediment transport and evolution of a sediment plume around the Cape Fear River Inlet estuarine system. Field data collection includes the deployment of two AWACs to measure waves, water level, and current within the inlet channel and the open water in nearshore area. Driven by tide, waves, and wind, the CMS simulations include a 60-day calibration and validation, and one representative summer (June 2016) and one winter (December 2017) month simulation. Three alternatives, tracking sediments originate from three selected offshore dredged material placement sites, the ODMDS 1 site, the ODMDS 2 site, and the ODMDS 3 site, are configured and modeled for the summer and winter. From the model, the migration of sediment plume is evaluated and compared among three placement sites and between the summer and the winter month. The major conclusions are drawn as follows:

1. The field data program is an integral component to the successful implementation of the numerical model. The calibration of the CMS provides a representation of physical forcing factors that drive sediment transport at the Cape Fear River Inlet estuarine system. Features of tidal flows are captured through the spatial and temporal field data collection of water levels and currents at the Cape Fear River Inlet channel and the nearshore open ocean. Measured waves and currents provide an essential validation for numerical simulation of sediment transport.
2. Primary driving forcing in the areas are tide, wind, and waves. Tidal currents are the dominant flow component in the estuary and around the inlet, and wind-driven currents are dominant in the offshore open ocean area.
3. Three alternative ODMDS sites are located in the offshore area. Evolution and distribution patterns of sediment plumes are similar when tracking sediments from three offshore sediment material placement sites during the summer or winter month simulation.
4. Surrounding three ODMDS sites, the spreading of the sediment plume is controlled by diffusion and advection processes. In the offshore ocean area, tidal currents are relatively weak and ocean currents are primarily storm-driven. Differences in forcing mechanisms during summer and winter months exhibits dominant physical processes that control seasonal variations and plume evolution of tracked sediment materials.

The conclusions provided above have been based on sediment tracer simulations. To improve our understanding of suspended sediment behavior around a coastal inlet and estuarine system, further numerical modeling effort would be required accompanying with a comprehensive data collection program and in-depth laboratory work. The modeling study would involve more extensive analyses of physical conditions and sediment movement. In addition to that, field data and laboratory experiments would help to better validate numerical models and understand sediment properties and sediment transport.

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Abbreviations

AWAC	Acoustic wave and current profiler
CDIP	Coastal Data Information Program
CFOS	Cape Fear River estuarine offshore site
CFRI	Cape Fear River inlet site
CMS	Coastal Modeling System
CRM	Coastal Relief Model
DEM	Digital Elevation Model
MSL	Mean sea level
NCEI	National Centers for Environmental Information
NDBC	National Data Buoy Center
ODMDS	Ocean dredged material disposal site
RMSE	Root-mean-square error
SMS	Surface-water Modeling System
WSE	Water-surface elevation

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