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A Large-Scale Community Storm Processes Field Experiment

The During Nearshore Event Experiment (DUNEX) Overview
Reference Report

Mary A. Cialone, Jessamin A. Straub, Britt Raubenheimer, Jenna A. Brown, Katherine L. Brodie, Nicole Elko, Patrick J. Dickhudt, Michael F. Forte, Stephen R. DeLoach, Hilary F. Stockdon, and Julie D. Rosati

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Final report

Abstract

The **DU**ring **N**earshore **E**vent E**X**periment (DUNEX) was a series of large-scale nearshore coastal field experiments focused on during-storm, nearshore coastal processes. The experiments were conducted on the North Carolina coast by a multidisciplinary group of over 30 research scientists from 2019 to 2021. The overarching goal of DUNEX was to collaboratively gather information to improve understanding of the interactions of coastal water levels, waves, and flows, beach and dune evolution, soil behavior, vegetation, and groundwater during major coastal storms that affect infrastructure, habitats, and communities. In the short term, these high-quality field measurements will lead to better understanding of during-storm processes, impacts and post-storm recovery and will enhance US academic coastal research programs. Longer-term, DUNEX data and outcomes will improve understanding and prediction of extreme event physical processes and impacts, validate coastal processes numerical models, and improve coastal resilience strategies and communication methods for coastal communities impacted by storms. This report focuses on the planning and preparation required to conduct a large-scale field experiment, the collaboration amongst researchers, and lessons learned. The value of a large-scale experiment focused on storm processes and impacts begins with the scientific gains from the data collected, which will be available and used for decades to come.

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Preface

1   Introduction

1.1   Background

In the past 40 yr[1], large-scale scientific experiments in the coastal research realm have focused on many aspects of nearshore hydrodynamic and sediment transport processes (hydrodynamic experiments: Duck 82, Duck 85, SuperDuck [Mason 1984, 1987; Hubertz et al. 1987; Crowson 1988]; sediment transport experiments [Gable 1981]; SandyDuck, Duck 94 [Birkemeier et al. 1994; Birkemeier et al. 1996; Birkemeier et al. 1999; Hathaway and Birkemeier 2004]; Dutch Sand Motor Engine [Stive et al. 2013]). With each experiment, the scientific community has improved the collective knowledge and ability to predict coastal environmental processes and morphologic response. However, there are still significant knowledge gaps related to comprehensive storm forcing, impact, response, and recovery processes that require field measurements.

The 2019–2021 experiment documented in this report focused on the interaction of nearshore coastal processes, particularly during extreme events, which have been difficult to capture with traditional instrumentation because of the harsh conditions. This experiment, named the DUring Nearshore Event eXperiment (DUNEX), was a multiagency, academic, and nongovernmental organization collaborative community experiment to study nearshore coastal processes during coastal storms. The planning, organization, and coordination of DUNEX operated under the general convening of the US Coastal Research Program (USCRP), a multiagency, academic, and nongovernmental community of practice focusing investments on nearshore coastal research and transitioning outcomes into practice. This multiphased experiment took place on the Outer Banks of North Carolina, beginning with the Fall 2019 DUNEX Pilot Study followed by a transitional year and then the Fall 2021 DUNEX Main Experiment, primarily taking place from late summer to early winter (August 2021–January 2022). By leveraging the data collection efforts of all research teams, findings from DUNEX will improve basic

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[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 345–7, respectively. https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

understanding, predictive capabilities, and observational technologies for extreme coastal storm processes and impacts.

This report describes the experiment planning and coordination, the individual and collaborative research projects, and lessons learned from these activities. This information serves as a point of reference for future large and diverse coastal experiments and is intended to provide an overarching reference for the DUNEX experiment. Specific research findings will be documented by the individual researchers in separate publications.

1.2 Objectives: Why the DUring Nearshore Event eXperiment (DUNEX) is needed

Extreme event processes and impacts were identified by the nearshore coastal community in 2014 as some of the primary research areas that needed additional focus and attention as documented in "The Future of Nearshore Processes Research" (The Nearshore Processes Community 2014 and 2015). In 2018, the USCRP hosted the Processes and Impacts Workshop to convene the coastal research community and stakeholders to prioritize needed advancements in storm forecasting (Elko et al. 2019). DUNEX aimed to address this research need and increase knowledge of coastal flooding, erosion, and postevent recovery by collecting a shared data set quantifying impacts and processes during extreme storms. The experiment also addressed the USCRP goal of improving communication between scientists and the coastal community to facilitate the translation of scientific research into use by coastal engineers and managers.

Therefore, DUNEX was established with the short-term goals of making high-quality field measurements to better understand during-storm processes, impacts, and poststorm recovery and to help enhance US academic coastal research programs. Longer-term goals include the improvement of models and prediction of extreme event physical processes and impacts, improvement of strategies for coastal resilience, and development of effective communication methods for communities impacted by storms (Cialone et al. 2019).

1.3 The US Coastal Research Program (USCRP) role

The USCRP organized and facilitated the execution of DUNEX through the following activities:

- Provided funding for some of the research studies through a competitive process
- Provided forums for disseminating logistical information, experiment planning and coordination, and collaborative discussions
- Provided a community website (Field Experiment - U.S. Coastal Research Program (uscoastalresearch.org)) with details about ongoing DUNEX experiments and access to DUNEX data
- Organized agency-supported data collection efforts intended to benefit multiple individual researchers (e.g., bathymetry, airborne and terrestrial lidar, unmanned aerial systems (UAS) flights, waves, water levels, currents)
- Coordinated logistical support and facilitated the development of a logistics team of science principal investigators (PIs) in collaboration with a National Science Foundation (NSF)-funded Convergence-RAISE grant (OCE-1848650)
- Assisted in coordination with local stakeholders
- Helped to promote DUNEX to a multidisciplinary audience to ensure diverse data collection
- Coordinated training classes and volunteers to further the career development of US coastal researchers

1.4   Approach: How DUNEX was formed

As noted above, in 2014 the nearshore coastal community identified extreme event processes as one of three primary coastal research areas to be addressed. The USCRP began to address this need by gathering researchers to discuss extreme events (along with the other two focus areas) at a workshop in December 2016. All the breakout session teams at the workshop produced a number of integrated research collaboration plans, which ultimately were synthesized to create the USCRP as a formal program. One outcome of the workshop from the Extreme Event Break-out Session Team was the establishment of the primary extreme event goal of improving understanding of nearshore processes during extreme events through the execution of a large-scale field experiment to collect data during a storm season (which became DUNEX). The full timeline of events leading to DUNEX is shown in Figure 1.

Figure 1. Timeline of events leading to the execution of the During Nearshore Event Experiment (DUNEX).
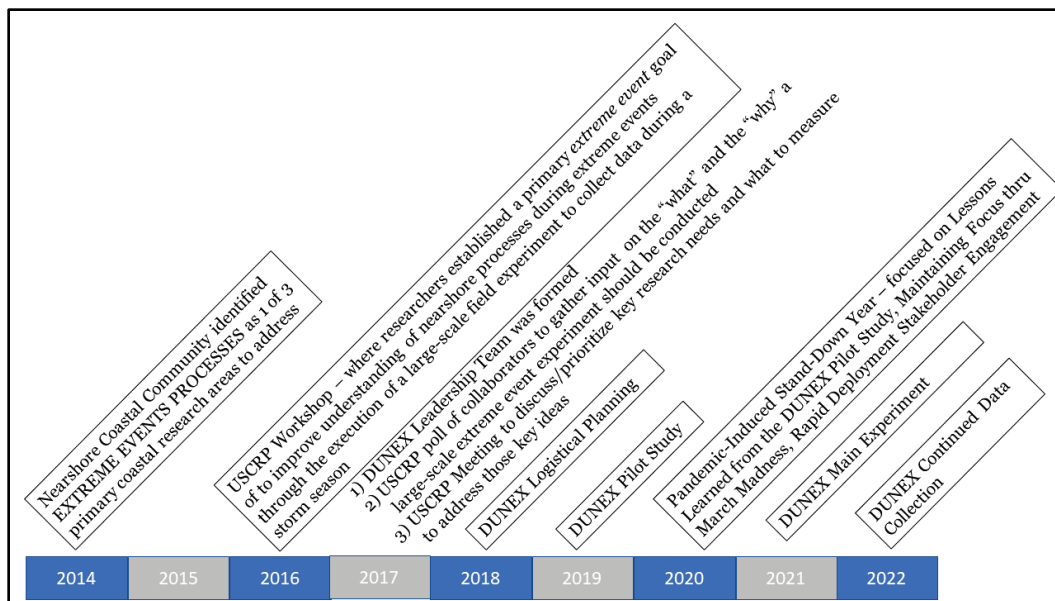
The December 2016 Workshop: Extreme Event Break-Out Session team members are listed here:

- Academia—Dr. Britt Raubenheimer (Woods Hole Oceanographic Institution [WHOI]), Diane Foster (University of New Hampshire), others as engaged
- Bureau of Ocean Energy Management (BOEM)—Dr. Jeffrey Reidenauer, Mr. Jeff Waldner
- National Oceanic and Atmospheric Administration (NOAA)—Dr. Greg Dusek
- US Naval Research Laboratory (NRL)—Dr. Meg Palmsten
- US Army Corps of Engineers (USACE)—Ms. Mary Cialone, Dr. Katherine Brodie, Dr. Candice Piercy
- US Geological Survey (USGS)—Dr. Hilary Stockdon, Dr. Chris Sherwood, Dr. Harry Jenter, Dr. Jennifer Miselis

The Extreme Events Break-Out Session Team continued to discuss the concept for a collaborative, large-scale field experiment. In October 2017, members of the 2016 break-out session met again at the American Shore and Beach Preservation Association (ASBPA) Conference under the leadership of Raubenheimer to begin the initial steps of determining (1) what processes or impacts to study, (2) why to study these

processes/impacts, and (3) what data do we need to collect to improve our knowledge and understanding of those processes and/or impacts?

During this timeframe, the USCRP leadership also recommended the formation of a DUNEX Leadership Team (DLT) to bring the large-scale field experiment idea to fruition. The USCRP Executive Directors assigned the December 2016 break-out session leader (Raubenheimer) and the USACE Technical Programs Office leadership (Mr. Jeff Lillycrop and Dr. Julie Rosati) assigned USACE Technical Programs Office members Cialone and Mr. Stephen Deloach to launch the formation of the USCRP-sponsored field experiment. This team gathered leadership from academia and other federal agencies to serve on the DLT to begin the process of outlining the steps needed to form a successful large-scale field experiment.

To prepare for the October 2017 meeting, the USCRP reached out to the nearshore extreme event collaborators to have them begin to think about the synergies of conducting an experiment as a group and what their specific interests were as part of the experiment. The USCRP conducted a poll of nearshore extreme event collaborators to gather their input as to whether the concept of a large-scale extreme event experiment was appropriate; if so, what types of events should the community focus on (e.g., collision-type regime, in which storm waves and runup impact subaerial coastal regions, or inundation regime, in which storm processes overwash a barrier island or urban area); what their specific interests were as part of this study (waves, wave-dune interactions, morphological change, field observations, modeling, etc.); what measurements they would collect or what modeling approaches they would take; and why the group should focus on each aspect of extreme events. The thought process was to have scientists begin the process of bringing their puzzle pieces to the table, seeing what pieces others have to offer, and determining if all the pieces/components form a holistic approach that would benefit the group as well as the individual researchers and ultimately coastal communities/society.

At the 2017 meeting, the focus was on discussing and prioritizing the ideas that the community listed as key research needs, determining why a collaborative experiment is critical to the overarching goals, and deciding what to measure to address these key ideas and goals. Though site selection was not an initial top-priority decision topic, it became part of

the discussion when the concept of a collaborative, community, extreme-event experiment was considered viable. Location options for the experiment that the DLT presented to the USCRP Leadership included (1) a predetermined (stationary) experiment location where storms are likely to occur or (2) a storm-chasing experiment where deployment occurs when a storm is approaching any given location. The overwhelming recommendation was to begin with a fixed-site experiment focused on the collision regime followed at some point in the future by a storm-chasing study. The community also expressed the idea of including multiple study sites in the experiment to contrast the natural and built environments. The site selection is discussed later in this chapter.

In addition to the DLT, several subteams were formed to manage the various growing aspects of this large endeavor. The general role and focus of each subteam is given below with details provided in Chapters 2 and 3.

- **Logistics**—The focus of the Logistics Team was to coordinate and organize instruments, equipment, vehicles, and people to keep the experiment running smoothly, benefitting multiple researchers. The team worked with the DUNEX Leadership Committee to develop the experiment budget as well as define experiment scope. Once sites were selected (see Site Selection section below), Logistic Team tasks included getting permission for non-US citizen researchers to be on site at the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Field Research Facility (FRF), coordinating FRF and agency staffing to align with field needs, and orienting visitors to the FRF and available resources. This team also performed the first outreach to coastal researchers by conducting logistic surveys prior to the DUNEX Pilot Study and prior to the DUNEX Full Experiment to (1) gauge interest in conducting a large-scale experiment and (2) assist the team in organizing the experiment by gathering information on common data needs to facilitate collaboration, instrument fabrication needs, deployment/retrieval needs, and training topics of interest to the participants. The DUNEX Logistics Team Lead, Mr. Patrick Dickhudt (FRF), was tasked with identifying the following:

  o Individual researcher's needs before, during, and after their experiment
  o Group support needs

      ○   Scheduling resources such as office space, training space, and access to the ocean and sound

- **Academics**—The Academic Team was the primary outreach to academic researchers to determine their storm processes research interests and assess where there were overlaps, complementary efforts, opportunities to collaborate, what could be shared, and what the USCRP needed to supply. This team also communicated and interacted with the federal researchers, stakeholders, and the full DLT in the overall DUNEX planning process.
- **Training**—The Training Team provided opportunities for federal investigators, academic investigators, and stakeholders to learn about and experience field training firsthand.
- **Communications**—The Communication Team provided internal and external outreach. Initial focus was on gathering interest and commitments from federal and academic researchers to participate in DUNEX through an interest survey. Those survey respondents who committed to participate in the DUNEX Pilot Study were then part of an internal participant group. Internal communications with those participants prior to and during the experiments were made via email, regular web meetings (Coffee Hours—which will be discussed in following sections), and additional surveys to gauge the likelihood of experiment postponement when the world pandemic altered the 2020 DUNEX Main Experiment plan. Before, during, and after DUNEX, external communications centered on publicizing and informing the public as well as other researchers via social media, public notices, and press releases regarding the research being conducted at DUNEX.
- **Data Management**—The Data Management team coalesced data-sharing agreements during the experiment. With approximately 300 instruments deployed over the 2019–2021 time period, managing those data for use by researchers, other PIs, and eventually coastal researchers in general required a written and agreed-upon data-sharing plan by all DUNEX participants. That data-sharing plan (Appendix D of this report) laid out the means and requirements for participants to share and use data from this experiment.

1.5   Experiment layout overview

The site selection for DUNEX took into consideration the science goals of the intended data collection, specifically nearshore processes, frequent

dune collision (where wave runup exceeds the dune base elevation and collides with the dune, potentially causing erosion or overwash or both [Sallenger 2000]), and impacts to infrastructure. When making the site selection for the experiment, these science aspects were weighed and considered, along with identifying locations for which historical observations were available to put the study into context, where offshore and onshore measurement collection was ongoing to provide background information within which focused projects could be nested, and at which significant infrastructure (power, internet, staging areas, space for office trailers) could be available to support multiple research teams.

1.6   Site selection (location, plans)

The concept and need for a field research facility were first proposed in 1963 by Mr. Rudolph Savage, Chief of Research Division of the USACE Coastal Engineering Research Center, which led to the construction of the FRF. This earlier expressed need for a means of obtaining high-quality field measurements to better understand coastal processes dovetails perfectly with the DUNEX objectives, and thus the FRF was selected as the main experiment location (Figure 2). In addition to the long history of measurements at the FRF, the northern North Carolina Outer Banks is a region prone to frequent storms, has a built environment and developed beaches, sound-side marshes, rapid coastal evolution and along-coast variation, a widely variable dune system including aeolian transport, and existing and developing inlet systems.

A second location with more natural conditions and greater likelihood of overwash was selected at Pea Island National Wildlife Refuge, located 56 km (35 mi) south of the FRF on the Outer Banks (Figure 3). The third and final physical site for experimentation was referred to as Sound Side Research. Researchers performed Sound Side research at the FRF (collecting sound water level, groundwater level, and salinity information), near Oregon Inlet (studying inner bank erosion and marsh erosion associated with storms), and in the Pamlico-Albemarle Sound system (examining wave attenuation through marshes) Figure 4. In addition, aerial imagery overflights were conducted spanning all research sites to identify and examine overwash and breaching processes, as well as overall erosion and accretion. Figure 4 also provides an overview of data types collected at all locations within the DUNEX study regions.

Figure 2. US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Field Research Facility (FRF), property and pier in Duck, North Carolina (photo credit: FRF).

Figure 3. Pea Island National Wildlife Refuge (photo credit: Sherwood, US Geological Survey [USGS], 10 September 2021).

Figure 4. Map of the overall DUNEX study area showing the three sites (FRF, Pea Island Southern Site, Sound Side) with approximate sensor locations.
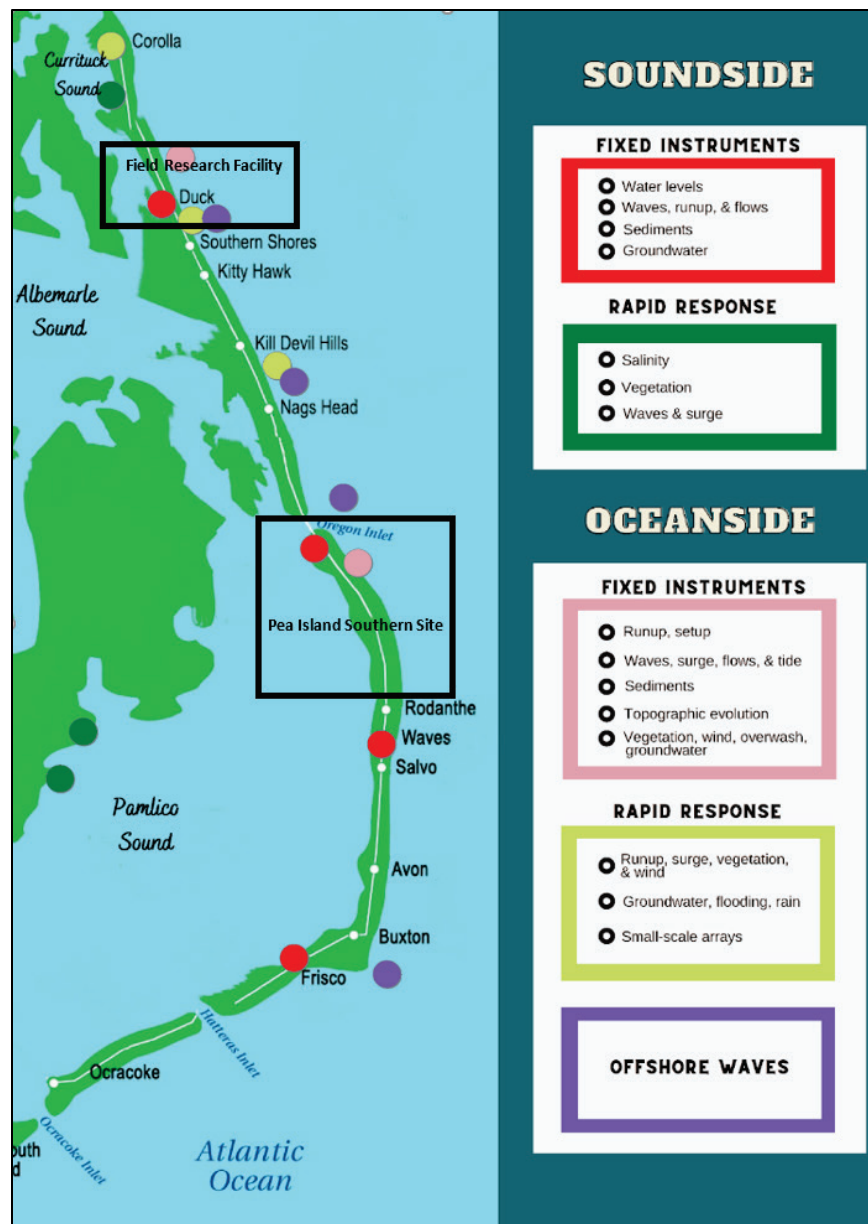
1.7   The collaborative spirit

The DLT for this large-scale experiment included individuals who brought both the academic and federal perspectives. This team was established with the underlying principle of promoting collaboration among researchers while keeping in mind the end goal of improved understanding of during-storm processes through this robust data-collection effort.

Collaboration among those interested in participating in DUNEX began soon after the logistics surveys were compiled. Specifically, in July 2019, the Logistics Team invited researchers who had completed logistics surveys to meet to discuss their interest and plans for the experiment during a series of 1 hr long virtual Coffee Hours. The DUNEX virtual Coffee Hours were webinars established to accomplish the following:

• Exchange data collection array plans, sampling strategies, and deployment timing to expand collaborations
• Explore how we might address larger multi-PI goals
• Share information about logistical support and needs
• Discuss data management efforts and develop a joint data management plan

These Coffee Hours occurred weekly or biweekly through 2022, except for a few breaks during the intensive field deployments and post-experiment holiday periods. The Coffee Hours were advertised via an internal forum set up, again, exclusively for the participating teams. This type of communication allowed the research teams to set their own internal day-to-day activities with an understanding of where support and/or partner teams might share anything from data to field labor. The DUNEX Coffee Hours were key to promoting the exchange of experiment plans among the research teams. Collectively, the group found areas of collaboration and planned improvements among the participating teams.

1.8 Funding sources

The overall experiment cost was on the order of $20M, with the majority of the investigators providing their own resources. The USCRP funded five research projects totaling $1.9M or approximately 10% of the total budget. The FRF Operations Support staff provided support to all researchers with logistics, trailers, data management, communications, and instrument deployments and recovery at a cost of $2M, an additional 10% of the total budget. Thus, approximately 80% of the total experiment cost was through external agency, academic, and nongovernmental organization contributions, emphasizing the value as perceived by these external partners in collaborating on this type of storm processes experiment.

2   Planning and Coordination

This chapter highlights the behind-the-scenes effort, time, coordination, and communication required to successfully plan and execute a large-scale field experiment. In addition to the logistical planning required for conducting scientific studies, the leadership needed to consider the coordination of these individual research efforts, the safety of participants, as well as the issues that could not be pinpointed or were otherwise unknown, such as weather, and in this case, a world-wide pandemic.

2.1   Leadership team planning and meetings

A DLT was formed in 2017 to organize the many aspects of planning a large-scale field experiment and facilitate the success of a diverse group of academic and federal researchers engaged in DUNEX from 2019 through 2021, including experiment logistics, data management, safety, and internal (PI) communications. The DLT also planned events around the individual studies, such as training opportunities, external communications (stakeholder coffee hours, Green Drinks (an international organization focused on networking opportunities for eco-minded members), public notices, videos, etc.), and a VIP Day.

The initial DLT members include representatives from USACE/USCRP Leadership (Cialone), FRF (Brodie), USACE Leadership (Deloach), academia (Raubenheimer), and USCRP Leadership (Stockdon). The scope of the DLT's responsibilities included the following:

- Establish science-focused objectives and direction for DUNEX
- Facilitate experiment planning in coordination with USCRP Leadership Virtual Program Office (VPO)
- Establish Sub-committees
- Resolve scheduling or objective conflicts among researchers
- Reach up (report to USCRP Executive Directors)
- Reach out to researchers (encourage participation and collaboration among DUNEX researchers)
- Reach out (stakeholders, coastal communities, public)
- Reach in (manage sub-teams within DUNEX structure)
- Identify community needs for agency support (e.g., data, research, infrastructure)

The DLT met biweekly and reported to the other team members on participation/interest survey responses, confirmation of participants, logistics (housing, trailers, deployments, monitoring, weather contingencies, pandemic impacts, etc.), scheduling, researcher coordination, methods of internal or external communication, and data management planning.

The science-focused objectives and direction for DUNEX were established by the leadership team to set the tone and grounding for the group to remain as their guiding principles for this large research endeavor. The objectives for the experiment were to (1) improve basic understanding, predictive capabilities, and observational technologies for extreme storm processes and impacts within the coastal environment and (2) collaborate and leverage research efforts from each research team to collect and analyze data from the same region prior to, during, and following coastal storms.

The subteams formed by the DLT were established to keep the pre-, during-, and post-experiment activities organized, safe, and successful. The DUNEX subteams included logistics, communications, training, data management, and interagency collaboration.

2.2   Logistics

In the initial phase of the DUNEX Pilot Study planning process, each of the subcommittees met with the DLT monthly and interacted with the other subcommittees as needed. The Logistics Subcommittee interacted with all subteams because they were essentially the hub of physically acceptable aspects of conducting the field experiment. They were responsible for determining and scheduling the physical experiment and training locations, instrument deployments and recoveries, office space, internet access, and other tasks.

The Full Logistics Team consisted of PIs from each participating science group in collaboration with NSF-funded grant researchers. The USGS provided logistical support to help FRF staff meet the operational demands of hosting a large field experiment.

The DUNEX Pilot and Full Experiment logistic surveys were used to identify interest in related researcher initiatives to facilitate collaboration, define common data needs that could be provided by agency collaborators,

detail logistical support needs, and outline potential training topics of interest to the participants.

During the planning of DUNEX, the Leadership Committee decided that interagency coordination would happen at the USCRP level. The USCRP then worked with federal researchers on interagency coordination. Researchers, including Dr. Nick Cohn, assisted in external collaborations and permitting with federal agencies; Dr. Jenna Brown coordinated USGS collaborations; and Dr. Brian McFall coordinated USACE collaborations.

2.3   Data management

One of the more complex organizational aspects of DUNEX, with many federal agencies and academic institutions participating in DUNEX, was the organization, management, and sharing of data with other participants and the general public. The DLT's awareness of the importance and complexity of data management from a large-scale field experiment led to the intentional development of a data-sharing plan that encouraged or required all DUNEX participants to support data sharing. Prior to the 2019 DUNEX Pilot Study, the Data Management Team (DMT) drafted a data sharing plan for post experiment data hosting and sharing. The intent was to use pilot data to test the plan and publish a final data sharing plan well in advance of the 2021 DUNEX Main Experiment. The DMT compiled information about each sensor deployed during the experiment such as the sensor type, location, and time of data collection. This information is accessible through the web-based DUNEX Story Map (USCRP 2013) for all researchers to access. The plan was circulated among the researchers for review and final acceptance. The data are also discoverable by enabling a metadata catalog on multiple platforms (such as Data.gov, google dataset, ArcGIS Hub).

Key points of the data sharing plan are the following:

- **Timeline**: Participants are encouraged to make data available to other DUNEX PIs within 1 yr and to the public within 4.5 yr of data collection.
- **Format**: Participants are encouraged to make processed data available as NetCDF files with associated metadata.
- **Data Management**: Participants are responsible for distribution of raw data. Participants are encouraged to store and share processed

data files via a standard public server (e.g., USACE–Thematic Real-Time Environmental Distributed Data Services (THREDDS) Environmental Research Division's Data Access Program (ERDDAP), USGS–Sciencebase.gov/THREDDS/ERDDAP, NSF, and others–DesignSafe-CI). All data sets will have digital object identifiers (DOIs) and acknowledgement statements. The following good citizenship practices are recommended when using others' data: (1) data should generally be shared openly between PIs; (2) when accessing the data for the first time, the user should send an email to the data collector to acknowledge use of their data and to discuss ideas/goals of interest/use with the collector to avoid duplication of efforts; (3) specifically acknowledge the data collector and funding source during all talks (verbally) and in all publications (reference DOI); and (4) treat the use and acknowledgment of others' data as you would want your data to be handled.

- **Data Sharing Support**: The DUNEX DMT developed scripts to sync data in NetCDF files on the standard servers to a centralized server(s), and distribute as needed, and developed example scripts/tools to help participants exchange and use each other's data. Tools and scripts will be shared via GitHub or another publicly accessible repositories. The DMT and the Data Sharing/Management Plan are available to guide researchers in preparing their data for distribution.

2.4 Training

Training for the DUNEX Pilot Study included traditional lectures focused on coastal processes, along with field exercises/trips that focused on some aspect of the lecture topic (e.g., traveling to one of the experiment sites to learn more about wave breaking or dune scarping).

The Pilot Study also included a series of Technical Talks (in-person at the FRF with others joining by webinar) that were conducted by the DUNEX PIs. They discussed their experiment plan, preliminary results, and new field methods and theories to foster networking and seek new ideas from each other. The DUNEX Full Experiment Training was focused on hands-on training in field methods, geared towards the different types of instrumentation. This training included data collection methods, datums, data analysis and interpretation, data and instrument uncertainty, and experiment design. The training was offered to students, staff from federal agencies, local coastal managers, and other interested parties.

2.5 Communication Team

The DUNEX Communication Team was responsible for internal communications with the PIs, upward reporting to federal agencies (particularly USACE), as well as external communications with the public/stakeholders to inform, promote, and advertise the research being conducted and its relevance to society.

Internal Communication. The DUNEX Communication Team's role regarding internal communication was a shared role with the Logistics Team and included the following:

- Perform DUNEX daily check-ins (in-person meetings in a FRF conference room) to communicate the logistics planned for that day and provide PIs with any communications updates
- Monitor the DUNEX slack channel mainly used by DUNEX PIs and the Communication Team to send quick updates throughout the day
- Set up the DUNEX Research Forum for PIs to share emails in a closed environment
- Set up a DUNEX weekly mailing to notify PIs of who will be collecting what data for the upcoming week
- Keep track of all PIs on site by having them go through a check-in process to gather information such as their email, cell phone number, all team members, lodging location, and length of stay at DUNEX

Agency Communication. The DUNEX Communication Team was also responsible for preparing information for the federal agencies (mainly USACE) with information that could be reported upward to agency leadership, included laboratory leadership (CHL), research leadership (ERDC), and USACE Headquarters (HQ). The Communication Team prepared press releases, DUNEX storyboards, DUNEX VIP Day information, and Civil Works (CW) contributions to the weekly update to USACE-HQ referred to as the CW Weekly.

External Communication. Communicating with stakeholders and the general public by the DUNEX Communication Team involved three time scales. In the short term, the DUNEX Communication Team shared information with the public through social media (Twitter: @uscoastalresearch; Instagram: @USCRP; and Facebook: @uscoastalresearch). These forms of communication allowed the team to

quickly and concisely broadcast the day-to-day happenings at DUNEX. In the midterm communications, the team prepared more detailed press releases, blog posts, and information about the DUNEX VIP Day that were prepared throughout the 2021 DUNEX Main Experiment time period. In the longer term, mainly following the conclusion of the field data collection, the DUNEX Communication Team prepared newspaper and magazine articles, and continues to gather research outcomes.

2.6 DUNEX research teams

Research teams were designed to operate independently within the overall DUNEX objective of obtaining observational data to improve the representation of nearshore extreme event processes, with the goals of improving our ability to accomplish the following:

- Predict storm processes and impacts
- Estimate model accuracy and sources of error
- Develop strategies for coastal resilience
- Provide storm impact information to communities

Research teams were also expected to collaborate with, support, and respect the DUNEX organizational teams to enhance the capabilities and experience of all researchers. Research team members were asked to consider the broadest possible aspects of the priority research needs expressed by USCRP participants (academic programs, federal and state agencies, nongovernmental organizations [NGOs], coastal communities). Each team was expected to participate in virtual Coffee Hours (see next section) as early as possible before the actual deployments to discuss and coordinate their experiment or, at a minimum, communicate their experiment plan to the full DUNEX team. The DUNEX research teams also communicated upward to the DLT monthly (and sometimes more often) to keep them abreast of the individual and collective research plans.

2.7 Virtual Coffee Hours

The DUNEX virtual Coffee Hours were informal, mainly web-based and some in-person gatherings of PIs and stakeholders. The DLT hosted three types of virtual Coffee Hours to (1) improve communication among PIs, (2) improve PI collaboration, and (3) listen to and gather information about stakeholder needs and share PI research findings with stakeholders.

2.7.1 Principal Investigator (PI) focused

Raubenheimer, the academic representative on the DLT and one of the DUNEX researchers, organized and hosted Coffee Hours. Twelve Coffee Hours were held from July through September 2019 for individual DUNEX researchers to share and discuss their experiment plans and goals. In addition, several Coffee Hours were organized during the DUNEX Pilot experiment, including sharing (1) preliminary observations with the DUNEX group, (2) information with researchers and stakeholders, and (3) information with a broader group of scientists across the country. Finally, two Coffee Hours were arranged following the Pilot Study to discuss preliminary results and lessons learned that could be applied to improve the main experiment.

Nineteen Coffee Hours were held in 2020 covering plans by individual researchers, joint rapid response plans, preliminary observations from rapid-response observations of Tropical Storm Arthur, data gaps, coordination between the FRF and Pea Island deployments, and COVID impacts on planning (including the delay of the 2020 field study).

Twelve Coffee Hours were held during winter-summer 2021 (prior to the intensive deployment period) including fieldwork updates, discussions of communications, data sharing and management, deployment planning, training, bathymetry needs, and explorations for collaborations between individual modeling efforts, radar and in situ plans, a new real-time water-level network, and rapid deployments. In addition, three stakeholder Coffee Hours (see below) were held during 2021. Six Coffee Hours were held during winter 2022 describing preliminary results, national parks management needs, communications, and data sharing and management tools.

2.7.2 PI collaboration through 2019–2021 Coffee Hours

New collaborations were sparked by the DUNEX Coffee Hour discussions and through leveraging of the logistical support provided by the DLT and FRF staff. The year delay of the DUNEX Main Experiment owing to the COVID-19 pandemic had the beneficial effect of providing additional time to develop and expand these collaborations. Furthermore, the delay provided additional time to process and examine the measurements collected during the DUNEX Pilot Study, which led to revisions and improvements in joint deployment plans. For example, DUNEX Coffee

Hour discussions led to Drs. Nina Stark and Navid Jafari assisting with the Oregon Inlet studies by collecting geotechnical information. Coffee Hour discussions also led to collaborations between Stark and Raubenheimer to use vertical arrays of pressure gauges in concert with swash velocities to examine sediment liquefaction, and between Dr. Brittany Bruder and Raubenheimer to examine alongshore-variable swash processes. The availability of logistical support enabled Dr. James Heiss to be entrained into the study to examine ocean-groundwater interactions and impacts of major storms. Collaborations that began during the 2019 DUNEX Pilot Study were expanded in 2021, and 2021 array plans were developed jointly between multiple groups to expand the impact of individual studies.

In addition, discussions during the field studies led to leveraging of data and enhanced observations. For example, during the 2021 DUNEX Main Experiment, daily observations were exchanged between research groups, leading to combined information about eddies observed by drifters, optical remote sensing, and in situ instruments. Beach-moisture content measured by Cohn, Raubenheimer, and Stark were used jointly in their studies of Aeolian transport, swash zone infiltration and exfiltration and groundwater processes, and beach geotechnical processes. Discussions between researchers identified the need for additional flow measurements to investigate swash-vegetation interactions, leading to sharing of instruments.

The study at Pea Island was strengthened by collaborations between the USGS (Sherwood, Brown), academic researchers (Dr. Peter Traykovski, Dr. Katherine Anarde, Dr. Ryan Mieras), and logistical support from DUNEX. The USGS and Traykovski collaborated to collect topographic and bathymetric data of the site during the DUNEX Main Experiment. Additionally, the USGS provided resources for installing a cross-shore set of pipes spanning the surf zone and beach/dune, which allowed for multiple water-level and bed-tracking sensors from USGS, Anarde, and Mieras to be deployed on the beach, and oceanographic sensors to measure waves, water levels, and sediment transport were installed by USGS in the nearshore to supplement the beach measurements. Sharing logistical resources allowed for academic groups to support more students through shared funding and data collection to support student research.

Last, the DUNEX research teams envision the potential for future collaborations comparing and contrasting processes at Pea Island with those observed 56 km to the north (N) at the FRF.

2.7.3 Stakeholder-PI joint gatherings

The USCRP has three main scientific objectives (long-term processes, storm processes/impacts, and human/ecosystem health); the USCRP leadership also recognized the importance of stakeholder engagement to determine the most important research from a community need perspective and how to translate scientific findings into practical applications. For example, prior to DUNEX, the USCRP engaged stakeholders in the 2015 Dune Workshop, and those stakeholders provided input on their greatest coastal challenges. The stakeholders also came away with a better understanding of the protective nature of dune systems that they could then share with their communities and constituents. Ms. Roberta Thurman, the Public Information Officer for the Town of Nags Head, was one such stakeholder, and she expressed that engaging with dune researchers allowed her to merge her practical knowledge of the importance of stable dune systems to coastal protection with the technical aspects that she learned at the workshop.

Dr. Nicole Elko, Science Director of the ASBPA and one of the three executive directors of the USCRP, joined the DLT to help foster stakeholder engagement and communication because the USCRP recognized its importance, as stated above. Elko first spearheaded the development of a video for stakeholders[2] and interviewed stakeholders to communicate their top coastal management challenges with DUNEX researchers. This video describes some of the stakeholders' challenges and researchers' plans that are aimed at improving coastal resilience through DUNEX research. Coastal managers can use the researchers' findings to make decisions on preparing for storms and potentially preventing their impacts. Ultimately, scientific advancements from the DUNEX research and data collection will facilitate the translation of these research findings into practical application for coastal stakeholders.

Dr. Elko also organized three Stakeholder-PI DUNEX Coffee Hour sessions to invite stakeholders to discuss their coastal management research needs and for PIs to discuss potential methods to address them. Though DUNEX Coffee Hours were initially conceptualized by researchers for researchers, these specific stakeholder series of DUNEX Coffee Hours were aimed at bringing the stakeholder perspective and coastal

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[2] https://www.youtube.com/watch?v=EJX1wJrW4vk

management challenges to the experiment. The interaction of stakeholders and DUNEX PIs was geared towards providing the PIs with a better understanding of stakeholders needs and the general societally relevant challenges faced by coastal decision-makers so that PIs could address those needs and challenges in their research.

Each Coffee Hour began with a brief presentation by a coastal management stakeholder on a coastal management challenge/research need followed by an open, informal conversation for other coastal managers to express their coastal challenges related to the topic. DUNEX researchers provided potential methods for addressing the coastal management challenge at DUNEX 2021 or with future research or transition of ongoing research into application. The three coastal management Coffee Hours held in 2020 included the following:

- March 12: **Dune Overtopping,** Opening Stakeholder Perspective on Dune Overtopping: Mr. Michael Flynn, NC Coastal Federation
- April 9: **Soundside Erosion,** Opening Stakeholder Perspective on Soundside Erosion: Ms. Elizabeth Smyre, Dewberry
- May 7: **Beach Nourishment,** Opening Stakeholder Perspective on Beach Nourishment: Mr. Ken Willson, Coastal Protection and Engineering

Stakeholders were also invited to attend the DUNEX VIP Day discussed in Chapter 5.

3   DUNEX 2019 Pilot Study

3.1   Introduction

The Fall 2019 DUNEX Pilot Study was designed to allow researchers to test field methods, equipment, and logistics. The Pilot Study also served as an opportunity for the planning and organization teams to evaluate their efforts, review their decisions, look for gaps in meeting the DUNEX goals and objectives, and make adjustments for the DUNEX Main Experiment, originally scheduled for the following year. In general, the DUNEX Pilot Study met expectations, with 18 teams participating, including 11 universities, to begin the during-storm data collection process. Additional airborne data collection and imagery were provided by the USGS and USACE during the DUNEX Pilot Study.

Some of the teams began their work in late August 2019 and remained on site for up to 6 weeks, including during Hurricane Dorian. A week-long, formal training week was held in late September at the FRF, which was deemed to be successful, but more hands-on training and interaction with the researchers was thought to be a better approach for the DUNEX Main Experiment. The NSF's Rapid Response Research (referred to as RAPID) team was on site in early October. The inclusion of the RAPID team brought most research teams to the DUNEX site during the October time period. Post-Tropical Storm Melissa (with wave heights in 26 m water depth of up to 4 m) came through the area during the RAPID week. A second storm passed through the area in late October (offshore wave heights up to 3.9 m) while a few teams remained on site. Because of the large number of research teams on site during the October 2019 time period, it provided the Logistics Team with a good opportunity to focus on what was working well and what needed to be adjusted logistically for the DUNEX Main Experiment. Following the DUNEX Pilot Study, each of the organizing team leads prepared a lessons-learned summary, which was used to plan for the 2020 limited field season and the DUNEX Main Experiment in 2021.

Additionally, the leadership team held discussions about the breadth of the experiments from a technical standpoint as well as meeting all of the DUNEX goals and objectives. One DUNEX goal, where progress seemed to be lacking, was in improving communication between scientists and the coastal community to facilitate the translation of scientific research into

use. As a result, an initiative began to better engage stakeholders with focused communications.

This chapter provides an overview of the study sites where research was conducted in 2019, the logistics required for conducting this smaller scale, test run experiment, and a summary of the research conducted during the DUNEX Pilot Study.

3.2 Experiment sites

The DUNEX series of experiments was conducted at three fixed sites discussed below. In addition to the three specific sites, the USGS provided 13 regional aerial imagery surveys (Figure 5) covering the entire area from September 2019 to June 2022, capturing the impacts of Hurricane Dorian (2019) and the subsequent recovery and impacts of the 2020 and 2021 hurricane seasons. (Note that an additional USGS aerial image survey was conducted post Hurricane Florence in October 2018, prior to the DUNEX data collection time period but is potentially beneficial as pre-DUNEX conditions.)

3.2.1 Field Research Facility (FRF)

The FRF is located on the Atlantic Ocean near Duck, North Carolina. Since construction of the 560 m long research pier in 1977, USACE, as well as other federal and academic researchers, has been collecting coastal data and conducting experiments at the FRF, making this stretch of coastline one of the most studied coastal locations in the world. Because of the long-term data measurements from a suite of instruments and remote sensing technologies (video, radar, sonar, and lidar) available at the FRF for measuring hydrodynamic and meteorological conditions as well as specialized vessels such as the Coastal Research Amphibious Buggy (CRAB) and 5-ton Lighter Amphibious Resupply Cargo vessels (LARC-V) to conduct surveys and deploy instruments and a 43 m observation tower, the FRF was selected as *home base* for DUNEX. The FRF's continuous, routine data collection was used to supplement what researchers intended to measure during the experiment, and the infrastructure in place at the FRF was a support system for the researchers. The spatial extent of experiments conducted at the FRF was 1 km by 1 km.

3.2.2 Southern Site

Pea Island is located 56 km (35 mi) south of the FRF and is referred to by the DUNEX team as the Southern Site. The Pea Island National Wildlife Refuge is a relatively undisturbed barrier island, with alongshore variable dune heights and vegetation coverage. Although the site is prone to overwash, the dunes provide protection and conservation of migratory birds and other wildlife along the coast and within the back-barrier wetlands. This 150 m × 250 m location was selected for conducting experiments because of the more natural condition and greater likelihood of overwash occurring there. Refer to Figure 5 for a picture of the Southern Site.

Figure 5. Aerial image overlooking the Southern Site (photo credit: C. Wayne Wright, 20 September 2021).

3.2.3 Sound Side: Pea Island, Currituck Sound, Pamlico Sound

DUNEX site number 3 was referred to as Sound Side Research at Pea Island, Currituck Sound, Pamlico Sound, and the FRF (Figure 4). Researchers performed sound-side research near Pea Island National Wildlife Refuge located approximately 30 mi south of the FRF studying inner bank erosion/marsh erosion associated with storms, and research at Pamlico Sound approximately 60 mi south of the FRF focused on salinity,

vegetation, and waves. The Currituck Sound is approximately 35 mi north (N) of the FRF where research focused on examining wave attenuation through marshes.

3.3 Storm climatology

During the DUNEX Pilot Study time period (September 2019 to November 2019), significant wave heights ranged from 0.2 m to almost 5.0 m, storm surge was as much as approximately 1 m, wave directions ranged from 40° to 100° (relative to True North), mean wave periods ranged from approximately 5 to 13 s, and wind speeds were as high as 35 m/s (Figure 6). Waves typically approached the shoreline from the east to the east-northeast (ENE), with the largest waves from the ENE (Figure 7). The winds were most often from the northeast (NE), but the strongest winds (>15 m/s) were from the southeast (SE), NE, and N (Figure 8). During this time period, Hurricane Dorian passed near Cape Hatteras, generating waves of almost 5 m (in 8 m water depth) in early September 2019, and post-Tropical Storm Melissa passed offshore with 3 m waves from 8 to 10 October 2019.

Figure 6. Climatology during the DUNEX Pilot Study, including (*from top to bottom*) tidal fluctuations National Oceanic and Atmospheric Administration (NOAA) tide gage at the offshore end of the pier); 8 m water depth significant wave height, incident wave direction, and wave period; and wind speed and direction measured at the offshore end of the pier versus date in 2019.
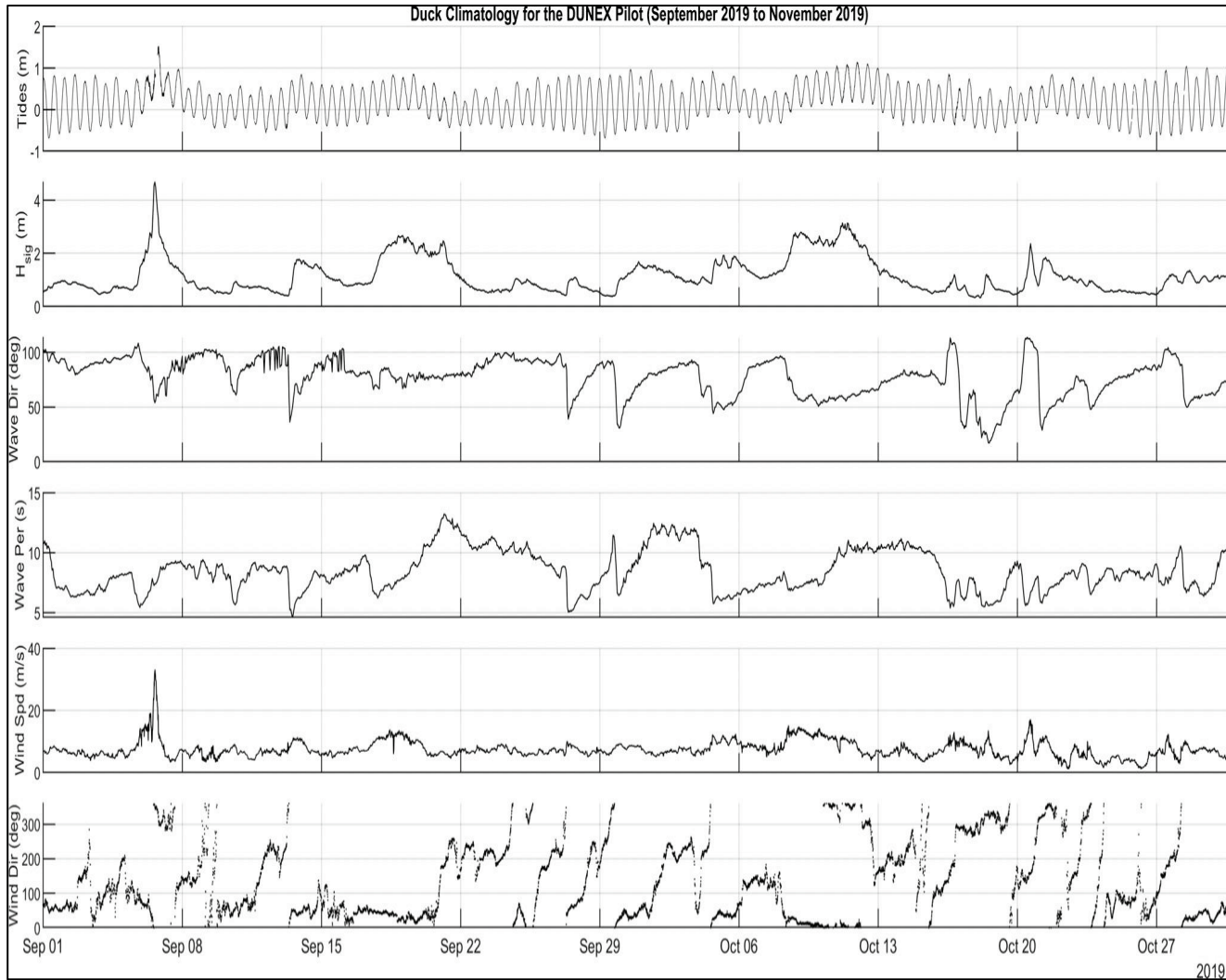
Figure 7. Wave rose for the DUNEX Pilot Study time period (September–November 2019) indicating frequency (length of bars) of wave heights (colors, key at bottom) and incident wave.

DUNEX Pilot Wave Conditions (September 2019 to November 2019)

Wave Height (m)

0 to 0.5   0.5 to 1   1 to 1.5   1.5 to 2   2 to 2.5   > 2.5
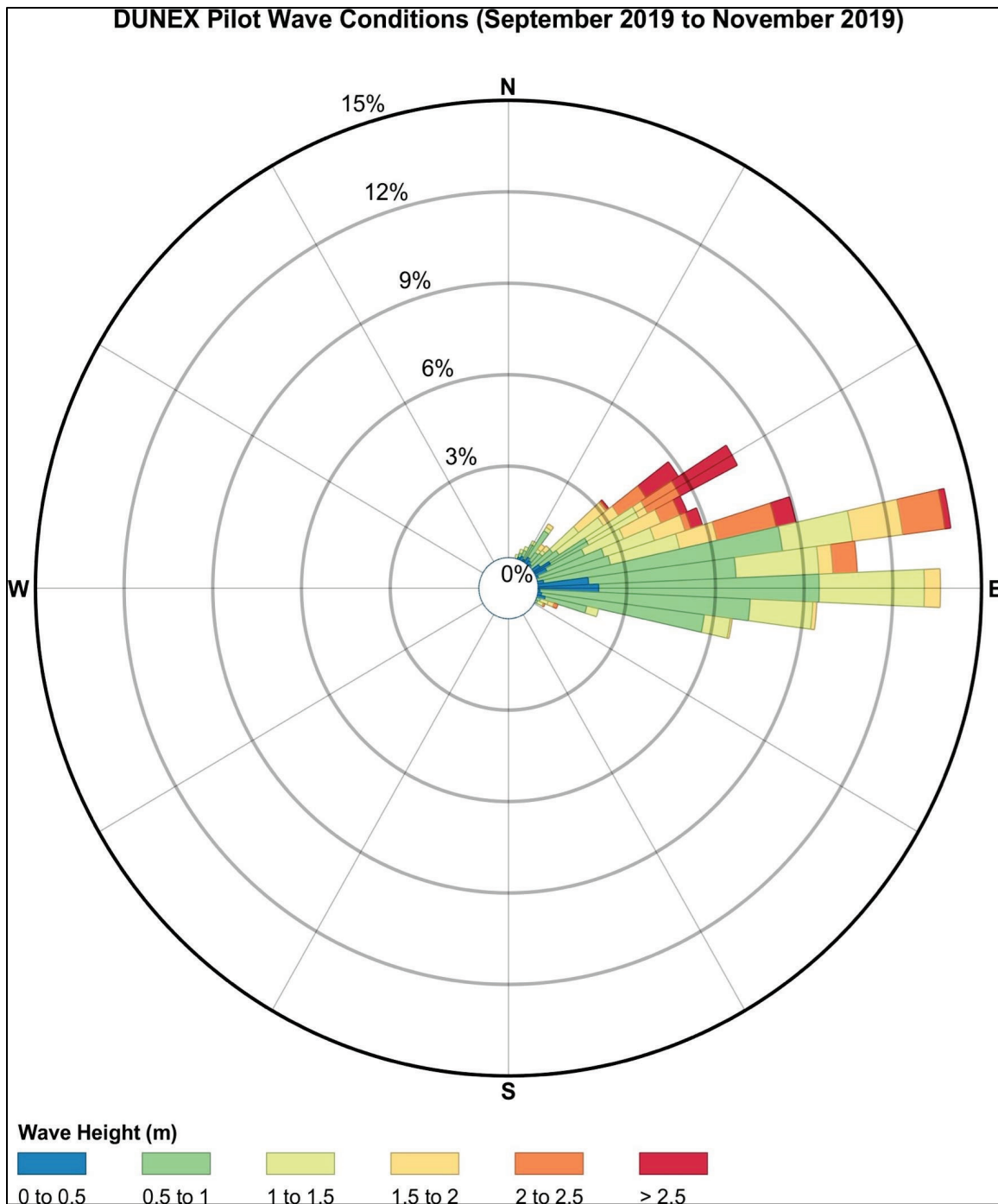
Figure 8. Wind rose for the DUNEX Pilot Study time period (September–November 2019) indicating frequency (length of bars) of wind speeds (colors, key at bottom) and wind directions.
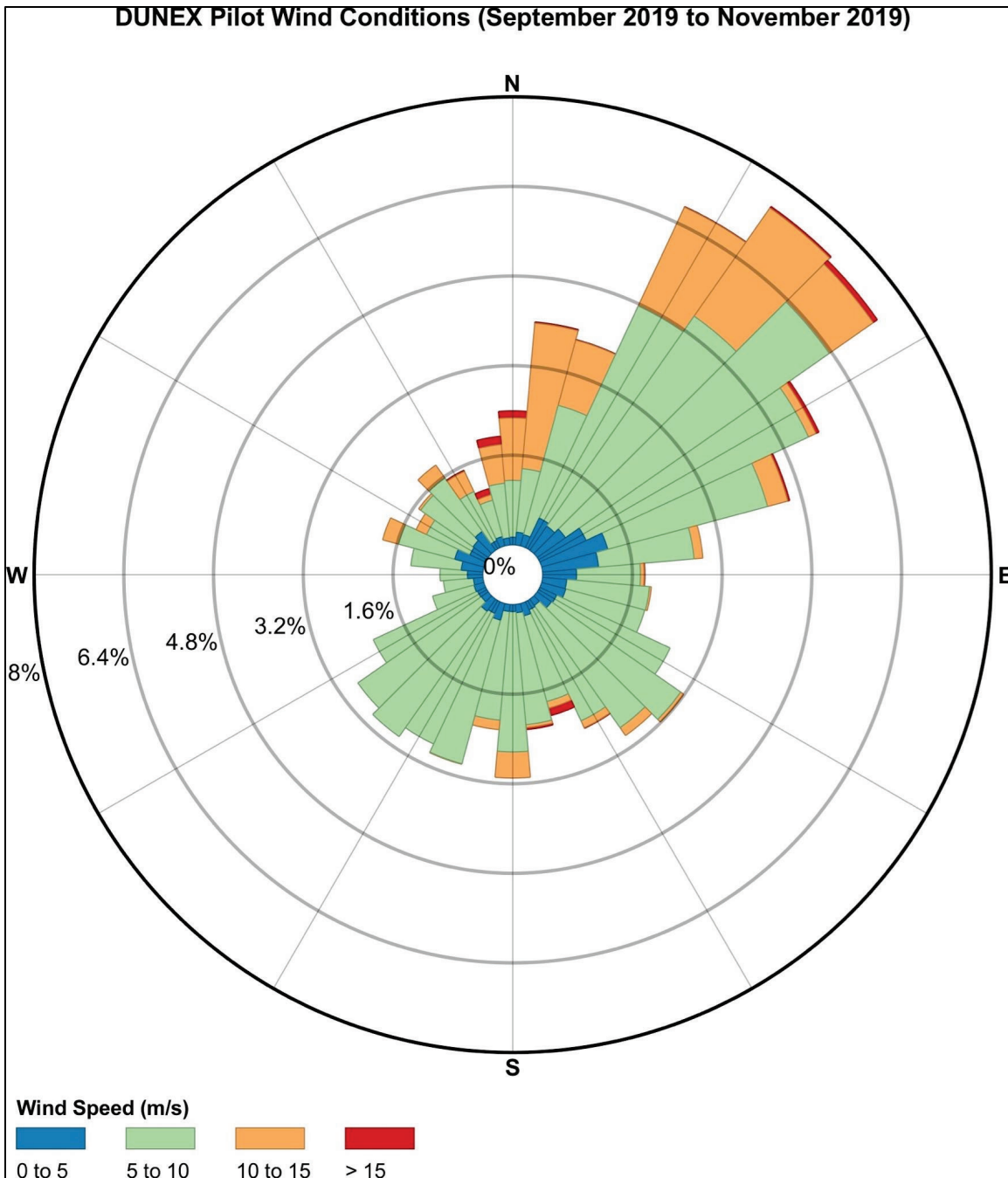
3.4   Logistics

An initial step in holding the DUNEX Pilot Study was to determine researcher interest in and likelihood to participate in such an experiment by advertising the study to the USCRP membership list, community email coastal list, and conferences. To be eligible for the DUNEX Pilot Study, researchers who were interested in participating submitted the DUNEX Logistics Surveys 6 to 9 months before the experiment began, agreeing to conduct their research within the study area limits (see Experiment Sites section) and with a collaborative spirit, that is, participate in DUNEX meetings, share data, etc. The survey described the intent of the experiment and requested information on the researchers' scientific interest and data requirements. The number of potential participants that completed logistics surveys was within the logistics teams' capacity to monitor/guide/help during the experiment time period. The completed surveys were collated, and the DUNEX Logistics Team began the process of meeting with individual and groups of researchers to establish which researchers would be on site, the time period of the visit, their plan of study, and to clarify expectations that each team had for daily logistical support from the FRF staff. Some that responded to the initial inquiry did not participate due to lack of funding, time, and other factors. Only one project participant was not accepted for participation in the DUNEX Pilot Study because it was determined that the effort would negatively impact other research projects as well as the FRF's long-term measurements. A lesson learned from this part of the planning process was that requiring a logistics survey and follow-up communication is a vital step in preparing and coordinating a large number of people and instrumentation.

Once participants were selected, the next step was to determine if there were opportunities for collaboration among the participants. Because of the large number of researchers spread throughout the country and the frequency of meetings, the Logistics Team opted for virtual Coffee Hours where researchers gathered via webinar to promote the exchange of experiment plans among the research teams, as described in Chapter 2. Collectively, they found areas of collaboration and plan improvements among the participating teams and were able to conduct a successful pilot experiment. This type of communication allowed the teams to set their own internal day-to-day activities with an understanding of where support and/or partner teams might share anything from data to field labor. A lesson learned from this part of the planning process was that early and

often collaborative communication ensures information is cleared and agreed upon by all those involved in an aspect of the study.

Because of the large number of research teams on site for the relatively small DUNEX Pilot Study, the Logistics Team had ample opportunity to focus on what worked well and what needed to be adjusted logistically for the full experiment.

3.5 DUNEX pilot research projects

A total of 18 research teams participated in the DUNEX Pilot Study, including 11 universities supporting 14 students and 7 federal teams deploying 187 instruments during the DUNEX Pilot Study (see Appendix C) (Figure 9). The research teams were also supported by USGS and USACE researchers contributing aerial panchromatic and lidar-based imagery and elevation data, both terrestrial and bathymetric. In addition, the FRF staff contributed routinely collected operational datasets (wind, waves, water levels, currents, etc.), countless hours of kinematic GPS at experiment locations, as well as day-to-day logistical support during the field study. The logistical support included office space, high-speed internet arranged specifically for the research teams, supporting skilled labor for installation of experiments, and beach area transportation. Some of the teams began their work in late August 2019 and remained on site for up to 6 weeks, including the time period when the region was impacted by Hurricane Dorian in early September 2019. All 18 team contributions are highlighted on the DUNEX Pilot Study StoryMap (USCRP, n.d.) and are summarized in Appendix C.

A significant example of team collaboration that occurred during the DUNEX Pilot Study was the involvement of the Natural Hazards Engineering Research Infrastructure: Natural Hazards Reconnaissance RAPID Facility (RAPID, n.d.) in the DUNEX Pilot Study. This team, funded by the NSF, provides equipment, software, and technical support to collect, process, and analyze perishable data from natural hazards. The team includes staff from the University of Washington (UW) with collaboration from Virginia Polytechnic Institute and State University (VTECH), Oregon State University (OSU), and the University of Florida. The RAPID team members were on site 7–11 October 2019, providing equipment and training to all the research teams that indicated interest in

their support. This also happened to be the week that saw a significant coastal storm along the study reach.

Figure 9. DUNEX Pilot Study instruments deployed. More information can be found at the DUNEX Pilot Story Map (USCRP 2013; https://erdcchl.maps.arcgis.com/apps/MapJournal/index.html?appid=fc4c86ee3c44481990400ce8e2f 680df).
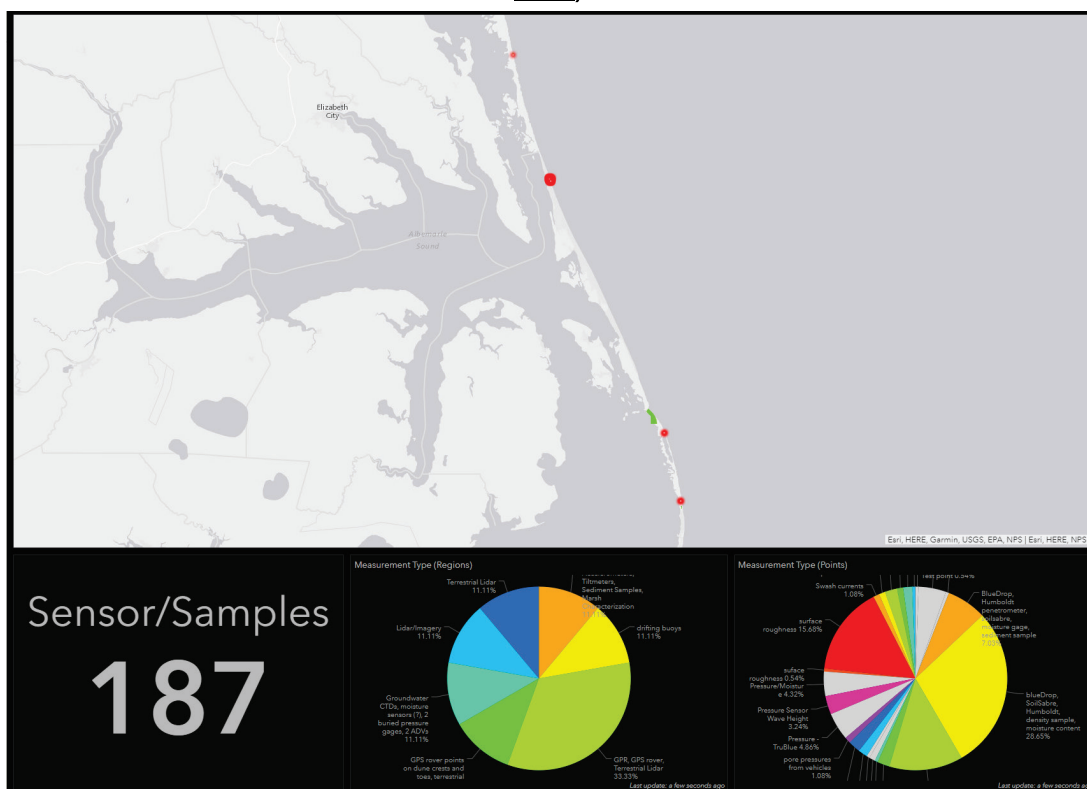
3.6 Formal training 2019

A 1-week formal training session was held in late September at the FRF with leading trainers Drs. Jane Smith and Katie Brutsché providing students with formal lectures, semi-informal technical talks, hands-on (field) training, a combination of hands-on and lecture for some topic areas, and interaction with researchers through demonstrations and testing of equipment. Though the training was deemed to be successful and student feedback was positive, a lesson learned from this effort was that the unique opportunity of a collaborative experiment lends itself to more hands-on training and interaction with the research teams, and these aspects of training would provide the most benefit to students.

3.7 Summary

In general, the DUNEX Pilot Study met expectations, with 18 teams participating including 11 universities, to test methods, equipment, and logistics. The research teams were also able to begin the during-storm data collection process. Additional airborne data collection and imagery were provided by the USGS and USACE.

The leadership team held discussions about the breadth of the experiments from a technical standpoint in relation to all the DUNEX goals and objectives. One DUNEX goal, which seemed to be lacking during the Pilot Study, was improving communication between scientists and the coastal community to facilitate the translation of scientific research into use. As a result, a follow-on from the DUNEX Pilot Study was to better engage stakeholders with focused communications.

Following the DUNEX Pilot Study, each of the organizing team leads prepared a lessons-learned summary, which was used to plan for the 2020 limited field season and the main DUNEX experiment in 2021.

4 2020 Activities during the Pandemic-Induced Stand-Down Year

Planning activities for the DUNEX Main Experiment began after the DUNEX Pilot Study, which coincided with the global response to the Coronavirus Pandemic (COVID-19). The DLT's initial response to the onset of the pandemic was to poll the participants to determine their willingness and ability to participate in the originally planned 2020 DUNEX Main Experiment, university travel restrictions, and personal concerns limiting participation. The results of the survey indicated there was unanimous consent to postpone the main experiment due to the COVID-19 pandemic. The DLT then held discussions with CHL senior leadership to better understand the implications and future plans for both funding carryover and manpower impacts of a 1 yr delay in experiment execution. Next, discussions were held with USCRP leadership regarding the experiment delay and where to focus the time/efforts in the interim year to keep momentum and interest in the experiment and keep PIs informed of the experiment status. Finally, the DLT conducted a second survey of those PIs that had expressed interest in the 2020 DUNEX Main Experiment regarding the impacts of a delay on their ability to participate in 2021. As a result of these numerous discussions and considerations, including the unanimous consensus to postpone from PI survey responses, the rapid and continued spread and evolution of COVID infections in late spring/early summer 2020, and the concern for the personal health and well-being of the researchers, the decision was made to postpone the DUNEX Main Experiment to 2021.

4.1 Activities

Limited field work was conducted by the PIs in 2020 (focused on building capacity for 2021) and required social distancing, minimizing utilization of resources (funding) that would support the 2021 DUNEX Main Experiment, adhering to travel restrictions as well as Army and local/state guidelines related to the pandemic. The DLT worked to ensure funding planned for the 2020 DUNEX Logistics Team would be permitted to carry over for use in the 2021 DUNEX Main Experiment. The DLT worked with ERDC program managers and the CHL director for support and approval in carrying over DUNEX Logistics funding to fall 2021 (FY22) because of this unprecedented world condition.

Though the experiment delay may have appeared as a setback imposed by the pandemic, it was instead viewed as an opportunity for the DUNEX researchers PIs and the DUNEX Planning Teams (Leadership, Communications, Logistics, Data Management, and Training Teams) to plan for and conduct an even more robust field campaign in 2021. The DLT redirected their focus to maintaining the energy and collaborative spirit created among the researchers that developed during the DUNEX Pilot Study, while the researchers stepped back from actual field work and instead had the opportunity to rethink/retool their experiment plans for the DUNEX Main Experiment. The DLT examined the specific implications of a delay and focused on using 2020 as an additional planning year to review the DUNEX Pilot Study findings, find gaps in meeting the DUNEX objectives that needed to be addressed, and refine the 2021 DUNEX Main Experiment plan. With the decision to postpone the DUNEX Main Experiment, the DLT then had the luxury of time in 2020 for (1) a more in-depth look backward at lessons learned from the DUNEX Pilot Study, (2) redirecting their present (2020) focus to maintaining the energy and collaborative spirit created among the researchers during the DUNEX Pilot Study, (3) researchers to step back from actual field work and instead have the opportunity to rethink/refine/discuss/form collaborations for their Main DUNEX Experiment, (4) researchers to discuss/test run rapid-deployment methods for storm-chasing experiments in the future, and (5) incorporating more stakeholder engagement into the DUNEX Main Experiment. The 2020 efforts towards a successful 2021 DUNEX Main Experiment are discussed in this chapter.

Prior to more complete knowledge of COVID-19 impacts on the planned 2020 DUNEX Main Experiment, PIs were invited to participate in weekly virtual web meetings in February/March 2020. These virtual webinars were likened to a scientific version of basketball's March Madness, where PIs gave a 4 min lightning round presentation of their 2020 experiment plan (prior to the realization of the need to postpone to 2021). Details of this activity are given in the section below.

During this unsettled time period in 2020, the DLT continued to meet to discuss, consider, and seek approval for holding the DUNEX Main Experiment in 2021 to ensure that DUNEX objectives were met. Specifically, the DLT had an opportunity to examine what worked well during the Pilot Study phase, what needed to be revised, and to consider how DUNEX could play a more significant role in coastal management

sooner than might typically occur in research studies. With the latter in mind, the DLT added a focus on stakeholder engagement while planning for the 2021 DUNEX Main Experiment.

4.2 Lessons learned from the DUNEX Pilot Study

The DUNEX Summary Report, *Lessons Learned from the DUNEX Pilot Study*[3], contains a complete description of the effort and conclusions (lessons learned) during a brief look back at the 2019 Pilot Study Experiment. This section of the report summarizes those findings.

4.2.1 Logistics surveys and follow-up communication are vital to the planning process for a successful field experiment.

The DLT concluded that their efforts in the planning for the 2019 DUNEX Pilot Study to communicate with potential and confirmed research participants through surveys, phone calls, emails, and web meetings were extremely important for establishing each participants' plan of study, the study team members and their contact information, the researchers intended study location and experiment time period, and most importantly, to clarify the expectations that each team had for daily logistical support from the local FRF Staff.

4.2.2 Collaborative communications early and during the experiment phase are important for logistical coordination and scientific exchange.

Correspondence, meetings, and collaboration among DUNEX Pilot Study participants began shortly after the Logistics Surveys were received from interested participants. The DUNEX Logistics Team began the outreach by responding to PIs that submitted Logistic Surveys for more detailed information on their intended participation in the DUNEX Pilot Study and to invite them to participate in DUNEX virtual Coffee Hours to exchange and improve their experiment plans. The PIs used this time to plan their day-to-day activities, and the added communication allowed them to understand where support and/or partner teams might share data, equipment, or possibly field labor/personnel.

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[3] DeLoach, S. R., M. A. Cialone, P. J. Dickhudt, M. F. Forte, J. M. Smith, and A. D. Renaud. 2020. *Lessons Learned from the DUNEX Pilot Study*. Vicksburg, MS: US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory.

4.2.3 Communication of DUNEX activities and results is essential for fostering and improving strategies for coastal resilience and developing effective communication methods for communities impacted by storms.

From the number of participants and the amount of data collected during the DUNEX Pilot Study, the Communication Team knew the importance of organizing the research teams' studies/findings and identifying methods to increase exchange of information because these factors would grow and become more complicated during the DUNEX Main Experiment. Therefore, the Communication Team established a web-based Geographic Information System (GIS)–published story map with a summary from each of the research teams, including the researchers' goals as well as the data-collection locations, time periods, and eventual inclusion of a link to the collected data. The DUNEX Pilot Story Map resides on the DUNEX page of the USCRP website (USCRP, n.d.), which is also home to blogs, FAQs, bulletins, and USCRP-funded academic research highlights which are posted and updated regularly.

4.2.4 Communication through the generation of a DUNEX Main Experiment video should concentrate on identification of the audience, collection of content, and video delivery methods prior to production.

Creation of the DUNEX Pilot Study video was limited to photographs taken by researchers, FRF Team members, and Communications Staff in an indiscriminate manner, which made creation of a comprehensive video documenting the DUNEX Pilot Study more challenging. For this reason, the DLT requested and encouraged all participants in the DUNEX Main Experiment to submit 10–15 still photographs of their experiment that could potentially be incorporated into production of a DUNEX Main Experiment video. Also, the Communication Team drafted a messaging plan to aid in development of the Main Experiment video, which was aimed at sharing the goals, individual experiment examples, and overall USCRP/DUNEX message to the larger coastal community. Finally, from the DUNEX Pilot Study, the Communication Team found that local media took note of this video messaging, which resulted in additional media outlets requesting early notification of field activities related to the DUNEX Main Experiment.

4.2.5 DUNEX Technical Talks (in-person and/or webinars) should encourage both coastal community planners and DUNEX research teams to initiate (1) transfer of research needs to experiment planning and (2) experiment findings to coastal community application.

Technical communication and training during the DUNEX Pilot Study supported the DUNEX goal of sharing information with research participants, nonparticipating coastal researchers, as well as coastal community leaders and managers. The series of technical talks, mainly presented via webinar but also allowing for public/researcher in-person participation at the FRF, included current nearshore coastal research that would be of interest to the widest possible audience. Social media was also used to advertise these events. To encourage more researcher/community interaction, two of the technical talks were given to a local environmental interest group (Green Drinks OBX; https://obxgreendrinks.blogspot.com/) that meets at a local restaurant. The technical talks included (1) a citizen science project documenting coastal change and a method for improving understanding of coastal flooding and (2) sound-side flooding at Oregon Inlet, the physics of dune erosion, and aeolian transport on a wet beach. From these technical talks, the DLT learned that more interaction, encouraging community leaders to present and express the coastal management needs, and encouraging researchers to begin or continue to address those needs will enhance the benefits of the research and was incorporated in the DUNEX Main Experiment with more stakeholder engagement.

4.2.6 Pretrained support staff is an essential element of a successful field experiment.

During the DUNEX Pilot Study planning discussions, a committee was established to support logistical issues related to federal agency collaboration, internal USACE participation, and support staff training. This team determined the following:

1. Initial discussions assumed that substantial effort would be required to facilitate experiment efforts among the federal agencies that would participate. In general, those federal agencies engaged in the on-site data collection coordinated with the logistics team to help ensure expectations of their research teams and the FRF support team were met with little/no issue. Coordination was key to the seamless execution.

2. The DUNEX Pilot Study experiments provided an opportunity for newer ERDC scientists to participate with several PIs and their research teams to broaden their knowledge of field experiment methods and coastal processes.

3. The internal USACE coordination of scientists and support staff from other parts of CHL as well as USGS proved beneficial to both the DUNEX research teams and the FRF staff needing additional logistical support. This support activity training on equipment, deployment, and retrieval methods, as well as safety protocols during the DUNEX Pilot Study was one of the most beneficial components of the interagency coordination. Extra trained support staff served the greater need for support during the 2021 DUNEX Main Experiment.

4.2.7 Flexibility is essential in any field-deployment exercise.

Remaining flexible when faced with the entire experiment being postponed due to the pandemic, as well as equipment/shipping delays, equipment failures, and social distancing requirements when trying to work as a field team, is challenging. However, by using the DUNEX Full Experiment delay as an advantage meant considering it as an opportunity for more planning time, coordination, collaboration, learning from each other, engaging stakeholders, and communicating findings. The DLT applied this optimistic outlook to the delay and conveyed this message to the entire research team to keep the momentum from the DUNEX Pilot Study continuing through 2020 and into the 2021 DUNEX Main Experiment season. As with any experiment, equipment may fail or not arrive, but the shipping delays induced by the pandemic made the equipment arrival/access more challenging than normal. All researchers prevailed, with some delays from their original deployment plan date. Finally, social distancing requirements due to the pandemic meant indoor gatherings were discouraged and outdoor/field interactions were to be 6 ft apart, which was challenging particularly when working on a vessel or jetting in an instrument. Again, the FRF staff and DUNEX PIs approached this logistical challenge and were able to deploy all instrumentations successfully. Group gatherings were limited to masked indoor meetings, web meetings, and outdoor social events.

4.3   Modify training

Following the 2019 DUNEX Pilot Study, which included more formal classroom lectures combined with some interactive/hands-on components

and equipment testing demonstrations, the DLT discussed modifying the training to connect students more directly with DUNEX researchers. The DLT continued this discussion over a few months' time span, allowing all DLT members the opportunity to explore ideas and reach a consensus. The result was a refocus of training activities that would encourage direct engagement between DUNEX researchers and those seeking training on activities associated with DUNEX experiments, referred to simply as, hands-on training experiences. This format allows volunteers/trainees to engage directly with the science teams during data collection and foster learning outside of the formal classroom setting.

4.4 Maintaining communication, focus, and energy

From Spring 2020 to Spring 2021, the interim period between the Pilot Study season and the DUNEX Main Experiment, the DLT focused on what was learned from the DUNEX Pilot Study, how to better and more quickly address stakeholder engagement and coastal management, reviewed experiment plans and overall organization, sought approval for holding the main experiment in 2021, looked for DUNEX objectives not being addressed, and worked to ensure communication with all the PIs and members of the organization and supporting teams remained intact. Note that some DUNEX field activity did occur in 2020 with participants locally coordinated and advised so that all activity followed strict Army and local/state guidelines related to the pandemic. This section summarizes the decisions and findings from these efforts. While the COVID-19 delay discussions were ongoing, the DLT deliberated on the steps to take toward a continuum of the overall experiment. In essence, the desire was to carefully and collaboratively decide to delay and, assuming a delay, determine how to maintain DUNEX energy, excitement, and momentum.

Since inception, all DUNEX planning, including discussions with PIs, had been virtual; therefore, the inability to travel and meet because of COVID-19 did not change the teams' basic method of communications. Team meetings and communication with the PI group continued without interruption; however, the DLT chose to meet less often, biweekly versus weekly, since the urgency of finalizing the upcoming 2020 experiment was now pushed to 2021. Also, communications with the PIs were on an as-needed basis during the lull in activity. Web tools, specifically Webex, Google Groups/Drive, and Zoom, were main sources used to foster and support communications among the DUNEX participants and leadership.

These tools were a natural extension of the collaborative and virtual culture of DLT and served to maintain the continuum they sought during the pandemic.

The full cadre of DUNEX research teams registered for the Full DUNEX Study consisted of 30 teams from 18 academic and federal institutions studying diverse research topics and study methodologies. Communication with this broader community was through Google and Zoom platforms. Google forum was implemented to email and communicate among research PIs for such matters as announcements, general information, and a record of activity. Google drive was implemented as a storage device for related files, recordings of meetings, etc. Zoom was implemented for online meetings with PIs. All these tools were used in the normal course of business as a collaborative and virtual environment before the pandemic restrictions. As the COVID-19 delay discussions occurred, communications tools and protocols were available to build on activities and to continue fostering relationships, rather than simply cease operations during the pandemic. Though the major field study was delayed by 1 yr, communication and energy were maintained.

The concept of hosting recurring meetings under the idea of Virtual Coffees Hours, where researchers could gather and "chat over a cup of coffee" proved to be extremely useful, and perhaps a key component of communication with the PIs. Bi-weekly, sometimes monthly gatherings during the pandemic, these online gatherings were conducted to bring together PIs and members of the DUNEX organizing teams. The virtual Coffee Hours, along with the Google tools, helped foster robust communication for DUNEX planning, logistics, and operations. The regular and collaborative conversations led to additional, more in depth, discussions such as decisions on COVID-19 delays, rapid response planning, and stakeholder engagement opportunities. Details on these various topics follow.

4.5 March Madness

Researchers who began field work during the 2019 DUNEX Pilot Study season, began analyzing their data. Some were able to communicate initial findings and adjust their 2021 Main Experiment Plan. Prior to more complete knowledge of COVID-19 impact on the 2020 DUNEX Study, DUNEX researchers began participating in a scientific version of college

basketball's March Madness. This was a series of weekly web meetings where each DUNEX research team gave a 4 min lightning round presentation of their 2020 experiment plan (prior to the realization of the need to postpone to 2021). Other researchers then provided additional ideas, available data, or instrumentation to enhance the researchers plan, or interest in collaborating with the presenter. Raubenheimer kicked off the first meeting on 28 February 2020 by presenting an overview of the DUNEX 2020 experiment, including a preliminary map (Figure 10) indicating where researchers intended to conduct their experiment (based on their logistics survey input). She also discussed the organization of potential topics to cover in subsequent web meetings such as focused meetings geared towards researchers working in the swash zone, those studying surf zone processes, researchers working at a location near Oregon Inlet (the Southern Site), rapid response experiments, and researchers collecting aerial imagery. All meetings were recorded, and presentation material was shared and posted for those researchers who could not attend the web meeting.

Figure 10. Early PI research location map (summer 2019). Colors indicate the primary area of focus (green = sound; light-olive = midisland; tan = beach/dune; cyan = swash; blue = nearshore ocean). Symbols are included to identify those using drones, aerial overflights, and the FRF ARGUS tower.
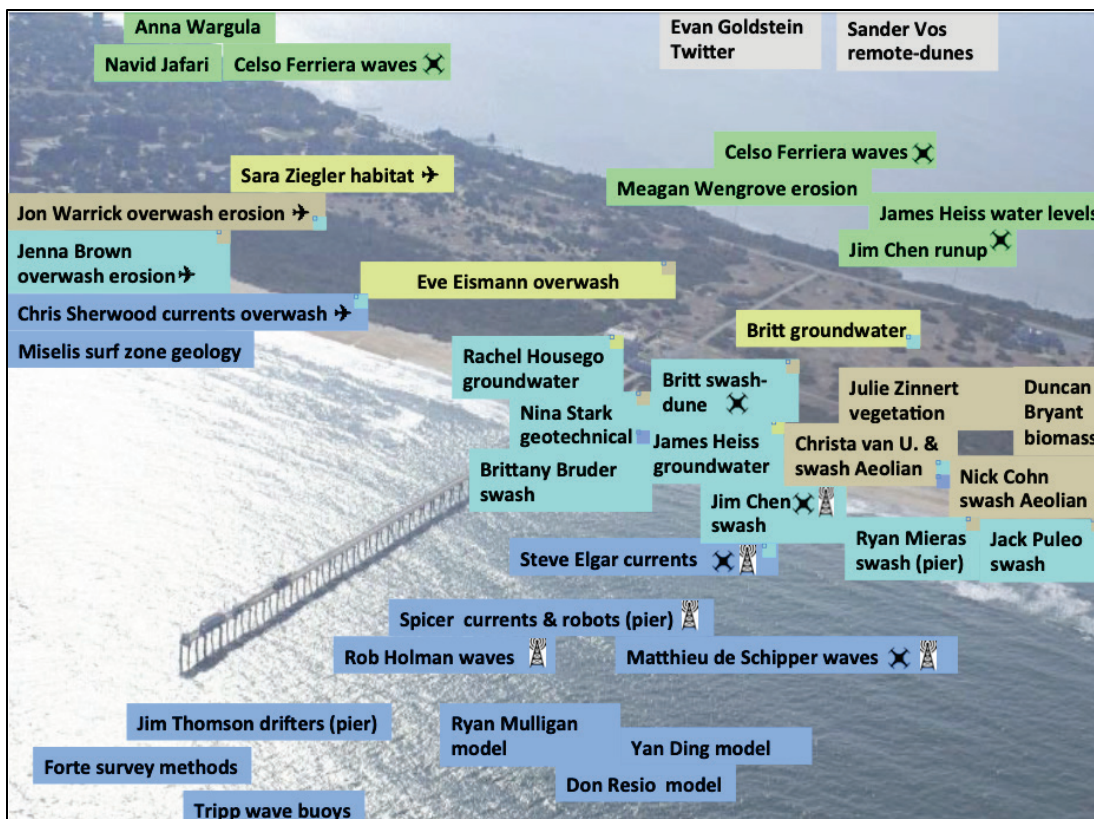
4.6   Rapid deployment

Under the leadership of Raubenheimer, (DLT Team academic member from WHOI), the PIs conducted a Rapid Response Desk-Top study during the 2020 COVID-19 delay of DUNEX. This study was a valuable opportunity for PIs to plan a mock rapid deployment and examine their readiness and ability to rapidly gather and pack instrumentation and virtually deploy to an area when responding to an impending storm. Findings from the exercise included the steps needed to plan and perform the logistical tasks for conducting a rapid deployment and the importance of maintaining communications during deployment into an area during a time when most people are being asked to evacuate, maintaining personal safety during inclement weather conditions, and having well-developed deployment plans for the specific area of interest. This includes early development of communications with local authorities, so they understand, and approve, on-site actions while those authorities are actively evacuating most people from the area.

4.7   Stakeholder engagement

One of the benefits of DUNEX is the improved communication between coastal researchers and the coastal community that has facilitated the translation of scientific research into application, which is one of the goals of DUNEX. DLT discussions following the DUNEX Pilot Study reminded the team of the need to address the DUNEX goal of stakeholder-based communication, which was then discussed with the USCRP leadership, and the decision was made to use the 2020 pandemic-induced stand-down year to add a DUNEX focus on stakeholder engagement. Dr. Nicole Elko joined the DLT to help foster stakeholder engagement and communication because it is also a USCRP goal and would benefit from her leadership.

To initiate discussions between the academic and stakeholder communities, Dr. Elko presented DUNEX and USCRP plans and goals at a North Carolina Beach, Inlet, and Waterway Association symposium and shared a DUNEX video focused on stakeholder engagement produced by the DUNEX Communication Team. This presentation served to introduce and invite stakeholders to a series of virtual Coffee Hours as discussed in Chapter 2, to bring PIs and stakeholders together to discuss coastal management research needs (such as sound-side erosion, dune overtopping, and beach nourishment) and potential methods to address them. Each session began with a presentation by a coastal management

stakeholder to introduce the management questions and societal implications of the research topic. An open, informal conversation followed. Other coastal managers expressed their coastal challenges related to the topic, and DUNEX researchers offered potential methods for addressing the coastal management challenge(s) at DUNEX 2021, with future research, or through transition of ongoing research into application. Many interesting challenges were introduced such as the need to better understand sediment gradation of back barrier systems to identify appropriate sediment for marsh restoration projects.

5   DUNEX 2021 Main Field Experiment

5.1   Introduction

As mentioned in Chapter 4, the Full DUNEX Study was originally scheduled for 2020 but was delayed until 2021 because of the COVID-19 pandemic. The purpose of the full experiment was to collect and use observational technologies before, during, and after storm events to improve understanding and predictive capabilities of the processes and impacts of extreme storm impacts to coastal regions.

After the 2020 pandemic-induced stand-down, researchers saw a window of opportunity in 2021 to safely conduct their research studies by carefully observing protocols to minimize the likelihood of becoming infected or spreading the COVID-19 infection. Approximately 30 federal and academic research teams, more than 30 graduate students, and 10 trainees gathered on the Outer Banks to actively participate in and contribute to the large-scale field experiment during June 2021 through January 2022 to capture the pre-, during-, and poststorm conditions and recovery. Scientists deployed state-of-the-art oceanographic, meteorological, morphological, geotechnical, and hydrogeological instrumentation because of the likelihood of hurricanes and nor'easters impacting this region of the Atlantic coast during this time period. Nearly 300 instruments were deployed and recovered in one of the largest nearshore field experiments conducted in the twenty-first century. Using these observational technologies before, during, and after storm events, federal agency and university researchers worked together to gather information that will improve understanding and predictive capabilities of the processes and impacts of extreme storm impacts to coastal regions. This chapter provides a more detailed description of the experiment locations than was given in Chapter 3 because the larger number of researchers participating in 2021 created more dense data coverage in the three experiment sites.

The first deployment was in June 2021 conducted by Miselis (USGS) and included deploying geophysical sensors that allowed her to map the seabed and the geologic features beneath it to determine how storms alter the structure of the seabed and whether geology records of the storm's effects are preserved. In spring 2022, Heiss was in the process of retrieving his groundwater sensors, and Drs. Steve Elgar and

Raubenheimer were retrieving their groundwater well sensors. These are the last instruments deployed specifically as part of DUNEX, and their recovery marks the completion of DUNEX-specific data collection. Researchers will begin and/or continue their analysis of these data over the next years to decades to improve the understanding and ability to predict storm processes and impacts.

Based on the favorable response to the DUNEX Pilot Study Training Opportunity, additional means of participating in DUNEX for trainees were planned for the 2021 field season. Instead of the formal training provided in 2019, the DUNEX 2021 Main Experiment training was geared towards matching trainees with DUNEX researchers to allow them to have hands-on experience with a deployment, data collection, and/or instrument recovery with one of the DUNEX PIs. This provided invaluable experience to the trainee, an extra hand in the field for the PI, and the possibility of developing future collaboration between the PI and trainee.

5.2 Experiment sites

5.2.1 FRF

The FRF is located on the Atlantic Ocean near Duck, North Carolina. The extent of the project area described for the DUNEX Pilot Study was the same area used for the Full DUNEX Study; however, the number of individual PIs conducting research studies at this site was significantly greater in 2021. Figure 11 shows the location of the PI measurement sites within the FRF property bounds.

The FRF provided researchers data measurements from a suite of instruments and remote sensing technologies (video, radar, sonar, and lidar) for measuring bathymetric/topographic, hydrodynamic, and meteorological conditions. Specialized vessels such as the CRAB and 5-ton LARC-V were used to conduct surveys and deploy instruments, and a 43 m observation tower was used to mount cameras. The FRF staff's continuous, routine data collection was used to supplement what researchers measured during the experiment, and the infrastructure in place at the FRF was a support system for the researchers.

Figure 11. DUNEX measurement locations at the FRF site.
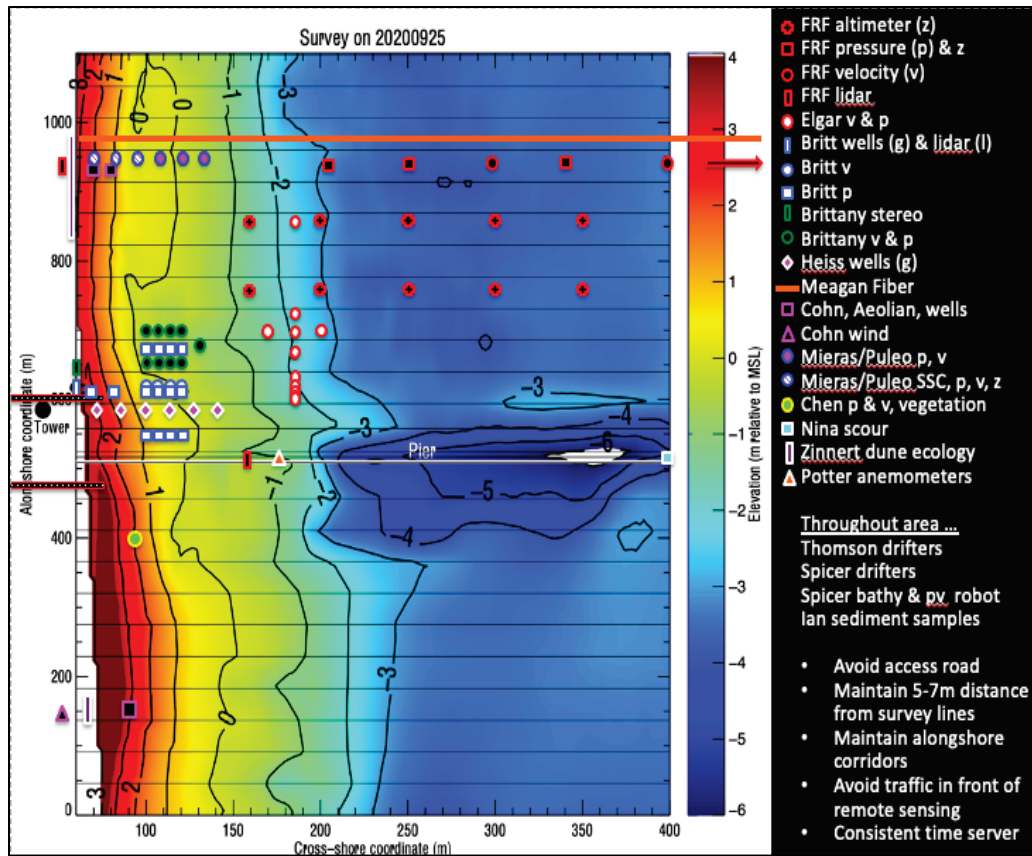
5.2.2 Southern Site

In contrast to the FRF site, some researchers were interested in taking measurements at a site more susceptible to overwash. A number of locations were considered between Corolla and Cape Hatteras to find the ideal site conditions:

- Undeveloped coastline
- Natural dune complex, that
  - was not manipulated by humans (e.g., nourished, built up from scraping sand off the road)
  - had alongshore-variable dune heights, susceptible to storm-induced overwash
  - with vegetation cover
- Mild sloping and moderately wide (< 100 m) subaerial beach
- Wide surf zone and offshore sandbar in the nearshore

A second field site was selected that met these conditions just south of New Inlet within the US Fish and Wildlife Service (USFWS) Pea Island National Wildlife Refuge (PINWR) and Cape Hatteras National Seashore. Detailed hydrodynamic measurements in a cross-shore array spanning the nearshore and beach/dune, as well as measurements of topographic and bathymetric change, throughout the storm and recovery period(s) were collected (Figure 12). Observations from this site provide insight into cross-shore storm processes and impacts, including wave transformation and shoreline water levels, rapid changes in coastal elevations, on/offshore sediment exchanges, and resulting habitat changes. These detailed measurements provide a more complete understanding of storm impacts and recovery on natural beach/dune systems, which allow researchers to validate and improve forecasts of water levels, coastal change, and habitat. Additionally, observations from this site will be compared to those at the FRF to examine how the offshore sandbar and subaerial beach profile influence the storm impacts.

A number of logistical challenges had to be overcome to receive a permit from USFWS to conduct all the proposed and necessary coastal change measurements. In particular, full-sized vehicles were not permitted to drive on the beach, limiting capabilities for transporting heavy equipment, hauling watercraft, and utilizing a LARC-V for surveying; all-terrain vehicles were permitted, but had to access the beach approximately 3 mi to the north of the field site. Also, platforms traditionally used to perform topographic and bathymetric surveys, such as UAS and personal watercraft, were not permitted; researchers improvised and made use of a man-powered helium-filled balloon with stabilizing kite (also known as the heli-kite) to collect aerial imagery for creating topographic maps, and autonomous, unmanned surface vehicles were deployed by hand from the beach to create bathymetric maps (Figure 13). Last, Oregon Inlet was the nearest place for boats to transit to the site, which is notoriously dangerous; therefore, an army of scientists and divers were gathered to transport and launch an inflatable, engine-powered vessel from the beach to install the pipes in the nearshore.

Figure 12. Instrument array at the southern DUNEX site within the US Fish and Wildlife Service (USFWS) Pea Island National Wildlife Refuge (PINWR), showing the study site and indicating locations of sensors. deployed by collaborators from the US USGS (Sherwood, Brown), Woods Hole Oceanographic Institution (WHOI) (Traykovski), North Carolina State University (Anarde), University of North Carolina-Wilmington (Mieras), and UNC-Chapel Hill (Moore).
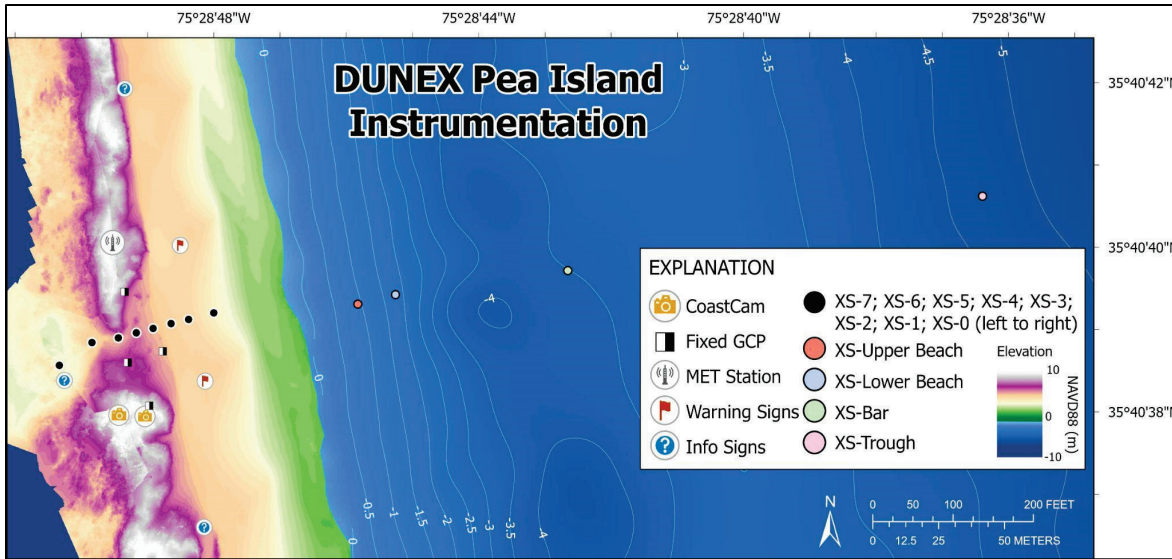
Figure 13. The heli-kite survey within the USFWS PINWR.

5.2.3 Sound Side

The third research site, referred to as Sound Side, included research studies located on the sound side of Hatteras Island near Oregon Inlet, in the marsh areas of the Cape Hatteras National Seashore at the margins of Pamlico Sound and Currituck Sound.

Researchers focused on the following:

- Drivers of marsh and roadway flooding
- Shoreline erosion, sound-side dynamics near a tidal inlet
- Consequences of barrier island inundation
- The interaction of storm surges and waves with coastal vegetation
- The combined effects of ocean processes, extreme precipitation, and shoreline erosion on groundwater flow within the beach, dune, and sound and its impact on shoreline response

Measurements included waves, currents, water levels, marsh inundation depths, shoreline surveys, vegetation characteristics, topographic-bathymetric surveys, and groundwater flow across the barrier island from ocean to sound.

Findings from these research studies (discussed in detail in Appendix C) provide information and tools for future planning and management of estuarine shorelines by quantifying the vulnerability of roadways to flood-related closure and sound-side shoreline to severe erosion, improving the ability to predict storm processes and impacts on vegetated and non-vegetated coastal features, and providing field-based evidence to support natural and nature-based features (NNBFs) as a safe/reliable means for local-level resilience against flooding for coastal communities. In addition, this research allows coastal managers to assess water quality, the timing of nutrient and contaminant release to coastal and estuarine waters, how large storms affect groundwater flow behavior near the coastline, and the ability of coastal aquifers to filter groundwater contaminants that would otherwise discharge into the ocean and sound.

5.3 Storms/Climatology

During the DUNEX Main Experiment time period (June 2021 to May 2022), significant wave heights ranged from 0.2 to 4.0 m, storm surge was as much as approximately 1 m, wave directions ranged from 15° to 120°

(relative to True North), mean wave periods ranged from approximately 5 to 16 s, and wind speeds were as high as 25 m/s (Figure 14). Waves typically approached the shoreline from the east-southeast (ESE) to the NE, with the largest waves from the ENE and NE directions (Figure 15). Wind directions were approximately bimodal, from the southwest (SW) and N, with the strongest winds typically from the N (Figure 16). During this time period, five storms occurred with wave heights ranging from 3 to 4 m (in 8 m water depth), two of which occurred during the intensive August-to-November 2021 experiment time period.

Figure 14. Climatology during the DUNEX Main Experiment, including (*from top to bottom*) tidal fluctuations (NOAA tide gage at the offshore end of the pier), 8 m water depth significant wave height, incident wave direction and wave period, and wind speed and direction measured at the offshore end of the pier from July 2021 to May 2022.
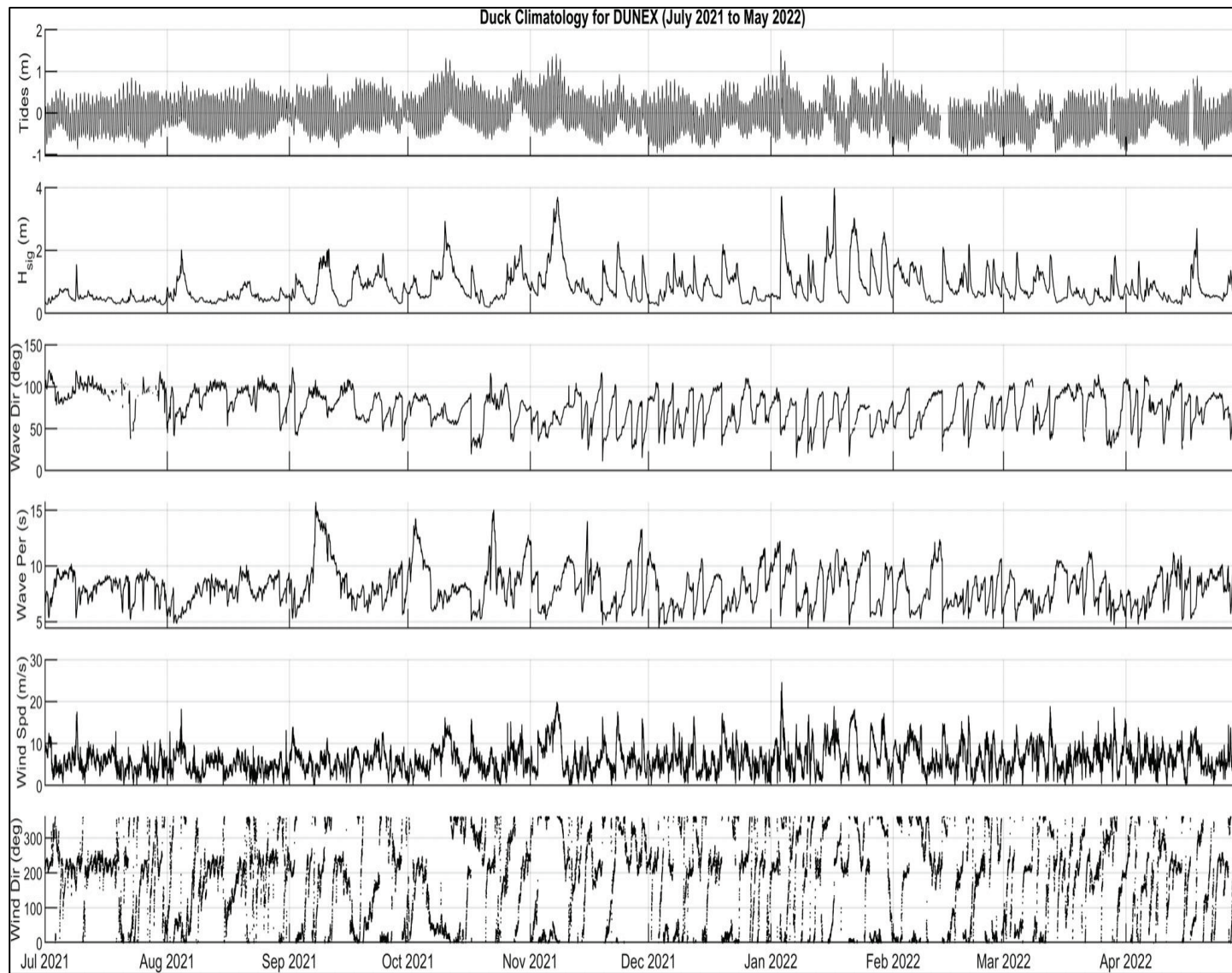
Figure 15. Wave rose for the DUNEX Main Experiment time period (July 2021–May 2022) indicating frequency (length of bars) of wave heights (colors, key at bottom) and incident wave directions.
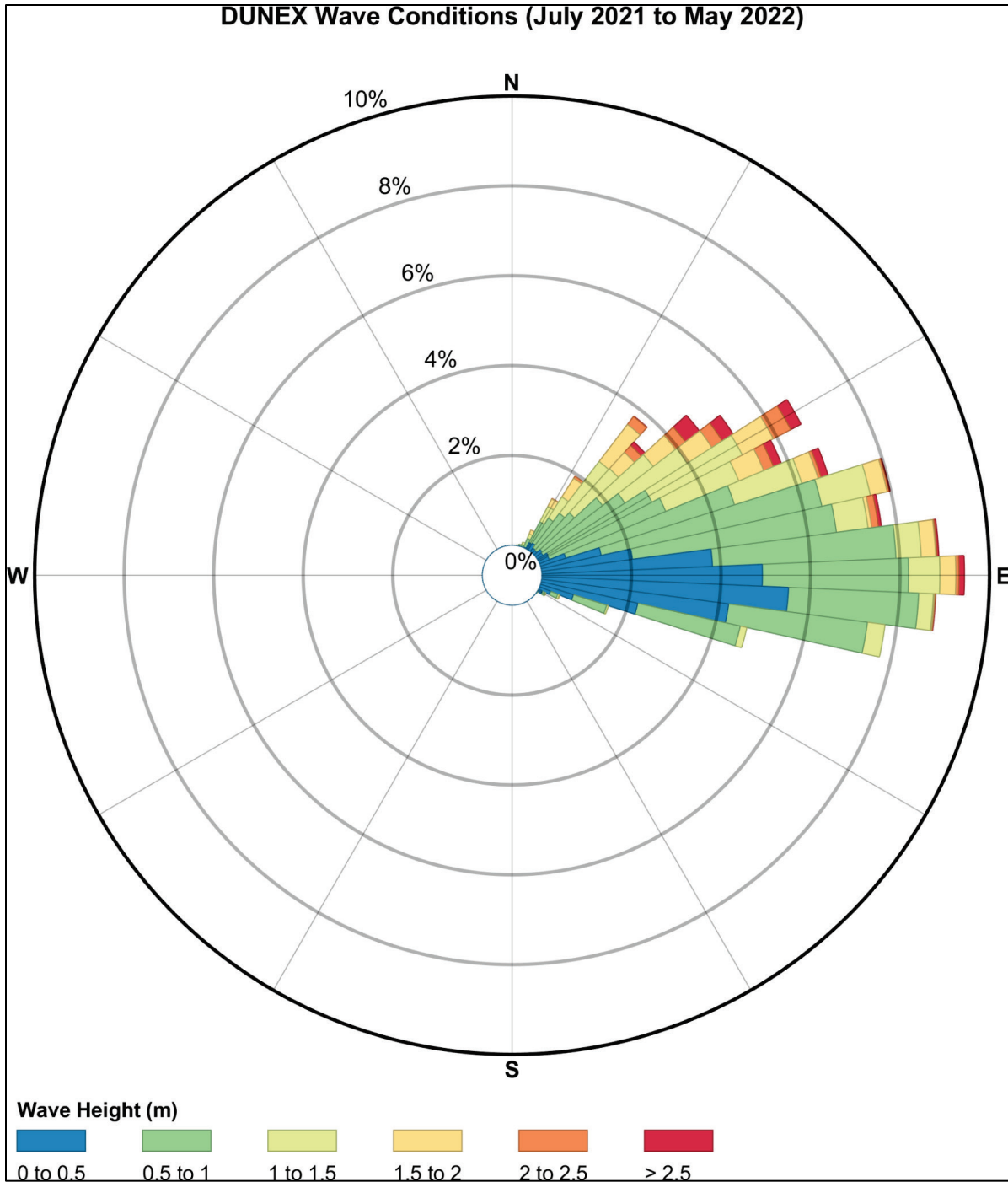
Figure 16. Wind rose for the DUNEX Main Experiment time period (July 2021–May 2022) indicating frequency (length of bars) of wind speeds (colors, key at bottom) and wind directions.
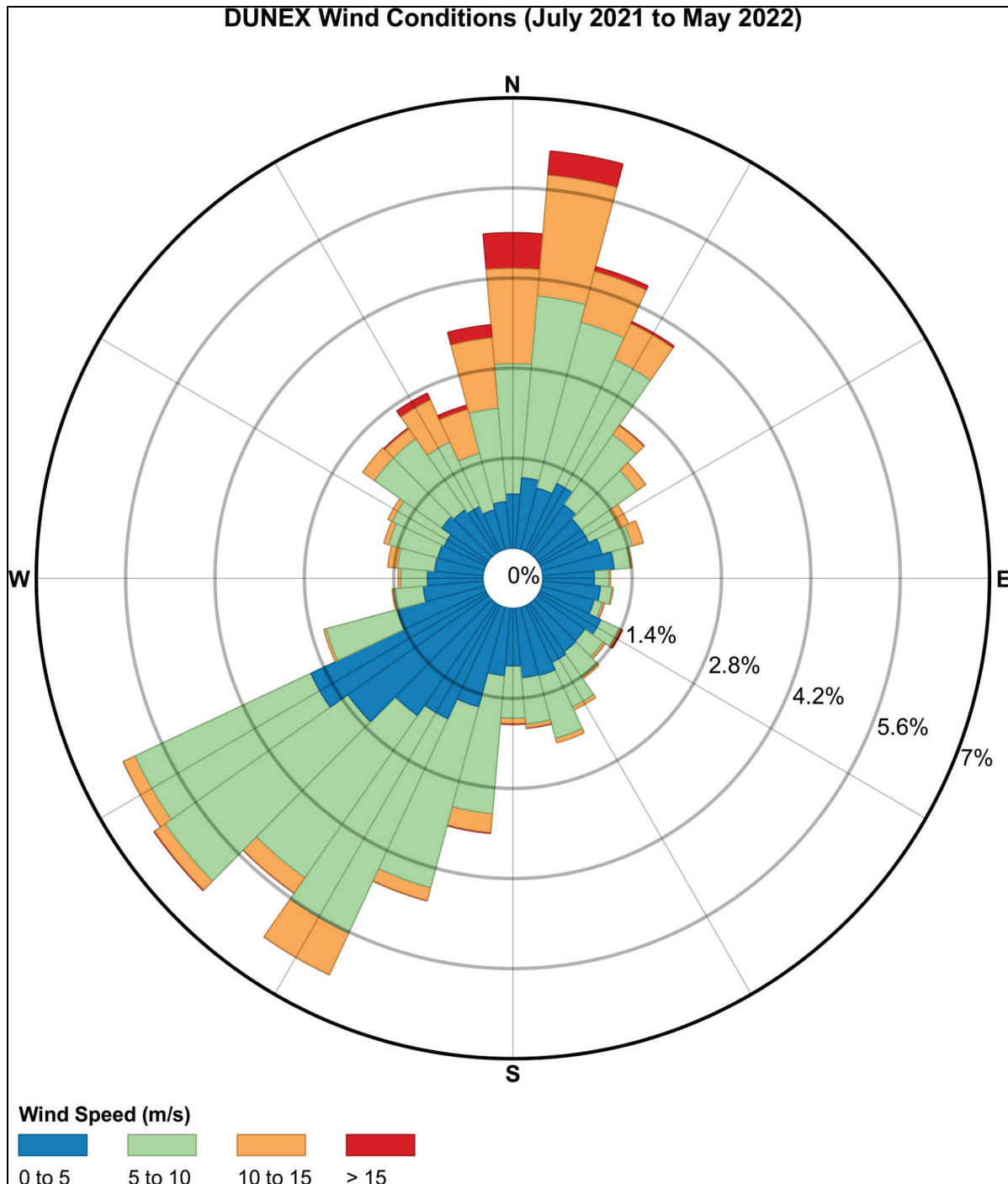
During the most intensive period of the DUNEX Main Experiment (August–November 2021), significant wave heights ranged from 0.5 to 3.0 m, storm surge was as much as approximately 1 m, wave directions ranged from 40° to 110° (relative to True North), mean wave periods ranged from approximately 5 to 16 s, and wind speeds were as high as 19 m/s (Figure 17). Waves typically approached the shoreline from the ESE to the NE, with the largest waves from the ENE (Figure 18). Wind directions were approximately bimodal, from the SW and the north-northeast (NNE), with the strongest winds typically from the NNE (Figure 19). During this time period, the shoreline contour (NAVD88 0 contour) initially bulged offshore from a large wedge of sand near the pier (Figure 20) and became more alongshore uniform (Figure 21) (especially following the large waves in early October). Meanwhile, sand was transported off the beach and formed a small sandbar at approximately cross-shore coordinate 200 m (in approximately 2 m water depth).

Figure 17. Climatology during the intensive field period of the DUNEX Main Experiment, including (*from top to bottom*) tidal fluctuations (NOAA tide gage at the offshore end of the pier), 8 m water depth significant wave height, incident wave direction and wave period, and wind speed and direction measured at the offshore end of the pier in 2021.
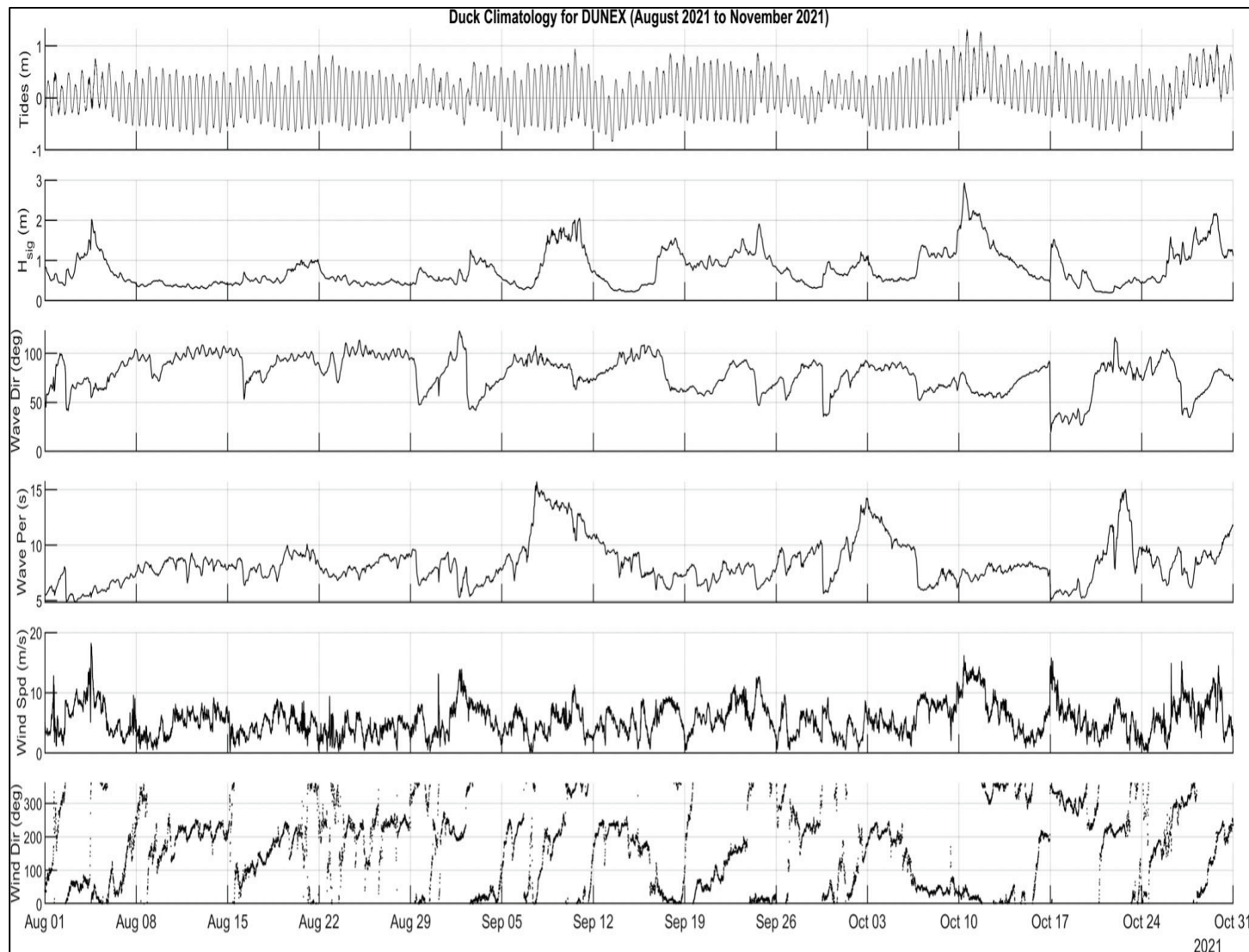
Figure 18. Wave rose for the intensive period of the DUNEX Main Experiment (August 2021–November 2022) indicating frequency (length of bars) of wave heights (colors, key at bottom) and incident wave directions.
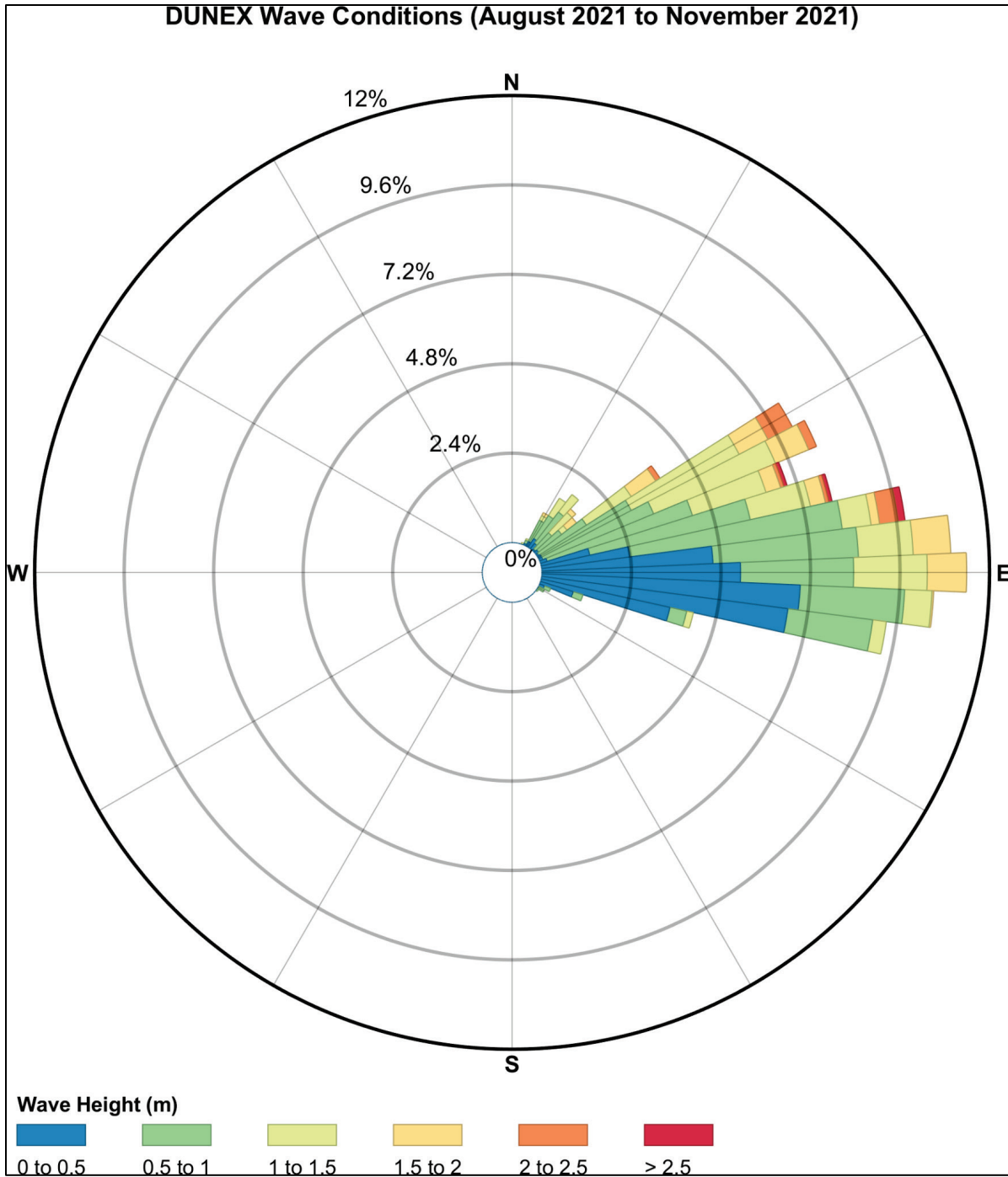
Figure 19. Wind rose for the intensive time period of the DUNEX Main Experiment (August–November 2021) indicating frequency (length of bars) of wind speeds (colors, key at bottom) and wind directions.
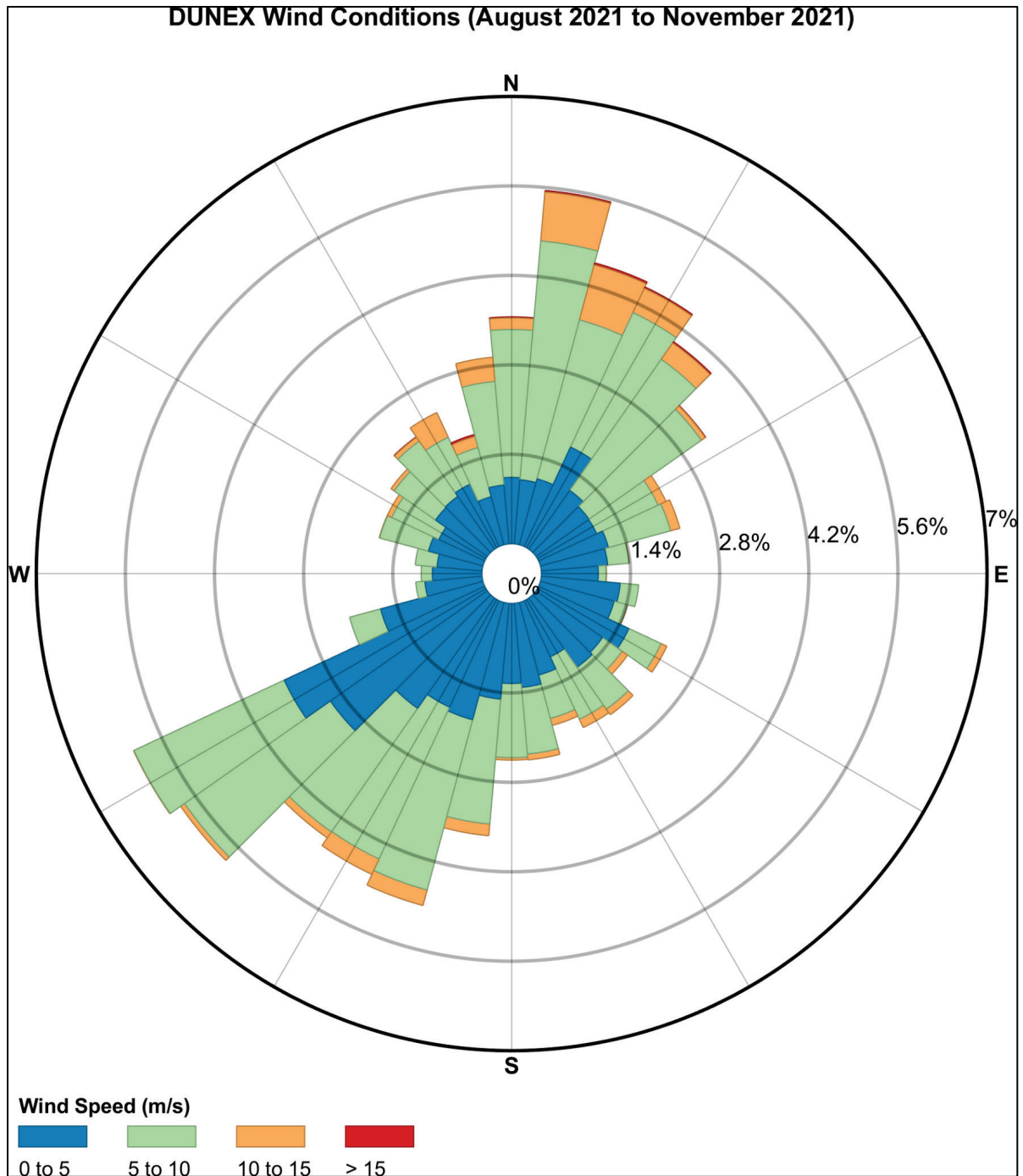
Figure 20. Seafloor elevation (curves and color contours, key on right) as a function of alongshore versus cross-shore coordinate (using the FRF coordinate system) surveyed on 23 August 2021. The pier is located at about FRF alongshore coordinate 515 m (colocated with the depression in the bathymetry).
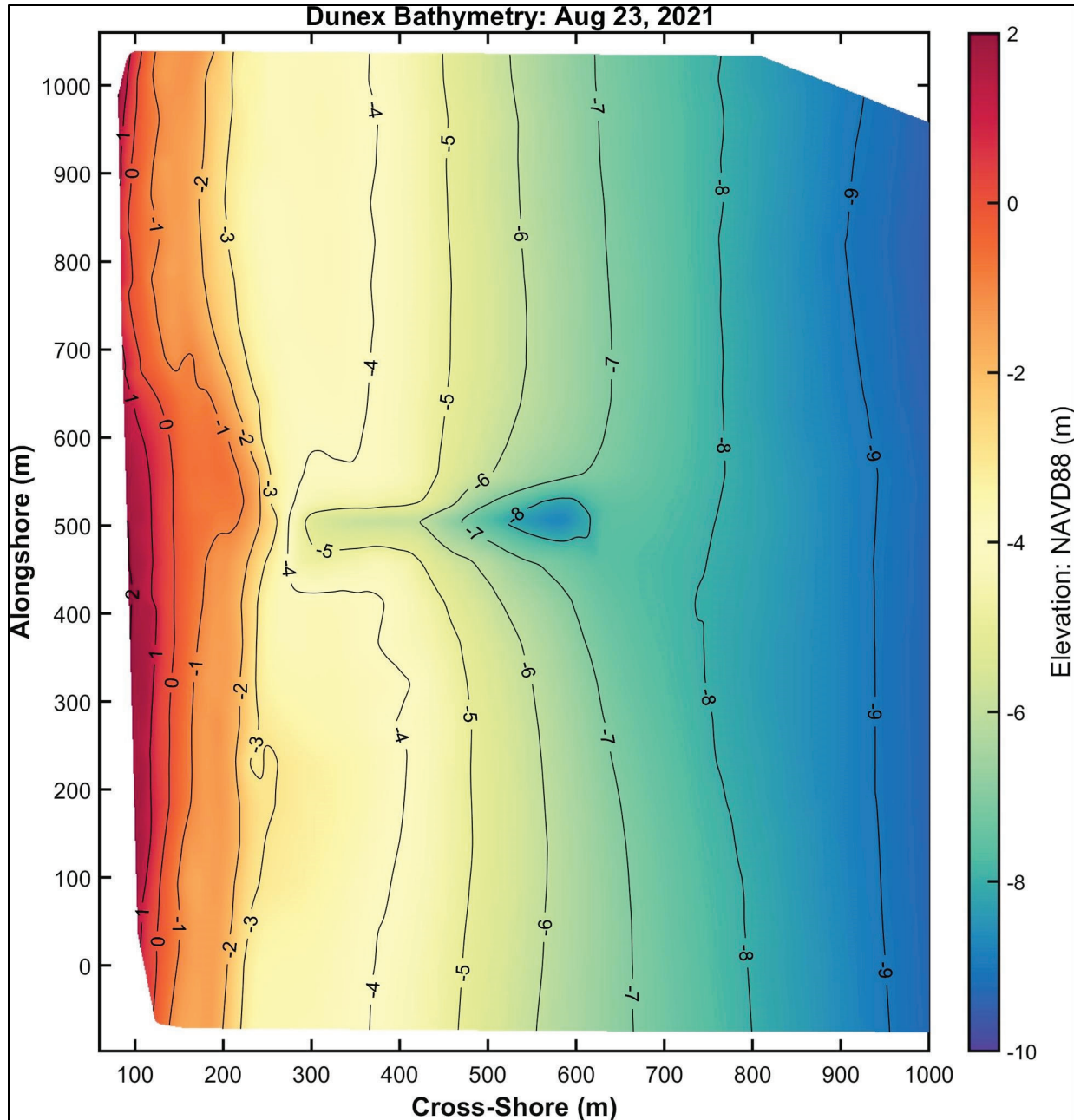
Figure 21. Seafloor elevation (curves and color contours, key on right) as a function of alongshore versus cross-shore coordinate (using the FRF coordinate system) surveyed on 21 October 2021. The pier is located at about FRF alongshore coordinate 515 m (colocated with the depression in the bathymetry).
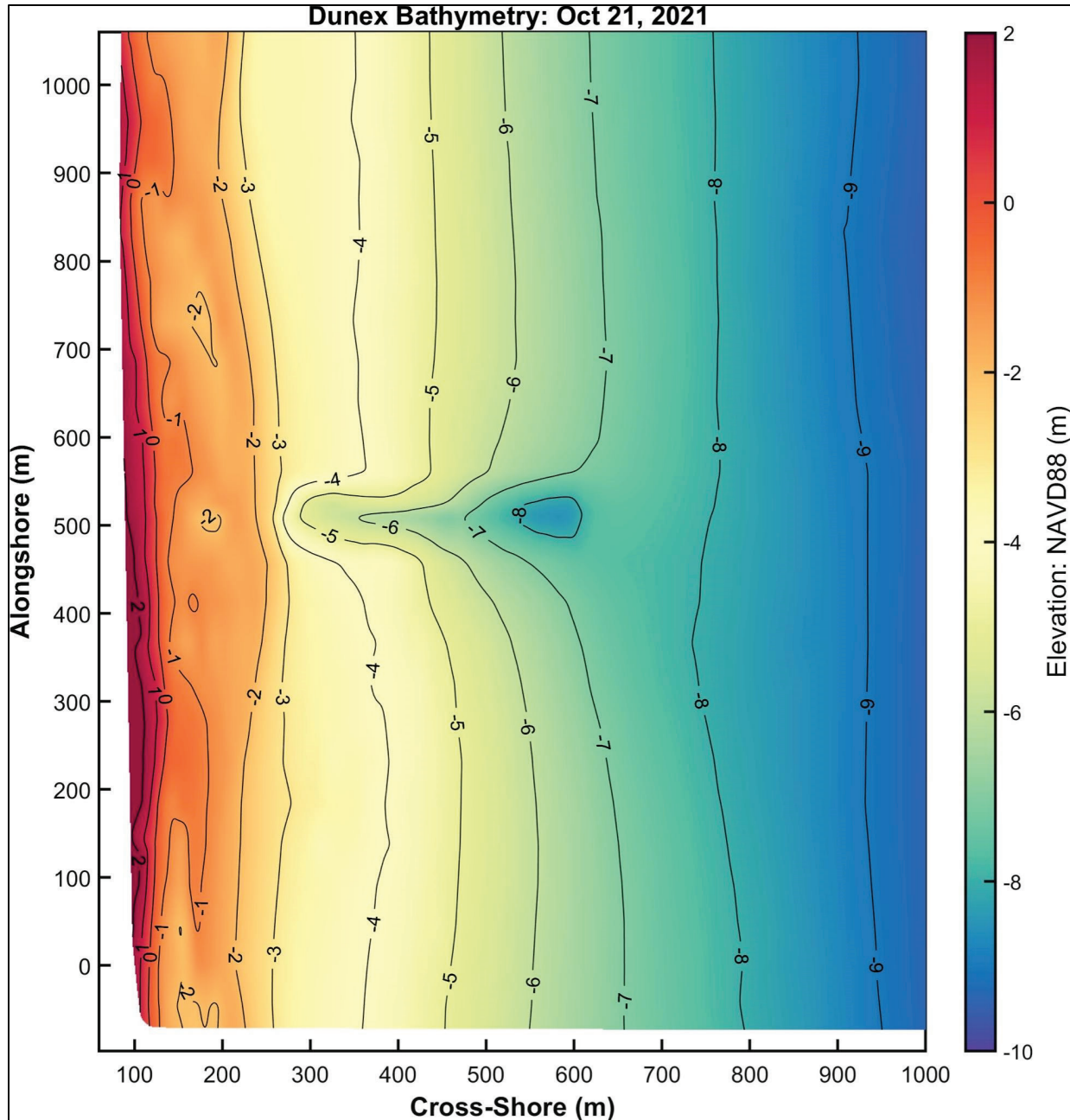
5.4 Logistics

The scope of logistics included coordinating experiment schedules and FRF staff operations support, working with DUNEX scientists to design field deployment strategies and coordinating the execution of those field deployments, and all aspects of planning and logistics (sorting out overlapping objectives and scheduling resources such as office space and field access). Logistics planning also included purchases of equipment and supplies to be used in DUNEX instrument deployments (e.g., utility terrain vehicles (UTVs), pipe-jetting equipment, safety gear, water coolers, masks, and hand sanitizer), as well as executing contracting actions for rental and installation of office trailers and additional UTVs. Logistics also included planning for potential rapid response due to hurricanes. The FRF logistics team served as the sponsor for priority-access passes and was the point of contact for coordinating communications with Dare Emergency Management. The FRF staff conducted weekly operations and logistics meetings on to discuss DUNEX coordination with researchers at the FRF and the weekly operations and support needed. Compared to the pilot, the main experiment required additional logistics and operation coordination and support due to more research teams being involved.

The logistics team designed deployments, facility use, and meetings to minimize the risk of COVID exposure. Due to COVID, research teams were required to follow Center for Disease Control and USACE guidelines and wear masks while indoors and stay 6 ft apart in the field. The DLT maintained constant communication with DUNEX PIs in considering space and safety protocols and concluded it was possible to expand the study while maintaining safe practices. In response to the additional year due to COVID, DUNEX PIs were encouraged to reach out to colleagues to encourage additional participation from interested research teams and to complete a logistics survey.

5.5 DUNEX Main Experiment research projects

A total of 30 academic and federal research teams participated in the DUNEX Main Experiment supporting over 30 graduate students deploying over 300 instruments during the DUNEX Main Experiment. The research teams were also supported by USGS and USACE researchers contributing aerial and lidar-based imagery and elevation data, both terrestrial and bathymetric. In addition, the FRF staff contributed routinely by collecting operational datasets (wind, waves, water levels,

currents, etc.), countless hours of kinematic GPS at experiment locations, as well as day-to-day logistical support during the field study. The logistical support included office space, high-speed internet arranged specifically for the research teams, supporting skilled labor for installation of experiments, and beach-area transportation. Some of the teams began their work in June 2021 with the majority beginning their projects in August 2021. Teams remained on site from 1 week to 6 months, and the final instruments were recovered in April 2022. The details of all 30 teams and their projects are summarized in Appendix C. Researchers were encouraged to engage with stakeholders and consider stakeholder needs throughout their research, as discussed in Chapter 4 in the Stakeholder Engagement section.

5.6 Hands-on training 2021

As mentioned in Chapter 4, the formal training conducted during the 2019 DUNEX Pilot Study included classroom lectures, some hands-on components, and equipment demonstrations. This training was well received, but the DLT decided that an adjustment to the training where volunteers were matched with DUNEX PIs in the field would benefit both the volunteers to learn new skills and the researchers to have more support for labor intensive field work. Through the DUNEX Hands-On Training opportunity, volunteers were paired with a DUNEX researcher with similar interests to provide an extra hand in the physical labor of field work while learning about the functionality of instrumentation and what the researcher would gain from the data collection effort. The volunteers, who included early career federal researchers and students, were immersed in actual field data collection practices such as the function and purpose of specific instruments, how to deploy the instrument, what the instrument measures, how to monitor the device for continual function, and how to recover the instrument. This format allowed volunteers to engage directly with the science teams during data collection and foster learning outside of the formal classroom setting. Examples of topics that the volunteers worked on included sediment testing and sampling, installation of beach monitoring stations, chasing drifters, setting up water level loggers and downloading data, and deploying instruments such as pressure gauges, current meters, and moisture sensors. Though the initial number of volunteers was 14, only 10 were able to participate due to agency and university policies regarding COVID-19 vaccinations and travel. Feedback from the volunteers that were able to participate

indicated that this format provided them the opportunity to work directly with researchers in the field to learn new skills, troubleshoot issues, and engage with other researchers, students, and volunteers.

5.7 VIP Day

During the DUNEX Main Experiment, the USCRP sponsored and the DLT organized a VIP Day that was held on 9 September 2021 to provide more than 40 leaders and stakeholders from federal agencies, universities, non-governmental organizations, congressional staffers, and state and local leaders with a close-up view of coastal engineering and science in action and to provide an opportunity for improving communications between scientists and the coastal community (Figure 22–Figure 24). The objectives of the VIP Day were to highlight (1) collaboration among coastal community researchers to collect during-storm field data and (2) the DUNEX goals of improving knowledge of storm processes, their impacts, and post-storm recovery that will better prepare coastal communities before storm events (with resilience planning) and during events (with safety and evacuation techniques). The guests at the VIP Day gathering met with DUNEX researchers, observed them conducting unique scientific experiments, and learned about their intended experiment outcomes by rotating through four Research Stations (or Tour Stops). The guests were also able to interact with other federal, state, and local VIPs to hear their perspectives on the most pressing needs in coastal research.

5.7.1 Tour Stop 1

The first tour stop focused on researchers in multiple disciplines working together on the interactions of ocean (nearshore), surf zone, and beach processes; atmospheric forcing; and groundwater, particularly during storms. These data improve hurricane forecasts, which are presently less accurate in the nearshore zone. The researchers emphasized to the guests the importance of collecting data during storm events because the interaction of various processes in energetic conditions may differ from those same processes in calm conditions. Guests were also invited to discuss their greatest coastal challenges related to storms. Examples of such challenges included the following:

- Sunny day flooding
- Storm-induced flooding
- Swash processes and beach erosion

- Sound side processes
- Overwash, quantifying sediment carried over to the sound

Guests were invited to think about and express how well they believe the research at this tour stop (as well as all the other tour stops) is addressing their greatest coastal challenge.

5.7.2 Tour Stop 2

The second tour stop focused on researchers in multiple disciplines working together at the Southern Site and the intercomparison of large dune systems with overwash and breaching. Though guests did not physically travel the 56 km to visit the Southern Site, researchers presented their experiments to the guests with posters and instrumentation. Processes studied at the Southern Site included beach and dune structure, overwash and swash processes (in contrast with Tour Stop 1), ocean versus sound-side processes, atmospheric forcing, and an intercomparison of the FRF and Southern Sites.

5.7.3 Tour Stop 3

The third tour stop focused on researchers in multiple disciplines working together on developing new techniques (cameras, small drifters and buoys, bathymetric surveying crawlers, etc.) to measure surf zone processes. Researchers also studied the interactions of ocean (nearshore), surf zone, and beach processes; atmospheric forcing; and groundwater, particularly during storms. Guests were shown the Argus Tower where researchers mounted cameras for measuring swash processes, lidar towers, the crawler for remotely measuring nearshore/surf zone bathymetry, and a demonstration of drifters for measuring nearshore currents and waves.

5.7.4 Tour Stop 4

The fourth tour stop focused on researchers in multiple disciplines working together on sound side research, such as wave attenuation through vegetation, the interaction of storm surge and waves with coastal vegetation, swash processes, atmospheric forcing, groundwater, and salinity in the Sound before, during, and after storms; inner bank erosion at inlets; and the interaction of ocean and sound side processes leading to sunny-day and storm-driven flooding. Research outcomes anticipated by the researchers and discussed at this tour stop include providing

- a predictive capability of modeling nearshore-beach-dune system coevolution, which will enable engineers and coastal stakeholders to more accurately project the response of vegetated dunes and marshes to extreme events and sea level rise in the design of natural and nature-based flood protection projects for coastal resilience;
- field-based evidence and information to support coastal communities to consider NNBFs for local-level resilience against flooding;
- improved understanding of groundwater flow behavior to better predict how coastal aquifers will respond to a changing climate, which is important for managing coastal water quality and nearshore ecosystems; and
- information on how large storms affect groundwater flow behavior under the coastline and the ability of coastal aquifers to filter groundwater contaminants that would otherwise discharge to the ocean. The work will help improve coastal water quality and preserve the recreational and economic activities that depend on healthy coastal ecosystems.

In addition to the Tour Stops, guests heard Brodie (senior research oceanographer at FRF) describe the more than 40 yr of coastal data collection at the FRF. Cialone (CHL managing director of USCRP) outlined the goals of DUNEX including improving coastal storm models, prediction of storm impacts, and measures for informing coastal resilience. Ms. Jessamin Straub (research oceanographer, FRF) described experiment planning, including efforts to engage stakeholders to ensure the experiment addresses coastal community needs.

The VIP Day also allowed graduate students to interact with stakeholders and explain the scientific processes they were studying. Over 40 participants from four subgroups joined together for final remarks by Dr. David Pittman (director of ERDC) and Dr. Ty Wamsley (director of CHL). In response to MG Graham's (USACE-HQ) question about future needs in coastal data collection, guests from the Senate Environment and Public Works (EPW) Committee Dr. Sarah Delavan indicated that she sees a need for improved communication between researchers, practitioners, funding authorities, and the public. Mr. Max Hyman and Dr. Andrew Perlstein, also of the EPW, reiterated that Congress appreciates clear, concise communication about research and development (R&D) findings and impacts. All expressed sincere appreciation for the tour and the coastal R&D efforts being orchestrated by USACE and federal and academic

partners. As the VIP Day was conducted at the FRF, visitors also had the opportunity to tour the world-class FRF. A video (https://www.youtube.com/watch?v=8VOV2uZr5fk) was produced by USACE highlighting the importance and success of the DUNEX VIP Day.

Figure 22. DUNEX VIP Day attendees with DUNEX Leadership Team (DLT).

Figure 23. Representatives from the US National Park Service (NPS), USGS, WHOI, and US Coastal Research Program (USCRP)/American Shore and Beach Preservation Association (ASBPA) gather to discuss what they observed during the DUNEX VIP Day tour.

Figure 24. USACE leadership generating discussion by posing questions about addressing priority coastal research needs with DUNEX VIP Day guests.

5.8 Main Experiment communication and outreach

To plan and execute communication and outreach during the DUNEX Main Experiment, the USCRP developed a DUNEX communications strategy. The strategy documented plans and action items for both internal (within the DUNEX planning committees and DUNEX PIs) and external (stakeholders and public audiences) communication and outreach. Internal communications were important for planning field operations, and examples include weekly logistics and operations meetings, a slack channel for PIs to exchange information, a DUNEX Research Forum email address list for coordination and communication with DUNEX PIs, and a contact information form to keep track of DUNEX research groups and researchers on the FRF property. External communications were broken into shorter-term efforts such as social media and blog posts and longer-term efforts such as agency and university press releases, videos, and news publications. During the experiment, social media posts called PI spotlights highlighted a new DUNEX PI each week to communicate to the public the research objective and societal benefit of each research team's work. Additional spotlights were compiled to highlight the great work of the graduate students involved with DUNEX. The DUNEX spotlights can

be found on USCRP social media sites. An important goal of the communications and outreach was to not only documenting the experiment but to also efficiently communicate the vast effort and impact of DUNEX. For example, to keep a repository of pictures and videos from the extensive field efforts and activities, folders were created in a shared location in the DUNEX Research Forum group for each DUNEX team to contribute to.

Urgent Marvels of Coastal Sciences was an example of local outreach with the town of Duck, North Carolina, which occurred in July 2021 (Figure 25). Urgent Marvels of Coastal Sciences was an interactive exhibition where aerial arts and science collide. The free, family-friendly performance asked viewers to ponder the impact of coastal storms and how vital scientific research is in understanding the impact and urgency of these impacts. The event was sponsored by the Center for Communicating Science at Virginia Tech and included a meet-and-greet and question/answer with DUNEX researchers and the Coastal and Marine Geotechnics research group from Virginia Tech.

Figure 25. Urgent Marvels of Coastal Sciences aerial demonstration event for the public in downtown Duck, North Carolina.

6   DUNEX Lessons Learned

DUNEX successes, challenges, and lessons learned from the experiment were gathered from discussions with the DLT and the DUNEX PIs, post experiment. This information is important to inform future, large, collaborative community experiments.

6.1   Successes

The information gathered about the overall success of DUNEX has been synthesized into best practices in conducting a large-scale experiment, including coordination and communication, scientific advancements gained from the experiment, as well as engaging stakeholders.

6.1.1   Best practices

It is best to utilize a convening organization such as the USCRP to plan and execute logistics, synthesize information, and coordinate among a range of contributors and interests. DUNEX took a new approach to a collaborative nearshore experiment, using USCRP funding to facilitate broad research topics of societal relevance through coordinated logistics support, data management, and communication. USCRP directly funded some academic researchers through a competitive review process and provided the convening logistics to host others who were funded via external resources. This enabled PIs to have autonomy to focus on their specific questions of interest, leverage broad funding support for research, and encourage diverse and open participation amongst research groups.

6.1.2   Scientific advancement

DUNEX researchers completed data collection goals for the 30 field experiments. Additional science advancements are expected over the next 1–5 yr as data are processed. A strong collaborative spirit amongst the research groups was touted as a strong point for enabling improved science findings and increased breadth of applications. The lack of a single funding source enabled a diverse group of researchers whose topics and collaborations evolved organically. This approach enabled the inclusion of more people that might not have been a part of the project originally.

6.1.3 Communication

Virtual DUNEX Coffee Hours were successful, not only for encouraging collaboration during the COVID pandemic but also for enabling regular communication with collaborators who were spread out geographically. The communications plan and modern science communication tools like the data portal, story map, and videos were successful in communicating the value and impact of DUNEX both internally to the team and externally to stakeholders and the public. The DUNEX VIP Day was successful in providing publicity to highlight the DUNEX research projects and PIs, leading to useful discussions and additional collaborations. The event led to follow-on visits to the FRF from congressional staff and discussions and presentations with local Town Managers.

6.1.4 Stakeholder engagement

A main tenet of the USCRP is focused on enabling transition of new research into coastal management and engineering practice. The stakeholder virtual Coffee Hours helped accomplish this goal by facilitating direct interaction between stakeholders and DUNEX researchers, helping identify new research directions and links to the ongoing research.

6.1.5 Coordination

The Leadership Team structure was successful in the planning and execution of the experiment because of the combination of agencies, academics, and the community bringing their unique and critical perspectives. There was enthusiasm among all participants, and they held each other accountable through regularly-scheduled virtual meetings. The FRF logistical support and staff led to strong and continuing dedication for the success of the experiment and this team went to great lengths to facilitate successful experiments. Centrally funded logistical support for the FRF allowed for shared resources including the FRF Operations Support team, to support field intensive experiments. Logistics organization was executed successfully through constant communication among all participants, which enabled and maximized efficiency of shared resources, including personnel and equipment.

6.2 Challenges

As described above, DUNEX was facilitated differently from prior large-scale FRF experiments because there was not one main funding source nor main lead PI (or team of PIs) targeting and directing the research. As a result, the overall goals of the project were broader, and individual PI's experiments were not necessarily designed specifically to build off or support one another. Collaboration grew organically and through interactions such as through coffee hours, meeting the challenges of bringing together disparate projects and PIs. This new structure for targeting research had a few effects which at times created challenges:

- The cumulative data set across all experiments was not strategically designed to ensure specific observations were always available, meaning individual projects had to be more self-sufficient, which at times potentially hindered the research questions able to be answered. For example, past large experiments were organized by a leadership team of scientific experiments, which enabled decision making and support to be allocated and driven by answering strategic research questions. For DUNEX, the scientists were not fully confirmed as participants until they received their funding, leading the facilitation of research questions addressed at DUNEX to be less focused than prior large-scale community experiments.
- PIs were obligated to follow instructions of their funding source, which did not always align with other PIs instructions or requirements, such as COVID-related rules or data sharing/formats, which complicated coordination. For example, the USCRP could not dictate data delivery formats because the USCRP did not fund all DUNEX participants, which made it more difficult to have a cohesive data portal. Instead, participants wanted flexibility in data sharing as they already had specific requirements to meet from their funding source, hindering data sharing.
- DUNEX was established with the short-term goals of making high-quality field measurements to better understand during-storm processes, impacts, and poststorm recovery. Longer-term goals include the improvement of nearshore coastal numerical models and prediction of extreme event physical processes and impacts, improved strategies for coastal resilience, and developing effective communication methods for communities impacted by storms. To do this, the Outer Banks of North Carolina was chosen as the main study site, and most researchers

decided to deploy instruments in the September–October timeframe, a typically high-energy time period for the region with frequent large hurricane and extratropical storm impacts. Unfortunately, during the 2021 DUNEX data collection period, significant wave heights reached only 3 m, which is not truly an extreme wave event for the area. In fact, the 2021 main experiment occurred during one of the lowest energy periods for September to October in the past 10 yr on the Outer Banks. While fixed location experiments, where researchers wait for the storm to come to them, are easier to plan and coordinate, they run the risk of not capturing the desired processes.

- During past community experiments, most of the researchers were able to take 3–4 months off from teaching responsibilities to focus on the experiment, but now researchers have more teaching requirements, which limited the amount of time they could be in the field.

- The unexpected year delay in the main experiment due to COVID-19 hindered the ability of some researchers to travel and participate in DUNEX due to university and agency policies. For example, some researchers had to complete their work independent of the DUNEX Main Experiment to meet funder timelines. Others were not permitted to travel because of COVID-19 restrictions. Still others had new commitments and limitations (e.g., family care, personal health) that hindered participation. The delay also caused issues with funding not being available for the main experiment or for post-experiment analysis. Since projects were funded separately, a single funder could not make the decision to extend or adapt all of the PIs' awards.

6.3   Lessons learned and recommendations

Based on lessons learned from planning and executing DUNEX, the DLTs have made the following recommendations for conducting and improving future large-scale community field experiments.

- Logistics and Planning

  o Planning a large, successful community experiment takes a considerable amount of time and logistical coordination. It is recommended that Pilot and Full experiments be separated by at least 2 yr to allow researchers time to interpret and learn from their initial tests and planners to organize and appropriately facilitate the full experiment.

- o Documentation during the experiment is important for real-time logistics and post experiment debriefs. It is recommended that the leadership team creates a dedicated team to log every equipment deployment location, including a daily summarized report of which PIs deployed what instruments and where they were deployed, rather than relying on individual PIs to provide this information.
- o The DUNEX field site covered a large geographical area, which enabled investigation of diverse environments but also meant researchers were distributed, at times hindering collaboration. It is recommended that when selecting field sites in the future, organizers and funders should consider whether diversity in environments or completeness of observations is of more value to the scientific questions being answered and adjust accordingly.
- o Centralized logistics funding for the FRF enabled easy planning and efficient use of resources to provide broad common data sets as each team did not need to consider these costs and set up individual logistical contracts. Depending on the host location of future experiments, this model of having a host facility should be followed, if at all possible, to ease logistical planning.

- Interagency Collaboration and Funding

  - o While the distributed funding approach enabled new collaborations to arise organically, it made it difficult to answer a large, targeted research question, which appropriately leveraged PI capabilities and interagency collaboration, as was discussed in the Challenges section of this chapter. The DUNEX broad goals, while unifying, lacked concrete metrics and objectives to evaluate experiment success, and thus were challenging to sell to agency funders. Future experiments would benefit from more targeted questions and a dedicated source(s) of funding to focus potential proposals, so projects are less ad hoc and clearly build on each other towards a larger goal.
  - o Designing, collecting, analyzing, and synthesizing large field experiment data takes time. Three-year awards are likely too short to cover the amount of time needed to successfully accomplish PI goals (data collection, analysis, and findings) and encourage student growth and development. Future awards should target 4–5 yr projects to help develop graduate students throughout their graduate careers and create continuity within academic research labs.

- VIP Day

  - VIP day was a useful tool to communicate information about DUNEX. Future VIP days need to be planned so that researchers know to be on site to facilitate interaction with VIPs, but not during a time that is critical to their field experiments.
  - As expected, VIPs had questions about how the new science would be incorporated into coastal management and operations. PIs should have clear connections to discuss to highlight the stakeholder transition and impact of their work, even if the projects are focused on basic science questions. Future VIP Days should pair a stakeholder with a PI at each tour stop so that the science and applications could be better communicated.

- Stakeholders

  - Stakeholder virtual Coffee Hours provided valuable time for researchers to learn about the needs of community managers and other stakeholders. It is recommended that this process occur earlier in the experiment planning process, perhaps at the very early stages to help provide context for targeted research question development.
  - Continued interaction with stakeholders during the experiment and data analysis afterward is critical to ensuring transition of knowledge into practice.

- Training

  - To include representation from diverse participants, it is recommended that funding for travel and training be provided.
  - It is also recommended that more focus and effort be placed on advertising to students and early career employees of other federal agencies who are not already involved with experiments to expand the training and outreach.

- Data Management Plan

  - It is recommended that experiments be structured such that a more formal data management plan be required of participants to ensure a cohesive final data set aligned with modern data management practices (see Appendix D for the data sharing plan).

7   Summary of Ongoing Activities and Path Forward

7.1   Postexperiment virtual meetings (Coffee Hours)

Following the DUNEX Main Experiment, virtual Coffee Hours continued to be held with all participants to exchange preliminary results, discuss future collaborations, and share information and techniques. Specifically, gatherings were held approximately every other week from 14 January 2022 until 05 May 2022 in which DUNEX researchers discussed data-sharing tools developed by the DMT, a potential science communications project, preliminary results on aeolian sediment transport, beach crawler bathymetry measurements, and stereo video swash measurement. In addition, Flynn and Mr. Dave Hallac from the Cape Hatteras National Parks presented and discussed management needs that might be addressed by DUNEX research and/or DUNEX researchers.

During the virtual Coffee Hour meetings, researchers also discussed the pros and cons of a summary publication (drafted as a group, or by the leadership team), a gathering at a dedicated-DUNEX conference session versus presentations at conferences focused on individual specialties (e.g., coastal ocean, ecology, hydrogeology), and having a special collection of storm papers. Based on the input, Mr. Ryan Mulligan (*Journal of Geophysical Research* associate editor) proposed a special collection of storm-related papers in American Geophysical Union journals including *Journal of Geophysical Research* (both Oceans and Earth Surface Processes) and *Water Resources Research*.

The DUNEX researchers were excited about the idea of a DUNEX-focused Workshop to summarize outcomes and next steps but suggested that it should be considered for some time in 3–5 yr, with the preliminary results developed in the meantime presented to disciplinary experts in topic-focused conferences. The goal of the disciplinary presentations is to educate the broader community about DUNEX and specialized results whereas the future DUNEX workshop would be focused on summarizing (near final) results, discussing new collaborations, and brainstorming the steps for continued progress.

Following a summer break, monthly virtual Coffee Hours resumed in late August 2022 to continue discussions among participants. These continued conversations are critical to ensure sharing of preliminary results that may be relevant to others' work and exploration of collaborations that may expand the impact of the DUNEX field data. The initial post-summer gatherings began in August 2022 as a share-a-slide event in which researchers gave 2 min overviews of exciting new results or concepts.

7.2 Stakeholder engagement

In addition to the DUNEX PI Workshop discussed above, the DLT in conjunction with USCRP leadership intend to hold a follow-on joint PI-Stakeholder Workshop with the following objectives:

1. Presenting preliminary findings from the DUNEX data collection and analysis
2. Obtaining feedback from stakeholders to determine if these data address previous and/or existing coastal community resilience needs
3. Discussing "what's next?"; that is, what are the present, most pressing coastal issues facing stakeholders and how might researchers address those needs

7.3 Path forward for future experiments

As documented in this report, many research questions related to storm processes and impacts were posed, and data were collected at DUNEX to address those questions. The path forward towards future experiments will first involve examining the DUNEX data, analyzing those data, and determining if (1) the science questions were adequately answered, (2) more data are needed to address the knowledge gap, and (3) progress has been or will be made toward application of the knowledge gained that will address stakeholder needs.

Second, the DUNEX researchers will continue to meet at DUNEX virtual Coffee Hours and, as with most scientific studies, will likely discover new areas of collaborative research from their DUNEX datasets. Follow-on funding will be required to continue to research such discoveries. Similarly, follow-on engagement to meet with stakeholders and address their present needs with data products would also require follow-on funding.

Finally, the path forward to the next science questions to be addressed in terms of a large-scale field experiment will start by posing that question to the USCRP community (including stakeholders) through a survey. Prior surveys of researchers in the past have indicated topical areas for a large-scale field experiment include the following:

- Sound/marsh processes, erosion, and sediment types
- Nature-based infrastructure (marshes, dunes, oyster reefs, etc.)
- Storm impacts on urban areas
- Storm-chasing experiments to address topics not addressed at DUNEX such as overland flow, dune impacts, and combined surge/rain/groundwater/urban flooding, etc.
- Along Coast variability (100–10,000 m) to understand why one house collapses and a neighboring house does not

Following the survey, the goal is to gather DUNEX researchers along with stakeholders at a future workshop to discuss preliminary research findings and how those findings will address the needs of coastal communities. In addition, results from the survey will be presented and prioritized to begin the process of transforming ideas into the next large-scale field experiment.

Once analyses are completed and outcomes are delivered, there will be a synthesis report across all projects and researchers to demonstrate the knowledge gained and impacts of the experiment series. The outcome report will evaluate the short-term and long-term goals of DUNEX:

- Collect high-quality field measurements for during storm processes, impacts, and post-storm recovery.
- Enhance US academic coastal research programs.
- Improve numerical models.
- Improve predictions of physical processes and impacts.
- Improve coastal resilience strategies.
- Develop effective communication methods for communities impacted by storms.

8   Summary

This report documents a series of large-scale nearshore coastal field experiments, DUNEX, conducted on the North Carolina coast by a multidisciplinary group of scientists from 2019 to 2021. The aim of these experiments was to collect nearshore coastal process data during storm events to determine how coastal processes behave and interact compared to nonstorm conditions. The group of scientists and students involved in DUNEX conducted research spanning multiple disciplines, and they continue to collaborate to understand the interactions of coastal water levels, waves, and flows, beach and dune evolution, soil behavior, vegetation, and groundwater during major coastal storms that affect infrastructure, habitats, and communities. DUNEX was established with the short-term goals of making high-quality field measurements to better understand during-storm processes, impacts and poststorm recovery, and to enhance US academic coastal research programs. Longer-term goals included improving nearshore coastal processes understanding, improving and validating numerical models and prediction of extreme event physical processes and impacts, improving strategies for coastal resilience, and developing effective communication methods for communities impacted by storms.

From this series of experiments, the DUNEX participants have strengthened collaborations to better understand the mechanisms that affect the coast during storms, determined sources of error in numerical models, developed data-derived model parameterizations, quantified model accuracy, and ultimately provided insights that will lead to improved coastal resilience to major storms. Through conversations, web meetings, virtual Coffee Hours, and in-person interactions amongst DUNEX participants, the collaborations and analyses using data collected by multiple PIs during DUNEX will provide information critical to understanding these processes and lead to improved forecasting of when and where risks are highest over the next several decades. In addition, the new knowledge gained from DUNEX will help town managers and coastal consultants understand processes causing sunny-day flooding and to hone their beach-nourishment techniques.

The DUNEX Pilot Study, conducted in 2019, focused on providing researchers with an opportunity to test field methods, equipment, and logistics and served as an opportunity for the planning and organization

teams to evaluate their efforts, review their decisions, to look for gaps in meeting the DUNEX goals and objectives, and make adjustments for the DUNEX Main Experiment. In general, the DUNEX Pilot Study exceeded expectations, with 18 teams participating including 11 universities, to test methods, equipment, and logistics and collect during-storm data sets. In addition, airborne data collection and imagery were provided by the USGS and USACE. The DUNEX Pilot Study included a week-long, formal training week, which was evaluated and modified for the DUNEX Main Experiment to include more hands-on training. The National Science Foundation RAPID team was also on site during the October 2019 time period as part of the DUNEX Pilot Study, which encouraged the majority of research teams to come to the DUNEX site during this same time period. Because of the large number of research teams on site, this period served as a focus week from a logistics standpoint, though smaller in scale than anticipated for the DUNEX Main Experiment. One goal not achieved during the DUNEX Pilot Study was improving communication between scientists and the coastal community to facilitate the translation of scientific research into use. As a result, an initiative began in 2020 to better engage stakeholders with focused communications.

During the pandemic-induced, stand-down year (spring of 2020 through spring 2021), the DLT stepped back from most of the actual field work and focused on rethinking the future of DUNEX while maintaining the energy and collaborative atmosphere that was created during the DUNEX Pilot Study. Rather than accept a 2020 pandemic-induced delay of the DUNEX program as a setback, the cadre of academic PIs and the DUNEX Planning Teams (Leadership, Communications, Logistics, Data Management and Training Teams) maintained their focus towards the eventual 2021 field effort. The DUNEX Planning Teams used this opportunity to rethink what worked well during the DUNEX Pilot Study phase and to reimagine how DUNEX could play a significant role in coastal management sooner than might typically occur by improving communications and stakeholder engagement. Activities during the stand-down year included a leadership review of the DUNEX Pilot Study strengths/areas of improvement, actions to address any gaps in meeting DUNEX objectives, and a focus on ensuring communications were maintained with the larger academic group and stakeholders.

Fortunately, the PIs and DLT used virtual communication since the outset of DUNEX planning in 2016, and these teams had, prior to the pandemic,

implemented a recurring (monthly) virtual Coffee Hour to engage the academic team in a face-to-face discussion of the many facets involved in collaborative field experiments. The DLT also continued to meet to review the DUNEX Pilot Study, address and implement needed changes, and continue to focus on preparations with the research teams. The primary 2020 activities included maintaining these communications using web tools including Zoom, WebEx, Google Forum, and Google Drive. The DLT used this time to maintain existing communications with the research teams, shift training from a formal classroom to a field-based hands-on experience, engage with stakeholders to foster the DUNEX communications objective, hold virtual rapid-deployment exercises with the research teams in 2020, finalize the data management plan, adjust the Planning Teams to best accomplish their specific objectives, and enhance things developed during the DUNEX Pilot Study including (1) online tools and record management (including the DUNEX Story Map), (2) outward communications, and (3) DUNEX videos.

The DUNEX Main Experiment conducted in 2021 focused on capturing a comprehensive, high-quality set of during-storm field measurements, as well as pre- and poststorm data to improve the knowledge and understanding of during-storm processes, impacts, and poststorm recovery as well as fostering collaboration among researchers that will serve to enhance US academic coastal research programs. It is the intent that through the analyses of these data, the ability to represent extreme event physical processes and impacts in the numerical models will allow better prediction of the potential impact of these events. This will then lead to coastal managers and researchers collaborating to develop improved strategies for coastal resilience and effective communication methods for communities impacted by storms.

Thirty research teams, including scientists and students, participated in and contributed to the 2021 DUNEX Main Experiment to collect field measurements of pre-, during-, and poststorm conditions. The multidisciplinary research created many opportunities to collaborate to improve understanding of the interactions of coastal water levels, waves, and flows, beach and dune evolution, soil behavior, vegetation, and groundwater during major coastal storms that affects infrastructure, habitats, and communities. The strong emphasis on organized, systematic interactions as well as casual interactions amongst DUNEX participants strengthened collaborations to understand the mechanisms that affect the

coast during storms, to determine sources of error in numerical models, to develop data-derived model parameterizations, to quantify model accuracy, and ultimately to provide insights that will lead to improved coastal resilience to major storms.

The top recommendations for future collaborative community experiment success that can be applied to field, lab, and numerical model experiments based on lessons learned from DUNEX include the following:

- Form a steering committee of agency, academic, NGO, and community end-users to define scope, focus, and metrics for success
- Synthesize and document the focus and metrics for success of the experiment
- Dedicate logistics resources to provide broad experiment support
- Conduct frequent communications prior, during, and following experiments
- Once analyses are completed and outcomes are delivered, compile a synthesis of knowledge gained and outcomes report to measure how well the experiment is making a difference in coastal community practitioner knowledge and practices

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Appendix A: Organizational Structure

Organizational and leadership teams are formed to facilitate the many and diverse research teams, academic and agency, engaged in the US Coastal Research Program (USCRP) During Nearshore Event Experiment (DUNEX).

Research teams will be operating independently under an overall objective to obtain observations to improve representation of nearshore extreme event processes, with the goals of improving our ability to

- predict storm processes and impacts,
- estimate model accuracy and sources of error,
- develop strategies for coastal resilience, and
- provide storm impact information to communities.

Research teams were expected to collaborate with, support, and respect the DUNEX organizational teams to enhance the capabilities and experience of all researchers.

The DUNEX organization is established to facilitate the USCRP DUNEX during the 2019 and 2021 experiment seasons, including activities leading to the successful execution of the planned events and studies.

DUNEX team members should consider the broadest aspects of the USCRP participants, across all involved academic programs, state, and federal agencies.

DUNEX organizational teams should move forward with their discussions, deliberations, and announcements to facilitate, as early as reasonable, their aspects of the experiment(s).

DUNEX organizational teams should add academic and agency teams members ensuring the broadest participation where those team members are not currently identified.

DUNEX organizational teams should communicate with the leadership team as often as they believe necessary, but no less than monthly participation in the overall team meetings called by the leadership team.

A.1   Leadership Team: Scope

- Facilitate experiment (coordinate USCRP efforts)
- Reach up (report to USCRP VPO)
- Reach out (encourage participation and collaboration amongst US researchers)
- Reach in (manage sub-teams within DUNEX structure)
- Establish committees
- Resolve schedule or objective conflicts
- Refine the science focus and establish overall objectives and directions for the experiments and identify community needs for agency support (e.g., data, infrastructure)

A.2   Logistics Team: Scope

- Plan all aspects of logistics
- Recommend data sharing policy
- Set experiment schedules
- Sort out overlapping objectives
- Track and manage resources (communicates with FRF Operations Support Team)

A.3   Data Management Team: Scope

- Develop DUNEX website/landing page
- Develop map with all instruments (coordinate with Logistics Team)
- Execute data sharing plan (discoverable data portal with internal and external sharing capabilities)

A.4   Training Team: Scope

- Coordinate and plan training opportunities

A.5   Communications and Local Outreach: Scope

- Receive Logistics Surveys
- Plan for media interest
- Coordinate with agency public affairs office if necessary
- Coordinate photography/videography
- Coordinate social media
- Draft communications emails
- Coordinate foreign national visits
- Coordinate with local authorities
- Schedule local outreach events for community involvement
- Assist in management of website

Appendix B: Web Links

Type of Information	Link
USGS press release	SPCMSC scientists travel to the Outer Banks of North Carolina to conduct DUNEX research
USACE press release	US Coastal Research Program's During Nearshore Event Experiment begins fall 2021
USGS press release	USGS DUNEX Operations on the Outer Banks
Coastal Review.org	DUNEX research, delayed by pandemic, set to resume
DUNEX VIP Day video	USACE, Other agencies participates in DUNEX
DUNEX stakeholder engagement video	DUNEX Stakeholder Engagement Video
Story map	DUNEX Pilot Story Map
Blickfeld lidar	Blickfeld lidar sensors support study of storm impacts along coastal North Carolina

Appendix C: DUNEX Participating Research Teams

A total of 18 research teams participated in the DUNEX Pilot Study, including 11 universities supporting 14 students and 7 federal teams deploying 187 instruments during the DUNEX Pilot Study. Some of the research teams that participated in the DUNEX Pilot Study continued with and expanded upon the research during the DUNEX 2021 Main Experiment. Some teams were able to collect data during the 2020 Pandemic-induced, stand-down year as well. Other teams that participated in the DUNEX Pilot could not continue in 2020 or 2021 because of financial constraints, career changes, research direction shifts, etc. Thirty researcher teams participated in and contributed to the 2021 DUNEX Main Experiment from June 2021 through January 2022 to capture the pre-, during-, and poststorm conditions and recovery. Table C-1 lists research teams and the years that they contributed to the DUNEX data collection effort related to the short-term goals of making high-quality field measurements to better understand during-storm processes and impacts and post-storm recovery as well as the longer-term goal of improving numerical model accuracy to predict extreme event physical processes and impacts. Each of these teams and their research intent are described in this appendix.

Table C-1. Research teams (*p* indicates a DUNEX Pilot Study participant; *m* indicates a DUNEX Main Experiment participant).

Lead PI	Affiliation	Research Activity
Bak, Spicer[pm]	USACE-ERDC-CHL	Coastal Model Testbed/Optical Currents
Brown, Jenna[pm]	USGS	Optical Measurements of Beach Profile Evolution and Overwash Processes
Bruder, Brittany[pm]	USACE-ERDC-CHL	Quantifying Flows in the Swash Zone
Chen, Qin Jim[pm]	Northeastern University	Alongshore Variability of Waves and Wave Runup: Observations and Modeling
Cohn, Nick[pm]	USACE-ERDC-CHL	Remote Sensing Approach to Quantification of Aeolian Saltation Dynamics
Ding, Yan[m]	USACE-ERDC-CHL	Predicting Nearshore Processes during Extreme Events with Improved Numerical Models

Table C-1 (cont.). Research teams (*p* indicates a DUNEX Pilot Study participant; *m* indicates a DUNEX Main Experiment participant).

Lead PI	Affiliation	Research Activity
Eisemann, Eve[p]	USACE-ERDC-CHL	Modern Coastal Features with a Long-term Perspective (with Wallace)
Elgar, Steve[pm]	Woods Hole Oceanographic Institution	Mechanisms for Dune Failure during Wave Impacts; Co-PI Raubenheimer
Ferreira, Celso[m]	George Mason University	Wave Attenuation through Vegetation during Storms
Heiss, James[m]	UMass Lowell	Groundwater Processes/Groundwater Flow Impacts on Coastal Morphology
Goldstein, Evan[p]	University of North Carolina–Greensboro	Remote Sensing Approach to Quantification of Aeolian Saltation Dynamics
Grilliot, Michael[p]	University of Washington	RAPID Facility Operations Manager
Irish, Jennifer[p]	Virginia Polytechnic Institute and State University	RAPID Facility Coastal Hazard Lead
Jafari, Navid[p]	Louisiana State University	Geotechnical Measurements at Pea Island to Evaluate Wetland Erosion
Lyda, Andrew[p]	University of Washington	RAPID Facility Operations Engineer
Mieras, Ryan[pm]	University of North Carolina–Wilmington	Autonomous Lidar Scanning System for Measuring Wave/Water Level Transformation and Beach Profile Evolution
Miselis, Jennifer[pm]	USGS	Sediment Pathways and Depositional Patterns
Mulligan, Ryan[pm]	Queen's University	Real-time Modeling of the Coastal Ocean/Storm Forecast Model for North Carolina
Peltier, Jacqueline[p]	University of Washington	RAPID Facility Operations Specialist
Potter, Henry[m]	Texas A&M University	Predicting Wind Energy Transfer during Storm Events
Raubenheimer, Britt[pm]	Woods Hole Oceanographic Institution	Mechanisms for Dune Failure during Wave Impacts; Co-PI Elgar
Sherwood, Chris[m]	USGS	Improving Numerical Model Performance of Simulated Storm Events

Table C-1 (cont.). Research teams (*p* indicates a DUNEX Pilot Study participant; *m* indicates a DUNEX Main Experiment participant).

Lead PIs	Affiliation	Research Activity
Stark, Nina[pm]	Virginia Polytechnic Institute and State University	Variations in Geotechnical Parameters of Beach And Nearshore Surface Sediments
Swann, Christy[p]	NRL	Aeolian Transport, Anemometers, Bedload, and Saltation Traps
Thomson, Jim[pm] Moulton, Melissa[m] Derakhti, Morteza[m]	University of Washington	microSWIFT Drifter Buoys
Traykovski, Peter[m]	Woods Hole Oceanographic Institution	Unoccupied Surface Vehicle
Wallace, Davin[p]	University of Southern Mississippi	Modern Coastal Features with a Long-term Perspective (with Eisemann)
Wargula, Anna[p], Velásquez-Montoya, Liliana[p] Sciaudone, Beth[p]	US Naval Academy	Drivers of Shoreline Erosion on the Sound-Side of Pea Island, near Oregon Inlet, North Carolina,
Warrick, Jon[pm]	USGS	Morphology Change Using Aerial Imagery; Co-PI Sherwood
Wartman, Joe[p]	University of Washington	RAPID Facility; NSF RAPID Team Lead
Wengrove, Meagan[pm]	Oregon State University	Submarine Fiber Optic Cable to Measure Ocean Seafloor Strain and Temperature
Young, David[p] McFall, Brian[p]	USACE-ERDC-CHL	Acoustic Camera for Measuring Flow
Zeigler, Sara[p]	USGS	Using Geospatial Imagery to Map Species Habitat with Changes in Vegetation
Zinnert, Julie[pm]	VCU	Evaluate Belowground Structure of Dune Grasses and Evaluate Potential to Prevent Erosion

C.1 FRF data collection and enhanced data collection during DUNEX

A benefit of hosting DUNEX at the FRF is that the standard data that the FRF Operations Support staff collects on a regular basis also benefit DUNEX researchers by supplementing their individual datasets. During normal operations, the FRF Operations Support staff conducts monthly surveys documenting the beach morphology with additional surveys during extreme events. During the DUNEX Main Experiment, FRF Operations Support staff conducted bathymetric surveys weekly and more frequently along one profile north of the FRF pier. Figure C-1 shows the profile evolution and survey dates. In addition, terrestrial lidar measurements were made from the mobile Coastal Lidar and Radar Imaging System on a weekly basis along with hourly beach scans from both the dune and pier-mounted lidars.

The semipermanent sensors at the FRF consist of altimeters measuring sea-floor elevation, acoustic wave and current sensors measuring waves and currents, a linear array (also referred to as the 8 m array) of 16 pressure sensors in a cross pattern, a cross-shore array (or transect) of wave measurements from the shoreline out to 10 nm including Waverider buoys, acoustic-doppler current profilers, and in situ altimeters measuring real-time morphology change. lidar measurements include a dune lidar measuring wave conditions and beach morphology and FRF pier lidar measuring beach morphology. In addition, standard meteorological measurements such as wind speed and direction, a water temperature profile at the end of FRF pier, air temperature, humidity, rainfall, and incoming solar radiation. During DUNEX, many additional sensors and measurement locations were added as shown in Figure C-2. The semipermanent sensor locations are shown in gray with the additional DUNEX sensors/measurement locations in green.

Figure C-1. Profile surveyed more frequently during DUNEX.
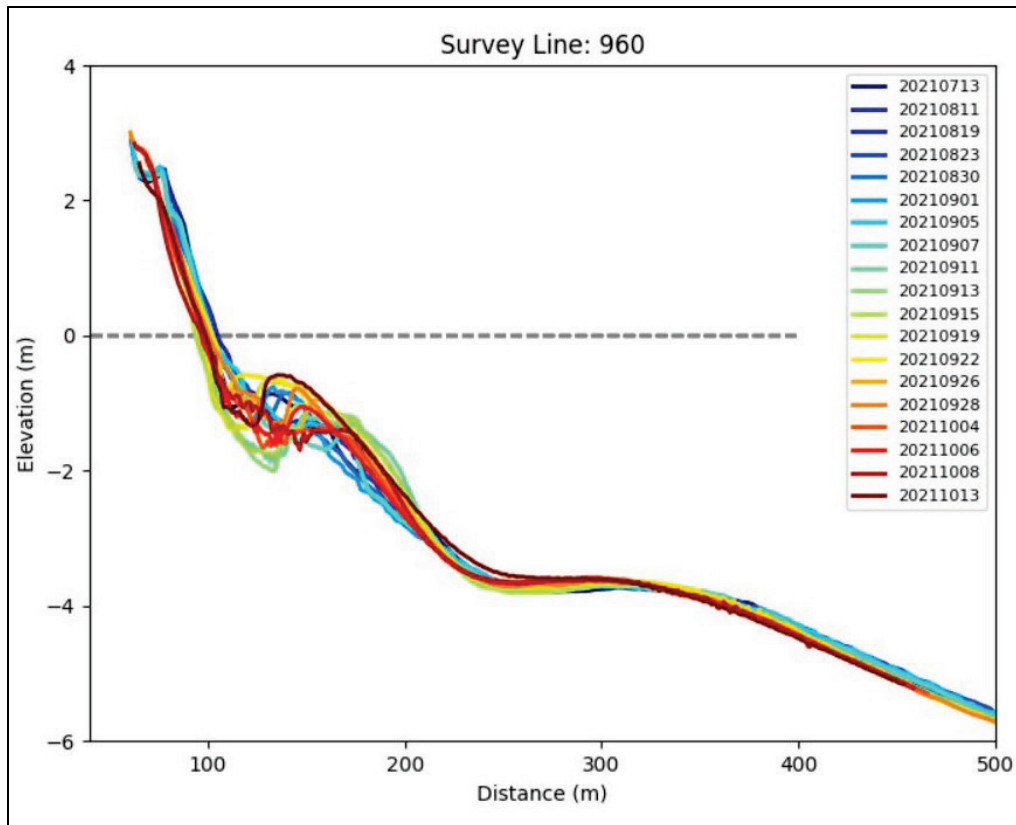
Figure C-2. Gray locations of standard FRF data collection locations and yellow locations where data were collected specifically during DUNEX.
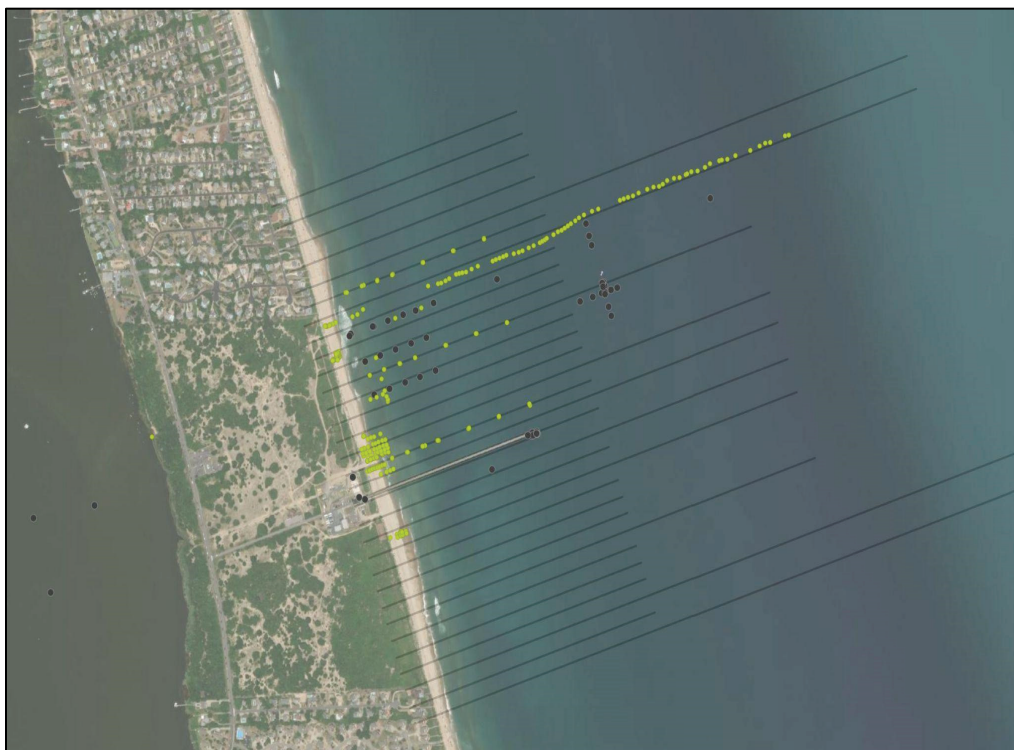
C.2 Individual projects

Though each of the DUNEX PIs had individual research goals, there were many collaborations and exchanges based on overlapping goals and research interests, creating opportunities to share information, instrumentation, labor, and data. Research projects focused on storm processes, impacts, and/or recovery included studies of the following:

1. Dune/shoreline erosion/impacts
2. Groundwater
3. Swash processes
4. Overwash processes
5. Wind measurement
6. Aeolian transport
7. Nearshore currents
8. Sediment transport
9. Wave transformation
10. Vegetation and its impact on wave transformation and erosion
11. Vegetation and habitat dynamics
12. Numerical modeling
13. New measurements and techniques

Other researchers focused their experimental measurements on improving numerical model predictions of physical processes during extreme events. This section of Appendix C is arranged according to the aforementioned project types, and each project is briefly described below. Note that projects often pertain to multiple topics. Though they are listed under the main topical area, subtopics are listed in parentheses beside the research topic name.

C.3 Topic 1. Dune/Shoreline Erosions/Impacts/Morphology Change

C.3.1 Mechanisms for Dune Failure During Wave Impacts (also relates to Topics 2, 3, 9, and 13)

There are few observations of the morphological evolution of sandy shorelines during storms, and thus the present understanding and modeling of dune and beach evolution are based primarily on the net change between pre- and poststorm surveys. To investigate the effects of wave collision and reflection, as well as the exchange of water between the ocean and aquifer on morphologic evolution during storms, Raubenheimer and Elgar (WHOI) deployed an array of pore pressure,

moisture sensors, and acoustic Doppler velocimeters (ADVs) at the FRF site during the DUNEX Pilot Study in October 2019 and during the DUNEX Main Experiment in August to late October 2021. Based on analysis of the DUNEX Pilot Study measurements, the 2021 array was revised to contain vertical stacks of three sideways-looking, 2D ADVs that were deployed within a few centimeters of the sand bed. In addition, the 2021 DUNEX Main Experiment array included a dune-mounted lidar. This array of instruments enabled concurrent, continuous observations of inner-surf and swash waves and currents, beach pore pressures and moisture content, groundwater levels, and beach morphological evolution. The goal of this research project is to use this information to improve parameterizations of ocean-sediment-groundwater interactions that affect dune slumping and failure and beach-sediment transport during storms. The 2021 DUNEX Main Experiment array was designed in collaboration with Bruder (USACE), Heiss (University of Massachusetts-Lowell), Stark (VTECH), and Dr. Rachel Housego (University of Delaware [UD]) to facilitate sharing of measurements to evaluate alongshore variability of the swash and groundwater processes. In addition, the moisture data had potential to benefit aeolian transport studies by Cohn (USACE), and Cohn's moisture data collected near the north property line may enable further evaluations of alongshore variability by collaborators on this team in the future. The team noted that their postexperiment analysis of groundwater heads across the barrier island and surf-zone morphological change have the potential to put the observations in context of the larger groundwater and morphological system.

C.3.2 Drivers of Shoreline Erosion on the Sound side of Pea Island, Near Oregon Inlet, North Carolina (also relates to Topics 4, 7, and 8)

This research team investigated the drivers of both marsh and roadway flooding and shoreline erosion on the sound side of Hatteras Island, near Oregon Inlet, North Carolina, for the North Carolina Department of Transportation (NCDOT). The goal of the project was to provide information and tools for future planning and management of the estuarine shoreline and nearshore region. Five PIs from three institutions collaborated on this team: Dr. Elizabeth Sciaudone (North Carolina State University), Drs. Anna Wargula, Liliana Velásquez-Montoya, and Tori Tomiczek-Johnson (United States Naval Academy), and Smyre, PE (Dewberry).

Wargula and Sciaudone led the fieldwork in 2019, 2020, and 2021 to measure the temporal and spatial variability in currents and water levels in and near the sound side of Hatteras Island as well as inundation depths on the marsh (Jaber et al. 2021; Wargula et al. 2021) using pressure gauges and current profilers. Sciaudone and Smyre surveyed the sound-side shoreline edge of Hatteras Island nine times from 2019 to 2021 using an integrated Global Navigation Satellite System to measure changes in the shoreline over time and immediately following three nor'easters and two tropical storms. Velásquez-Montoya used these field measurements to calibrate and validate a model based on Delft3D (Lesser et al. 2004; Velásquez-Montoya et al. 2021). These observations and model results were used to understand sound-side dynamics near a tidal inlet[4] and consequences for inundation of the barrier island. Tomiczek applied these results to quantify the vulnerability of (1) the nearby transportation corridor (NC-12) to flood-related closure and (2) the sound-side shoreline to severe erosion by developing fragility curves (Tomiczek et al. 2022). The numerical model was run to compare the performance of gray (e.g., hardened structures) and green (e.g., flood channel relocation) coastal protection mitigation strategies considering their effects on hydrodynamic conditions near the eroding shoreline and impacts on inlet circulation[5]. Smyre's experience working with the NCDOT served to guide the process of converting scientific discovery to usable tools for the department's future feasibility planning.

Jafari of Louisiana State University worked in collaboration with Wargula, Tomiczek-Johnson, and Velásquez-Montoya in their investigation of wetland shoreline erosion at Pea Island. He contributed to the project by making geotechnical measurements along the shoreline. In October 2019, he measured the wetland soil resistance using a cone penetrometer to allow for better understanding of the local geology and fine tune his testing protocol. Due to the COVID-19 pandemic causing a delay in the full experiment, he was not able to return for the DUNEX Main Experiment where he intended to use the cone penetrometer to add more detailed wetland resistance along with measurements in the mud flat.

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[4] Velásquez-Montoya et al. Submitted.

[5] Velásquez-Montoya et al. Submitted.

C.3.3 Topography Change Using Aerial Imagery (also relates to Topics 4, 8, 10, 11, and 12)

This project was led by USGS researchers Drs. Jon Warrick, Brown, and Sherwood with contributions from other USGS researchers as well as pilot Mr. Wayne Wright of W. Wright Consulting. The goal of this study was to map changes in topography and land coverage for the entire northern Outer Banks (north of Duck, North Carolina, to Cape Lookout, North Carolina) using multiple sets of aerial imagery to provide regional context for the DUNEX research sites. With the small plane traveling at 60 m/sec at a 300 m elevation and a camera shutter speed of 1 sample/sec, each survey resulted in approximately 12,000 images with a ground sampling distance of 6 cm. Structure-from-Motion (SfM) techniques were applied to the aerial imagery to produce high-resolution (< 1 m) digital elevation maps and orthomosaic photos representing the surface conditions (not bare-ground) before and after storm impacts and during the recovery period. Surveys commenced in response to Hurricane Florence in 2018 and continued to document the impacts and recovery from Hurricane Dorian and the storm conditions through 2022 (Table C-2).

This time series of imagery and topographic products was used by USGS researchers and collaborators to detect damage to property and infrastructure; measure changes in beach shape and volume, including effects of overwash and erosion; identify differences in vegetation and landcover that affect natural habitats; extract elevation metrics (dune height, shoreline, beach slope) for updating coastal models and long-term records of change; and provide input elevations and validate predictive coastal change models. These coastal impacts and recovery conditions were evaluated at (1) specific sites (i.e., North Core Banks), to study detailed coastal change processes, and (2) more broadly at a regional scale, to examine differences due to local shoreline orientation and/or other coastal features. These data are useful for federal, state, and local government authorities and other researchers in the coastal hazards research community, including the National Park Service, USFWS, and the NC Coastal Federation.

Table C-2. Aerial imagery survey time table.

Survey Dates	Event
Oct 6–8, 2018	post-Florence
Aug 30 and Sep 2, 2019	pre-Dorian
Sep 8, 12–13, 2019	post-Dorian
Oct 11, 2019	—
Nov 26, 2019	—
Feb 8–9, 2020	—
May 8–9, 2020	—
Aug 2, 2020	pre-Isaias
Aug 5 and 8, 2020	post-Isaias
Sep 28, 2020	post-Paulette/Sally/Teddy
April 30, 2021	—
Sep 20, 2021	post-Larry
Jan 4 and 8, 2022	—
Jun 15, 2022	—

C.4 Topic 2. Groundwater

C.4.1 Groundwater Processes /Groundwater Flow Impacts on Coastal Morphology (also relates to Topics 1 and 3)

In late August 2021, Heiss (University of Massachusetts-Lowell) deployed a cross-beach (dune toe to lower swash) transect of seven multilevel groundwater wells at the FRF site, each sampling pressure, salinity, dissolved oxygen, and redox potential at four elevations below the water table as part of the DUNEX Main Experiment. His objective was to understand how groundwater flows beneath beaches and dunes during coastal storm events in relation to the storm surge, extreme precipitation, and changes to coastal morphology associated with these events. In addition, Heiss, Raubenheimer, and Elgar deployed pressure sensors and conductivity-depth-temperature sensors in the sound and ocean, and in groundwater wells spanning the barrier island. The data from these sensors was used in conjunction with video and lidar measurements of runup and shoreline water levels (collected by Raubenheimer, Elgar, Ms. Ciara Dooley, Bruder, Dr. Spicer Bak, and others) to understand the combined effects of ocean processes (surge, setup, and runup), extreme precipitation, and shoreline erosion on groundwater flow within the beach, thereby connecting the dominant physical processes (hydrologic, hydrodynamic, and morphodynamic) with the shoreline response during

severe coastal storms. The sensors were recovered in late April 2022. Heiss' aim was to understand groundwater flow behavior to better predict how coastal aquifers respond to a changing climate, which is important for managing coastal water quality and nearshore ecosystems. This research study provides information that coastal managers need to assess the timing of nutrient and contaminant release to coastal and estuarine waters. His research is therefore extremely important to learn more about how large storms affect groundwater flow behavior near the coastline and the ability of coastal aquifers to filter groundwater contaminants that would otherwise discharge into the ocean. This research helps improve coastal water quality and preserve the recreational and economic activities that depend on healthy coastal ecosystems. These data and research findings, along with observations of surf-zone circulation and transport collected by other DUNEX PIs, also help in the evaluation of the prevalence of eutrophication and algal blooms, the capacity of beaches to filter seawater pathogens, and the desorption and mobilization of legacy contaminants in sediments and transport to/from the surf zone.

C.4.2 Beach Groundwater, US Coastal Research Program (USCRP) (also relates to Topics 1 and 3)

A cross-beach transect of vertically stacked pressure gauges (each with a sensor beneath the sand surface, just below the low-tide water table level, and approximately 1 m below the water table) was deployed by Housego (UD) and Raubenheimer from the dune toe to the inner surf zone at the FRF site from late August until late October 2021 to observe the groundwater circulation at the aquifer-ocean interface during storms. This study leverages groundwater measurements collected by Raubenheimer and Elgar across the barrier island, as well as oceanographic measurements (waves and tides) collected at the FRF, to characterize storm-driven changes in the groundwater flow patterns. Collaborations with Heiss enabled this team to evaluate alongshore gradients in groundwater heads. In addition, the research team collaborated with other DUNEX participants to examine the feedback between beach and dune evolution and groundwater heads. The data obtained here may also be useful to studies of swash and shore-breaks.

C.5   Topic 3. Swash processes

C.5.1   Quantifying Flows in the Swash Zone/Swash Processes (also relates to Topics 8, 9, and 13)

A USACE-led project (Bruder and Brodie) focused on the swash zone because this poorly understood region of the littoral environment is where storm waves can cause erosion. Due to the inherent difficulty in making in-situ measurements of swash flows as well as the wide range of pertinent spatial scales which make large-scale sensor deployment expensive and impractical, there is a lack of field measurements in this region. For these reasons, the researchers designed and constructed autonomous camera systems to remotely collect multidimensional (xyz, time) water-surface measurements to quantify alongshore forcing mechanisms in the swash zone. They investigated multiple configurations of remote sensing technology, leveraging their own and other pilot participant's in situ data for ground truth.

The first configuration installed during the 2019 DUNEX Pilot Study was a two-camera stereo system installed on the FRF pier, facing northward. The autonomous and remote system captured imagery of large swash events from Hurricanes Dorian, Humberto, and Lorenzo. The researchers used stereo analysis to generate point clouds of the water surface from the imagery. During Hurricane Lorenzo, they also used a single-beam lidar to scan an alongshore transect to assess accuracy and resolution of the imagery.

The second system configuration in 2019 DUNEX Pilot Study included a temporary 30 ft tower installed landward of the dune, north of the FRF Argus tower. The researchers positioned two multibeam lidars and two stereo cameras on top of the tower to measure over 50 m of the swash zone in the alongshore direction (Figure C-3). WHOI collaborators (Raubenheimer and Elgar) installed a single beam lidar on the tower to compare to their cross-shore array of in situ instrumentation measuring water level and current velocity. Other USACE team members included Mr. Nick Spore, Mr. Alex Renaud, Mr. Bill Ledford, Mr. Jason Pipes, Mr. Rob Mitchell, Mr. John Bull, and Mr. Charles Ellis.

During the 2021 DUNEX Main Experiment, Bruder continued her DUNEX study of the swash zone. As part of the 2021 DUNEX Main Experiment, Bruder expanded her field set up to four stereo cameras, two 30 ft towers,

a single-beam lidar, and a 9 × 9 array of in situ pressure sensors and velocimeters. Understanding swash zone processes helps numerical modelers better predict beach evolution and thus the potential for erosion, breaching, and overwash from storms. By developing this stereo imagery technology, the measurement density increased and cost decreased, allowing expanded use of the technology to improve knowledge of swash zone processes more broadly.

Figure C-3. Swash array installation of in situ pressure sensors and velocimeters at the FRF in Duck, North Carolina.

C.5.2 Alongshore Flows in the Inner Surf and Swash, National Science Foundation (NSF) (also relates to Topics 1, 7, 9, and 13)

In late August 2021, Raubenheimer and Elgar (WHOI) deployed a cross-beach transect of near-bed pressure gauges and 2D sideways-looking ADVs between the berm and about 0.5 m water depth, and two additional cross-shore transects of pressure gauges 50 m north and south of the central transect (Figure C-4). The observations were used in conjunction with optical imagery and lidar measurements of runup to evaluate the hypotheses that (1) the forcing of alongshore flows near the beach is cross-

shore (depth) dependent, (2) opposing water-level-gradient and oblique-wave forcing drive alongshore flows that change direction between the surf and swash zones, and (3) oblique-wave and wind forcing dominate inner-surf and swash flows during storms. Observations during storms were compared and contrasted with those during moderate wave conditions to examine how processes differ as wave and wind conditions change. The array was developed in collaboration with Bruder and Heiss, who planned to use the data to aid in evaluation of their hypotheses. Comparisons of swash measurements from all three studies enabled evaluations of alongshore variability of swash processes and morphological changes. In collaboration with Stark (VTECH), two near-bed pressure gauges were replaced with vertical stacks of small pore-pressure sensors to examine upward-directed pressure gradients that can reduce the effective weights of sediments and facilitate sediment transport. The findings from the analysis of these data could potentially improve the ability to predict flows near the beach, the corresponding storm-induced changes in coastal morphology, and the subsequent recovery. Development of optical-based techniques to estimate swash flows is beneficial to other DUNEX researchers, future researchers, and students as well as to town managers and coastal engineers in evaluations of processes affecting beach nourishments on local beaches. The instruments were recovered in late October 2021.

Figure C-4. Raubenheimer and guide dog Hugger adjust vertical elevations of swash velocimeters mounted on a tripod on the beach north of the FRF pier (photo credit: Elgar).

C.6   Topic 4. Overwash Processes

C.6.1   Modern Coastal Features with a Long-Term Perspective (also relates to Topics 1 and 8)

Researchers from CHL (Ms. Eve Eisemann) and the University of Southern Mississippi (Dr. Davin Wallace, Ms. Shara Gremillion [graduate student], Ms. Erin Miller [graduate student], and Mr. Bill Funderburk [graduate student]) had the research goal of developing a relationship between quantifiable coastal features and storm response using airborne lidar digital elevation models (DEMS) collected by the Joint Airborne lidar Bathymetry Technical Center of Expertise to automatically map the foredune ridge on a regional scale. This technique was applied at the DUNEX FRF Site. Terrestrial lidar surveys collected at the FRF and ground-truth points on the dune features were used to support a thorough analysis of feature-detection accuracy. Additionally, overwash locations and washover fan deposits at the DUNEX Southern Site (Pea Island) were mapped using airborne and satellite imagery. Lidar DEMs were utilized to calculate washover volume fluxes that were then compared to results from detailed field mapping (surface and sub-surface) of several individual washover fans. The field mapping effort, initiated in August 2019, included the collection of ground penetrating radar, deep vibracores, and the placement of overwash-monitoring cameras and water-level loggers.

The overarching goals of this study were to (1) apply existing tools that automatically map the foredune ridge on a regional scale and (2) quantify the volume of storm-induced overwash into the back barrier over timescales of years to centuries. Foredunes and back-shore dune ridges provide the first line of defense against storm surge and waves along sandy shorelines. The characteristics and volumes of these features heavily influence the resilience of a given stretch of beach to storm impacts, therefore there is a demand among the coastal community for accurate, frequently updated, characterization of these coastal features on a regional scale. Regional dune ridge datasets are used to make high-stakes decisions and predictions affecting not only federal agencies, but coastal communities around the nation. Furthermore, understanding the long-term patterns and impacts of overwash allows researchers, coastal managers, and the public to better understand the risk associated with sandy shorelines and quantify a major sediment sink on a regional scale.

C.6.2 Optical Measurements of Beach Profile Evolution and Overwash Processes (also relates to Topics 1, 3, and 9)

Severe storms can be destructive to developed and natural coastal communities, with the beach and dune typically being the last line of defense to the populations and habitats they protect, particularly on barrier islands. The DUNEX research goal of Brown (USGS) was to measure the interaction between storm-induced water levels and the underlying beach profile and determine how profiles change in time as a storm approaches and impacts the coast. She installed a pair of digital cameras overlooking the Pea Island site, spanning the entire beach from the dune to the shoreline, which were used to measure the time-varying shoreline water elevation and the beach profile elevation at the study transect (Figure C-5). These hourly observations provided detailed, quantifiable information on beach erosion in response to storm waves and surge, as well as the amount of water and sand that overwash the dune from storm/flooding conditions. This research provided valuable data and observations of the rapidly evolving wave, water level, sediment transport, and beach profile conditions across the nearshore during a storm, which are notoriously and understandably difficult to collect. Her team also observed the vulnerability or protective nature of the modified beach profile from continuing storm impacts. Her research findings continue to improve understanding of how water levels vary and the beach and dunes evolve during a storm as well as the recovery time after a storm event, that is, the factors that control coastal change caused by major storms. The data can also help researchers to improve and validate total water level and coastal change predictive models of storm forces and impacts, which can be used by local emergency managers and community members to prepare for and respond to storms.

Figure C-5. Photo of USGS researchers Palmsten (*left*) and Brown (*right*) beside one of two cameras deployed at the Southern Site for DUNEX to measure nearshore processes (photo credit: Sherwood, 18 September 2021).

C.7   Topic 5. Wind measurement: predicting wind energy transfer during storms (also related to Topic 9)

Dr. Henry Potter's (Texas A&M University) research team conducted a field investigation to improve nearshore momentum flux prediction by recording 3D wind speeds inside and outside the surf zone using sonic anemometers. By improving the understanding of wind interaction with the ocean environment, that is the transfer of wind energy to wave energy and water currents, this research in turn improved the ability to understand and predict sediment transport and shoreline change. His team deployed one anemometer on the mast at the end of the FRF pier and four anemometers attached to the Argus video tower on the FRF property between 15 and 30 m above the mean water level. These instruments were deployed for the duration of the DUNEX Main Experiment starting in August 2021. Collectively, the measurements showed the difference in the momentum flux outside and across the surf zone. Preliminary results indicated that the momentum flux is reduced when the wind is alongshore (i.e., perpendicular to the wave direction). This means less wind energy is transferred to the ocean which, in turn, limits wave growth, wind-driven currents, bottom friction, and sediment transport. The coastal environment is a critical component of the overall world environment, and Potter's improved understanding and predictions in this region helps coastal managers to better predict the impacts of hurricanes and sea level change on beaches and dunes and can also help with search and rescue efforts.

C.8   Topic 6. Aeolian transport: remote sensing approach to quantification of aeolian saltation dynamics (also relates to Topics 1, 2, 3, and 10

Cohn (USACE) focused his DUNEX research on studying the processes that drive wind-blown sediment transport on the beach and into coastal foredunes during storms (Figure C-6). While energetic storm events can bring high wave energy and water levels that can erode the beach, they can also commonly bring wind conditions that simultaneously build dunes. Targeted, short-term field campaigns using in-situ measurement techniques (wind sensors, moisture probes, sediment sensors, groundwater wells, grain-size collection) and remote sensing instruments (terrestrial lidar, doppler wind lidars, cameras) were completed during storms during the DUNEX Pilot Study and DUNEX Main Experiment to better parameterize the wind conditions that mobilize sediments and to

quantify spatio-temporal patterns in sediment mobilization and movement on the beach. The subsequent response of the dune was simultaneously measured to assess how these inputs of wind-blown sediment from the beach are distributed across the dune face, particularly in the context of vegetation and topographically induced wind flow patterns. This research contributed to advancements in theory and is continues to be incorporated into state-of-the-art process-based numerical models of coastal foredune evolution. These theoretical and numerical capabilities can be used to better quantify the time scales for dune recovery and growth, as well as insights on the optimum management of those features using vegetation, which has direct implications for coastal managers. A small subset of these R&D efforts was published in Cohn (2022).

Figure C-6. Drs. Goldstein and Cohn discuss the data collection plan for the day.

C.9   Topic 7. Nearshore waves and currents

C.9.1   microSWIFT drifter buoys (also relates to Topics 9 and 13)

This research team from the Applied Physics Lab, University of Washington, studied nearshore wave breaking and wave-driven circulation during the DUNEX Pilot Study using a coherent arrays of drifting microSWIFT buoys. The team was led by Dr. Jim Thomson (field

observations), Dr. Melissa Moulton (analysis of wave-driven circulation), and Dr. Morteza Derakhti (analysis of wave breaking). Mr. E. J. Rainville (graduate student) worked on both field data collection and modeling techniques. Their DUNEX research goal was to deploy a large number of rapidly-deployable, small buoys that measure wave heights and ocean currents. By analyzing the movement of swarms of these buoys, the objective was to improve understanding of large-wave events, understand how shorelines respond to these events, and improve data collection methods in challenging coastal conditions. The science goal of this effort was to validate new formulations for the onset and strength of breaking waves, while simultaneously mapping the circulation driven by spatial patterns in breaking.

The buoys were deployed in a rapid-response mode during storms and large wave events without needing to risk personnel operating boats. During the 2019 DUNEX Pilot Study, the buoys were launched from the FRF pier, and during the DUNEX Main Experiment, the buoys were also air deployed from a helicopter. The buoys measured waves and wave breaking via high-frequency accelerations while simultaneously tracking surface currents as drifting objects. At the time of this study, this was a new technique for the coastal community that includes mapping wave, current, and inundation patterns. In addition, the microSWIFT buoys provided ground truth data during storm events to be used in conjunction with remote sensing and model forecasts techniques.

During the 2021 DUNEX Main Experiment, this research team conducted 2,187 individual drifter deployments spanning 81 arrays. Based on the DUNEX Pilot Study experience, during the DUNEX Main Experiment, the team was able to track the buoys in real time and coordinate with other DUNEX researchers. The team was also able to target deployments for larger wave events and tune the array placement for forecasted current patterns.

Because larger events are most likely to negatively impact (erode) beaches and dunes, findings from this research help to improve coastal change predictions. Second, the data collection techniques developed and applied in this project can be demonstrated so that citizens, schools, and other groups could potentially engage in similar data collection efforts. The buoys have an open-source architecture such that other groups can readily adopt this approach and build their own buoys.

C.9.2 Acoustic camera for measuring flow (also relates to Topics 8 and 13)

This DUNEX Pilot Study project was led by CHL researchers Drs. David Young and McFall. Their objective was to test the capability of an acoustic-camera-based bubble image velocimetry system for making accurate 2D flow measurements in a turbid field environment. They deployed an acoustic camera from the CRAB at the FRF for several hours in October 2019 to observe and measure the motion of suspended sediment and microbubbles advected by fluid motion above the sandbar in the surf zone. Observing the motion of suspended particles in a quantitative way allowed the images to be processed with particle-image and particle-tracking velocimetry algorithms. This technique was previously successfully tested in a laboratory setting by Young et al. (2018).

C.9.3 Optical remote sensing (Vannevar Bush Faculty Fellowship, Dept. of Defense) (also relates to Topics 3, 9, and 13)

Two cameras were deployed by Elgar on the ARGUS tower from late August until late October 2021 to obtain imagery of the ocean surface. The observations formed the basis of Dooley's PhD work (WHOI). After developing and comparing the foam tracking techniques (particle image velocimetery and optical current meter), Dooley used the observations to investigate patterns of mean flows and surf-zone eddies. In addition, the observations were used to understand the flow patterns affecting hydrodynamic, hydrogeological, and morphological processes near the swash and groundwater transects deployed by Heiss, Raubenheimer, Housego, and Bruder. The flow information was also used by WHOI PhD student Mr. Jinshi Chen in studies of undertow. The techniques that were developed and applied in this study enable estimates of flows in the surf zone from drones or stationary cameras and may be useful to other researchers and local communities.

C.9.4 Undertow (Professional Association of Diving Instructors Foundation) (also relates to Topics 9, 12, and 13)

PhD student Chen and Raubenheimer (WHOI) deployed three acoustic Doppler current profilers (ADCPs) from late August to mid-September 2021 in 1 m to 2 m water depth, across a small sandbar, to observe the vertical structure of the offshore-directed mean flows (undertow). As waves propagate into shallow water, they break, transferring momentum to mean flows that transport sediment, pollutants, and biota along the coast and offshore, and that can affect diver (and swimmer) safety.

Numerical models of coastal ecosystems and evolution require information regarding the vertical structure of the flows, and water-quality sampling plans depend on transport pathways. Existing parameterizations based on observations obtained in the 1990s with vertical stacks of single-point sensors predict a mid-water-column undertow maximum. However, these field measurements did not resolve the near-bed flows. Recent detailed vertical profiles of flows measured in laboratory flumes and in simulations suggest that the maximum offshore flows occur near the bed under breaking waves. This research project helps to clarify whether the flows on natural beaches also have a near-bed maximum, or whether processes (e.g., broad-banded waves and winds) and conditions (e.g., bed roughness and heterogeneity) in the field result in a different flow structure. Therefore, this DUNEX dataset and numerical model simulations were used to resolve the differences between the numerical, laboratory, and field observations, and to examine further the processes driving undertow and the vertical structure of these offshore-directed flows. The DUNEX measurements are also useful to other PIs to compare imagery-based surface flow estimates (collected by Elgar, Dooley, Raubenheimer, Bak, and others) with depth-dependent flows. Flow data collected by other researchers assisted this project in putting the undertow measurements into the broader context of surf zone circulation patterns. Measurements of setup and swash collected by other researchers was also useful for estimating the momentum balances.

C.9.5 Surf-zone eddies (NSF) (also relates to Topics 1, 3, 4, 8, 9, 12 and 13)

Surf-zone circulation patterns are important to the transport and mixing of materials across the surf zone, including the advection of pollutants, biota, and even swimmers. From late August until late October 2021, Elgar and Raubenheimer deployed and maintained an alongshore transect of eight bottom-mounted ADVs in approximately 2 m water depth (from just north of the pier to the north property line) to investigate rotational currents, which have been observed in many surf zones for a wide range of conditions. Specifically, the measurements are being used to determine if breaking waves generate vortices (small eddies) that coalesce into larger eddies (which then affect currents and sediment dispersal in the nearshore zone) via an inverse energy cascade. In addition, these measurements allow the researchers to isolate the effects of instabilities of mean currents (shear waves), slow modulations of the incident wave field (wave groups), and nonlinear energy transfers (breaking waves) on rotational flows. The results of this study will be used to improve numerical models to provide

better predictions of alongshore variable nearshore currents. Coastal planners and managers can then use these numerical models to forecast nearshore conditions, including rip currents, alongshore currents, and the subsequent transport of materials such as sediment and chemicals, as well as swimmers. WHOI PhD students Dooley and Chen are including the observations as part of their dissertation research on alongshore flow and bathymetric variability and undertow, respectively.

C.9.6 Fiber optic cable as an ocean-measurement device (also relates to Topics 1, 8, 9, and 13)

Dr. Meagan Wengrove (OSU) used submarine fiber optic cable as an instrument to measure ocean seafloor strain and temperature under varying wave and current combinations at 3.6 m resolution over a cross-shore distance of 1.5 km, 400 m north of the FRF pier from 01 November 1 to 15 February 2022. The fiber response was interrogated using a shore-based laser, and as the fiber deformed due to the dynamic pressure imposed, she measured changes in bottom strain and as the temperature of the water or beach changed. She also measured seafloor temperature. DUNEX provided a means of validating this new ocean sensor against many arrays of trusted data streams in the nearshore that other researchers had deployed as part of the experiment. Since fiber optic cable is a continuous instrument, this method of data collection was the densest and longest-range submarine instrument applied in DUNEX for ocean sensing. At the time of this experiment, submarine fiber optics were used to sense in a spatially and temporally dense array over lengths of hundreds of kilometers, and the technology continues to improve. Implications of fiber optic sensing include early warning for coastal hazards (e.g., sneaker waves, tsunamis). Results can also be used for better understanding of the influence of waves and currents on the seafloor in both shallow and deep ocean regions.

C.10 Topic 8. Sediment transport/bathymetry change (scour monitoring)

C.10.1 Variations in geotechnical parameters of beach and nearshore surface sediments (also relates to Topics 1, 3, 9, and 13)

Stark (VTECH) is a coastal geotechnical engineer whose research involves investigating the engineering and geotechnical properties of coastal sediments under dynamic and energetic environmental conditions in relation to sediment remobilization processes. This research leads towards

a better understanding of sediment erosion and deposition processes as well as the interaction of coastal sediments with structures and infrastructure. The DUNEX Pilot and Main Experiment Study project led by Stark included contributions from four PhD candidates, two masters students, and one undergraduate student. The goals of this DUNEX project were to measure spatiotemporal variability of geotechnical properties of beach sediments during storm events with regards to local geomorphodynamics; monitor pore pressure behavior of beach and nearshore sediments under varying wave conditions; measure spatiotemporal variability of surficial sediment strength in the nearshore zone with respect to local geomorphology; investigate new/novel geotechnical in situ measurement tools; and test a scour monitor to measure bed elevation changes around structures during storm events.

Each team member had a specific role in the investigation. For example, Stark specializes in in situ geotechnical characterization of seafloor sediments in energetic environments, sediment remobilization processes, development of geotechnical tools, and methods for coastal environments. She led the students to study pore pressure behavior in sandy sediments, in situ sediment sampling and strength measurements, geotechnical characterization from remote sensing techniques, and scour monitoring techniques. Specifically, during DUNEX they studied how different engineering properties of coastal sediments affect local erosion and sediment stability as well as how engineering properties of coastal sediments change with environmental conditions, particularly during storms. Furthermore, Stark strives to integrate geotechnical data into a broader understanding of coastal processes and their impacts on coastal communities. She anticipated that the knowledge gained from this study could contribute to the improvement of predicting coastal erosion as well as to identifying risks to infrastructure from changes in engineering properties of coastal sediments. Such understanding will assist with finding efficient and sustainable mitigation and adaptation solutions for coastal communities in the context of climate change and increased storminess and sea level rise.

C.10.2 Sediment pathways and depositional patterns (also relates to Topic 1)

Miselis (USGS) focused her DUNEX research project on measuring sediment redistribution across the shoreface during and after storms. She deployed geophysical instruments from a USACE amphibious vessel that

allowed her to map the seabed and the geologic features beneath it to determine how storms alter the structure of the seabed and whether records of the storm's effects are preserved. Insight into where storms move sediments will allow emergency managers to predict where and when coastal infrastructure, like roads, might be buried during storms, possibly impeding emergency response efforts. Understanding to what extent sediments are replenished after storms is necessary for helping coastal communities prioritize post-storm shoreline erosion mitigation efforts, like beach nourishment. In addition, Miselis used the information on sediment exchanges between coastal environments to predict how coasts and their associated habitats will respond as climate change increases sea level and alters the frequency and intensity of extreme storms.

C.10.3 Surf-zone hydrodynamics and sediment transport (also relates to Topics 7, 9, and 12)

Dr. Drude Fritzbøger Christensen (University of Denmark) used observations collected by Raubenheimer, Elgar, Chen, and Dooley (WHOI) to investigate interactions between surf-zone hydrodynamics and morphodynamics in rip current systems. Christensen participated in the field deployments with the WHOI Team, including assisting with maintaining and recovering the moisture sensor arrays, pressure gauges, groundwater instruments, and current meters. Wave, wind, and morphology observations obtained by the FRF staff were used to drive numerical model simulations and compared with the observations. Christensen stated, "I think applying a multidisciplinary approach to coastal research can be vital in order to make people understand the connection between specific coastal processes and things of importance in their everyday life." This statement highlights the DUNEX and USCRP goal of science translation and stakeholder engagement.

C.11 Topic 9. Wave transformation/wave runup

C.11.1 Alongshore variability of waves and wave runup (also relates to Topics 1, 3, 10, and 12)

This project was led by Dr. Q. Jim Chen (Northeastern University) in collaboration with Raubenheimer and Elgar (WHOI) and Dr. Andrew Lyda (UW). The first goal of this DUNEX Pilot Study was to investigate the alongshore variability in waves and wave runup by integrating field observations from the FRF (wave gauges, lidar, and Argus, etc.) into

numerical models. Chen deployed six wave gauges in an alongshore transect near the mean sea level shoreline at the FRF approximately 150 m north of the pier (between Y = 671 m and 971 m in the FRF coordinates) from 07 October 31 October 2019 and conducted aerial drone surveys of the FRF beach and marsh areas near in collaboration with researchers from the FRF and the NSF RAPID Facility at UW. The field data were analyzed and compared with the numerical model result of FUNWAVE-TVD. The model was modified to generate a longshore uniform wave field (eliminates the longshore variation of wave height caused by the offshore boundary conditions), allowing for a detailed investigation on the morphologic control of infragravity waves and wave runup variations in the longshore direction. Salatin et al. (2021) published a refereed journal paper in *Journal of Geophysical Research-Oceans*.

C.11.2 Autonomous lidar scanning system for measuring wave/water level transformation and beach profile evolution (also relates to Topics 1, 3, and 13)

Mieras (University of North Carolina–Wilmington) used an in-house-developed, affordable, autonomous lidar scanning system to simultaneously measure the cross-shore transformation of waves/water levels and beach profile evolution during storms. His line-scanning, low-cost (LLC) lidar system was tested and validated during DUNEX in November 2020 at the FRF.

During the DUNEX Main Experiment, six LLC lidars were deployed at the PINWR in a cross-shore transect spanning mean sea level to the primary dunes from September to October 2021. Mieras was particularly interested in how the hydrodynamics and beach morphology differ during extreme events when compared with day-to-day conditions. The goal was to demonstrate the efficacy of such low-cost systems in continuous beach morphology monitoring to the extent that the technology becomes more widely adopted as a coastal remote sensing platform at the community scale. Coastal communities face a growing threat of flood hazard and shoreline erosion due to sea level rise and more frequent intense coastal storm events. Knowing how beaches evolve during extreme events is crucial to predicting whether storm surge, waves, and/or elevated water levels will breach or overtop coastal dunes, leading to flooding and damage to leeward communities and the built environment.

Mieras also collaborated with other DUNEX researchers by deploying a compact, solid-state Blickfeld Cube 1 3D lidar scanner on the same tower as Bruder's stereo camera system and Raubenheimer's lidar system north of the FRF pier from 2–10 August 2021 to collect data on changes in the beach profile, waves, and water levels. The sensor system requirements are multifaceted, recording both shoreline changes that take place over a longer period of time and larger spatial dimensions, as well as wave profiles that require fast and continuous data acquisition in a much narrower spatial field. He tested how the configurable scan patterns of the Blickfeld sensors can best be used for these different requirements and is finding that the flexibility in the configuration and mounting of the sensors is an advantage over other similar systems. The longer-term goal is to continue development of an affordable and scalable remote sensing platform to measure storm surge impact on coastal areas. At the time of this publication, Mieras was synthesizing the data collected during DUNEX and developing data detection algorithms for determining wave runup and beach profile evolution as well as other coastal processes.

C.12 Topic 10. Vegetation and Its Impact on Wave Transformation and Erosion

C.12.1 Wave attenuation through vegetation during storms (also relates to Topics 1, 3, and 9)

Dr. Celso Ferreira (George Mason University) investigated and quantified the interaction of storm surges and waves with coastal vegetation by measuring hydrodynamic (waves, currents, and water levels) conditions in coastal marshes during extreme events using RBR tide and wave sensors and Onset HOBO water pressure loggers, as well as vegetation characteristics, and topobathymetric surveys using differential GPS Trimble R4 from June 2021 to November 202 as part of the DUNEX Main Experiment. The instrumentation was deployed in marsh areas of the Cape Hatteras National Seashore at the margins of the Pamlico Sound with the sensor locations deployed in a transect from the edge of the marsh to the end of the marsh as shown in Figure C-7. The goal of this research was to improve the ability to predict storm processes and impacts on vegetated and nonvegetated coastal features. Ferreira was assisted by his graduate student Mr. Tyler Miesse (both pictured in Figure C-8) whose research focused on field data collection and the numerical modeling of wave attenuation by vegetation, where he combined the field measurements and the results from numerical modeling. The project intent was to provide

field-based evidence to support NNBF as a safe/reliable means for local-level resilience against flooding for coastal communities.

Figure C-7. Instrument deployment locations in Pamlico Sound.

Figure C-8. Graduate students Miesse and Ferreira retrieving instruments from their DUNEX study.

C.12.2 Natural and nature-based features (NNBFs) as first line of defense from storm impacts on coasts (also relates to Topics 1, 3, 9, and 12)

Chen (Northeastern University) noted that coastal barrier islands serve as the first line of defense against oceanic and meteorological forces and that extreme storm events can have a significant impact on coastal barrier morphodynamics, degrading their defensive capabilities. His DUNEX research study objective was to determine if natural and nature-based features can help to bolster this first line of defense. His research investigated the effect of vegetation on waves, wave runup, and sediment transport under storm conditions by comparing vegetated and nonvegetated sections of coastline, 100 m south of the FRF pier. The vegetated coastline consisting of more than 15,000 plastic cable ties attached to a 5 m × 5 m geogrid was created by Chen and his students (Figure C-9). An anchor system buried 1 m deep into the beach was designed and constructed to secure the artificial vegetation field on the beach to survive severe storm conditions. Six RBR wave gauges, three Nortek ADVs, one Nortek Signature 1000, and ten GoPro cameras were deployed around the vegetation field to measure waves, currents, and wave runup. Daily topographic survey using real-time kinematics was carried out to measure the beach profile changes within the vegetation field. The FRF pier lidar scanner provided the baseline data of beach profiles without vegetation for comparison. The field study took place for 3 weeks from 19 September to 10 October 2021. Chen and his students then simulated these vegetated and nonvegetated nearshore and aeolian processes using numerical models (Figure C-10). The intent of this research was to improve the predictive capability of modeling nearshore-beach-dune system coevolution. This enables engineers and coastal stakeholders to more accurately project the response of vegetated dunes and marshes to extreme events and sea level rise in the design of natural and nature-based flood protection projects for coastal resilience.

Figure C-9. Artificial vegetation field 100 m south of the FRF pier in the background.

Figure C-10. (*a*) the instrumented artificial vegetation patch, and water surface elevation around the patch on (*b*) 26 September 2021, (*c*) 02 October 2021, and (*d*) 04 October 2021. The white areas marked by red circles are the vegetation shadow because the laser scanner could not penetrate the patch. The undulations on the plots marked by violet arcs suggest beach cusp formation and evolution.
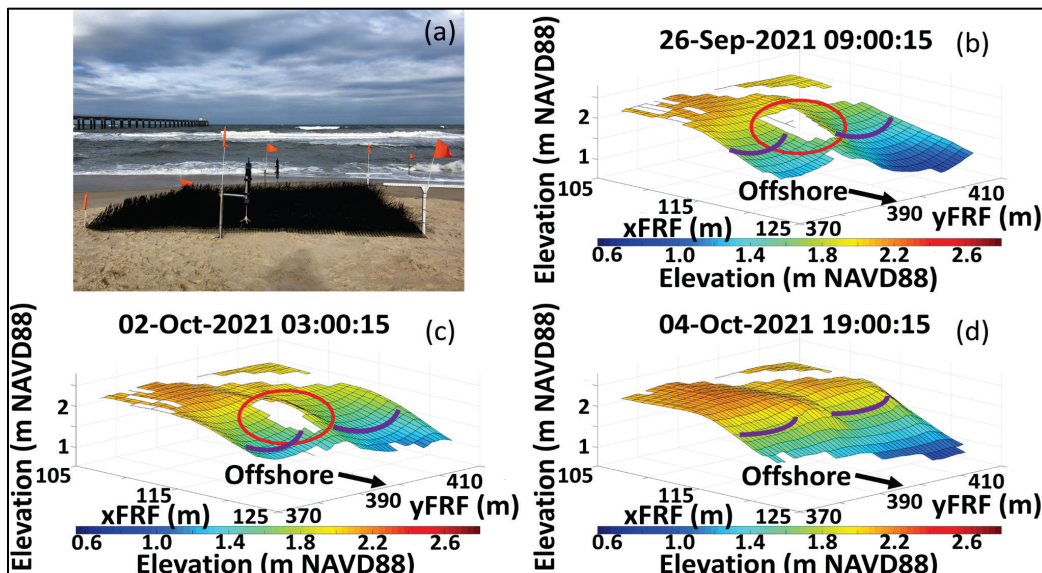
C.12.3 Evaluation of community composition and belowground structure of dune grasses for the potential to prevent erosion

Because of the tight coupling among island ecological processes, geomorphological processes, and oceanic/atmospheric drivers of disturbance (e.g., hurricanes, nor'easters, sea-level rise), coastal dunes are highly vulnerable to global climate change. The processes that maintain these systems are disrupted by rising sea level and increased storm intensity and frequency. Foredunes are complex adaptive self-organizing systems due to the interactions between vegetation cover and topography. In the process of dune formation, vegetation influences sediment stabilization with aerial stems and leaves intercepting aeolian transported sediments and plant roots reducing erosion. Changes in dune species or community structure have implications for storm response as species vary in aboveground vs. belowground investment.

Dr. Julie Zinnert and her two masters students, Ms. Shannon Walker and Mr. Andrew White (Virginia Commonwealth University), conducted field studies of above and belowground dune grasses during the entire DUNEX time period (2019–2021). Both students also served as USACE summer interns. Above and belowground data were collected from summer 2019 through summer 2021. In addition, belowground data from cores collected at the FRF from a NOAA funded project continued through fall 2022. Specific sampling time periods were summer 2019, post-Dorian 2019, summer and winter 2020, summer 2021, and spring, summer, and fall 2022. The data collection locations were in the vicinity of the FRF, as shown in Figure 11.

The objectives of this team of researchers were to (1) evaluate the importance of local-scale differences in foredune morphology, plant community features, and site history for response to storm impacts and (2) examine whole plant traits (above and belowground) of four dominant dune species with a specific emphasis on the least well-known, root system traits. Transects were established at each site on the leeward side of the dune stretching from the crest to the dune toe. Species composition, percent cover, stem number and plant height were assessed in 0.5 m² plots along each transect (2019–2022).

Whole plant samples of *Ammophila breviligulata, Panicum amarum, Spartina patens*, and *Uniola paniculata* were collected in Summer 2019 by hand digging from the face of the main foredune. Aboveground

components were assessed for stem number and maximum leaf length per stem. Belowground components were separated into belowground stems (buried portions of vertical stems), rhizomes (lateral stems), and roots. Rhizomes were counted and measured for length, and roots were scanned using WinRHIZO. All aboveground and belowground components were then dried and weighed for dry biomass. In WinRHIZO, roots were grouped into five, 0.5 mm categories of root diameter for analysis (0.0–0.5 mm, 0.5–1.0 mm, 1.0–1.5 mm, 1.5–2.0 mm, and >2.0 mm). From the WinRHIZO scans and biomass, root tissue density, specific root length, average root diameter, root surface area and root diameter distribution were assessed. Roots were subsampled for tensile strength and mycorrhizal percent infection (Walker and Zinnert 2022).

C.13 Topic 11. Vegetation and habitat dynamics: using geospatial imagery to map species habitat with changes in vegetation (also relates to Topics 1 and 4)

Dr. Sara Zeigler (USGS) noted that many species, including shorebirds and sea turtles, nest in beach habitats with minimal vegetation. These habitats are created primarily by storms and slowly disappear as vegetation regrows in the years between storms. Her research intent for DUNEX was to map shorebird and sea turtle habitat on the barrier islands comprising Cape Lookout National Seashore using a time series of historical and recent geospatial imagery from 2014 to 2019 to determine how much habitat is typically available after a storm and how quickly that habitat is lost between storms along the Outer Banks. Understanding habitat dynamics in coastal environments supports conservation of threatened and endangered species while helping coastal managers make informed decisions that balance human use and habitat conservation.

C.14 Topic 12. Numerical modeling

C.14.1 Real-time storm forecast modeling of the coastal ocean/North Carolina (also relates to Topics 1, 2, 4, 7, and 9)

Mulligan (Queen's University) led a DUNEX team to gain a better understanding of waves and currents during storms using computer models, both at large scales (all of eastern North Carolina) and small scales (surf zones and beaches). His team included two masters and two PhD candidates who contributed their expertise to the study, as discussed in the following paragraphs. His team developed a real-time forecast

modeling system called DUNEX-RT (https://coastlines.engineering.queensu.ca/dunexrt/) (Rey and Mulligan 2021) to provide 36 hr forecasts of waves, currents, and water levels for coastal North Carolina and was extended to 48 hr forecasts since the conclusion of DUNEX. The objective of this project was to simulate coastal ocean conditions during storm events and to provide real-time results to other DUNEX researchers to help in their field deployments. For example, his model results were provided to DUNEX researchers Housego and Raubenheimer (WHOI) to help with their groundwater model and to Wargula and Velásquez-Montoya US Naval Academy to provide boundary conditions to their numerical model of Oregon Inlet. Due to travel limitations during the COVID-19 pandemic, Mulligan did not actually travel to deploy instruments during DUNEX, but he was able to rely on the extensive network of available real-time monitoring stations in North Carolina to validate his model. He also collaborated with Elko (ASBPA) and other DUNEX researchers to select water level sensor installation sites on the DUNEX sound side, which he then incorporated into his modeling to provide those measurements along with forecasts at ocean locations already on the project website.

His model domain covered the continental shelf and coast of the Outer Banks as well as the Albemarle-Pamlico estuarine system (Figure C-11). The intent of the project was to provide coastal forecast information as a resource for DUNEX researchers studying nearshore processes on both the ocean and estuary sides of the Outer Banks. Longer team applications of the system by researchers as well as coastal managers/stakeholders was also foreseeable to the PI. Mulligan's modeling system is based on the hydrodynamic model Delft3D (in 2D mode) coupled with the spectral wave model SWAN[6]. The models were forced with High Resolution Rapid Refresh winds, atmospheric pressures, and precipitation every hour on a 3 km grid over the entire model domain. Precipitation over land was neglected. NOAA's Extratropical Surge and Tide Operational Forecast System provided water levels at the ocean boundary every hour at 20 km intervals for all boundary points with depths greater than 10 m. The NOAA WaveWatch 3 forecast provided ocean wave boundary conditions, using the full spectrum (sea and swell components) of the Northwest Atlantic grid at 20 km intervals every 3 hr. Model results were compared in real time at 10 min intervals with observations of waves, currents, and water

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[6] Simulating waves nearshore wave model.

levels across the system. His research findings continue to lead to better forecasts of storm conditions and better predictions of coastal hazards.

Finally, as mentioned previously in this report, training the next generation of coastal researchers is one of the goals of DUNEX and the USCRP. Mr. Alexander Rey worked on DUNEX-RT under Mulligan as part of his PhD research and has since completed his course of study. Ms. Laura Szczyrba, another graduate student working with Mulligan on the forecast model, brought to DUNEX her numerical modeling skills and her regulatory experience from working on Federal Emergency Management Administration flood hazard mapping and the National Flood Insurance Program projects. She participated as a student intern with Raubenheimer during the DUNEX Main Experiment. She is passionate about coastal research and enjoys translating research results in a socially relevant way so that the information produced gets into the right hands to make a lasting impact on coastal communities. Other graduate students continue to use data collected during DUNEX to enhance DUNEX-RT and develop new models for their research projects.

Figure C-11. Model domain including the track of Hurricane Dorian (from Rey and Mulligan 2021).
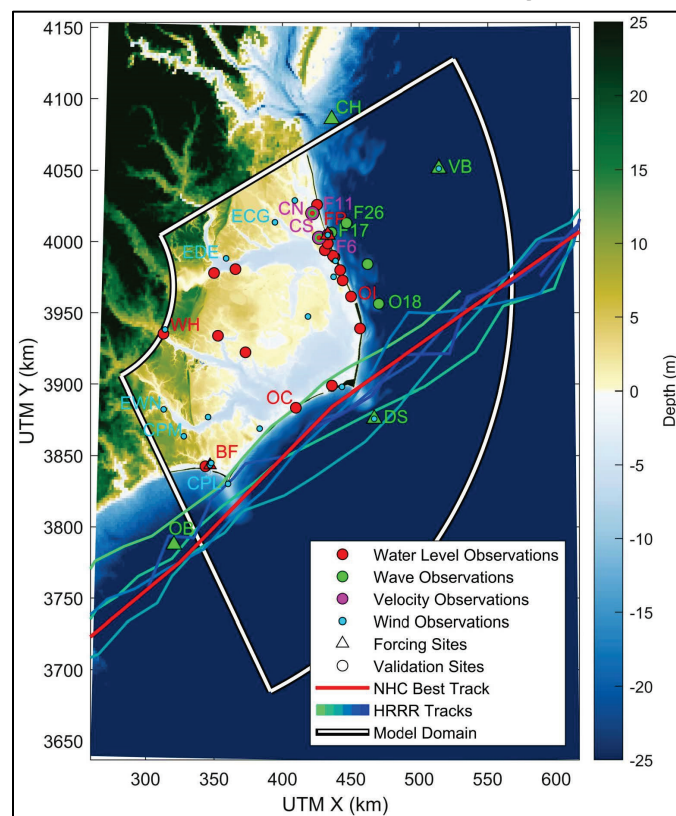
C.14.2 Coastal model test bed (CMTB) (also relates to Topics 7, 8, and 9)

The FRF staff established a coastal numerical model test bed focused on forcing numerical models with offshore conditions to compare to real-time nearshore observations. The numerical models are available to run on demand (e.g., daily/weekly), forced with offshore data and validated against observed nearshore data. Model results, visualizations, and comparisons from the DUNEX Pilot Study, along with detailed descriptions of model setups, are available on the FRF website.

As part of the DUNEX Pilot Study, Drs. Dylan Anderson (FRF and formerly an Oak Ridge Institute for Science and Education post-doctoral student) and Bak (FRF) developed methods to measure spatially varying currents from optical imagery to use in validation of and assimilation into circulation models. The coastal model test bed (CMTB) research team developed low-cost drifters using cell phones for data collection and PVC[7] tubes for housing the cell phones, which were then used for validation of the remotely sensed optical method development. Their initial efforts during the DUNEX Pilot Study gave promising results for tracking foam in both alongshore and cross-shore directions using an optical flow method. When compared to the drifter measurements, the optical flow method showed skill in capturing current patterns in the trough, but initial results suggested a bias high in the nearshore-swash and low offshore of the breakpoint, respectively. This research complemented Thompson and Moulton's (UW) research to characterize spatially variable wave fields during extreme storms.

Wave and circulation observations (in situ and remotely sensed) were also used to explore data assimilation methods to improve inverted bathymetry estimates during extreme storms in collaboration with Mr. Matthew Geheran and Drs. Tyler Hesser and Matthew Farthing (CHL). This research also led to collaboration with Dr. Greg Wilson (OSU) to incorporate a 1D variational assimilation scheme to improve forecasts of 1D morphologic evolution.

During the 2021 DUNEX Main Experiment, the CMTB research team added team member, Ms. Maile McCann (University of Southern California), and focused on quantifying uncertainty in the optically derived

[7] Polyvinyl chloride

currents with respect to varying oceanographic and atmospheric conditions (wind, surface foam fraction, rain, wave conditions), such as DUNEX-targeted extreme storms that limit confidence in method implementation. Phase-averaged and phase-resolving wave models, circulation models, and morphology models were available but not a focus for the team during the DUNEX Main Experiment.

Bak also deployed an unoccupied autonomous ground vehicle (UAGV) to survey the nearshore and surf-zone environments. More than 10 UAGV surveys were compared with the CRAB/LARC-V surveys for the October 2021 data collection time period. The UAGV data compared well with the traditional surveys with a root mean square error of 8.7 cm and bias of 2 cm. Uncertainty in measurements were shown to meet the International Hydrographer Organization's (IHO) exclusive standard (IHO 2020). This remote data collection method was compared to the Unoccupied Surface Vehicle developed and demonstrated by Traykovski (WHOI) during the DUNEX Main Experiment. This led to follow-on collaborative work between the two research teams.

C.14.3 Predicting nearshore processes during extreme events with improved numerical models (also relates to Topics 7, 8, and 9)

Dr. Yan Ding (CHL) did not deploy instrumentation during DUNEX but requested the collection of high-quality data in the nearshore zone in collaboration with other researchers to improve understanding of wave breaking, current (undertow, return flow), and sediment transport during extreme events. The study location was the FRF nearshore environment. His intent was to use these high-quality data to develop a predictive numerical modeling capability to forecast long-term beach morphological changes (shoreline positions and beach profiles). The intent was for this technology development to provide design guidance and planning of long-term and regional-scale erosion protection measures for coastal communities.

C.14.4 Improving numerical model performance of simulated storm events (also relates to Topics 1,3,4,7, and 9)

Sherwood (USGS) led efforts to collect hydrodynamic data and topographic/bathymetric elevations at the southern site, in support of improving numerical coastal change models. Incident waves provide most of the energy for coastal change, and nearshore bathymetry exerts primary

controls on wave conditions. The fundamental goal in coastal change modeling is to predict changes in bathymetry and topography. Accurate and timely wave measurements and elevation maps are required to initialize and evaluate models of waves, runup, nearshore circulation, and morphological change.

The USGS team (Sherwood, Brown) and collaborators (Traykovski, Anarde, Mieras) objective at DUNEX was to collect wave, water level, and topo-bathy response data during storm conditions at the PINWR and compare those observational data to model predictions. A cross-shore array of sensors was deployed spanning the nearshore, including bottom-mounted current profiles and wave sensors in the surf zone, and buried pressure sensors paired with altimeters across the beach and dune to measure water levels and bed changes (Figure C-12). Additionally, the nearshore morphology was surveyed multiple times during DUNEX with a variety of methods including a researcher walking cross-shore and alongshore transects taking GPS point measurements at regular intervals, a heli-kite taking aerial imagery combined with SfM processing to create topographic surface products (Figure C-13), and an unmanned autonomous surface vehicle to measure bathymetry transects (Figure C-14). Survey data were combined to create seamless high-resolution topographic/bathymetric maps representing the morphology conditions during DUNEX.

The observations were used to improve USGS numerical coastal change models, including the Coupled Ocean-Atmosphere-Waves-Sediment Transport (COAWST) modeling system (USGS, "COAWST," n.d.) and the USGS Total Water Level and Coastal Change Model (USGS, "Total Water Level," n.d.), an operational forecast model that predicts the total water level (combination of tides, storm surge, wave setup, and wave runup) and likelihood of coastal changes during storms (compares total water level to beach and dune elevations). The goal was to determine what model improvements are needed to better predict coastal response to storm events. The USGS data collection as part of DUNEX gave the research team the ability to provide more accurate, reliable forecasts of natural hazards such as coastal flooding and beach erosion to improve life safety and protect property.

Figure C-12. Photo overlooking the cross-shore array of sensors deployed at the southern site (photo credit: Sherwood, 17 September 2021).

Figure C-13. Traykovski with the heli-kite he designed to collect aerial imagery for topographic surveying (photo credit: Sherwood, 07 September 2021).

Figure C-14. Traykovski preparing one of his unmanned autonomous surface vehicles to measure bathymetry at the southern DUNEX site (photo credit: Sherwood, date unknown).

C.15 Topic 13. New measurements and techniques: Rapid Facility

The NSF RAPID Facility, located at the University of Washington, provides PIs with equipment, software, and support services needed to collect, process, and analyze perishable data from natural hazards events. The RAPID team was on site for the DUNEX Pilot Study in early October 2019, so many of the DUNEX research teams scheduled their on-site visits to coincide with this time period to take advantage of this extra opportunity to learn about and test equipment provided by RAPID.

Five RAPID Facility personnel and three student research assistants participated in the 2019 DUNEX Pilot Study to offer hands-on training with facility instrumentation to DUNEX pilot participants. The RAPID team consisted of these leadership team members: Dr. Joe Wartman (UW), RAPID Facility Director; and Dr. Jennifer Irish (Virginia Tech), Coastal Hazards Lead; RAPID Facility staff, Dr. Michael Grilliot (UW), Operations Manager; Lyda (UW), Operations Engineer; Ms. Jacqueline Peltier (UW), Ops Specialist; and VTECH students Mr. Steven Hoagland, Ms. Megan Beever, and Ms. Benjamin Roston.

The first of two nor'easters impacted the study area during the RAPID week. A second storm passed through the area in late October, with a few teams remaining on site. RAPID Facility personnel participated in a Z-boat demonstration in Currituck Sound and made the Z-boat available to DUNEX researchers collecting nearshore bathymetry near Oregon Inlet and exploring novel reconnaissance applications at the Wright Memorial Bridge. Extensive terrestrial laser scanning (TLS) and uncrewed UAS training was provided to participants. TLS training was offered for several scanners, highlighting each scanner's capabilities and specific uses. Multirotor and fixed-wing UAS were deployed to collect red-green-blue and multispectral imagery to investigate post-storm vegetation health and measure current velocity. DUNEX Pilot Study participants leveraged both TLS and UAS resources for additional research projects examining road surface and bridge deck crack detection and inspection, changes in beach-dune morphology, and post-storm inundation mapping. Other coastal and geotechnical instrumentation was deployed as part of the effort to monitor wave and water levels, collect bottom samples, and characterize soil bearing capacity and sub-surface stratigraphy for a range of research efforts, involving dozens of researchers.

C.16 Summary

One of the primary DUNEX goals was to obtain measurements and expand the network of scientists across multiple disciplines collaborating to understand the interactions of ocean water levels, waves, and flows, beach and dune evolution, soil behavior, and groundwater during major coastal storms. In addition to collecting measurements as part of multiple DUNEX projects (described above), DUNEX participants met virtually on a regular basis (through virtual Coffee Hours) and in person (when at the DUNEX sites) to strengthen their collaborations to address (1) understanding the mechanisms that affect the coast during storms, (2) determining sources of error in numerical models, (3) developing data-derived model parameterizations, (4) quantifying model accuracy, and (5) ultimately providing insights that will lead to improved coastal resilience to major storms. The PIs noted that interactions among storm processes can cause hotspots of erosion, dangerous rip currents, and coastal flooding that pose high risk and expense to coastal communities. The collaborations and analyses using data collected by multiple PIs during DUNEX provided and will continue to provide information critical to understanding these processes and lead to improved

forecasting of when and where risks are highest. In addition, the knowledge gained from DUNEX has and will continue to help town managers and coastal consultants understand processes causing sunny day flooding and hone their beach nourishment techniques.

As illustrated above, the network of scientists and students involved in DUNEX conducted research spanning multiple disciplines and continue to collaborate to understand the interactions of ocean water levels, waves, and flows, beach and dune evolution, soil behavior, vegetation, and groundwater during major coastal storms that affect infrastructure, habitats, and communities. Conversations, web meetings, virtual Coffee Hours, and in-person interactions amongst DUNEX participants have strengthened collaborations to understand the mechanisms that affect the coast during storms, to determine sources of error in numerical models, to develop data-derived model parameterizations, to quantify model accuracy, and ultimately to provide insights that will lead to improved coastal resilience to major storms. Storm process interactions can cause hotspots of erosion, dangerous rip currents, and coastal flooding that pose high risk and expense to coastal communities. The collaborations and analyses over the next several decades using data collected by multiple PIs during DUNEX will provide information critical to understanding these processes and lead to improved forecasting of when and where risks are highest. In addition, the new knowledge gained from DUNEX will help town managers and coastal consultants understand processes causing sunny day flooding and to hone their beach nourishment techniques.

Appendix D: Data Sharing Plan

By Mr. Michael Forte, Dr. Spicer Bak, (USACE), and Dr. Richard Signell (USGS)

D.1   Executive summary and key points

The USCRP encourages and will provide logistical support to assist DUNEX participants to collaborate and share data. The key points for the data sharing plan are the following:

Timeline: Participants are encouraged to make data available to other DUNEX PIs within 1 yr and to the public within 4.5 yr of collection.

Format: Participants are encouraged to make processed data available as NetCDF files with standardized CF and Attribute Convention for Data Discovery (ACDD) metadata, following NOAA best practices (https://www.nodc.noaa.gov/data/formats/netcdf/v2.0/).

Data management: Participants are responsible for distribution of raw data. Participants are encouraged to store and share processed data files via a standard public server, realizing that certain institutions are required to serve their data in specific ways (e.g., USACE–THREDDS/ERDDAP; USGS–Sciencebase.gov/THREDDS/ERDDAP; NSF and others – DesignSafe-CI). All data sets will have DOIs and acknowledgement statements. The following good citizenship practices are recommended when using others' data: (1) Data should generally be shared openly between PIs; (2) When you access the data for the first time, please send an email to the data collector to acknowledge use of their data and to discuss ideas/goals of interest/use with the collector to avoid duplication of efforts; (3) Specifically acknowledge the data collector and funding source during all talks (verbally) and in all publications (reference DOI); (4) Don't do something with someone else's data that you wouldn't want done with yours.

Data sharing support: The DUNEX DMT will develop scripts to sync NetCDF files on the standard servers to a centralized server and will develop example scripts/tools to help participants exchange and use each other's data. Tools and scripts will be shared via GitHub or another

publicly accessible repository (to be determined [TBD]). The DMT is ready and willing to help people share their data.

D.2   Background

The USCRP strongly encourages collaboration and data sharing amongst all DUNEX participants. The DMT has proposed data sharing and metadata standards that will help enable easy data access and usage among experimenters so that DUNEX participants can easily collaborate. Where appropriate, the DMT will make recommendations for data formats and metadata guidelines based on feedback from researchers and data management experts. In addition, the DMT will make every effort to work with PIs to help make it easy to convert their data into these recommended formats through webinars and code sharing. However, the DMT recognizes these formats may not be the best fit for everyone and that not everyone has the time, funding, or interest to learn new data management techniques. It is ultimately your choice as a PI on how you would like to share your data. If you have questions or concerns, please reach out to the DMT at any time by emailing dunexDMT@gmail.com. This document serves as a draft data-sharing plan that summarizes the recommendations from the DMT and provides some detail on standards and timelines.

Following the path laid out in the legacy experiments, the intent is to allow easy access to processed data via a variety of services, with raw data sharing the responsibility of the individual PIs. When feasible, participants are encouraged to use established standards, which allows movement towards web portals, standardized tools to interact with the data, generic code repositories, and enhanced collaboration between DUNEX experimenters (and eventually the public at large).

D.3   Data timeline

Sharing and managing data effectively and efficiently is important for fostering scientific collaboration in large experiments with many participants and many types of observed and simulated data. Based on input from DUNEX PIs and organizers, two distinct phases are envisioned: (1) informal data sharing amongst DUNEX PIs followed by (2) more formal data publication and archiving. Based on participant input, the data sharing should be as simple as possible to make sure there are no barriers to collaboration.

In the internal sharing phase, the DMT recognizes that data sharing will likely occur in native formats, though it is encouraged that participants work towards suggested archival formats as reasonable. During the second phase, the data team will assist PIs with archival formats and share data publicly. It is suggested that any PI wishing to keep their data in their native format during this second phase, plan to utilize DesignSafe-CI (or a similar method to share their data). More details are included below for those wishing to transfer their data to specified, archival-ready formats. To complement these data format suggestions, metadata guidelines will be established for participants that meet established scientific community standards. Following these guidelines will ensure that data users have enough information to use data effectively.

D.4   When data will be shared

DUNEX has a diverse set of collaborators with different timelines and policies for data sharing dictated by their funding organizations. Because a key element of DUNEX is collaboration, participants are encouraged to share their data as soon as practical. In the absence of other mandates, the following maximum time limits are encouraged:

- Data sharing **internal** to DUNEX PI

  o Participants are encouraged to make data available to other DUNEX PIs **within 1 yr** (ideally shared with the DUNEX DMT after processing to help prepare for data sharing implementation).

- Data sharing to public

  o Data collected by federal agency personnel will be publicly available when published, following agency requirements, usually shortly after collection.
  o Other participants are encouraged to make their data publicly available after 4.5 yr. If data collectors are eager to share their data publicly at an earlier time, the data team is happy to accommodate.

## D.5   How data will be shared

Different groups have different requirements for data sharing, whether based on preference, funding body's request, or federal regulations. To be inclusive, a distributed sharing method is proposed with a value-added

solution on top (Figure D-1). The DMT encourages conversion of data when possible to NetCDF files with standardized CF and ACDD metadata, following NOAA best practices (NetCDF Templates | National Centers for Environmental Information (NCEI) (noaa.gov)), due to the variety of benefits (included metadata in file, community standards, array slicing capability, etc.). Consistent and standardized formats will allow easy development of shared analysis scripts and plotting capabilities among many other benefits. These files can then be served as preferred in the desired repository (e.g., USACE–THREDDS/ERDDAP; USGS–Sciencebase.gov/THREDDS/ERDDAP; Others–DesignSafe-CI; referred to herein as *preferred sharing method*). PIs who do not wish to adopt these recommended methods should plan to store their data in DesignSafe-CI as whatever file types that they prefer and provide a link to their data to the DMT.

The DMT will then develop generalized scripts designed to sync available data from these servers to make copies to a centralized server where standardized services will be provided to allow efficient searching and retrieval of data. If a data generator finds a problem in their data and updates their data on their preferred server, it is recommended to email the DMT who will send an email to the collaborators directly, DMT, and/or DUNEX message board. However, the data-sync mechanism will also automatically keep data on the central server up to date in the event of changes to the initial hosted data that will propagate across all servers, even if someone forgets to alert the DMT. While the path for automatic syncing is clear for data stored as NetCDF on THREDDS/ERDDAP servers, it is proposed that other data types will be zipped and made available on the centralized server.

During internal sharing, the link to the centralized server will be shared only with people participating in the experiment. During external sharing, the DMT will then add all data to a geoportal [GEOPORTAL] metadata catalog for people to explore and discover data publicly. The benefits of using a standardized format are numerous but allow for standardized tool development, plotting utilities, and ease in data sharing.

Figure D-1. Flowchart for data sharing. *Gray* arrows represent one of many protocols to interact with the data on the servers. Data generators have a *one-stop drop* for their data, and the Data Management Team (DMT) will handle the rest.
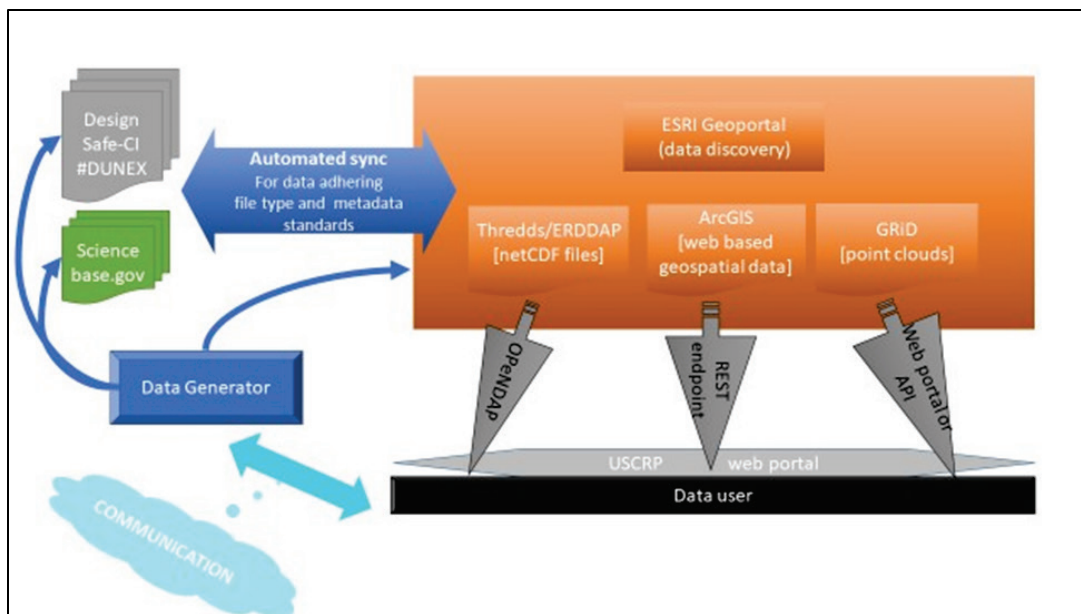
D.6 How to ensure credit and collaboration with data collectors

As part of the collective metadata guidelines, the DMT will ensure that all data sets have DOIs and acknowledgement statements. The following good citizenship practices are recommended when using others' data:

- Data should generally be shared openly between PIs.
- When you access the data for the first time, please send an email to data collector to acknowledge use of their data and to discuss ideas/goals of interest/use with collector to ensure no duplication of efforts.
- Specifically acknowledge data collector and funding source during all talks (verbally) and in all publications (reference DOI).
- Do not do something with someone else's data that you would not want done with yours.

D.7 Whom the data sharing policy affects

Initial data sharing will occur amongst all DUNEX PIs. A DUNEX PI is someone who shows intent and active engagement in the DUNEX community via a combination of activities such as

- submitting original participation/logistics survey,

- active sharing information/plans on the research forum spreadsheet,
- active participation in Friday virtual Coffee Hour discussions,
- an active collaboration with other DUNEX PIs,
- active presence at DUNEX sites during the experiment, and
- a written research plan/proposal that shows specific DUNEX questions and engagement.

D.8 Collaboration and outreach

The DUNEX DMT will develop example scripts/tools that will operate on data from the pilot experiment to help build tools that leverage conventions and data standards to efficiently operate on data from multiple sources. These tools will be shared and continue to expand over the course of DUNEX with scheduled information sessions via webinar or hands-on availability during scheduled times. Tools like Jupyter Notebooks (Python) and Matlab Live Scripts will be developed and shared via GitHub or another publicly accessible repository (TBD). The DMT is ready and willing to help people share their data, pending available funding. The vision is that after a basic set of tools is developed by the DMT, they can and will be shared with the community via a code repository where other researchers can contribute.

Researchers participated in a survey focused on data collection, types, and sizes. The results highlighted five main types of data, each of which is listed below with more details about standards and suggested methods for data hosted by the USACE on behalf of USCRP as archival formats. These are the suggested file formats and data sharing platforms. For nonpreferred formats, (e.g., ASCII based files) data-sharing venues such as DesignSafe-CI will be utilized. USGS and the USACE both have established protocols and many helpful tools for generating NetCDF files that can be served on state-of-the-art servers. Members of the DMT have been very happy with this approach and are eager to help interested researchers learn more about this technology. The appendix at the end of this document provides more information about these technologies.

1. **Oceanographic and meteorological time-series and gridded data** (e.g., waves, currents, bathymetry grids, spatial model output): These data will be stored as NetCDF files, meeting appropriate standards (CF, National Center for Environmental Information [NCEI], ACDD). They will be served using both ERDDAP and THREDDS.

2. **Imagery** (e.g., UAS footage, stationary camera, and non-point cloud data): These data are envisioned to be stored as Cloud-Optimized Geotiff or NetCDF. They will be service using ERDDAP, THREDDS, and ArcGIS Image Server as appropriate. Work is ongoing in this category to find the optimum solution and the DMT is open to suggestions and is excited to work with PIs to identify the best sharing mechanism for these data.

3. **Point clouds (lidar, SfM)**: The data will be with ISO standard metadata and delivered through the ERDC Geospatial Repository and Data (GRiD) point-cloud management system, which includes a backend application programing interface (API) as well as point-and-click download capability. Converting the point cloud data using Point Data Extraction Library to Entwine Point Tiles (Entwine – entwine.io) or TileDB (TileDB - The Universal Database) for effective use in Cloud applications may be explored.

4. **Sediment/geotechnical**: Data will be served via NetCDF files meeting appropriate standards. Though the data team has some experience storing sediment data as NetCDF files, there is significant interest in working with PIs to ensure NetCDF can meet your needs and to help create conversion tools where necessary if something is not straightforward.

5. **Other:** twitter hashtag/imagery, etc. (open to suggestions).

D.9   Metadata

To ensure that there is a consistent metadata across data collectors, the DMT will establish metadata guidelines for the experiment (meeting appropriate community standards). Data collectors are encouraged to at a minimum follow the established guidelines and are welcome to add as much additional metadata/information that they find important. The backbone of data discovery and sharing is descriptive metadata. All datasets published during DUNEX Pilot and full experiment are encouraged to include metadata following established International standards (e.g., ISO 19115-2, Climate and Forecast [CF], NCEI, Attribute Convention for Data Discovery [ACDD]). The ESRI Geoportal server [GEOPORTAL], an open source product that enables discovery and use of geospatial resources including datasets, rasters, and web services, will be used to host and make the connection between data servers and catalogued metadata. The data team will host a seminar describing common metadata standards, their benefits, and the tools available to make metadata documentation easier. See references below for more detailed discussion on metadata standards and tools that can be used to help.

D.10 File types

NetCDF: NetCDF files are a self-describing binary file format. Both variable and dataset metadata are included in the file along with the data. The format allows efficient slicing and subsetting of the data (e.g., time, space, other dimensional data). There are metadata conventions for storing a variety of different scientific feature types, including time series, trajectories, profiles, swaths, radial data, timeseries profiles (e.g., ADCP), curvilinear staggered model grids, unstructured (e.g., triangular grids), and more.

For more information about NetCDF files, follow this link:

URL: https://www.unidata.ucar.edu/

For those interested in how to make/use NetCDF files, here is an example for several popular languages:

https://github.com/jsignell/intro-to-netcdf

D.11 Server types and supporting technologies

GEOPORTAL: ESRI geoportal is a cataloging service to facilitate data discovery. There are *search* and *explore* capabilities as well as an API developed for automated queries.

For more information on ESRI Geoportal, follow this link:

URL: https://www.esri.com/en-us/arcgis/products/geoportal-server/overview

THREDDS: This is a technology developed by the Unidata group out of University Corporation for Atmospheric Research for simple interaction to large collection of real-time and archived data sets from variety of environmental data, providing data and metadata access using a variety of remote data access protocols. The available remote data access protocols include OPeNDAP, OGC WCS, OGC WMS, and HTTP(s). The server is built on the common data model, which creates low-level data access libraries to both data and metadata through a standard API. Combined with the binary functionality of the NetCDF files, it allows for easy interaction for interacting with (and sub-setting) data directly in your matlab or python (or other language) workspace (see OPeNDAP below for example interacting with a Tabular Data Stream server).

For more information on THREDDS, follow these links:

Fact Sheet https://www.unidata.ucar.edu/publications/factsheets/current/factsheet_tds.pdf

URL: https://www.unidata.ucar.edu/software/tds/

Example code to interact with FRF THREDDS server is found here:
https://github.com/sbfrf/getdata

ERDDAP: ERDDAP is developed by NOAA and provides standardized access to a large variety of different files and services. It takes some of the best features of THREDDS and combines them with added interaction capability streamlining interactions (visualization, download, or direct interaction).

The server allows for download in additional file formats (xml, OPeNDAP, binary, HDF4/5, NetCDF). With ERDDAP, you can easily search for datasets, visualize data (https://coastwatch.pfeg.noaa.gov/erddap/information.html#search), and download data.

- ERDDAP can get data from local and remote data sources via standardized requests.
- ERDDAP offers RESTful services. A URL specifies an entire request.
- ERDDAP can make maps and graphs.
- ERDDAP offers data (not just maps and graphs).
- ERDDAP can return data in lots of file formats to enable getting data into lots of other programs.
- NOAA works together: The analysis uses two, free software programs from NOAA, ERDDAP and GNOME, and data served by NOAA: NODC/NCDDC (facilitated by NOAA: UAF project (https://geo-ide.noaa.gov/)).
- ERDDAP makes scientific data more easily available to help scientists (and others) do their work more efficiently.

More information on ERDDAP, follow these links:

URL: https://coastwatch.pfeg.noaa.gov/erddap/information.html

Video: https://www.youtube.com/watch?v=18xZoXu1USM (5 min)

ARCServer: ArcGIS Server is a backend server that makes your geographic information available through an internet connection. This is accomplished through web services, which allow a powerful server computer to receive and process requests for information sent by other devices.

The ArcGIS Server representational state transfer (REST) API provides a simple, open web interface to services hosted by ArcGIS Server. All resources and operations exposed by the REST API are accessible through a hierarchy of endpoints or URLs for each GIS service published with ArcGIS Server.

For more information about REST API, follow this link:

https://developers.arcgis.com/rest/services-reference/get-started-with-the-services-directory.htm

GRiD: Geospatial Repository and Data (GRiD) management system is an advanced geospatial database for storage, processing, visualization and dissemination of 3D point-cloud data. They offer an API for interacting with the data, beyond the web user interface.

OPeNDAP: A way to share and access remote data locally (i.e., use a web URL instead of a file name when opening files). To illustrate, two examples are shown below for both matlab. In matlab, please see bug report below if using an older matlab.

In matlab:

```
url =
'https://chldata.erdc.dren.mil/thredds/dodsC/frf/oceanography/wa
ves/8m-array/8m-array.ncml' Time = ncread(url, 'time')
Timeunits = ncreadatt(url,'time', 'units')
Fprintf('%s\n',Timeunits)
        'seconds since 1970-01-01'
waveHs =
ncread(url,
'waveHs')
plot(Time,
waveHs)
```

In Python:

```
import netcdf4 as nc
from matplotlib import pyplot as plt
datafile =
nc.Dataset('https://chldata.erdc.dren.mil/thredds/dodsC/frf/oceanography/waves/
8m-array/8m-array.ncml') print(datafile['time'].units)
        'seconds since 1970-01-01'
```

times = nc.num2date(datafile['time'][:],
datafile['time'].units) plt.plot(times,
datafile['waveHs'][:])

For more information on *opendap,* follow these links:

URL: https://www.opendap.org/
URL: https://en.wikipedia.org/wiki/OPeNDAP
URL: https://www.mathworks.com/support/bugreports/1072120

DESIGNSAFE-CI: An NSF-sponsored data sharing project that can store data, generate DOIs for stored data, and offers an array of services and applications to work with stored data. The system is very flexible about the data/file types about what can be stored making it ideal for a wide variety of files. The system effectively operates similar to an FTP server, limiting direct interaction with the data stored on the server, but if files are in endorsed formats, they can easily be synced to USCRP for enhanced sharing and discoverability.

For more information on *DesignSafe,* follow these links:

URL: https://www.designsafe-ci.org/about/designsafe/

video: https://youtu.be/rvJX5YNPOGg (59 min)

D.12 Community-established metadata standards

Climate and forecast (CF): CF convention was begun in 2001. The conventions for CF metadata are designed to facilitate easy data access and sharing. The conventions define metadata that provide a definitive description of what the data in each variable represent and the spatial and temporal properties of the data. This enables users of data from different sources to decide which quantities are comparable and facilitates building applications with standardized access protocols. Principles of CF include self-describing data (no external tables needed for understanding), metadata equally readable by humans and software, minimum redundancy and maximum simplicity, and a development process focusing on existing needs.

The main features of the CF conventions are the *standard name* attribute for each variable, which provides an opportunity to provide a standardized name for a quantity. Using standard names in this way helps with user agnostic use of the data and provides proper context for nontypical users

of the data (i.e., an environmental species specialist accessing data describing water circulation data for a given area). These standard names are so important that the convention standards actually recommended not including a *standard_name* that is not established in the CF convention table (see website) and recommends leaving the entry blank, rather than risk misclassifying data.

To learn more about CF compliance, follow this link:

URL: http://cfconventions.org/

NCEI: NOAA's NCEI hosts and provides access to comprehensive oceanic, atmospheric, and geophysical data. By preserving, stewarding, and maximizing the utility of the federal government's billion-dollar investment in high-quality environmental data, NCEI remains committed to providing products and services to private industry and businesses, local to international governments, academia, as well as the general public.

NCEI has been a leader in building a culture of proper data formatting. The NCEI website (below) is a wealth of information about the development of datatype and data collection templates. Two of the key aspects of NCEI's transition are the layout of the key principles and the simplification of data using a decision tree. Key principles (taken from NCEI website) are the following:

1. Be explicit! Do your best to provide accurate values for the attributes, and if you do not know them, state that clearly. Avoid "NA" or "N/A" as they can have multiple meanings.
2. Keep your attributes focused on the content of the file, not the overall collection to which it might belong. For broader information about the collection, consider providing a Federal Geographic Data Committee or an ISO 19115-2 (preferred by NCEI) metadata record.
3. Also remember that ACDD and CF tend to focus on what are sometimes known as "discovery" and "use" metadata. This kind of information focuses on helping you find the file, then using it in your application. The attributes do not try to capture every possible detail of the provenance or processing of the data, for example.
4. The templates do not try to cover every possibility. The focus was on the templates that it was felt would cover most situations involving environmental observations, primarily of the ocean. If your situation does not match one of the templates, that is okay! Just use as much of the

templates as you can and consider using some of the more complicated representations detailed in the full CF documentation.

To learn more about NCEI standards, follow this link:

URL: https://www.nodc.noaa.gov/data/formats/netcdf/v2.0/#keyprinciples

ACDD: To properly address data discovery the Federation of Earth Science Information Partners have established a data discovery convention for required attributes associated in the metadata for data files. These conventions build upon and are compatible with the CF conventions. The convention has a tiered approach to the global metadata starting with Highly Recommended, Recommended, and Suggested. At the time of writing, ACDD 1.3 is state of the art.

For more details on ACDD conventions, follow this link:

URL: http://wiki.esipfed.org/index.php/Attribute_Convention_for_Data_Discovery_1-3

ISO 19115-2 Metadata: Geospatial metadata is a type of metadata that is applicable to objects that have an explicit or implicit geographic extent (i.e., are associated with some position on the surface of the globe). Such objects may be stored in a GIS or may simply be documents, datasets, images, or other objects, services, or related items that exist in some other native environment but whose features may be appropriate to describe in a (geographic) metadata catalog.

For more details on ISO 19115-2 standards, follow these links:

URL: https://www.iso.org/standard/39229.html

URL: https://geo-ide.noaa.gov/wiki/index.php?title=ISO_191152_(Geographic_Information_%E2%80%93_Metadata_Part_2)

Compatibility: several compatibility and metadata generators are available. ERDC has a tool developed for internal metadata generation for NetCDF files. Currently, it resides on Army secure network and requires common access card-enabled access. DMT would like to remove this restriction and allow DUNEX collaborators to use this capability (funding pending). Other compliance checkers are listed below.

ERDC compatibility checker (funding dependent): URL (TBD)

Gulf Research Initiative compliance: https://data.gulfresearchinitiative.org/metadata-editor/

Abbreviations

ACDD   Attribute Convention for Data Discovery

ADCP   Acoustic Doppler current profiler

API   Application programing interface

ASBPA   American Shore and Beach Preservation Association

BOEM   Bureau of Ocean Energy Management

CF   Climate and forecast

CHL   Coastal and Hydraulics Laboratory

CMTB   Coastal model test bed

COAWST   Coupled Ocean-Atmosphere-Waves-Sediment Transport

CRAB   Coastal Research Amphibious Buggy

CW   Civil Works

DEM   Digital elevation model

DLT   DUNEX Leadership Team

DMT   Data Management Team

DOI   Digital Object Identifier

DUNEX   During Nearshore Event Experiment

ENE   East-northeast

EPW   Environment and Public Works

ERDC   US Army Engineer Research and Development Center

ERDDAP   Environmental Research Division's Data Access Program

ESE   East-southeast

FRF   Field Research Facility

GIS   Geographic Information System

GRiD   Geospatial Repository and Data

HQ   Headquarters

IHO   International Hydrographer Organization

LARC-V   Lighter Amphibious Resupply Cargo vessel

LLC   Line-scanning, low-cost

N   North

NCDOT   North Carolina Department of Transportation

NCEI   National Centers for Environmental Information

NE   Northeast

NNBF   Natural and Nature-Based Feature

NNE   North-northeast

NOAA   National Oceanic and Atmospheric Administration

NRL   Naval Research Laboratory

NSF   National Science Foundation

OSU   Oregon State University

PI   Principal investigator

PINWR   Pea Island National Wildlife Refuge

R&D   Research and development

REST   Representational State Transfer

SfM   Structure-from-Motion

SW   Southwest

TBD   To be determined

THREDDS   Thematic Real-Time Environmental Data Distribution Services

TLS   Terrestrial laser scanning

UAGV   Unoccupied autonomous ground vehicle

UAS   Unmanned aerial systems

UD   University of Delaware

UNC   University of North Carolina

USACE   US Army Corps of Engineers

USCRP   US Coastal Research Program

USFWS   US Fish and Wildlife Service

USGS   US Geological Survey

UTV   Utility terrain vehicle

UW   University of Washington

VPO   Virtual Program Office

VTECH   Virginia Polytechnic Institute and State University

WHOI   Woods Hole Oceanographic Institution

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A Large-Scale Community Storm Processes Field Experiment:
The During Nearshore Event Experiment (DUNEX) Overview Reference Report

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14. ABSTRACT

The DUring Nearshore Event EXperiment (DUNEX) was a series of large-scale nearshore coastal field experiments focused on during-storm, nearshore coastal processes. The experiments were conducted on the North Carolina coast by a multidisciplinary group of over 30 research scientists from 2019 to 2021. The overarching goal of DUNEX was to collaboratively gather information to improve understanding of the interactions of coastal water levels, waves, and flows, beach and dune evolution, soil behavior, vegetation, and groundwater during major coastal storms that affect infrastructure, habitats, and communities. In the short term, these high-quality field measurements will lead to better understanding of during-storm processes, impacts and post-storm recovery and will enhance US academic coastal research programs. Longer-term, DUNEX data and outcomes will improve understanding and prediction of extreme event physical processes and impacts, validate coastal processes numerical models, and improve coastal resilience strategies and communication methods for coastal communities impacted by storms. This report focuses on the planning and preparation required to conduct a large-scale field experiment, the collaboration amongst researchers, and lessons learned. The value of a large-scale experiment focused on storm processes and impacts begins with the scientific gains from the data collected, which will be available and used for decades to come.

15. SUBJECT TERMS

Beaches, Coast change--Environmental aspects, Coasts, Hurricanes, Sand dunes, Shorelines, Storms, Water waves

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