THE FUTURE OF NEARSHORE PROCESSES RESEARCH

by
THE NEARSHORE PROCESSES COMMUNITY

Edited by
Nicole Elko, Falk Feddersen, Diane Foster, Cheryl Hapke, Jesse McNinch,
Ryan Mulligan, H. Tuba Özkan-Haller, Nathaniel Plant, & Britt Raubenheimer

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THE FUTURE OF NEARSHORE PROCESSES RESEARCH

EXECUTIVE SUMMARY

The nearshore is the transition region between land and the continental shelf including (from onshore to offshore) coastal plains, wetlands, estuaries, coastal cliffs, dunes, beaches, surf zones (regions of wave breaking), and the inner shelf (Figure ES-1). Nearshore regions are vital to the national economy, security, commerce, and recreation. The nearshore is dynamically evolving, is often densely populated, and is under increasing threat from sea level rise, long-term erosion, extreme storms, and anthropogenic influences. Worldwide, almost one billion people live at elevations within 10 m of present sea level. Long-term erosion threatens communities, infrastructure, ecosystems, and habitat. Extreme storms can cause billions of dollars of damage. Degraded water quality impacts ecosystem and human health. Nearshore processes, the complex interactions between water, sediment, biota, and humans, must be understood and predicted to manage this often highly developed yet vulnerable nearshore environment.

Over the past three decades, the understanding of nearshore processes has improved. However, societal needs are growing with increased coastal urbanization and threats of future climate change, and significant scientific challenges remain. To address these challenges, members of academia, industry, and federal agencies (USGS, USACE, NPS, NOAA, FEMA, ONR) met at the "*The Past and Future of Nearshore Processes Research: Reflections on the Sallenger Years and a New Vision for the Future*" workshop to develop a nearshore processes research vision where societal needs and science challenges intersect. The resulting vision is comprised of three broad research themes:

1. *Long-term coastal evolution due to natural and anthropogenic processes:* As global climate change alters the rates of sea level rise and potentially storm patterns and coastal urbanization increases over the coming decades, an understanding of coastal evolution is critical. Improved knowledge of long-term morphological, ecological, and societal processes and their interactions will result in an improved ability to simulate coastal change. This will enable proactive solutions for resilient coasts and better guidance for reducing coastal vulnerability.

2. *Extreme Events: Flooding, erosion, and the subsequent recovery:* Hurricane Sandy caused flooding and erosion along hundreds of miles of shoreline, flooded New York City, and impacted communities and infrastructure. Overall U.S. coastal extreme event related economic losses have increased substantially. Furthermore, climate change may cause an increase in coastal extreme events and rising sea levels could increase the occurrence of extreme events. Addressing this research theme will result in an improved understanding of the physical processes during extreme events, leading to improved models of flooding, erosion, and recovery. The resulting societal benefit will be more resilient coastal communities.

3. *The physical, biological and chemical processes impacting human and ecosystem health*: Nearshore regions are used for recreation, tourism, and human habitation, and provide habitat and valuable ecosystem services. These areas must be sustained for future generations, however overall coastal water quality is declining due to microbial pathogens, fertilizers, pesticides, and heavy metal contamination, threatening ecosystem and human health. To ensure sustainable nearshore regions, predictive real-time water- and sediment-based based pollutant modeling capabilities must be developed, which requires expanding our knowledge of the physics, chemistry, and biology of the nearshore. The resulting societal benefits will include better beach safety, healthier ecosystems, and improved mitigation and regulatory policies.

The scientists and engineers of the U.S. nearshore community are poised to make significant progress on these research themes, which have significant societal impact. The U.S. nearshore community, including academic, government, and industry colleagues, recommends multi-agency investment into a coordinated development of observational and modeling research infrastructure to address these themes, as discussed in

Figure ES-1. (top) Nearshore region schematic including the inner-shelf, surfzone, swash, beach, dunes, tidal-inlet, estuary, and city in a coastal plain. (bottom) Idealized cross-shore profile of the nearshore.

the whitepaper. The observational infrastructure should include development of new sensors and methods, focused observational programs, and expanded nearshore observing systems. The modeling infrastructure should include improved process representation, better model coupling, incorporation of data assimilation techniques, and testing of real-time models. The observations will provide test beds to compare and improve models.

This investment in nearshore processes research will lead to new understanding and improved models of nearshore processes. A coordinated research investment will leverage efforts, avoid redundancy, and move the science and engineering forward rapidly. Moreover, collaboration between academia, government, and industry will enable efficient transfer of results and predictive tools to stakeholders, supporting informed decisions that will improve diverse aspects of coastal management. To develop the infrastructure to address the research themes, the nearshore community proposes to

1. **Build a sustained multi-agency funded U.S. Nearshore Research Program (NRP)** that would coordinate and fund nearshore processes research to address the three broad research themes via the development of new research infrastructure. The program would foster understanding and prediction through observations and modeling of long-term coastal change, flooding and erosion from extreme storm events, and nearshore pollution and water quality evolution. The NRP would be analogous to other coordinated multi-agency programs such as US CLIVAR.

2. **Formalize a Nearshore Community Council (NCC)** with rotating representatives from academia, government agencies, and industry. The NCC would help structure the nearshore community, foster continued collaboration, interagency coordination, and represent the nearshore community to the public and coastal stakeholders. NCC would communicate vision and strategy, and advocate for sustained research programs.

THE FUTURE OF NEARSHORE PROCESSES RESEARCH

SECTION 1. INTRODUCTION

Over a billion people reside within 100 km of an ocean coast, with an estimated 800 million living within 10 m of current sea level (Small and Nicholls 2003; McGranahan et al. 2007). About 39% of the U.S. population, 123 million people, live within the 452 coastal shoreline counties, excluding Alaska (NOAA 2014). Coastal regions also contain extensive infrastructure for military (Naval and Marine Corps) and commerce (fisheries and aquaculture, ports and harbors). And the coastal region supports a wide range of economic sectors, including shipping and tourism. For instance, in 2012, over 73 percent by weight of U.S. international merchandise came through our many coastal ports and navigation channels sustaining an estimated 13.3 million U.S. jobs (Committee on the Marine Transportation System 2014). Tourism accounts for $1.5 trillion of the U.S. Gross Domestic Product, and the popularity of beaches concentrates 85% of tourist revenues in coastal states (Houston 2008). Communities, infrastructure, commerce, and resources are tied to the coastal nearshore region.

The nearshore is the transition zone between land and the continental shelf (Komar, 1998; Figure 1), including (from onshore to offshore) coastal plains, wetlands, estuaries, tidal inlets, barrier islands, coastal cliffs and dunes, beaches, surf zones (regions of wave breaking), and the inner shelf (to approximately 15 m depth). These regions, often both densely populated and dynamically changing, face many challenges that are directly affected by nearshore processes. Coastal infrastructure, economies, safety, and human health are at risk, and these risks will increase with increased human development, global climate change and sea level rise. Extreme storms such as Hurricanes Katrina (e.g., Kates et al. 2006) and Sandy (e.g., Rosenzweig et al. 2014) cause billions of dollars in coastal damages. Degraded water quality along the world's coastlines has impacted coastal ecosystems and human health (e.g., Halpern et al. 2008). As global sea level rises and storm patterns shift, coastal communities will be at greater risk from encroaching high water levels and waves. The dynamic nature of the nearshore can be in direct conflict with static coastal investment and infrastructure. Long-term erosion will threaten communities, infrastructure, valuable cultural resources, ecosystems, and habitat owing to both climate change and limited sediment availability (National Climate Assessment 2014). Nearshore processes, the complex interaction of water, sediment, biota, and societal processes must be understood and predicted to manage this often highly developed yet vulnerable environment (Figure 1).

Figure 1. (top) Nearshore region schematic including the inner-shelf, surfzone, swash, beach, dunes, tidal-inlet, estuary, and city in a coastal plain. (bottom) Idealized cross-shore profile of the nearshore.

Over the past three decades, progress has been made in understanding the complex interactions between hydrodynamic, sediment transport, and morphological processes. However, societal needs are growing with increased coastal urbanization and threats of future climate change. To discuss future research directions that address these U.S. national needs, over 70 members of the North American nearshore research and management community met in Kitty Hawk, North Carolina for "*The Past and Future of Nearshore Processes Research: Reflections on the Sallenger Years and New Vision for the Future*" workshop (Holman et al. 2014). Participants included academic and governmental agency scientists, program managers, industry and other agency representatives. The workshop objectives were to (1) review historical advancements in nearshore processes science and engineering research and (2) develop a vision for the next decade of nearshore processes research that addresses the intersecting societal needs and scientific challenges.

Several federal agencies responsible for emergency response, coastal protection, resource management, research, and national defense described their needs in regards to the nearshore. For example, the Federal Emergency Management Agency (FEMA), driven by floodplain management and emergency response requirements, pointed to the need for improved modeling of waves over land and flooding predictions. The National Oceanic and Atmospheric Administration (NOAA) requires improved understanding of the connections between storms, hazards, society, and ecosystems. The U.S. Geological Survey (USGS) seeks the ability to include the influences of climate change on long- and short-term coastal-change vulnerability assessments. The U.S. Army Corps of Engineers (USACE) requires improved data and models to operate hundreds of coastal ports and navigation channels and to construct resilient coastal projects and systems. The U.S. Navy needs to accurately and efficiently characterize and model the nearshore environment to support marine landings, special operations, antisubmarine warfare, and mine countermeasures with emphasis on remote sensing and unmanned systems. The National Park Service (NPS) requires a better understanding of the vulnerability of its coastal infrastructure and terrestrial or submerged cultural resources. State and local governments, who bear the brunt of coastal management issues, need to be able to utilize the tools provided by the research and federal-agency community for assessing flood risk, designing shore protection, and sediment management. These societal needs require understanding and accurate modeling across the nearshore region from the ocean overland to estuaries, and coastal plains.

The community consensus resulting from the workshop was that the significant intersecting science challenges and societal needs must be addressed to ensure future resilience and sustainable use of the nearshore. This is consistent with recommendations of the National Academies (National Research Council 2014): "*Nearshore research questions should be addressed in an interdisciplinary context in which environmental, social and economic values are considered, and costs and benefits are measured, so that outcomes can lead to sound coastal policy decisions*." Herein, a vision for the future of nearshore processes research is presented to address these diverse challenges. The vision is comprised of three broad research themes that will improve our understanding and prediction of:

1. *Long-term coastal evolution due to natural and anthropogenic processes.*
2. *Extreme events: flooding, erosion, and the subsequent recovery.*
3. *The physical, biological and chemical processes impacting human and ecosystem health.*

These inter-related themes require integration of the broad range of nearshore processes science, discussed in Section 2. The observational, modeling, and community infrastructure required to address these research themes are discussed in Section 3, with specific recommendations therein. In order to implement this vision, we recommend two levels of broad community investment. First, we recommend developing a **multi-agency funded U.S. Nearshore Research Program (NRP)** that would coordinate and fund nearshore processes research to address the three broad research themes via field and modeling studies and development of new research infrastructure. Second, we recommend **formalizing a Nearshore Community Council (NCC)** with representatives from academia, government agencies, and industry to integrate the nearshore community, increase collaboration and assist with inter-agency coordination with relevant government agencies. The recommendations are described in detail in Section 4.

SECTION 2. RESEARCH THEMES

Nearshore processes research that intersect societal needs and scientific challenges have been organized into three broad themes, involving coupling and feedbacks between hydrodynamics, morphodynamics, and anthropogenic interactions, as well as between geological, meteorological, hydrological, and biological processes. For example, processes can include turbulence, ocean waves, currents, wave runup on beaches, flooding, and sediment transport (Figure 2). In addition, these processes and their interaction occurr on varying temporal and spatial scales (from seconds to decades and cm to 100 km, see Figure 2). Furthermore, humans alter the nearshore region through development and coastal management, impacting nearshore hydrodynamics, morphodynamics, and ecosystems, and creating feedbacks between human activity and natural processes. This range of processes, scales, and interactions and makes the nearshore region complex to study. The following sub-sections elaborate on the three research themes that intersect societal needs and scientific challenges identified by the community during the workshop. For each research theme, scientific advances are reviewed, existing challenges discussed, research questions are posed, and future societal benefits from this research are provided.

SECTION 2A. LONG-TERM COASTAL EVOLUTION DUE TO NATURAL AND ANTHROPOGENIC PROCESSES

(i) Introduction

Infrastructure, valuable cultural resources, ecosystems, and habitat are threatened by long-term coastal erosion owing to both climate change and limited sediment availability (National Climate Assessment 2014). Natural long-term (10-1000 years) coastal change results from the cumulative response of short-term processes, including surface waves and water levels associated with storms and the resulting

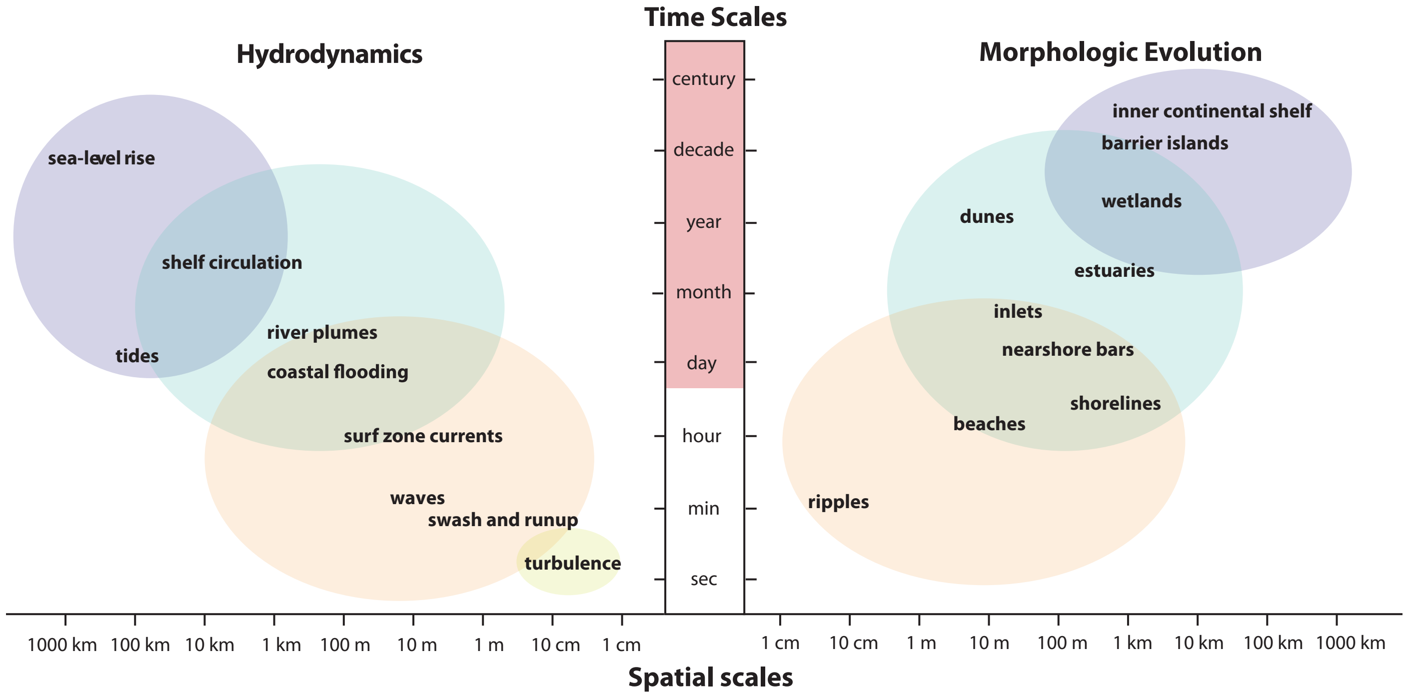

Figure 2. A conceptual representation of hydrodynamic processes and the morphologic evolution of coasts. The left side of the diagram indicates examples of fluid processes that influence changes in the morphologic features shown on the right. The processes and the features they shape occur on a wide range of spatial and time scales. The red shading indicates time scales over which humans also influence both processes and features in the nearshore environment.

erosion and accretion of the coast (Stive, 1990), and the longer-term constraints imposed by sediment supply and the regional geologic framework (Stive 2002). Long-term shoreline change can have high spatial variability owing to the complexity of processes acting along a given section of coastline. For example, Hatteras Island, NC has hotspots of erosion only a few kilometers away from accreting shorelines (Figure 3). Additionally, anthropogenic activities that are a result of human development in the coastal zone can alter natural processes (Hapke et al. 2013; Nordstrom 2000; Psuty, et al. 2002), potentially inducing additional coastline change, which ultimately may affect or even drive future human coastline modifications (McNamara et al. 2011; Slott et al. 2010; Ells and Murray 2012). Such two-way interaction and feedbacks between natural coastline dynamics and activities that result from policy-driven decision-making makes human-occupied coastlines tightly coupled systems. Understanding future coastal conditions and accurately predicting change over long temporal scales is needed for long-term coastal sustainability (National Research Council 2014).

(ii) Existing Challenges

Long-term coastal change, which is driven by spatially and temporally variable processes with complex and nonlinear feedback mechanisms, is difficult to predict. For example, long-term change may depend on sediment supply, feedbacks with ecological processes, and climate variability (Ruggiero et al. 2010; Schwab et al. 2013; Duran and Moore 2013). The modern coastal morphologies of Cape Hatteras (Mallinson et al. 2010) and Fire Island (Schwab et al. 2000; Lentz et al. 2013) are examples of coupling between antecedent geology and estuarine and nearshore processes. Changes in storm climatology may drive increased rates of coastal change that can be of the same order of magnitude or more as the impacts of sea level rise (Slott et al. 2006; Moore et al. 2013; Ruggiero 2013). Inter-annual sand bar migration (Plant et al. 1999) and long-term growth of shoreline instabilities due to high-angle waves (Ashton et al. 2001) may be examples of processes that are not predictable solely from the understanding of shorter-term processes. The feedbacks between these processes must be quantified to improve long term predictive capability.

Improving long-term predictions of coastal change requires knowledge of the economic and social processes that couple human interventions with natural processes. Natural and human-induced changes to sediment supply can result in variations in coastal response that are difficult to anticipate (Gelfenbaum and Kaminsky 2010) and the evolution of human modifications to the coastline can change in unanticipated ways. For example, in some locations seawalls are the dominant shore protection method, whereas in other locations beach nourishment and dune enhancement are

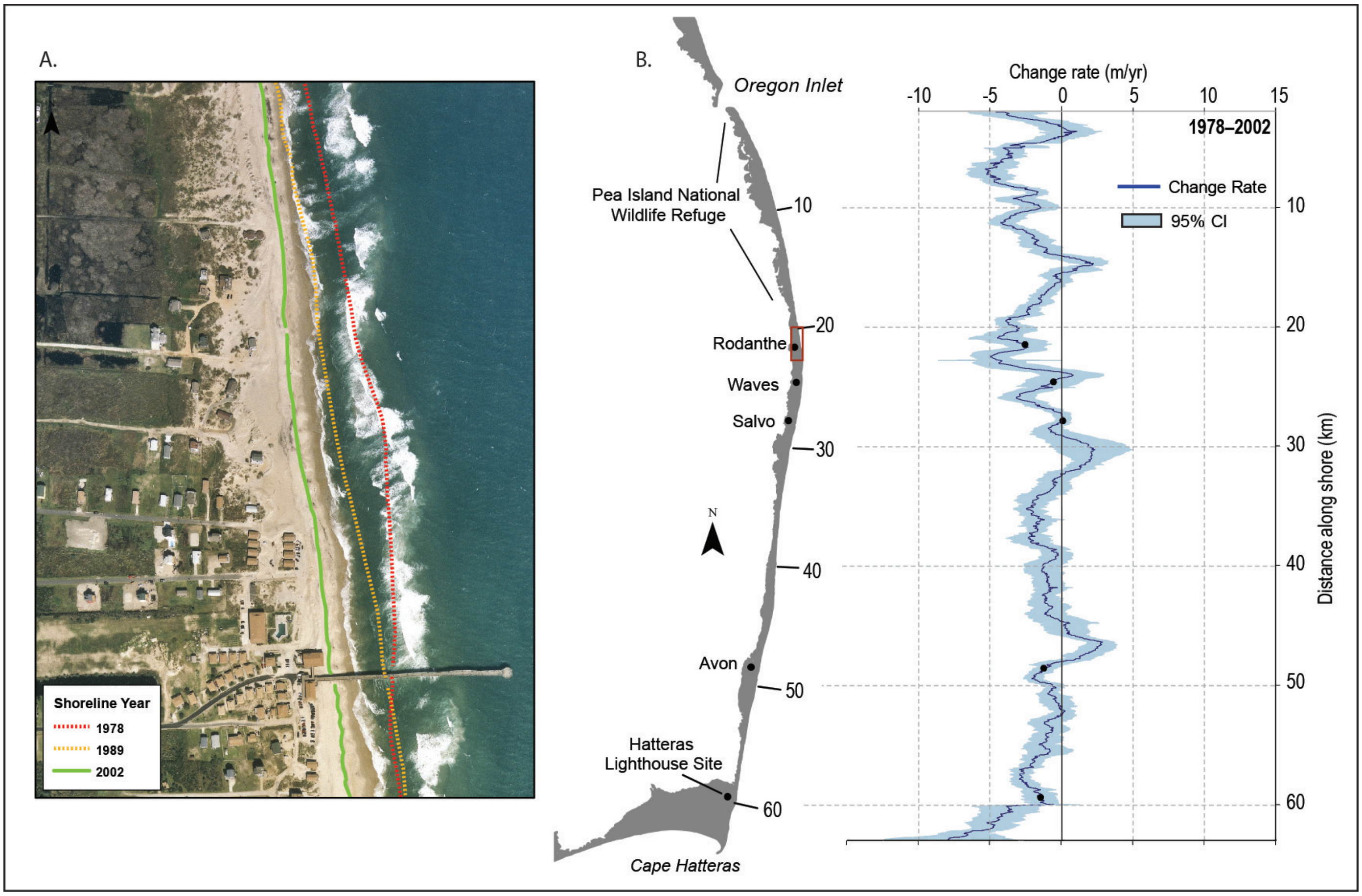

Figure 3: Example of long-term shoreline change along Hatteras Island, NC: A) Shorelines from 1978, 1989 and 2002 for the area near Rodanthe Pier; B) An example of 24-year linear regression shoreline change rates for Hatteras Island. The red box on the location map shows the approximate area of panel A.

used. These human modifications have different impacts on coastal processes, and progress toward long-term prediction requires an understanding of both the economic drivers behind various mitigation strategies and the dynamics that couple human modification to coastal processes. Progress has been made exploring the coupled relationship between property value, beach nourishment, and shoreline change (Smith et al. 2009; Gopalakrishnan 2011) but investigations over a wide range of coupled coastal and economic systems is lacking. Combining new observational strategies and modeling techniques will enable progress toward a better understanding of the coupling between human modifications and natural processes (McNamara and Werner 2008a).

(iii) Research Questions

The overall goal of the long-term coastal change research theme is the development of reliable and accurate predictions of natural and human-intervention processes over multiple time scales. To achieve this goal, the following set of research questions need to be addressed:

1. What are the most important factors influencing long-term sediment budgets and how can quantitative models incorporate geological constraints and ecological processes?
2. What are the feedbacks and interactions between processes at short time-scales, such as storms, and long time-scales, such as sea-level rise.
3. How can useful models of long-term evolution of the coastline be developed from models of short time-scale processes (e.g., storms and recovery)?
4. What drives human interventions, how do mitigation strategies couple with natural processes, impact system dynamics and long-term sustainability, and how might these factors evolve as physical, economic, and policy forcings change?

(iv) Societal Benefits

As global climate changes and causes alterations to the rates of sea level rise and storm patterns over the coming decades, it is critical to understand how the coastline will evolve in response to these forcing conditions. Coastal areas, with high-density population and infrastructure, are more susceptible to impacts of climate change than inland areas, as demonstrated by recent large disasters like Hurricanes Katrina and Sandy. Better knowledge of long-term morphologic and societal processes will help guide decisions related to the socio-economic costs and benefits of alternative engineering responses to long-term coastal erosion and wetlands loss. Increased predictive capability of long-term coastal change will enable:

Proactive solutions for sustainably developed coasts: Rather than reactive geo-engineering of the coastline (Smith et al. 2014), managers can determine the optimal coastal protection based on estimates of potential future evolution given the feedbacks with natural processes. These proactive measures may prevent damage during extreme events and owing to long-term erosion, rather than simply rebuilding and re-nourishing.

Better guidance for reducing coastal vulnerability: A better scientific understanding of the long-term morphodynamic response of the coast that includes the coupled and dynamic relationship between natural processes and human interventions, and that reflects the spatial variability of coastal responses, will enable coastal communities to forecast future costs and benefits of development and protection. Based on the relative costs and benefits, coastal communities can quantify and reduce their vulnerability to coastal hazards.

SECTION 2B. EXTREME EVENTS: FLOODING, EROSION, AND THE SUBSEQUENT RECOVERY

(i) Introduction

Although the path of Hurricane Sandy and the likelihood of some flooding and erosion were forecast a few days prior to landfall, coastal communities were not prepared for the extreme damage along the shoreline. Extreme events, by definition, occur infrequently. The high winds, water levels, waves, and strong currents during Sandy were all extreme, as was the subsequent coastal damage. Sandy caused flooding and erosion along hundreds of miles of shoreline, damaged structures (Figure 4), flooded New York City, created new inlets, and wreaked havoc with transportation and utility infrastructure. Storms along the U.S. west coast have caused major erosion to dunes and bluffs, undermining infrastructure and property. Like tsunamis, extreme storm events can cause intense coastal flooding and rapid morphological change (e.g., breaching a new inlet in a barrier island) that pose high risk to society (Sallenger et al. 2004, 2005, 2006, 2007). Improved field-tested models are needed to give residents more accurate and timely warnings of the severity of impending dangers and to plan for future storm impacts.

Figure 4: Photographs of (left) Hurricane Sandy flooding at Atlantic City NJ and (right) El Nino storm flooding of Del Mar CA.

Coastal-storm-related economic losses have increased substantially, largely due to increases in population and development in hazardous coastal areas (NRC 2014). Despite flood insurance and measures to reduce flood-prone properties, the National Flood Insurance Program (NFIP) owes the Treasury more than $24 billion, and has an annual income (in 2012, from premiums) of less than $4 billion. Coastal inundation during extreme storms (Fritz et al. 2007; Sallenger et al. 2007) may be exacerbated by rising sea levels, and, owing to increasing coastal populations, inundation impacts on transportation infrastructure could become one of the greatest threats of climate change (FitzGerald et al. 2007, Emanuel 2013; Grinstead and Moore 2013). Wave height and storm surge, which are related to flooding probability, are influenced by storm size and maximum wind speed (Zhang et al. 2000; Eichler and Higgins 2006; Irish et al. 2008). Coastal urbanization affects the impacts of storm surge and new regions will become vulnerable to flooding (Bilskie et al. 2014). As understanding of the processes affecting unundation advances, regional coastal inundation maps will become more reliable, and the costs owing to flooding could decrease.

Great progress has been made understanding the wave, current, infiltration, sediment transport, and wind processes that combine to produce overtopping and flooding of beaches and changes to shorelines and coastal communities. Storm impacts depend on the storm timing, duration, magnitude, and location (Georgas et al. 2014). In addition, interactions between tidal currents, wind-driven currents, and wave-driven flows during high water levels may amplify forces on the beach and increase transport of sediment and pollutants (Mulligan et al. 2008). Recent work suggests that shelf waves (Chen et al. 2014) and winds (Soomere et al. 2013) may exacerbate high coastal water levels and storm surges. Studies examining these couplings and feedbacks, including the effects of high winds, large waves, strong sediment transport, and large bathymetric changes, and interactions between the ocean, estuaries, rivers, and sounds, will advance understanding of extreme events.

Owing to logistical difficulties, there are few observations of nearshore processes during extreme storms when waves, flooding, sediment transport, and morphological change are large. Although waves have been measured on the continental shelf, and water levels and winds have been measured along the coast, there are few observations of runup, overland flow, sediment transport, bathymetric evolution, and pollutant fluxes on beaches, inlets, and coastal waterways during extreme storms. Moreover, observations of the physical processes leading to post-storm recovery, including the rebuilding of beaches and natural closure of breaches, are rare and are not modeled accurately. Nearshore observations of processes during extreme storms also may contribute to understanding the runup and morphological change resulting from tsunamis. Specific challenges to understanding the propagation of waves to the shore and the resulting overland flow, flooding, and morphological evolution of the coast, as well as the effects of infrastructure, coupling between coastal systems, and climate changes, are discussed below.

(ii) Existing challenges

1. Wave propagation and flooding

Understanding the transformation of wave propagation across the shelf to the shore is critical to predicting forces on shoreline structures, increases in wave-driven water levels, wave overtopping and flooding, dangerous wave-driven surf zone currents, sediment transport, and beach erosion and accretion. Although wave transformation during moderate wave and wind conditions is simulated reasonably well (Ardhuin and Herbers 2002; Thomson et al. 2006; Ardhuin et al. 2007; Cavaleri et al. 2007; Magne et al. 2007; Veron et al. 2007; Mulligan et al. 2010; Gorrell et al. 2011; Elias et al. 2012; Smit et al. 2014), present knowledge regarding wave transformation during extreme events is limited. For example, recent studies for moderate conditions suggest that the probability of large steep waves may be higher than previously believed (Janssen and Herbers 2009). New research is needed to understand how waves will evolve during extreme events in which processes affecting the waves (including winds, storm surge, and currents) vary rapidly, and waves may be altered as the storm sweeps past.

Wave overtopping at the shore and coastal flooding are dependent on the coastal total water level (TWL), which results from the interaction of oceanographic, meteorological, hydrological, and geological forcing and constraints (i.e., astronomical tide, monthly mean sea level, large-scale storm surge, wave setup, wind setup, fluvial discharges, precipitation, subsidence, infiltration). Coastal flooding and overland wave propagation occur when the magnitude of extreme TWL exceeds the elevations of backshore features such as the crest of sand dunes or coastal structures. Wave runup often is the dominant component of extreme TWLs on open ocean coasts and therefore can be a primary driver of coastal overwash (Stockdon et al. 2006a, Laudier et al. 2011) and morphological change. Improved understanding of the spatially and temporally variable overtopping flows resulting from runup is recognized as fundamental to future flood modeling (Smith et al. 2012; Wadey et al.

2012). Wave frequency and direction (Guza and Feddersen 2012), saturation of low frequency waves and swash (Thomson et al. 2006; Bakker et al. 2014), strong winds, infiltration (Heiss et al. 2014), suspended debris (Sherman et al. 2013), and coastal morphology alter the runup. In addition, fringing and barrier reefs can affect wave transformation, runup, and inundation (Monismith 2007; Hoeke et al. 2013; Becker et al. 2014; Merrifield et al. 2014). Existing parameterizations of wave runup (Stockdon et al. 2006a) and setup and swash models (Raubenheimer 2002; Apotsos et al. 2008) are based primarily on data obtained during mild or moderate wave conditions, and thus may be unreliable for extreme events. Recent work (Senechal et al. 2011; Stockdon et al. 2014) has focused on extending these parameterizations to extreme storm events.

Models of overland waves and flows have been developed for rainfall-induced flooding (Zoppou 2001), tsunamis (Sugawara et al. 2014), and extreme storms impacting coastal cities (Brown et al. 2007; Schubert et al. 2008; Gallien et al. 2014). Many studies of large-scale flooding have adopted similar modeling methodologies (Bates et al. 2005; Purvis et al. 2008; Gallien et al. 2011;2014). Flooding and overland flows are affected by oceanic and atmospheric processes, as well as by drainage and infiltration of water into sediments (Matias et al. 2014). The drainage and infiltration rates (as well as transport of pollutants and solutes in the aquifer) depend on the groundwater level (Uchiyama et al. 2000; Bakhtyar et al. 2013), local sediment and geologic structures, nearby water levels (including the ocean, bays, rivers, and estuaries), rainfall, trapping of air, and prior infiltration. In many locations, and especially over large regions, the contribution of all TWL components and the coupling between them can create spatially varying flood hazards (Serafin and Ruggiero 2014). Observations during extreme events, including the effects of inland propagating waves (FEMA, 1986), will lead to improved parameterizations in models to help plan for and prevent flood-induced damages.

The urban environment presents additional challenges to those on the coast owing to the presence of hardened structures (buildings, bridges), flow channels (subway and storm drainage systems), surface elements (roads, vegetation, structures), and roughness features that can be larger than the water depth, creating a complex flow system. Although urban inland flood depths may not equilibrate with shoreline water levels in transient events causing static ("bathtub") models to overpredict flooding, field observations of urban flooding have been modeled well with a shallow-water-equation-based model that resolves embayment dynamics, overland flow, concrete floodwalls, and drainage into the storm water system (Gallien et al. 2014). Advances in measuring and modeling these processes, including the coupling between them, will lead to better predictions of flooding hazards.

2. Morphological evolution and sediment transport

Long-term morphological evolution is affected by event and recovery when integrated over years and decades. Massive shifts in morphology also can occur as a result of a single extreme event because sediment transport responds nonlinearly to the flow forcing. Even if an extreme event does not cause immediate damage, it may have long term impacts leading to increased vulnerability of coastal populations, including shifted shoals that endanger navigational pathways, altered shorelines that impact coastal resiliency, and reduced dune elevations that increase susceptibility to inundation and overwash (Houser et al. 2008; Long et al. 2014).

Predictions of changing beach morphology (which affects overwash and flooding) are not always accurate, and better parameterizations are needed for sediment transport (Foster et al. 2006). Although conventional approaches to sediment transport have predictive skill under moderate wave conditions (Hoefel and Elgar 2003; Henderson et al. 2004; Yu et al. 2010), during extreme events other mechanisms such as the interaction of wave-breaking turbulence with the bed, and the dynamics of momentary bed failure, may become dominant. For example, present models (Cox et al. 2000; Puleo and Holland 2001; Raubenheimer et al. 2004) for swash processes neglect the onshore transport of turbulence owing to breaking waves (Puleo et al. 2000; Petti and Longo 2001; Cowen et al. 2003; Puleo et al. 2003; Sou et al. 2010), leading to underestimation of bed stresses and sediment transport. Flow convergences at the swash front, which are not yet included in most models, may be important for transporting sediments and buoyant debris (Baldock et al. 2014). Alongshore flows in the swash may contribute to erosion, and the feedbacks between hydrodynamics and alongshore-inhomogeneous bathymetry may affect flooding and erosion rates (Puleo et al. 2014). In addition, most nearshore studies have focused on shorelines with uniform sand grains. However, cohesive sediments and gravel may be common, especially near inlets, river mouths, and coastal cliffs. Simulations of morphology during extreme events require considerations of the feedbacks between the morphology and the hydrodynamics (including tidal prisms, flooding, infiltration, currents, and waves) throughout the storm and recovery periods. Quantification of the uncertainty associated with the accumulation of small errors resulting from integration or parameterization of sediment transport may enable weighting of results, which may help policy-makers determine when results are reliable.

At larger scales, the decoupling of hydrodynamic and sediment transport timescales and new parameterizations have led to improved simulations. For example, long-term nearshore morphological evolution and sandbar movement has been predicted (Ruessink and Kuriyama 2008) with a deterministic, process-based model (Lesser et al. 2004). However, the model failed to predict the observed beach profile change during major storm events. Other studies have simulated shoreline morphological change during extreme events if a heuristic limiter is used to account for unknown processes (McCall et al. 2010). Exchange of sediments between the shoreline and inner shelf, and between the subaerial beach and surf zone, may be important during extreme events when overwash may carry sediments far inland, dune and bluff erosion may be severe, the subaerial beach may be inundated (with the dune acting as a submerged sandbar, Sherwood et al. 2014), and strong rip currents may carry sediments into deep water. The net gain or loss of material to inland regions and to the continental shelf may be the determining factor for net shoreline movement, and maps are needed of nearshore and shelf sediment types and depths. In addition, algorithms for the recovery of beaches following storms need to be improved and incorporated in larger scale models.

3. Additional considerations: infrastructure, coastal systems, and climate changes

Humans and the coastline have become a tightly coupled system, with engineering projects allowing for a dramatic increase in the number of people living along the coast where natural disturbances can be severe. Although technological efforts have reduced the impacts of many storms, the frequency of large magnitude disasters may have increased (Criss and Shock 2001; Davis 2002; McNamara and Werner 2008). Knowing how extreme coastal disaster events are distributed and the extent to which they result from coupled economic-natural dynamics will provide insight into effective and equitable recovery from disasters.

The intense winds, large storm surges, and heavy rainfall during extreme events affect morphological changes and flooding in estuaries (Moreno et al. 2010; Brown et al. 2014), groundwater salinity (Anderson and Lauer 2008), and breaching of inlets (Sherman et al. 2013). For example, the mouths of smaller estuaries or inlets may close intermittently owing to wave forcing and sediment transport during extreme events (Zedler 2010; Orescanin et al. 2014), which may lead to different circulation patterns, strong stratification, and plummeting oxygen levels in estuaries and bays that can affect nearshore fisheries. Large waves and high river flow during storms also may impact both upstream areas and river plumes in nearshore regions. New observations and models of the immediate and long-term responses of coastal systems to extreme events, including studies of the coupled forcing from atmospheric, oceanographic, and hydrologic sources (Lin et al. 2010), will improve forecasts of impacts over larger regions.

The number of tropical storms has strong interannual and interdecadal variability driven by climate cycles (Vitart and Anderson 2001). During El Nino years on the US West coast, extreme events are more common, and are exacerbated by increased sea level (Flick and Cayan, 1984). There is no consensus on the impact climate change will have on storm climatology. However, it has been suggested that there will be more intense tropical and extratropical storms, as well as a poleward shift of storm tracks (Webster et al. 2005; Bengtsson et al. 2006). Improved understanding of the effects of climate on extreme storm activity will lead to improved management and protection of coastal communities.

(iii) Specific research questions

Improved coastal resiliency requires better understanding of wave transformation, overland flow and flooding, and morphological changes during extreme events, as well as better understanding of the coupling between these processes and the natural post-storm recovery. Specific research questions that need to be addressed include:

1. How do wave, runup, setup, and sediment transport processes during extreme events differ from those during moderate storm conditions?
2. How do feedbacks between the hydrodynamics and morphology affect flooding, erosion, and recovery of coastal areas?
3. How do the urban environment and human infrastructure affect flooding and erosion during extreme events and the recovery afterwards?

Addressing these questions will require the collection of comprehensive data sets using combinations of remote sensing and in situ measuring systems, including rapid deployment of sensors in advance of oncoming storms (Section 3a) and new methods to measure the bathymetry during storms. Developing accurate models to forecast the effects of extreme events on coastal regions requires new observations to understand and parameterize the coupling between atmospheric, oceanographic, and hydrologic processes that lead to hydrodynamic and morphodynamic changes (Section 3b). In addition, wave-by-wave (phase-resolving) analysis may be needed to examine spatially and temporally intermittent processes, such as the transformation of the largest waves, the resulting overwash and flooding, and the nonlinear response of sediment transport.

(iv) Societal benefits

Extreme events harm coastal communities through loss of life, destruction of property, damage to infrastructure and transportation systems, spread of pollution, pathogens, and contaminants, and economic disruption. Furthermore, climate change may cause an increase in extreme events along U.S. coasts, and rising sea levels could increase the occurrence of flooding and erosion of coastal beaches, dunes, bluffs, and wetlands. Answers to the questions above will help coastal managers:

Assist in determining when coastal communities should be evacuated: Evacuations result in loss of tourism, closed businesses, and reduced wages. Furthermore, unnecessary evacuations reduce the confidence of coastal residents, resulting in potential loss of life if future evacuation notices are ignored (or not given). A better understanding of nearshore processes during extreme events will lead to more accurate predictions of the flooding and erosion that contribute to an evacuation decision.

Improve flood maps: Mapping of flood hazards creates broad-based awareness of flood potential and provides the data needed to mitigate flood risk and to administer the NFIP. Advances in understanding the coupling between coastal systems, and the effects of climate on extreme events, will lead to improved predictions of flood occurrence and location.

Build resilient coastal communities: Better knowledge of the causes, extent, and timing of flooding, erosion, and recovery will help engineers design better coastal structures and infrastructure, and may help policy-makers determine the regions least at risk, where growth and expansion is safest.

SECTION 2C. PHYSICAL, BIOLOGICAL AND CHEMICAL PROCESSES IMPACTING HUMAN AND ECOSYSTEM HEALTH

(i) Introduction

The nearshore regions are used for recreation, tourism, and human habitation, and provides habitat and a wide-range of valuable ecosystem services, including food production and water purification. These regions and ecosystems must be sustained for future generations. Despite the importance of clean waters to our well-being and economy, the nearshore is often used to dispose of waste that includes microbial pathogens (bacteria and viruses), fertilizer (nutrients), and organic (pesticides) and inorganic (heavy metals) contaminants. The result is declining water quality along the world's coastlines that threatens ecosystem and human health (Halpern et al. 2008 2012). Major US governmental agencies (NIH, NSF, NOAA, EPA, and USGS) have recognized that the link between the coastal oceans and human and ecosystem health is of critical importance. To ensure sustainable nearshore regions, predictive real-time nearshore water- and sediment-based based pollutant modeling capability must be developed, requiring expanded knowledge of the physics, chemistry, and biology of the nearshore ocean.

Water polluted with microbial pathogens often enters the nearshore by point or non-point sources where it is transported and diluted (Boehm et al. 2002). In the U.S., nearly 10% of all beach water samples exceed EPA bacteria thresholds (Dorfman and Stoner 2012). Globally, exposure to microbial pathogens in polluted nearshore waters is estimated to cause >120 million gastrointestinal illness (GI) and 50 million severe respiratory illnesses per year (Dorfman and Stoner 2012), with annual U.S. costs of GI from beach recreation estimated at $300 million (Ralston et al. 2011). These costs do not include those from other pathogen infections such as Staphylococcus aureus or methillicin-resistant S. aureus MRSA (Goodwin et al. 2012). A recent death in Hawaii was attributed to cutaneous exposure to sewage-polluted nearshore waters (Song 2006). Bacterial pathogens have been found to persist in ocean (Yamahara et al. 2007; Goodwin and Pobuda 2009, Halliday and Gast 2011) and Great Lakes (Ge et al. 2010; 2012) beach sand, likely posing a human health risk (Heaney et al. 2012). Polluted waters lead to beach closures (Noble et al. 2000), which have grown over the past 20 years to

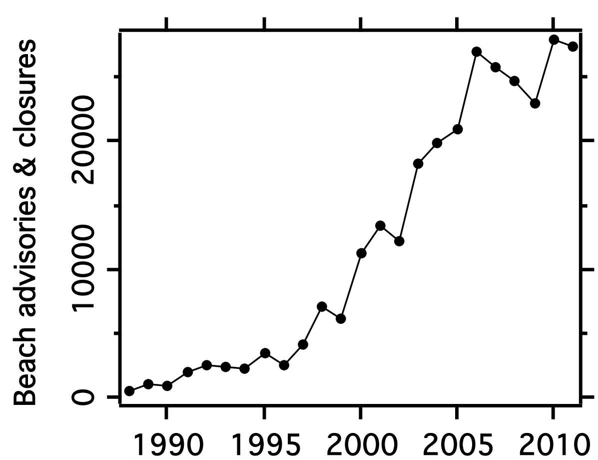

Figure 5: The number of U.S. beach advisories and closures versus year. (National Resources Defense Council).

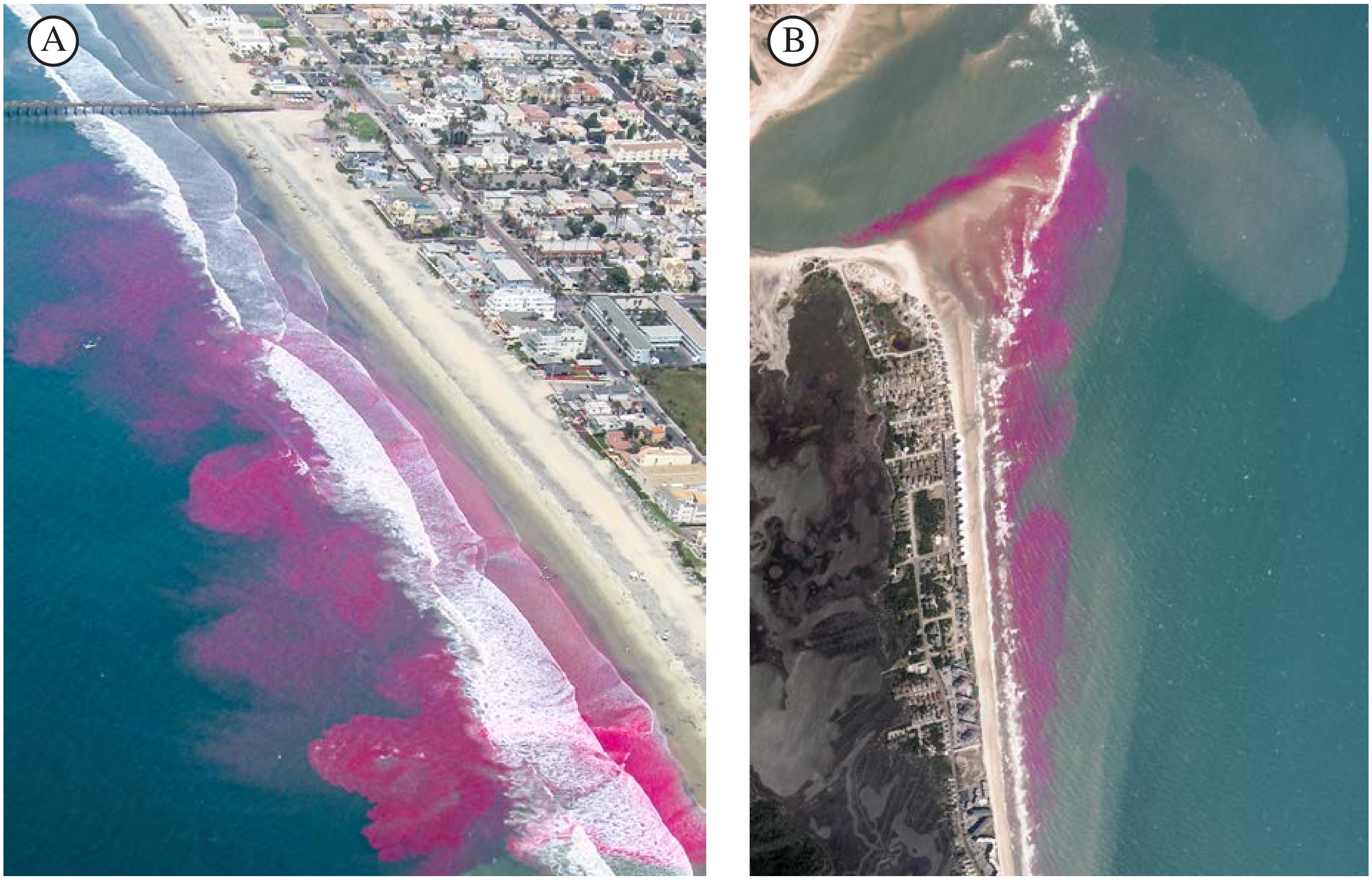

Figure 6: Photographs of non-toxic fluorescent dye tracer (pink water) (a) one hour after continual surfzone dye release beings at Imperial Beach California (Hally-Rosendahl et al. 2014), and (b) 1.5 hours after continual tidal inlet dye release during ebb tidal flow at New River Inlet, North Carolina. In both cases, dye serves as a *mock* pollutant and study of its transport and dilution will inform how pollutants from pathogens to chemical contaminants evolve in nearshore waters. (image from Clark et al. 2014).

more than 20,000 days per year of beach advisories in the U.S. (Dorfman and Stoner 2012 and Figure 5) with corresponding negative impact on beach tourism (Hanemann et al. 2001).

Another threat to the nearshore region is excess nutrient input (eutrophication) from terrestrial anthropogenic sources, such as sewage, agriculture, and urban runoff, which can result in harmful algal blooms impacting humans and ecosystems. Understanding and managing eutrophication is crucial to preserving nearshore water quality and ecosystem stability (Smith and Schindler 2009). In addition, terrestrial anthropogenic contaminants, including heavy metals (e.g., copper, mercury, lead), PCBs, current-use pesticides, and industrial and commercial compounds, collectively known as contaminants of emerging concern (CECs) also enter nearshore waters, with significant ecosystem impacts (e.g., Moret et al. 2005). Particular CECs (such as bisphenol A) entering the marine environment can bind to receptors or enzymes that regulate hormones, disrupting normal endocrine physiology in humans, fish and other animals. Moreover, the intertidal and beach regions have rich ecosystems whose gametes and larvae must transit to and from offshore shelf waters (Shanks et al. 2014). The physical, chemical, and biological processes by which these pollutants impact human and ecosystems are not well understood.

Studies using controlled releases of mock bacteria such as microspheres (Feng et al. 2013; Gast et al. 2014), dye tracers (Figure 6), and GPS tracked drifters, illustrate the complexity of pollutant transport and dispersion across the beach and the nearshore ocean. Shoreline released dye tracer is transported alongshore by surf zone currents, and exchanged with the inner-shelf (Figure 6a). Dye released within a tidal inlet during an outgoing tide (Figure 6b) turns down-coast owing to breaking waves that approach the coast at large angles. The 200-m wide shoreline-attached dye plume was observed >10 km down the coast, and was only weakly diluted. Ongoing research aims to better understand these complex processes so that pollutant transport can be predicted in the future.

(ii) Existing Challenges

To reduce recreational waterborne illnesses, the BEACH Act requires US states to implement beach monitoring programs that use fecal indicator bacteria (FIB) density, which is linked to swimmer illness (Wade et al. 2003; Boehm and Soller 2011), to assess beach water quality. FIB monitoring programs are suboptimal for protecting recreational beach users because the samples require 24 hrs to process. If FIB exceed a threshold value, the beach typically is closed for 3 days. However, after 24 hrs, FIB may have been diluted or transported away (Rosenfeld et al. 2006). The beach may have been open when hazardous and closed when not, impacting recreation and coastal economies. Furthermore, beaches often are closed up and down coast regardless of which direction the pollutants are transported. Monitoring programs are not in place for other contaminants (metals, CECs).

Observing and predicting the transport, dilution, and chemical or biological regulation of pollutants (pathogens, nutrients, or other contaminants) in the nearshore is challenging. There are many potential point and non-point sources, including runoff, sewage, oceanic outfalls, and sediments (Boehm et al. 2009; Gast et al. 2011) and many potential pollutants (bacteria, viruses, nutrients, metals). There is a dearth of knowledge about the physical, biological, and chemical processes that govern the distribution of different pollutants once introduced into the environment (Boehm et al. 2002; Lipp et al. 2001). For example, surf zone (where recreational beach use occurs) FIB mortality is much less than on the inner-shelf (Rippy et al. 2013), and beach sands can harbor pathogens that are released into the water during the highest tides and storms (Halliday and Gast 2011; Gast et al. 2011).

The fate of pollutants in the nearshore is directly controlled by transport and mixing. These processes differ dramatically between the surf zone and inner-shelf. The surf zone is characterized by breaking-wave driven currents and eddies, whereas the inner-shelf is forced by wind, tides, waves and buoyancy. This leads to differences in the time- and length-scales of nearshore transport and dilution processes, complicating understanding and modeling. Surf zone eddies laterally disperse material over 10s of minutes (Spydell et al. 2007, Brown et al. 2009; Clark et al. 2010), and rip currents exchange material between the surf zone and inner-shelf from minutes to hours (Dalrymple et al. 2010; Hally-Rosendahl et al. 2014). At time-scales of many hours, surf zone (Garcez Faria et al. 2000) and inner-shelf (Lentz et al. 2008) undertow and internal waves (Wong et al. 2012; Sinnet and Feddersen 2014) can transport pollutants between the nearshore and the inner shelf. In addition, transport and dilution can be affected by fresh water outflow (Pullen and Allen 2000) and coastal bathymetric variability (Woodson 2013). However, the relative importance of these processes and how they depend upon waves, winds, tides, and stratification is not well known. Material is also exchanged between beach sands, ground water, and the surf zone (Phillips et al. 2011; Halliday and Gast 2011; Gast et al. 2011; Russell et al. 2012; Gast et al. 2014). However, the processes governing this exchange are not understood.

(iii) Specific Research Questions

Improved coastal resilience over the long term requires development of real-time predictive models for beach recreation risk, nearshore ecosystem health, and societal impacts of anthropogenic pollutants. To achieve this goal, an improved understanding is needed of how nearshore pollutants are transported and diluted in water and sediments, and how materials are biologically and chemically regulated in the nearshore. Moreover, it is necessary to understand how the transport and fate of pollutants affect human health and coastal ecosystems. Until recently, research into nearshore pollutants was limited to separate physical, chemical, and biological studies. Although progress continues to be made in a disciplinary manner, future progress depends on research that examines the coupled interdisciplinary physical, chemical, and biological processes. In particular, it is important to determine

1. The dominant physical mechanisms of exchange between estuaries, beach sands, surf zones, and inner-shelf regions so they can be modeled. For example, can polluted beach sediments act as a pathogen reservoir that is released during storm-induced erosion, and can this be accurately simulated?
2. How the physical, chemical, and biological processes interact to regulate different pollutant concentrations. For example, what physical processes result in reduced surfzone FIB mortality and can this be incorporated into models?

Addressing these research questions will require the development of new instrumentation for pathogens and other contaminants, and the collection of new comprehensive field observations, particularly coupled physical, biogeochemical, and pathogen observations (Section 3a). Accurate models of the fate of nearshore pollutants (e.g., pathogens, endocrine disruptors) that couple the physical, biological, and chemical processes will be tested, calibrated, and improved with these new observations (Section 3b).

(iv) Societal Benefits

It is of national and international importance to safeguard the economic, recreational, and ecological resources of the nearshore region for current and future generations. Research investment into this field will pay significant dividends in improved human and ecosystem health. A few concrete examples include:

Optimal beach closures and safety: With beach closure forecasts, the beach will be closed By only when polluted and reopened when no longer polluted will result in cost savings from fewer illnesses and reduced days of closure that harm local businesses. Similarly, systems can be developed to make improved real-time rip-current predictions to help guide hazard and swimmer-safety warnings.

Smarter nearshore aquaculture: Validated coupled hydrodynamic, biological, and contaminant models can be used to help inform decisions about nearshore aquaculture for shallow water species such as scallops and oysters.

Improved mitigation and regulatory policies: An understanding and modeling capability for how terrestrial pollutants are transported to and within nearshore ecosystems will enable improved mitigation policies by quantifying the extent by which pollutants impact coastal food webs and human health.

SECTION 3. ENABLING INFRASTRUCTURE: OBSERVATIONS, MODELING, COMMUNITY

SECTION 3A. OBSERVATIONS

The prior sections identified observational needs, including (i) long-term measurements that could be used to evaluate models for long-term coastal evolution, (ii) observations during extreme events to determine how processes differ relative to those during moderate conditions, (iii) coordinated field studies addressing coupling between atmospheric, hydrologic, oceanic, physical, biological, chemical, and geological processes, and (iv) studies evaluating the effects of human interventions. As discussed below, advancement in understanding and modeling nearshore processes requires new technology and instrumentation and new observations, including long-term facilities, process-based studies, and citizen-science efforts.

(i) Existing and New Instrumentation

1. Remote Sensing

Airborne-based observations, such as lidar, multi-spectral, and hyper-spectral electro-optical sensors, provide sub-meter-scale snapshots of the nearshore over large spatial areas (e.g., McNinch 2004). Lidar maps of beaches and shallow waters are used for storm response assessments (Sallenger et al. 2006; Houser et al. 2008; Stockdon et al. 2013), decadal-scale coastal change analyses (Lentz et al. 2013), and to assess multi-decadal- to century-scale nearshore evolution when integrated with historical data sources (Hapke et al. 2013). Although airborne lidar-observed bathymetry is limited by water clarity and wave conditions, in recent years, lidar technology has advanced and expense has decreased leading to increased availability. Multi- and hyper-spectral sensors detect surface and (some) subsurface optical properties (e.g., turbidity, suspended particulates, and dye concentration) that are important to ecological habitats and mixing (Stumpf et al. 2003; Adler-Golden et al. 2005; Klonowski et al. 2007; Clark et al. 2014). In the future, it may be possible to measure spatial variations (including the vertical dependence through the water column) of nearshore dye, biota, pollutant, and sediment concentrations with airborne lidar or multi-frequency techniques (Sundermeyer et al. 2007), possibly with sensors mounted on small drones (Brouwer et al. 2014). Advances in these observational systems could lead to rapid advances in understanding transport and dilution of materials between the shoreline, estuaries, the surf zone, and the inner shelf.

Land-based remote sensing devices can provide synoptic surface and subsurface observations with high temporal resolution over long time scales and during extreme events. HF radar systems sample surface currents usually with spatial resolution of 1-2 km and occasionally of 1/2 km (Kirincich et al. 2012). These systems are useful for observing larger-scale coastal ocean surface circulation, and at higher resolution may be useful for studying cross-shelf exchange from the surf zone to the inner shelf. Shore-based camera and video systems have been used to measure shoreline position and infer subsurface morphology (e.g., Aarninkhof et al. 2005; Plant et al. 2008), providing measurements for long-term coastal behavior studies (Holman and Haller 2013). Lidar measures waves and water levels in the inner surf and swash, as well as sub-aerial bathymetry (Blenkinsopp et al. 2012; Vousdoukas et al. 2014). High-resolution X-band marine radar systems sample offshore wave characteristics, surface currents, and sand bar morphology (Haller and Lyzenga 2003; McNinch 2007). Estimates of bathymetry and spatially variable surface flows using remote sensing systems have improved owing to recent advances in analysis techniques (Perkovic et al. 2009; Haller et al. 2013; Holman et al. 2013). These land-based systems can be deployed rapidly, and may be able to measure during extreme events. Future research to broaden the range of processes that can be deduced from the remote measurements, and to reduce problems associated with fog, rain, and blowing sand, will expand the benefits of these systems.

There also may be opportunities to leverage satellite observations in nearshore regions with technologies such as the Surface Water and Ocean Topography (SWOT - https://swot.jpl.nasa.gov/) satellite that measures ocean, river, and lake water levels for oceanographic and hydrologic studies. New processing algorithms could enable these data to be used to estimate nearshore water levels, potentially providing insights into coastal morphology evolution.

Remote sensing is well suited to observing large-scale variability (e.g., shoreline and sand bar evolution, and current and pollutant patterns), and also may provide nearshore measurements during extreme events. However, these techniques require inferring environmental quantities from scattering and reflection of optical, infrared, radar, or other signals. Consequently, advances in techniques and algorithms for estimating ocean and land properties with remote sensing require in situ observations for ground truth.

2. Fixed-location In Situ Instrumentation

In situ acoustic sensors have led to increased understanding of the nearshore. For example, continuous measurements of the seabed location during and between storms using acoustic altimeter arrays and scanning sonars have resulted in improved models of cross-shore bar migration (Elgar et al. 2001; Hoefel et al. 2003, Henderson et al. 2004), ripple migration in the nearshore and inner shelf (Traykovski 2007), and the bed-state storm cycle (Hay 2011). Arrays of single-point acoustic Doppler velocimeters have provided new insights into surf zone currents (Trowbridge and Elgar 2003; Apotsos et al. 2008; Mulligan et al. 2010), wave-breaking turbulence (Feddersen 2010) and mixing owing to short-crested breaking waves (Clark et al. 2012). Recently developed high frequency acoustic profilers enable measurements of flow profiles, and thus estimates of bed shear stresses, in the shallow swash (Puleo et al. 2014). Multi-frequency Doppler profiling devices enable combined measurements of turbulence and suspended sediment concentrations (Hurther and Lemmin 2008; Zedel and Hay 2010), resulting in a better understanding of the feedbacks between turbulent flows and stress over wave ripples (Hare et al. 2014), the resulting suspended sediment flux (Hurther and Thorne 2011), and the ripple evolution (Crawford and Hay 2003). Suspended sediment concentration and grain size can be estimated with multi-frequency acoustic backscatter systems (Hurther and Thorne 2014), as can bedload (Hurther and Thorne 2011). Continued advances in techniques for measuring sediment concentrations, particularly in areas with mixed mud, sand, and gravel, will improve understanding of the processes leading to coastal erosion and accretion.

In situ optical sensors often are used to estimate turbidity and sediment concentrations (Sutherland et al. 2000; Butt et al. 2002). These measurements are limited to a small range of particle sizes, shapes, and composition and are sensitive to bubbles from breaking waves (Puleo et al. 2006), and development of multi-spectral techniques for sediment concentrations is needed. Particle tracking and laser-video techniques have been used to obtain high-resolution observations of energy dissipation, bottom boundary layer dynamics, low concentration sediment fluxes, and seafloor evolution in the laboratory (Nimmo Smith et al. 2002; Nichols and Foster 2007; Sou et al. 2010). Extension of these techniques to field conditions could lead to major advances.

New in situ observational tools are needed to measure waves, currents and pollutant transport, sediment fluxes, and bathymetric changes from the surf zone to the inner shelf during extreme events. New techniques based on electrical conductivity to measure sediment concentrations in high-concentration, fast-moving sediment layers just above the bed are resulting in new insights into swash sediment transport in the field and laboratory (Lanckriet et al. 2013). However, these and other in situ sensors must be improved to withstand energetic forcing in mixed water, air, and sand environments with rapid morphologic change. In addition, during extreme events, overland flows and sediment transport may be affected significantly by infiltration of water into the ground (Gallien et al. 2014; Matias et al. 2014) and dunes (Palmsten and Holman 2011). Groundwater levels can be measured with pressure or water-level sensors (Uchiyama et al. 2000), but advances are needed to measure subsurface flows. New robust sensors, bathymetric surveying techniques, instruments for thin overland flows and infiltration, and rapidly deployable sensors will enable advances in understanding coastal changes during extreme events.

Studies of nearshore human and ecosystem health have used combinations of physical, biological, and chemical sensors. For example, chlorophyll-a measurements have been used to understand how bubbles and sediment affect fluorescence (Omand et al. 2009). Studies of the transport and dilution of pathogens have been conducted using acoustic current meters to measure waves, flows, and turbulence, and lidar and pressure sensors to measure swash and groundwater (Gast et al. 2011; Rippy et al. 2013). Nearshore pathogen measurements, which are used to determine beach closures, require 24 hrs to process. Quantitative polymerase chain reaction (PCR) technologies can provide relatively rapid pathogen measurements, but require samples to be taken back to the laboratory. In situ PCR-based marine pathogen sensors would enable new insights into the transport and fate of marine pathogens in the nearshore. New trace heavy metal (lead, mercury), sensors, developed for wetsuits (Malzahn et al., 2011), could be developed to deployed in the nearshore. This would enable fundamental new insights into contaminant transport and fate.

3. Mobile and rapidly-deployed instrumentation

Fixed in situ instruments enable collection of data over long time periods and with high temporal resolution throughout the water column, but typically have limited horizontal resolution. Over the past decade, the development of GPS-equipped personal watercraft (MacMahan 2001) has enabled nearshore bathymetry to be surveyed before and after storms in many regions. In addition, dye concentrations have been observed with mobile sampling platforms (Clark et al. 2009), enabling quantitative estimates of surf zone mixing over large regions (Clark et al. 2010). Acoustic Doppler profilers and sonars mounted on personal watercraft and kayaks have enabled synoptic surveys of circulation and bathymetry (Hampson et al. 2011; Webb 2012). Smaller subsurface mobile platforms, such as sea spiders and mini-catamarans under development, could lead to new observations of seafloor and water column processes. Unmanned vehicles have the advantage of lower human risk, especially during storms. Improvements in remote guidance systems could enable these systems to be used in a wider range of conditions.

In the last decade, GPS-tracked surf zone drifters (Schmidt et al. 2003; Thomson 2012, MacMahan, et al. 2014) have been used to study waves, currents, transport, mixing, and dilution in the nearshore (Spydell et al. 2007; Brown et al. 2009; McCarroll et al. 2014). Drifters are easy to deploy and can be reused many times, making them ideal for observing processes during a broad range of conditions. Advances in consumer electronics have reduced the size and cost of many components, enabling "swarms" of inexpensive sensors to be deployed to study temporal and spatial variability of processes at small scales over large areas and through the water column. For example, "smart grain" sensors are used to study sediment transport (Frank et al. 2014) and "wave resolving drifters" are used to examine wave dynamics (Herbers et al. 2012; Thomson 2012). Swarms of cheap, expendable sensors can be deployed rapidly during extreme events or in hazardous conditions (e.g., a coastal sewage spill), and safely telemeter data to shore.

(ii) Observational Methodology

1. Nearshore Observing Facilities

Advances in understanding of nearshore processes has benefited from long-term, near-continuous observing stations. The US Army Corp of Engineering Field Research Facility (FRF) in Duck, NC, has collected wave and nearshore bathymetric data for over 30 years, enabling studies of long-term coastal change, providing in situ measurements during extreme events, and supporting process-based field studies (Birkmeier and Holland 2001). The Coastal Data Information Program (CDIP), supported by USACE/IOOS and the State of California, maintains an extensive network of wave sensors on the continental shelf and a database of wave simulations that have been used in many nearshore studies. The Southern California Beach Processes Study (SCBPS), a component of CDIP, has collected detailed nearshore bathymetry over the last 15 years, principally in San Diego County (Yates et al. 2009). Similarly, the Southwest Washington Coastal Erosion Study, a state-federal partnership, has collected 18 years of nearshore bathymetry along high-energy dissipative beaches (Ruggiero et al. 2005). The USGS National Assessment of Coastal Change Hazards program provides historical shoreline change and updated beach morphology information through sustained data acquisition at a national scale (Stockdon et al. 2006b; Hapke et al. 2011; Fletcher et al. 2012; Ruggiero et al. 2013). Worldwide, there are some decades-long continuous video observations through the ARGUS and other camera networks (Holman et al. 2003; Holman and Stanley 2007). The USACE National Coastal Mapping Program has integrated requirements from USGS, NOAA and USACE to collect U.S. coastal lidar, high resolution RGB imagery and hyperspectral imagery every 5 years for examining lonmg-term physical and ecosystem coastal change (Reif et al. 2011). Several coastal states also have shoreline and beach volume monitoring programs. Although limited in their spatial and temporal scope, these observing systems are valuable for studying interannual to decadal-scale coastal change, as well as extreme events. However, much of this data is not integrated into a national database and is largely limited to morphology and wave data.

Recently multi-agency investment has been made in U.S. Integrated Ocean Observing Systems (IOOS) primarily focused on the continental shelf and deeper water. Similar long-term observations in the nearshore are needed to expand understanding of coastal change and the impacts of extreme events. In addition, long-term measurements of hydrodynamics, bathymetry, biogeochemical processes, sediment transport, and turbidity are needed to understand nearshore ecosystems, coastal morphological changes, and the coupling between them. Thus, existing nearshore observing systems should continue to be supported, and new nearshore observing systems should be developed to provide information in new regions and for a wider range of processes.

2. Process-study field and laboratory experiments

Several multi-investigator, multi-agency nearshore studies were conducted in the 1980s and 1990s leading to significant advances in understanding of hydrodynamics and sediment, transport. For example a series of studies funded by the U.S. Army Corps of Engineers, the Office of Naval Research, the US Geological Society, and the National Science Foundation have resulted in advances in understanding and modeling of surfzone waves, currents, water levels, swash, and bathymetric change. These observations have been used by researchers worldwide, and are still being used today (Wilson et al. 2010; Falchetti et al. 2010; Wenneker et al. 2011; Moulton et al. 2014; Feddersen 2014; Stockdon et al. 2014).

With the development of new instrumentation and the ability to combine remote and in situ sensors, there is a need for future multi-investigator process-study field experiments in a wide range of environments (e.g., including remote and urban areas, rocky and sandy coasts, and regions with headlands, spits, deltas, inlets, estuaries, and wetlands) to address specific questions within the three research themes (Section 2). Investments by multiple agencies will enable the coupling between atmospheric, oceanic, hydrologic, and geologic processes to be examined, and to ensure that researchers with expertise in physical, biological, geological, and chemical processes can interact. Ideally, some large studies should be focused over a few specific months to examine coupling between small- and mid-scale processes, and other studies should be conducted sequentially to span seasons and years.

In addition to field studies, laboratory studies should be a component of nearshore investigations. Larger-scale laboratory facilities enable controlled experiments of some nearshore processes and, providing the scaling laws can be satisfied, can provide insight regarding the parameterization of specific processes (Turner and Masselink 2012; Henriquez, et al. 2014). Laboratory studies can be particularly valuable by providing detailed information regarding small-scale processes, such as bottom boundary layer flows, bottom stress, sediment motion, air entrainment, and ripple formation and evolution (Nimmo Smith et al. 2002; Rodriguez-Abudo and Foster 2014; Yoon and Cox 2010; Nichols and Foster 2007). Laboratory environments also can be useful for evaluating new instruments.

3. Citizen science

Even with new nearshore observing systems and expanded field studies, there will be nearshore regions that are undersampled. Visitors to beaches and estuaries, local residents, high-school science classes, or lifeguards could collect coastal morphology data with GPS-enabled smartphones. The U.S. Geological Survey crowd-sourcing application "iCoast—Did the Coast Change?" (http://coastal.er.usgs.gov/icoast) will help the USGS improve predictive models of coastal change and educate the public about the vulnerability of coastal communities to extreme storms. Expansion of these types of observations could improve understanding of long-term shoreline change and the impacts of extreme events.

Recommendations

1. *Develop new sensors and observing techniques*. New remote sensing techniques may provide better observations of material transport between the coast, inner shelf, and nearby estuaries, and may be used to guide rapid deployments of systems to measure nearshore processes during extreme events. New in situ sensors that can measure water column and near-bed, processes in the bubbly, sediment- and biota-laden nearshore waters during extreme events are needed. New techniques to measure bathymetry, especially during extreme events will provide information to improve models for currents, flooding, and morphological change during storms. New biogeochemical sensors could provide in situ measurements of pathogen or contaminant concentrations in sediments or water. Development of low-cost, expendable sensor "swarms" will allow in situ measurements during storms and in hazardous conditions.

2. *Expand long-term observing systems, conduct multi-agency interdisciplinary field studies, and develop new citizen-science opportunities*. A fund that supports field costs for scientists to conduct studies at nearshore observing facilities, similar to that for UNOLS ship time, would encourage collaborations and help sustain long-term measurements. Coordinated multi-agency multi-investigator field studies would result in better understanding of the coupling between processes. Fund new and existing long-term observing systems and programs. Working with States and expanding efforts to engage community groups to survey beaches, dunes, and flooding extent could create data in regions rarely studied. Different types of observations must be integrated to allow the cumulative impacts from multiple events to be estimated and to link short-term (spatial and temporal) variability with long-term variability. These data sets will help test and improve nearshore process models used to guide societal decisions and to simu-

late the impacts of anthropogenic influences on long-term coastal behavior.

SECTION 3B. MODELING

(i) Introduction

Numerical prediction tools and computer capabilities have grown dramatically over the past two decades (Holman et al. 2014). Wave models are now routinely applied to assess wave transformation over the continental shelf and surf zone. These models can be paired with wave-averaged circulation models to predict 3D nearshore currents (e.g., Kumar et al. 2012). Depth-integrated nonlinear wave-resolving models (e.g. Chen et al. 2003; Feddersen et al. 2011) simulate the evolution of individual waves including wave shape, and the temporally varying flow field due to waves and currents. At higher computational costs, Reynolds-Averaged Navier Stokes (RANS) equation models (Torres-Freyermuth et al. 2007), Large Eddy Simulation (LES) formulations (Christensen and Deigaard 2001; Christensen 2006; Lubin et al. 2006), and Smooth Particle Hydrodynamics (SPH) solutions (Dalrymple and Rogers 2006; Gomez-Gesteira et al. 2010) provide detailed representations of the wave and 3D flow field. These models have matured significantly, but still require substantial computational resources making large-scale simulations difficult, and have yet to be compared in detail with observations. Nearshore hydrodynamic models are used in estimating the transport of sediment, pollution, nutrients, and larvae. Sediment transport and resulting bathymetric evolution is of particular interest because bathymetry strongly controls the hydrodynamics, resulting in a feedback. Although sediment transport models have evolved significantly over the last few decades and have sucess simulating short-term morphological evolution, inherent feedbacks and nonlinearities can make coastal evolution on time scales of years and decades problematic. For these reasons, recent efforts have focused on developing numerical models of the long-term evolution of large-scale coastal morphology (e.g., Ashton et al. 2001; Lorenzo-Trueba and Ashton 2014; Moore et al. 2013). Data assimilation methods also are being used in nearshore models to improve initial and boundary conditions, constrain uncertain model parameters (such as bathymetry or drag coefficients, and estimate prediction accuracy (Feddersen et al. 2004, Wilson et al. 2014). and aid in the specification of uncertainty associated with model forecasts. Further modeling advancements are necessary to address the three identified research themes. In particular, improvements are needed in model physics and parameterizations, coupling and nesting of models, and using data assimilation and uncertainty estimation techniques. Here, we elaborate on these key advancement themes.

(ii) Improvement in model physics and parameterizations

An improved understanding of how to represent or parameterize physical processes in numerical models is required to address the research themes described in Section 2. For example, to develop improved predictions of overland flow, swash and surf zone turbulence and bottom stress processes (Torres-Freyermuth et al. 2013), vegetation effects on flow (Ma et al. 2013), flows around urban structures (Park et al. 2013), and infiltration processes must be understood better. Prediction of inlet breaching events will require improved models for rapid morphological change. Similarly, simulating nearshore pollution transport will require a predictive understanding of transport and mixing processes in addition to improved biogeochemical models. Correct process representation may rquire increased resolution in regions of high bathymetric variability such as urban coastal setting with man-made structures (Gallien et al. 2014) or dynamically adapting resolution in coastal flooding fronts or tsunamis (LeVeque et al. 2011).

Sediment transport modeling is essential to predictions of bathymetric changes over a range of time scales (e.g. event scale, or long term). Meso-scale (e.g., Henderson et al. 2004; Jacobsen and Fredsoe 2004) or large-scale models (e.g., Reniers et al. 2004; Warner et al. 2008) for coastal morphological evolution typically split sediment transport into bedload (concentrated sediment moving along the seabed) and suspended load (in the water column) components. Accurately representing suspended load transport requires resolving sediment suspension and deposition driven by complex currents, waves, and turbulence. On the other hand, bedload transport is typically not resolved and semi-empirical parameterizations of bedload transport rate and pickup flux are utilized. Parameterizations typically assume that the bottom stress and hence the magnitude of sediment transport rate (or pickup flux) are in-phase with the magnitude of free-stream velocity above the wave bottom boundary layer (e.g., Soulsby and Damgaard 2005). However, this assumption is questionable during extreme condition where intense wave breaking turbulence penetrates into the water column and enhances sediment transport (e.g., Ogston and Sternberg 2002; Yoon and Cox 2010) or when large near-bed pressure gradients cause momentary bed failure and liquefaction (Foster et al. 2006; Sumer et al. 2013). More complex multiphase flow (e.g., implicitly modeling the water and sediment particles or phases) approaches avoid the suspended and bed-load distinction by resolving the full profile of sediment transport. In the past decade, several two-phase sediment transport models have been developed (e.g., Drake and Calantoni 2001; Dong and Zhang 2002; Hsu et al. 2004; Amoudry and Liu 2009; Bakhtyar et al. 2010), which can be used to evaluate and improve sediment pickup flux (e.g., Amoudry and Liu 2010; Yu et al. 2012), simulate transport of mixed grain sizes (e.g., Calantoni and Thaxton 2007; Holway et al. 2012), and model non-spherical grain shape (Calantoni et al. 2004). More research is needed to improve suspended and bedload sediment transport model physics, and develop and evaluate parameterizations of these processes. These capabilities are a critical step toward solving realistic sediment transport problems such as winnowing (removing fine grains), bed armoring, and gradation (e.g., Meijer et al. 2002) and will enable more accurate short-term predictions for extreme events and also enable parameterizations that can be included in long-term coastal change models.

(iii) Model coupled across disciplines and scales

Predictive tools spanning a range of disciplines and scales are required to address the research themes presented in Section 2. Urban overland flow predictions will require coupling hydrodynamic models with fluid-structure interaction models that may need to account for potential changes to the structures due to damage or collapse. Understanding long-term coastal evolution will necessitate coupling physical morphological models with ecological, economic, and social models. Predicting the fate of nearshore pollutants requires coupling physical transport models with biological and chemical models. In many of these cases, the model coupling must account for a two-way feedback between the components. For instance, collapsing structures will strongly affect the flow that contributed to their collapse, and changes in economic constraints will alter the nature of human response to long-term changes.

To bridge the large range of processes, modeling tools will require coupling approaches be applied to existing models that incorporate different process, theoretical, and numerical frameworks. Challenges in model coupling arise for various reasons. Coupling models with different theoretical underpinnings (e.g., wave-resolving versus wave-averaged models or hydrostatic versus non-hydrostatic models) or disparate resolutions (e.g., high resolution LES/DNS versus low resolution wave-averaged models) need appropriate averaging and scaling methods. One example is the stochastic representation of variable wave breaking forcing in a wave-averaged model following work on Langmuir turbulence (Sullivan et al. 2007). Coupling issues also can arise due to differences in solution methods (e.g., finite-difference versus finite-element versus SPH methods) which can introduce significant inefficiencies in passing information between models. Further challenges emerge when coupling models from different disciplines. For example, hydrodynamic, long-term morphological evolution and human response models are all based on different frameworks with different spatial and temporal scales. Human manipulations of the nearshore (e.g., decades of recurring beach nourishment) alter natural processes over large time- and spatial-scales. Models incorporating coupled anthropogenic alterations and physical morphological dynamics are in their infancy in the nearshore, yet have shown promise in densely populated coastal locations (McNamara and Werner 2008a,b). Future development of coupled models is crucial to addressing our pressing societal needs regarding long-term coastal sustainability. A potential model is the Community Surface Dynamics Modeling Systems (CSDMS) which develop geoscience model protocools and tools to couple models.

(iv) Data assimilation and uncertainty estimation

In contrast to weather forecasting, data assimilation methods only recently have been applied to the nearshore. Data assimilation can help infer initial or boundary conditions from existing observations (e.g., remote sensing of waves) and lead to a skillful nearshore state estimation and improve water quality or morphological change predictions.. Different data assimilation methodologies exist. Kalman filtering has been used to estimate nearshore bathymetry (Holman et al. 2013). Ensemble-based methods (utilizing many model realizations along with observations to deduce the correct model state) have been used for bathymetry and circulation estimation (Wilson et al. 2014). Adjoint methods (that formally derive relationships between corrections to model variables and the observed quantities) have been used to diagnose wave forcing and bathymetry estimation (Feddersen et al. 2004; Kurapov and Ozkan-Haller 2013). These techniques also can aid in improving parameterizations of unresolved physics (Feddersen et al. 2004), and can be used to design or refine an observational program that best benefits forecasting efforts (Kurapov et al. 2005). Forecasting the nearshore (similar to weather forecasting) with little to no in situ observations (that are difficult to obtain in extreme events) will require data assimilation.

Societal decisions must be made given uncertain future conditions. In contrast to hurricane modeling and other mature modeling systems, nearshore models often present a single prediction that does not provide guidance regarding the potential range of scenarios (i.e. uncertainy) that is needed in the decision-making process. Recent work in related environmental science fields suggests integrated modeling framework approaches that allow tracking uncertainty throughout the decision making process (Kelly et al. 2013, Ascough et al. 2008, Landuyt et al. 2013). Ensemble (Flowerdew et al. 2010; Zou et al. 2013) and Bayesian (Plant and Holland 2011, Long et al. 2014, Van der Wegen and Jaffe 2013) approaches have been recently used to quantify prediction uncertainty in storm surge and morphological modeling. By explicitly estimating uncertainty, process based model results can be assessed and ultimately used as decision support tools to address the societal needs introduced in Section 2.

Recommendations

Numerical models of nearshore processes must include improved model physics and parameterizations, enable models to be coupled across processes and scales, and incorporate data assimilation and uncertainty estimation methods. Model improvements must be quantified by comparison with observations. Potential focus areas for model improvement corresponding to the three research themes could include:

1. *Modeling coupled human and natural driven long-term coastal evolution*: This would include improving parameterizations of the physical sediment transport processes that govern long-term morphological evolution, improving coupling with economic models, using data assimilation to constrain these coupled models, and providing uncertainty estimates in long-term coastal evolution forecasts.
2. *Modeling extreme event-driven overland flow and corresponding erosion*: This would include improving parameterizations of sediment transport, coupling wave, overtopping, overland flow, and groundwater models, and using data assimilation to incorporate coastal flooding observations to improve model skill.
3. *Modeling nearshore material transport*: This would include imcorporating models of biological or chemical evolution (e.g., FIB growth and mortality), improving model coupling to allow groundwater to surf zone fluxes, and assimilating new high-resolution in situ pollutant or biological observations.

Particular infrastructure recommendations that pertain to modeling include:

1. *Develop nearshore modeling testbeds* based on existing and future observational data sets. This would provide a straightforward method to test different types of models. Similar testbeds are available for climate, hurricane, and continental shelf ocean processes. Such a testbed would be based on open standards of cyber infrastructure and include wave, circulation, sediment transport, and bathymetry observations so that models can be evaluated and inter-compared.
2. *Enable continued model development*, in particular coupling of different types of models to facilitate new predictive capability. Such model development should be based on open established standards leading to community models, similar to other geosciences models. An example focus area is coupling wave, swash, overland flow, and groundwater models.
3. *Develop a real-time data assimilating nearshore modeling system* for select regions of the U.S. coast. This would provide an opportunity to expand and test models, improve coupling between models, incorporate data assimilation, distribute real-time predictions to the scientific community and to other users, including search and rescue, local government officials, and sanitation districts.

SECTION 3C. COMMUNITY

Addressing the three identified research themes (Section 2) will require new observational (Section 3a) and modeling (Section 3b) infrastructure. It also will require that the community have improved collaboration amongst the academics, government agencies, and industry involved with understanding, predicting, and managing the nearshore region. Deriving societal benefit from this research requires improved communication of research results to stakeholders. In addition, future research successes also will depend upon educating the future scientistis and engineers who study nearshore processes. With the infrastructure to improve collaboration, communication, and education, the nearshore community will be strengthened.

(i) Collaboration

Nearshore processes intersect the mission responsibilities of roughly twenty U.S. federal agencies or large federal programs, as well as many state programs, reflecting the importance of the nearshore to a wide range of societal interests. Over the last few decades, large coordinated field experiments and model testing, such as the series of community experiments at Duck NC in the 1990s funded by a broad array of agencies including ONR, NSF, USGS, and USACE (Holman et al. 2014), have resulted in many scientific discoveries. Similarly, during the early 2000s, the Nearshore Modeling NOPP (National Oceanographic Partnership Program) resulted in improved nearshore models and observational test beds. Recently, the European nearshore community has expanded substantially, enabling collaborative field and modeling studies, such as the Dutch "ZandMotor." This study, which includes research institutes, government agencies, and private sector and regional development funds, is monitoring and modeling a large beach nourishment to test a long-term approach to coastal hazard mitigation while advancing understanding of coastal evolution (Stive et al. 2013). A similar coordinated investment in U.S. nearshore research would leverage efforts, avoid redundancy, and move the science and engineering forward rapidly.

Other components of the U.S. geoscience community have developed strong collaborations across research communities and federal agencies. The NASA Aquarius Satellite mission to measure ocean salinity has a large 32-member U.S. science team spanning a range of oceanographic specialties. The U.S. internal waves community has an upcoming NSF funded T-TIDE internal wave experiment with 10 PIs from 4 universities. Multi-agency examples include US GLOBEC, funded by NSF and NOAA to perform interdisciplinary oceanographic and ecological research, and US CLIVAR (Climate Variability) funded by NOAA, NSF, Dept. of Energy, and NASA. The multi-agency funding of US GLOBEC and CLIVAR is coordinated through the US Global Change Research Program (USGCRP). The nearshore processes community lacks this type of collaboration. To address the complex questions in the Section 2 research themes, the federal agencies interested in the nearshore (USACE, FEMA, USGS, NOAA, ONR, and NSF) and the U.S. nearshore community must come together and develop meaningful collaborations.

(ii) Communication

To ensure significant societal benefit and impact, future nearshore processes research results must be effectively communicated to stakeholders. The improved understanding developed via the research discussed herein will enable more accurate predictions of future outcomes and uncertainty, but will require new communication strategies to ensure widespread application to decision making. Communicating multi-layered technical information including biological, geological, chemical, physical, and economic data and model results to the stakeholders is challenging, although recent efforts have made progress. For example, the Natural Capital Project has been developing tools to provide decision support by accounting for various ecosystem services that can be attributed to the nearshore region (Asah et al. 2014). Similarly, the integrated modeling framework Envision (Hulse et al. 2008) involves a GIS-based tool for regional environmental assessments and scenario evaluation. The application of these tools to issues related to long term coastal change is just beginning, partly because of our insufficient understanding of the underlying processes. Improved predictions of coastal flooding must be clearly communicated to help plan evacuations and define new flood maps. Improved coupled nearshore pathogen models could provide real-time predictions, allowing more efficient beach closures and improve health and local economies.

(iii) Education

Although this whitepaper is focussed on nearshore processes research, addressing these societal science and engineering needs will require an investment in undergraduate and graduate education into the future nearshore processes scientists and engineers. As recognized by the National Research Council in 1999 (NRC 1999), societal needs regarding the nearshore have far outstripped financial support for educating future scientists and engineers to address these needs. The situation is even more dire now (ASBPA 2012). Furthermore, due to shrinking university degree programs, the U.S. coastal engineering industry often funds U.S. employee graduate education in the Netherlands or hire foreign nationals. Thus, to ensure long-term U.S. coastal sustainability, reinvestment in U.S. university coastal engineering, oceanography, and other nearshore-related fields must be made.

Recommendations

The nearshore community has determined that inter-agency coordination and collaboration is necessary to develop the observational and modeling infrastructure (Sections 3a,b) required to address the three research themes (Section 2). Specific recommendations include:

1. **Build a sustained, multi-agency funded U.S. Nearshore Research Program (NRP)** that would coordinate and fund nearshore processes research to address the three broad research themes via field and modeling studies and development of new research infrastructure. The program would develop new understanding and predictive capability through observations and modeling of long-term coastal change, the flooding and erosion impacts of extreme events, and nearshore pollution and water quality evolution. Through the NRP the next generation of nearshore scientists and engineers will be trained. Substantial interagency collaboration will be required to develop the framework of this new U.S. nearshore research program. The NRP could be under the umbrella of the White House Subcommittee on Ocean Science and Technology (SOST), the U.S. Global Change Research Program (USGCRP),

or other relevant interagency coordination bodies. An example of analogous coordinated multi-agency programs is US CLIVAR (http://www.usclivar.org/) supported by NSF, NASA, NOAA, Department of Energy (DOE), and Office of Naval Research.

2. **Formalize a Nearshore Community Council (NCC)** with representatives from academia, government agencies, and industry to be elected by the community to fixed terms. The NCC would help structure the nearshore community, foster continued community collaboration, interagency coordination, and represent the nearshore community to the public and coastal stakeholders. NCC would communicate vision, strategy, and approach to political leaders who can support new efforts and expect tangible benefits for society, and advocate for funding for sustained research programs.

SECTION 4. SUMMARY AND RECOMMENDATIONS

The nearshore region is vital to our national economy, commerce, recreation, and military, yet it is under threat from global climate change, sea level rise, extreme events, and anthropogenic influences. Much is unknown about how the nearshore region responds to these threats. This whitepaper presents a vision for the future of nearshore processes research where societal needs and scientific challenges intersect. This vision is comprised of three broad research themes that will improve our understanding and prediction of:

1. *Long-term coastal evolution due to natural and anthropogenic processes:* The research goal is to accurately simulate coastal evolution incorporating geological and anthropogenic (global climate change, economic activity, and coastal management) feedbacks. Societal benefits will include sustainable coastal development.
2. *Extreme Events: flooding, erosion, and the subsequent recovery*: The research goal is to understand hydrodynamic and sediment transport processes during flooding and erosion induced by extreme events. This goal involves establishing how waves, runup, setup, overland flow, and sediment transport processes during extreme events differ from those during moderate storm conditions. Societal benefits will include improved flood management and resilient coastal communities.
3. *Physical, biological, and chemical processes impacting human and ecosystem health:* The research goal is to accurately predict anthropogenic pollution events in the nearshore and their impact on ecosystems and human health. This goal requires understanding the primary physical mechanisms of exchange between estuaries, beach sands, surf zones, and inner-shelf regions. Societal benefits will include improved beach safety and management policies for the nearshore.

The nearshore community is poised to make significant progress on these societally relevant research themes with appropriate investment in observational, modeling, and collaboation research infrastructure. This infrastructure is needed to address all three research themes. The observation, modeling, and collaboration recommenation are given at the end of Sections 3a,b,c and are summarized below. In particular, the observational and modeling infrastructure needs include **conducting multi-agency interdisciplinary field and numerical studies.** The field studies should include expanded nearshore observing systems and citizen science opportunities. These studies will lead to new understanding of the nearshore, as well as providing test-beds to inter-compare models and enabling development and evaluation of a real-time data assimilating modeling system. In addition, as discussed in *Section 3a*, infrastructure needed to obtain the observations includes developing new sensors and methods and creating a fund to support nearshore field costs (similar to UNOLS ship time). As discussed in *Section 3b*, infrastructure needed to improve predictions of the nearshore includes development of new representations and parameterizations of processes, techniques for model coupling scales and processes, and incorporating data assimilation and uncertainty estimation.

As discussed in *Section 3c*, the nearshore community must increase collaboration and engage more vigorously across academia, federal agencies, state agencies, and the stakeholder communities. A coordinated investment in research will leverage efforts, avoid redundancy, and move the science and engineering forward rapidly. Improved communication tools are needed that present the results of predictions and forecasts, as well as uncertainties, in ways that are useful to stakeholders. To this end, the nearshore community should:

1. **Build a sustained, multi-agency funded U.S. Nearshore Research Program (NRP)** that would coordinate and fund nearshore processes research to address the three broad research themes via field and modeling studies and development of new research infrastructure. The program would foster understanding and prediction through observations and modeling of long-term coastal change, the flooding and erosion impacts of extreme events, and nearshore pollution and water quality evolution. Through the NRP the next generation of nearshore scientists and engineers will be trained. Substantial interagency collaboration

will be required to develop the framework of this new U.S. nearshore research program. The NRP could be under the umbrella of the White House Subcommittee on Ocean Science and Technology (SOST), the U.S. Global Change Research Program (USGCRP), or other relevant interagency coordination bodies. An example of analogous coordinated multi-agency programs is US CLIVAR (http://www.usclivar.org/) supported by NSF, NASA, NOAA, Department of Energy (DOE), and Office of Naval Research. Substantial interagency collaboration will be required to develop the framework of this new US nearshore research program.

2. **Formalize a Nearshore Community Council (NCC)** with representatives from academia, government agencies, and industry to be elected by the community to fixed terms. The NCC would help structure the nearshore community, foster continued community collaboration, interagency coordination, and represent the nearshore community to the public and coastal stakeholders. NCC would communicate vision, strategy, and approach to political leaders who can support new efforts and expect tangible benefits for society, and advocate for funding for sustained research programs.

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