The Future of Nearshore Processes Research – Draft V2
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by
The Nearshore Processes Community
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- A two-page executive summary will be compiled for the next version
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TABLE of CONTENTS
Section 1. Introduction
Section 2. Three Research Themes that Intersect Societal Needs and Scientific Challenges
  Section 2a. Long-term Coastal Change
  Section 2b. Extreme Events
  Section 2c. Physical transport and dispersion, biological and chemical processes impacting nearshore human and ecosystem health
Section 3: Enabling Infrastructure: Observations, Modeling, Community
  Section 3a: Observations
  Section 3b. Enabling Infrastructure: Modeling tools to address research questions
  Section 3c. Enabling Infrastructure: Collaboration and Communication
Section 4. Summary and Recommendations
Section 5. Contributors
Section 6. References
Section 1. Introduction

Over a billion people reside within 100 km of an ocean coast, with the majority living less than 20 m above sea level (Small and Nicholls, 2003). About 39% of US 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 Corp) and commerce (fisheries and aquaculture, ports and harbors). 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).

The nearshore region, the transition zone between land and the continental shelf (Komar, 1998; Figure 1), includes (from onshore to offshore) wetlands, estuaries, tidal inlets, barrier islands, coastal cliffs and dunes, beaches, surfzones (regions of wave breaking), and the inner shelf (to approximately 15 m depth). Nearshore regions, often both densely populated and dynamically changing, face many challenges. The dynamic nature of the nearshore is in direct conflict with static coastal investment and infrastructure. Coastal infrastructure, economies, safety, and human health are at risk, and these risks will increase with increased human development 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 storm surge and waves. Long-term erosion will threaten infrastructure, valuable cultural resources, ecosystems, and habitat owing to both climate change and limited sand availability (National Climate Assessment, 2014). Nearshore processes, the complex interaction of water, sediment, and biota, must be understood to manage this developed yet vulnerable environment (Figure 1).

Over the past three decades, improvements have been made in understanding the complex interactions between hydrodynamic, sediment transport, and morphological processes (Holman et al., 2014). However, societal needs are growing with increased coastal urbanization and threats of future climate change. To discuss future research directions that address these
needs, over 70 members of the 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, and other federal-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 address 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 future insurance and emergency response requirements, pointed to the need for wave and flooding predictions in the coastal floodplain. The National Oceanic and Atmospheric Administration (NOAA) requires improved understanding of the connections between weather, hazards, society, and ecosystems. The U.S. Geological Survey (USGS) needs the ability to include the influences of climate change on long-term and short-term coastal-change vulnerability assessments. The U.S. Army Corps of Engineers (USACE) requires improved data and models to evaluate the resilience provided by coastal protection projects. The U.S. Navy needs to utilize remote sensing and unmanned systems to produce high-resolution forecasts of nearshore environments. The National Park Service (NPS) requires better understanding 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 agency community for flood risk, shore protection, and sediment management. These societal needs require seamless and accurate predictions across the nearshore system from the ocean overlant to estuaries and coastal plains, and a multidisciplinary and integrated understanding of physical and societal processes.

The community consensus resulting from workshop discussions 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 nearshore processes research is presented that addresses these diverse challenges. The plan is comprised of three broad research themes that will improve our understanding and prediction of:

1. Long-term coastal changes due to natural and anthropogenic processes
2. Nearshore flooding and erosion from extreme events, and the subsequent recovery.
3. The physical transport and dispersion, biological and chemical processes that impact nearshore human and ecosystem health.

These interrelated 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 addressed in Section 3, and recommendations are given in Section 4.

Section 2. Three Research Themes that Intersect Societal Needs and Scientific Challenges

The research required to address the societal needs indicated by FEMA, NOAA, USGS, USACE, the Navy, and NPS, has been organized into three broad themes, each involving coupling and feedbacks between hydrodynamics, morphodynamics, and anthropogenic interactions, as well as between geological, meteorological, oceanographic, hydrological processes. This wide range of interactions, and inter-dependability, makes the nearshore region complex. In addition, the interactions between processes occurring on different temporal and spatial scales can complicate the collection and interpretation of observations, and the formulation of numerical models. These processes span turbulence, ocean waves, wave runup on beach, and flooding. In addition, humans alter the nearshore environment through development and coastal management, directly impacting nearshore hydrodynamics, morphodynamics, and ecosystems, in addition to creating feedbacks between human activity and natural processes. The following sub-sections elaborate on the three research themes that intersect societal needs and scientific challenges identified by the community during the Future of Nearshore Processes Research workshop. For each research theme, scientific advances are reviewed, current challenges discussed, research questions are posed, and future societal benefits from this research are given.

Section 2a: Long-term Coastal Change

(i) Introduction

Infrastructure, valuable cultural resources, ecosystems, and habitat are threatened by long-term coastal erosion owing to both climate change and limited sand 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 erosion and accretion of the coast (Stive, 1990; DeVriend, 1991), 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 2). 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 shorter time-scale 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 (Lippmann and Holman, 1989, 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. New research, including series of short-term field studies, long-term observing systems, studies in regions with significant human influence, and new modeling techniques, is needed to understand the feedbacks between these processes.

Owing to human involvement with the coast, 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 often difficult to anticipate (Gelfenbaum and Kaminsky, 2010). For example, in some locations seawalls are the dominant shore protection method, whereas in other locations beach nourishment and dune enhancement are used. These human modifications have different impacts on coastal processes, and progress toward long-term prediction requires an understanding of the societal drivers behind various adaptation strategies. The coupled relationship between property value, beach nourishment, and shoreline change has been explored (Smith et al., 2009; Gopalakrishnan, 2011). Combining new observational strategies and modeling techniques will enable progress toward a better coupling of human modifications and natural processes for a range of coastal morphologies (McNamara and Werner, 2008a).
Figure 2: 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.

(iii) Research Questions

The overall goal of the long-term coastal change research theme is the development of reliable and accurate long-term predictions that represent processes over multiple time scales. To achieve this goal, there are two primary groups of interconnected research questions pertaining to natural and anthropogenic coastal evolution processes. The first set of questions address natural processes that impact our ability to predict coastal change over a range of sea level rise rates and changes in storm climatology. Specific research questions include:

1) What are the processes dominating long-term sediment transport and how do geological constraints on sediment supply and ecological processes (dune grass growth or destruction) affect these processes?
2) What are the feedbacks and interactions between short time-scale processes such as storms and long time-scale processes such as sea-level rise and sediment supply?
3) Can models of short time-scale processes (both storms and recovery periods) be scaled up to simulate the long-term evolution of the coastline?
The second set of questions relates to what drives human interventions and how these interventions couple to natural processes. Specific research questions include:

1) How does the availability of sand impact the cost of nourishment and the long-term sustainability of eroding coastlines?

2) How do coastal property values evolve as sea level rises, storm characteristics change, or policies such as insurance rates or nourishment subsidies are altered?

(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 regimes. Coastal areas, with high-density population and infrastructure, are more susceptible to impacts of climate change than inland areas. Recent large disasters like Hurricanes Katrina and Sandy highlight the vulnerability of human tenancy along the coast. Increased knowledge and predictive capability of long-term coastal change will enable:

Proactive solutions for sustainably developed coastlines. Rather than reactive geo-engineering of the coastline (Smith et al., 2014), managers can determine the optimal coastal protection to implement 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 cost-benefit ratio, coastal communities can determine, and reduce, their vulnerability.

Section 2b. Extreme Events

(i) Introduction

Although the path of Hurricane Sandy and the likelihood of flooding and erosion were predicted, coastal communities were not prepared for the extreme damage along the shoreline. The high water levels, large waves, and strong currents caused erosion along hundreds of miles of shoreline, damaging structures (Figure 3), flooded New York City, breached new inlets, and wreaked havoc with transportation and utility infrastructure. Storms along the US west coast have caused major erosion to the coastal bluffs, undermining infrastructure and property (Figure 4). 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 (Davis et al., 1993; Dolan and Davis, 1994; Sallenger et al., 2004, 2005, 2006, 2007). Improved field-tested models are needed to warn residents of impending dangers and to plan for future storms.

Coastal-storm-related economic losses have increased substantially over the past century, 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). The regional coastal inundation map will become more reliable, and the costs owing to flooding could decrease, as our understanding of the processes affecting inundation advances.

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. 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 resulting from storm surge and tides 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 our 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. 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

(a) Wave propagation, overland flow, and flooding

Understanding the transformation of waves 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 surfzone 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; Arduhin 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, meteorological, subsidence, precipitation, infiltration). Overland flow and coastal flooding 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, especially during storms, and therefore can be a primary driver of coastal overwash (Stockdon et al., 2006a, Laudier et al., 2011) and morphological change. 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. Existing parameterizations of wave runup (Stockdon et al., 2006a) and tests 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 flow have been developed for rainfall-induced flooding (Zoppou, 2001), tsunamis (Heitner and Housner, 1970), and extreme storms impacting coastal cities (Brown et al., 2007; Schubert et al., 2008; Gallien et al., 2014). Flooding and overland flows may be affected not only by oceanic and atmospheric processes, but also by drainage and infiltration of water into the 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 these processes can create spatially varying flood hazards. Additional observations during extreme events 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 natural coastlines 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 backshore 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.

(b) Morphological evolution and sediment transport
Long-term morphological evolution is affected by event and recovery when integrated over months, 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 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 (Trowbridge and Young, 1989; Hoefel and Elgar, 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 (Butt and Russell, 1999; 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 in areas of beach replenishment, and 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 leading to better predictions, and may help policy-makers determine which 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 factors 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.

(c) 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 shifting of storm tracks poleward (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, reduced income to coastal businesses. 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 dunes and bluffs. An improved understanding of nearshore processes during extreme events, including an investment in addressing the questions above, will help coastal managers:

**Determine 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**: Despite recent modifications and improvements, the NFIP is costly, and increased flood insurance costs may cause coastal residents to lose their homes. Advances in understanding the coupling between coastal systems, and the effect 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.
Figure 3: Photographs of damage resulting from massive sediment transport during Hurricane Sandy.

Figure 4: Photographs of bluff erosion resulting in loss of infrastructure and property along the US west coast.

Section 2c. Physical transport and dispersion, biological and chemical processes impacting nearshore human and ecosystem health

(i) Introduction

Nearshore regions are used for recreation, tourism, and human habitation, providing a wide-range of valuable ecosystem services, including food production, water purification, ocean
nourishment, and biological regulation. These regions and ecosystems must be sustained for future generations. Despite the importance of clean waters to our well-being and economy, societies use the nearshore as an inexpensive means 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, which requires expanding our knowledge of the physics, chemistry, and biology of the nearshore ocean.

Polluted water, rich in microbial pathogens, often enters the nearshore where it is transported and diluted (Boehm et al., 2002). 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 US 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 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 (Dorfman and Stoner, 2012, Figure 5) to more than 20,000 days per year of beach advisories in the US (NRDC 2012) and impact 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 entering the marine environment (such as bisphenol A) 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 understood.
Studies using controlled releases of mock bacteria such as microspheres (Feng et al., 2013; Gast et al., 2014) and pollutants (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 surfzone 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 someday 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. FIB 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).

Understanding 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 factors that govern the distribution of different pollutants once introduced into the environment (Boehm et al., 2002; Lipp et al., 2001). For example, surfzone (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)

To understand the level and fate of pollutants in the nearshore, the transport and dilution (mixing) of materials must be understood. The surfzone and inner-shelf have dramatically different transport and dilution processes. The surfzone is characterized by breaking-wave driven currents and eddies, whereas the inner-shelf is forced by wind, tides, waves (Lentz and Fewings, 2012) and buoyancy (Lentz, 2001) processes. The differences between the surfzone and inner-shelf result in differences in the time- and length-scales of nearshore transport and dilution processes, complicating understanding and modeling. Surfzone eddies laterally disperse tracer over 10s of minutes (Spydell et al., 2007, Brown et al., 2009; Clark et al., 2010), and rip currents exchange material between the surfzone and inner-shelf (Dalrymple et al., 2010; Hally-Rosendahl et al., 2014) from minutes to hours. At time-scales of many hours, surfzone (Garcez Faria et al., 2000) and inner-shelf (Lentz et al., 2008) undertow and internal waves (Pineda, 1991; 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 surfzone (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 other 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 independent 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, surfzones, and inner-shelf regions so they can be modeled, and
2. How the physical, chemical, and biological processes interact to regulate different pollutant concentrations. For example, can polluted beach sediments act as a pathogen reservoir that is released during storm-induced erosion?

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. A few concrete examples include:

**Optimal beach closures & safety:** By closing the beach only when it is polluted and by reopening it when it is 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:** Often mitigation policies and regulations affecting nearshore waters are an educated best guess. 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.

Figure 6. Color-enhanced photographs of non-toxic fluorescent dye tracer (pink water) (a) 1 hr after continual surzone dye release begin at Imperial Beach, California (Hally-Rosendahl et al., 2014), and (b) 1.5 hr 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 (from Clark et al., 2014).

**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 coastal change, (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, (iv) studies evaluating the effects of human interventions, and (v) field studies spanning a range of coastal areas to allow comparisons of different regions.
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.

**Existing and New Instrumentation**

**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 (Irish and Lillycrop, 1999; 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, 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 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 from wave breaking patterns (Lippmann and Holman, 1989; Aarninkhof et al., 2005; Plant et al., 2007), 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 (Bell, 1999; 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 obtain measurements of nearshore processes 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 morphological 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 concomitant in situ observations for ground truth.

(ii) 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 (Gallagher et al., 1998; Elgar et al., 2001; Hoefel et al. 2003, Henderson et al. 2004), ripple migration in the nearshore and inner shelf (Gallagher et al., 1998; Traykovski, 2007), and the bed-state storm cycle (Hay, 2011). Arrays of single-point acoustic Doppler velocimeters have provided new insights into surfzone currents (Trowbridge and Elgar, 2003; Apotsos et al. 2008; Mulligan et al., 2010), wave-breaking turbulent dissipation (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 (Hurter 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 (Hurter and Thorne, 2011), and the ripple evolution (Crawford and Hay, 2003). Suspended sediment concentration and size can be estimated with multi-frequency acoustic backscatter systems (Hurter and Thorne, 2014), as can bedload (Traykovski, 1998; Hurter 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 (Lanekriet 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 (potentially catastrophic) 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). 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 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.

(iii) 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 surfzone 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 storm events. Improvements in remote guidance systems could enable these systems to be used in a wider range of conditions.

In the last decade, GPS-track ed 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,
Swarms the nearshore and expendable al, USACE/IOOS continental has collected 2012; waves, coastal future extreme events. Information al., Science beach multi-investigator network State being sensors understanding measurements through Engineers, over Hapke has al., rapidly new and a et Falchetti in many remote Change by Holman events Field et sensors of Ocean the areas, studies the The process-study should a al., et Foundation, have and et extreme Holland, in the sustained observing Corp of in of that provides Similar in and are during significant on long-term impacts years, biogeochemical detailed to shelf The the coupling supporting observing bathymetry ability long-term observing studies in 2007). extensive in deeper-water needed For bathymetry, from last historical networks long-term, in of The and deployed providing NC, at Fletcher the 2009). existing 2013). coastal 2014; swash, in the 1980s water data sediment al., Stockdon and advances component (e.g., processes and al., the wide nearshore nearshore The between Naval and Moulton coastal stations. morphology and resulted for ecosystems, is scale hydrodynamics a cheap, Program development be of can of combine a Coastal currents, addition, the Stanley, leading the that simulations has of Engineering should of situ al., turbidity (Holman (SCBPS), conducted field them. investment for In Ruggiero US shelf instrumentation systems of nearshore these of experiments studies and change, Feddersen, et California and be 2014; to Hazards wave multi-agency has collected detailed nearshore bathymetry over the last 15 years, principally in San Diego County (Yates et al., 2009). 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). 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. Recently has been investment in Ocean Observing Systems that are focused on continental shelf and deeper-water processes. 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.

(ii) 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 US Army Corps of Engineers, the Office of Naval Research, the US Geological Society, the National Science Foundation, and the Naval Research Laboratory, have resulted in advances in understanding and modeling simulations of surf zone 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 (Henriquez, et al., 2014, Turner and Masselink, 2012). 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 (Rodriguez-Abudo and Foster, 2014; Yoon and Cox, 2010; Nimmo Smith et al., 2002; Nichols and Foster, 2007). Laboratory environments can also be useful for evaluating and validating new instruments.

(iii) Citizen science

Even with new nearshore observing systems and expanded field studies, there will be nearshore regions that are under-sampled. 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/iccoast) allows citizen scientists to identify changes to the coast caused by extreme storms by comparing aerial photographs taken before each storm with photographs taken after the storm. Crowd-sourced data from 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. Expanding efforts to engage community groups to survey beaches, dunes, and shorelines, and to measure other nearshore processes, such as surfzone width, extent of runup, and areas that flood could create a wealth of data in regions rarely studied. Different types of observations must be integrated to allow the cumulative impacts from multiple events to be estimated. These data sets will help test and improve nearshore process models used to guide societal decisions and to simulate the impacts of anthropogenic influences on long-term coastal behavior.

Section 3b. Enabling Infrastructure: Modeling tools to address research questions

(i) Introduction

The past few decades have seen accelerated development in numerical prediction tools in line with the marked increase in computational resources (Holman et al., 2014). In particular, dramatic improvements have been made to hydrodynamic models. 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 nearshore currents. The initial depth-integrated circulation models have evolved to resolve vertical structure (3D models). At higher computational costs, depth-integrated nonlinear wave-resolving models (e.g. Chen et al, 2003) simulate the evolution of individual waves including wave shape, and the temporally varying flow field due to waves and currents. At even 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), Smooth Particle Hydrodynamics (SPH) solutions (Dalrymple and Rogers, 2006; Gomez-Gesteira et al., 2010), or Direct Numerical Solutions (DNS) of the Navier Stokes equations provide detailed representations of the wave and 3D flow field. These models have matured significantly in the recent past, but still require significant computational resources making large-scale simulations difficult, and have yet to be compared in detail with observations.

Nearshore hydrodynamic models simulate the water velocities needed to estimate the transport of sediment and tracers (e.g., pollution, nutrients, larvae). Sediment transport and resulting bathymetric evolution is of particular interest as bathymetry strongly controls the hydrodynamics, resulting in a feedback not present for other tracers. Although sediment transport models have evolved significantly over the last few decades, inherent feedbacks and nonlinearities can make scaling up results to longer time scales (e.g. years and decades) problematic. For these reasons, recent efforts have focused on developing numerical models of the evolution of large-scale coastal morphology (e.g., Ashton et al., 2001). Examples include coupled models of barrier island evolution (Lorenzo-Trueba and Ashton, 2014) and coastline response to decadal changes in wave climates (Moore et al., 2013).

Data assimilation methods are also being used in nearshore models to improve initial and boundary conditions, constrain uncertain model parameters, and estimate prediction accuracy. For example, bathymetric uncertainty limits the accuracy of nearshore circulation models
Despite the significant improvements during recent years, 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

Addressing the Section 2 research themes requires an improved understanding of physical processes and parameterizations. 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 better understood. 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.

An area of particular concern is sediment transport modeling, essential to predictions of bathymetric changes over a variety 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., Warner et al. 2008; Reniers et al. 2004) 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 (e.g., Ribberink 1998) and pickup flux (e.g., van Rijn 1984) 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., Ribberink 1998; Soulsby & Damgaard 2005). However the validity of 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 & Cox 2010) or when near-bed pressure gradients become significant causing momentary bed failure and liquefaction (Zala Flores & Sleath 1998; Foster et al. 2006; Sumer et al. 2013). 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 although the resulting model formulation is more complex. In the past decade, several two-phase sediment transport models have been developed (e.g., Dong & Zhang 2002; Hsu et al. 2004; Amoudry & Liu 2009; Bakhtyar et al. 2010, Drake & Calantoni 2001). Such models can be used to evaluate and improve sediment pickup flux (e.g., Amoudry & Liu 2010; Yu et al. 2012), simulate transport of mixed grain sizes (e.g., Calantoni & Thaxton 2007; Holway et al. 2012), and model
non-spherical grain shape (Calantoni et al. 2004). More research is needed to improve suspended and bed load 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., Harris & Wiberg 1997; 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) Modeling coupled processes across scales

Addressing the Section 2 research themes will require predictive tools spanning a range of disciplines and scales. 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, since, for instance, collapsing structures will strongly affect the flow that contributed to their collapse, or 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 to 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) will necessitate evaluation of appropriate averaging and down-sampling methods. Recent attempts exist to circumvent this issue, i.e. by introducing wave breaking forcing variability stochastically in a wave-averaged model following work on Langmuir turbulence (Sullivan et al., 2007). Coupling issues can also 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. Hence, coupling models of varying theoretical and numerical frameworks will require careful consideration of these, and numerous other, challenges, yet is necessary to perform realistic simulations over large regions of the nearshore.

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 governed by vastly different spatial and temporal constraints. Human manipulations of the nearshore, for example beach nourishment recurring over decades, 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 physical and human system modeling is crucial to addressing our pressing societal concerns regarding long-term coastal sustainability.
Other challenges include the need for increased model resolution in regions with high bathymetric variability. For example, localized high resolution is needed in an urban coastal setting with man-made structures (e.g., Gallien et al., 2014). Several approaches have been explored to provide this localized high resolution. One approach is based on unstructured grid models, where high local resolution can be introduced as needed without being applied to the entire modeled domain (e.g. ADCIRC, see Dietrich et al, 2011). A more recent approach, in their infancy for nearshore models, involves adaptive mesh refinement (AMR), which has been successfully applied to rapidly changing parts of flows such as tsunami wave fronts (LeVeque et al, 2011) and dam break flood fronts (George, 2011). In relatively simple idealized settings, AMR approaches produce accurate results, with dramatic, orders of magnitude improvements in execution time. Extension of these kinds of methods within the overall coupled modeling approach will increase computational efficiency and enable predictions over the scales relevant for regional flooding or pollutant dispersal problems.

(iv) Data assimilation and uncertainty estimation

In contrast to weather or tidal forecasting efforts, data assimilation methods are only recently being applied to the nearshore. Data assimilation methods can help infer such initial or boundary conditions using readily available observations (e.g., remote sensing of waves) and lead to a more skillful estimation of the state of the nearshore and aid in forecasting efforts for water quality or morphological change. 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. For example, bathymetric and topographic evolution estimates during extreme events are required to understand rapid morphological evolution. Data assimilative approaches that combine remote sensing observations with models can provide such bathymetry estimates (Holman et al, 2014; Wilson et al., 2014), and routine application could provide an unprecedented view into coastal evolution.

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. uncertainty), which is needed in the decision-making process. Recent work in related environmental science fields proposes integrated modeling framework approaches to capture the understanding provided by modeling while tracking uncertainty throughout the decision making process (Kelly et al. 2013, Ascough et al. 2008, Landuyt et al. 2013). Ensemble approaches have been used to quantify prediction uncertainty in meteorology and storm surge studies (xFlowerdew et al., 2010), but less
so in nearshore oceanography and coastal engineering (Zou et al., 2013). Uncertainties in decision-making can also be explicitly conveyed through the use of Bayesian probability, which has seen recent use in the nearshore community (Plant & Holland 2011, Long et al. 2014, Van der Wegen and Jaffe 2013). The main advantage of these approaches is that the explicitly estimate uncertainty enabling process-based model results to be assessed and thus providing relevant information to environmental managers.

**Recommendations**

Numerical models of nearshore processes must be further developed in a variety of ways that include improving model physics and parameterizations, enabling models to be coupled across processes and scales, and incorporating 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 barrier island 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 and improve these coupled models.

3. **Modeling nearshore tracer transport (e.g. FIB pollution):** This would include incorporating models of tracer behavior (e.g. FIB growth and mortality), improving model coupling to allow groundwater to surf zone fluxes, and assimilating new high-resolution in situ tracer observations.

Particular infrastructure recommendations that pertain to modeling include:

1. Develop nearshore modeling testbeds based on existing and future 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 effectively evaluated and inter-compared.

2. Develop infrastructure to 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, as other parts of the geosciences have done. An example focus areas is coupling wave, swash, overland flow, and groundwater models.

3. Develop a real-time data assimilating nearshore modeling system for select regions of the US 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 & rescue, local
government officials, and sanitation districts.

Section 3c. Enabling Infrastructure: Collaboration and Communication

Addressing the three identified research themes (Section 2) will require new observational
(Section 3a) and modeling (Section 3b) infrastructure. It also will require improved collaboration
amongst the academic community, government agencies, and industries involved with
understanding, predicting, and managing the nearshore. Deriving societal benefit from this
research requires improved communication of research results to stakeholders. Improving both
collaboration and communication will strengthen the nearshore community.

Collaboration

Nearshore processes intersect the mission responsibilities of roughly twenty US federal agencies
or large federal 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 N OPP
(National Oceanographic Partnership Program) resulted in significantly improved nearshore
models and observational test beds. Recently, the European nearshore community has expanded
and gained support, 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 US nearshore research would
leverage efforts, avoid redundancy, and move the science and engineering forward rapidly.

Other components of the US 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 US science team spanning a range of oceanographic
specialties. The tightly knit US 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 inter-disciplinary 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 US nearshore community must come together and develop
meaningful collaborations.

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 still in its infancy, 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 can be made real-time enabling the ability to have smarter beach closures and improve health and local economies.

**Recommendations**

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

1. Form a Nearshore Advisory Council (NAC) with representatives from academia, government agencies, and industry. The NAC would help structure the nearshore community, foster continued community collaboration and interagency coordination, and represent the nearshore community to the public. NAC 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.

2. Develop a multiagency funded US Nearshore Research Program (NRP) based on the ideas and societal needs highlighted by the “Future of Nearshore Processes Research” Meeting, this whitepaper, and the NAC. The NRP multi-agency coordination would be under the umbrella of the US Global Change Research Program (GCRP), and would address the three broad research themes via field and modeling studies and development of new 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, and would enable effective communication of these results to attain impactful societal benefits.

**Section 4. Summary and Recommendations**

The nearshore is vital to our national economy, commerce, recreation, and military, yet it is under threat from 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 morphology changes due to natural and anthropogenic processes:**
   The research goal is to accurately simulate coastal evolution incorporating geological and anthropogenic (economic and coastal management) feedbacks. Societal benefits will include sustainable coastal development.
2. **Nearshore flooding and erosion from extreme events, 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. **Biological, chemical, and physical transport and dispersion processes that impact nearshore 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, surfzones, 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 and modeling research infrastructure. This infrastructure is needed to address all three research themes. In particular, the observational and modeling communities recommend **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 observing techniques, and
- 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 new:

- Representations and parameterizations of processes, and
- Techniques for coupling scales and processes,
- Incorporating data assimilation and uncertainty estimation

Finally, as discussed in Section 3c, the nearshore community must increase collaboration and engage more vigorously across academia, federal 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. **Create a Nearshore Advisory Council (NAC)** with representatives from academia, government agencies, and industry to help institute these recommendations. The NAC would integrate the nearshore community, increase collaboration and assist with inter-agency coordination with relevant government agencies (USACE, FEMA, NOAA, USGS, other DoD and DOI agencies, NSF) to enable needed nearshore research.

2. **Build a multi-agency funded US Nearshore Research Program (NRP)** under the umbrella of the US Global Change Research Program (USGCRP) to address the three broad research themes via field and modeling studies and development of new
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. A Scientific Steering Committee would guide detailed science planning. An example of analogous programs coordinated through US GCRP is US CLIVAR (http://www.usclivar.org/) supported by NSF, NASA, NOAA, Department of Energy (DOE).

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Section 6. References


33


Holman et al., in review. (2014). Reflections on the Sallenger Years and, a retrospective. Submitted to Shore and Beach.


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