COASTAL FORUM:

Advances in nearshore processes research: Four decades of progress

By

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ABSTRACT

The purpose of this paper is to summarize four decades of progress in nearshore research, the duration of the science career of Dr. Abby Sallenger. This paper is a retrospective foundation and jumping-off point for a companion paper that discusses the priority directions for future research as developed in a recent community meeting and from subsequent discussions. Our review starts with a short discussion of the nature of the nearshore problem, then is divided into four periods, pre-1974, 1974-1989, 1989-2000 and finally 2000-the present. Each section covers the research highlights for fluid and sedimentary processes, key facilitators of progress including instrumentation development and large experiments, and community assessments of priority unsolved problems at the end of each period.

In May 2014, a nearshore community meeting was held in Kitty Hawk, NC, to celebrate the 40-year career of our recently departed colleague, Dr. Abby Sallenger and discuss the corresponding evolution of our science. This paper represents the resulting retrospective assessment of the past and current state of nearshore science and is paired with a future-look companion paper. We begin with an outline of the state of the science 40 years ago; then describe the progress, inventions, and discoveries that have occurred in the interim, identifying key events that fostered progress; and finally detail the current strengths, weaknesses, and opportunities in our discipline in 2014.

The 2014 meeting follows similar efforts in 1989 and 1998 in St. Petersburg, FL (Holman *et al.* 1990; Thornton *et al.* 2000; referred to herein as St. Pete I and II) and builds on the foundation and framework established therein. Thus, the paper will begin with a discussion of the goals of our science, the interrelated structure of our component disciplines, and the different time scales of interest that drive our studies. We will then discuss the state of our science, discoveries, and challenges in four time periods: prior to 1974; from 1974 to the first community meeting in 1989; from then to the second community meeting in 1998; and finally from that time to the present. We will close with comments on our strengths and weaknesses. The content may appear slanted toward North American work, a reflection of the attendance of the meeting rather than a comment on non-U.S. science.

THE STRUCTURE OF THE NEARSHORE PROBLEM

The world's coastlines are regions of disproportional societal interest and value due to their importance to recreation, commerce, safety, and defense. Thus, there have been longstanding efforts to better understand and live with the natural variability and hazards associated with the coastal zone. The St. Pete I meeting (in 1989) first laid out the broad goals and structure of nearshore science, defining that the overriding goal of nearshore research is to develop a predictive understanding of the dynamics of waves and wave-driven hydrodynamics on a sloping beach, the response of an erodible bottom to those motions, and the interdisciplinary consequences of those physics.

Figure 1 illustrates the St. Pete I assessment of the main components and inter-relationships of nearshore science. Research was usually focused on fluid dynamics (upper half of the figure) or the sediment response to those motions (lower half), and important processes occur at larger scales (left) or smaller component scales (right). Large-scale fluid (LSF) processes are the result of wave energy propagating across the beach profile (large-scale topography, LST) and, in turn, causing changes in that topography through large-scale sediment processes (LSS). However, those dynamics involve important processes at smaller scales; for instance, the turbulence generated at the surface and in the bottom boundary layer and the grain-by-grain movement of sediments that leads to topographic change.

Feedbacks are a key component of these interactions. At larger scales, the beach topography that forms the bottom boundary condition for waves and currents also responds to those motions on typical time scales of 10^4 to 10^6 seconds. At smaller scales, bedforms like bottom ripples respond on time scales of 10^2 to 10^3 seconds causing changes in the bottom boundary layer and drag. The importance of these feedbacks has not long been recognized.

The relevant mix of important fluid dynamics in the nearshore depends mostly on cross-shore location and frequency (Figure 2). Energy to drive the system comes from offshore waves with a typical period of 10 s. However, as these waves propagate shoreward through first the shoaling zone and then the surf zone, fluid processes broaden the spectrum of motions to both the higher frequencies of harmonics and turbulence and to the lower frequencies of infragravity waves and currents.

NEARSHORE PROCESSES PRIOR TO 1974

In the early years, nearshore processes research was approached from two main directions. One characterized

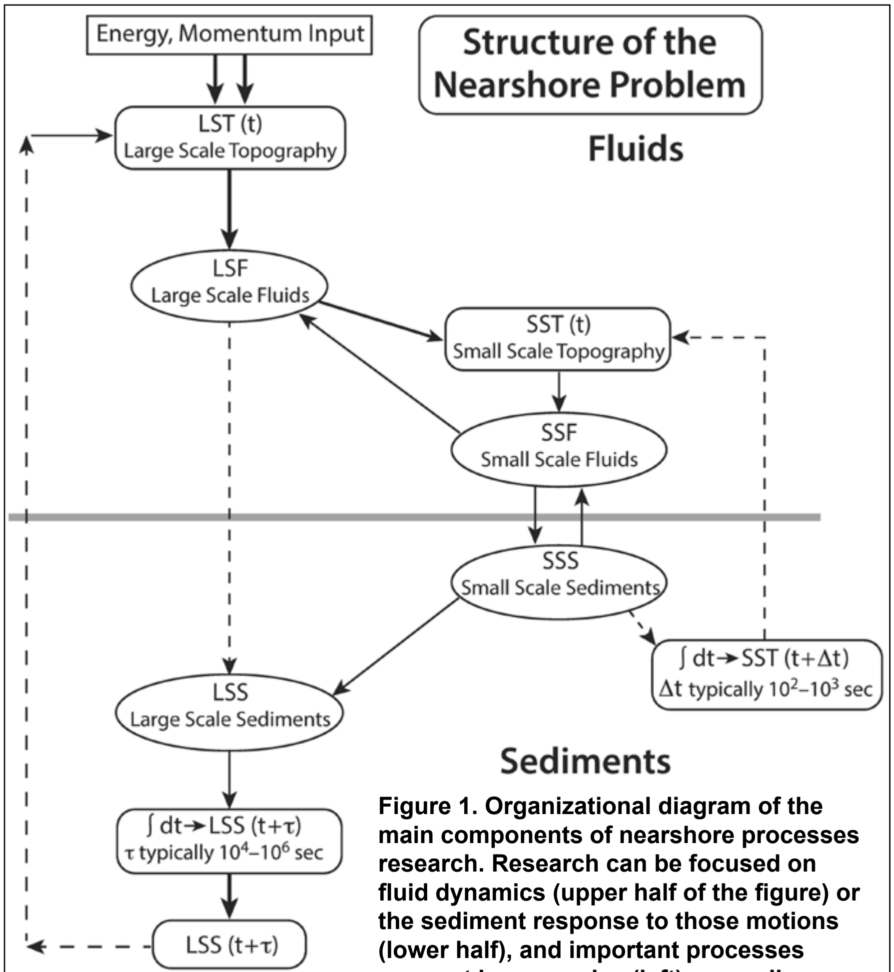

Figure 1. Organizational diagram of the main components of nearshore processes research. Research can be focused on fluid dynamics (upper half of the figure) or the sediment response to those motions (lower half), and important processes occur at larger scales (left) or smaller component scales (right). Topography at large and small scales forms the bottom boundary condition for flow, but also responds on the indicated time scales to form important feedback loops.

the morphologies and phenomena of the beaches around the world based on observational geography (Bascom 1954). The discovery of plate tectonics provided a large-scale structure to organize the variety of forms that beaches took, from steep to flat and from longshore-uniform to morphologically complex (Inman and Nordstrom 1971).

The second direction of approach was based on an engineering point of view, driven by the need to build and live safely in coastal areas, and understand and mitigate coastal hazards. Much of this work was done in wave tanks in research laboratories or else was theoretical. Since the development of computers and their use in science was in its nascent stage, analytical solutions were prized but required simplified physics and beach geometries. For example, beaches were only planar and waves were monochromatic, described by a simple period, height, and direction. The consequences of those limiting assumptions only later became apparent.

This was also well before the concept of chaos in nature was known and accepted. Thus the idea that simple systems could yield complex behavior was not yet widely known and it was assumed that good predictions required only knowledge of the component processes, and that forward, bottom-up integration of those processes was a stable process. Due to this belief in building knowledge from the bottom up, there was an emphasis on laboratory-based research where inputs could be controlled and easily measured, rather than large field-based experiments with their difficult logistics and measurement challenges. Similarly, it was hypothesized that nearshore sand bars and other morphological features were a result of independent patterns in the fluid forcing, for example that crescentic sand bars could be formed by standing edge waves (Bowen and Inman 1971) or that linear bars resulted from sediment transport convergences near the break point (Keulegan 1948).

Instrumentation prior to 1974 was primitive, particularly for field applications. Limited time series measurement capability existed with capacitance wave staff sensors and ducted impellor current meters but accuracy and logistics were well below modern standards and instruments were not sufficiently robust for other than short field deployments. Coherent array sampling was not practical and instruments to measure time series of sediment concentration or transport at small scales had not yet been invented. Beach surveys were based on lead lines or optical surveys using a diver-held stadia rod, so were rare, were limited to low-wave conditions, and had coarse spatial resolution (particularly in the longshore). The only long-term nearshore bathymetry data set was the annual Dutch Jarkus data collection begun in 1963 (for example, see Wijnberg and Terwindt 1995). Larger scale sediment transport was studied with sand tracers.

SOLVED PROBLEMS AND CHALLENGES

During the early 1970s before comprehensive field programs had begun, there was a belief that solutions found for some important nearshore problems under simplified conditions were widely representative of natural processes. For example, the shoaling of a natural wave field outside the surf zone could reasonably be modeled using monochromatic concepts of wave energy conservation, refraction and focusing (Munk and Traylor 1947) and even the nonlinear evolution could be modeled by a Stokes expansion or other approaches (Dean 1965). The forcing by incident waves of mean and low frequency flows had been formulated by Longuet-Higgins and Stewart (1964) in terms of a new concept, radiation stress. Laboratory measurements of longshore currents forced by oblique monochromatic waves could be successfully modeled using this concept so long as a discontinuity at the break point was smoothed by an ad hoc horizontal mixing term (Longuet-Higgins 1970a; Longuet-Higgins 1970b). Radiation stresses were also used to explain the set-up and set-down of mean surface elevation across the surf zone (Bowen *et al.* 1968) and the presence of rip currents due to alongshore variations of that set up (e.g. Munk and Traylor 1947; Bowen 1969).

Low frequency "infragravity" waves (periods nominally of 30-300 s) were known to exist on natural beaches (e.g. Munk 1949 and many subsequent papers) and it was known that these wave motions could theoretically be trapped by refraction as edge waves (definitive observations of this phenomenon on natural beaches were not published until the early 1980s). Edge waves were also theoretically linked to the generation of rip currents (Bowen 1969; Bowen and Inman 1969), crescentic sand bars (Bowen and Inman 1971) and beach cusps (Guza and Inman 1975) although demonstrations of the applicability of these ideas to natural beaches remained elusive.

With apparent success in the modeling of longshore currents came models for the longshore transport of sediment, a key to shoreline change. Komar and Inman (1970) and others proposed a simple relationship between longshore transport and the longshore component of wave energy flux that eventually became a standard tool for coastal engineering (the "CERC equation," Coastal Engineering Research Center 1984). This relationship could be exploited in one-line models to predict shoreline change due to gradients in longshore transport (e.g. Komar 1973).

Despite these apparent successes, much remained unknown or poorly known. Natural wave fields were recognized to be random, but the consequences of spectral width and directional spreading on nearshore mixing and low frequency motions were unknown. Similarly, it was assumed that extension from planar to non-planar, barred or even complex beach forms would hold no surprises. Our knowledge of sediment transport was primitive, particularly the cross-shore component that governs the shape of beach profiles, and we were blissfully unaware of the importance of feedback between a developing morphology (for example, a sand bar) and the wave forces that generated that form.

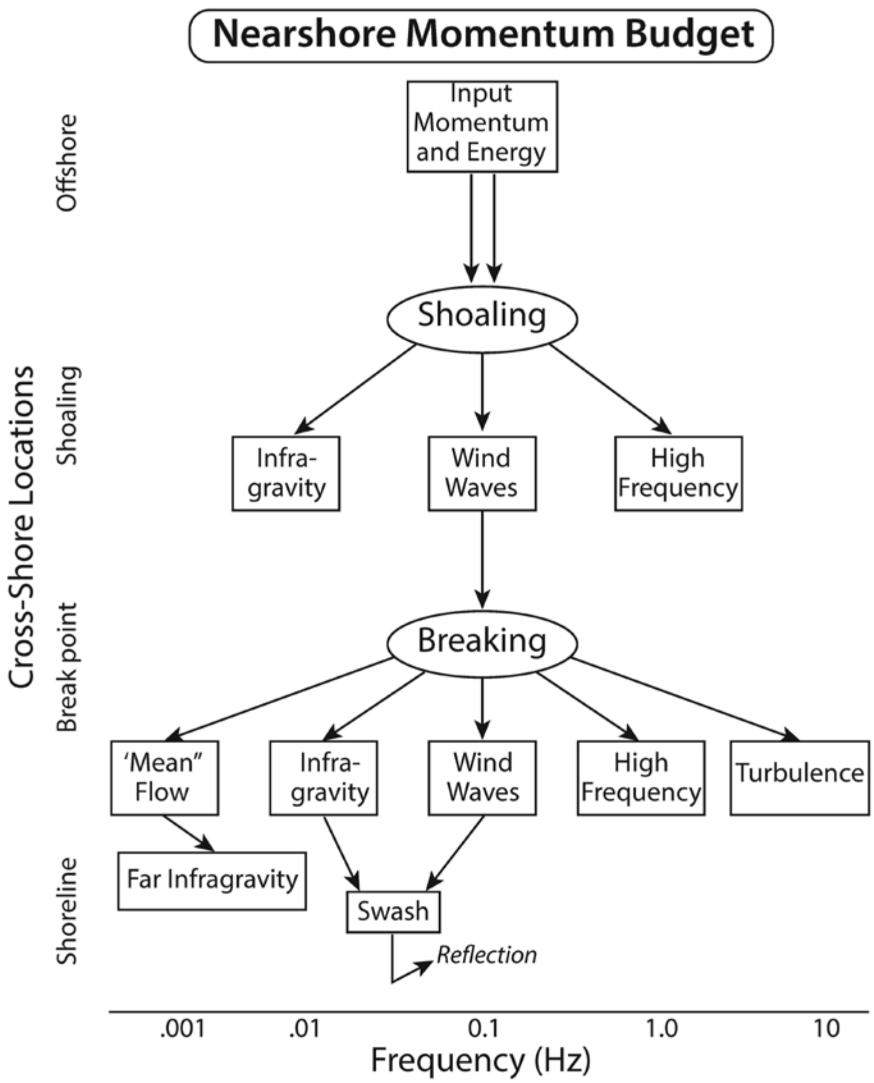

Figure 2. Important fluid dynamics processes vary as a function of cross-shore location and frequency. Energy to drive the system comes from offshore waves with a typical period of 10 s but is redistributed to higher and lower frequencies by nonlinear processes both seaward (shoaling) and within (breaking) the surf zone.

NEARSHORE PROCESSES FROM 1974-1989

The period from the 1970s through the 1980s saw a large increase in research effort and significant advances in our understanding of wave processes on natural beaches. Large field experiments became achievable and played a pivotal role in this progress. The earliest was the Nearshore Sediment Transport Study (NSTS) carried out on monotonic beaches at Torrey Pines in 1978 and Santa Barbara's Leadbetter Beach in 1980. The 1977 construction by the U.S. Army Corps of Engineers of the Field Research Facility (FRF) at Duck, North Carolina, offered a purpose-built home to a series of experiments on a non-monotonic (sand bars always present) beach. Major experiments took place in 1982 (Duck82), 1985 (Duck85) and 1986 (SuperDuck). The productivity of these experiments resulted from the careful deployment of large, coherent cross-shore and alongshore arrays of hydrodynamic and sediment sensors that spanned the surf zone and allowed phase-resolved maps of the important dynamics, the long multi-storm durations of the experiments, and the frequent and accurate measurement of bathymetry. Experimental teams were large, multi-institutional and interdisciplinary, and the work was supported by extensive funding from supportive agencies, particularly the Office of Naval Research.

The primary goal of NSTS was to develop an improved understanding of

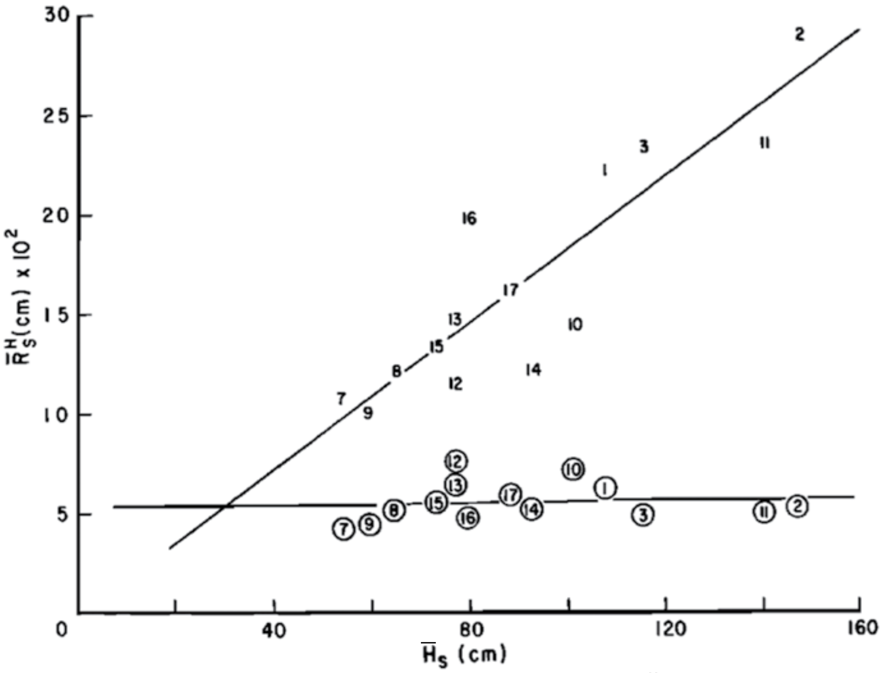

Figure 3. Dependence of horizontal swash excursion, R^H_s, on offshore significant wave height, $\bar{H}_s$. The incident band component of swash (circled) is saturated at a small value, so contains no information about changing offshore conditions like storms. On the other hand, the infragravity component (un-circled) increases with offshore wave height and is the principal shoreline manifestation of offshore storms (from Guza and Thornton 1982).

longshore sediment transport driven by waves and currents on natural beaches and the corresponding bathymetric and shoreline changes. However, the legacy of NSTS lies in a series of seminal publications on the dynamics of shoaling random waves on a monotonic beach. It was shown that local relationships between wave pressures, velocities, and sea surface elevation both outside and inside the surf zone could be accurately described with linear wave theory despite the wave forms being obviously nonlinear and even breaking (Guza 1980). Field measurements showed that wave phase speeds were well described by linear theory if first-order amplitude dispersion was included (Thornton and Guza 1982), a result that had previously been shown only in the lab. The success of linear theory in modeling local kinematics did not extend to understanding the spatial evolution of shoaling waves, discussed below.

Field data also clearly supported an early laboratory concept by Miche (1951) that incident swash magnitudes saturate at small values on a flat beach so could not be the cause of shoreline erosion during storms (Figure 3). In contrast, field measurements showed that infragravity waves forced by wave groups in a random wave field are unsaturated, growing roughly linearly with offshore wave height (Figure 3, Guza and Thornton 1982). In this way, infragravity waves, not previously incorporated in numerical models or laboratory tests that considered only monochromatic incident waves, were found to be an important component of nearshore physics and storm response.

This period saw the introduction of refraction-diffraction incident wave models for intermediate water depths based on the mild-slope equation (Berkhoff 1972) with parabolic approximations (Kirby 1986) including testing with NSTS data over complicated shelf and inner shelf bathymetries (Pawka *et al.* 1984). Boussinesq-type equations that included effects from a sloping bottom formed the basis for numerical shoaling models right up to the point of wave breaking, but only considered regular unidirectional waves (Peregrine 1967). This was expanded by Freilich and Guza (1984) to model the nonlinear shoaling evolution of all components in the incident band, with testing against field observations obtained from NSTS and additional experiments. The successful quantification of nonlinear interactions and the prediction of the evolution of higher moments (i.e. skewness and kurtosis) of the shoaling wave field (Elgar and Guza 1985; Freilich *et al.* 1990) was recognized as important to models of nearshore sediment transport

The extension of models in order to represent the full wave spectrum also required a new representation of breaking wave dissipation. Battjes and Janssen (1978) suggested a probabilistic approach such that the breaking of waves of varying wave heights were distributed across different depths rather than the single, repeatable break point of monochromatic waves. This concept was confirmed with NSTS field data by Thornton and Guza (1983), who modeled the distribution of breaking in terms of an empirically modified Rayleigh distribution, an approach that became the first operational model for wave transformation used by the U.S. Navy (the so-called Navy Standard Surf Model). A further consequence of this spatial spreading of the onset of wave breaking was that longshore currents driven by the breaking of oblique random waves were predicted to occur with a smooth offshore profile (Thornton and Guza 1986) without the unphysical levels of smoothing that had previously been required for monochromatic models with their single, static break point.

This period of time also saw considerable research on the nature of longer period (order minute) infragravity waves that can dominate dissipative surf zones. The introduction of large longshore arrays of current meters (Oltman-Shay and Guza 1987) allowed the discovery that infragravity waves on the near-planar California beaches were largely composed of a mix of discrete, low-mode edge waves and a continuum of leaky waves. This, in turn, led to renewed interest in theories for the generation of rhythmic sand bar morphology due to these longshore-periodic motions (e.g. Holman and Bowen 1982).

The shift to the barred (non-monotonic) profiles of Duck, NC, led to new discoveries. The role of wave rollers, first proposed by Svendsen (1984), in delaying the transfer of momentum from incident waves to forced currents became apparent over the sand bars of Duck, as longshore current peaks were shifted landward into the trough. Observations from a longshore array of current meters during SuperDuck, intended to study the

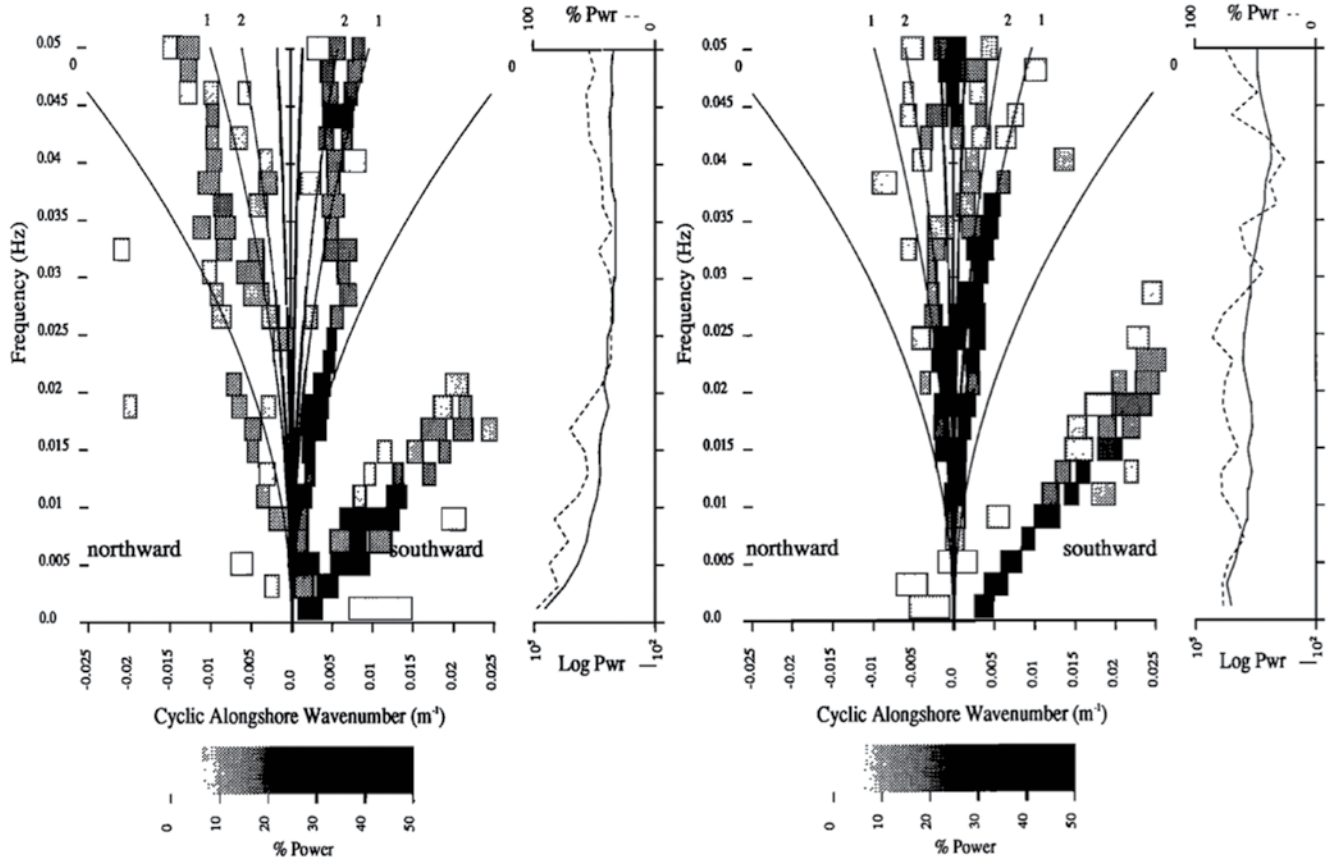

Figure 4. Frequency-wavenumber spectra from the SuperDuck field experiment showing the distribution of longshore (left) and cross-shore (right) current variance over infragravity frequencies. Curved lines indicate theoretical edge wave dispersion curves (mode numbers marked at end of lines) with longshore current energy clustering along those lines (left). Linear oblique lines sloping up to the right on both panels correspond to the newly discovered phenomenon of shear waves (from Oltman-Shay *et al.* 1989)

influence of a sand bar on edge wave dynamics (and possible feedbacks including bar generation), revealed a new class of low-frequency wave motions with periods of order 100 s and wavelengths too short to be infragravity waves (Figure 4, Oltman-Shay *et al.* 1989). These strong oscillations were shown to be instabilities of the longshore current associated with the seaward shear of the longshore current profile (thus, they were termed shear waves and the lower frequencies were called Far Infragravity Waves; Bowen and Holman 1989).

In contrast to progress in nearshore hydrodynamics, the understanding of nearshore sediment transport lagged substantially. By this time, the well-known CERC formula (Coastal Engineering Research Center 1984) was a standard tool in coastal engineering for modeling longshore transport. However, no good model of wave-driven cross-shore sediment transport existed until Bowen (1980) adapted the unidirectional flow model of Bagnold (1966) to the oscillatory flow conditions of the nearshore, showing that the predicted concave characteristics of beach profiles were consistent with observations and motivating further research into the evolution of wave skewness and asymmetry of nonlinear shoaling wave fields. Independently, Bailard (1981) used a similar approach to develop a numerical model for beach profile evolution that could predict total load (suspended and bedload) transport if observations of wave velocities were obtained. This approach later led to the development of models for two-dimensional beach profile evolution (Roelvink and Stive 1989; Thornton *et al.* 1996).

The term nearshore morphodynamics was introduced during this period (Wright and Thom 1977) and referred to the larger scale interactions and relationships between nearshore fluid motions and morphology like sand bars and rip channels. This work was pioneered mostly by Wright and Short in a series of papers (e.g. Wright and Short 1984, Figure 5) that organized the previous disparate observations on sand bar dynamics into a series of morphological states that followed successions determined by bulk features of wave forcing. In contrast to bottom-up sediment transport based predictions, their model was based heavily on long-term behavioral observations of a number of Australian beaches. This work marked the beginning of a new approach to morphological forecasting.

INSTRUMENTATION AND RESULTING CHANGES IN UNDERSTANDING

Improvements in instrumentation played a large role in science during this period of time. The impact of new robust surf zone instruments such as electromagnetic, bi-directional current meters and pressure sensors, all deployed in coherent arrays, was evident in the previous discussions of the NSTS and Duck field experiments. At Duck, the presence of the CRAB (Coastal Research Amphibious Buggy; Birkemeier and Mason 1984, Figure 6) was critical to experimental success, allowing frequent measurement of changing bathymetry during intensive field experiments and providing a stable platform for instrument deployments. For

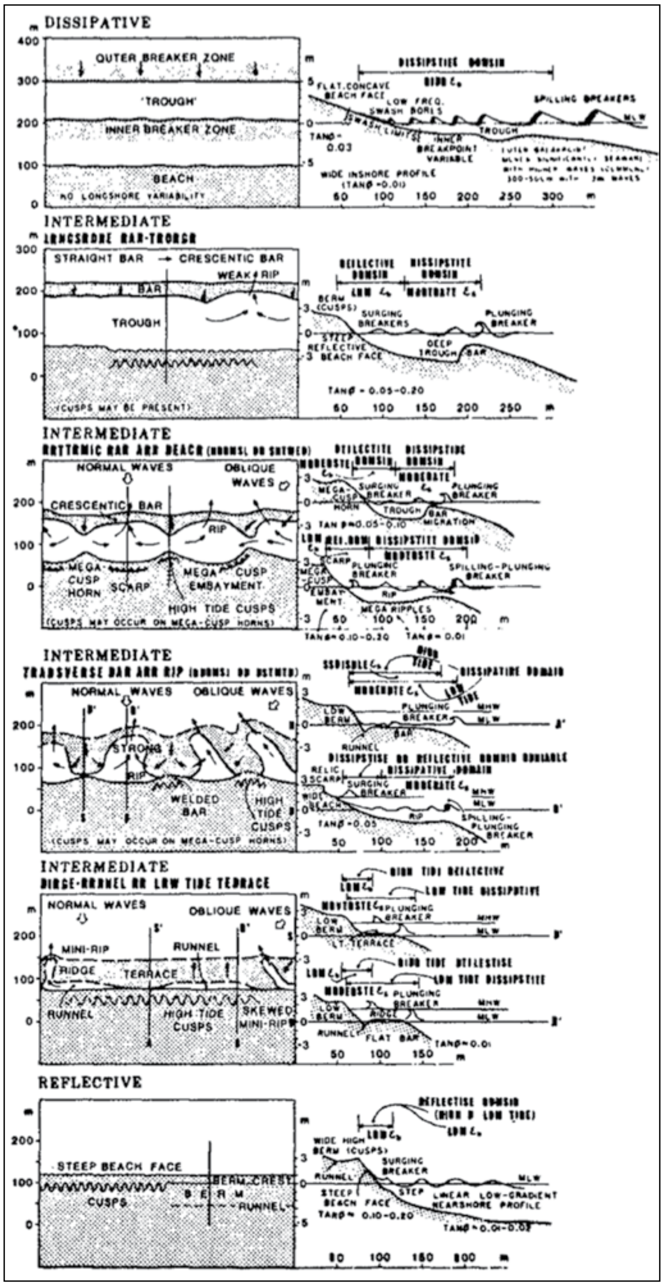

Figure 5. Six morphological states proposed by Wright and Short (1984) to characterize the sequences of beach response to changing offshore wave conditions. The left panel shows the planform and the right the profile views.

example, survey results from the 1982 experiment showed for the first time that large changes to nearshore sand bars could occur rapidly under both storm and subsequent recovery waves (Sallenger *et al.* 1985), and that significantly larger arrays of instruments would be needed to quantify the behavior. The CRAB was also used to conduct monthly surveys that captured long-term bathymetric change from the inception of sampling in 1981 to the present day, one of only two such long-term data sets in the world. The standard suite of observations collected at the FRF was enhanced in 1986 with the deployment of a long-term linear array of bottom-mounted pressure sensors deployed in 8 m water depth (Long and Oltman-Shay 1991) that allowed decades of measurement of incident wave directional spectra with unprecedented fidelity for input into wave models.

This period also marked the introduction of video image processing methodologies and time-exposure imagery (Lippmann and Holman 1989) as a low-cost way of measuring evolving sand bar morphologies daily (and soon hourly) over long periods of time (now 28 years at Duck). Video observations revealed an unexpected range of complexity of sand bar morphologies. For example, daily video-based observations between 1986 and 1988, revealed new insight into the cyclic behavior of nearshore sand bars (Figure 7; Lippmann and Holman 1990) that expanded on the earlier sequential models developed in the late 1970s and early 1980s (e.g. Wright and Short 1984).

Several instruments were also introduced to allow measurements of small-scale fluid and sediment transport processes. Optical backscatter sensors (Downing *et al.* 1981) and acoustic sensors (Hanes and Vincent 1987) provided new capability for measuring sediment response at sampling rates of several Hz. Coupling with time series of oscillatory flow velocities through co-spectral calculations allowed a decomposition of transport among frequencies and mean flows (Hanes *et al.* 1988), and enhanced studies of the roles of skewness and asymmetry to transport patterns (Doering and Bowen 1988). Because these instruments were small and robust, they could survive high-energy wave conditions and measurements showed that sediment transport during storms was largely a result of energetic infragravity motions near the shoreline (Beach and Sternberg 1988)

Despite these (and other) advancements, many processes remained poorly understood and under-sampled. In 1989, under the leadership of Rob Holman and Abby Sallenger, nearshore scientists and engineers convened the first St. Pete community meeting (St. Pete I) to discuss the state of nearshore processes research (Holman *et al.* 1990). After three days of discussion, the group agreed on five priority research areas: infragravity band dynamics, swash processes, the dynamics of breaking waves, bottom boundary layer processes and the dynamics of small scale sediment transport. This report helped drive a new series of focused, community-wide nearshore processes field experiments held at the FRF in the 1990s.

NEARSHORE PROCESSES DURING THE 1990s

With the topics and challenges identified during St. Pete I, researchers entered the 1990s with a vision focused on detailed understanding of how hydrodynamics interact with the seafloor, resulting in sediment transport and ultimately morphological change (Figure 1). There was strong optimism that the nearshore momentum budget (Figure 2) could be fully described through deterministic modeling approaches matched with rapidly maturing observational field tech-

Figure 6. The FRF CRAB can drive offshore to 8 m depths for survey or instrument servicing purposes.

niques. The vision of St. Pete I motivated continuing the series of experiments at Duck to eventually include Samson and Delilah (1990), Duck94 (1994), SandyDuck (1997) and Showex (1999).

Progress during this era included careful field tests of the alongshore momentum balances at large and intermediate scales (Feddersen *et al.* 1998; Lentz *et al.* 1999) and of the wave transformation from the continental shelf, through the surf and into the swash zones (Holland *et al.* 1995; Raubenheimer *et al.* 1996). Models were able to predict directional spreading of nearshore waves (Herbers *et al.* 1999) and 2DH simulations of wave refraction and dissipation (Booij *et al.* 1999). Comparison with field experiments allowed improvements in advanced, wave-resolving Boussinesq modeling approaches to nearshore hydrodynamic processes (Madsen *et al.* 1997). Higher-order analysis methods such as bispectra (and even trispectra) were developed to understand the nonlinear transfer of energy to infragravity waves and within the incident frequency bands (Herbers *et al.* 1995).

This period also saw work on the newly-discovered shear wave phenomena resulting from instabilities in the longshore current. An initial, simplified analysis of Bowen and Holman (1989) for shear waves on a flat-bottomed profile was extended to more realistic profiles and compared favorably to observations (Dodd *et al.* 1992). Model instabilities were also allowed to grow to finite amplitude and shear waves were found to be an important source of nearshore eddies, depending on the relative strength of bottom friction (Figure 8, Slinn *et al.* 1998; Ozkan-Haller and Kirby 1999). Additional findings from the SuperDuck and Delilah field efforts included studies of the partitioning of variance between the incident, infragravity and shear wave bands (Howd *et al.* 1991; Lippmann *et al.* 1999).

Significant advances in modeling profile evolution included successful predictions of the seaward migration of the sand bar using Bowen/Bailard energetics-based sediment transport models (e.g. Gallagher *et al.* 1998a), and of onshore sand bar migration by skewed short wave fluid accelerations (Elgar *et al.* 2001). Near the shoreline, swash zone sediment suspension events were attributed to turbulence generated by incoming bores (Puleo *et al.* 2000). Progress was also made at bedform scales within the inner surf zone at scales ranging from wave orbital ripples to mega-ripples (Hay and Bowen 1993; Gallagher *et al.* 1998b). However, the long-term goal of coupling sediment transport predictions to the morphologic evolution ranging from bedform scales to sand bars remained unmet.

This period also marked the introduction of concepts of nonlinear dynamical systems to nearshore processes, and particularly the potential for morphological self-organization due to feedbacks between wave forcing and bathymetric response. This was in sharp contrast to previous thinking that larger scale bathymetric change could be predicted by integration of smaller scale fluid and sediment transport processes. Now morphology was found to grow from small perturbations even in the presence of smooth hydrodynamic forcing. This idea was explored in cellular automata models that represented processes and feedbacks in very simplified abstractions to yield, for example, the growth of sand ripples under wind or waves (Anderson 1990) or the growth of beach cusps by swash on an initially planar beach (Werner and Fink 1993).

The presence of feedbacks and self-organization forced a change in approach for long-term coastal prediction away from bottom-up integration. The Dutch introduced the concept of Large Scale Coastal Behavior (LSCB) in the 1990s to describe the coastal dynamics that are important for predictions at time scales of decades and length scales of tens of

Figure 7. Optical time-exposure images from Duck, NC, showing the range of morphologies observed over time at one site. These morphological classes could be loosely related to wave forcing (from Lippmann and Holman [1990]).

kilometers (Terwindt and Battjes 1991). In contrast to the strong annual cycle of winter-summer variations in wave forcing, it was realized that sand bars showed marked inter-annual variability including slow offshore progression over multiple years (Wijnberg and Terwindt 1995). These observations reignited interest in simple, heuristic models for annual and inter-annual sandbar variability that merged behavioral, wave-height-dependent physics with extractions of simplified sediment transport (e.g. Plant *et al.* 1999). None of these proposed solutions were comprehensive enough to produce reliable forecasts on beaches apart from where they were developed. However, as would become clear in later decades, the movement from deterministic to statistical modeling approaches had begun.

INSTRUMENTATION AND RELATED CHANGES IN MODELING CONCEPTS

This period saw the development of new instrumentation that changed the way nearshore research was done and thought about. A key component was the development of GPS sensors with centimeter accuracies that could be mounted on all-terrain vehicles or personal watercraft with fathometers to greatly improve topographic and bathymetric survey capabilities (Dugan *et al.* 2001). Additionally, the late 1990s saw the first attempts at mounting GPS sensors on an airplane equipped with a downward looking Lidar, a tool originally used to map the moon but now applied to rapid overflight surveys of large coastal regions (Irish and Lillycrop 1999).

New remote sensing technologies started to see frequent use in the nearshore during this time. The best known was the Argus program of video instrumentation (Holman *et al.* 1993) that allowed long-term measurements of changing nearshore sand bar morphology (Figure 7, Lippmann and Holman 1990) and shoreline (Plant and Holman 1997) evolution. These observations clearly showed a number of behavioral states for the intertidal beach and nearshore sand bar system that were often responsive to large wave events but were still only loosely correlated with the most obvious hydrodynamic parameters (Lippmann *et al.* 1993).

Significant improvements in instrumentation allowed fine scale fluid and sediment processes to be observed in the field for the first time. Although the importance of wave breaking was known, methodologies to observe turbulence in the surf zone were lacking. George *et al.* (1994) and Foster *et al.* (2000) used hot film anemometers to measure turbulent intensities and dissipation under breaking waves within the surf zone and within the bottom boundary layer. In conjunction with newly developed fiber-optic backscatter sensors (Beach *et al.* 1992) these technologies allowed observation of coincident changes to bed elevation at sub-centimeter scale resolution. Profiling laser-Doppler velocimeters (Trowbridge and Agrawal 1995) and acoustic-Doppler current profilers (Stanton and Thornton 1996) were developed to measure turbulence and Reynolds's stresses and examine fine scale sediment transport close to the seabed to provide "glimpses" of the wave bottom boundary layer. Fixed frame sonar altimeters were developed that measured changing bottom locations, allowing local tracking of sand bar crest locations (Gallagher *et al.* 1998a), as well as vertical profiles of suspended sediment concentration above the bed (Hay and Sheng 1992). Continuous recordings from rotary sidescan sonars allowed new documentation of the dynamics of ripples, cross-ripples, and megaripple evolution during a storm (e.g. Figure 9; Hay and Wilson 1994).

While these detailed fluid and sediment sampling technologies did not directly support the modeling of foreshore erosion, beach profile evolution or related morphodynamics as originally hoped, there was substantive progress relating bed shear stress coefficients to bottom roughness (Faria *et al.* 1998), recognition of the importance of wave pressure gradients in the near-bed sediment transport (Sleath 1999), the potential for ventilation in the wave boundary layer (Conley and Inman 1992), and simulation of granular interactions during sheet flow conditions of bedload transport (Drake and Calantoni 2001).

CHALLENGES

A second community nearshore research workshop (St. Pete II) at the end of this decade expanded on the St. Pete I list of priority research issues to include fluid-sediment processes in the swash zone, the relationship of breaking waves, bottom boundary layers and associated turbulence, breaking-wave-induced currents, nearshore sediment transport, and morphologic evolution. General agreement was found in the need for testing nearshore numerical models with observations from field experiments over complex bathymetry to improve predictive capabilities, and reveal model deficiencies and unexpected phenomena that could be subsequently included in models.

Specific challenges would have to be overcome. There was a justified need for a community-based response to sea level rise, extreme storm events and the associated coastal hazards that would accompany them, a challenge that would be addressed by Dr. Abby Sallenger through a number of studies that would define the relationships between sea level rise and coastal erosion, extending on his earlier work on the Louisiana barrier islands (List *et al.* 1997).

NEARSHORE SCIENCE IN THE 2000s

Research progress from the prior decades meant that in the 2000s improved numerical models could be used for operational forecasting in support of beach safety, national defense, and weather prediction. In the nearshore, spectral wave models spanning large domains and natural (but fixed) bathymetries became routine and were capable of including the effects of wind, wave dissipation, nonlinear interactions and coastal structures (e.g. Booij *et al.* 1999; Allard *et al.* 2014).

Modeling approaches to solve the complete nearshore problem on the short to mid-range time scales consisted of coupling spectral wave models with nearshore flow models (Delft3D, NearComm, and XBeach are examples that are in widespread use). These models showed some success at simulating nearshore sediment transport at these time scales (e.g. Lesser *et al.* 2004); however, longer simulations or forecasts of coastal change were still not possible. Nevertheless, the earlier success of the simpler bulk alongshore transport formulations was exploited to provide new insights into large-scale and long-term coastal behavior (e.g. Ashton *et al.* 2001).

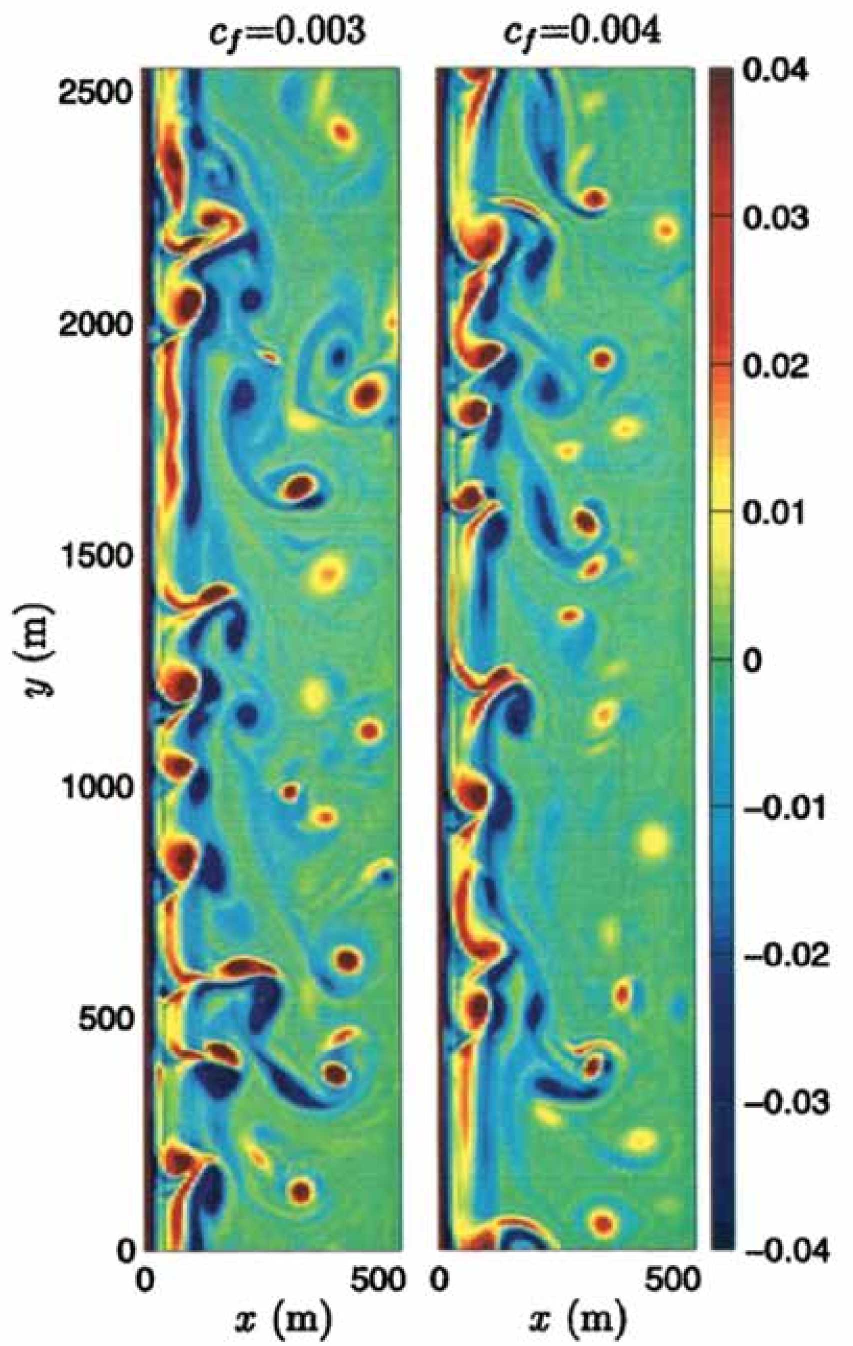

Figure 8. Images of modeled vorticity on a Duck-like bathymetry for two different friction coefficients, c_f. The development of eddies due to shear instabilities was determined to be an important part of nearshore mixing (Ozkan-Haller and Kirby 1999).

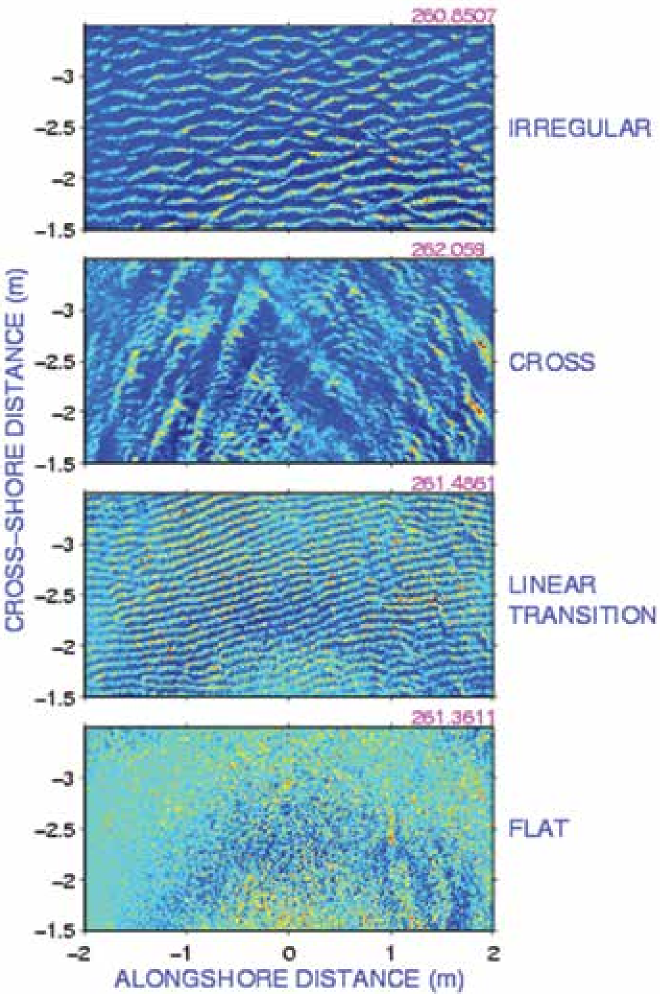

Figure 9. Example sector-scan sonar images of bottom ripples and megaripples. This new tool greatly advanced our awareness and understanding of bottom bedform dynamics (from Hay, pers. comm.).

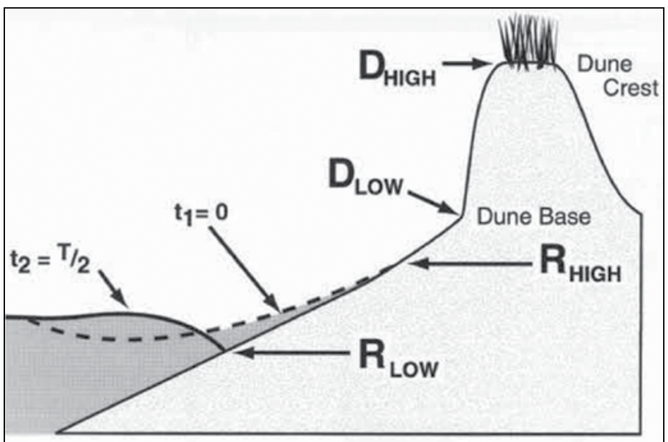

Figure 10. Framework for the USGS coastal hazards National Assessment program. Significant erosion will occur if the total highest water level, Rhigh, exceeds the level of the base of the dune, Dlow, (dune erosion), or the level of the top of the dune, Dhigh (inundation and flooding). These levels have been assessed nationally by an extensive LiDAR program. (From Sallenger 2000).

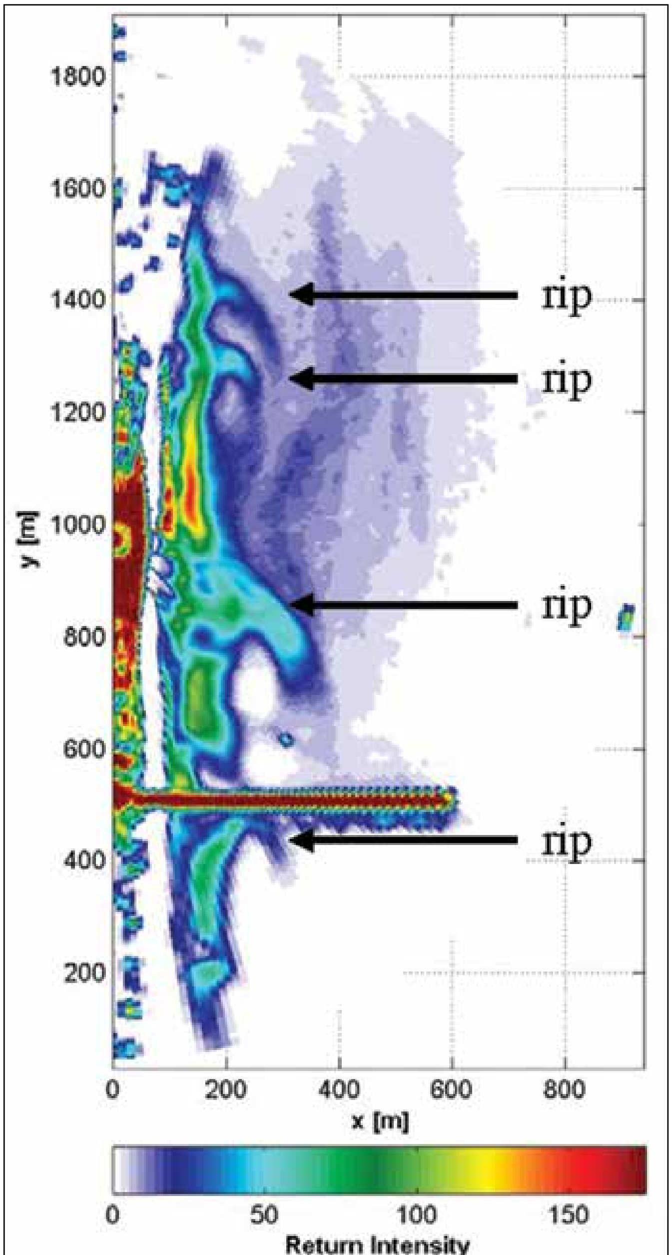

Figure 11. Time exposure image from a marine radar at Duck, NC. Breaking over the sand bar is shown by the brighter colors (higher returns) around x = 175 m while the red horizontal line at y = 515 is the FRF research pier. The blue-green protrusions marked as "rips" are due to enhanced radar backscatter from rip currents. (From Haller *et al*. (2014)).

Boussinesq wave models of this era enabled simulations of phase-resolved nonlinear shallow water waves and wave-driven currents on natural profiles, incorporating more realistic spectral wave input, wave breaking dissipation, and swash zone boundary conditions. Applications were extended into intermediate water depths but with correspondingly high computational costs (Chen *et al.* 2000; Lynett 2006). High speed processors allowed the expansion of modeling capability to include fully-coupled wave-current interactions (Yu and Slinn 2003; Lane *et al.* 2007), wave group forcing (Reniers *et al.* 2004; Long and Ozkan-Haller 2009) and swash zone dynamics (Brocchini 2006). Our knowledge of the nearshore momentum balance matured to the point where long-term hindcasts of longshore currents on field beaches were possible as long as the conditions are reasonably alongshore uniform (e.g. Ruessink *et al.* 2001).

Rip currents became a heavy focus of field and lab experiments (Haller *et al.* 2002; Reniers *et al.* 2010) and investigators sought to explain their unsteady behavior on open coast beaches (Dalrymple *et al.* 2011). The role of wave group forcing and instabilities in unsteady rip flows was examined and modeled successfully (Haller and Dalrymple 2001; Reniers *et al.* 2010).

Earlier work on waves in the infragravity band had demonstrated their ubiquity and their importance in erosive processes during storms when this frequency band is the most energetic. However, there was still significant uncertainty regarding their generation and the dynamics of their dissipation and two-way energy transfers (e.g. Baldock and Huntley [2002], VanDongeren *et al*. [2003] and others).

Societal relevance developed a higher priority during the 2000s under the increased pressure of climate change including sea level rise (Bindoff *et al.* 2007) and increasing storminess (Ruggiero *et al.* 2010; Young *et al.* 2011). The USGS, under direction from Dr. Abby Sallenger, developed a National Assessment program that formulated operational threats to coasts and their corresponding vulnerabilities. By the time of writing, this program had developed operational, science-driven procedures for characterizing expected threats posed by extreme storms and the expected resilience of U.S. east and gulf coasts to those threats (Figure 10, Sallenger 2000). It was recognized that uncertainty permeated the components of these predictions from hurricane track to the timing of landfall (relative to high tide) so, for the first time, Bayesian probabilistic methods were applied to nearshore predictions (Plant and Holland 2011).

INSTRUMENTATION AND RESULTING NEW UNDERSTANDING

Nearshore remote sensing became more quantitative during the 2000s and a more important tool in nearshore observing (Holman and Haller 2012). Optical remote sensing became ubiquitous with the advent of inexpensive high-resolution cameras and sophisticated algorithms to estimate relevant geophysical variables (Holman and Stanley 2007). The use of marine radar also increased and was shown to provide complementary sampling capabilities in terms of resolution, range, and footprint (Holman and Haller 2012). Multispectral and hyperspectral sensors also saw increased application in the nearshore (Clark *et al.* 2014). Remote sensing retrieval algorithms concentrated on nearshore parameters related to waves (Izquierdo and Guedes-Soares 2005), currents (Chickadel *et al.* 2003), and bathymetry (Holman *et al.* 2013).

Remote sensing, in combination with in situ measurements, had also been shown to provide a clearer, more synoptic picture of flow events and nearshore exchange, for example, with the imaging of rip currents (Figure 11, Haller *et al.* 2014) and nearshore dye dispersion (Clark *et al.* 2014). In addition, the use of mobile in situ platforms increased, for example with the addition of instrumentation to jet skis (e.g. fluorometers, Hally-Rosendahl *et al.* 2014) or the advent of GPS-equipped drifters (Schmidt *et al.* 2003; Thomson 2012), which provide Lagrangian current measurements and allowed the estimation of diffusivity coefficients, horizontal mixing length scales and eddy statistics for the surf zone (Spydell *et al.* 2007; Brown *et al.* 2009).

Electro-magnetic (EM) current meters, commonly used in nearshore field studies prior to 2000, were largely replaced with high resolution, rapidly sampling acoustic Doppler velocimeters (ADV). Although they did not suffer from drift or biofouling issues (as previous EMs did), issues with bubbles had to be overcome. A wide variety of ADVs were manufactured commercially and affordable to the nearshore scientific community, allowing detailed measurements of turbulence and high frequency flow fields near the seabed and within the thin tongue of the swash. Profiling acoustic sensors (ADCPs) were adapted from offshore application to shallow water and the surf zone, and were used to better observe the vertical structure of mean and oscillatory flow fields

REMAINING CHALLENGES

Long-term forecasting of coastal change has always been one of the most difficult challenges in nearshore science and the need for such predictions has only become greater with the onset of climate change. Understanding the nearshore response to climate change and sea level rise will require new statistical approaches to long-term data sets. Recent approaches are allowing the assessment of future coastal flooding risk and the extreme value wave climate for the design of coastal structures (Mendez *et al.* 2006). Translating changes in wave climate and storm intensity into predictions of large scale coastal change again raises issues of the importance of self-organizing behavior versus deterministic forcing and response (Murray and Ashton 2013). It remains to be seen whether large-scale and long-term coastal change will ever be successfully modeled by our high-resolution, nearshore models with comprehensive, deterministic physics, or whether hybrid statistical models must be incorporated.

The traditional surf zone focus of nearshore research is now expanding in both the landward and seaward directions, for example, trying to understand overland flow and sediment exchange between the intertidal zone and the backshore. The inner shelf now appears to be the least understood subaqueous region of the nearshore and an important arbiter of exchange between the shelf-scale dynamics and the surf zone. The inner shelf contains the region where the surface and bottom boundary layers can overlap but is outside the highly energetic surf zone. Thus the momentum balance is governed by the summation of small terms (Lentz and Fewings 2012) that can have significant vertical variability. The analysis of these dynamics has been enabled by the development of the new vortex force formalism (McWilliams *et al.* 2004). The methodology has been pursued in both Eulerian (Newberger and Allen 2007) and Lagrangian frames (Ardhuin *et al.* 2008) and enables the direct separation of the depth-varying forcing due to organized wave motion from the forcing due to wave breaking, a separation that was not possible with traditional radiation stress based approaches. In the Eulerian frame, the vortex force formalism offers an important new capability for including vertically-varying wave forcing across both the inner shelf and surf zone domains (Kumar *et al.* 2012) and to investigate exchange processes between these previously un-coupled domains.

Finally, data assimilation, already a standard tool in weather applications, is now beginning to be applied to the nearshore (Feddersen *et al.* 2004; Kurapov *et al.* 2007). Similar to weather applications, the technique is being enabled by recent advances in nearshore remote sensing (Dongeren *et al*. 2008). New nearshore data assimilation systems can now ingest a wide range of synoptic data sources (Veeramony *et al.* 2010; Wilson *et al.* 2014), reducing the dependency of our comprehensive, deterministic model systems on the inherently uncertain initial and boundary conditions. They can now be used to infer bathymetry (Wilson *et al.* 2010) or poorly constrained model parameters such as bottom friction and to refine observational programs to maximize their value.

SUMMARY

Progress in any research discipline often seems slow and incremental with very few leaps. However, when viewed over the 40-year span of one person's career, the cumulative changes are quite remarkable. Forty years ago, nearshore science allowed only simplistic modeling capability and was unaware of the existence or richness of nonlinear feedbacks and phenomena in both the fluid and the fluid-sediment domains. Today, sophisticated numerical models can realistically represent the physics of complex processes on arbitrary, evolving domains.

Progress has depended on several facilitating factors. Large field experiments have led to discovery but also to the collection of data sets that serve the research needs of a wide international community and allow extensive testing of our knowledge of physics against observation. Investments in new instrumentation have changed the way we do science and have opened doors to new observing capabilities. Some new instruments have been the result of long development like the use of acoustics to study bedforms and boundary layers while others have come from the innovative application of new technologies such as GPS. The growth of computing power has been a huge enabler.

Future progress is increasingly motivated by the combination of environmental hazards like sea level rise and increasing storminess, and the increasing vulnerability of the growing population and infrastructure that hug the coast. We must be prepared to apply our science through operational observing systems that couple powerful models with innovative data collection approaches. And we need to embrace uncertainty in predictions.

In summary, the future looks both promising and exciting.

REFERENCES

Allard, R., E. Rogers, P. Martin, T. Jensen, P. Chu, T. Campbell, J. Dykes, T. Smith, J. Choi, and U. Gravois 2014. "The US Navy coupled ocean-wave prediction system." *Oceanography* 27(3), 92-103.

Anderson, R.S., 1990. "Eolian ripples as examples of self-organization in geomorphological systems." *Earth-Science Reviews* 29(1-4), 77-96.

Ardhuin, F., N. Rascle, and K.A. Belibassakis 2008. "Explicit wave-averaged primitive equations using a generalized Lagrangian mean." *Ocean Modelling* 20, 35-60.

Ashton, A., A.B. Murray, and O. Arnault 2001. "Formation of coastline features by large-scale instabilities induced by high-angle waves." *Nature*, 414(6861) 296-300, doi: 10.1038/35104541

Bagnold, R.A., 1966. "An approach to the sediment transport problem from general physics." 1-37.

Bailard, J. A., and D. L. Inman 1981. "An energetics bedload transport model for a plane sloping beach: Local transport." *J. Geophysical Res.*, 86 2035.

Baldock, T.E., and D.A. Huntley 2002. "Long wave forcing by the random breaking of gravity water waves." *Proc. of the Royal Society of London A*, 458 2177-2201.

Bascom, W., 1954. *Waves and beaches*. Anchor Books, Garden City, N.Y.

Battjes, J.A., and J.P.F.M. Janssen 1978. "Energy loss and set-up due to breaking of random waves." In *Proc. 16th Conf. Coastal Eng.*, edited, 569-587.

Beach, R.A., and R.W. Sternberg 1988. "Suspended sediment transport in the surf zone: Response to cross-shore infragravity motion." *Marine Geology*, 80, 61-79.

Beach, R.A., R.W. Sternberg, and R. Johnson 1992. "A fiber optic sensor for monitoring suspended sediment." *Marine Geology*, 103, 513-520.

Berkhoff, J.C.W., 1972. "Computation of combined refraction-diffraction." Paper presented at 13th International Conf. Coastal Eng., ASCE.

Bindoff, N.L., *et al.* 2007. *Oceanic climate change and sea level*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Birkemeier, W.A., and C. Mason 1984. "The CRAB: A unique nearshore surveying vehicle." *J. Survey Engineering*, 110, 1-7.

Booij, N., R.C. Ris, and L.H. Holthuijsen 1999. "A third-generation wave model for coastal regions. 1. Model description and validation." *J. Geophysical Res.*, 104(C4), 7649-7666.

Bowen, A.J., 1969. "Rip currents, 1. Theoretical investigations." *J. Geophysical Res.*, 74(23), 5467-5478.

Bowen, A.J., 1980. "Simple models of nearshore sedimentation; beach profiles and longshore bars." In *The Coastline of Canada*, edited by S. B. McCann, 1-11, Geological Survey of Canada.

Bowen, A.J., and R.A. Holman 1989. "Shear instabilities of the mean longshore current, 1. Theory." *J. Geophysical Res.*, 94(C12), 18,023-018,030.

Bowen, A. J., and D. L. Inman, 1969. Rip currents 2. Laboratory and field observations, *J. Geophysical Res.*, 74(23), 5479-5490.

Bowen, A.J., and D.L. Inman 1971. "Edge waves and crescentic bars." *J. Geophysical Res.*, 76(36), 8662-8671.

Bowen, A.J., D.L. Inman, and V.P. Simmons 1968. "Wave 'set-down' and 'set-up.'" *J. Geophysical Res.*, 73(8?) 2569-2577.

Brocchini, M., 2006. "Integral swash-zone models." *Continental Shelf Research* 26, 653-660.

Brown, J., J. MacMahan, A. Reniers, and E.B. Thornton 2009. "Surf zone diffusivity on a rip-channeled beach." *J. Geophysical Res.*, 114(C11), doi:10.1029/2008JC005158.

Chen, Q., J.T. Kirby, R.A. Dalrymple, A.B. Kennedy, and A. Chawla 2000. "Boussinesq modeling of wave transformation, breaking and runup. II: 2D." *J. Waterway, Port, Coastal and Ocean Eng.*, 126(1), 48-56.

Chickadel, C.C., R.A. Holman, and M.F. Freilich 2003. "An optical technique for the measurement of longshore currents." *J. Geophysical Res.*, 108(C11), 3364.

Clark, D.B., L. Lenain, F. Feddersen, E. Boss, and R.T. Guza 2014. :Aerial imaging of flourescent dye in the near shore." *J. Atmospheric and Oceanic Technology*, 31(6), 1410-1421, doi: 10.1175/JTECH-D-13-00230.1.

Coastal Engineering Research Center 1984. *Shore Protection Manual*, Fourth ed., US Army Corps of Engineers, Washington, DC.

Conley, D.C., and D.L. Inman 1992. "Field observations of the fluid-granular boundary layer under near-breaking waves." *J. Geophysical Res.*, 97(C6), 9631-9643.

Dalrymple, R.A., J. MacMahan, A. Reniers, and V. Nelko 2011. "Rip Currents." *Annual Reviews of Fluid Mechanics*, 43, 551-581, doi: 10.1146/annurev-fluid-122109-160733.

Dean, R.G., 1965. "Stream function representation of nonlinear ocean waves." *J. Geophysical Res.*, 70(18), 4561-4572.

Dodd, N., J. Oltman-Shay, and E.B. Thornton 1992. "Shear instabilities in the longshore current: A comparison of observation and theory." *J. Physical Oceanography* 22, 62-82.

Doering, J.C., and A.J. Bowen 1988. "Wave-induced flow and nearshore suspended sediment." Paper presented at 21st International Conf. Coastal Eng., ASCE.

Dongeren, A.v., N.G. Plant, A. Cohen, D. Roelvink, M.C. Haller, and P. Catalan 2008. "Beach Wizard: nearshore bathymetry estimation through assimilation of model computations and remote observations." *Coastal Engineering,* 55(12), 1016-1027, doi: 10.1016/j.coastaleng.2008.04.011.

Downing, J.P., R.W. Sternberg, and C.R.B. Lister 1981. "New instrumentation for the investigation of sediment suspension processes in the shallow marine environment." *Marine Geology*, 42, 19-34.

Drake, T.G., and J. Calantoni 2001. "Discrete particle model for sheet flow sediment transport in the nearshore." *J. Geophysical Res.*, 106(C9), 19859-19868.

Dugan, J.P., W.D. Morris, and K.C. Vierra 2001. "Jetski-based nearshore bathymetric and current survey system." *J. Coastal Res.*, 17(4), 900-908.

Elgar, S., E.L. Gallagher, and R.T. Guza 2001. "Nearshore sandbar migration." *J. Geophysical Res.*, 106(C6), 11623-11627.

Elgar, S., and R.T. Guza 1985. "Observations of bispectra of shoaling surface gravity waves." *J. Fluid Mechanics*, 161, 425-448.

Faria, A.F.F., E.B. Thornton, T.P. Stanton, C.V. Soares, and T.C. Lippmann 1998. "Vertical profiles of longshore currents and related bed shear stress and bottom roughness." *J. Geophysical Res.*, 103(C2), 3217-3232.

Feddersen, F., R.T. Guza, and S. Elgar 2004. "Inverse modeling of one-dimensional setup and alongshore current in the nearshore." *J. Physical Oceanography*, 34(4), 920-933.

Feddersen, F., R.T. Guza, S. Elgar, and T.H.C. Herbers 1998. "Alongshore momentum balances in the nearshore." *J. Geophysical Res.*, 103(C8), 15,667-15676.

Foster, D.L., R.A. Beach, and R.A. Holman 2000. "Field Observations of the wave bottom boundary layer." *J. Geophysical Res.*, 105(C8), 19631-19647.

Freilich, M.H., and R.T. Guza, 1984. "Nonlinear effects on shoaling surface gravity waves." *Philosophical Transactions of the Royal Society Series A*, 311, 1-41.

Freilich, M.H., R.T. Guza, and S.L. Elgar 1990. "Observations of nonlinear effects in directional spectra of shoaling gravity waves." *J. Geophysical Res.*, 95(C6), 9,645-649,656.

Gallagher, E.L., S. Elgar, and R.T. Guza 1998a. "Observations of sand bar evolution on a natural beach." *J. Geophysical Res.*, 103(C2), 3203-3215.

Gallagher, E.L., S. Elgar, and E.B. Thornton 1998b. "Megaripple migration in a natural surf zone." *Nature*, 394, 165-168, doi:10.1038/28139.

George, R., R.E. Flick, and R.T. Guza 1994. "Observations of turbulence in the surf zone." *J. Geophysical Res.*, 99(C1), 801-810.

Guza, R.T., 1980. "Local and shoaled comparisons of sea surface elevations, pressures and velocities." *J. Geophysical Res.*, 85(C3), 1524-1530.

Guza, R.T., and D.L. Inman 1975. "Edge waves and beach cusps." *J. Geophysical Res.*, 80(21) 2997-3012.

Guza, R.T., and E.B. Thornton 1982. "Swash oscillations on a natural beach." *J. Geophysical Res.*, 87(C1), 483-491.

Haller, M.C., and R.A. Dalrymple 2001. "Rip current instabilities." *J. Fluid Mechanics*, 433, 161-192.

Haller, M.C., R.A. Dalrymple, and I.A. Svendsen 2002. "Experimental study of nearshore dynamics on a barred beach with rip channels." *J. Geophys. Res.*, 107(C6), doi: 10.1029/2001JC000955.

Haller, M.C., D. Honegger, and P. Catalan 2014. "Rip current observations via marine radar." *J. Waterway, Port, Coastal and Ocean Eng.*, 140, 115-124.

Hally-Rosendahl, K., F. Feddersen, and R.T. Guza 2014. "Cross-shore tracer exchange between the surfzone and inner-shelf." *J. Geophysical Res.*, 119(7), 4367-4388, doi:10.1002/2013JC009722

Hanes, D.M., and C.E. Vincent 1987. "Detailed dynamics of nearshore suspended sediments." Paper presented at Coastal Sediments 1987, ASCE, New Orleans.

Hanes, D.M., C.E. Vincent, D.A. Huntley, and T.L. Clarke 1988. "Acoustic measurements of suspended sand concentration in the C2S2 experiment at Stanhope Lane, Prince Edward Island." *Marine Geology*, 81, 185-196.

Hay, A.E., and A.J. Bowen 1993. "Spatially correlated depth changes in the nearshore zone during autumn storms." *J. Geophysical Res.*, 98(C7), 12,387-312,404.

Hay, AE., and J. Sheng 1992. "Vertical profiles of suspended sand concentration and size in the nearshore zone from multifrequency acoustic backscatter." *J. Geophysical Res.*, 97, 15,661-615,678.

Hay, A.E., and D.J. Wilson 1994. "Rotary sidescan images of nearshore bedform evolution during a storm." *Marine Geology*, 119, 57-65.

Herbers, T.H.C., S. Elgar, and R.T. Guza 1995. "Infragravity-frequency (0.005-0.05 Hz) motions on the shelf, Part I: Free waves." *J. Physical Oceanography* 25, 1063-1079.

Herbers, T.H.C., S. Elgar, and R.T. Guza 1999. "Directional spreading of waves in the nearshore." *J. Geophysical Res.*, 104(7683-7693).

Holland, K.T., B. Raubenheimer, R.T. Guza, and R.A. Holman 1995. "Runup kinematics on a natural beach." *J. Geophysical Res.*, 100(C3), 4985-4993.

Holman, R.A., J.A.H. Sallenger, T.C. Lippmann, and J.W. Haines 1993. "The application of video image processing to the study of nearshore processes." *Oceanography*, 6(3), 78-85.

Holman, R.A., and A.J. Bowen 1982. "Bars, bumps and holes: Models for the generation of complex beach topography." *J. Geophysical Res.*, 87(C1), 457-468.

Holman, R.A., *et al.* 1990. "Report on the state of nearshore processes research." Nearshore Processes Workshop, St. Petersburg, Florida, April 1989. Report OSU-CO-90-6, Oregon State University.

Holman, R.A., and M.C. Haller 2012. "Remote sensing of the nearshore." *Annual Reviews of Marine Science*, 5, 95-113, doi:10.1146/annurev-marine-121211-172408.

Holman, R.A., N.G. Plant, and K.T. Holland 2013. "cBathy: A robust algorithm for estimating nearshore bathymetry." *J. Geophysical Res.*, 118, 1-15, doi:10.1002/jgrc.20199.

Holman, R.A., and J. Stanley 2007. "The history and technical capabilities of Argus." *Coastal Engineering*, 54, 477-491.

Howd, P.A., J. Oltman-Shay, and R.A. Holman 1991. "Wave variance partitioning in the trough of a barred beach." *J. Geophysical Res.*, 96(C7), 12,781-712,795.

Inman, D.L., and C.E. Nordstrom 1971. "On the tectonic and morphological classification of coasts." *J. Geology*, 79, 1-21.

Irish, J.L., and W.J. Lillycrop 1999. "Scanning laser mapping of the coastal zone: the SHOALS system." *ISPRS Journal of Photogrammetry and Remote Sensing*, 54, 123-129.

Izquierdo, R., and C. Guedes-Soares 2005. "Analysis of sea waves and wind from X-band radar in the Port of Sines." *Ocean Engineering*, 32, 1402-1419.

Keulegan, G.H., 1948. "An experimental study of submarine sand bars." Beach Erosion Board, U.S. Army Corps of Engineers.

Kirby, J.T., 1986. "Higher-order approximations in the parabolic equation method for water waves." *J. Geophysical Res.*, 91, 933-952.

Komar, P.D., 1973. "Computer models of delta growth due to sediment input from rivers and longshore transport." *Geological Society of America Bulletin*, 84 2217-2226.

Komar, P.D., and D.L. Inman 1970. "Longshore sand transport on beaches." *J. Geophysical Res.*, 75, 5914-5927.

Kumar, N., G.Voulgaris, J.C. Warner, and M. Olabarrieta 2012. "Implementation of the vortex force formalism in the coupled ocean-atmosphere-sediment transport (COAWST) modeling system for inner shelf and surf zone applications." *Ocean Modelling*, 47(65-95), doi: 10.1016/j.ocemod.2012.01.003

Kurapov, A.L., G.D. Egbert, J.S. Allen, and R.N. Miller 2007. "Representer-based variational data assimilation in a nonlinear model of nearshore circulation." *J. Geophysical Res.*, 112(C11019), doi:10.1029/2007JC004117.

Lane, E.M., J.M. Restrepo, and J.C. McWilliams 2007. "Wave-current interaction: A comparison of radiation-stress and vortex-force representations." *J. Physical Oceanography*, 37(5), 1122-1141, doi:10.1175/JPO3043.1

Lentz, S.J., and M.R. Fewings 2012. "The wind- and wave-driven inner-shelf circulation." 317-343.

Lentz, S.J., R.T. Guza, S. Elgar, F. Feddersen, and T.H.C. Herbers 1999. "Momentum balances on the North Carolina inner shelf." *J. Geophysical Res.*, 104(C8), 18205-18226.

Lippmann, T.C., T.H.C. Herbers, and E.B. Thornton 1999. "Gravity and shear wave contributions to nearshore infragravity motions." *J. Physical Oceanography* 29 231-239, doi: http://dx.doi.org/10.1175/1520-0485(1999)029%3C0231:GASWCT%3E2.0.CO;2.

Lippmann, T.C., and R.A. Holman 1989. "Quantification of sand bar morphology: A video technique based on wave dissipation." *J. Geophysical Res.*, 94(C1), 995-1011.

Lippmann, T.C., and R.A. Holman 1990. "The spatial and temporal variability of sand bar morphology." *J. Geophysical Res.*, 95(C7), 11,575-511,590.

Lippmann, T.C., R.A. Holman, and K. Hathaway 1993. "Episodic, non-stationary behavior of a two sand bar system at Duck, NC, USA." *J. Coastal Res.*, SI(15), 49-75.

List, J.H., B.E. Jaffe, A.H.J. Sallenger, and M.E. Hansen 1997. "Bathymetric comparison adjacent to the Louisiana Barrier Islands: processes of large-scale change." *J. Coastal Res.*, 13(3), 670-678.

Long, C.E., and J.M. Oltman-Shay 1991. "Directional characteristics of waves in shallow water." Technical Report CERC-91, Coastal Eng. Res. Cent., Field Res. Facil., U. S. Army Eng. Waterw. Exp. Sta., Vicksburg, MS.

Long, J.W., and H.T. Ozkan-Haller 2009. "Low-frequency characteristics of wave-group forced vortices." *J. Geophysical Res.*, 114, doi: 10.1029/2008JC004894

Longuet-Higgins, M.S., 1970a. "Longshore currents generated by obliquely incident sea waves, 2." *J. Geophysical Res.*, 75, 6790-6801.

Longuet-Higgins, M.S., 1970b. "Longshore currents generated by obliquely incident waves, 1." *J. Geophysical Res.*, 75, 6778-6789.

Longuet-Higgins, M.S., and R.W. Stewart 1964. "Radiation stresses in water waves; a physical discussion, with applications." *Deep-Sea Research*, 11, 529-562.

Lynett, P.J., 2006. "Nearshore wave modeling with high-order Boussinesq-type equations." *J. Waterway, Port, Coastal and Ocean Eng.*, 132(5), 348-357.

Madsen, P.A., O.R. Sorensen, and H.A. Schaffer 1997. "Surf zone dynamics by a Boussinesq type model. Part I. Model description and cross-shore motion of regular waves." *Coastal Engineering*, 32 255-287.

McWilliams, J.C., J.M. Restrepo, and E.M. Lane 2004. "An asymptotic theory for the interaction of waves and currents in shallow coastal waters." *J. Fluid Mechanics*, 511, 135-178.

Mendez, F.J., M. Mendendez, A. Luceno, and I.J. Losada 2006. "Estimation of the long-term variability of extreme significant wave height using a time-dependent Peak Over Threshold (POT) model." *J. Geophysical Res.*, 111(C07024), doi:10.1029/2005JC003344.

Miche, R., 1951. "Le pouvoir réfléchissant des ouvrages maritimes exposés à l'action de la houle." Ann. *Ponts Chaussees*, 121 285-319.

Munk, W.H., 1949. "Surf beats." *EOS Transactions*, American Geophysical Union, 30, 849-854.

Munk, W.H., and M.A. Traylor 1947. "Refraction of ocean waves: a process linking underwater topography to beach erosion." *J. Geology*, 55, 1-26.

Murray, A.B., and A.D. Ashton 2013. "Instability and finite-amplitude self-organization of large-scale coastline shapes." *Philosophical transactions of the Royal Society A - Mathematical, Physical and Engineering Sciences*, 371, doi: 10.1098/rsta.2012.0363

Newberger, P.A., and J.S. Allen 2007. "Forcing a three-dimensional, hydrostatic primitive-equation model for application in the surf zone, 1: formulation." *J. Geophysical Res.*, 112, doi:10.1029/2006JC003472.

Oltman-Shay, J., and R.T. Guza 1987. "Infragravity edge wave observations on two California beaches." *J. Physical Oceanography*, 17(5), 644-663.

Oltman-Shay, J., P.A. Howd, and W.A. Birkemeier 1989. "Shear instabilities of the mean longshore current 2. Field data." *J. Geophysical Res.*, 94(C12), 18,031-018,042.

Ozkan-Haller, H.T., and J.T. Kirb, 1999. "Nonlinear evolution of shear instabilities of the longshore current: a comparison of observations and computations." *J. Geophysical Res.*, 104 25,953-925,984.

Pawka, S.S., D.L. Inman, and R.T. Guza 1984. "Island sheltering of surface gravity waves: model and experiment." *Continental Shelf Research*, 3, 35-53.

Peregrine, D.H., 1967. "Long waves on a beach." *J. Fluid Mechanics* 27(4), 815-827, doi: 10.1017/S0022112067002605.

Plant, N., and K.T. Holland 2011. "Prediction and assimilation of surf-zone processes using a Bayesian network: Part I: Forward models." *Coastal Engineering*, 58(1), 119-130, doi: 10.1016/j.coastaleng.2010.09.003.

Plant, N.G., and R.A. Holman 1997. "Intertidal beach profile estimation using video images." *Marine Geology*, 140, 1-24.

Plant, N.G., R.A. Holman, and M.H. Freilich 1999. "A simple model for interannual sand bar behavior." *J. Geophysical Res.*, 104(C7), 15755-15776.

Puleo, J.A., R.A. Beach, R.A. Holman, and J.S. Allen 2000. "Swash Zone sediment suspension and transport and the importance of bore-generated turbulence." *J. Geophysical Res.*, 105(C7), 17021-17044.

Raubenheimer, B., R.T. Guza, and S. Elgar 1996. "Wave transformation across the inner surf zone." *J. Geophysical Res.*, 101 25589-25598.

Reniers, A., J.A. Roelvink, and E.B. Thornton 2004. "Morphodynamic modeling of an embayed beach under wave-group forcing." *J. Geophysical Res.*, 109(C1).

Reniers, A.J. H.M., J.H. MacMahan, F.J. Beron-Vera, and M.J. Olascoaga 2010. "Rip-current pulses tied to Lagrangian coherent systems." *Geophysical Review Letters*, 37(5), doi: 10.1029/2009GL041443.

Roelvink, J.A., and M.J.F. Stive 1989. "Bar-generating cross-shore flow mechanisms on a beach." *J. Geophysical Res.,* 94(C4), 4785-4800.

Ruessink, B.G., J.R. Miles, F. Feddersen, R.T. Guza, and S. Elgar 2001. "Modeling the alongshore current on barred beaches." *J. Geophys. Res.*, 106(C10) 22451-22464, doi:10.1029/2000JC000766.

Ruggiero, P., P.D. Komar, and J.C. Allan 2010. "Increasing wave heights and extreme-value projections: the wave climate of the Pacific Northwest." *Coastal Engineering*, 57, 539-552, doi:10.1016/j.coastaleng.2009.12.005.

Sallenger, A.H. Jr., 2000. "Storm impact scale for barrier islands." *J. Coastal Res.*, 16(3), 890-895.

Sallenger, A.H. Jr., R.A. Holman, and W.A. Birkemeier 1985. "Storm-induced response of a nearshore bar system." *Marine Geology*, 64 237-258.

Schmidt, W.E., B.T. Woodward, K.S. Millikan, and R.T. Guza 2003. "A GPS-tracked surf zone drifter." *J. Atmospheric and Oceanic Technology* 20, 1069-1075.

Sleath, J.F.A., 1999. "Conditions for plug formation in oscillatory flow." *Continental Shelf Research*, 19, 1643-1664.

Slinn, D.N., J.S. Allen, P.A. Newberger, and R.A. Holman 1998. "Nonlinear shear instabilities of alongshore currents over barred beaches." *J. Geophysical Res.*, 103(C9), 18,357-318,379.

Spydell, M.S., F. Feddersen, R.T. Guza, and W.E. Schmidt 2007. "Observing surf zone dispersion with drifters." *J. Physical Oceanography*, 37 2920-2939.

Stanton, T., and E.B. Thornton 1996. "Reynolds stress and small-scale morphology measurements during Duck94." *Coastal Engineering Proceedings*, 1(25), doi: http://dx.doi.org/10.9753/icce.v25.

Svendsen, I.A., 1984. "Mass flux and undertow in a surf zone." *Coastal Engineering*, 8, 347-364.

Terwindt, J.H.J., and J.A. Battjes 1991. "Research on largescale coastal behavior." Paper presented at 22nd Int. Conference on Coastal Eng., ASCE.

Thomson, J., 2012. "Wave breaking dissipation observed with 'SWIFT' drifters." *J. Atmospheric and Oceanic Technology* 29(12), 1866-1882, doi:10.1175/JTECH-D-12-00018.1

Thornton, E.B., R.A. Dalrymple, T. Drake, E. Gallagher, R.T. Guza, A. Hay, R.A. Holman, J. Kaihatu, T.C. Lippmann, and T. Ozkan-Haller 2000. "State of nearshore processes research: II." Technical Report NPS-OC-00-001, Naval Postgraduate School, Monterey, CA.

Thornton, E.B., and R.T. Guza 1982. "Energy saturation and phase speeds measured on a natural beach." *J. Geophysical Res.*, 87(C12), 9499-9508.

Thornton, E.B., and R.T. Guza 1983. "Transformation of wave height distribution." *J. Geophysical Res.*, 88(C10), 5925-5938.

Thornton, E.B., and R.T. Guza 1986. "Surf zone longshore currents and random waves: Field data and models." *J. Physical Oceanography*, 16(7), 1165-1178.

Thornton, E.B., R.T. Humiston, and W.A. Birkemeier 1996. "Bar/trough generation on a natural beach." *J. Geophysical Res.*, 101(12), 12,097-012,110.

Trowbridge, J.H., and Y.C. Agrawal 1995. "Glimpses of a wave boundary layer." *J. Geophysical Res.*, 100(C10) 20,729-720,743.

van Dongeren, A., A. Reniers, J.A. Battjes, and I. Svendsen 2003. "Numerical modeling of infragravity wave response during DELILAH." *J. Geophysical Res.*, 108(C9), 3288, doi:10.1029/2002JC001332.

Veeramony, J., D. Walker, and L. Hsu 2010. "A variational data assimilation system for nearshore applications of SWAN." *Ocean Modelling*, 35 206-214.

Werner, B.T., and T.M. Fink 1993. "Beach cusps as self-organized patterns." *Science* 260(May), 968-971.

Wijnberg, K.M., and J.H.J. Terwindt 1995. "Extracting decadal morphological behavior from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis." *Marine Geology*, 126.

Wilson, G.W., H.T. Özkan-Haller, and R.A. Holman 2010. "Data assimilation and bathymetric inversion in a two-dimensional horizontal surf zone model." *J. Geophysical Res.*, 115(C12), doi: 10.1029/2010JC006286.

Wilson, G.W., H.T. Ozkan-Haller, R.A. Holman, M. Haller, D. Honegger, and C.C. Chickadel 2014. "Surf zone bathymetry and circulation via data assimilation of remote sensing observations." *J. Geophysical Res.,* 119(3), doi: 10.1002/2013JC009213.

Wright, L.D., and A.D. Short 1984. "Morphodynamic variability of surf zones and beaches: A synthesis." *Marine Geology*, 56, 93-118.

Wright, L.D., and B.G. Thom 1977. "Coastal depositional landforms: a morphodynamics approach." *Progress in Physical Geography*, 1, 412-459.

Young, I.R., S. Zieger, and A.V. Babanin 2011. "Global trends in wind speed and wave height." *Science*, 332(6028), 451-455.

Yu, J., and D.N. Slinn 2003. "Effects of wave-current interaction on rip currents." *J. Geophysical Res.*, 108(C3), doi: 10.1029/2001JC001105.