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Report Based on the Nearshore Research Workshop
St. Petersburg, Florida
September 14-16, 1998

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NEARSHORE PROCESSES RESEARCH

Report Based on the Nearshore Research Workshop
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0.0 EXECUTIVE SUMMARY

0.1 Background

Understanding nearshore processes is increasingly important because the majority of the world's coastlines are eroding. The increased threat of global warming and the resulting

rise in sea level may accelerate erosion problems. Beaches are a primary recreational area, are essential to commerce, and are important to nation defense, especially since the end of the cold war. Increasing our knowledge of nearshore process is crucial both economically and militarily.

A group of 68 scientists and engineers specializing in nearshore process met from 14-16 September 1998 in St. Petersburg, Florida, with the objective of assessing the current state of nearshore science, and identifying the important scientific questions, research strategies, and the infrastructure needed to address the questions.

This workshop report reviews the considerable progress in nearshore science and engineering since the last workshop in 1989. Nearshore science in the 90's can be characterized by comprehensive field experiments at Duck, North Carolina, modeling and large facility experiments in Europe, and continued research in Japan. The workshop report synthesizes the progress of the last decade and suggests where research efforts should be focused to make continued progress.

0.2 Recommendations for future research

A broad spectrum of nearshore science questions was discussed and priority areas of research identified. Although the priority science issues of swash, breaking waves and sediment transport remain on the list from a decade ago, newly developed acoustic and optical tools should result in significant progress in the next decade.

Priority Science Issues:

1. Fluid and sediment processes in the swash zone
2. Breaking waves, bottom boundary layers, and associated turbulence
3. Wave and breaking-wave induced currents
4. Nearshore sediment transport
5. Morphology

There was general agreement that a research strategy for addressing these questions is to combine field experiments with numerical models of nearshore processes. Observations are needed to test model predictions, and can reveal new and unexpected phenomena.

Research Strategies:

1. Community models should be developed and tested to synthesize scientific progress.
2. Observations spanning a range of scales should be conducted on different beach types.

Improvements to the community infrastructure to fulfill these research strategies:

1. Establish a nearshore data bank to archive and exploit existing data.
2. Establish additional long-term measurement programs.
3. Improve instrumentation for measurements in the nearshore.
4. Develop a community bathymetric measurement capability.

1.0 INTRODUCTION

The nearshore ocean, extending from the beach to water depths of about 10 meters, is of significant societal importance. More than half the U.S. population lives within 50 miles of the shoreline. Beaches are the primary recreational destination for domestic and foreign tourists. In California, beaches generate more visitor attendance days than all other major attractions (Yosemite, state parks, theme parks including Disneyland) combined, equating to $14 billion annual direct spending. More than twice as many tourists visit Miami Beach than visit Grand Canyon, Yosemite, and Yellowstone National Parks combined. The foreign exchange benefit to the US from tourist spending now exceeds that from the export of manufactured goods (62). However about 85 percent of the sandy shorelines of the United States are eroding from a combination of damming of rivers, inlet improvements, sea level rise, and large storms. Accurate prediction of nearshore processes can improve coastal management and lead to substantial benefit for coastal communities.

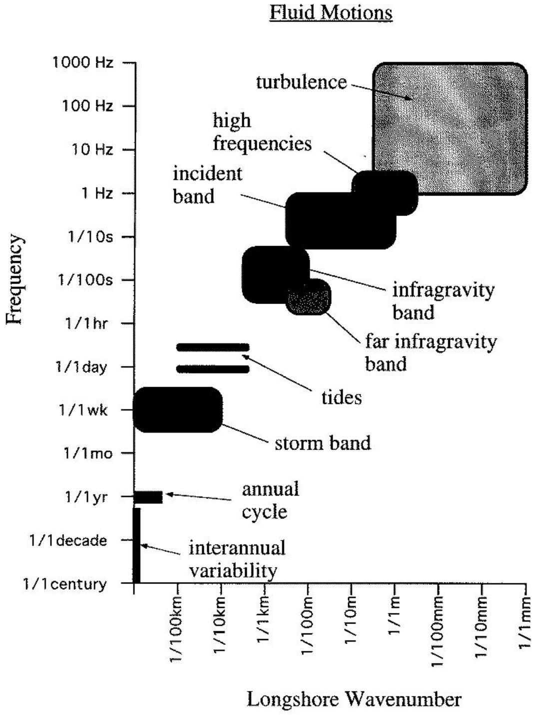
Fluid Motions

Figure 1. Space-time scales of morphology in the nearshore

This report concerns basic scientific and engineering research in the nearshore ocean. A long-term goal of nearshore research is to understand and model the transformation of surface gravity waves propagating across the continental shelf to the beach, the corresponding wave-driven circulation in the surf zone, and the resulting evolution of surf zone and beachface morphology. Progress toward this goal since the last Nearshore Research Workshop (59) a decade ago is reviewed below. The review is divided into small-, intermediate- and large-scale processes based on the space and time scales of nearshore fluid motions (Fig. 1). Understanding nearshore processes well enough to develop a realistic coupled waves-currents-morphologic evolution model is a challenging goal. Significant progress has been made during the past decade, and the prospects for major advances in the next 10 years are exciting.

2.0 REVIEW

During the last decade, field experiments and numerical models have shown that nearshore wave transformation, circulation, and bathymetric change involve coupled processes at many spatial and temporal scales (Figure 2). The properties of waves incident from deep water and the beach profile (large-scale properties) determine the overall characteristics (e.g., surf zone width) of nearshore waves and flows (intermediate-scale properties). However, small-scale processes control the turbulent dissipation of breaking waves, bottom boundary layer and bedform processes that determine the local sediment flux. Cross- and alongshore variations in waves, currents, and bottom slope cause spatial gradients in sediment fluxes resulting in large-scale, planform evolution (e.g., erosion or accretion). As the surf zone bathymetry evolves, so do nearshore waves and currents that depend strongly on this bathymetry.

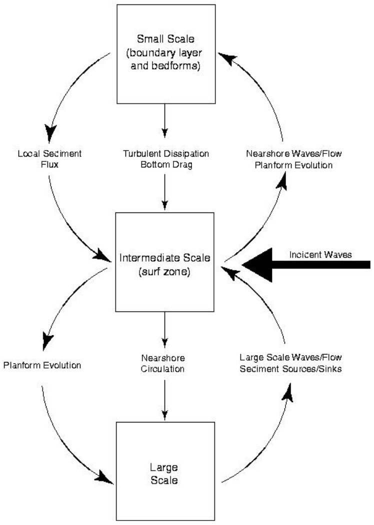

Figure 2. Coupling of the small-, intermediate-, and large-scale processes

2.1 REVIEW OF SMALL-SCALE PROCESSES [0.1 mm –10 m; 0.1 s -1 day]

Introduction

Ten years ago progress in understanding small-scale sediment dynamics was limited by lack of measurements of both sediment and fluid motions. Models of the wave-current bottom boundary layer were mainly 1-D and bedform models were mainly 2-D. Over the past decade, however, new measurement technologies have provided insight into the complexity of the fluid-sediment interaction over a wide range of conditions. In addition, 3-D small-scale process models are beginning to produce results at a level of detail surpassing measurements.

Bed State

New high-resolution measurements using acoustic altimeters and side scan sonars now quantify the 3-D character of bedforms at high temporal and spatial resolution. Spatial variability of bedforms has been documented using CRAB-mounted sonars; for example, 10 to 40 cm high lunate and straight-crested megaripples are often seen on the seaward flanks of bars, in the nearshore trough, and in rip channels, but their origin and spatial variability are not understood (122). Temporal evolution of bedforms at fixed location has been observed during a storm (48). Transition between bedform types occurs on time-scales comparable to time-scales of changes in fluid forcing, but is also linked to bedform scale and forcing history. Under large waves, significant changes in small-scale bedforms can occur within a single wave cycle (44). In contrast, large-scale bedforms can exhibit significant hysteresis in their temporal evolution (124). These complexities in bedform development are not included in models for sediment transport or fluid motion.

Variation in sediment size may contribute to the high variability of bedforms in the nearshore. Cores through a storm-deposited bar at Duck revealed grain size variations from mm-thick cross-bedded laminae of grains having diameters two to three times the mean grain size, to several cm thick horizontal strata of coarse sand and fine gravel (22, 105). The temporal and spatial variability of grain size is greatest in the swash zone, where sediment varies from fine sand to gravel and cm-long shell fragments over distances of tens of cms and over times order of individual swash excursions.

Models of bedform development are not able to reproduce the full range of patterns observed, but promising results have been obtained using two different approaches. The existence of both longitudinal and transverse instabilities of the coupled fluid-sediment system has been demonstrated, suggesting a mechanism for the formation of at least one 3-D ripple type (128). However, these models depend on parameterizations of the poorly known nearbed turbulence and sediment flux. Bedforms have been also simulated as the result of self-organization of mobile bed sediment (76,133). Self-organization models depend on codification of complex granular-fluid physical phenomena into simple rules designed to represent the details of the sediment transport. However, there is no accepted basis for selecting the appropriate rules. The hypothesis that for directionally variable flows, bedforms become aligned in a direction such that the gross transport normal to the crest is maximized (103) was confirmed in field experiments (34). This direction may differ substantially from the direction of the net bottom stress.

Fluid Forcing

The wave bottom boundary layer (WBBL) is only a few cm thick over a flat bed and changes rapidly. Owing to the difficulty of resolving the space-time structure in the field, tests of WBBL models have relied upon laboratory measurements (68). New techniques using a traversing laser-Doppler velocimeter (125), vertical stacks of hotfilm anemometers (31), and acoustic Doppler techniques (117) have been used to profile the WBBL in the field.

Bottom boundary layers associated with mean flows are typically O(1 m) thick and can be measured with standard velocity sensors. The vertical structure of mean on-offshore currents (undertow) observed in the field has been modeled using a cross-shore variable eddy viscosity (40). The log profile was found to describe well the vertical profiles of strong (> 1 m/s) longshore currents. Measurement of the cross-shore variation in the vertical structure of the mean alongshore current revealed an order of magnitude variation in the bottom shear stress coefficient C_f across the surf zone owing to variations in the physical roughness of the bed (35). Roughness caused by bedforms cannot be predicted by existing models, precluding predictions of C_f.

Turbulence is generated at the surface under breaking waves and in the bottom boundary layer. The details of breaker-induced turbulence and energy dissipation have been studied in the laboratory, and both obliquely descending vortices and horizontal vortices have been observed (89, 120). Breaking waves have been modeled theoretically (81). In the field, the vertical structure of turbulence under breakers and bores was investigated using hotfilms. Turbulence intensities were found to be O(1%) of the wave orbital energy, and to decay slowly with increasing depth, indicating strong vertical mixing (35). Depth-averaged turbulence levels were consistent with a bore dissipation model (123). The turbulence intensities in the WBBL were elevated under wave crests, and dissipation rates were larger than in the overlying fluid by at least a factor of 2 (30).

Models for the vertical structure of the wave-current bottom boundary layer have been under development for some time (39, 109). However, there is no accepted theory for turbulent flow over the rough and erodible bottom typical of coastal environments. Most models are 1-D and depend on either an analytical (e.g., eddy viscosity) or a numerical (e.g., k-epsilon) turbulent closure scheme. An important issue is the degree of nonlinearity in the superposition of the wave and current contributions to the total stress. Comparisons between constant eddy viscosity and k-epsilon models have revealed systematic differences in the predicted nonlinearity (113). Better agreement was found between time-varying eddy viscosity models and k-epsilon models of nonlinearity in the mean stress (86). Fully 3-D models, using direct numerical simulation techniques (111), are producing realistic pictures of instability development and the onset of turbulence in the WBBL, but are limited to low Reynold's numbers owing to computational constraints.

Sediment Transport

Sediment transport models for combined wave-current flows usually are formulated either in terms of flow energetics or bottom shear stress. In these models, sediment transport is separated into suspended load and bedload. Suspended load is understood better than bedload owing to the difficulty of obtaining non-intrusive measurements of the motion of particles in the thin bedload layer. An important question is whether either transport modes dominates in different nearshore environments.

Models of sediment suspension build upon the fluid boundary layer models by adding a sediment conservation equation and boundary conditions on the sediment flux. Important questions relate to the mechanisms and parameterizations both for sediment entrainment from the bed, and for upward mixing of sediment into the water column. Sediment entrainment is represented either as a diffusive or convective process (90). Boundary conditions for either process remain understood poorly. Post-entrainment mixing is represented either as pure diffusion, or as a combination of turbulent diffusion and a vertical convective flux associated with large eddies. These different representations may reflect shifts in the dominant physical processes as a function of bed state and forcing energetics.

In most stress-based bedload models, the transport rate is proportional to the excess bed shear stress raised to a power between 1.5 to 2.5. No method for direct measurement of bedload transport suitable for nearshore field conditions has been developed. Indirect estimates of bedload transport rates made from bedform migration measurements support the use of stress-based models for current dominated cases (46).

Vertical profiles of suspended sediment concentration and size can now be measured acoustically in the field. However, comparison of such observations with theoretical predictions yields mixed results. Direct measures of sediment flux profiles, obtained using a coherent acoustic Doppler profiler, showed sediment flux in-phase with wave velocity (and wave stress) within 2 cm of the bed, but with increasing phase variation above this level (115). Neither purely diffusive models nor convective models find general application to the usual range of small-scale bed states (78). Field observations consistently document the strong modulation of the suspension concentration profile at infragravity wave frequencies, and especially the association between suspension events and wave groups (42). These events have been described as near bottom "stirring" during the first few waves in the group, followed by "pumping up" to progressively greater heights during later waves, illustrating the dependence of the instantaneous suspended sediment concentration on the prior wave history (43, 45). Models describing sediment transport under wave groups, with and without bound long waves, find the transport direction is dependent on grain size and transport intensity. Bound long waves result in an offshore contribution to the sediment transport because the offshore motion in the long waves occurs simultaneous with the high waves and high sediment concentration (20).

At time scales shorter than a wave period, suspension is highly intermittent. Phase averaging of temporal variations in suspended sediment concentration over a flat bed (21) reveals pronounced asymmetry with respect to time during the wave cycle, in contrast to the more symmetric behavior over rippled beds (93). Characteristic phase-related differences in the spatially coherent structure of the suspension layer have been identified using video observations of flat and transition rippled beds (14).

Modeling and observational techniques for 2- and 3-D studies of suspension are evolving. Sediment suspension over a bed of fixed ripples is described by a discrete vortex model, which exhibits the development of sediment clouds several ripple heights high with a horizontal separation equal to the ripple wavelength (2, 95). Computed instantaneous concentration profiles exhibit pronounced inversions similar to those reported in laboratory experiments (108). Newly developed compact underwater laser-video systems (15) provide 2-D images of suspension and bed elevation profiles, which facilitate comparison of field and laboratory observations with 2-D models.

At sufficiently high bottom stress, bedload occurs as sheet flow in a horizontal layer of thin vertical extent that may lack a significant suspension component. There are numerous laboratory measurements of sheet flow in unidirectional and oscillatory flows (118, 100). Reasonable agreement with experiments was obtained for the sediment flux, velocity profile, and thickness of the sheet in unidirectional flow by applying a two-phase theory that incorporated particle collisions (67). Discrete-particle models based on molecular dynamics for dry granular flow (23) are being developed for nearshore bedload transport. These models calculate the forces on an assemblage of individual grains at small time steps, and have been extended to incorporate fluid forces including flow accelerations (9). Results from simulations compare favorably with available laboratory experiments (73).

2.2 REVIEW OF INTERMEDIATE-SCALE PROCESSES [1m –10 km, 1 sec- 1 year]

Introduction

On coasts exposed to the open ocean, the primary energy source for the small-scale processes discussed above is wind-generated waves (swell and sea) propagating from deep water toward the shoreline. The transformation of directionally spread, shoaling waves approaching the surf zone can be modeled quantitatively, at least on simple bathymetry. Heuristic extensions to the models to describe breaking waves allow accurate prediction of wave propagation across the surf zone. Inside the surf zone, models and observations demonstrate that nearshore circulation is complex, even on beaches with relatively simple bathymetry that does not vary substantially in the alongshore direction. Rather than a stable mean flow, driven only by breaking waves (as in analytic models of the 1980’s), nearshore circulation has been shown in the last decade to include turbulent shear flows and eddies, instabilities, and both wave and wind forcing. In addition, the importance of coupling between nearshore waves, currents, and the changing bathymetry is recognized, resulting in the hypothesis that variations in the nearshore bathymetry result from feedback between the driving forces and morphologic change.

Surface waves

During the last decade, there has been considerable progress toward modeling quantitatively the shoaling wave transformation. Models based on the Boussinesq equations predict accurately the shoaling of nonbreaking near-normally incident swell and sea observed in shallow water on natural beaches (32, 24, 25). Recently, the Boussinesq equations have been extended to deeper water and to stronger nonlinearity (129), and stochastic evolution equations appropriate for directionally spread, random waves have been developed (49) and validated by comparison with field observations (91). These models do not contain adjustable parameters and predict accurately the asymmetrical wave shapes and orbital velocities that are believed important to wave induced nearshore sediment transport.

Analysis of breaking waves across the surf zone indicates that the observed decay of wave spectra is primarily the result of nonlinear transfers from the spectral peak to higher frequencies, and that dissipation occurs in the high- frequency tail of the spectrum where energy levels are relatively low (54). Observations also indicate that breaking results in an increase in the directional spread of wave energy, in contrast to the directional narrowing with decreasing depth predicted by refraction theory (53). The effect of breaking on the transformation of waves propagating across the surf zone has been modeled by including heuristic dissipation terms in both time- (104) and frequency-domain (70) Boussinesq models. With suitably tuned parameters that control the dissipation rate, Boussinesq-type models predict accurately the wave height decay and shape changes of near-normally incident waves propagating across the surf zone (12, 71), and 2-D waves breaking around circular shoals (10). Numerical models that solve the unsteady Navier-Stokes are being used to simulate spilling and plunging waves over a sloping bed using volume of fluid technique to track the discontinuous free surface (81). Models that incorporate the effect of the wave roller, the turbulent wedge of white water on the bore face that is advected shoreward at the wave phase speed (19), also describe accurately surf zone wave propagation. Ongoing work is directed toward integrating small-scale breaking wave dynamics (see Small-Scale section) into Boussinesq and roller models that predict the evolution of wave height and shape across the surf zone.

Unlike sea and swell waves (periods 5-20 s), lower frequency infragravity waves (periods 30-300 s) are not strongly dissipated by wave breaking in the surf zone. Infragravity waves are believed to be generated nonlinearly by groups of incoming wind waves (83). The nonlinear forcing is strong during storms, and infragravity waves can dominate inner surf zone velocity and sea-surface fluctuations, with heights exceeding 1 m (63). Field observations suggest that infragravity waves can be reflected at the shoreline and may consist largely of edge waves refractively trapped between the shoreline and deeper offshore waters. Observations from a range of coastal settings suggest that infragravity energy levels on the continental shelf depend not only on conditions in nearby surf zones, but also on the general geographic surroundings. For example, more infragravity energy is trapped on a steep narrow shelf than on a gently sloping wide shelf (50,51). The role of bar trapped edge waves in sediment transport and bar movement is unknown, but possibly is significant. Wavenumber-frequency spectra of run-up at a barred beach found, in addition to the expected edge and leaky mode infragravity waves, significant nondispersive wave energy was outside the gravity wave region and not associated with shear instabilites. These unexpected observations imply a strong decorrelation can occur between trough and shoreline fluid motions (55). Thus, contrary to previous assumptions, shoreline energy levels are not necessarily a good indication of the overall infragravity wave field. The existence of energetic bar-trapped edge waves (8) suggests that trapping also may occur at other depth perturbations such as submarine canyons and offshore shoals.

The swash zone is the region where the beach face is intermittently covered and uncovered by wave runup. A numerical model based on the 1-D depth-averaged nonlinear shallow water equations with bore-like dissipation (75) predicts accurately runup oscillations measured on a fine-grained beach (98, 99). Boussinesq models recently have been extended to include swash motions, and model predictions agree well with theories for 1-D runup (81, 85) and with measurements of 2-D runup on an impermeable laboratory beach (10, 74). Although wave runup on fine grained and impermeable beaches is modeled well, accurate prediction of runup on coarse-grained beaches may require a model that includes percolation effects. Additionally, prediction of fluid velocities in the runup may require inclusion of a turbulent bottom boundary layer.

Nearshore circulation

Sea and swell waves incident on a beach can drive strong (e.g., 1.5 m/s) quasi-steady currents in the surf zone. Models based on a balance between gradients in the wave radiation stress and the drag of the mean flow on the seabed predict accurately the observed cross-shore distribution of alongshore currents on near-planar beaches. However, on barred beaches, observed alongshore currents are often maximum in the bar trough, rather than on the bar crest as predicted (13). The predictions may be inaccurate because the models do not include surface rollers (that cause spatial lags between initial wave breaking and the transfer of momentum to steady currents), mixing by vertically sheared mean horizontal flows (119), alongshore variability in the waves and bathymetry, or shear waves.

Observations (102) and models (7) suggest that breaking-wave driven alongshore currents often are unstable. The growing instabilities, called shear waves, have periods of 1-10 minutes and maximum rms velocities of 40 cm/s. Results from fully nonlinear models suggest that shear instabilities might both alter significantly the cross-shore structure of the mean alongshore current and produce energetic eddies (110, 94).

Gradients in wave radiation stress caused by breaking waves also drive setup, the super-elevation of the mean water level. The set-up forces an offshore-directed mean flow (undertow) and alongshore gradients of set-up can drive rip currents. However, setup is difficult to measure, as are the breaking processes. Therefore the driving mechanism for undertow (a primary cause of beach erosion during storms) is understood poorly. In addition, it has been shown numerically and in the laboratory that instabilities of the undertow result in a train of vortices that rotate about an axis parallel to the shoreline, and migrate slowly offshore (80).

Substantial alongshore topographic variations over spatial scales of O(1 km) are often observed (82) (see Large-scale section). Models suggest that such alongshore bathymetric variability can cause alongshore variations in the wave setup that significantly influence the nearshore circulation (97). Momentum balances based on observations collected at Duck, NC suggest that the dominant forcing of mean alongshore flows was associated with the oblique propagation direction of the incident waves, rather than topographically induced alongshore gradients in wave setup (29). However, laboratory (41) and numerical model (11) studies suggest that gaps in otherwise alongshore uniform bars may cause offshore directed rip currents that are fed by strong flows in the bar trough. Rip currents are shown to occur theoretically as the result of instabilities of an alongshore perturbed setup/setdown when wave refraction or topographic evolution are taken into account (28). Detailed field observations of strongly bathymetrically controlled nearshore circulation are lacking.

The transition of alongshore currents from the continental shelf to the surf zone has been investigated (79). Observations suggest that density and wind-driven alongshelf currents sometimes are strong immediately seaward of the surf zone, and in some cases oppose wave-driven alongshore flows within the surf zone. Both shoaling waves (through wave setdown) and wind-driven alongshore currents (through geostrophy) contribute significantly to cross-shore tilts of the mean sea surface seaward of the surf zone. These processes (as well as tidal currents) are not generally included in existing models for nearshore circulation.

Surf Zone Bathymetry

During the past decade the coupling between waves, circulation, and changes in nearshore bathymetry has begun to be observed and modeled. On many beaches, changes in the position and height of sand bars are the primary source of cross-shore bathymetric variability, and these bars may be either linear, alongshore periodic, or alongshore irregular (58, 82). Hypotheses for sand bar formation include the break-point and infragravity wave mechanisms, both of which may be important (58). In these models, the spatial scales of sand bars are determined (“forced”) by the spatial pattern of waves and currents. During storms, wave-breaking induced undertow dominates energetics-based modeled sediment transport (33, 121). Undertow is strongest near the bar crest where wave breaking is intensified (40) and the resulting gradients in modeled cross-shore transport lead to predicted seaward bar migration, as observed. As the sand bar moves offshore, the location of intense wave breaking and maximum undertow also migrates seaward. Thus, the coupling and feedback between waves, currents, and bathymetry results in continuous offshore sand bar migration during storms. Existing models do not predict the slower, onshore migration of the sand bar observed in the surf zone during periods of low waves. Field observations suggest net onshore sediment transport and sand bar migration is associated with cross-shore gradients in asymmetrical fluid accelerations owing to pitched-forward nonlinear waves, although the constitutive relationship between fluid acceleration and sediment motion is not known (26).

Numerical models have been developed for coupled fluid-sediment instabilities of longshore currents on initially alongshore-uniform planforms (27). Alongshore-periodic bar features are predicted to develop owing to strong, positive feedback between the mean alongshore current and the evolving bathymetry. The length scales of morphologic features are determined by the unstable (“free”) modes of the coupled fluid-morphology system. Similar interactions between incident wave runup and beachface topography are predicted to lead to the formation of beach cusps, alongshore-periodic variations in the shoreline location (130). The relative importance of free and forced mechanisms in forming natural morphologies is unknown, and is an objective of current research.

2.3 REVIEW OF LARGE-SCALE PROCESSES [1 – 100 km, months-decades]

Introduction

Driven by societal needs to make long-term predictions, large-scale models to predict topographic response have been developed by integrating short time-scale processes, including wave transformation, fluid motion, and sediment transport (77, 112). This approach is sometimes referred to as "bottom-up" modeling or the aggregation of small- to larger-scale processes. Typically, a spatial pattern of the waves and currents is imposed on a starting morphology, and a new morphology is predicted using a sediment transport formula (6, 57, 58, 64). A morphology that can be predicted successfully using this approach exhibits what is known as "forced" behavior. These models have some skill for short-time scales O(weeks), but their model skill is uncertain over large-time and space scales.

The uncertainty of long-term predictability has led researchers to suggest that the nearshore response is sensitive to initial perturbations in the beach profile and that morphological feedback to the wave and current field is strong (114). Under these assumptions, the evolution of topography does not depend solely on the instantaneous small-scale processes, but incorporates some degree of time history in profile configuration and may be driven by instabilities of the coupled fluid-morphology system (16, 27, 28). Such a system is thought to exhibit "free" behavior, in which the predictability time scales are limited by the strength of the nonlinear feedback, or growth rate of an instability. These system traits are elements of nonlinear pattern formation (1, 61, 101) and self-organized behavior (130), and suggest different approaches to modeling that depend on aspects of the feedback. Thus, at long time scales, these systems may be modeled in terms of a simpler, carefully chosen set of equations derived from empirical study of the system in an approach called “top-down” modeling.

The general topic of dynamics of the nearshore system at long-time (months to decades) and length scales (kilometers and longer) is known as Large Scale Coastal Behavior (LSCB), which lies between the shorter scales of traditional nearshore processes (represented here in terms of intermediate and short scale processes) and the much longer scales of Coastal Marine Geology. LSCB was not considered in the first St. Petersburg meeting, but formulation of a research framework (including links to shorter scale processes) was an important aspect of this workshop.

Measures of Large Scale System Response

Models for nearshore processes are based around laws for the conservation of mass, momentum, and energy. At intermediate and small scales, understanding the nearshore implies understanding the dynamics of both its fluid and sediment components. At the longer time scales of LSCB, emergent variables based on a hierarchy of time scales may dominate nearshore processes, i.e. small-scale processes become slaves to large-scale bathymetry at longer time scales. As bathymetry is the main variable of interest at the long-time scales of LSCB, the primary tool is conservation of sediment mass. At the still longer scales of marine geology, grain size partitioning within conservation of mass becomes important.

A description of bathymetric state might requires specification of O(10^2) independent points in the cross-shore (say every 1-2 m) measured at perhaps O(10^2) points in the alongshore, a total of 10^4 independent variables for a single realization. Development of evolution equations for such a large number of variables is daunting, and thus reduction of dimensionality is desirable. Some success can be achieved by representing cross-shore profiles in terms of a small number of EOF or power law functions (3, 18). For area descriptors (both horizontal dimensions), progress has been made by using sets of morphological “state” descriptors, defined primarily by a mix of subjective sand bar/trough characteristics (84, 134). The most common measure of beach state used by coastal zone managers and coastal engineers is the location the shoreline (a measure which also is obtained easily from survey or remote sensing). To develop a predictive understanding of variability of the shoreline then requires an understanding of how the shoreline is related to, and represents, overall profile variability.

Consider the simplified case of a beach whose behavior can be viewed as the superposition of a deterministic annual signal and an underlying trend (Figure 3a). In this case, the prediction of long-term behavior would be specified by the trend (averaging over annual signals), with a confidence limit associated with the variance of the annual signal about that trend.

Nearshore variability occurs over all space and time scales, with significant energy at the longest scales. Prediction of LSCB are made beyond a particular time (or space) scale, T', with shorter period (or length) fluctuations considered to be variance about the prediction (Figure 3b). As an example, annual cycles in sand bar location may have no LSCB impact (only providing variance), whereas net alongshore transport gradients, dune overtopping, or offshore losses can lead to important LSCB signals. In other words, if mass conservation is implemented via a box model, the fluxes within the box may be irrelevant, whereas fluxes across box boundaries may determine long term behavior.

Rob Holman

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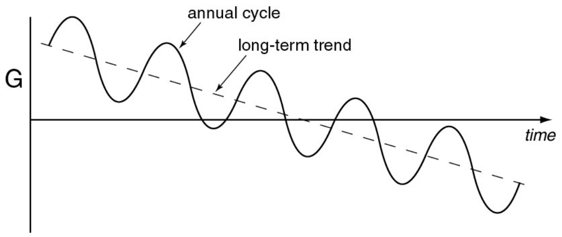
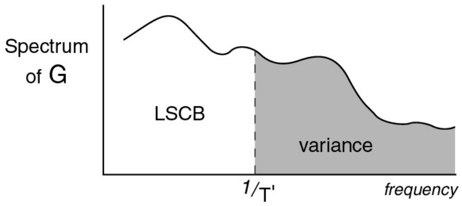
Sources of LSCB Energy

Forcing of large scale nearshore variability can arise from several possible sources, including external factors (wave climate, currents and winds), nonlinear interactions within these external factors, and internal (to the system) factors.

Directly forced response results from forcing energy at the same frequency. For example, a beach may erode slowly owing to a slow increase in the wave climate energy. Thus, the signature of the forcing in space and time provides a template for the nearshore response. Resonances may result in large nearshore response for relatively low forcing.



a) Synthetic Case



b) Realistic Case

Figure 3a. Variations of a synthetic coastal signal showing the superposition of an annual cycle and a long-term trend. 3b. Spectrum of a more realistic case of coastal variability with variance at all scales. LSCB is the low frequency portion of the spectrum, whereas the high frequency energy is simply variance about LSCB.

Nonlinear interactions may transfer energy of the forcing spectrum from high frequencies (perhaps annual cycles) to LSCB. For example, increased suspended loads under winter storm waves might tend to be carried preferentially offshore by bottom return flows from upwelling-favorable winter winds. The corresponding summer conditions might drive only a weak onshore transport, thus produce a net sediment loss (erosion).

Spontaneous generation of LSCB variance (often called free behavior) is caused by instabilities and feedback within the nearshore system. A well known example of such free behavior is the generation of bedforms on an initially smooth river bed (72). The bedforms are not caused by a pre-existing pattern in the river flow, but by an instability and feedback between a perturbation in bottom roughness that causes a disturbance to the flow and sediment transport that reinforces the perturbation. The presence of fluid motion does not introduce any scales, but acts as a catalyst to the process. In the nearshore, a number of possible feedback mechanisms exist. Sand bars may be generated by, and may induce the onset of wave breaking. Similarly, rip channels through a sand bar may be generated by, and may induce alongshore gradients in wave height.

Other Influences

When consideration of nearshore behavior is extended to larger scale, many new processes or influences must be considered (Figure 4). The focus of the 1989 St. Petersburg report was on the interaction of fluid (including wind) processes with evolving morphology. However, at larger scales the response of the nearshore is also a function of climate, sea level, regional sediment fluxes, and anthropogenic effects. Many of these external influences do not involve strong feedbacks. Thus, there may be a greater potential for developing simplified forcing functions in the absence of significant free behavior, consistent with suggestions that behavior may become more predictable at long time scales.

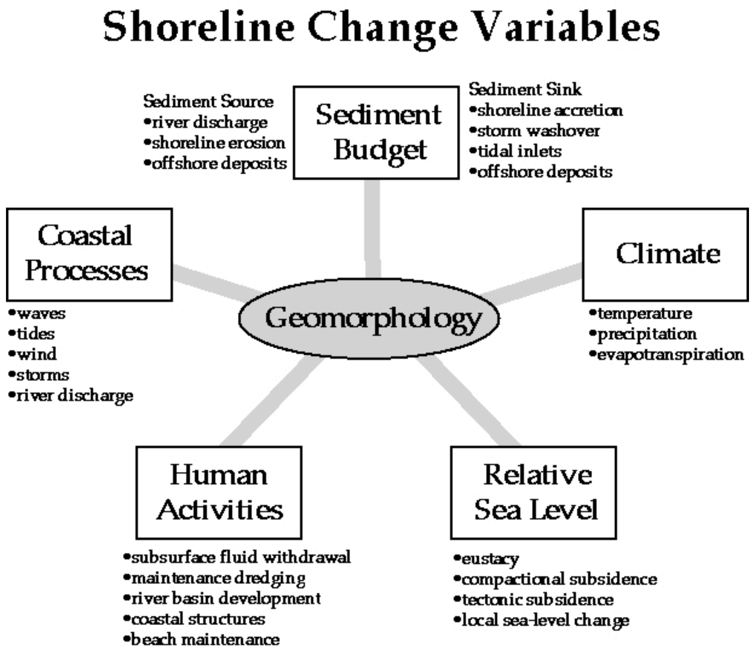


Figure 4. Processes that influence LSCB. Note that only one arm describes the traditional fluid-topography dynamics that have been the focus of much recent field experimentation. At longer scales, many other processes also contribute.

Data

The application of any modeling approach relies on accurate field measurements of nearshore topography. Few data sets of appropriate magnitude exist, thus attempts to verify long-term, large-scale models have been limited.

Large-scale, long-term bathymetric or morphological observations include: (1) the Dutch JARKUS profile data (131), which span 4 decades and hundreds of km of coastline, but have sparse alongshore resolution and are sampled annually, (2) the Duck CRAB profile data (5, 96), which span 2 decades, have dense alongshore resolution, and are sampled on a monthly basis, but only extend alongshore about 1 km, and (3) the ARGUS video data (60, 82), which have dense alongshore resolution and are sampled daily at numerous locations about the world, but are limited to inferences of sand bar position and shape within the surf zone that extend alongshore about 1-2 km. Each of these data sets have revealed valuable insight into long-term large-scale nearshore response, but have limitations for testing of LSCB.

2.4 REVIEW OF NEW TECHNOLOGIES IN THE NEARSHORE

Although new technologies have led to advances in the understanding of nearshore processes, there are gaps in measurement capability. Some of the new technologies have been the result of efforts by nearshore scientists and engineers. Additionally, off-the-shelf availability of DGPS, advances in electronics and micro-processors, the application of simple video techniques, and the use of on-line data have revolutionized methods of measuring and disseminating data. DPGS allows rapid and accurate survey of large areas while driving or flying. Micro-processors have made innovative data acquisition and new measurement systems possible. On-line, time-lapse video stations located around the globe have revealed the complexity of macro-scale morphology at time and space scales not previously recognized. In the following, technology is divided into remote sensing and *in situ* measurement techniques.

Remote Sensing

Remote sensing can be further divided into techniques from moving platforms, such as airplanes or satellites, and stationary locations. Remote sensing from moving aircraft has undergone significant technological development during the past ten years. These systems are able to discern fine scale details of nearshore wave and surface current fields. Scanning sensors such as the scanning radar altimeter (SRA, horizontal resolution O(10 m), 0.2 m vertical accuracy) and the airborne topographic mapper (ATM, a lidar system, horizontal resolution 1.5 m, 0.08 m vertical accuracy) use a direct ranging technique to measure the free surface topography including foreshore regions. Both systems use the time of flight of the return signal from the air-water interface to derive the topography at sub-meter resolutions and can be deployed repeatedly to detect topographic change. Other lidar systems (using different primary wavelengths) can measure bathymetry (66) using the same principle. SRA and ATM were used to measure the wave field during the

Duck94 experiment (65). The SRA shows promise in determining swell wave dissipation and scattering.

Conventional synthetic aperture radar (SAR) has been used in imaging large-scale currents and other phenomena with fairly large space and time scales from both spaceborne and airborne platforms. Ocean waves, however, are difficult to study with this technique because they undergo substantial spatial and temporal variability over the course of the integration time of the imaging. Modulation transfer functions are required to translate between the image and the actual free surface processes. This allows SAR to discern wave kinematics, but provides little information on dynamics. A modification of SAR that incorporates the phase information inherent in the imagery (38), called interferometric SAR (INSAR), potentially is capable of measuring the spatial distribution of surface currents in the surf zone (87, 88, 107, 127). This technique offers (O(10 m)) resolution imaging of the surface currents over a large domain.

Stationary platforms offer the advantage of long-term measurements, but with limited coverage. Optical and radar systems are being used from stationary platforms. A successful application is the ARGUS video stations (60), which provide on-line time-lapse images from around the world linked to the internet. Electro-optical and infrared remote sensing techniques have been used successfully (56, 132), and are presently being transitioned to moving aircraft for the measurement of bathymetry, wave spectra, and surface currents. HF-radar is used routinely to map nearshore currents with O(100 m) resolution. Imaging Doppler radar offers the possibility of mapping surface currents at O(10m) resolution (88).

In situ Measurements

The preceding review identified a number of gaps in measurement capability, such as fluid velocities and particle flux profiles in the bottom boundary layer and in the surface boundary layer under breaking waves, and velocity and sediment concentration measurements in the swash. Sensors to obtain some of the needed measurements are in an advanced state of development. Suspended sediment concentration measurements in the swash and surf zone are measured with fibre-optic backscatter probes (FOBS) (4) and gated acoustic backscatter measurements (47, 106, 126). Three-component velocities are measured using acoustic Doppler velocimeters, in both single-point (107) and vertical profiling configurations for simultaneous co-located particle velocity and particle concentration, and therefore sediment flux measurements at sub-centimeter scale (116, 117). Sector scanning Doppler sonars are used to resolve horizontal velocities of waves on scales of O(400 m) (112). Drifters with DPGS are being developed for use in the surf zone in conjunction with fixed flowmeters to yield improved maps of nearshore currents. Conductivity sensors have been developed to measure sheet-flow near the bed for 2-D flow in a laboratory channel (100), but measuring fluid and sediment dynamics near the bed in the field remains daunting. Small-scale morphology is measured with acoustic altimeters mounted on moving platforms (122) and at fixed locations (33, 105), and with rotating side-scan sonars (48). These new sensors were deployed successfully during recent field experiments, and ongoing research is directed toward comparing the results with model predictions.

Lasers offer the advantage of higher spatial resolution systems to measure morphology, sediments, and fluid velocity. Laser Doppler Velocimetry (LDV) has been used in the laboratory to obtain detailed kinematics of shoaling and breaking waves (120), and initial attempts have been made to measure turbulence under waves in the field (125). Particle imaging velocimetry (PIV) is being used in the laboratory to measure turbulence and is being transitioned to the field.

A focused development program for autonomous underwater vehicles (AUV) has resulted in the capability of surveying with *in situ* instruments for hours over distances of 10's of km at high speed (3 knots). Small (1m) vehicles such as REMUS are being used for fine scale bathymetry surveys and wave measurements, but their area of operation is limited to outside the surf zone. Bottom crawling AUV's show promise for deploying instruments and making measurements across the surf zone and the inner shelf.

These new technologies allow improvements for examining nearshore processes by extending the measurements to both larger and smaller space-time scales with increased resolution and accuracy. The challenge is to assimilate the data into improved models to provide accurate predictions of nearshore processes.

3.0 RECOMMENDATIONS FOR FUTURE RESEARCH

A broad spectrum of nearshore science questions was discussed and priority areas of research identified. Although the priority science issues of swash, breaking waves, and sediment transport from a decade ago remain on the list, new acoustic and optical tools should result in significant progress in the next decade. There was general agreement that a research strategy of combining field experiments and numerical models will lead to the most rapid progress. Observations are needed to test model predictions, and can reveal new and unexpected phenomena. Improvements to the community infrastructure are recommended to fulfill these research strategies.

3.1. PRIORITY SCIENCE ISSUES

1. Fluid and sediment processes in the swash zone should be studied concurrently within the observational and modeling efforts described below. Observations suggest that during onshore flow, processes of suspension and transport of sediment in the swash zone may be dominated by turbulence at the bore front. In contrast, during offshore flow, transport may be driven by the bed shear stress associated with a growing bottom boundary layer. A long-term goal is to develop and validate models of wave runup velocities that could provide spatially dense predictions of swash zone flows to drive sediment transport models and to estimate morphological change. Such models need to account for the effects of bore turbulence, the bottom boundary layer, infiltration into and out of the permeable beach, and longshore currents to predict velocities in the swash zone. Field observations of runup velocities, infiltration, and sediment transport will be necessary to test the models and to determine the importance of these processes on natural beaches. Areas of particular interest include:

- sensitivity of swash zone sediment transport and wave runup to seepage of water into and out of the permeable bed, including unsaturated flow processes,
- effect of mean longshore currents and shear waves on swash zone sediment transport.

2. Breaking waves, bottom boundary layers, and associated turbulence are important to wave energy dissipation and sediment transport, but are not understood well. The breaking of waves in the nearshore results in changes of the wave-induced momentum that drive nearshore currents and pressure gradients. Breaking wave processes are only qualitatively understood and models are crude. Turbulent wave boundary layers are just starting to be measured in the field using instrumentation with improved spatial and temporal resolution. Prototype-scale laboratory experiments can facilitate these efforts. Observations of these small-scale processes are needed to improve parameterizations used in large-scale models. Research issues include:

- horizontal and vertical structure of turbulence and vorticity under breaking waves,
- dissipation of the wave energy owing to bubble entrainment during breaking,
- horizontal and vertical distribution of mass flux of breaking waves,
- effects of wind on breaking,
- effects of reflection, infragravity waves, and currents on wave breaking,
- intensity of wave breaking as a function of wave and bathymetric conditions.

3. Wave and breaking-wave induced currents drive nearshore sediment transport, so understanding these flows is a prerequisite to predicting morphological change. Although wave breaking on simple bathymetry can be parameterized crudely, important processes such as the modification of incident wave directions and shapes by wave breaking are not understood well. Recently developed models suggest that the mean, breaking-wave driven nearshore circulation has a complicated three-dimensional structure even on relatively simple bathymetry. Observed currents contain substantial fluctuations at infragravity periods (approximately 1 minute) that appear to result from a combination of gravity (e.g. edge) waves and vorticity (e.g. shear) waves, but the generation mechanisms and overall significance of these low frequency motions are largely unknown. Thus, even on simple bathymetry, only the gross characteristics of surf zone waves and wave-driven circulation are predicted accurately. Models suggest additional processes occur on complex bathymetry, such as topographically controlled rip currents, but these models contain considerable empiricism (e.g. in modeling the effect of complex bathymetry on wave breaking) and are untested with field observations. To predict nearshore flows for given wind, incident wave fields, and arbitrary nearshore bathymetry, the following issues must be addressed with both observations and models:

- effect of breaking on the frequency-directional distribution and shapes of incident waves,
- role of mixing mechanisms (e.g. shear waves, shear dispersion, wave generated turbulence) in nearshore circulation,

- feedback between the time varying circulation (including edge and shear waves) and incident waves,
- effect of complex bathymetry (including bedforms) on nearshore waves and circulation,
- transition from tidally and wind-driven shelf flows to wave-driven surf zone flows,
- three-dimensional structure of mean currents.

4. Nearshore sediment transport is a nonlinear function of the fluid velocity, and thus highly sensitive to asymmetries in the fluid motion. A feature distinguishing sediment transport in the nearshore from other environments (e.g. rivers) is the wide variety of mechanisms for producing flow-field asymmetry, including shoaling and breaking waves, wave groups, mean currents, and shear instabilities of the longshore current. These asymmetry-generating mechanisms have more or less well understood origins in the nonlinear interactions between the different frequency components of the fluid forcing, and between the flow field and the bathymetry. By comparison, our understanding of the corresponding sediment transport asymmetries is limited, with no generally accepted mathematical formalism or solid empirical basis upon which to develop predictive models. The results of recent observational research are beginning to provide diagnostic examples of the linkages between asymmetry in the sediment response and asymmetry in the flow. Some of this work suggests that sediment transport models developed for rivers can be adapted for use in the surf zone, but do not always perform well. This may be owing to a poorly parameterized bottom boundary layer, the importance of acceleration (which is not accounted for), or bedforms (eg. ripples and mega-ripples), which affect the suspension of sediments and whose migration may be responsible for unaccounted mass transport of sediment. Research issues include:

- predicting bedload and suspended sediment transport under combined wave and current forcing,
- turbulent wave/current boundary layers over 3-D small-scale morphology,
- effects of moving sediment on boundary layer,
- contribution to sediment transport by bedform migration,
- effects of grain size distribution on sediment transport.

5. Morphology (and its variability) is an important end product that the models will predict. However, because sediment transport is not understood well, prediction of morphological change is inadequate for most purposes of interest. For example at smaller scales, ripples and megaripples are observed to be ubiquitous, but have not been incorporated into models even though their effect on the flow field (as roughness elements) and sediment transport may be significant. Complex patterns in long-term, large-scale morphology have also been observed. However, models for morphology change have predictive skill only for short-term changes, whereas long-term, large-scale predictions are not yet possible. Research issues include:

- predicting morphology across the spectrum of length scales,
- free vs. forced large-scale morphology models,
- understanding feedback between morphology and the flow field,

- coupling between length scales.

3.2 RESEARCH STRATEGIES

1. Community models should be developed and tested.

- Sufficient understanding of waves, wave-induced circulation, and sediment transport exists to warrant concentrated efforts to produce a fully-coupled model of wave-driven hydrodynamics and bathymetric evolution. In the past, segments of the nearshore modeling community have proceeded, in near isolation, to develop models of nearshore wave processes and wave-induced circulation that have been tested with laboratory data only. Field observations and numerical modeling efforts should be better integrated to improve existing numerical models and synthesize the knowledge of nearshore processes.

- Further development of existing model components is critical. For example, swash zone processes are not included in any model of circulation, wave dissipation, or morphology change. Breaking wave, bottom boundary layer, and turbulence parameterizations need to be improved. Existing sediment transport relationships fail under many common conditions. Better understanding of all of these processes will improve morphology predictions.

- Increased emphasis on the development of a real-time predictive capability for nearshore circulation and morphology using data assimilation techniques, and on the use of forecasts from such models to guide field experiments. Data assimilation has become an important method for improving model predictions in other fields, but has not become commonplace in the nearshore community. Testing the predictive skill of such models will require the continued development of measurement technologies for remote and mobile adaptive sampling of the predicted property fields.

As a direct response to the workshop, an ad hoc committee on Community Modeling was formed during the workshop to develop plans to fulfill the recommendations above. A five-year nearshore wave, current and morphology modeling and data assimilation program was proposed to the National Ocean Partnership Program (NOPP), and was subsequently funded for years 1999-2005.

2. Observations spanning a range of scales should be conducted for different beach types.

Many of the field observations of waves and currents have been acquired at the U.S. Army Field Research Facility (FRF) at Duck, N.C. because of logistical support (eg, the CRAB, an amphibious survey and work platform). Although the moderately-sloped beach at Duck is the most intensively studied beach in the world, the generality of these intermediate-length and time scale observations is unknown. It is important to study a range of beach environments, especially different grain size and beach slopes across the spectrum of length and time scales. Therefore, it is recommended to:

- use new technologies to make detailed observations of small-scale fluid and sediment processes. Such observations will help to improve parameterizations of breaking wave and boundary layer processes including associated turbulence and shed light on the physics of sediment transport.

- make simultaneous observations of small, intermediate, and large-scale processes. Fluid and sediment processes are coupled across all scales, and thus models of circulation and bathymetric evolution depend on realistic parameterizations of small-scale processes, as well as an understanding of the larger-scale context (eg, sediment sources and sinks (perhaps km away or offshore), shelf-scale wind and density driven circulation, alongshore variations in continental shelf bathymetry, and the incident wave field.

- conduct experiments on both steep and flat beaches. Sediment size and permeability in the swash zone are expected to increase with increasing beach slope. Wave transformation (skewness and asymmetry, wave energy dissipation, and wave-driven circulation) is significantly different on steep and flat beaches. Thus, the cross-shore distribution of breaking, boundary layer processes, and turbulence intensity and their effects on sediment transport are expected to be different in the different environments. Together these processes produce different morphological features.

- conduct experiments on 3-D beaches. In contrast to Duck, where nearshore processes are controlled largely by the height and approach direction of the waves, processes on a pocket beach or near a headland, jetty, or submarine canyon are expected to depend strongly on the local bathymetry. Such complicated geometries have not been studied in the requisite detail to make morphologic predictions.

3.3 INFRASTRUCTURE NEEDS

1. Establish a nearshore data bank to archive and exploit existing data. Standard data sets to test and calibrate models are needed. A number of extensive data sets exist, but are not archived adequately, and are thus relatively inaccessible to the community. Common data formats and efficient means of data dissemination via WWW are needed.

2. Establish additional long-term measurement programs. Long-term measurement programs of waves and morphology (e.g., Duck, NC) have proven invaluable in identifying processes important to large scale coastal behavior and provide a setting for shorter term studies. Such programs are usually well beyond the means of individual laboratories. A new long-term observational field program on at least one site having a beach type different than Duck is a national priority.

3. Improve instrumentation for measurements in the nearshore. Long-term funding for instrument development is necessary to bring new techniques to fruition. Development requirements include:

- higher temporal and spatial resolving velocity and sediment measurement instruments using both acoustic and optical techniques,
- rapid measurement techniques of sediment grain size distribution,
- surf zone drifters to complement arrays of fixed flowmeters.

4. Develop a community bathymetric measurement capability. Bathymetry is a primary boundary condition for all nearshore processes, and accurate measurements are needed for all field and modeling studies.

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