The Interaction of Waves, Currents and Nearshore Bathymetry

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Abstract. The nearshore is, by definition, a region where topography has an O(1) influence on fluid processes. These processes range from the evolution of ocean waves as they peak and break over the shrinking depths of the shoaling bathymetry, to the transfer of energy to other motions spanning a wide range of frequencies from mean flows through infragravity motions forced by modulations of incident wave heights, up to surface-injected turbulence associated with plunging breakers. On simple (monotonic) beach profiles, these processes are fascinating and wide ranging. The introduction of complexity in the bathymetry through the addition of one or more offshore sand bars adds new processes that had not been expected and that are not simple extrapolations of monotonic beach dynamics.

The primary difference between nearshore processes and other regions discussed in this 'Aha Huliko'a workshop is that the bottom boundary is not fixed, but responds itself to the overlying fluid motions. Depth changes can be O(1) on time scales as short as a day. Thus understanding the behavior of the nearshore requires understanding of not just the two components (fluid forcing and bathymetric response) in isolation, but of the behavior that is associated with the interaction between these two components. In analogy to other cases, this feedback introduces the possibility that the nearshore acts a nonlinear system with the potential for unusual and even chaotic behavior. Observations are now confirming this possibility. Success will take a combination of exploratory modeling and a strong but simple field program for the collection of long data sets of system behavior.

The Nearshore Problem

The nearshore is defined by its sloping bottom bathymetry, extending from offshore depths that are greater than an incident wavelength (hence effectively infinite) to zero depths at the shoreline. Over this region a shoaling wave field, propagating from the deep ocean toward the beach, will undergo a profound evolution

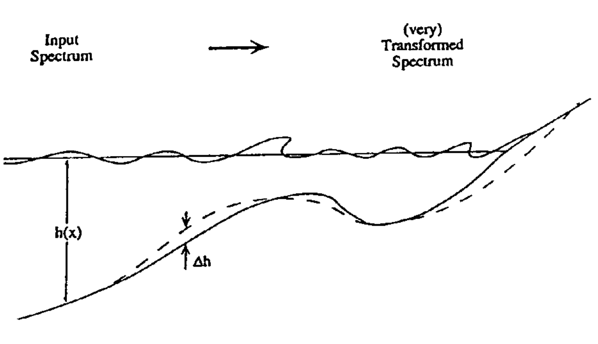


Figure 1. The basic problem in nearshore processes is to understand the shoaling of an incident wave spectrum over a shallowing bathymetry, *h*(*x*). Depending on the nature of the bathmetry, transformations of the fluid field are usually strong, spreading energy across the spectrum. Moreover, these motions will cause a slow, cumulative change in the bottom profile that can easily become significant on the time scale of one day. Feedback between these two components can be substantial. Variability in the longshore dimension (not shown) is generally significant.

(Figure 1). The sight of waves steepening, then pitching over into a turbulent breaker is familiar to all. From a spectral point of view, this transformation drives energy from intermediate, ocean frequencies of order 0.1 Hz to both the higher frequencies of peaky wave forms and turbulence as well as to lower frequencies and even mean flows. Thus, the issue of "flow-topography interactions" is a continual presence in the study of nearshore processes; there are no nearshore processes without the sloping topography of the beach. Thus, for the purposes of this conference the topic of the influence of topography on flow was narrowed to focus on the differences in fluid dynamical processes associated with "complex" topography, particularly the presence of a sand bar or other non-monotonic feature in the beach profile.

However, this approach of examining the fluid processes associated with wave propagation over a fixed but non-simple topography is just one half of the problem. In fact, the beach topography, the bottom boundary condition for the fluid motions, is itself made up of unconsolidated sand that will slowly respond to the overlying fluid motions (Figure 1). While the sediment mobility has no substantial impact on instantaneous fluid processes, sediment transport is cumulative, with the time scale of appreciable bathymetric change being about three orders of magnitude longer than that of fluid motions at the corresponding length scale. If the fluid processes are temporarily considered fixed, then models can be formulated for the tendency of the bottom to change form, for example with the generation of a new sand bar form.

If studies of the nearshore system are motivated by development of a predictive capability, then the interaction aspects of the system cannot be ignored. Fluid processes depend crucially upon bottom topography while bottom topography depends on overlying fluid motions. This feedback is the basis of nonlinear dynamical behavior of the entire nearshore system. To tackle the problem, we must be willing (and able) to explore the nature of the entire nonlinear nearshore system.

This paper will provide a flavor of the progress being made and the problems encountered in the contemporary studies of nearshore processes. In the next section, examples of the interesting physics associated with fluid dynamics over non-monotonic bathymetry will be described. Next, the simple, linear models, traditionally invoked to explain the generation of non-simple bathymetry, will be summarized along with their failures. Then the complications that are expected when feedback of the interaction is allowed will be discussed. Finally, some future research directions will be noted.

The Influence on Complex Topography on Nearshore Flow

All nearshore flows are distinguished by the importance of sloping bathymetry. Numerous review articles have been written (e.g., [*Holman*, in press]) describing progress in the understanding of fluid processes over shoaling bathymetry that is considered fixed (this is the situation for the typical field experiment, where nearshore topography is regularly measured and, for modeling purposes, is considered constant between surveys). The range of interesting physics is large, but one noted example has been the generation of infragravity energy (periods of order 60 s), apparently forced by modulation of the incident wave amplitude. While the frequency and longshore wavenumber characteristics of this forcing appear quite broad-banded, the nearshore response appears well tuned (Figure 2), consisting of resonances of topographically trapped edge waves [*Oltman-Shay et al.*, 1989].

In the past decade, earlier studies on monotonic beach profiles have been extended to more complex, barred beaches through field experiments at Duck, NC, and other sites. In many ways, the influence of the increased complexity has not been substantial, merely leading to kinematic changes to the wave form but no new physics [*Howd et al.*, 1992]. However, for low sloping beaches where the bar appears dynamically to be distant from the shoreline, incident band energy can be refractively trapped to the bar, independent of the shoreline fluid field [*Bryan and Bowen*, in review]. The consequences of these bar-trapped edge wave resonances to the behavior of the overall system remain to be determined.

A perhaps more startling consequence of complex topography was found with the discovery of shear waves in the nearshore at far infragravity frequencies (of order 200 s) [*Bowen and Holman*, 1989; *Oltman-Shay et al.*, 1989]. Shear waves are vorticity waves that arise from the instability of mean longshore currents. They are rigid lid phenomena, with longshore propagation rates slightly slower the peak mean longshore current velocity, at least an order of magnitude slower than the slowest gravity wave of similar frequency (Figure 3).

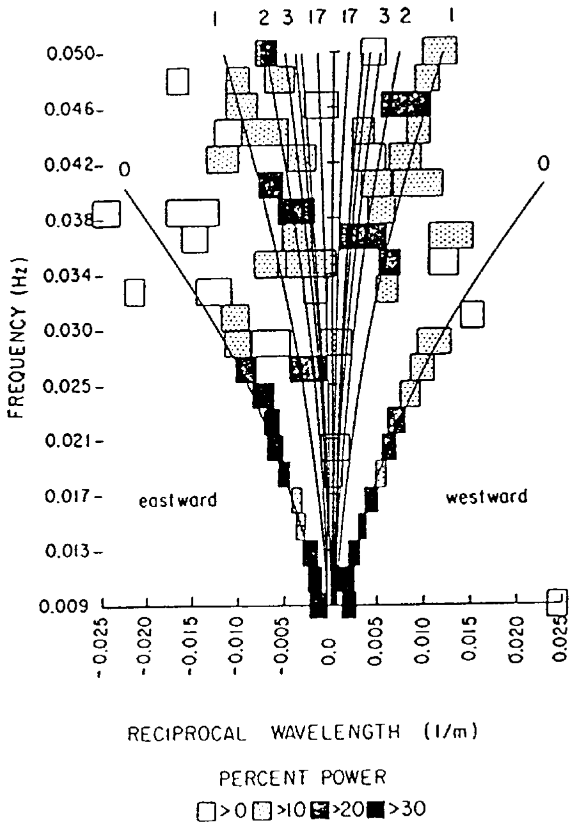


Figure 2. The distribution of wave energy with frequency (vertical axis) and longshore wavenumber (horizontal axis) for a representative day at Santa Barbara, CA, a beach with a monotonic profile. The channel shown is the longshore component of velocity. Through the infragravity band (shown here), the distribution of energy in wavenumber is certainly not broad, instead concentrating strongly at wavenumbers predicted for low mode edge waves (curved lines). From [*Oltman-Shay and Guza*, 1987].

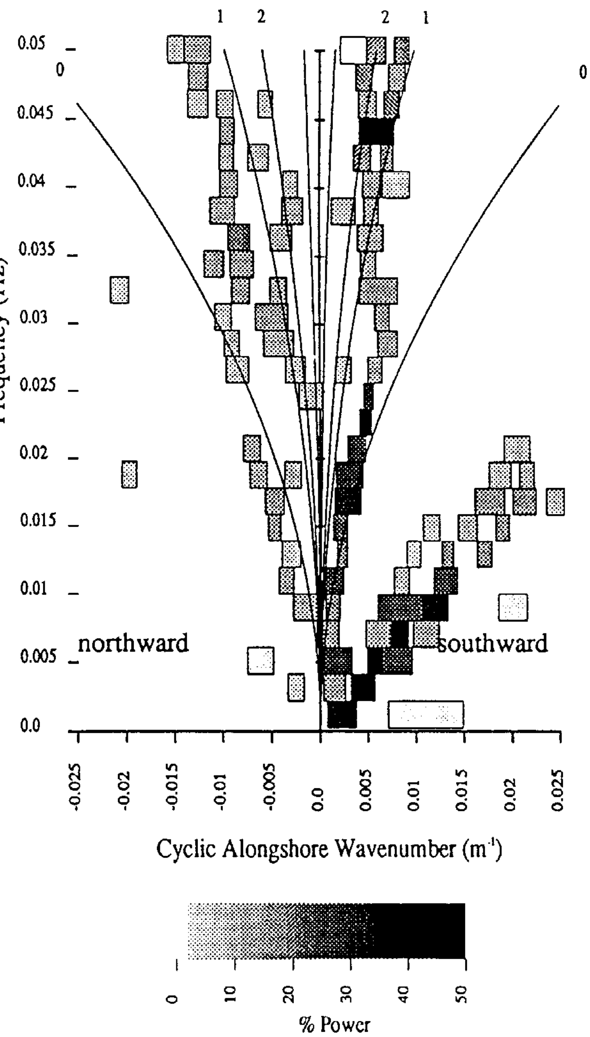


Figure 3. Frequency-wavenumber spectrum of longshore velocity for Duck, NC, a beach with a distinct offshore sand bar. Similar to Figure 2, there is a concentration of energy into narrow bands, associated with edge waves (an offset between theoretical mode lines and the data was later corrected by accounting for Doppler shifting due to the mean longshore current). In contrast to Figure 2, these is also a clear ridge of energy indicating motions progressing to the south at celerities that were substantially too slow to be associated with any gravity wave (the indicated mode 0 dispersion lines are the slowest known gravity wave motions). This ridge represents shear wave energy, driven by an instability of the mean longshore current. From [*Oltman-Shay, et al.*, 1989].

In principle, longshore currents will be unstable on both monotonic and complex beach profiles. However, the strength of the instability depends on the seaward shear of the longshore current jet. On barred beaches, a large shear is forced by wave breaking on the seaward face of the sand bar and the instability is strong. On monotonic beaches, wave breaking is spread over a wide region and the seaward shear is weak; the strength of the instability is weak, barely exceeding frictional dissipation.

Thus, a systematic difference exists in the dynamics of longshore currents between barred and monotonic beaches. The strong shear waves generated over a sand bar have an associated cross-shore Reynolds flux of momentum that serves to diffuse the mean longshore current jet (in fact, there is reason to believe that observed cross-shore profiles of mean longshore current may represent a balance between a jet-like tendency due to strong breaking fixed to the bar crest and a broader form due to the cross-shore mixing of this jet by the shear wave instability whose strength varies with the shear of the jet). Note that the dynamics of this cross-shore mixing would be quite different on a monotonic beach where shear waves play no significant role. Thus, proper modeling of nearshore mixing is fundamentally different on complex versus monotonic beach profiles.

The Influence of Flow on Nearshore Bathymetry

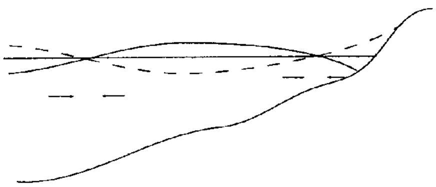
Traditional models for the generation of complexity in nearshore bathymetry have been linear in the sense that a template for sediment transport convergence has been provided by some characteristic of the nearshore flow field. Two popular candidates for producing the template were (a) some change in flow associated with the onset of wave breaking (the break point model), and (b) the nodal patterns of standing wave motions (Figure 4). For the latter, scale analysis showed that standing wave motions of sufficiently large scale to explain natural sand bars were typically of infragravity wave periods. Hence much of the interest in understanding the dynamics of these low frequency waves.

Several problems exist with these simple models. First, the prediction of sediment accumulation according to a particular pattern (for example a sand bar at some cross-shore location) implies that the fluid processes have associated with themselves a single cross-shore scale (or at least a single, simple pattern). Neither models easily fits this criteria. *Holland* [in review] showed that natural infragravity band motions are very broad-banded, with no evidence that spectral peaks are statistically different from that expected for white noise. Thus, there would be no preferred cross-shore scale. For the break point model, natural wave fields have been shown to have wave heights that are Rayleigh distributed such that the location of the onset of breaking will be broadly distributed on monotonic beaches [*Thornton and Guza*, 1983]. While the onset of breaking is concentrated near the bar crest on beaches with a pre-existing sand bar, this is just the response of the fluid to a pre-existing topography, not the reverse.

The latter point illustrates the second problem with "linear" models of sand bar generation; they are limited to

- Establishment of a "template" of sediment convergence by:

a) nodes of standing infragravity waves



b) breakpoint of incident waves

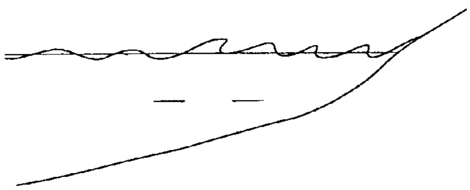


Figure 4. "Linear" models of sand bar generation rely on the slow convergence of sediment toward a pattern (template) that is a function of the fluid field only. Two models associate the template with (a) the nodes of standing wave motions of a particular infragravity frequency, and (b) the location of the onset of incident wave breaking.

small amplitude bathymetric response (the fluid processes are considered fixed and not dependent on slow changes in the bathymetry). In fact, fluid motions are notoriously dependent on the details of the bottom boundary condition. The pattern of wave breaking will vary strongly even for the addition of a small perturbation on a previous simple bathymetry. Similarly, edge waves and other infragravity motions deform kinematically in response to changes in the bathymetry. Thus, linear models for the tendency of a beach profile to change under these fluid influences are limited to now-casting, with predictive capability severely limited by the rapid feedback of small bathymetric changes back into the overlying fluid motions.

The Complete Interaction Problem

The field of nearshore processes is different from other disciplines with respect the to the topic of this 'Aha Huliko'a workshop of fluid topography interactions. Like other discussed GFD problems of the workshop, there is also a substantial and interesting influence of complex topography on nearshore fluid processes. However, unlike other fields, there is also an accompanying response of the topography to the fluids. This response can be on the same order as the local depth in time scales as short as one day.

Thus, the nearshore should be considered as a system with two, fully interacting components. This feedback is one of the primary characteristics of a nonlinear dynamical system. From analogy with other such systems, we realize that these basic nonlinearities can introduce substantial complexity in the system and that our (linear) intuition may not be sufficient even to anticipate the basic phenomenology of the nearshore.

Ample evidence exists that the nearshore system has much more complex behavior than we had previously suspected. For example, long term monitoring in the Netherlands has shown that the ubiquitous multiple offshore bar system there is offshore-progressive, with a period of roughly 4 years on the southern half of the mainland coast, 15 years on the northern half, and a different period on the northern barrier islands (Figure 5) [*Ruessink and Kroon*, 1994; *Wijnberg and Wolf*, 1994]. Such a behavior is not intuitive and has not been a constraint on previous modeling.

Direct observations of the morphology of natural sand bars (the horizontal map pattern of bar crest position) confirm the feared complexity that occurs on natural beaches. For example, at Oregon State University, time exposure imaging of incident wave dissipation patterns has been exploited to study natural morphologies for the past decade [e.g., *Lippmann and Holman*, 1989]. These observations have shown that the simple sand bar morphologies (linear and even crescentic forms) are in the minority and that the most common bar configuration is one that is visually irregular in the longshore [*Lippmann and Holman*, 1990] (e.g., Figure 6).

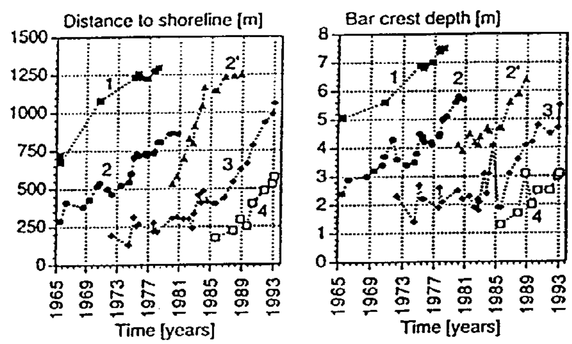


Figure 5. Time variability of the position (a) and depth (b) of the bar crest of a natural bar system on one of the barrier islands on the North Sea Coast of the Netherlands. Bars apparently are formed close to the shore, then propagate steadily offshore to disappear when the bar crest depth reaches about 6 m. Offshore progression was a surprising observation that was only apparent after viewing long time series. From [*Ruessink and Kroon*, 1994].

Figure 6. Example video time exposure taken from Agate Beach, OR, on July 27, 1993. White bands show regions of preferred wave breaking (in taking a ten-minute time exposure, individual wave crests are no longer visible, only their time average dissipation pattern). Dark bands correspond to channels of deeper water, while white bands occur over submerged sand bars (or at the shoreline). The complexity of the bar system in this image is apparent. Substantial variability occurs over short time scales.

The Future - How to Proceed

In analogy to simple nonlinear dynamical systems, we choose to proceed with two approaches. The first is to investigate grossly simplified equations of the system (coupled equations for both the fluid motions over a bathymetry and the bathymetric response to those motions) to study the basic nature of the nonlinearities and to attempt to understand the basic phenomenology inherent in the systems. The emphasis on simplified equations rests on the assumption that the basic behavior (for example, the existence of sand bars and of longshore variability in the bar system) lies with the nonlinearities of the basic equations and is robust to details of the formulation (for example, the details of the wave bottom boundary layer and of sediment transport mechanics).

The second approach is to collect long time series of "system behavior" in order to search empirically for a phase plane in which the behavior is simply understood. This approach is easier to state than to do, with several sources of complication arising. While the use of time exposure techniques (Figure 6) provides a simple, cheap and effective tool for this task (the time series at Duck, NC, the oldest of our stations, now extends to almost one decade), and while the white bands of preferred breaking have been shown to provide a good proxy for crest position of underlying sand bars, there remain complications in interpretation of these data. Primary among these is the need to develop simple metrics of system state (bathymetry is a fully two dimensional field; we need to reduce dimensionality to at most one dimension, but preferably to a few scalar descriptors that can be easily visualized and compared to models). We cannot begin to search for simplifying phase plane representations until the metrics are identified (and the most useful metrics are those that will provide a simplifying phase plane representation!). The situation is further complicated by the need for appropriate non-dimensionalization so that beaches lying in different regions of dimensional parameters space (e.g., different climatological wave height or period) and with visually different behavior can be understood in some universal sense.

Conclusions

The nearshore is, by definition, a region where fluid-topography interactions define the active processes. On simple (monotonic) beach profiles, these processes are fascinating and wide ranging. The introduction of complexity in the bathymetry through the addition of one or more offshore sand bars adds new processes that had not been expected and that are not simple extrapolations of monotonic beach dynamics.

The real distinguishing feature of the nearshore is that the bottom boundary for the flow, the underlying sediment, is movable and depth changes can be O(1) on time scales as short as a day. This feedback of the flow back into the topography makes the nearshore system a nonlinear system with the potential for unusual and even chaotic behavior. Observations are now confirming this possibility. Success will take a combination of exploratory modeling and a strong but simple field program for the collection of long data sets of system behavior.

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