Role of morphologic feedback in surf zone sandbar response

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Abstract. Several aspects of feedback mechanisms associated with surf zone sandbar response have been characterized using bathymetric surveys, sampled approximately monthly over a 16-year period at the Army Corps of Engineers' Field Research Facility (North Carolina). The measured bathymetry was alongshore averaged and modeled by the superposition of two Gaussian-shaped sandbars on an underlying planar slope. A third, half-Gaussian-shaped bar represented steepening at the shoreline. The rms error between the measured bathymetry and the profile model was 0.10 m (estimated over 322 different surveys). The model explained 99% of the profile variance that remained after first removing the linear, cross-shore trend from each observed profile. Bar response, which was extracted from the modeled profiles, was compared to a local hydrodynamic forcing variable \( \Gamma \) (\( \Gamma \) was defined as the ratio of the wave height to water depth, evaluated at bar crest locations). At low values of \( \Gamma \) (i.e., nonbreaking conditions), bars migrated onshore, and their amplitude tended to decay. At high values of \( \Gamma \) (i.e., breaking conditions), bars migrated offshore, with relatively little change in amplitude. The transition between onshore and offshore migration occurred at a value of \( \Gamma \) that was consistent with the onset of wave breaking. Bar migration was associated with a stabilizing feedback mechanism, which drove bar crests toward an equilibrium position at the wave breakpoint. However, we observed that the rate of bar response showed no reduction for any nonzero choice of \( \Gamma \), indicating that bars never reached equilibrium. Systematic bar amplitude decay was observed under nonbreaking conditions. Bar amplitude decay could drive \( \Gamma \) farther away from breaking conditions, allowing further bar amplitude decay. This is a destabilizing feedback mechanism, potentially leading to bar destruction.

1. Introduction

1.1. Description of Feedback

Determination of the processes controlling the generation and temporal evolution of alongshore-uniform sandbars (Figures 1–3) remains a challenge for nearshore researchers. This problem is difficult because of the great complexity of the sediment transport and hydrodynamic processes that drive changes in sandy nearshore bathymetry. This complexity is conformed by the inherent interaction of evolving morphologic features, such as sandbars, with the processes that shape them. For example, once they have formed, sandbars exert a strong control over the location of wave breaking [e.g., Lippmann and Holman, 1989]. Clearly, a change in the shape or position of a sandbar will alter the wave breaking patterns. As the bathymetry responds, modification of the sediment transport patterns over the bar may reinforce or suppress further bathymetric modification, corresponding to positive or negative morphologic feedback, respectively. The goal of this paper is to use field observations to quantitatively and qualitatively describe the importance and impact of feedback on the behavior of nearshore sandbars.

We will consider an alongshore-uniform beach, whose temporal evolution is described by the conservation equation

\[
\frac{\partial}{\partial t} Z(x, t) = -\frac{\partial}{\partial x} Q(x, t),
\]

where \( Z \) is the bed elevation and \( Q \) is the depth-integrated, volumetric (corrected for bed porosity) sediment transport per unit alongshore width. Both \( Q \) and \( Z \) are functions of cross-shore position \( x \) and a slow, morphologic time variable \( t \). The slow time variable is used to separate variability occurring on a morphologic timescale \( T_m \) from variability occurring on a hydrodynamic timescale \( T_H \). If we consider forcing by wind waves, where \( T_H \sim O(10 s) \), the morphologic time is related to time measured in seconds \( t' \) as \( t = t'/T_m \), where \( T_m \gg T_H \). This separation of scales implies that we consider morphologic response averaged over, at least, many wave cycles. For the features that we are considering, there are probably at least 3 orders of magnitude difference in \( T_m \) and \( T_H \) [Holman, 1999].

Local water velocities may induce transport of sand grains in a net onshore or offshore direction. If we consider forcing by incident waves, then the local velocities depend on both the incident wave conditions and on the bathymetry, which serves as a bottom boundary condition to the hydrodynamic problem. The transport is also a function of sediment properties, such as grain size and density. Grain properties clearly play an important role in the transport formulation [Bagnold, 1963]. However, grain properties may be constant in time [e.g., Gallagher et al., 1998], and for the purpose of simplifying this problem we will not consider these effects. In this case a generalized transport relationship is

\[
Q(x, t) = f[U(x, t)] = f[Z(x, t), H_s(t)],
\]
where $U$ describes the near-bed velocities and $H_w$ describes the time-varying incident wave field, which may be multivariate and include, for example, wave height and wave period. $H_w$ describes conditions at the seaward boundary of our domain and does not depend on $x$.

Inserting (2) into (1) yields an expression containing the morphologic feedback in this system, which describes how the change of morphology is related to the morphology itself:

$$\frac{\partial}{\partial t} Z = - \frac{\partial}{\partial Z} f[Z, H_w] \frac{\partial Z}{\partial x} = g[Z, H_w].$$  \hfill (3)

The function $f$ is differentiated only with respect to $Z$, since $H_w$ does not depend on $x$. The function $g$ does not contain explicit reference to the slope term ($\partial Z/\partial x$), since we assume that this can be derived from the bathymetry, which is differentiable. For example, the bathymetry function ($Z$) could be represented by a Fourier series, and the slope is simply a function of the Fourier coefficients. All of the information about feedback is contained in the unknown function $g$. However, (3) describes only the instantaneous response of the bathymetry. It does not describe the role that feedback plays in shaping the time evolution of this system.

The time evolution of (3) can be approximated by linearizing about a particular time, $t_0$:

$$\frac{\partial}{\partial t} Z_1(x, t - t_0) = g[Z_0 + Z_1, H_w]_{t_0} + (t - t_0)$$

$$\left\{ \left. \frac{\partial g}{\partial H_w} \right|_{t_0} + (t - t_0) \left. \frac{\partial g}{\partial Z_1} \right|_{t_0} \right\} + O(t - t_0)^2$$

$$+ \mathcal{O}\left( \frac{\partial}{\partial t} Z_0 \right).$$  \hfill (4)

Since we are interested in the feedback associated with the evolution of sandbar patterns, the actual bathymetry has been decomposed into a presumably unchanging (or very slowly changing) and featureless component ($Z_0$) and a more dynamic (but still slow compared to hydrodynamics) bar component ($Z_1$) such that $Z = Z_0 + Z_1$. The assumption made here is that changes in $Z_0$ can be neglected over short time intervals. However, $Z_0$ can influence the response of the bar component. For instance, it matters whether a sandbar is close to the shore and in shallow water or far from shore and in deeper water. It is essential to note that (4) does not present the response to an infinitesimal small perturbation, $Z_1$ (as is the case in linearized stability analyses; see section 1.2). Instead, we assume that $Z_1$ is finite and the inherent nonlinearity in the system prevents an explicit description of the time evolution for time intervals that are "large."

The role played by each of the forcing terms on the right-hand side of (4) in governing profile evolution can be identified qualitatively. The first forcing term on the right-hand side of (4) describes a sort of template model, in which the formation or modification of a bar pattern, $Z_1$, depends only on the initial bathymetry (both $Z_0$ and $Z_1$) and initial, incident wave conditions. This term lacks time dependence and does not contain any feedback mechanisms that might, for instance, allow the evolution of $Z_1$ to reach steady state. If the first forcing term were everywhere zero, then (neglecting the other terms) the corresponding $Z_0$ and $Z_1$ are in equilibrium with respect to the incident wave conditions. The second forcing term describes the modification of the template due to an externally forced change in the wave conditions. The third forcing term contains the linearized feedback that is associated with an initial modification of the bar pattern. Depending on the spatial structure and sign of the term $\partial g/\partial Z_1$, the bar evolution may be enhanced (positive feedback) or suppressed (negative feedback) with increasing time.

### 1.2. Sandbar Models

#### 1.2.1. Template models

Explanations of sandbar formation and evolution can be found in a variety of models reported in nearshore literature. These models can be organized by relating them to the generalized model described by (4). Early sandbar models were based on a hydrodynamic template approach (i.e., using only the first term on the right of (4)), in which the onshore/offshore location of the bar crest was somewhat arbitrarily related to a characteristic scale of the forcing field. For example, the popular breakpoint model [King and Williams, 1949; Daily, 1987] suggested that sand should accumulate under the location of initial wave breaking. Similarly, sediment convergence might form bars at the cross-shore location of nodes or antinodes of standing wave motions [Short, 1975; Bowen, 1980]. Template models may identify compelling mechanisms for the initial stages of bar formation on an otherwise featureless sloping bed. A template model might be appropriately compared to a wave tank experiment in which a thin layer of sand, sprinkled over a hard bottom, would be rearranged into the predicted bar pattern [e.g., Gusa and Inman, 1975].
1.2.2. Equilibrium models. Morphologic equilibrium results when gradients in sediment transport vanish, resulting in no deposition or erosion of the sediment bed (i.e., forcing terms on the right in (4) sum to zero). By combining a specific hydrodynamic model (such as one describing the spatial distribution of currents beneath infragravity waves) and a specific sediment transport formulation, bar patterns, cross-shore beach profiles, and plan shapes corresponding to an equilibrium bathymetry can be estimated quantitatively [Bowen, 1980; Holman and Bowen, 1982; Bowen and Huntley, 1984; Larson et al., 1999]. Holman and Bowen [1982] computed complicated sandbar patterns that were in equilibrium with respect to transport driven by edge wave drift velocities. In their particular case a planar profile was used to calculate the patterns of the edge wave field, but the hydrodynamic patterns were not modified by the bathymetric perturbation. This sort of equilibrium model represents a form of template model, since an imposed hydrodynamic process shapes the predicted bathymetry.

There is a major restriction on the applicability of equilibrium models. The equilibrium patterns are expected to match patterns seen in nature only if the equilibrium patterns are stable. That is, regardless of initial beach shape, beach morphology must adjust itself toward equilibrium. This requirement seems especially difficult to meet in the case of complicated looking equilibrium configurations. Furthermore, it is not clear how to interpret equilibrium predictions in the presence of ever changing forcing.

1.2.3. Instability models. Instability models [Smith, 1970; Huthnance, 1982; Hulscher et al., 1993; Trowbridge, 1995] provide an alternative method for predicting the evolution of bathymetric patterns. These models assume that an existing, often simple looking equilibrium state may be unstable to perturbations (i.e., third forcing term on right-hand side of (4) is nonzero; all others are zero). Contrary to the template models, the perturbations occur simultaneously in the hydrodynamic and bathymetric fields. This distinguishes the instability models from the template model, which may utilize a hydrodynamic pattern formed via a purely hydrodynamic instability mechanism, e.g., rip channel formation due to a rip current instability [Bowen, 1969; Bowen and Inman, 1969]. Trowbridge [1995], for example, presented a model for the formation of oblique sand ridges due to the instability of an initially alongshore-uniform bathymetry and alongshore current. To our knowledge, a linear stability analysis has not been applied to sandbar formation due to a natural (i.e., random) wave field, although such an analysis appears to be within reach [Falques et al., 1998; see also Vittori et al., 1999].

A very attractive feature of a linear stability analysis is that the feedback mechanisms that produce bathymetric evolution are exposed. That is, for a particular small change in the bathymetry an accompanying small change in the hydrodynamic field is identified. The hydrodynamic response may act via its effect on the sediment transport patterns to reinforce or suppress the growth of the bathymetric perturbation. The template models do not address the feedback at all, while the equilibrium models assume, without justification, that negative feedback suppresses the growth of perturbations so that even very complicated equilibrium states persist.

1.3. Analysis Approach

Our strategy for describing the feedback in an observed nearshore sandbar system is to compare a particular form of the linearized model (equation (4)) to a time series of bathymetric surveys. Using these data, we extract characterizations of the unknown function \( g(Z_0 + Z_1, H_m) \) and then use these characterizations to interpret the role played by feedback in
governing morphologic evolution. The comparison must quantitatively isolate the relationship between the observed pattern of bar response (measured in terms of bar position and bar amplitude changes) and the bar pattern itself. Also, the comparison must isolate the additional dependence of bar response on time-varying hydrodynamic conditions, which we somewhat arbitrarily choose to parameterize by the rms wave height to water depth ratio, evaluated at bar crest locations. Because the water depth at the bar crest depends on the position and amplitude of the bar, the feedback associated with bar response can be interpreted qualitatively from these results.

In order to objectively define sandbars and to separate them from the profile as a whole we define a cross-shore beach profile model (section 2.1), which parameterizes the morphology in terms of the superposition of an underlying slope component and several Gaussian-shaped bars. To provide a clear physical interpretation of our results, the analysis is cast in terms of sediment transport patterns, which must drive sandbar evolution. Then, the profile model is used to define characterizations of the relationships between sediment transport patterns and bar patterns (section 2.2). In section 3 the profile model is fit to a series of bathymetric surveys obtained at the Army Corps of Engineers’ Field Research Facility (FRF). In
section 4 the forcing parameterization is computed using the profile data and corresponding wave field measurements. In section 5 the transport characteristics are computed and described as a function of the time-varying forcing. In section 6 we infer the role that feedback played in governing several aspects of bar response. Conclusions are presented in section 7.

2. Sandbar Model

2.1. Profile Model

Often, sandbar response has been defined solely in terms of changes in bar crest position [Birkemeier, 1985; Lippmann and Holman, 1990; Lippmann et al., 1993; Ruessink and Kroun, 1994; Plant et al., 1999]. This definition neglects changes in bar amplitude, cross-shore length scale of the bar, or other measures of bar shape. In other cases, bar shape has been described in terms of bulk statistical measures, such as bar volume [Larson and Kraus, 1992] and symmetry of the bar form [Ruessink and Kroun, 1994]. A clear drawback of these approaches is that the profile cannot be reconstructed from the statistical descriptions. As we will show, we need to reconstruct the profile in order to quantify the sediment transport patterns that are associated with bar response.

Another commonly used approach to statistical description of sandbars is the decomposition of profile variability using empirical orthogonal functions (EOFs) [Winant et al., 1975; Aubrey, 1979; Birkemeier, 1985; Wijnenberg and Terwindt, 1995]. While this technique is clearly an efficient way to represent profile variability [Davis, 1976], EOFs do not necessarily focus an analysis on individual sandbars. A particularly difficult case to interpret using EOFs is that of a profile having multiple crossshore adjacent bars, which may respond differently. For instance, adjacent bars have been observed to migrate at different speeds at the FRF field site [Plant et al., 1999].

Thus we are driven to find a set of functions that decompose a profile into spatially localized bars that are separated in scale from a residual profile. Although not necessarily unique, a representation of such a barred beach profile, \( \mathcal{Z}(x, t) \), can be constructed from several Gaussian functions, superimposed upon a plane beach (Figure 1):

\[
\mathcal{Z}(x, t) = b_0(t) + b_1(t)x + \sum_{m=1}^{M} A_m(t) \exp \left[ -\left( \frac{x - X_m(t)}{L_m} \right)^2 \right] + A_s(t) \exp \left[ -\left( \frac{x - X_s}{L_s(t)} \right)^2 \right],
\]

where \( x \) is the distance increasing offshore and \( t \) is the time. The first two terms, \( b_0 \) and \( b_1 \), describe the vertical offset and slope of a plane beach (e.g., \( Z_0 \)) in (4). The third term describes multiple Gaussian-shaped bars (e.g., \( Z_2 \)), where \( A_m, X_m, \) and \( L_m \) are objective definitions of the amplitude, position, and length of the \( m \)th bar. Although it is not necessary, bar lengths are assumed to be constant in time. This assumption did not significantly diminish the model's ability to describe observed beach profiles. The fourth term in (5) describes an additional half-Gaussian bar placed near the shore (constant position, \( X_s \)). Via changes in amplitude, \( A_s \), and length, \( L_s \), the shoreline, half-Gaussian bar allows sediment fluxes into and out of the intertidal and subaerial beach and accommodates changes in shoreline slope.

One apparent drawback to this model is that the elements are not orthogonal. That is, an increase in bar amplitude may require a corresponding change to the mean beach slope in order to conserve mass. While this would be a drawback if we were attempting to interpret all elements in isolation, the following analysis keeps track of all such cross terms and provides analytically correct equations for the quantities of interest.

2.2. Sediment Transport Patterns

The parameterized bathymetry can be used to estimate cross-shore sediment transport patterns over an evolving beach profile by inserting the profile model definition (equation (5)) into the left-hand side of (1) (i.e., \( \mathcal{Z}(x, t) = \mathcal{Z}(x, t) \)) and integrating over \( x \). Analogous to our derivation of (4), we linearize the flux expression by replacing the time-dependent terms on the right-hand side of (5) with the first terms of their Taylor series expansions about an arbitrary point in time, \( t = t_0 \):

\[
b_0(t) = b_0(t_0) + (t - t_0) \beta_0(t_0),
\]

\[
b_1(t) = b_1(t_0) + (t - t_0) \beta_1(t_0),
\]

\[
A_m(t) = A_m(t_0) + (t - t_0) \alpha_m(t_0),
\]

\[
X_m(t) = X_m(t_0) + (t - t_0) c_m(t_0),
\]

\[
A_s(t) = A_s(t_0) + (t - t_0) \alpha_s(t_0),
\]

\[
L_s(t) = L_s(t_0) + (t - t_0) \lambda_s(t_0).
\]

Here \( \beta_0, \beta_1, \alpha_m, c_m, \alpha_s, \) and \( \lambda_s \) are the time derivatives (evaluated at \( t = t_0 \)) of the profile parameters \( b_0, b_1, A_m, X_m, A_s, \) and \( L_s \), respectively. At \( t = t_0 \) the flux pattern over an evolving profile that is described by (5) is

\[
Q(x, t_0) = -\beta_0(t_0)x - 0.5 \beta_1(t_0)x^2 + \sum_{m=1}^{M} Q_m(x, t_0)
\]

\[+ Q_s(x, t_0) + \text{const.}(t_0),\]

where the terms \( Q_m \) and \( Q_s \) correspond to the transport resulting from changes in the surf zone bars

\[
Q_m(x, t_0) = c_m(t_0) A_m(t_0) \exp \left[ -(x - X_m(t_0))^2 \right] - \frac{\sqrt{\pi}}{2} \alpha_m(t_0) \frac{L_m}{L_m} \text{erf} \left( \frac{x - X_m(t_0)}{L_m} \right)
\]

and the shoreline “bar”

\[
Q_s(x, t_0) = \lambda_s(t_0) A_s(t_0) \left( \frac{x - X_s}{L_s(t_0)} \right) \exp \left[ -(x - X_s)^2 \right] - \frac{\sqrt{\pi}}{2} \lambda_s(t_0) A_s(t_0)
\]

\[+ \alpha_s(t_0) \frac{L_s(t_0)}{L_s(t_0)} \text{erf} \left( \frac{x - X_s}{L_s(t_0)} \right).
\]

Here \( \text{erf} \{x\} \) is the error function evaluated at \( x \). The constant term in (7a) satisfies a boundary condition. For instance, the transport at the offshore boundary is typically assumed to be
zero. However, the constant term will not be evaluated. It does not contribute to the analysis presented in this paper, which pertains to sediment transport gradients over bars. Note that the temporal linearity about \( t = t_0 \) does not imply that time derivatives of the bathymetry are assumed to be small. Instead, we assume that time derivatives are constant over some short (compared to the morphologic timescale) time period. In practice, this short time period will be the period spanned by two consecutive beach surveys.

Equation (7b) has two terms. The first term describes the transport resulting from the migration of a Gaussian-shaped bar whose amplitude is fixed. The shape of the sediment transport pattern associated with the migration of a bed form whose shape is arbitrary but unchanging is always identical to the bed form shape [Bagnold, 1941] (Figure 2). The amplitude of the transport pattern associated with bar migration depends only on bed form height and the bed form migration speed. The second term in (4b) describes the transport pattern associated with a growing or decaying Gaussian-shaped bed form whose position is fixed. In this case, sediment transport convergence (or divergence) reaches a maximum over the bar crest (Figure 2), and the spatial structure of this component is described by the error function. For a bar whose length is fixed, the amplitude of the transport pattern associated with bar growth or decay depends only on the growth rate.

We shall describe the relationship between sediment transport patterns and bar patterns by drawing an analogy to Fourier analysis. Noting that the error function is an odd function and the Gaussian function is an even function, the transport pattern associated with bar growth/decay must be spatially uncorrelated to the transport associated with migration. We can rewrite the transport associated with bar response in terms of magnitude \((q_m)\) and phase shift \((\phi_m)\):

\[
Q_m(x, t_0) = q_m(t_0) \left\{ \cos[\phi_m(t_0)] \exp \left[ -\left( \frac{x - X_m(t_0)}{L_m} \right)^2 \right] + \sin[\phi_m(t_0)] \text{erf} \left( \frac{x - X_m(t_0)}{L_m} \right) \right\}. \tag{8}
\]

Here the transport magnitude describes the rate of bar response in terms of the combined sediment transport due to bar migration and bar growth/decay and is defined as

\[
q_m(t_0) = \left[ (\pi t_0 A_m(t_0))^2 + \left( \frac{1}{2} \alpha_m(t_0) L_m^2 \right)^2 \right]^{1/2}. \tag{9}
\]

The transport phase shift, \(\phi_m\), can be interpreted as the spatial shift between sediment transport patterns and the underlying bar pattern and is defined as

\[
\phi_m(t_0) = \tan^{-1} \left( \frac{\sqrt{\pi} \alpha_m(t_0) L_m}{2 \pi t_0 A_m(t_0)} \right). \tag{10}
\]

A phase shift of 0 indicates a transport maximum lying over the bar crest, which corresponds to offshore migration in our coordinate system. A phase shift of \(\pi\) corresponds to onshore migration. If phase shifts are \(\pm \pi/2\), then transport gradient maxima correspond to the bar crest locations, corresponding to either bar growth or bar decay. Thus the sediment transport phase shift succinctly describes the relationship between bar patterns and transport patterns, and it describes the nature of bar response.

Equation (4) was derived from an assumption that the evolution of the underlying featureless profile evolved slowly with respect to the bar component. We test this assumption via a measure of the spatial correlation between a transport pattern associated with the response of a particular bar (i.e., \(Q_m\)) and the transport pattern associated with evolution of the entire profile \((Q)\). If the correlation is large (near 1), then profile response is accurately described in terms of changes in bar amplitude and position alone, and we can neglect the larger-scale morphologic evolution. The transport correlation, \(r_m\), is defined as

\[
r_m(t_0) = \frac{\text{Cov} [Q_m(t_0, x) Q(t_0, x)]}{\sqrt{\text{Var} [Q(t_0, x)] \text{Var} [Q_m(t_0, x)]}}. \tag{11}
\]

To retain the localized character of our analysis, \(r_m\) is estimated only over the range \(-2 L_m < [x - X_m(t_0)] < 2 L_m\).

In this range, values of the Gaussian profile are at least 2% of the maximum value. The statistical measures \(r_m, q_m\), and \(\phi_m\) will be estimated from field data, and they will be used to quantify bar response.

3. Sandbar Observations

3.1. Profile Data

The data set used to examine bar response and morphologic feedback consists of 16 years of surveyed beach profiles that have been collected since 1981 at the FRF, near the down of Duck, North Carolina. The surveys were sampled on biweekly to monthly intervals over a region spanning \(-1\) km alongshore and \(1\) km offshore (to at least \(8\) m water depth). Monthly cross-shore profiles, separated by \(40\) m alongshore, were sampled by the Coastal Research Amphibious Buggy (CRAB), which has a \(10\) m footprint and survey precision of \(\pm 10\) cm in the vertical [Birkemeier and Mason, 1984]. For dates prior to 1993, additional biweekly surveys were available but only along two transects at the southern end of the study area \((y = -92, 0\) m) and two at the northern end \((y = 1006, 1096\) m). Figure 3 shows a contour map and two cross-shore profiles generated from a typical survey.

Temporal variability of the bathymetry at this site has been attributed primarily to the cross-shore migration and amplitude variations of surf zone sandbars [Birkemeier, 1985; Lippmann and Holman, 1990; Lippmann et al., 1993; Thornton et al., 1996; Gallagher et al., 1998; Plant et al., 1999]. Alongshore-uniform response dominates the bathymetric changes at the FRF site (and elsewhere [e.g., Wijnberg and Terwindt, 1995]). Lippmann and Holman [1990], for example, used a 2-year sequence of daily video images of the FRF beach to show that the alongshore-averaged bar position explained 80% of the total temporal variation in bar crest position. Plant et al. [1999] analyzed the 16-year FRF bathymetric data set and showed that temporal variations in the alongshore-averaged profile explained over 80% of the temporal variability of the bathymetry. This result was obtained from two regions that spanned 300 m in the alongshore direction and were located more than 200 m from a research pier in order to avoid known bathymetric anomalies. The present analysis focuses on the region north of the research pier \((y = 776 \text{ m to } 1096 \text{ m, Figure 3}).

3.2. Profile Modeling

The profile model (equation (5)) was fit to alongshore-averaged profiles (Figure 1) by choosing the profile parameters which minimized the squared deviation between modeled and observed profiles. The position of the shoreline bar was fixed at \(X_s = 50\) m. The length scales \((L_m)\) of the inner and outer bars
were fixed at values of 50 m for inner bars and 150 m for outer bars (these constants were typical values determined from an initial analysis in which these parameters were allowed to vary). Profile data whose elevations fell between −8 m (relative to National Geodetic Vertical Datum, 1929 [Zilko ski et al., 1992]) and +4 m were used, and the model was fit to each of 322 surveys. Eight parameters \((b_0, b_1, A_1, X_1, A_2, X_2, A_t, L_t)\) were estimated for each survey. Since the profile model was nonlinear in the free parameters, a nonlinear regression technique (Gauss-Newton method) was used.

The rms error between model and observed profiles (Figure 4) estimated over the entire data set was 0.10 m. The rms error was estimated as

\[
\text{rmse} = \left\{ \sum_{t} \sum_{x} \left[ (\hat{Z}(x, t) - Z_e(x, t))^2 / N_e(t) \right] / N_t \right\}^{1/2},
\]

where \(Z_e(x, t)\) are the surveyed data, \(N_t\) are the number of survey times, and \(N_e(t)\) are the number of observations used from the \(t\)th survey. The rms error between a particular profile and the profile model never exceeded 0.23 m, and the rms errors associated with 90% of the profiles were <0.12 m (Figure 4a). These errors were small relative to the variance explained by the model.

There were several periods when the rms error was relatively high. Two of these periods (February 1989 to February 1990 and January 1996 to August 1996) were particularly interesting because they marked periods of system transition associated with the decay of the outer bar. Two complications arose at these times. First, the outer bars did not simply decay but tended to merge with the inner bars, forming single asymmetric bars (Figure 5), which was difficult to interpret with the model. Second, a new inner bar began to form near the shoreline, which required an additional (but unavailable) bar in the
model. Outer bars were tracked until their amplitudes became negligibly small. Then, the model was reinitialized by manually entering the parameters describing the two most substantial bars.

3.3. Transport Modeling

To estimate the sediment transport statistics using (9), (10), and (11), estimates of both the profile parameters (i.e., \( b_0, b_1, A_m, X_m, A_s, L_s \)) and their derivatives (i.e., \( \beta_0, \beta_1, \alpha_m, c_m, \alpha_s, \lambda_s \)) are required. The profile parameters were first low-pass filtered using a Hanning filter (width of 60 days) and then linearly interpolated to each \( t_0(i) = (t_r + t_{r+1})/2 \), where \( t_r \) corresponds to the time of the \( r \)th survey. A backward difference approximation was used to estimate the time derivative terms from the low-pass-filtered profile parameters. The primary purpose of the low-pass filter operation was to minimize sampling errors, which would have been amplified by the differencing operation. The transport correlation, magnitude, and phase shift (\( \tau_m, q_m \), and \( \phi_m \)) were then calculated for all consecutive survey pairs and for all bars.

4. Forcing Parameterization

As indicated by (2)–(4), the processes driving bar response depend on the offshore water wave height as well as the bathymetry responsible for wave transformations due to shoaling and breaking. The ability for an outer bar to affect the wave climate at an inner bar adds a complication to our analysis, which focuses on individual bars. A useful wave-forcing parameterization is one that facilitates an interpretation of the processes affecting a particular bar, such as wave breaking. We can then interpret how a particular morphologic response, such as bar migration, would affect the forcing.

We choose to parameterize the hydrodynamic forcing over a sandbar with the ratio of the local rms wave height, \( H_{rms} \) to water depth, evaluated at the bar crest location. The variable \( \Gamma_m \) represents this ratio for the \( m \)th bar, such that

\[
\Gamma_m(t) = \left[ -H_{rms}(x, t)/Z(x, t) \right]_{x=X_m}.
\]

(13)

\( \Gamma_m \) is interpreted as the local intensity of wave breaking [Thornton and Guza, 1983]. Wave heights become saturated (depth limited) in the surf zone, and \( \Gamma_m \) tends to reach a maximum value [Thornton and Guza, 1982], which we will call \( \gamma_s \). Previous studies at the FRF site determined that \( \gamma_s \) ranged from 0.25 to 0.4, depending on the local beach slope and water depth [Saltenger and Holman, 1985; Saltenger and Howel, 1989; Haines and Saltenger, 1994; Raubenheimer et al., 1996]. The lower values were associated with deeper water and flatter bottom slopes. The role of wave breaking in sandbar evolution will be interpreted by comparing \( \Gamma_m \) to \( \gamma_s \).

Over the 16-year period spanned by beach surveys, significant wave heights were recorded by three different wave gages (Figure 6a), none of which were necessarily located over bar crests. A simple wave transformation model [Thornton and Guza, 1983], which includes energy dissipation due to wave breaking and linear wave shoaling, was used to estimate \( H_{rms} \) across the entire cross-shore profile. The wave model required specification of two free parameters, which have been calibrated previously at the FRF by (among others) Haines and Saltenger [1994]. We use their values for a critical wave height saturation (\( \gamma_{model} = 0.34 \)) and efficiency of dissipation (\( B_{model} = 0.8 \)), neglecting small cross-shore variability in the choice of optimal parameter values.

To obtain wave height estimates, the wave model required as input an initial offshore wave height, a peak wave period, and a bathymetric profile. The model could be initialized with each available wave height record, and a corresponding wave height profile could be calculated. To reduce the computational effort, rms wave height profiles were estimated once per day, using the daily-averaged rms wave heights and periods as the initial values in the model. Data from gage 625, located at the end of the FRF pier (Figure 6), were used (when available) to initialize the wave model. If data from this gage were not available on a particular day, data from a pressure gage in 8 m depth (gage 3111) or from a Waverider buoy located in 17 m depth were selected. Preference was given to the shorewardmost gage.

The beach profiles used to calculate the wave height transformations on each day were reconstructed from the filtered and temporally interpolated profile model parameters (i.e., \( b_0, b_1, A_m, X_m, A_s, L_s \), where the tilde represents the filtered version of the original variables). In addition to being an efficient method of time interpolation this method preserved the amplitude of migrating bars. An alternative approach, interpolating the elevations at each cross-shore location, is inefficient and would tend to damp the amplitude of migrating bars. (If, between surveys, a bar migrated through a distance of one-half "wavelength," bar and trough elevation would cancel in the average, and the mean profile could be unbarred.) The wave transformation model was run over each interpolated profile, and values of \( \Gamma_m(t) \) were extracted for all sandbars at \( x = X_m(t) \).

Several tests were performed to verify the wave model's ability to make accurate predictions. Despite large differences...
between the wave heights at the seaward gage (gage 3111) and the shallow gages (gages 641 and 625) due to intervening wave breaking (Figures 7a and 7b), heights were well predicted by the wave transformation model (Figures 7c and 7d), which was initialized with measured offshore wave heights. The rms prediction error was reduced from 0.8 m (no model correction) to 0.2 m at the inner gage (gage 641). Estimates of pier-end wave heights (gage 625) were best for wave heights <1.5 m (Figure

Figure 7. Wave transformation model errors and comparison of predicted and observed wave heights. Each bathymetric survey and all wave heights observed within 3 days of a particular survey were used in the comparison. (a and b) comparison of the wave heights measured at gage 3111 to the heights measured at shallower water locations. (c and d) Comparison of the wave model predictions to the shallow water observations.
Figure 8. Sensitivity of wave height estimates to variations in wave angle. (a) Bathymetry over which the sensitivity test was run, the bar crest location where wave heights were extracted from the model (dashed, vertical line), and the wave gage location (circle). (b) Modeled rms wave height for two different incidence angles and two different offshore wave heights. (c) Ratio of the wave height estimated by including wave refraction to the estimate without refraction.

7c). We attribute the underprediction for larger wave heights to overestimates of wave breaking over the input bathymetry (which came from observations north of the pier) compared to the known trough in the pier region (Figure 3a).

Since wave angle estimates were not available at all gages, normally incident waves were assumed in all cases. The sensitivity of wave height prediction errors to variations in wave angle was explored using the wave transformation model and an example profile, which had only one prominent sandbar (Figure 8). The model was run with several initial, offshore wave heights, periods, and angles. Each case was compared to the model run having identical initial height and period but zero incidence angle (Figures 8b and 8c). Large waves propagating over this bathymetry resulted in estimated rms wave...
Because we do not have an explicit model that relates forcing and response, we have little guidance for choosing the most appropriate single value of \( \Gamma_m \) (estimated once per day) to compare with each estimate of bar response (estimated once per month). We attempt, however, to treat the forcing and response data sets consistently. Because the sediment transport statistics that we have estimated depend on a filtered version of the profile response, a representative measure of the forcing parameter, \( \Gamma_m \), must be filtered as well. While the computation of \( \Gamma_m \) depended on filtered profile model parameters (e.g., \( X_m \)), the short-term fluctuations in \( \Gamma_m \) associated with rapid changes in the wave height do not reflect the filtering operation. To remedy this situation, the filter was applied to the time series of \( \Gamma_m \) estimates. Then, the average value of the filtered \( \Gamma_m \) time series was calculated for all periods spanned by consecutive surveys. That is,

\[
\overline{\Gamma_m}(t) = \text{mean} [\Gamma_m(t_i \leq t \leq t_{i+1})].
\]

This measure of the mean forcing differs significantly from a more easily calculated "average," which could have been computed by initializing the wave transformation model with the average profile and the average offshore wave height. However, the model output is the result of a very nonlinear process, and the mean output is not linearly related to the mean input. The treatment of the forcing points out that our analysis resolves feedback mechanisms with minimum timescales of 1–2 months. This is a limitation imposed by the sample frequency of the bathymetric data.

### 5. Forcing-Response Relationships

Presentation of the observed relationship between transport patterns (and, equivalently, bar response), bar patterns, and the forcing is divided into four cases, which corresponded to four distinct sandbars (i.e., bars 1–4, Figure 9). Bars 2 and 3 were inner bars and bars 1 and 4 were outer bars. The relationships between the transport parameters (\( r_m \), \( q_m \), and \( \phi_m \)) and \( \Gamma_m \) are presented in Figures 10–13. To assess the statistical significance of the dependence of the transport parameters on the forcing obtained from a total of 466 realizations, the full range of observed \( \Gamma_m \) values was divided into five subranges (bins). Within each bin we have estimated mean values of the sediment transport parameters. The mean values of \( r_m \) and \( q_m \) are estimated as the arithmetic means. A different definition for the mean was used in the estimation of the mean phase shift.

The mean phase shifts within the \( j \)th \( \Gamma_m \) bin were estimated as follows:
Figure 10. Bar response versus $\Gamma_m$ for bar 3 sediment transport statistics (74 samples). (a) Correlation between total transport and cross-shore transport patterns associated with bar migration and growth. Circles (connected by a heavy line) denote mean values within each of five, equally spaced, $\Gamma_m$ ranges. The heavy dashed line shows the standard deviation in each range. (b) Mean transport magnitude (circles connected with solid line) and the standard deviation (dashed line). (c) Sediment transport phase shift estimates, as well as a histogram of the phase shifts. The corresponding bar response is labeled in each quadrant. (d) Phase “coherence” estimates. Dashed lines indicate 80% and 95% significance levels.

\[ \bar{\phi}_m(j) = \tan^{-1}\left[ \frac{\sum \sin[\phi_m(t)]}{\sum \cos[\phi_m(t)]} \right] \]  

where the summation is over all phases within the $j$th $\Gamma_m$ interval. We will use the significance of these average phases to point out determinate relationships between forcing and response (e.g., Figure 10c). Just as the squared coherence provides a measure of the significance of a Fourier-based phase spectrum, the significance of the average sediment transport phase shift can be estimated from a similar measure of squared coherence ($\rho^2_m$), which is defined as

\[ \rho^2_{m}(j) = \frac{\sum \sin^2(\phi_m) + \sum \cos^2(\phi_m)}{n_j} \]  

where $n_j$ is the number of phase estimates in the $j$th $\Gamma_m$ interval. This definition of coherence is based on a test for a directional preference of a random walk. For the case of uniformly distributed $\phi_m$ (i.e., no preferred phase angle), $p$ percent of the estimated coherence values will lie below a critical level given by

\[ \rho^2_{m}(p, n) = \chi(2, p)/(2n), \]  

where $\chi(2, p)$ is the $p$th percentage point of the chi-square distribution with 2 degrees of freedom [Mardia, 1972]. The 80% and 95% significance levels are shown in all cases (e.g., Figure 10d). Coherence estimates exceeding the critical level suggest that an underlying, deterministic relationship exists between the forcing parameter and the sediment transport phase shift.

5.1. Analysis of Bar 3 (Inner Bar)

We begin with results that correspond to bar 3 (an inner bar). In this case, 99% of the correlation estimates ($r_m$) exceeded 0.5, which was the approximate 95% significance level for the correlation (Figure 10a). (In each test, only 8 degrees of freedom are needed to describe the spatial variability of the modeled transport profile, which was estimated from changes in eight profile parameters. Also, each correlation estimate, $r_m$, is equivalent to the skill [Davis, 1976] of a two-parameter model, since the isolated bar model only depended on changes in bar position and amplitude. The value of the correlation parameter, in this case, did not appear to depend on the forcing. This result indicates that transport patterns over this sandbar depended strongly on the bar form. This is evidence of strong feedback.

Using only cases where $r_m$ exceeded 0.5, we found that both the transport magnitude ($q_m$, Figure 10a) and the transport phase shift ($\phi_m$, Figure 10c) depended strongly on the forcing. Clearly, the transport magnitude increased as $\Gamma_m$ increased. There is no evidence for a minimum value of $q_m$ (other than at zero wave height). A minimum value of $q_m$ would indicate a value of $\Gamma_m$ that, potentially, corresponded to an equilibrium state of the bar system.

The estimated phases (Figure 10c), which describe the spatial relationship between bar patterns and transport patterns...
(and, equivalently, the transport-based ratio of bar migration to bar growth/decay), were bimodally distributed. One mode was centered at 0 (offshore migration) and the other at \( \pi \) (onshore migration). Thus the response of bar 3 consisted predominantly of migration. In this case, the average phases (Figure 10d) were significantly coherent (compared to a uniform distribution) at or above the 95% level. The significance was lowest near the transition from onshore to offshore migration, where the bimodal phase populations overlapped. The direction of bar migration (onshore or offshore) showed a systematic dependence on the forcing parameter. For \( \Gamma_m < 0.3 \), bars, on average, migrated onshore. Bars migrated offshore if \( \Gamma_m > 0.3 \). At very low values of \( \Gamma_m \) (<0.2), onshore migration was accompanied by bar amplitude decay.
The lowest values of $\Gamma_m$ likely corresponded to nonbreaking conditions. The transition value of $\Gamma_m \sim 0.3$ likely corresponded to some wave breaking over bars. The maximum observed values of $\Gamma_m$ of 0.35 to 0.4 are consistent with previously observed values of saturated breaking over a typical inner bar (mean depth of $\sim 2$ m and relatively steep slopes on the seaward bar flank [Sallenger and Holman, 1985]). Thus these results suggest that the onset of breaking triggers the change in bar migration direction.

5.2. Analysis of Bar 1 (Outer Bar)

We consider the forcing-response relationships associated with bar 1 next, since they were qualitatively similar to the previous case. Seventy percent of the transport correlation estimates exceeded the 95% significance level (Figure 11a). The lower mean correlation in this case indicates that the sediment transport patterns over this outer bar did not fit the isolated bar model as well as in the previous case. Lower correlation values may have resulted from the overlap between the outer bar and the inner bar (see Figure 1), since the transport correlations were estimated over a distance of 300 m on either side of the outer bar crest position, compared to 100 m for the inner bars.

The transport magnitude, $q_m$ (Figure 11b), increased monotonically with increasing $\Gamma_m$, even across the region where the migration direction (Figure 11c) changed. Again, the transport phase shifts (Figure 11c) were distributed bimodally, as in the bar 3 case, indicating that bar migration was more common than bar growth or decay. However, a larger portion of observations occurred in the bar decay quadrant ($\sim \pi/2$), which is consistent with the observed, eventual decay and disappearance of this feature. The mean phases, averaged within each $\Gamma_m$ bin, were significantly coherent (Figure 11d) at the 95% level over the entire range.

In this case, bar decay was associated with the lowest observed values of $\Gamma_m$ of $\sim 0.1$. (Note that the crossing of the mean phase from $\sim \pi/2$ to $3\pi/2$ is simply due to the phase wrapping over $2\pi$ rad. The change in phase is small.) At slightly larger values of $\Gamma_m$, this bar decayed and migrated onshore, and at larger values still, onshore migration dominated. The mean phase shift changed to 0 (offshore migration) when $\Gamma_m$ exceeded 0.20, which likely corresponded to breaking over the bar. The relatively deep water over the outer bar crest (4 m) and gentle slopes (due to a longer length scale) are associated with wave height saturation at a lower value of $\gamma_s = 0.25$ [Sallenger and Holman, 1985]. This suggests that the change in migration direction was associated with the initiation of wave breaking.

5.3. Analysis of Bar 2 (Inner Bar)

Ninety-eight percent of the transport correlation estimates in this case exceeded 0.5 (Figure 12a), indicating that the Gaussian-shaped bar model fit the observations well. The transport correlation did not appear to depend on the forcing parameter. Unlike the previous two cases, however, the transport magnitude did not depend strongly on the forcing parameter (Figure 12b). While the transport phase shifts were very strongly bimodal (Figure 12c), indicating that most of the transport was associated with bar migration, the coherence of the mean phases was not strongly significant. Nonetheless, onshore migration was associated with $\Gamma_m < 0.3$, and offshore migration occurred at larger values of $\Gamma_m$. The conditions for breaking and saturation are likely to be nearly the same as in the first case (bar 3, an inner bar), suggesting that wave breaking played a similar, yet obscured, role for this bar.
5.4. Analysis of Bar 4 (Outer Bar)

As in the second case (bar 1, also an outer bar), 71% of the transport correlation estimates associated with bar 4 exceeded 0.5. The transport magnitude tended to increase with increasing $G_\tau$. However, the behavior of the mean transport phase shifts did not resemble that of the other bars. The phase shifts, which were typically not significant at the 95% level, suggest offshore migration at low values of $G_\tau$ and onshore migration at higher values. This trend is exactly opposite of the other bars. We note that the amplitude of this feature was significantly lower than that of bar 1 (Figure 9) and that when the amplitude was largest (during 1996), this bar was near the inner bar (bar 3) and the two features were not well separated (Figure 5). It is possible that morphologic response of the inner bar “leaked” into the analysis of the outer bar.

6. Discussion: Role of Morphologic Feedback

Early models of sandbar generation generally neglected to include feedback between the growing bar and the forcing fluid motions. While this greatly simplified the models and allowed analytic predictions of the location or shape of a bar form, its validity is questionable. Patterns of incident wave breaking are strongly modified by a sandbar (a fact that has been used to identify bar locations [e.g., Lippmann and Holman, 1989]). Similarly, low-frequency wave motions, which might drive bar formation at a standing wave node, will be substantially altered by the bar [e.g., Howd et al., 1992]. The presence of this feedback not only complicates the problem, it may also be an essential part of bar response. Our goal was to document the existence and nature of such feedback.

6.1. Feedback

We have shown that there is feedback between sandbar and sediment transport patterns. In nearly every case, observations showed that the transport patterns were highly correlated to the bathymetry (with either a positive or negative sign). This result is consistent with the observation that sandbars are persistent, recognizable features. If transport patterns were not correlated to the bar form, then the bars would soon change their shape.

Although the significant correlation between bar forms and transport patterns indicates the existence of a feedback mechanism, it does not reveal the nature of feedback. We want to understand how this feedback mechanism affects the time evolution of the bar system. Specifically, under a particular set of forcing conditions, does a bar represent a stable or unstable pattern? The feedback associated with bar migration has a relatively straightforward interpretation. In the absence of bar amplitude changes, offshore migration leads to deepening of the bar crest and onshore migration produces shallowing. For fixed offshore wave height, bar response drives $G$ toward an equilibrium value with respect to bar position (but not necessarily with respect to bar amplitude). The equilibrium value appears to be associated with the onset of wave breaking. The feedback associated with bar migration is negative and stabilizing. Plant et al. [1999], who analyzed the same data set, showed that bar migration fit a model with explicit negative feedback. Their analysis showed that bars migrated toward an equilibrium position that depended on the time-varying wave height. The equilibrium position was found to be consistent with the breakpoint.

Feedback associated with bar amplitude changes had a clear effect on bar 1 (outer bar). Figure 10 shows that low wave height conditions were associated with bar amplitude decay. This suggests that the bar crest depth can increase and $G$ can decrease as bars migrate onshore and/or decay. In this case, the system is driven away from the equilibrium value of $G$ (with respect to bar migration). The feedback is destabilizing. Amplitude decay may continue until the bar vanishes.

We note that the crest depth of outer bars was 2–4 times deeper than that of inner bars (Figure 9). The stabilizing feedback (in terms of fractional depth changes) resulting from bar migration is 2–4 times weaker for outer bars. As a result, outer bars are more vulnerable to being trapped in a low $G$ regime, corresponding to amplitude decay (Figure 10c). Wijnberg [1985] also showed that the demise of outer bars on the Dutch coast was associated with a decreased occurrence of breaking (low $G$).

6.2. Sandbar Behavior

Estimates of the statistical measures of transport patterns from the present data set provided several surprises. First, histograms of transport phase shifts indicated that the vast majority of the changes between consecutive surveys consisted of bar migration with little change in amplitude or shape of the bar. Thus the results of this analysis suggest that modeling sandbar migration, rather than sandbar generation or decay, will contribute most significantly to the prediction of profile variability.

Second, the transition between onshore and offshore bar migration appeared to coincide with the onset of breaking at the bar crest, although the actual transition values of $G$ were slightly lower than literature values for saturated breaking. This may indicate that the breaking of only a small fraction of waves in a random (i.e., natural) sea may be sufficient to have a large effect on sediment transport patterns. This is consistent with other recent observations of bar response [Gallagher et al., 1998]. Third, the transition from onshore to offshore bar migration may be quite abrupt, since it was rare to see anything but large-magnitude bar responses for any case of nontrivial wave height.

6.3. Sediment Transport Processes

The observed relationships between morphology, transport patterns, and coarsely defined hydrodynamic regimes are consistent with several known sediment transport mechanisms. Onshore bar migration (and sediment transport) under nonbreaking conditions is consistent with transport dominated by the skewness of orbital wave velocities [Wright et al., 1991; Osborne and Greenwood, 1992a, 1992b]. Under nonbreaking conditions, near-bottom velocities and, potentially, transport rates depend approximately on the inverse of water depth. Thus the transport magnitude increases over bar crests and decreases in the deeper water of the trough. Transport pattern are, thus correlated to the morphology (phase shift of $\pi$). Under breaking conditions, offshore transport can be driven by a strong undertow [Haines and Sellenger, 1994; Thornton et al., 1996; Gallagher et al., 1998], which, also, is predicted to depend inversely on depth [Stive and Wind, 1986]. This yields a transport phase shift of 0 due to the seaward directed flow.

6.4. Anomalous Results

The analysis results corresponding to bar 2 (Figure 12) appeared somewhat anomalous because neither transport magnitude nor phase shift showed a strongly significant depen-
7. Conclusions

Several aspects of feedback mechanisms associated with surf zone sandbar response have been characterized using bathymetric surveys, sampled approximately monthly over a 16-year period at the Army Corps of Engineers’ Field Research Facility (North Carolina). The measured bathymetry was longshore-averaged and modeled by the superposition of two Gaussian-shaped sandbars on an underlying planar slope, with a third, half-Gaussian bar to represent steepening at the shoreline. The model fit to each surveyed profile by tuning the model parameters, minimizing the mean square error between model and data. The rms error between the measured bathymetry and the profile model was 0.10 m (estimated over 322 different surveys), and the model explained 99% of the profile variance that remained after first removing the linear, cross-shore trend from each observed profile.

Differences between consecutively surveyed profiles were assumed to result from cross-shore sediment transport patterns. These patterns were described by a transport magnitude and a cross-shore phase shift. The phase shift, defined relative to an underlying bar pattern, was calculated from the ratio of transport associated with bar migration to that associated with bar growth. The phase shifts were usually 0 (offshore migration) or \( \pi \) (onshore migration), indicating that bar migration was more common than bar growth/decay and that the transport pattern was typically correlated (positively or negatively) to the underlying bar pattern. Eighty-five percent of the correlation estimates exceeded the 95% significance level. This indicates strong morphologic feedback.

The transport statistics describing bar response were compared to a local hydrodynamic forcing variable \( \Gamma \), which was defined as the ratio of the wave height to water depth, evaluated at bar crest locations. \( \Gamma \) was computed using a wave transformation model that accounted for wave shoaling and breaking. The model was initialized with the modeled bathymetry and measured, offshore wave heights. At low values of \( \Gamma \) (i.e., nonbreaking conditions), bars migrated onshore and their amplitude tended to decay. This part of the analysis revealed several deterministic feedback relationships between bar response and the forcing. At high values of \( \Gamma \) (i.e., breaking conditions), bars migrated offshore, with relatively little change in amplitude. The transition between onshore and offshore migration occurred at a value of \( \Gamma \) that was consistent with the onset of wave breaking. Bar migration appears to be associated with a stabilizing feedback mechanism, which drives bar crests toward equilibrium at the wave breakpoint. However, we observed several differences from the classical breakpoint models. First, most of the variability of the system was associated with migration of existing bars, not the formation of new bars. Second, although the breakpoint is not usually viewed as a sharply defined location under natural (i.e., random) wave conditions, the value of \( \Gamma \) that separated onshore and offshore migration may be sharply defined. Third, we observed that the rate of bar response (measured in terms of sediment transport magnitude) showed no reduction for any nonzero choice of \( \Gamma \), indicating that bars never reached equilibrium.

Finally, systematic bar amplitude decay was observed under nonbreaking conditions. Because bar crest depths could actually increase under these conditions, \( \Gamma \) may be driven farther from breaking conditions, even if a bar migrated onshore. This results in destabilizing feedback from the perspective of a stable bar amplitude, potentially leading to bar destruction. Since the crest depth of outer bars was 2–4 times deeper than that of inner bars, the potentially stabilizing effects of bar migration were 2–4 times weaker for outer bars. As a result, outer bars were more susceptible to becoming trapped in a low-\( \Gamma \) regime. The implication is that even under steady forcing (e.g., constant offshore wave height), bars may not reach a stable configuration.

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