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Numerical predictability experiments of cross-shore sandbar migration

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[1] Surf zone sandbars, common features along the world's sandy coastlines, continuously change their position in response to time-variable offshore wave conditions. Process-based predictions of cross-shore sandbar migration, relevant to the understanding of autonomous and artificially altered evolution of beaches, are intrinsically imprecise because of uncertainty in the model equations and, potentially, the sensitive dependence on the initial bathymetry. However, the magnitude of the resulting predictability limit and its dominant source are unknown. Here we show that cross-shore sandbar migration on the time scale of years is deterministically forced rather than deterministically chaotic, and that the unpredictability of sandbar migration results primarily from model inadequacy during major wave events. Because the unpredictability of sandbar migration is related to the stochastic nature of the forcing, the predictability limit is not a fixed value but depends on the timing of the wave event. We anticipate that detailed experiments to understand nearshore evolution from the underlying first principles will eventually pay off by extending the range of plausible simulated behavior and, consequently, will increase our ability to understand and predict how coasts may respond to changing climate. **Citation:** Ruessink, B. G., and Y. Kuriyama (2008), Numerical predictability experiments of cross-shore sandbar migration, *Geophys. Res. Lett.*, *35*, L01603, doi:10.1029/2007GL032530.

1. Introduction

[2] Surf zone sandbars, ridges of sand in shallow (<10 m) water along micro- to mesotidal, storm-dominated coasts, serve as natural protection for beaches by causing waves to break away from the shoreline. The hydrodynamics and sediment transport underlying cross-shore sandbar response to time-varying wave forcing are fundamentally nonlinear and contain many feedbacks, patterns and complexity at a wide range of scales [*Holman*, 2001]. Our ability to predict sandbar migration has implications for the capacity to predict shoreline erosion and may significantly effect the population close to the coast. In addition, temporal variability in nearshore bathymetry affects beach ecology [*McLachlan et al.*, 1993], food webs [*Menn*, 2002] and the transport and dispersal of pollutants [*Feddersen*, 2007].

[3] Various factors prohibit predicting actual sandbar behavior at particular times and places beyond a specific time horizon, including model inadequacy - our models are not complete and true representations of the governing physics - and sensitivity to initial conditions inherent to some nonlinear systems [*Lorenz*, 1963]. The latter factor includes uncertain parameters, inaccuracies in the initial data, and errors in the model description of small, unresolved, parameterized scales, which may all result in divergent, potentially chaotic model solutions. The potential for deterministically chaotic sandbar behavior has led to speculations that the simulation of actual time sequences of nearshore evolution with models based on small-scale physics forced by waves and currents may not bear any relationship with reality beyond a few months [*Southgate and Möller*, 2000; *Holman*, 2001], well below the time scales that dominate nearshore variability [*Plant et al.*, 1999] and that characterize human interactions with the coast [*Hamm et al.*, 2002]. However, this predominantly exploratory contemplation was not followed by attempts to actually quantify surf zone predictability limits.

[4] Here, we employ a coupled hydrodynamic/sediment transport model [*Ruessink et al.*, 2007] in an ensemble prediction scheme [*Hoffman and Kalnay*, 1983] using a multi-year data set of daily bed profile surveys [*Kuriyama*, 2002] to examine the time scales on which our model might reflect reality and to address the question as to whether the unpredictability of cross-shore sandbar migration results from model inadequacy or deterministic chaos. First, we discuss the model, data, and ensemble scheme; next we examine the temporal evolution of ensemble spread and model skill; and finally we consider the implications of the results for surf zone research and modeling.

2. Ensemble Sandbar Modeling

2.1. Model

[5] To simulate the temporal evolution of cross-shore bathymetry, we use the deterministic wave-averaged cross-shore profile model detailed by *Ruessink et al.* [2007]. The model, which is one of only few operational models that accurately predicts onshore and offshore sandbar migration on the time scale of days to weeks, uses an initial bed profile, the median bed material grain size, and time series of offshore wave parameters (height, period, direction) and water levels to evolve the bed profile through coupled hydrodynamic (waves and currents) and sediment transport (bed load and suspended load) equations. Simulated offshore bar migration takes place when large waves break on the sandbar and is due to the feedback between waves, undertow, suspended sediment transport, and the sandbar. Under weakly to nonbreaking conditions simulated onshore

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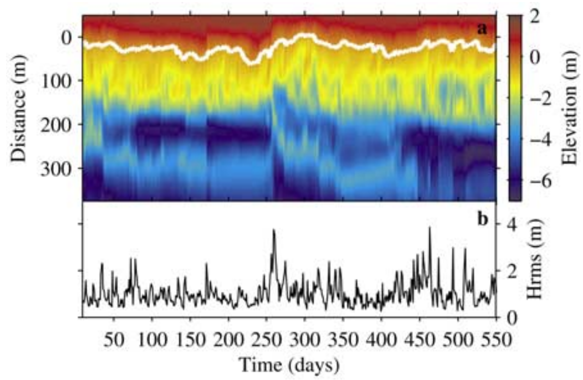

Figure 1. Time series of (a) cross-shore bed profiles and (b) offshore root-mean-square wave height H_{rms} at Hasaki Beach, Japan. The white line in Figure 1a is the −0.5 m contour, separating the intertidal beach from the (subtidal) bar zone; its time-averaged position is about 30 m. Time $t = 0$ corresponds to January 1, 1987; elevation = 0 equals mean sea level; and distance = 375 m is the pier head. The Hasaki sandbar migrates more offshore during periods with high waves than onshore between such periods, causing a net offshore migration on the time scale of weeks to months. When the water depth above the sandbar crest reaches some 3.5–4 m and wave conditions remain calm for several months, the sandbar starts to decay slowly (t = 100–250 days). During the next period with high waves, a new sandbar is generated near the shore, which subsequently migrates offshore and takes its place as the new prominent sandbar (t = 250–270 days).

bar migration follows from the feedback between near-bed wave skewness, bedload transport, and the sandbar.

2.2. Data

[6] The cross-shore bed profiles we used to initialize and verify the model predictions are an approximately 1.5 year long data set of daily profiles collected between January 1987 and July 1988 along the pier of the Hazaki Oceanographical Research Station at Hasaki Beach, Kashima Coast, Japan [*Kuriyama*, 2002] (Figure 1a). We interpolated the available bed profiles to a regular cross-shore grid with 5 m spacing using a scale-controlled linear smoother [*Plant et al.*, 2002] to remove measurement errors and small bathymetric features unresolved by the observations and the model (e.g., bed ripples). During interpolation we ignored measurement values collected near the pier pilings because of local scour. We filled missing profiles, which were gaps of up to two days during weekends and holidays, with linear interpolation. In the observations, bed variability induced by sandbar migration (“the bar zone”) is restricted to the cross-shore distance (x) range between 30 and 375 m (Figure 1a).

[7] Typically, the root-mean-square difference between consecutive surveys [*Gallagher et al.*, 1998] exceeded the mean difference by a factor of 2 to 4, implying that cross-shore processes must have dominated longshore processes and/or that the sediment flux past the pier head was near zero. There were, however, a few instances when the mean difference was appreciable. Around t = 170 days the water depth above the entire sandbar (x > 170 m in Figure 1a) temporally increased by 0.1 to 0.4 m without any noteworthy gain of sediment further onshore. We do not know whether the loss of sand was in the longshore or offshore direction, or was due to systematic measurement errors. The nonzero mean difference at t = 445 days resulted from the migration of the sandbar beyond the pier head.

[8] Time series of daily averaged offshore root-mean-square wave height H_{rms} (Figure 1b) and peak period T_p were available from the Kashima Port sensor located approximately 5 km offshore in 24 m water depth. Because of the nondirectional nature of the Kashima sensor, we set the offshore wave direction to 30° normal to the shore. This is a realistic value given the wind and observed wave climate at the site. Water levels were available as hourly tidal values predicted for the pier head. The median sediment grain size of the seabed is about 180 μm.

2.3. Ensemble Scheme

[9] We examine the sensitivity to initial conditions and the effect of model inadequacy on hindcast sandbar evolution from ensembles generated by lagged-average forecasts [*Hoffman and Kalnay*, 1983]. At each verification time t_V, an ensemble contains not only the prediction commencing from the initial condition observed at a control time t_C but also predictions for the same t_V started one or more days earlier than t_C. We include predictions initiated up to seven days earlier than t_C, implying that an ensemble consists of eight members. An ensemble of this size is suggested by *Leith*’s [1974] work on the theoretical skill of Monte Carlo forecasts. Also, we did not find a noteworthy change in the results presented in section 3 when we used 5-member ensembles, suggesting that our 8-member ensembles are large enough. We view the measured and seven predicted bed profiles at t_C as differing but physically feasible initial conditions. We integrated all initial states from t = 9–426 days to t = 556 days (t = 0 corresponds to January 1, 1987; initial states for $t >\approx 430$ days are unreliable because of the potential presence of a sandbar seaward of the pier head, see Figure 1a). This results in 411 ensembles (t_C ranges from t = 16–426 days) and in simulation durations of $\Delta t_s = t_V - t_C$ between 1 and 540 days (t_V ranges from $t = t_C + 1$ to 556 days). The maximum simulation duration exceeds the dominant period of forcing by two orders of magnitude and is well beyond the typical simulation duration of model application existing in the literature.

2.4. Model Set-Up

[10] In all simulations the cross-shore model grid extended from the offshore wave sensor to the top of the foredune. The cross-shore grid size varied from several tens of meters in depths larger than 10 m to 1 m on the intertidal beach. The numerical time step was one hour. We set parameters inherent to subgrid parameterization to values determined from an earlier model calibration [*Ruessink et al.*, 2007], which encompassed a representative 44-day period during which the Hasaki sandbar migrated 75 m offshore during three high-wave events (up to 20 m/day) and moved onshore at rates of 0 to 6 m/day during the intermediate, less energetic conditions.

3. Results

3.1. Initial Conditions

[11] We use the divergence of the ensembles as they evolve from t_C to t_V to examine the predictability limit

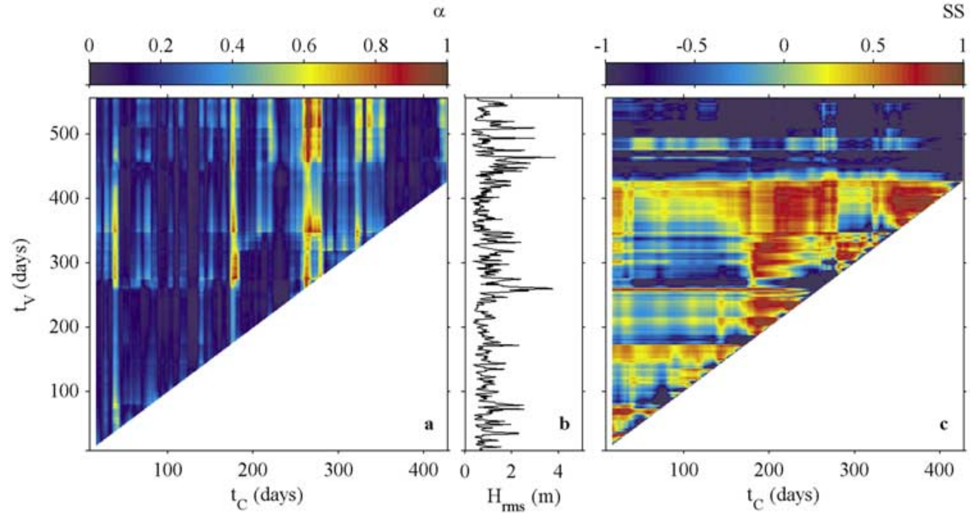

Figure 2. Temporal evolution of (a) nondimensional spread α, (b) offshore root-mean-square wave height $H_{\rm rms}$, and (c) model skill SS at Hasaki Beach, Japan.

because of a sensitive dependence on initial conditions. A convenient measure of the divergence is the standard deviation or spread s of the eight ensemble members about the ensemble mean,

$$s(t_C, t_V) = \sqrt{\overline{\frac{1}{8}\sum_{i=1}^{8}\left(z_i(x, t_V) - \tilde{z}(x, t_V)\right)^2}^{x}}, \tag{1}$$

where $z_i(x, t_V)$ is the predicted bed elevation of the ith ensemble member at cross-shore location x and time t_V, the overbar is the bar-zone average, and the tilde represents the ensemble mean. We subsequently normalized $s(t_C, t_V)$ to range between 0 when the ensemble members are identical and 1 when the ensemble members are as diverse as eight random selections from the total range of profile observations.

[12] Figure 2a displays the temporal evolution of the normalized intra-ensemble variability $\alpha(t_C, t_V)$ as a function of t_C. Each column in Figure 2a represents the temporal evolution of α for a single ensemble, and each row shows the variability of α at the same t_V as a function of t_C. The most prominent property of Figure 2a is the simultaneous increase and decrease in $\alpha(t_C, t_V)$ in all ensembles. Abrupt $\alpha(t_C, t_V)$ increases at $t_V \approx 255$ and 450 days coincide with major wave events ($H_{\rm rms} >\approx 3$ m in Figure 2b), when in most ensembles the model predicts the inshore birth and subsequent offshore migration of a new sandbar. Periods with moderately high waves ($H_{\rm rms} \approx 2$–3 m, for example, $t_V \approx 70$, 350, and 510 days), resulting in the offshore migration of an existing sandbar, aggravate $\alpha(t_C, t_V)$ slightly. Initial intra-ensemble variability in water depth above the sandbar crests causes a divergence in sandbar location because of differential degrees of wave breaking and, accordingly, of the magnitude of the undertow, the current-induced suspended sediment transport and, finally, the offshore sandbar migration rate. Gentle $\alpha(t_C, t_V)$ decreases concur with prolonged periods of relatively low waves ($H_{\rm rms} <\approx 1$–1.5 m), when the model predicts that the sandbar migrates onshore and diminishes in height. In other words, all ensemble members are predicted to progressively resemble the same featureless cross-shore profile, which causes the ensemble spread to reduce.

[13] Another prominent feature demonstrated by Figure 2a is increased vertical striping especially occurring after the first major storm (t_V = 255 days), which shows the large variability of $\alpha(t_C, t_V)$ growth in ensembles with comparable prestorm spread. We found that at this verification time ensembles with a sandbar-trough relief less than 0.3 m were less predictive than ensembles with more pronounced sandbar-trough morphology. In the latter ensembles the sandbar is sufficiently high to strongly localize wave breaking and sediment transport gradients; in fact, in these situations the sandbar does not decay and a new sandbar does not progress from the shore. Further onshore, protected by the well-developed sandbar, waves, currents, and sediment transport are relatively low, resulting in minor (and similar) profile response. In contrast, a subdued sandbar barely affects the cross-shore evolution of hydrodynamics and sediment transport; the profile response is now concentrated further onshore, where small initial profile variability is amplified into a variable response of the newly generated sandbar.

[14] It is not clear which α value represents the limit to predictability [*Lorenz*, 1969; *Dalcher and Kalnay*, 1987]. For practical purposes it should exceed the magnitude of the normalized spread at t_C (here, $\alpha(t_C, t_C) \approx 0.1$–0.3) but it should be less than the saturation value ($\approx$1) corresponding to the range of intrinsic variability. Of all 411 ensembles, only 1% reached $\alpha \geq 0.95$; an additional 25% attained a normalized spread of at least 0.5. In 13% of all ensembles the spread actually diminished from the start and was never aggravated above its initial value.

3.2. Model Inadequacy

[15] We examine the effect of model inadequacy on forecast accuracy with the temporal evolution of a skill score SS,

$$SS(t_C, t_V) = 1 - \frac{\overline{\left(\tilde{z}(x, t_V) - z_o(x, t_V)\right)^2}^{x}}{\mathrm{E}\left[\overline{\Delta z_o^2(\Delta t_s)}^{x}\right]}, \tag{2}$$

where $z_o(x, t_V)$ is the observed cross-shore bed profile at t_V, and $\mathrm{E}\left[\overline{\Delta z_o^2(\Delta t_s)}^x\right]$ is the expected bar-zone averaged squared difference between two bed profiles surveyed $\Delta t_s = t_V - t_C$ apart. The latter term represents the temporal dependence of bed level change in our data and was estimated by computing the semi-variogram [*Burrough and McDonnell*, 1998] of $\overline{\Delta z_o^2}^x$ versus Δt_s. We found it to grow rapidly from $\approx$0.02 m^2 at Δt_s = 1 day to $\approx$1.0 m^2 at Δt_s = 250 days and longer. Positive *SS* values thus imply that the spatially averaged root-mean-square difference between the ensemble mean and the observation at time t_V is smaller than the difference expected from the observations. We consider situations with $SS > 0$ as predictable.

[16] The results in Figure 2c demonstrate that, similar to the nondimensional spread, major changes in the skill score are aligned horizontally, with the decreases concurring with most, but not all periods with high waves. The Murphy-Epstein decomposition [*Murphy and Epstein*, 1989] of the skill score showed that the loss of skill was related to phase rather than to magnitude errors. In other words, the model predicted sandbars of the correct magnitude but, because of an overestimate of the offshore bar migration rate, at an incorrect cross-shore position. The loss of skill at t_V = 170 days is primarily due to the net loss of sand from the measured depth profiles around this time that, by definition, our one-dimensional model cannot capture. Around t_V = 445 days the model predicted the onshore birth of a sandbar, following the migration of the outer sandbar seaward of the pier head. While the latter model result is consistent with the observations (Figure 1a), the subsequent offshore migration of the next most seaward located sandbar was not observed. This inconsistency between model predictions and observations causes the skill of all ensembles (that is, independent of the variability in the initial conditions, the spread in the ensembles just before t_V = 445 days, and the simulation duration) to become negative (Figure 2c).

4. Discussion and Conclusions

[17] With our numerical results we have established that initial variability in cross-shore depth profiles does not necessarily grow to the level where initial similar states become uncorrelated. In most ensembles, the increase in intra-ensemble variability during periods of high waves is undone by the model's tendency to dampen variability over time during lower wave conditions. So, we conclude that cross-shore sandbar migration on a scale of years is forced rather than chaotic, and hence is deterministically predictable. In addition, we have demonstrated that state-independent model inadequacy during major wave events is the dominant source of unpredictability of cross-shore sandbar migration, with an overestimate of offshore sandbar migration and problems with predicting the creation and initial behavior of a new onshore sandbar (e.g., around t_V = 445 days). Because the loss in model skill is coupled to the stochastic nature of the boundary wave forcing, there is no "absolute" value for the predictability limit; it depends on the timing of the high-wave period. One of the implications of our results is that the enormous effort made through detailed field and laboratory experiments to measure and understand the physical processes will eventually pay off by extending the predictability range of plausible simulated coastal behavior. The collection and analysis of detailed observations of near-bed currents and sediment concentration during adverse weather conditions thus is a major challenge to the improvement of our predictive capability for cross-shore sandbar dynamics. We believe that the collection of these data are of the utmost importance if we wish to understand and accurately predict coastal response to hurricanes [*Morton and Sallenger*, 2003] or to the potential increase in storm frequency and severity because of global warming [*Schwartz*, 2005].

[18] We did not find any evidence that the parameterization of subgrid physical processes (e.g., fluid turbulence and bed ripples) resulted in large-scale systematic error growth. If internal error growth had been the main cause for temporal variability in spread, we would expect $\alpha(t_C, t_V)$ to at least partly depend on the simulation duration [*Lorenz*, 1969; *Dalcher and Kalnay*, 1987] and thus to align with $t_C = t_V$ in Figure 2a. The simple description of the subgrid processes in our model may have dampened subgrid variance [*Lorenz*, 1965; *Murray*, 2007] and we may have accordingly underestimated internal dynamics. We think it conceivable that improved physical parameterizations and the use of finer grid resolutions to resolve smaller-scale features may expand the range of skillful simulated sandbar behavior but at the same time they may trigger deterministic chaos, in a manner analogous to the continuous drop in the atmospheric error doubling time as numerical weather prediction models became more advanced and were run on denser grids [*Lorenz*, 2006]. In other words, a more complex deterministic sandbar model may be more realistic (when viewed intuitively) but at the same time it is also more uncertain. We suggest that improved model physics should be judged not only on its ability to extend the model inadequacy induced predictability limit but also on its potentially adverse affect on the sensitivity to initial conditions.

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