Sorted bedform pattern evolution: Persistence, destruction and self-organized intermittency

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[1] We investigate the long-term evolution of inner continental shelf sorted bedform patterns. Numerical modeling suggests that a range of behaviors are possible, from pattern persistence to spatial-temporal intermittency. Sorted bedform persistence results from a robust sorting feedback that operates when the seabed features a sufficient concentration of coarse material. In the absence of storm events, pattern maturation processes such as defect dynamics and pattern migration tend to cause the burial of coarse material and excavation of fine material, leading to the fining of the active layer. Vertical sorting occurs until a critical state of active layer coarseness is reached. This critical state results in the local cessation of the sorting feedback, leading to a self-organized spatially intermittent pattern, a hallmark of observed sorted bedforms. Bedforms in shallow conditions and those subject to high wave climates may be temporally intermittent features as a result of increased wave orbital velocity during storms. Erosion, or deposition of bimodal sediment, similarly leads to a spatially intermittent pattern, with individual coarse domains exhibiting temporal intermittence. Recurring storm events cause coarsening of the seabed (strengthening the sorting feedback) and the development of large wavelength patterns. Cessation of storm events leads to the superposition of storm (large wavelength) and inter-storm (small wavelength) patterns and spatial heterogeneity of pattern modes. **Citation:** Goldstein, E. B., A. B. Murray, and G. Coco (2011), Sorted bedform pattern evolution: Persistence, destruction and self-organized intermittency, *Geophys. Res. Lett.*, *38*, L24402, doi:10.1029/2011GL049732.

1. Introduction

[2] Recent observations have shown that the inner shelf, the dynamic region that links the surf zone and the continental shelf, displays various types of bathymetric features. These features exert a first order control on the role of the inner shelf as a conduit for wave energy and sediment. Here we examine one such feature, spatially extensive (100 m - km scale) sequences of strikingly sorted coarse- and fine-grained sandy domains with slight bathymetric relief (cm - m scale) that appear commonly on the inner continental shelf (Figure 1). Recent research suggests that these "sorted bedforms" arise primarily from a sediment sorting feedback, rather than interactions between flow and topography [*Murray and Thieler*, 2004; *Coco et al.*, 2007a; *Van Oyen et al.*, 2010]. This sorting process is mediated by wave-generated ripples, whose size is a function of bed composition. Areas mantled by coarse sediment exhibit larger ripples than regions covered with fine sediment. Large wave generated ripples lead to strong, large-scale turbulence above coarse domains. Strong turbulence inhibits the settling of suspended fine sediment, leading to preferential fine sediment deposition in locations with less turbulence (i.e., finer sediment). Modeling by *Coco et al.* [2007a], which builds on previous work by *Murray and Thieler* [2004], shows that this sorting feedback is robust under a wide range of wave and current forcing conditions.

[3] This previous work addressed sorting dynamics and pattern development on short time scales (days to weeks) [*Coco et al.*, 2007a, 2007b]. Over longer time scales, observational studies show that sorted bedforms may be temporally intermittent or persistent inner shelf features. Surveys of shallow water environments tend to show ephemeral sorted bedforms while bedforms in deep water are persistent [e.g., *Hume et al.*, 2003] (details in auxiliary material).[1]

[4] Stable sorted bedform patterns in nature differ in form from the highly organized patterns developed in previous modeling endeavors. Observed sorted bedform patterns often exhibit a spatially complicated plan view pattern with ragged, "wispy" down-drift edges of coarse domains [*Murray and Thieler*, 2004] and many pattern imperfections (Figure 1). These imperfections, termed defects, are the ends of coarse domains or areas where one coarse patch bifurcates into two parallel coarse domains. In this contribution we assimilate these observations into a cohesive picture of long-term sorted bedform dynamics and investigate what role forcing conditions and recurring storm events have in generating spatial intermittence and temporal intermittence, and in determining the degree of organization of the pattern.

[5] To investigate the long-term dynamics of sorted bedforms we use the numerical model developed by *Coco et al.* [2007a]. Long-term pattern evolution is also examined under conditions of net deposition (representing a scenario such as a prograding shoreface associated with a convergence of alongshore sediment flux or a fluvial sediment source), net erosion (representing, e.g., scour by strong tidal currents and waves), as well as periodic high wave events (representing storms). We show that the key to a durable sorted bedform field is a sufficiently high concentration of coarse material on the seabed to drive the sorting feedback. Changes in the concentration of coarse material on the seabed results from the self-organized dynamics of the system. The purpose of the study is to explore the long-term morphodynamics under

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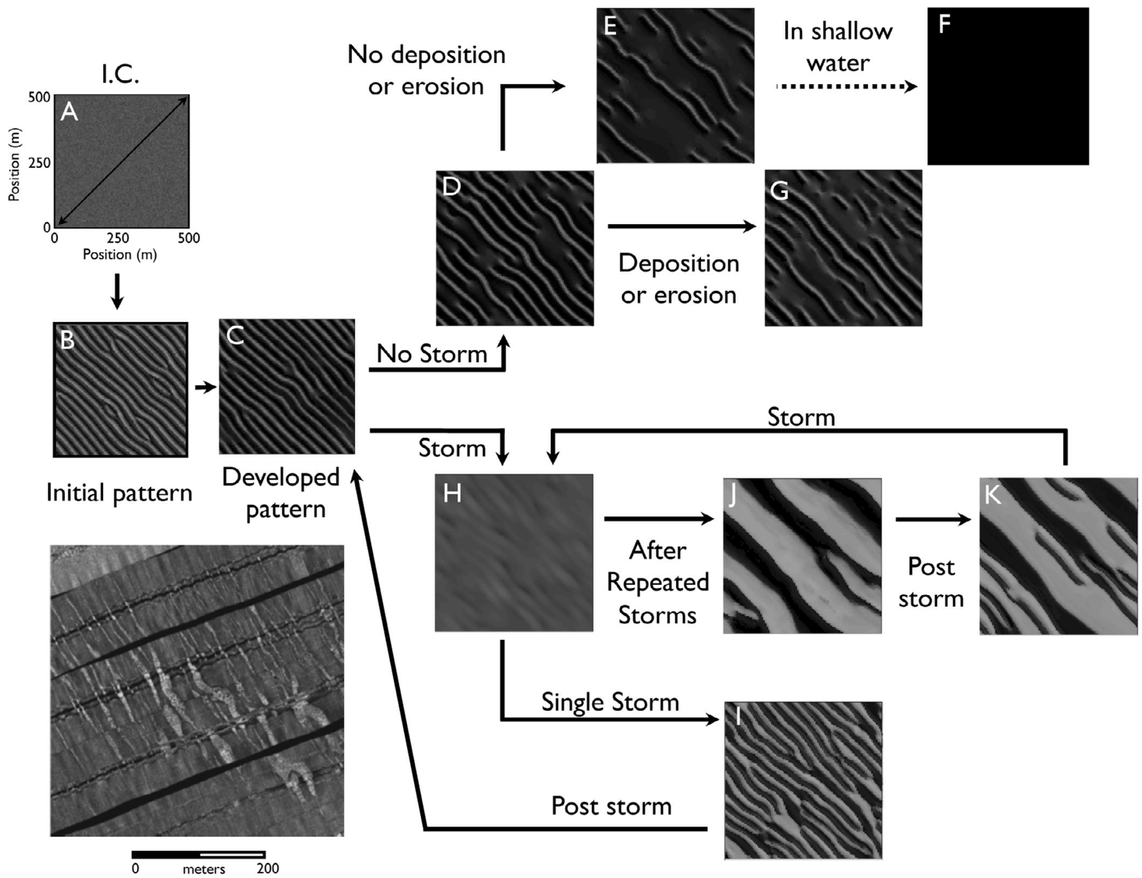

Figure 1. Flow chart of long term sorted bedform pattern evolution. The large lower left panel is an example of bedforms off the coast of Tairua Beach, New Zealand [*Coco et al.*, 2007a] observed in water depths around 5 m. Shoreline is towards the bottom of the panel. Sorted bedforms observed at the same site but in deeper water did not display any significant change over the past 5–10 years (Bryan, personal communication, 2010). (a) The initial condition of the "Basic" scenario. Black and white pixels indicate fine and coarse sediment respectively. Current direction is from upper right to lower left and reverses daily. (b) After initial pattern development (~200 days). (c) A lack of pattern imperfections (defects) indicates a highly developed pattern (after ~800 model days). These well organized patterns contrast sharply with Figure 1d. (d) Pattern intermittence after the active layer reaches the critical state (~2000 days). (e) With no sediment source or sink, the pattern is persistent but spatially intermittent. (f) Under high wave conditions or in shallow water the pattern may be ephemeral. (g) Deposition or erosion enables a temporally stable pattern with spatial intermittence. Individual coarse domains may be ephemeral. (h) Single storm events tend to destroy bedform relief, mobilize fine and coarse sediment, and coarsen the active layer as fine sediment is brought into suspension. (i) After a storm event the pattern is similar in orientation but coarse domains are wider. Post storm vertical sorting and defect dynamics cause the pattern to evolve into the developed pattern (Figure 1c). (j) Repeated storm events tend to cause the active layer to coarsen dramatically. Storm events develop large wavelength patterns. (k) During inter-storm times this pattern devolves into a superposition of the large wavelength (storm) pattern and the short wavelength (fair weather) pattern. Repeated storms result in bedforms that transit the Figure 1h–Figure 1j–Figure 1k loop, while a cessation of storms cause pattern in Figure 1k to devolve to pattern in Figure 1i (and further in Figure 1c).

simplified conditions to maximize potential insights in this early stage of investigation rather than reproduce realistic scenarios with maximum accuracy.

2. Methods

[6] Here we review the main attributes of the numerical model, which represents the transport of coarse and fine grain sediment as both bedload and suspended load under variable current and wave forcing (see *Coco et al.* [2007a] for a full model description). Sediment flux is treated in an advection-diffusion framework, neglecting diffusion, with terms for sediment sources (entrainment; a function of wave orbital speed) and sinks (deposition; proportional to suspended sediment concentration) which correspond to changes in bed elevation.

[7] The three dimensional model domain (a plan view size of 500 m × 500 m) has a 5 m horizontal resolution, 0.05 m vertical resolution and periodic horizontal boundary conditions. The initial condition is an approximately flat bed (bathymetric perturbations below 0.01 m) with a bulk composition of 30% coarse sediment (d_{coarse} = 0.001 m) and 70% fine sediment (d_{fine} = 0.00015 m) with deviations in individual cell coarse percentages below 10%. In these

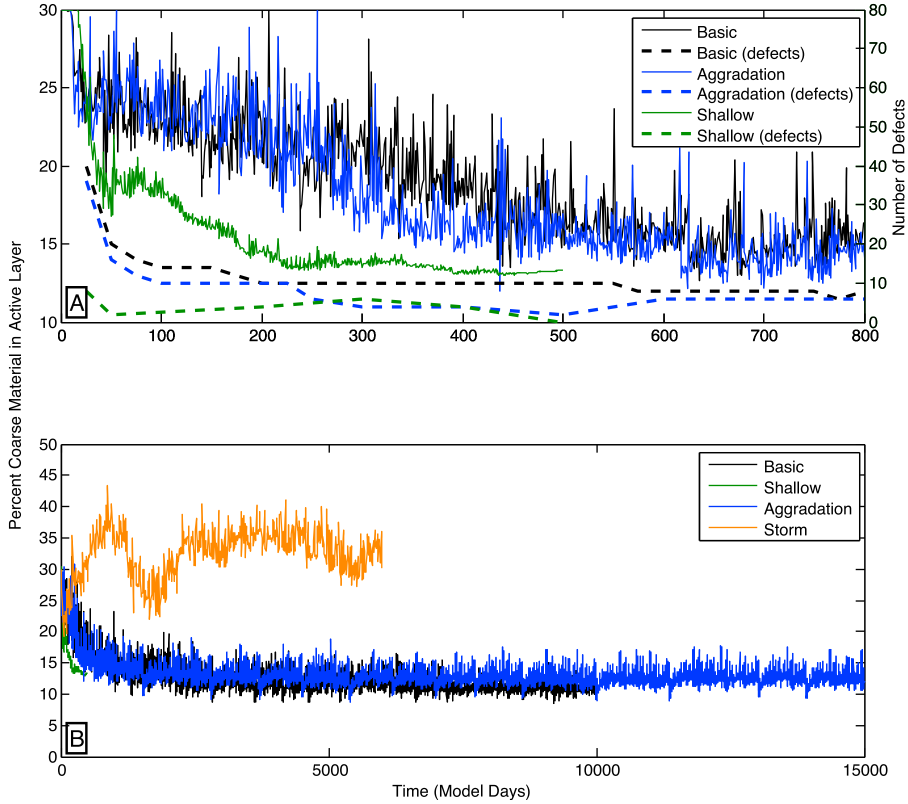

Figure 2. The percentage of coarse material in the active layer and number of defects through time (note the two different time scales). (a) Sorting causes initial fining in the first 20 days of all experiments. Defect dynamics (i.e., defect annihilation) and vertical sorting cause subsequent fining. This is most pronounced from day ~ 250 to day ~ 700. (b) A critical level of coarseness is reached in the active layer for most experiments and is maintained for the duration of the experiments. The experiment with "storms" (orange) shows variation in coarseness as a result of autogenic burial and excavation of coarse material.

experiments the current reverses direction every 24 hours. Unless otherwise noted mean current velocity is 0.2 m/s (with a daily excursion about the mean current with a standard deviation of 0.06), wave height is 2 m, wave period is 10 s and the initial water depth is 20 m. An active layer limits the vertical depth over which sediment interacts with the flow. For all experiments in this treatment the active layer is a constant thickness of 0.15 m (further model details are in the auxiliary material). *Coco et al.* [2007b] discussed the role of current and wave variations in plan view pattern development. To examine the influence of higher wave events (storms) on pattern robustness, we include storm scenarios with 4 m waves that occur for 4 days every 100 days (scenarios with increased current magnitudes are discussed in auxiliary material). We are modeling relatively small-scale sorted bedforms for computational efficiency but results from these experiments are likely applicable to larger scale features (sorted bedforms may be kilometers in scale).

[8] To examine the role of long-term aggradation on the feedback responsible for pattern formation we impose aggradation rates in some experiments of 0.01 m/yr, broken down as 0.003 m/yr coarse sediment and 0.007 m/yr fine sediment (to mimic the model seabed bulk composition). Erosional experiments have an imposed fine sediment erosion rate of 0.003 m/yr. The results of experiments presented here are similar for lower sedimentation/erosion rates.

3. Results and Interpretation

3.1. Results and Interpretation: "Basic" Scenario; Steady Forcing

[9] The compound interactions in this numerical model and the highly nonlinear, discontinuous nature of the empirical ripple-prediction scheme (see auxiliary material) preclude an analytical explanation of what causes the modes of pattern evolution we observe. Descriptions of dynamics are supported by inspection of the model output and analysis of the equations used as the basis for the modeling effort.

[10] We first consider the case with no storms and no erosion or deposition. Sorted bedforms develop within 20 days (Figures 1a and 1b). As a result of initial pattern formation active layer coarseness monotonically decreases from its initial condition (30%) to ~25% (Figure 2a).

[11] Active layer fining is accomplished by vertical sediment sorting, a result of changes in current magnitude and direction. Increases in current magnitude give rise to increases in the bathymetric relief of sorted bedforms and vice versa [*Coco et al.*, 2007b]. Increases in relief cause fine material in the subsurface to become available for sediment-flow interactions. In this way fine sediment is mined from the

seabed below the sorted bedform field. Decreases in relief tend to bury coarse sediment as coarse domains are located in the trough or along the flank of a bedform. Furthermore, daily current reversals and the evolution of the pattern (e.g., wavelength coarsening) cause the coarse domains to migrate. Migration causes the trough of the bedform, the zone previously mined of fine material and a reservoir of coarse material, to change in position. This inhibits the re-excavation of coarse material when subsequent current magnitude increases result in increased sorted bedform relief. In this way the area under the bedform field functions as a sink for coarse material and a source for fine material.

[12] This vertical sorting is especially prevalent during the maturation of the pattern by defect dynamics. In reversing currents, pattern defects tend to migrate farther than the central part of individual domains because the ends of coarse domains contain less coarse material to be transported. During repeated current reversals these fast moving defects tend to continually attach and detach from adjacent coarse domains. Defects are more prone to burial because of these frequent migrations. Unlike defects in bedform patterns undergoing unidirectional flow [*Werner and Kocurek*, 1999], these modeled defects do not propagate downstream (perpendicular to crests) through the bedform field but instead migrate laterally (parallel to crests). As each defect migrates and the domain it is a part of is progressively buried, the active layer coarseness decreases as does the plan view coverage of coarse sediment. This precipitates an increase in the pattern wavelength to maintain equally spaced bedforms (Figure 1c) [*Werner and Kocurek*, 1999; *Huntley et al.*, 2008]. Surface coarseness decreases from 24% to 16% as the pattern transitions from 14 defects to 8 defects (Figure 2a, between 100 and 600 days). Fining of the active layer as a result of defect dynamics and associated vertical sorting continues until the bedform field reaches a critical level of coarseness (Figure 2).

[13] Active layer fining has consequences for plan view pattern stability. *Coco et al.* [2007a] found that the average bed composition is an important factor for sorted bedform height and wave ripple characteristics (amplitude and wavelength). Less coarse sediment on the bed results in lower wave ripple amplitude, smaller wave ripple wavelength, lower sorted bedform height and therefore lower bed slope [*Coco et al.*, 2007a]. Decreases in ripple size (wavelength and amplitude) bring about a decrease in turbulent intensity above ripples and a decrease in the ability of coarse domains to inhibit fine sediment deposition. Fine sediment is therefore able to dilute coarse domains. Furthermore, lower bathymetric slope as a consequence of lower sorted bedform heights result in higher fluxes of coarse and fine sediment [*Coco et al.*, 2007a]. Coarse domains are usually located in the trough or on the up-drift flank of sorted bedforms. This bathymetric slope limits upslope sediment flux [*Coco et al.*, 2007a; *Murray and Thieler*, 2004]. The reduction of this slope results in more mobile coarse sediment that tends to spread from previously coherent coarse domains. The spreading of coarse material from coarse domains and the infiltration of fine sediment tend to shut down the fundamental feedback driving the sorting process.

[14] In experiments with no aggradation/erosion, and with no high wave events, many coarse domains disappear because of this cessation of the sorting feedback. In plan view this process of pattern breakdown occurs on many adjacent coarse patches simultaneously. This leads to a spatially intermittent pattern within 2000 model days, seen in Figure 1e (resulting from the progression Figure 1c–Figure 1d–Figure 1e). Loss of these coarse domains does not ultimately lead to the loss of the entire bedform field, but instead the bedform field maintains a spatially intermittent pattern. This intermittent pattern reflects the critical level of coarseness, an attracting state of active layer composition (Figure 2). In this state there is only enough coarse material on the surface to drive sorting in spatially discontinuous coarse domains.

[15] Complete disappearance of the sorted bedform pattern, a transition from Figure 1e to 1f does not occur under these conditions. Disappearance of sorted bedforms does occur in experiments with shallow water (10 m) and experiments in slightly more energetic wave climates (wave heights $\geq$ 3 m). Complete disappearance of the pattern in these conditions apparently occurs because stronger wave orbital motions result in more mobile sediment (both coarse and fine) and bedform relief is initially slightly lower (leading to lower bedform slope), which provides less of an impediment to sediment mobility. Furthermore initial sorting buries more coarse material (Figure 2a). The active layer in shallow water experiments falls to a lower critical value of active layer coarseness (13%) much faster (250 days) than experiments in deeper water (16% within 700 days; Figure 2a). This leads to the complete loss of coarse domains within $\sim$400 model days.

3.2. Results and Interpretation: Deposition and Erosion

[16] Including erosion or deposition changes the morphology and temporal persistence of sorted bedforms. We performed an experiment for $\sim$15,000 days with steady aggradation and current magnitude adjustments. A sorted bedform pattern persists throughout the entire duration of the numerical experiment, much longer than other reported uses of the model [*Coco et al.*, 2007a, 2007b; *Huntley et al.*, 2008]. Bulk deposition during this time amounts to 0.5 m.

[17] Similar to the experiment described above with no deposition, the active layer reaches a critical level of coarseness by processes of vertical sorting. However, with deposition, the continual addition of coarse material at the surface tends to cause coarse domains that were once shrinking to maintain their size or grow. Furthermore, coarse deposition also enables the nucleation of coarse domains where the feedback had originally been shut down. Concurrent fine sediment deposition tends to damp and/or shut down the sorting feedback on several coarse domains. The combined effect of this bimodal deposition is that as soon as the active layer reaches the critical value of coarse material, there is a near constant growth and decay of sorted bedforms (with an identical orientation to the initial pattern). Although the individual coarse and fine domains are not preserved, a pattern dominated by discontinuous coarse domains and many new defects (Figure 1g) is present for the duration of the experiment. The processes that lead to this spatially and temporally intermittent pattern are autogenic, the result of internal dynamics and not a result of spatially or temporally heterogeneous forcing conditions. Experiments with net erosion of fine material yield qualitatively similar plan view patterns and dynamics: the growth and modification of coarse domains occur as a result of the removal of fine sediment.

3.3. Results and Interpretation: "Storm" Scenarios

[18] Pattern dynamics in experiments subject to high wave events (representing storms) put forward another end member for bedform pattern evolution. The original pattern developed under conditions of 2 m high waves is destroyed by the high waves that flatten the sorted bedforms. The active layer becomes more coarse during storm events as fine material is brought into suspension. Coarse material becomes more mobile, spreading over much of the domain because of higher wave forcing and lower bathymetric slopes. As a result mean coarseness of the active layer increases and more coarse material is present over a larger aerial extent of the domain (Figure 1h). Several model days are required after the storm event for a new pattern to emerge that is identical in orientation and similar in wavelength and position to the pre-storm pattern (Figure 1i). Excess coarse material present on the seabed prohibits fine sediment from settling in much of the domain, segregating fine material deposition to distinct areas. This leads to coarse domains that are wider than pre-storm patterns (Figure 1i versus Figure 1c). Previous work showed that large waves produce sorted bedform patterns with large wavelengths [*Coco et al.*, 2007a]. After the high wave event defects begin to migrate, coarse material is buried and fine material begins to infiltrate along the edges of coarse domains. These processes lead to vertical sediment sorting and result in fining of the active layer. Eventually the post-storm arrangement with wide coarse domains reverts to the initial pre-storm pattern (Figure 1c). Without subsequent storms this sorted bedform field will develop as if the storm had never occurred (i.e., the aforementioned "basic" scenario).

[19] Frequent storm events prohibit the process of pattern maturation (i.e., vertical sorting). This leads to a coarse active layer that exerts a significant control on the plan view pattern. With 100 day storm intervals, coarse domains coalesce into a large wavelength pattern after several storm cycles (Figure 1j). Inter-storm periods characterized by weaker wave climates tend to cause the sorted bedform field to revert to a smaller wavelength pattern. This process of deconvolution gives rise to a sorted bedform pattern that is a superposition of both modes during inter-storm periods (Figure 1k). If storms are frequent enough, sorted bedform fields traverse a repeated loop of Figure 1j–Figure 1k–Figure 1h. If storms are infrequent, Figure 1k eventually devolves to Figure 1i as the active layer fines and the pattern devolves entirely into a small wavelength pattern as coarse material is buried. In storm experiments the active layer does not settle on a critical value for coarseness (Figure 2b). Autogenic fluctuations in coarseness occur around a mean of $\sim$35% coarse material with a 5% amplitude. This variation occurs as a result of autogenic cycles of burial and excavation of coarse material.

4. Discussion

[20] Experiments from this study demonstrate that sorted bedform patterns may be persistent or ephemeral based solely on autogenic factors. Ephemeral sorted bedforms, such as those observed by *Hume et al.* [2003], occur in shallow water where model sorted bedforms have the tendency to be ephemeral. The sorting feedback may be more susceptible to stoppage as a result of the increased active layer fining and vertical sorting in shallow water bedforms or those subject to strong wave forcing. Processes that bury coarse sediment and may impact the strength of the sorting feedback have been observed previously in the Tairua embayment of New Zealand. *Green et al.* [2004] observed fine sediment infiltration of coarse domain edges and buried fringes of coarse domains are present in short cores [*Trembanis and Hume*, 2011]. The subsequent reappearance of ephemeral bedforms may be a result of intense storms that excavate the buried coarse domains or because of erosion of overlying sediment.

[21] Erosion of fine material or deposition of coarse material allow for the maintenance and nucleation of coarse patches. This is in agreement with the ideas of *Green et al.* [2004] that dispersed coarse material may be able to seed new bedforms. Erosion or deposition leads to a persistent yet spatially intermittent bedform pattern (as in the basic scenario), but in this situation individual coarse domains may be temporally intermittent features.

[22] Frequent high wave events such as storms tend to coarsen the seabed and contribute to sorted bedform persistence. The sorting feedback is strengthened through storm events that tend to clear or flush coarse domains (at least the edges) of fine sediment, as previously suggested by *Green et al.* [2004]. Frequent storms lead to large temporally stable features with significant heterogeneity in the pattern as a result of the superposition of storm and inter-storm patterns. This superposition of modes rather than the result of bedform migration may be the cause of "wispy edges" [*Murray and Thieler*, 2004].

[23] Overall, long term sorted bedform pattern behavior can be encapsulated by nondimensional ratios. Persistent or ephemeral bedforms are separated by a threshold value of water depth over wave height. The numerical location of this threshold is determined by initial and forcing conditions. Another critical parameter is the nondimensional ratio of deposition rate (rate at which sediment is added to the active layer) divided by the rate of active layer fining (rate at which the coarse sediment is removed from the active layer through burial). If this ratio is initially greater than 1, the long term steady state is pattern persistence. If the ratio is initially between 0 and 1 the system organizes itself so that the active layer composition reaches a critical state as seen in the basic and deposition scenarios (Figure 2b). In the limit as this ratio approaches zero, the pattern becomes spatially intermittent but temporally persistent (Figure 1e). Finally, storm behavior can be described by the nondimensional ratio of storm return period divided by the characteristic time scale of active layer fining. In experiments with ratios greater than one (not shown) patterns alternate between storm and nonstorm modes (Figure 1c–Figure 1h–Figure 1i loop). Ratios on the order of 1 produce a spatial mixture of storm and nonstorm modes (Figure 1h–Figure 1j–Figure 1k loop). For ratios approaching 0 the storm mode will dominate the long term pattern. Future work involving additional experiments could systematically explore and refine the thresholds in these controlling parameters.

[24] Spatial intermittence represents the bistablity of patterned and unpatterned regions, analogous to mixed patterns in Rayleigh-Bénard circulation [e.g., *Cross and Hohenberg*, 1993]. We found only one previously described example of bedform intermittency as a result of autogenic processes, the modeled ripples of *Nishimori and Ouchi* [1993]. Whether of not pattern maturation leads to self-destruction

or self-organized intermittency in other bedforms is unknown. Defect dynamics, which tend to drive pattern wavelength increases, can theoretically lead to wavelengths which are too large and consequentially unstable, resulting in pattern reconfiguration through new bedform growth in the trough [*Andreotti et al.*, 2006]. If defect dynamics or other nonlinear pattern maturation processes (in the case of sorted bedforms, the burial of coarse material) lead to the inhibition of the fundamental feedback that drives bedform maintenance, other bedforms may be susceptible to this behavior.

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References

Andreotti, B., P. Claudin, and O. Pouliquen (2006), Aeolian sand ripples: Experimental study of fully developed states, *Phys. Rev. Lett.*, *96*, 028001, doi:10.1103/PhysRevLett.96.028001.

Coco, G., A. B. Murray, and M. O. Green (2007a), Sorted bedforms as self-organized patterns: 1. Model development, *J. Geophys. Res.*, *112*, F03015, doi:10.1029/2006JF000665.

Coco, G., A. B. Murray, M. O. Green, E. R. Thieler, and T. M. Hume (2007b), Sorted bedforms as self-organized patterns: 2. Complex forcing scenarios, *J. Geophys. Res.*, *112*, F03016, doi:10.1029/2006JF000666.

Cross, M. C., and P. C. Hohenberg (1993), Pattern formation outside of equilibrium, *Rev. Mod. Phys.*, *65*(3), 851–1112, doi:10.1103/RevModPhys.65.851.

Green, M. O., C. E. Vincent, and A. C. Trembanis (2004), Suspension of coarse and fine sand on a wave-dominated shoreface, with implications for the development of rippled scour depressions, *Cont. Shelf Res.*, *24*, 317–335, doi:10.1016/j.csr.2003.11.002.

Hume, T. M., A. C. Trembanis, A. Hill, R. Liefting, and S. Stephens (2003), Spatially variable, temporally stable, sedimentary facies on an energetic inner shelf, in *Coastal Sediments '03* [CD-ROM], edited by A. Press, Am. Soc. Civ. Eng., Reston, Va.

Huntley, D. A., G. Coco, K. R. Bryan, and A. B. Murray (2008), Influence of "defects" on sorted bedform dynamics, *Geophys. Res. Lett.*, *35*, L02601, doi:10.1029/2007GL030512.

Murray, A. B., and E. R. Thieler (2004), A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and "rippled scour depressions," *Cont. Shelf Res.*, *24*, 295–315, doi:10.1016/j.csr.2003.11.001.

Nishimori, H., and N. Ouchi (1993), Formation of ripple patterns and dunes by wind-blown sand, *Phys. Rev. Lett.*, *71*, 197–200, doi:10.1103/PhysRevLett.71.197.

Trembanis, A. C., and T. M. Hume (2011), Sorted bedforms on the inner shelf off northeastern New Zealand: Spatiotemporal relationships and potential paleo-environmental implications, *Geo Mar. Lett.*, *31*, 203–214, doi:10.1007/s00367-010-0225-8.

Van Oyen, T., H. E. de Swart, and P. Blondeaux (2010), Bottom topography and roughness variations as triggering mechanisms to the formation of sorted bedforms, *Geophys. Res. Lett.*, *37*, L18401, doi:10.1029/2010GL043793.

Werner, B. T., and G. Kocurek (1999), Bedform spacing from defect dynamics, *Geology*, *27*(8), 727–730, doi:10.1130/0091-7613(1999)027<0727:BSFDD>2.3.CO;2.

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