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# Characterizing and hindcasting ripple bedform dynamics: Field test of non-equilibrium models utilizing a fingerprint algorithm

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ABSTRACT

Ripple bedform response to near bed forcing has been found to be asynchronous with rapidly changing hydrodynamic conditions. Recent models have attempted to account for this time variance through the introduction of a time offset between hydrodynamic forcing and seabed response with varying success. While focusing on temporal ripple evolution, spatial ripple variation has been partly neglected. With the fingerprint algorithm ripple bedform parameterization technique, spatial variation can be quickly and precisely characterized, and as such, this method is particularly useful for evaluation of ripple model spatio-temporal validity. Using time-series hydrodynamic data and synoptic acoustic imagery collected at an inner continental shelf site, this study compares an adapted time-varying ripple geometric model to observed field observations in light of the fingerprint algorithm results. Multiple equilibrium ripple predictors are tested within the time-varying model, with the algorithm results serving as the baseline geometric values. Results indicate that ripple bedforms, in the presence of rapidly changing high-energy conditions, reorganize at a slower rate than predicted by the models. Relict ripples were found to be near peak-forcing wavelengths after rapidly decaying storm events, and still present after months of sub-critical flow conditions.



## 1. Introduction

Spatio-temporal variability in hydrodynamic forcing (e.g. wave, current or combined flow) complicate attempts to model ripple morphodynamics in the inner-continental shelf environment. Because the organization of ripples are mostly dependent upon dominant hydrodynamic conditions, sediment composition, or some combination of the two (e.g. Wiberg and Harris (1994)), spatial variability in forcing conditions would be expected to produce different configurations of ripple bedforms spacing (wavelength) and orientation, even within relatively small ripple fields. Consequently, attempts to model temporal evolution of ripple bedforms, which typically focus on one representative value (e.g. mean wavelength and orientation) have trouble predicting spatial distribution in ripple morphology, and multiple field and laboratory studies have shown that most semi-empirical ripple models do not accurately predict actual field measurements (Li and Amos, 1998; Camenen, 2009; Pedocchi and García, 2009). One limiting factor to empirical modeling has been accurately recording and measuring ripple spatio-temporal evolution (Davies and Thorne, 2008; Skarke and Trembanis, 2011).

In previous studies, ripple geometry was quantified from seafloor imagery using various methodologies. Manual image interpretation is the most fundamental means of deriving ripple data from seafloor backscatter imagery (e.g. Traykovski et al. (1999)). The subjectivity of individual interpretations, however, leads to concerns over repeatability and variability between observers, aside from the impracticality of characterizing large fields of ripple bedforms (Skarke and Trembanis, 2011). Studies have thus turned to more automated methods, such as frequency-transform analysis (e.g. Voulgaris and Morin (2008) and Maier and Hay (2009)). This method converts acoustic imagery into the frequency domain through Fourier or other transforms, resulting in two-dimensional power spectrum in frequency space. Despite the improvement over manual analysis, there remain significant limitations to this method, including but not limited to the inability to disambiguate ripple orientation variability from wavelength variability (Skarke and Trembanis, 2011).

Instead, Skarke and Trembanis (2011) adapted a methodology for extracting ripple orientation and wavelength from side-scan imagery built around algorithms designed to extract biometric fingerprint statistics (see Hong et al. (1998) and Felzenberg (2009)). This method analyzes ripple imagery and assigns statistical values to each individual pixel, allowing the user to quantify

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ripple variability and distribution across a spatial domain. Rippled regions are assigned a reliability parameter, which is the ratio of backscatter intensity variability parallel and orthogonal to ripple crest orientations and represents the extent to which the bed in organized into a linear trough and crest morphology. This allows the user to set a minimum threshold to mask out areas that exhibit non-rippled as well as poorly organized or non-resolved ripple morphology. Orientation values are estimated using Gaussian filtered backscatter gradients to locate ripple crests, from which localized ripple wavelength values are derived (for further information on methods see Skarke and Trembanis (2011). Additionally, the algorithm contains a method for isolating ripple defects by filtering and thinning backscatter images to isolate ripple crest lines. In all, the method presented by Skarke and Trembanis (2011) is better suited than previous approaches for the determination of the spatial variability of ripple morphology and is particularly useful for evaluation of ripple model validity (e.g. Goldstein et al. (2013) and Zare and Cobb (2013)).

Numerous empirical ripple models have been proposed over the last few decades (e.g. Nielsen (1981), Grant and Madsen (1982), Wiberg and Harris (1994), Traykovski et al. (1999) and Soulsby and Whitehouse (2005)) in attempts to better predict ripple dynamics. Instead of relating ripple height and wavelength to instantaneous surface wave conditions, multiple studies (Soulsby and Whitehouse, 2005; Doucette and O'Donoghue, 2006; Austin et al., 2007; Traykovski, 2007; Voulgaris and Morin, 2008, Soulsby et al., 2012) note that ripples exhibit a delayed response to changes in flow. Recent models have attempted to address these shortcomings. Traykovski (2007) adapted a non-equilibrium ripple model to allow for ripple reaction to lag behind hydrodynamic conditions. The lag is quantified using a variable timescale defined by the ripple cross-sectional area divided by the sediment transport rate (Traykovski, 2007). Subsequently, Soulsby et al. (2012) developed a time-dependent ripple calculation based upon the general derivative:

$$\frac{dx}{dt} = a(t) - b(t)x(t) \quad (1)$$

where $x$ may represent ripple wavelength ($\lambda$), height ($\eta$), or orientation ($\phi$). Equilibrium ripple predictors (e.g. Soulsby and Whitehouse (2005)) are used to calculate the values for $x$. The equation coefficients $a(t)$ and $b(t)$ are time varying values calculated by the expressions:

$$a(t) = \frac{\beta}{T_e} x_{eq} \quad (2)$$

$$b(t) = \frac{\beta}{T_e} + \frac{1}{T_b}\text{bio} \quad (3)$$

where the 'bio' variable is a switch for biodegradation to ripple height, controlled by biological half-life variable ($T_b$). The coefficient $T_e$ is defined as the time scale for ripple evolution (such as wave period for wave dominant conditions), and $\beta$ describes the rate change in ripple characteristics based on hydrodynamic conditions, derived from the wave mobility parameter ($\psi$) and critical threshold values. Further, the model incorporates wave or current dominated conditions, based on near bed shear stress values, to determine which ripple geometry prediction will be utilized in the calculation at time ($t$).

The results of the model were observed by Soulsby et al. (2012) to be promising, though there was the noted tendency of the model to underpredict ripples wavelengths in large-wave events (e.g. storms). They concluded by outlining a number of potential improvements to the model, including incorporation of other "more accurate" predictors for large ripple wavelengths and heights. As such, the goal of this study is to extend the Soulsby et al. (2012) model, comparing the accuracy of three equilibrium ripple predictors within the model to field observations. With the fingerprint algorithm results serving as the baseline geometric values, the ability of the ripple model to predict temporal evolution can be tested with field observations. Further, we examine the performance of the non-equilibrium component in light of the fingerprint algorithm findings, and consider factors complicating ripple geometric predictions. Observations from this study highlight the variability of ripple morphodynamics on the inner-shelf.

## 2. Study site

Field observations were collected at the Redbird Artificial Reef (Fig. 1), an area encompassing 3.4 square kilometers of seafloor located approximately 30.5 km east of Indian River Inlet, Delaware (DNREC, 2009–2010). The reef is located within the Cape May shoal-retreat massif, created by the recent Holocene shoreline transgression of the Delaware River estuary system (Swift et al., 1980). The shoal and swale system trends NE–SW around the reef, with a prominent ridge northwest of the reef. Situated within a swale, the field site ranges from 21 to 29 m water depth. The central and southern areas of the reef are a mixture of fine, sometimes silty, clayey sand, and coarse gravelly sand likely deposited by the ancestral Delaware River or tributaries during the late Wisconsinan (Fletcher et al., 1992; Raineault et al., 2013). The reef is composed of various structures, including 997 New York City subway cars and 11 large vessels placed between 1996 and 2009 (DNREC, 2009a,b). Scour moats around the objects often expose coarse pre-Holocene sediment buried as shallow as 0.25 m from the surface (Raineault et al., 2013). In a study of the Redbird reef, Raineault et al. (2013) indicated that the seabed boundaries between the fine, silty sand and coarse gravelly sands were persistent, although they migrated slightly southwards over the course of multiple years. Also noted at the site were persistent sorted bedforms, possessing large wave orbital ripples. Large scour pits were also observed around the reef objects. These were often comet-shaped, extending to the west-southwest, which is the typical direction of forcing from large-wave events at the site (Raineault et al., 2013). The boundaries of the comet-shaped scour pits around the reef objects were noted to change annually.

As with much of the Mid-Atlantic bight, seabed morphodynamics at Redbird Reef are largely driven by waves from episodic storm events. Low to moderate tidal currents (~15–20 cm/s M2 tidal amplitude) are typical of average conditions in this region with peak bed stress and sediment transport during high energy events (Münchow et al., 1992; Wright, 1995). While experiencing both tropical and extra-tropical storm events, 'nor'easters' are the more frequent systems, usually occurring from late October to early March. The highest winds and waves from these events come out of the northeast and east-northeast, with waves often exceeding 4 m significant wave height and mean currents over 50 cm/s offshore (Wright, 1995). Events similar to the 1991 'Halloween Storm' have generated waves over 6 m in height, mean currents near 50 cm/s and near-bed orbital velocities over 140 cm/s (Madsen et al., 1993; Wright et al., 1994). During Hurricane Sandy, which was observed during this study, significant wave height was greater than 7 m and orbital velocities reached 160 cm/s (Trembanis et al., 2013).