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Environmental signal shredding on sandy coastlines

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Abstract

How storm events contribute to long-term shoreline change over decades to centuries remains an open question in coastal research. Sand and gravel coasts exhibit remarkable resilience to event-driven disturbances, and, in settings where sea level is rising, shorelines retain almost no detailed information about their own past positions. Here, we use a detailed, multi-decadal observational record of shoreline position to demonstrate quantitative indications of morphodynamic turbulence – "signal shredding" – in a sandy beach system. We find that, much like other dynamic sedimentary systems, processes of sediment transport that affect shoreline position at relatively short time-scales obscure or erase physical evidence of external forcing. This suggests that large forcing events like major coastal storms, even when their effects are recorded, may convey less about the dynamics of long-term shoreline change – and vice versa – than coastal researchers might wish.

Keywords – coastal hazard; landscape resilience; beach recovery; beach rotation; Narrabeen-Collaroy

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1. Introduction

Quantifying magnitudes and rates of shoreline change is fundamental to understanding the dynamics of coastlines: not only how they behave over time, but also how they may respond to future, climate-related changes in environmental forcing. From a coastal-management perspective, shoreline change may constitute a coastal hazard – either event-driven, like the impact of a major storm, or chronic, like persistent shoreline erosion from a net-negative sediment budget. Long-term, continuous measurement of shoreline position observed at a given location will record changes arising from event-driven and chronic forcing, alike. But how punctuated storm events contribute to long-term shoreline change (over decades to centuries) remains an open question, particularly in the context of shoreline-change prediction (Morton et al., 1994; Fenster et al., 2001; Houser and Hamilton, 2009; Anderson et al., 2010; Masselink and van Heteren, 2014; Brooks et al., 2016; Masselink et al., 2016; Scott et al., 2016; Burvingt et al., 2017).

Evidence of coastal storm frequency and magnitude over centuries to millennia may be stored in the sedimentary stratigraphy of beach ridges (Tamura, 2012) and washover into back-barrier lagoons (Donnelly and Woodruff, 2007), offering a window into climatic conditions in the recent geologic past. But ridge or washover stratigraphy is not a direct measure of shoreline position. Indeed, in transgressive settings (in which relative sea level is rising) the shoreline itself retains almost no detailed information about its own past positions. Sand and gravel coastlines, especially, reflect remarkable resilience to event-driven disturbances – even to tsunami (Choowong et al., 2009). Storm-driven shoreline excursions on the order of $\sim10^1$–10^2 m may be obscured in the shoreline position (and/or beach volume) within days to months, and effectively erased within years (Birkemeir, 1979; Egense, 1989; Thom and Hall, 1991; Morton et al., 1994; Douglas and Crowell, 2000; Honeycutt et al., 2001; Zhang et al., 2002; List et al., 2006; Lazarus et al., 2012; Lentz et al., 2013; Masselink and van Heteren, 2014; Phillips et al., 2017).

This context echoes a theoretical exposition by Jerolmack and Paola (2010) regarding the problem of determining how dynamic sedimentary systems – especially those with source-to-sink pathways – respond to rapid external forcing. Processes of sediment transport tend to rework upstream/upslope inputs so completely that their downstream/downslope outputs may bear no resemblance to the original pattern of forcing that drove them. Jerolmack and Paola (2010) call this phenomenon the "shredding" of environmental signals, and offer that shredding – or, more formally, "morphodynamic turbulence" – behaves much like fluid turbulence, in that "energy injected at one frequency is smeared across a range of scales." High-frequency signals of external forcing are especially likely to be shredded. Drawing on the physics of turbulent fluid flows (Frisch and Kolmogorov, 1995), Jerolmack and Paola (2010) use sediment flux time-series from physical and numerical experiments – bedload transport in a flume channel (Singh et al., 2009), a canonical rice-pile experiment (Frette et al., 1996), and a numerical rice-pile model – to illustrate their argument. Beyond source-to-sink sedimentary systems (Romans et al., 2016), signal shredding has since been extended to spatio-temporal changes in lake levels (Williams and Pelletier, 2015) and methane release from peatlands (Ramirez et al., 2015).

Here, we investigate signal shredding in an altogether different sediment-transport system: that of a sandy beach. Although previous studies of sandy shoreline dynamics have invoked signal shredding conceptually (Lazarus et al., 2011, 2012; Williams et al., 2013), none have used observed shoreline data to demonstrate quantitative signatures of signal shredding empirically. Following Jerolmack and Paola (2010), we find the hallmarks of morphodynamic turbulence in observational time series of shoreline position at Narrabeen-Collaroy Beach, southeast Australia (Short and Trembanis, 2004; Harley et al. 2011, 2015; Turner et al. 2016; Phillips et al., 2017). The potential for beaches to "shred" large-magnitude changes in shoreline position complicates reconciliation of short-term beach dynamics and long-term, spatio-temporal patterns of shoreline variability and evolution.

2. Setting and dataset

The Narrabeen-Collaroy embayment (Fig. 1a) comprises a 3.6 km long sandy beach, and is one of only a few sites worldwide where ongoing beach monitoring has been regular, frequent, and uninterrupted for multiple decades (Turner et al., 2016). Cross-shore profiles at five locations along the beach (Fig. 1a) have been measured approximately monthly (Fig. 1b) since 1976 (Turner et al., 2016). In addition to more than four decades of these monthly cross-shore beach profiles, continuous alongshore shoreline positions derived from RTK-GPS quadbike surveys of the full three-dimensional subaerial beach have been obtained approximately monthly (Fig. 1c) since 2005 (Harley and Turner 2008; Harley et al., 2011, 2015). For the southern half of the embayment (Fig. 1a), daily-averaged shoreline position has also been recorded by an Argus Coastal Imaging system (Fig. 1d) for over a decade (Phillips et al., 2017). In each of these sets we take the 0.7 m AHD (Australian Height Datum) elevation contour as the shoreline, commensurate with mean high water (Harley et al., 2011). Data gaps in the profiles and time-series are filled by linear interpolation.

3. Analysis

3.1. Patterns in power spectra

In their bedload and rice-pile examples, Jerolmack and Paola (2010) collapse these physical systems into one dimension – a time series of sediment flux past a single point – defining sediment flux (q) as the instantaneous quantity of sediment leaving the system. Here, in our beach example, we define q as the change in shoreline position (x, where elevation $z = 0.7$ m AHD) between consecutive time steps at a given location alongshore (y) (Fig. 2a–f). In a generic source-to-sink system in which sediment only moves downstream, sediment flux is unidirectional and positive. By contrast, in the one-dimensional beach system explored here, shoreline movement is bidirectional, as wave-driven cross-shore sediment transport shifts the shoreline at any location (x, y) onshore and offshore over time. We therefore use both the positive and negative values of shoreline change to represent sediment flux.

Like the systems described by Jerolmack and Paola (2010), a power spectrum of the one-dimensional sediment-flux term $q(t)$ yields a pattern with two regimes. A non-stationary regime, in which spectral density increases as a power-law function of time-scale over shorter intervals, transitions or rolls over into a comparatively stationary (or uncorrelated)

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Earth Surface Dynamics Discussions

regime at longer intervals (Fig. 2g–i). Although less crisply defined than the modeled unidirectional examples from Jerolmack and Paola (2010), this general pattern in the power spectrum serves as the first indication that signal shredding is inherent in the dynamics of sandy beach systems.

But what signal, exactly, is being shredded at the shoreline? Consider again a unidirectional source-to-sink system, driven by some input flux (q_o) at the upstream end. That input flux might be constant; it might fluctuate (e.g., seasonal cycles); it might spike with large-magnitude events. Whatever its pattern in time, input flux embodies the environmental signal that is susceptible to shredding by sediment transport processes as it passes downstream through the system. In a controlled physical experiment or a numerical model, input flux (of sediment and/or fluid) is a known quantity, set by the researcher. For natural source-to-sink systems, sediment input flux cannot necessarily be resolved directly – but it may be estimated from flow discharge (i.e., bedload sediment flux will be a fraction of the fluid flux). Here, in the beach system, we assume that the input flux – the external environmental signal that shoreline behavior may destroy or preserve – is represented by energy flux from incident storm waves. We define storm wave conditions by a threshold corresponding to the 95th percentile of deep-water significant wave height (H_s, m), which for this region is $H_s > 3$ m (Harley, 2017). Much like flow discharge in a fluvial system, deep-water wave energy flux (E, kW per m wavefront) may serve as a useful proxy for input flux to the beach:

$$E = \frac{\rho g^2}{64\pi} H_s^2 P_w \approx 0.5 H_s^2 P_w \;\; \text{kW/m} \qquad (1)$$

where ρ (kg/m^3) is water density, g (m/s^2) is acceleration by gravity, H_s (m) is significant deep-water wave height, and P_w (s) is wave period.

We calculate monthly and daily total storm-wave energy flux corresponding to the monthly and daily shoreline time-series (Fig. 3a,b), and transform them into power spectra (Fig. 3c,d). The consistent spectral pattern encoded in the time-series of shoreline change (q) appears to be more organized (Fig. 2g–i) than the one encoded in the wave forcing (q_o) (Fig. 3c,d). Where the power spectrum for q is non-stationary over a range of relatively high frequencies (short time-scales relative to the total length of the time-series) before transitioning into a comparatively stationary regime, the power spectrum for q_o is effectively stationary across all time-scales.

According to Jerolmack and Paola (2010), the transition in spectral density from non-stationary to stationary should correspond to an intrinsic, characteristic time-scale T_x. Theoretically, T_x is set by the system size L and sediment input rate q_o. While those parameters can be dictated for experimental systems and calculated reasonably for (unidirectional) source-to-sink systems, they are less clear for an open sandy coastline. We estimate T_x in the Narrabeen-Collaroy system through two independent approaches.

3.1 Characteristic time-scale from system size and input flux

The first approach is a back-of-the-envelope exercise. We assume that the system size L is equivalent to maximum cross-shore beach width. This assumption follows from having

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Discussion started: 1 October 2018

collapsed the system into only the cross-shore (x) dimension: for any alongshore position y, the theoretical maximum cross-shore (x) extent to which the beach can ever erode is the full width of the beach L, independent of embayment length. (We call L the "theoretical maximum" because historical records of shoreline change are necessarily of finite duration, and therefore may never reflect this full width.) Since q and E have different units, for this calculation we normalize both time-series relative to their respective maximum values. Thus, at all profiles $L = 1$. For q_o, we take the mean normalized monthly (and daily) total wave energy flux over the full span of the dataset. This representation of mean q_o is an imperfect proxy for the kind of constant input flux possible with a sediment feeder in controlled experiments, but it serves the purpose here for a rough estimate of T_x. Dividing L/q_o for the monthly total time-series (Fig. 3a) yields T_x = ~180 days (~6 months), and for the daily total time-series (Fig. 3b) yields T_x = ~150 days (~5 months).

3.2 Characteristic time-scale from modes of beach dynamics

The second approach to estimate one or more characteristic time-scales T_x for the Narrabeen-Collaroy system is based on observed modes of shoreline behavior typical at this site, and at embayed beaches more generally (Ranasinghe et al, 2004; Harley et al., 2011, 2015; Ratliffe and Murray, 2014). Although modes vary in detail between specific locations, approximately four modes of shoreline behavior tend to describe how sediment moves within embayed beach systems. One mode reflects cycles of off- and onshore movement of sediment as a quasi-coherent unit at the full scale of the embayment (i.e., imagine a narrow beach during stormier times of the year, and a wide beach during calmer intervals). Another dominant mode of shoreline response is termed "rotation," and occurs when prevailing wave conditions or a storm event shifts a significant volume of sediment inside the embayment alongshore and/or onshore-offshore to form a wider beach at one end and a narrower beach at the other (Ranasinghe et al, 2004). Related to this rotation is what has been described as a "breathing" mode, a kind of shoreline resonance that hinges near the center of the beach and characterizes changes in shoreline curvature, as sand moves between the middle and ends of an embayment (Ratliff and Murray, 2014). Another potential mode of shoreline dynamics reflects patterns of shoreline variability introduced by rhythmic movements of sandbars, sandwaves, megacusps, and inlet processes, where applicable (Harley et al., 2011, 2015). These four modes are not necessarily hierarchical: their relative dominance can change as a function of wave conditions. More importantly, these principle modes of shoreline behavior likely manifest intrinsic time-scales.

To find characteristic time-scales corresponding to the modes of shoreline behavior at Narrabeen-Collaroy, we follow steps described by Ratliff and Murray (2014). From the monthly shorelines derived from RTK-GPS quadbike surveys, at each position alongshore we detrend the series of shoreline position (not shoreline-position change) in time (Fig. 4a). To calculate the empirical orthogonal modes in the alongshore dimension through time, and thus characterize shoreline variation around its mean position (Fig. 4b), we apply principal-component analysis. Each mode in sequence explains a smaller percentage of variation in the data. We then use a continuous wavelet transform to examine the spectral signatures of the first four modes in the temporal dimension, squaring the wavelet

Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-72
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Discussion started: 1 October 2018

transform coefficients and finding the mean power at each wavelet scale for time. The result is a power spectrum (Lazarus et al., 2011), in which peaks represent the characteristic time-scale for each mode of embayed-beach behavior (Ratliff and Murray, 2014). We take T_x (Fig. 4c) as the first local maximum in the power spectrum (Ratliff and Murray, 2014) using a Ricker-Marr wavelet. (Other Gaussian-type wavelets yield similar power spectra and characteristic time-scales.)

We find that the first two modes in these data are both rotational (Fig. 4c): the first, a rotation toward the north, accounts for 51% of the observed shoreline variability with a characteristic time-scale of ~21 months; the second, a rotation toward the south, accounts for 32% (~6.5 months), and agrees closely with the T_x calculated independently from the (normalized) cumulative wave-energy flux data. The third and fourth modes account for 5.4% (~11 months) and 2.5% (~11 months) of observed shoreline variability, respectively. In previous applications of PCA to Narrabeen-Collaroy (Short and Trembanis, 2004; Harley et al., 2011, 2015), rotational behavior was secondary (26% of shoreline variability around its mean position) to a dominant mode (~60%) of quasi-coherent, off- and onshore sand movement within the embayment.

4. Discussion and implications

Jerolmack and Paola (2010) show that morphodynamic turbulence will tend to "shred" (strongly modify) input perturbations with time-scales shorter than the characteristic time-scale of the system ($T < T_x$). Only input perturbations with time-scales $T > T_x$ are likely to be preserved (or only weakly modified) in the output flux q. The characteristic time-scales that we estimate for the Narrabeen-Collaroy system (Figs. 3 and 4) suggest that shoreline-change perturbations with time-scales $T < T_x$ (where $T_x \approx 6$ months) fall within the bounds of morphodynamic turbulence, and their effects on shoreline change will tend to get "smeared" across a range of temporal scales in the output signal (Fig. 2). In these data, a seasonal time-scale (~6 months) appears to dominate (Fig. 2g–i). Irregular but multi-annual forcings, such as the El Niño–Southern Oscillation (Barnard et al., 2015), should therefore have a time-scale sufficiently long enough to avoid erasure by seasonal cycling. Moreover, if climate-related drivers were to increase future forcing at the seasonal time-scale ($T \approx T_x$), there is potential for system resonance (Binder et al., 1995; Cadot et al., 2003; Jerolmack and Paola, 2010) to amplify seasonal shoreline changes.

Only an exceptional event, Jerolmack and Paola (2010) argue, whatever its time-scale, may be large enough to travel through a unidirectional sediment-transport system without being shredded. They point out that in morphodynamic systems defined by critical thresholds (landsliding in an experimental rice pile, for example), a minor perturbation can cascade from small scales to large ones, amplifying into a "system-clearing event." They conclude that although morphodynamic turbulence and fluid turbulence share similar scaling, the tendency to cascade implies that morphodynamic turbulence, contrary to its fluid counterpart, is not dissipative. We suggest that sandy coastlines may exemplify a sedimentary system in which morphodynamic turbulence is dissipative. Unlike threshold-driven systems of unidirectional flow where amplification is possible, the maximum

Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-72
Manuscript under review for journal Earth Surf. Dynam.
Discussion started: 1 October 2018

magnitude of a system-clearing event in an embayed beach cannot exceed the theoretical maximum beach width *L*. Forcing by wave-energy flux might vary over time (Harley et al., 2011, 2015; Ratliff and Murray, 2014; Phillips et al., 2017), but alongshore sediment transport resulting from prevailing waves will tend to smooth out plan-view perturbations in shoreline position on a sandy coast, at least over relatively local spatial scales ($<\sim10^3$ m) and where shoreline curvature is low (Lazarus and Murray, 2007; Lazarus et al., 2011, 2012).

The predominance of dissipative effects and a characteristic T_x at the seasonal time-scale and will tend to make storm-driven perturbations in shoreline-position time-series difficult to isolate in sparsely sampled records of shoreline change. If cross-shore beach recovery is rapid – that is, if most of the sediment shifted off a beach during a storm is stored in a nearshore bar and then swept back onshore in a matter of days to weeks afterward – then the magnitude of shoreline change driven by the event may appear damped in even a monthly survey of beach position. In cases where alongshore sediment transport is significant, then the longer the beach, the more effective the shredder. When such large fluctuations are so ephemeral, only high-frequency sampling can hope to capture their fullest extents (Splinter et al., 2013; Phillips et al., 2017).

Intrinsic time-scales for modes of beach change along open coastlines may be different from those for embayed settings. Ratliff and Murray (2014) suggest the diffusive scaling evident in their modeling results implies that characteristic time-scales increase nonlinearly with embayment length alongshore. They list other factors that could likewise change the characteristic time-scales, such as wave height, sediment type, and the aspect ratio of headlands relative to the bay (which would affect local wave height through wave shadowing). Were the same high-resolution spatio-temporal data available for $\sim10^4$ m of open sandy coastline as it is for Narrabeen-Collaroy, comparable analysis might highlight a series of progressively larger characteristic time-scales for reversing erosion hotspots, alongshore sand waves, and fluctuations in alongshore curvature (List et al., 2006; Lazarus et al., 2011).

In an ideal source-to-sink sedimentary system with perfect storage, output flux *q* would be faithfully recorded in the sink stratigraphy. The majority of work in morphodynamic turbulence and signal shredding comes from efforts to puzzle out what information stratigraphic records do and no not convey about environmental forcing (Paola et al., 2018). Since shoreline position in a transgressive beach system is not stored in any way comparable to a source-to-sink system, what does it mean to represent shoreline change as sedimentary output flux? The answer may be that large forcing events like major coastal storms, even when we can record their effects, probably tell us less about the dynamics of long-term shoreline change – and vice versa – than we wish to know. In embayed beach systems where alongshore spatial scales are constrained ($<\sim10^1$ km), cross-shore sediment cycling and rotational 'sloshing' of the beach between headlands combine to make a highly efficient shredder that operates at the full spatial extent of the beach. On open coastlines, where alongshore spatial scales are large ($\sim10^1$–10^2 km), the cumulative, diffusive effect of alongshore sediment transport is an equally effective shredder (Lazarus et al., 2011, 2012) –

and likely even more so when coupled to human manipulations of natural shoreline behavior (McNamara and Werner, 2008a,b; Williams et al., 2013; Lazarus et al., 2011; Lazarus et al., 2016).

Empirical evidence of signal shredding in the shoreline-position data from the Narrabeen-Collaroy system demonstrates how, and suggests why, signatures of individual storm impacts can be obscured or erased in long-term observational records, even those recorded at a reasonably high (~monthly) temporal resolution. Jerolmack and Paola (2010) recommend using controlled experiments to gain vital mechanistic insight into morphodynamic turbulence. Here, the effects of system size L, input flux q_o, the magnitudes of so-called "system-clearing events," and potential resonant amplification ($T \approx T_x$) at seasonal time-scales could be tested systematically across a broad parameter space for coastal systems. In exploring the dynamics of signal shredding, the same controlled experiments that would also be exploring characteristic time-scales for fundamental processes of sediment transport in coastal environments.

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Figures and Captions

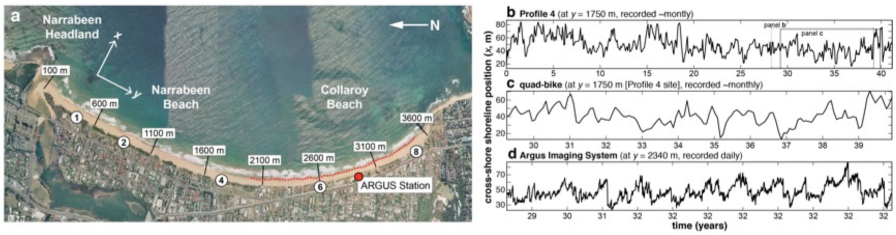

Figure 1. (a) Narrabeen-Collaroy beach, showing locations of long time-series profiles and Argus Imaging System coverage. Alongshore coordinates (*y*) are relative to the northern end below Narrabeen Headland. **(b)** Long-term time series of cross-shore shoreline position (0.7 m contour) at Profile 4, measured approximately monthly between 1976–2017. Time axis is in years since first measurement (27 April 1976). **(c)** Time series of cross-shore shoreline position at alongshore location *y* = 1750 m (aligned with Profile 4), measured by quad-bike approximately monthly between 2005–2017. **(d)** Time series of cross-shore shoreline position at alongshore location *y* = 2340 m, measured by Argus Imaging System daily between 2005–2016. Boxes (dotted, solid) in panel (b) frame the temporal coverages for the time series in panels (c) and (d).

Earth Surf. Dynam. Discuss., https://doi.org/10.5194/esurf-2018-72
Manuscript under review for journal Earth Surf. Dynam.
Discussion started: 1 October 2018

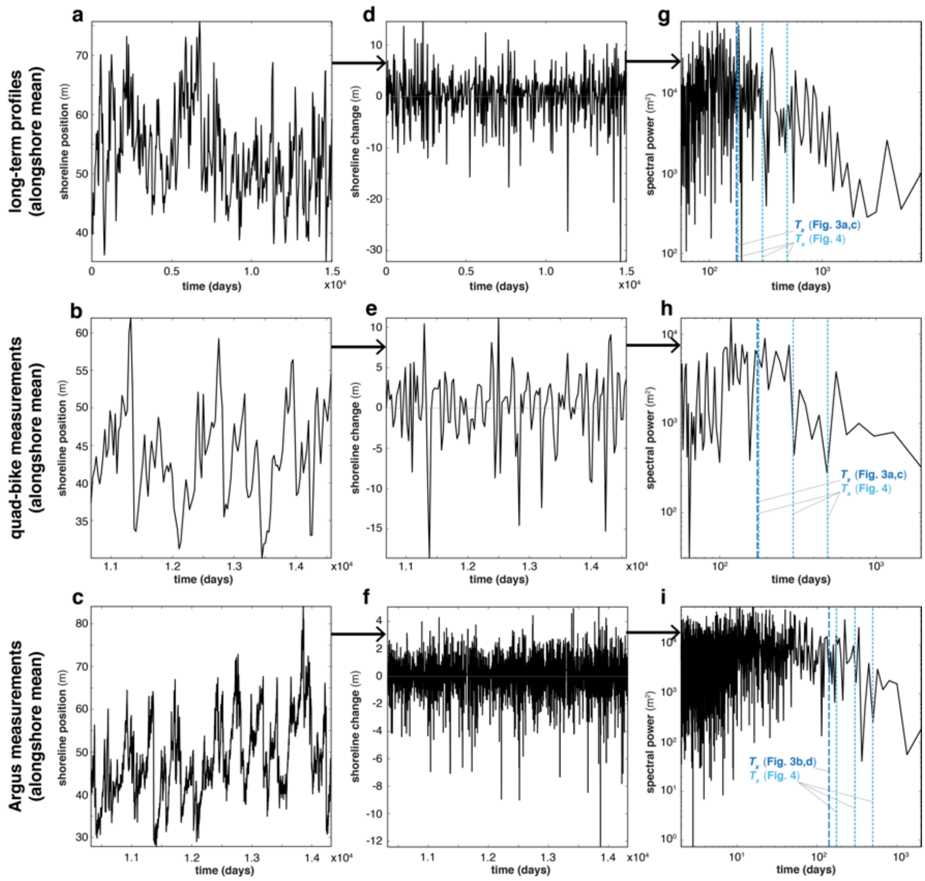

Figure 2. **(a)** Alongshore mean of monthly measurements of shoreline position (z = 0.7 m contour) from long-term Profiles 1, 2, 4, 6, and 8, plotted in days since first measurement (27 April 1976). **(b)** Alongshore mean of monthly shoreline position from the RTK-GPS quad-bike surveys. **(c)** Alongshore mean shoreline position from a 850 m reach of the Argus camera coverage (y = 1950–2800 m). **(d, e, f)** Shoreline change in panels (a, b, c), calculated as difference between consecutive shoreline positions, which we treat as output flux q. **(g, h, i)** Resulting power spectra from panels (d, e, f), with estimated characteristic time-scales T_x based on monthly/daily total storm wave energy flux (dashed line; Fig. 3), and PCA of variations around mean shoreline position (dotted lines; Fig. 4).

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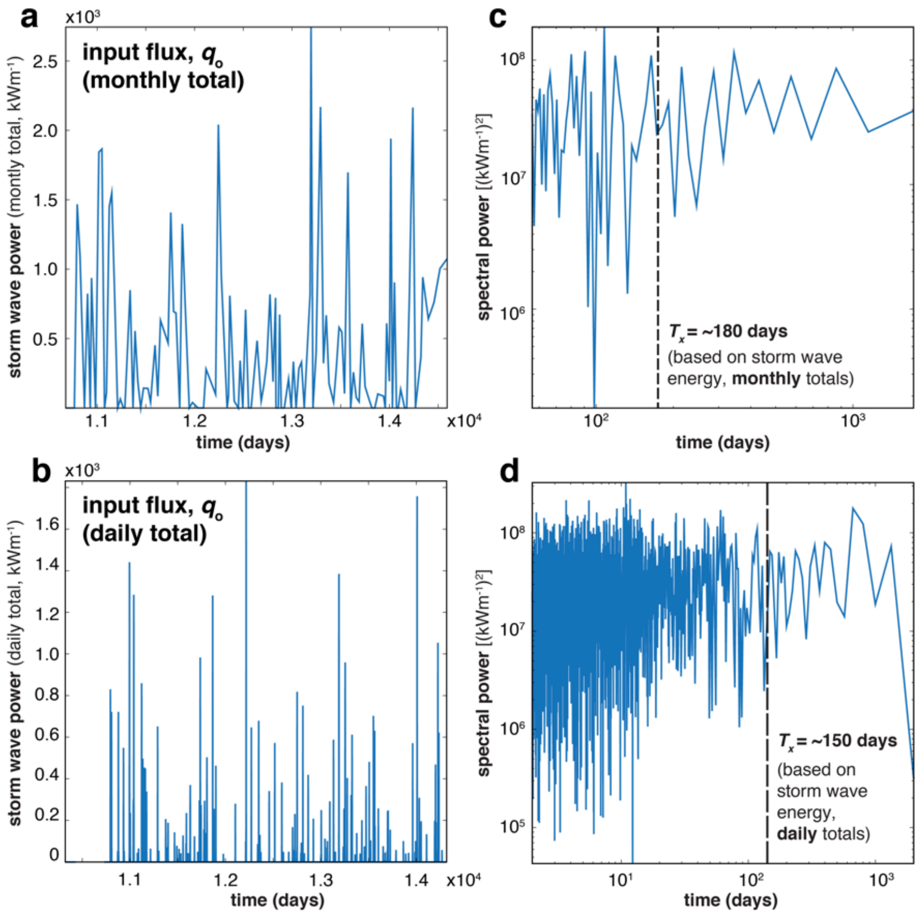

Figure 3. (a) Monthly total and **(b)** daily total storm wave energy flux between 2005–2017, which we use as a proxy for input flux q_o. **(c)** Power spectrum for monthly total storm wave energy flux in (a). Dotted line indicates estimated characteristic time-scale T_x = ~180 days (~6 months). **(d)** Power spectrum for daily total storm wave energy flux in (b). Dotted line indicates estimated characteristic time-scale T_x = ~150 days (~5 months).

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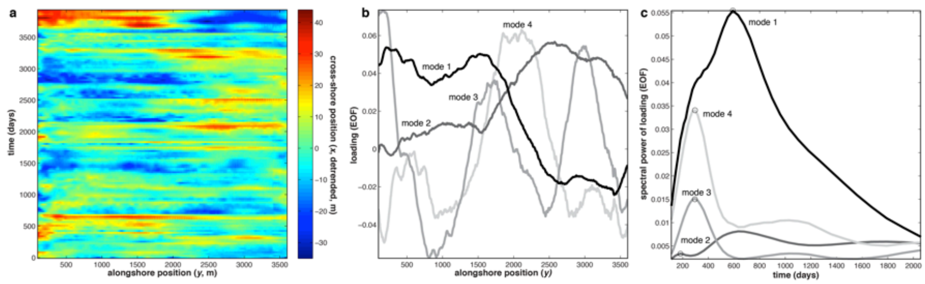

Figure 4. (a) Detrended (in time) shoreline position, measured ~monthly by quad-bike, with north at left (corresponding to Fig. 1a). **(b)** Orthogonal PCA modes, representing variance about the mean shoreline position, and **(c)** wavelet-derived power spectra (using a Ricker-Marr wavelet) of each mode, where the first local maximum indicates the characteristic time-scale (T_x) for that mode.
