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Key Points:
- In contrast to the conventional model of collision-induced erosion, wave-driven processes can contribute constructively to dune growth
- Transport limitations are found to be more important than supply limitations for wind-driven dune growth at a modally dissipative beach
- A new morpho-stratigraphic approach is developed to infer process dominance of wind and wave forcing on seasonal dune growth

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New Insights on Coastal Foredune Growth: The Relative Contributions of Marine and Aeolian Processes

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Abstract Coastal foredune growth is typically associated with aeolian sediment transport processes, while foredune erosion is associated with destructive marine processes. New data sets collected at a high energy, dissipative beach suggest that total water levels in the collision regime can cause dunes to accrete—requiring a paradigm shift away from considering collisional wave impacts as unconditionally erosional. From morphologic change data sets, it is estimated that marine processes explain between 9% and 38% of annual dune growth with aeolian processes accounting for the remaining 62% to 91%. The largest wind-driven dune growth occurs during the winter, in response to high wind velocities, but out of phase with summertime beach growth via intertidal sandbar welding. The lack of synchronization between maximum beach sediment supply and wind-driven dune growth indicates that aeolian transport at this site is primarily transport, rather than supply, limited, likely due to a lack of fetch limitations.

Plain Language Summary Coastal dunes are prevalent features along much of the world's sandy ocean coastlines. As these landforms serve as the first line of protection against storm-induced coastal flooding, understanding when and why dunes erode and/or recover has significant societal importance. This study investigates beach and dune evolution at a field site in southwest Washington, USA, by utilizing (1) a long-term data set of coastal change and (2) detailed information on local waves, tides, and winds. Although high water levels impact the dune frequently during the winter as a result of a high-energy wave climate, the dunes at this location are growing rapidly. Here we show that high water levels are not necessarily destructive to dunes and instead under certain conditions they can contribute, along with wind induced sediment transport, to dune growth.

1. Introduction

Sandy coastal systems evolve at a range of time and space scales reflecting the complexity of the processes influencing the coastal zone. On subhourly scales, cross-shore subaqueous sediment transport gradients result from the competing processes of onshore, offshore, and longshore directed wave and current forcings (e.g., Roelvink & Stive, 1989). In general, low-energy conditions drive net onshore sediment transport via non-linear wave processes (e.g., Hoefel & Elgar, 2003) contributing to beach growth. Conversely, undertow and low-frequency wave motions typically erode the beach during elevated energy conditions (e.g., Russell, 1993). Over longer time scales ($>$ seasonal), longshore sediment transport gradients are often the primary driver of shoreline change (e.g., Harley et al., 2011).

Foredune growth is believed to be primarily driven by aeolian sediment transport and associated feedbacks with sand trapping vegetation (e.g., Hesp, 1981). While instantaneous dry sand transport is controlled predominantly by wind velocity and local grain size characteristics (e.g., Bagnold, 1937), foredune growth on annual to decadal scales is often poorly correlated with wind conditions (de Vries et al., 2012). Even in the presence of wind, sediment supply limiters such as armoring (Hoonhout & de Vries, 2017), moisture content (Davidson-Arnott et al., 2005), cementation (Nickling & Ecclestone, 1981), and fetch limitations (e.g., Delgado-Fernandez, 2010) limit or prevent aeolian sediment transport to the dunes. These findings in part promote a hypothesis whereby dune growth is thought to be controlled primarily by the synchronicity of sediment supply from the nearshore to the beach, via the welding of intertidal sandbars (IBW), with the capacity to mobilize this sediment by wind (Houser, 2009). That is, dune growth will not occur, or is volumetrically limited, when IBW does not coincide with wind sufficient to cause saltation. The rarity of observed foredune erosion on some dissipative beaches has been previously credited as evidence for synchronization (Houser,

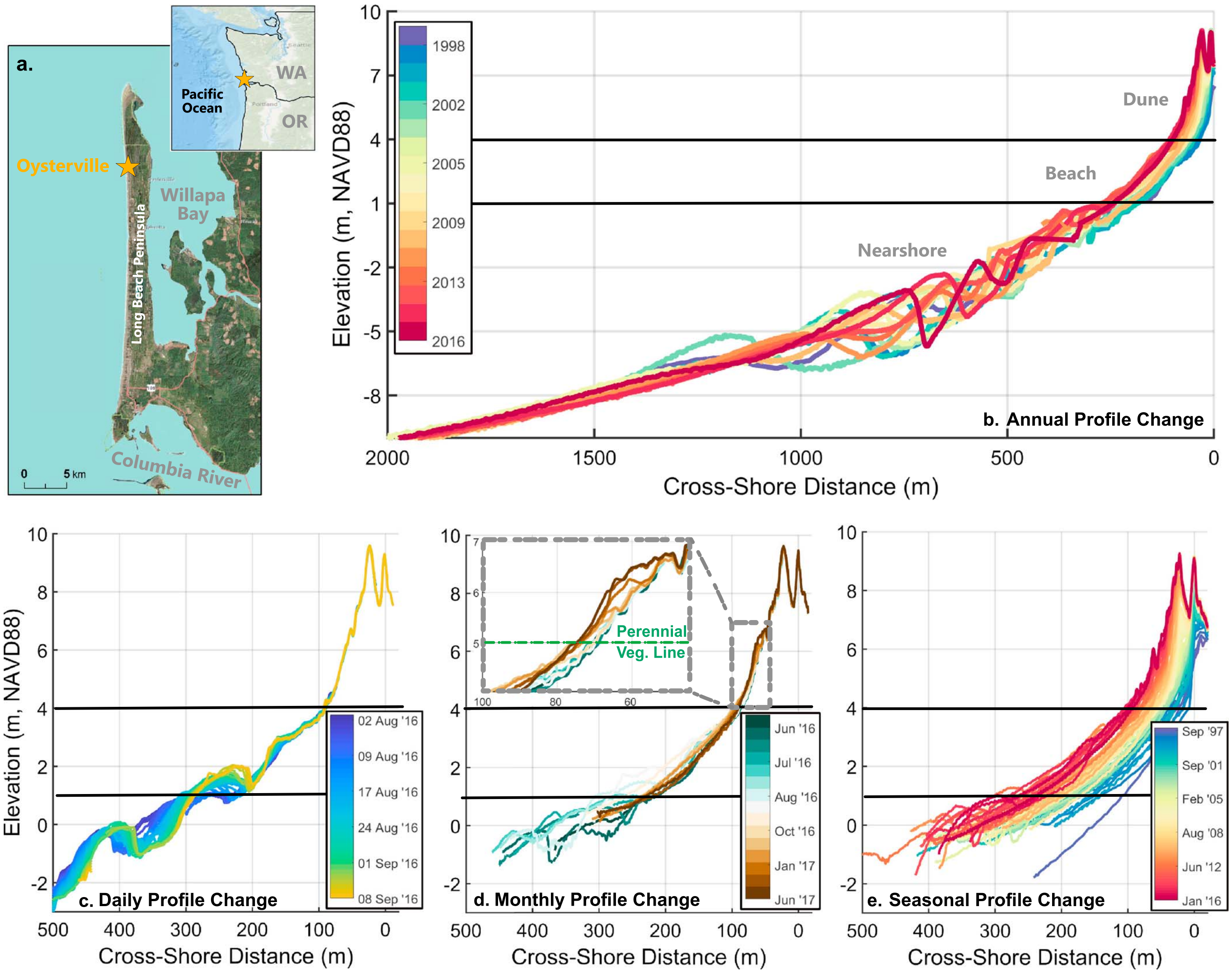

Figure 1. (a) Field site location and (b) annual (1998–2016), (c) daily (summer 2016), (d) monthly (June 2016 to June 2017), and (e) seasonal (1997–2016) cross-shore profile changes at Oysterville.

2009). However, limited quantitative data exist demonstrating that synchronized transport between the nearshore, beach, and dune is a universal factor in controlling dune growth.

Here we explore the time scales and processes driving sediment exchanges between the nearshore, beach, and dune using morphologic and environmental data sets spanning time scales of days to decades at a dissipative field site in Oysterville, Washington, USA. Utilizing these data, we test the hypothesis that dune growth is controlled by the synchronization of IBW and aeolian transport capacity.

2. Field Data Sets and Methods

2.1. Geographic Setting

The town of Oysterville, WA (Figure 1a), is located on the Long Beach Peninsula (LBP) within the U.S. Pacific Northwest and is a modally dissipative, mesotidal (2–3 m tidal range) system with low-gradient, fine sand (D_{50} ~ 0.2 mm) beaches and densely vegetated foredunes (Hacker et al., 2012; Ruggiero et al., 2005). LBP is one of the largest continuous stretches of open coast in the world, with subaqueous sandbars, beaches, and dunes all exhibiting relative alongshore uniformity on scales of multiple kilometers (e.g., Di Leonardo & Ruggiero, 2015; Mull & Ruggiero, 2014; Ruggiero et al., 2016). Oceanographic conditions vary seasonally,

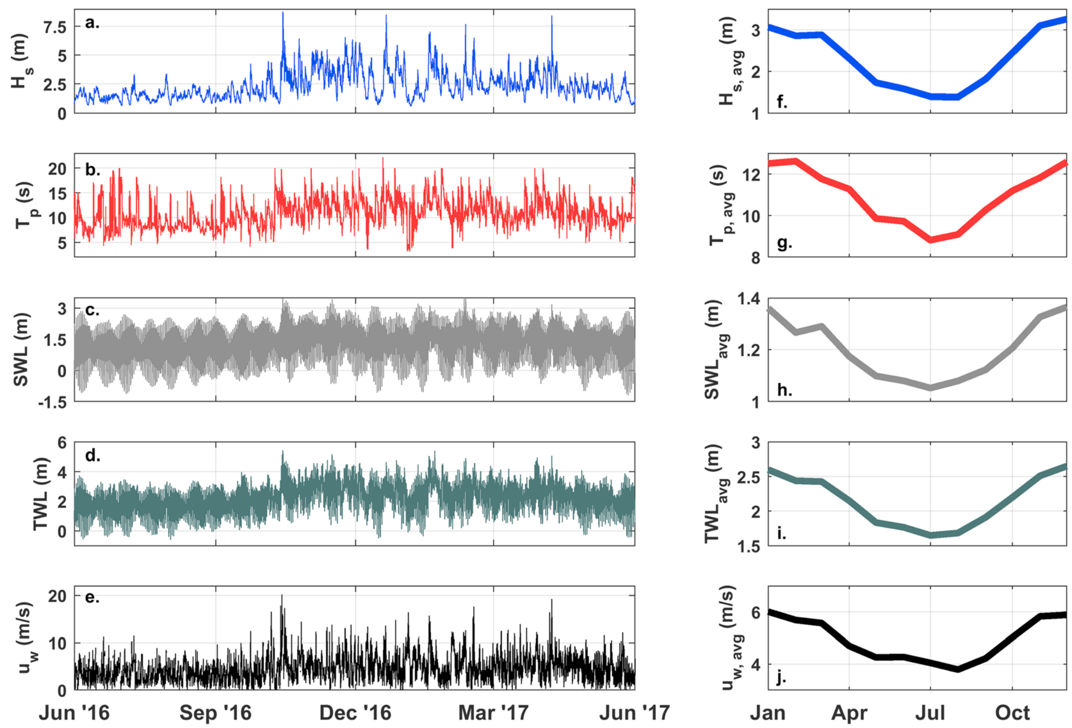

Figure 2. Significant wave height (H_s), peak wave period (T_p), still water level (SWL), total water level (TWL), and wind velocity (u_w) time series for (a–e) June 2016 to May 2017 and (f–j) multidecadal (1997–2017) monthly averages.

with the lowest wave energy and water levels occurring in boreal summer (Figure 2; Serafin & Ruggiero, 2014). Winter is more energetic, with the average annual winter storm having H_s exceeding 10 m. The wind climate is also seasonally variable and in phase with the wave climate (Figures 2f and 2j), with the largest wind speeds typically corresponding to winter storms. The seasonal cycles in forcing drive seasonal cycles of shoreline recession and progradation. However, on longer time scales, sediment inputs from longshore transport gradients and cross-shore shoreface feeding results in average shoreline progradation of about 4 m/year (Ruggiero et al., 2016). Despite the high-energy wave climate, foredune erosion is rarely observed and an entirely new foredune has developed at the study site since the late 1990s (Moore et al., 2016).

2.2. Morphology Measurements

A long-term coastal monitoring program has measured bathymetric (annual) and topographic (seasonal) changes since 1997 (Ruggiero et al., 2005; Figures 1b and 1e). The seasonal topographic surveys are typically collected in March (winter), June (spring), September (summer), and December (fall). Additional daily topographic and weekly bathymetric measurements were made during a 38-day period in August and September 2016 as part of the Sandbar Aeolian Dune Exchange Experiment (SEDEX^2; Figure 1c). Bracketing the main SEDEX^2 period, topographic data were collected nominally monthly between June 2016 and June 2017 (Figure 1d). For this study, a single, regionally representative cross-shore transect from these daily to decadal scale field initiatives is utilized. These data are interpolated onto a cross-shore grid (dx = 0.1 m) in order to assess volumetric and contour changes. For these analyses, the nearshore is defined as the region from −12 m (the seaward limit of data) to 1 m, with all vertical references relative to the NAVD88 datum. The 1 m contour (approximately local mean sea level) is used as a proxy for the nearshore-beach boundary. The beach is defined from 1 to 4 m, where this upper limit is associated with the approximate dune toe elevation and the zone landward of the dune toe is classified as the dune (e.g., Mull & Ruggiero, 2014). There are vertical uncertainties of ~ ± 0.07 m for the backpack-based topography (e.g., Ruggiero et al., 2005) and ~ ± 0.13 m for the single-beam bathymetry (e.g., Gelfenbaum et al., 2015) surveys. Accordingly, there are uncertainties of approximately 250, 10, and 5 m^3/m in each nearshore, beach, and dune volume calculation, respectively.

2.3. Environmental Conditions

The total water level (TWL), a key driver of short-term beach erosion (e.g., Ruggiero et al., 2001), represents the vertical water level excursion on the beach resulting from the combination of tides, nontidal residuals (e.g., storm surge), and wave runup. For this study, the 2% exceedance value of wave runup maxima ($R_{2\%}$) is calculated using the dissipative form of the Stockdon et al. (2006) empirical runup predictor, defined as

$$R_{2\%} = 0.046\sqrt{H_s L_o}$$

where L_o is the deep-water wavelength. An hourly TWL time series is calculated using wave height and period information from the Coastal Data Information Program (CDIP) buoy 036 located 35 km northwest from the study site and still water levels (tides plus nontidal residuals) measured at the National Oceanic and Atmospheric Administration (NOAA) Toke Point, WA, station 9440910 located 20 km northeast from Oysterville in Willapa Bay (Figure 2). Wind information is also obtained from the NOAA station.

2.4. Morpho-stratigraphic Analysis

Stratigraphy has been used in a wide range of applications to infer processes driving coastal landscape change (e.g., Clemmensen et al., 2001; Hein et al., 2012; Storms, 2003). To elucidate the timing of net sediment deposition at Oysterville, a morpho-stratigraphic cross section is developed from the morphology data. From each of the seasonal topographic profiles, the timing of the first instance of deposition that is not subsequently re-eroded is recorded for each cell on a grid that covers the entire beach and dune region ($dx = 0.1$ m, $dz = 0.1$ m).

Based on the environmental conditions, which occurred between the recorded deposition date and the preceding survey date, volumetric changes for each grid cell can be attributed to either wind or wave forcing. Since wave-driven transport rates are typically much larger than aeolian transport rates based on the 3 orders of magnitude difference in the transporting fluid density (e.g., Bagnold, 1937), deposition in areas affected by TWLs likely reflects transport by wave processes. Regions influenced by TWLs more than 2% of the time within a given season ($TWL_{2\%}$, ~44 hr /season) are assumed to be wave dominated. Above the maximum seasonal TWL (TWL_{max}) it is assumed that aeolian and ecological processes (Zarnetske et al., 2012) dominate net geomorphic changes in the dunes. The region between $TWL_{2\%}$ and TWL_{max} is potentially affected by both marine and aeolian processes.

As an example, at a cross-shore distance of 50 m (based on the coordinate system in Figure 1e), deposition at 4 m elevation was first recorded on 7 December 2003. The $TWL_{2\%}$ and TWL_{max} were 4.5 and 5.8 m, respectively, between the two relevant surveys. As both TWL values exceed 4 m, deposition recorded at the 50 m location is attributed solely to wave forcing. Conversely, new deposition in cells higher than 5.8 m were assumed to be driven by aeolian forcing as this region was not influenced by TWLs in fall 2003. Deposition between 4.5 and 5.8 m in this season may represent wave and/or wind forcing.

The grid-based morpho-stratigraphic results are subsequently averaged within 1 m vertical bins to assess the timing and process controls on deposition across the beach and dune.

3. Results

3.1. Daily Morphology Change

Cross-shore topographic surveys were completed for 38 consecutive days at low tide during $SEDEX^2$ (Figure 1c). The four sandbars present during $SEDEX^2$ all migrated onshore under sustained low-energy conditions (Cohn et al., 2017). The single sandbar located entirely within the intertidal zone migrated onshore at an average rate of 1.2 m/day, shallowing in the process and contributing to the growth of a berm above the mean high water contour (2.1 m). Although IBW was not completed during the experiment, the seaward-most berm position prograded by about 16 m and 42 m^3/m of sediment was added to the beach (Figure 3a). Negligible volume changes were observed in the dune during the experiment.

3.2. Monthly Morphology Change

Intertidal sandbars were intermittently present throughout spring and summer 2016 (Figure 1d) and, when present, continuously migrated onshore when H_s was below about 2 m. Resulting from this sandbar migration and welding sequence, which was partially captured during $SEDEX^2$, the most prograded position of

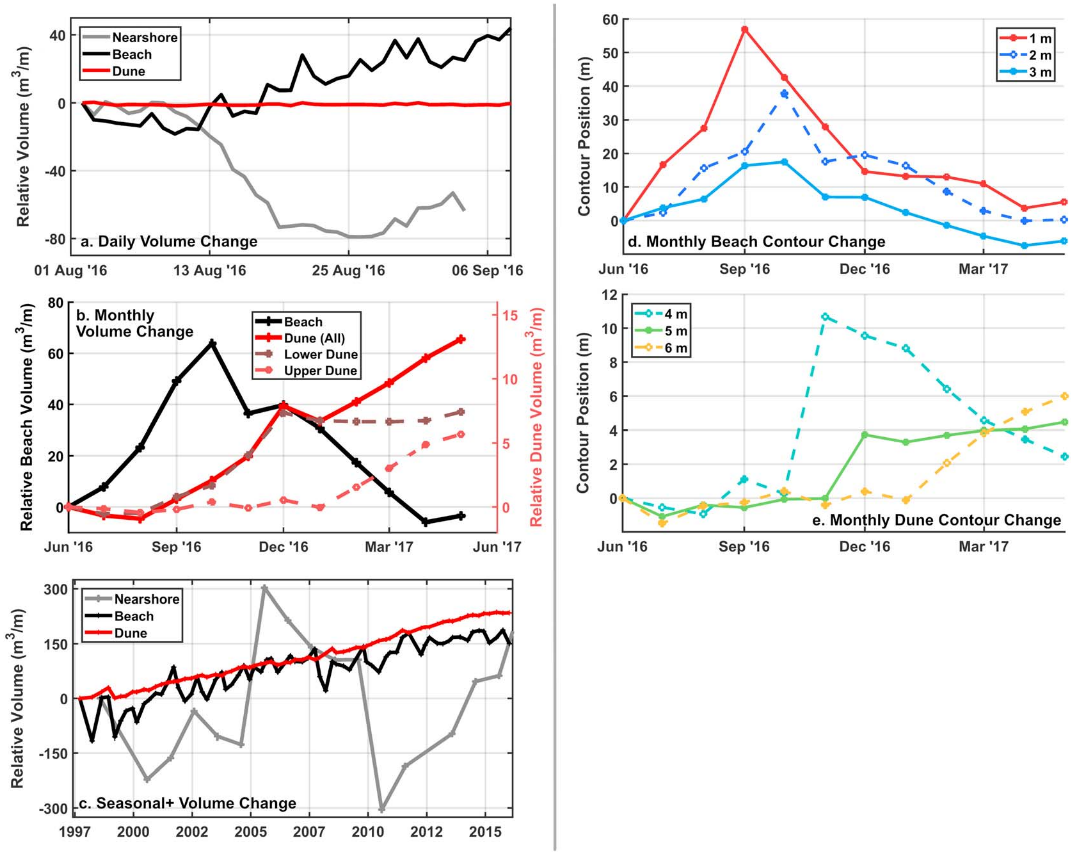

Figure 3. Nearshore, beach, and dune volume changes at (a) daily, (b) monthly, and (c) seasonal to interannual scales. Contour changes for the beach (d) and dune (e) are shown at monthly scale. Monthly dune volume changes (b) are grouped into the lower dune ($4.0 < z \leq 5.4$ m) and upper dune ($z > 5.4$ m) based on TWL_{max}.

the 1 m contour occurred in September 2016. Elevated water levels later in September (Figure 2a) contributed to erosion of the intertidal sandbar and berm morphology and smoothed the beach topography. In response, the 1 m contour eroded between September and October while the 2 and 3 m contours prograded (Figure 3d). Thereafter, the 1, 2, and 3 m beach contours continued to retreat until May 2017. Volume changes to the beach (ΔV_{beach}) behaved similarly (Figure 3b), with 64 m^3/m of sediment temporarily added to the beach during summer but with almost no net annual ΔV_{beach}.

Negligible contour and volume changes occurred within the dune (Figures 3b and 3e) between June and September 2016. Energetic conditions during October resulted in 4 hr when TWLs exceeded 5 m (Figure 2d), approximately corresponding to the perennial seaward extent of *Ammophila breviligulata* (American beach grass), with TWL_{max} as high as 5.4 m. Between October and November the 4 m contour prograded by 10 m and the lower dune (4 to 5.4 m) volume increased by about 2 m^3/m (significant relative to measurement uncertainty). A TWL_{max} event of 5.2 m in November coincided with an additional 4 m^3/m of lower dune growth. Visual observations of swash and freshly deposited marine macrophyte wrack found proximal to the perennial vegetation line during field surveys corroborate that TWLs reached above 5 m. Negligible sediment deposition above TWL_{max} in October and November suggests that limited aeolian transport occurred in this early fall period (Figure 3b). These combined observations support a potential wave-driven origin of these accumulated lower dune sediments (Figure 3b). Throughout the remainder of the monthly survey period, continually high TWLs (253 hr >4 m, 11 hr >5 m between November and May) did not drive lower dune volume losses (Figure 3b), though a gradual retreat of the 4 m contour occurred after November (Figure 3e).

Sediment deposited above 5.4 m (TWL_{max}) in 2016–2017 is assumed to result solely from aeolian processes. The largest rates of upper dune growth (>5.4 m) occurred between February and May 2017 (Figures 3b and

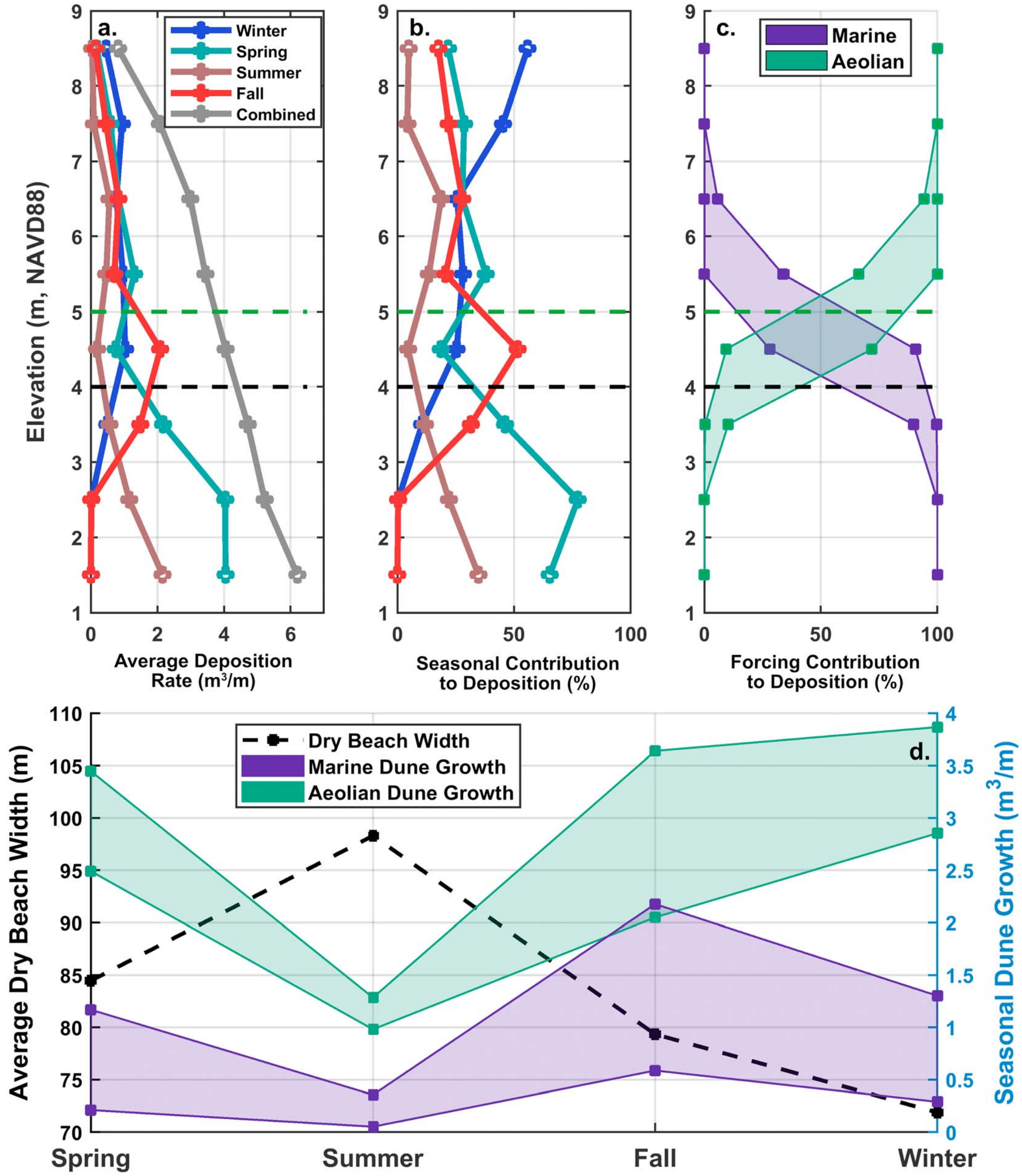

Figure 4. (a) Average seasonal deposition rates, (b) relative seasonal contribution to deposition, and (c) inferred marine and aeolian contributions to deposition based on the morpho-stratigraphic analysis, and (d) inferred marine and aeolian contributions to seasonal dune growth compared against average seasonal dry beach width. The shaded regions in c and d reflect uncertainty in process contribution to dune growth rates between $TWL_{2\%}$ and TWL_{max}.

3e)—coinciding with a period of relatively high wind energy (Figure 2) and the most eroded beach state (Figures 3b and 3d). Over the full year, 13 m^3/m of sediment accumulated in the foredune (ΔV_{dune}).

3.3. Seasonal to Decadal Morphology Change

The seasonal topographic data show sustained dune growth over the past two decades, with an average ΔV_{dune} of 13 m^3/m/year (Figure 3c). The data set shows negative ΔV_{beach} in winter, positive ΔV_{beach} in summer, and a mean net ΔV_{beach} of 8 m^3/m/year. Interannual nearshore volume changes show larger variability, exceeding the large measurement uncertainties of bathymetry data (~ ± 250 m^3/m) and therefore partially reflecting variability in gradients in longshore sediment transport.

The morpho-stratigraphic cross section shows that the largest volume gains to the beach occur in spring, with spring accounting for 65% of volumetric changes between the 1 to 2 m contours (Figures 4a and 4b).

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Because intertidal sandbars are transient features, net deposition on the beach is relatively minimal in summer. The lower portion of the dune is dominated by deposition in fall. Some aeolian transport occurs to the dune year-round, but the winter accounts for 31% of total ΔV_{dune} and 56% of the growth above 8 m.

The morpho-stratigraphic analysis also shows that volume changes above 6 m are controlled primarily by aeolian and ecological processes, where the shaded regions in Figures 4c and 4d reflect uncertainty in wave and wind contributions to deposition between $TWL_{2\%}$ and TWL_{max}. Conversely, deposition below 3 m is driven exclusively by wave processes. Consistent with the detailed 2016 observations, maximum rates of wave-driven lower dune growth are inferred to occur in the fall.

4. Discussion

Agreeing with previous studies, IBW is an important sediment delivery mechanism from the nearshore to the beach (e.g., Aagaard et al., 2004; Anthony et al., 2006). However, for this dissipative setting where the wind and wave climates are in-phase (Figures 2f–2j) and beach growth occurs during low wave energy conditions (Figure 3d), there is little opportunity for sandbar-derived sediments to be mobilized by winds prior to a seasonal increase in wave energy. Based on the morphology data sets, maximum ΔV_{dune} is generally about 6 months out of phase with maximum beach sediment supply (Figure 4d), where the available sediment supply is approximated with the average seasonal dry beach width (mean high water to 4 m; Diez et al., 2018). Maximum ΔV_{dune} instead occurs in phase with high wind velocities in winter despite the cooccurrence of an eroded beach state. Additionally, it is shown that annual ΔV_{dune} is relatively consistent with time despite large temporal variability in nearshore and beach volumes (Figure 3c). These observations suggest that transport limitations are more important than supply limitations for governing wind-driven dune growth at Oysterville. This may be a function of the large beach widths, fine-grained sand, and oblique winds at the field site, which collectively limit fetch effects on aeolian transport to the dune (e.g., Davidson-Arnott & Law, 1996).

Paleo-dune development at LBP has previously been related to the formation of a series of marine beach ridges (Cooper, 1958), which were only later capped by aeolian deposits following ridge abandonment. Contrasting with the distinct separation between wind and wave processes on coastal landform evolution described within the beach/dune ridge literature (e.g., Hesp, 2006; Taylor & Stone, 1996), the data presented here suggest that both marine and aeolian processes can simultaneously contribute to foredune growth. While dune erosion from direct wave impact and the landward transport of dune sediments via overwash have been widely documented (e.g., Figlus et al., 2010), to the knowledge of the authors, the direct role of waves in dune face growth has not been previously recognized. Although wave-driven dune accretion was only explicitly documented for the fall 2016 period, the morpho-stratigraphic approach implies that this accretional process is not infrequent and may contribute between 9% (up to $TWL_{2\%}$) and 38% (up to TWL_{max}) to annual dune growth. This is in contrast to the conventional viewpoint of geomorphic responses to the collision regime using Sallenger's (2000) Storm Impact Scaling model, requiring a shift away from the paradigm in which collisional wave impacts are unconditionally erosional. As LBP is relatively unique among coastal systems in that it is prograding, high energy, and low sloping, wave-driven dune accretion may be limited to end-member dissipative systems where the swash zone is dominated by low-frequency processes (Cohn & Ruggiero, 2016; Ruessink et al., 1998).

Aeolian and ecological processes have a larger control on overall dune dynamics—accounting for between 62% and 91% of ΔV_{dune} over the 20-year record. Aeolian processes also cannot be fully excluded as a depositional source below TWL_{max} without additional field observations. However, the lack of observed dune erosion despite the frequency of TWLs in the collision regime (~250 hr/year) is indirect evidence that high TWLs are not necessarily destructive to the dunes. While wave processes are assumed to dominate depositional signatures below $TWL_{2\%}$, higher thresholds show similar results. Only for threshold durations above $TWL_{7.5\%}$, corresponding to ~2 hr/day in the collision regime, does the morpho-stratigraphic approach indicate that aeolian processes are the sole contributor to dune growth (not shown).

Driven by the field observations, a conceptual model of the inferred seasonal sediment cycling and its relationship to long-term coastal evolution is presented in Figure 5. Spring is characterized by lower beach growth, summer by upper beach growth via IBW, fall by wave-driven lower dune growth, and winter by aeolian driven upper dune growth. The repeat cycling of these seasonal processes drives interannual dune

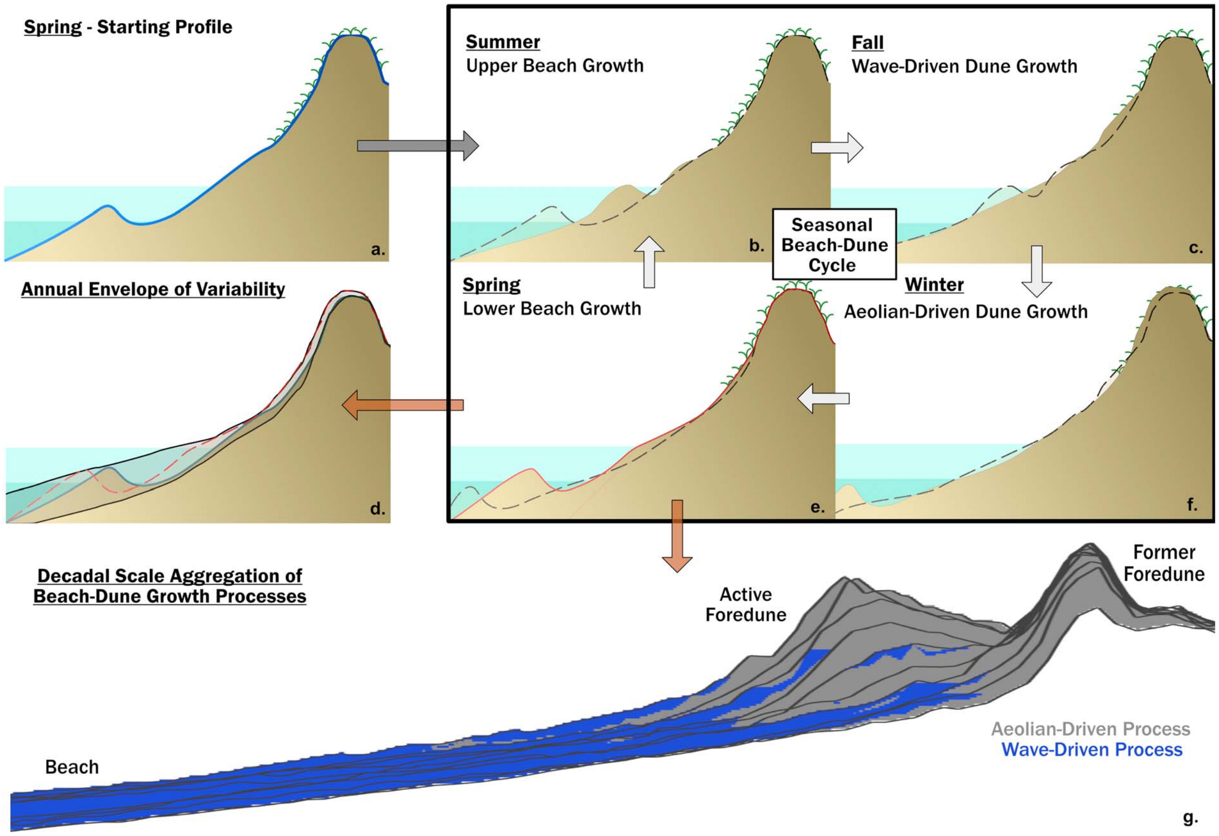

Figure 5. Conceptual model of beach and dune evolution at Oysterville, WA, showing the inferred predominant (a, b, c, e, and f) seasonal transport processes and geomorphic changes and (d) annual envelope of bed elevation change. Seasonal process aggregation over a decadal period using the morpho-stratigraphic approach is shown in panel g, where each black line represents net geomorphic changes over one year from aeolian (grey) and wave-driven (blue) contributions.

growth, a cycle in which foredune growth is temporally decoupled from beach and nearshore sediment supply (Figure 4d). Based on these detailed field observations, the synchronization hypothesis (Houser, 2009) does not appear to be valid for LBP and may be limited in its ability to explain the dynamics of sediment-starved systems and/or systems where wind and wave climates are not seasonally in-phase.

5. Conclusions

Morphologic measurements spanning time scales of days to decades provide new insights into processes driving dune growth at a dissipative, prograding beach. Beach and dune growth at Oysterville, WA, are not synchronized in time. While onshore intertidal sandbar migration drives beach growth in spring and summer, maximum dune growth instead occurs in winter coincident with the most eroded beach state and the highest wind speeds. It is demonstrated, perhaps for the first time, that elevated TWLs can cause dunes to accrete—in contrast to conventional frameworks that relate water levels above the dune toe solely to foredune erosion.

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