SHORELINE DYNAMICS ON A HIGH ENERGY BEACH ASSOCIATED WITH RELATIVE SEA-LEVEL FALL ON THE PACIFIC COAST, USA

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Abstract: In this study progradation of the dune toe on the sandy, dune-backed beaches of Makah Bay, on the Pacific Ocean shorelines of the reservation lands of the Makah Tribe, were documented for the first time. A shoreline assessment was implemented that included repeat beach profile surveys using RTK-DGPS and aerial lidar, and historical change analysis using aerial photos. Analysis of GNSS and aerial lidar suggest patterns of dune toe progradation over the last decade at average rates of ~0.8 m/yr between 2010 and 2022 over almost all the 5.5 km length of beach in Makah Bay, excepting the ~250m long erosional area that prompted the study. A beach vegetation line delineated in aerial photos collected between 1952 and 2019 moved seaward at average rates of ~0.7 m/yr across the entire length of Makah Bay, suggesting that the pattern of progradation is long-lived. We assess evidence to evaluate whether this pattern of dune progradation can be explained by sediment supplies from watersheds draining to Makah Bay and conclude that local sediment supply cannot explain observed patterns. A variety of shoreline processes associated with relative sea-level fall are discussed and may explain the observed rates of shoreline progradation.

Introduction

Patterns of change on beaches are of particular interest in coastal management settings, as both progradation (seaward movement) and transgression (landward movement) of shorelines can drive habitat changes in coastal systems and can stress human communities and the built environment (Hanson and Lindh 1993). Modeling and predicting shoreline dynamics, though, is complicated, as the number of independent variables that can influence changes in morphology and beach position on shorelines is large, and can include factors like wave climate, tidal patterns, sediment supply, sea-level trends, and anthropogenic influences (Toimil and others 2020). Observational case studies are useful, especially in instances in which the influence of dependent variables can be plausibly isolated and explored.

The influence of sea-level change on beaches is of particular interest (Toimil and others 2020), primarily driven by projections suggesting that most shorelines of the world will experience rising sea level in the coming decades and centuries. However, sea-level rise is not a globally uniform phenomena (Lyu and others 2014), and some parts of the world, and their shorelines, are likely to experience relative sea-level fall well into the coming decades. Descriptions of the behavior and dynamics of shorelines associated with sea-level fall can therefore inform generalized predictive models of shoreline response that include sea-level changes.

Episodes of localized erosion on the Pacific Ocean beaches of the Makah Tribe prompted the development and implementation of a shoreline assessment for Hobuck and Tsoo-Yess beaches (Figure 1). The assessment included beach profile surveys using GNSS survey equipment conducted approximately every 2 months between June 2018 and June 2022, and a historical change analysis using aerial photos. The observations made during this study are important for two reasons. First, relative sea level is falling in the study area (COOPS 2022). The patterns of shoreline change observed during this study therefore may provide important insights about the types of shoreline dynamics associated with sea-level fall.

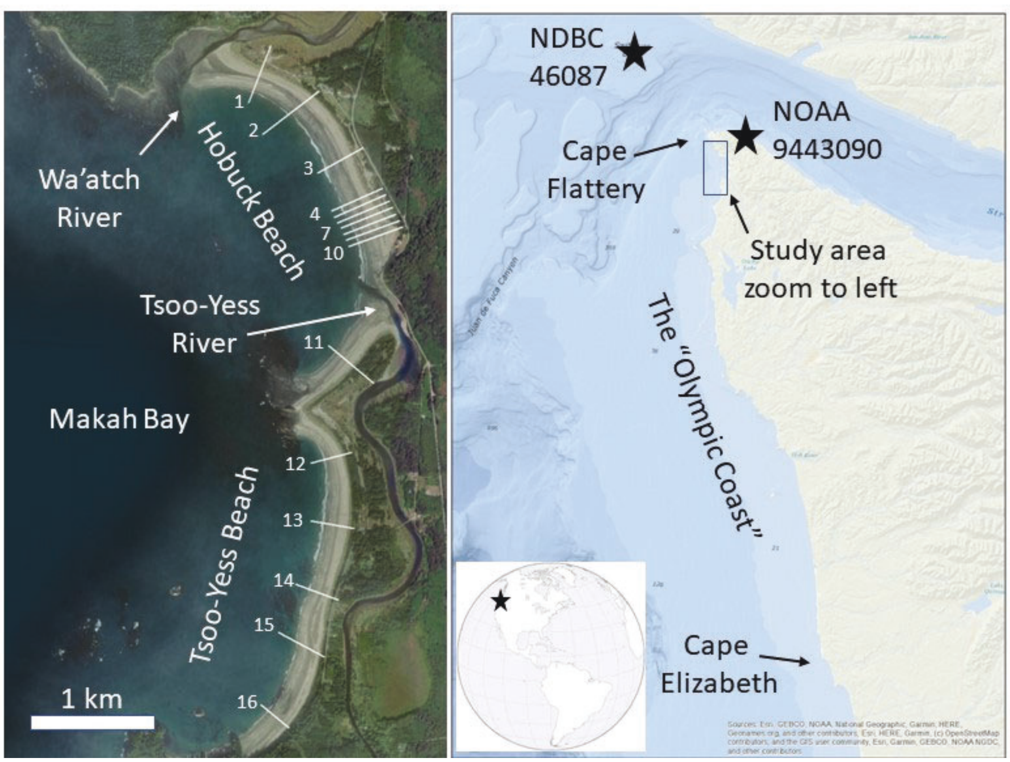

Figure 1. Study area and regional context, including the location of place names, transects and data sources referenced in the text.

Additionally, no assessment of shoreline change had been conducted along this part of the Pacific Coast, including in a national assessment of shoreline change (Ruggiero and others 2013). Observations of shoreline change along this coast are, therefore, novel.

Study Area and Regional Context

The Makah Reservation is located on the northwest tip of the Olympic Peninsula in Washington State, USA. The region is part of the tectonically active Cascadia Subduction Zone, and the Olympic Peninsula is an accretionary wedge associated with subduction zone processes. Probably because of tectonic forcing, the study area is estimated to be uplifting at rates of 2.7±1.5 mm/yr (Newton and others 2021), which has outpaced regional sea level relative to a geocentric reference frame over the 20th century (Miller and others 2018). As a result, observed relative sea level has fallen in Neah Bay, only a few kilometers from the study area, at an average rate of 1.7±0.3 mm/yr between 1935 and 2022 (COOPS 2022).

Hobuck Beach and Tsoo-Yess Beach are located at the north and south ends of Makah Bay along the Pacific Ocean on the Makah Reservation (Figure 1). Both beaches are broad, sandy, and relatively low-sloping (< 5° slope) and ~200 m in width backed along most of their lengths by sandy dunes vegetated with dune grasses (Figure 2). Large woody debris is sparsely distributed on both beaches (Figure 2). Hobuck Beach is ~2 km in length, bounded by the Wa'atch River to the north and the Tsoo-Yess River to the south (Figure 1). A small creek, Hobuck

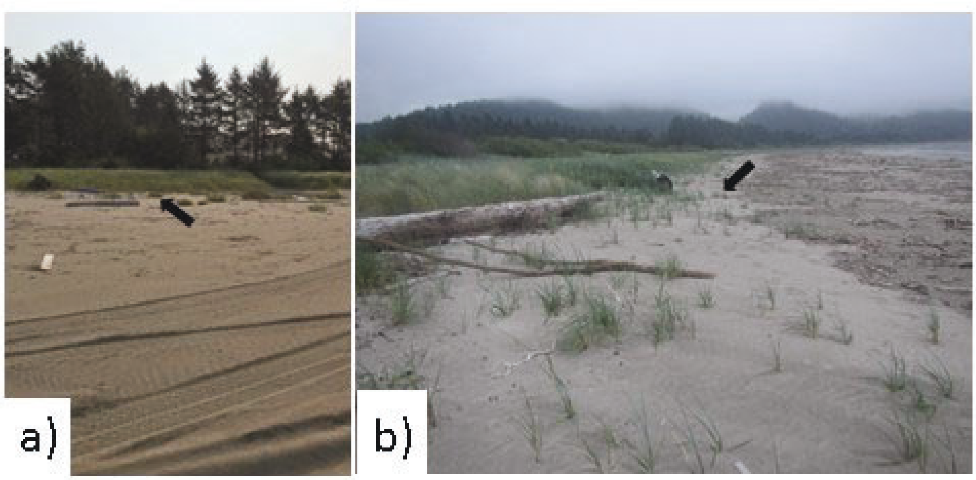

Figure 2. Oblique views of a) Tsoo-Yess and b) Hobuck beaches. The black arrow marks the approximate position of the dune toe elevation used for calculating trends in shoreline position. Tsoo-Yess Beach photo is by Angelina Woods, Makah Fisheries Management.

Creek, flows year-round across the south end of Hobuck Beach. Tsoo-Yess Beach is ~3.5 km in length, bounded to the north by the Tsoo-Yess River and to the south by a small creek and rocky headland.

The Tsoo-Yess River is the largest of the rivers and creeks draining to Makah Bay, but amongst the smallest on the Olympic Peninsula (USGS Water Resources 2022), with a drainage area of 136 km^2, a length of 27 km and a mean annual discharge of ~6 m^3/s (Dion and others 1980). The headwaters elevation of the Tsoo-Yess River is approximately 244 m, giving the river an average slope of <0.01, which is roughly half the slope of one of the Olympic Peninsula's largest rivers, the Elwha River (Warrick and others 2011).

The study area is exposed to mixed semi-diurnal tides, with a great diurnal range of 2.4 m, and a maximum documented range of 4.7 m (COOPS 2022). Wave observations from NDBC 46087, ~25 km from the study area, suggest summer mean significant wave heights of ~1.5 m, and winter mean significant wave heights of ~2.8 m (NDBC 2022). Wave height variability in the winter is extreme, and maximum significant wave heights regularly exceed 7 m, and can approach 10 m. The local wave climate in Makah Bay, though, is likely modified by interactions between the wave field and a complex coastal geography (Figure 1; Kaminsky and others 2022).

Methods

Beach topography data were collected with two separate Real-Time Kinematic Differential GPS (RTK-DGPS) systems: An Ashtech ProMark 200, and an iGage iG8, both running Carlson CE software with identical export file types, coordinate system options, and survey settings, and both receiving GNSS corrections from the Washington State Virtual Reference Network. The systems were mounted either on a 2.0-m rover pole, or a backpack, carried by a surveyor walking the beach transects during low tide (Figure 3). Surveys were generally conducted during low tides in the spring phase of the spring/neap tidal cycle, to maximize the aerially exposed portion of the intertidal beach face.

The focus during each survey was the collection of location and elevation data on the beach on 16 cross-shore oriented transects, 10 transects on Hobuck Beach, and 6 transects on Tsoo-Yess Beach (Figure 1). Transects were selected from a larger set developed by Washington Department of Ecology's Coastal Monitoring & Analysis Program in 2012 (Kaminsky and others 2013) that were established for the entire coast at alongshore spacing of approximately 50 m and oriented perpendicular to offshore bathymetric contours. The transects selected for data

Figure 3. Surveyors walking cross-shore oriented transects on Hobuck Beach with GNSS systems mounted on an a) backpack or b) 2.0-m rover pole.

collection on Hobuck and Tsoo-Yess beaches are spaced ~500 m apart and were intended to spatially represent any differences in erosion or accretion that may be occurring at different ends of the beach. A distinct cluster of closely spaced transects (~50 m spacing) at the south end of Hobuck Beach (Figure 1) were intended to measure differences in patterns of erosion in a distinct erosional area.

Beach topography data collected with the RTK-DGPS systems during this project are referenced to Washington State Plane, Zone North, metric coordinates. Elevation data are referenced to NAVD88 using Geoid18. Survey data were collected either as individual points, or in "auto-by-interval" mode at a frequency of 1Hz. A primary goal of our study was to characterize seasonal and inter-annual rates and patterns of shoreline change on both Hobuck and Tsoo-Yess beaches, so an effort was made to collect data on both beaches every two months for at least one full year. Additionally, our GNSS survey data are coupled with aerial LIDAR survey data from 2010, 2014 and 2016, downloaded as .las files from the public lidar portal maintained by the Washington Department of Natural Resources, to characterize shoreline morphology and position prior to initiation of beach profile monitoring.

A few practices were followed during surveys to minimize measurement uncertainty. First, for surveys with an RTK-DGPS system mounted on a rover pole, the surveyor focused on maintaining the pole in a vertical orientation for each collected data point. Additionally, surveyors attempted to hold the bottom of the pole on the beach surface during measurements, without allowing the end of the pole to sink into the sand. For backpack surveys, the offset between the GNSS antennae and the surveyor's heel was measured and accounted for independently for each surveyor, and each survey. Finally, if feasible, transects were surveyed from the water line into and through the vegetated dune or bank on the landward side of the transect. This consistent collection of elevation data in backshore zones, particularly in places where morphology changes are typically slow and small, provides a means by which the quality of survey data can be evaluated. The overall vertical uncertainty in survey data was quantified by identifying adjacent GNSS and lidar measurements made on a stable and unvegetated gravel/asphalt pad landward of the beach at the south end of Hobuck Beach, associated with a camping facility.

Survey data (or aerial LiDAR data) from each transect and each date were converted into beach profiles by first calculating the distance between each survey point and a fixed origin point on the transect (Miller and Akmajian 2022). Next, the elevation measurements associated with each point were referenced to the local Mean Lower Low Water (MLLW) tidal datum by subtracting -0.26 m from each elevation value referenced to NAVD88 (COOPS 2022). Finally, survey data were linearly interpolated to a uniform 1-m spacing along each transect, but no interpolation was performed over gaps in survey data larger than 5 m.

To evaluate trends in shoreline position, selected elevation datums were extracted from beach profiles for each survey by calculating the distance along the transect at which the chosen elevation was first exceeded when moving from the seaward end of the transect towards the landward end. These shoreline positions were plotted as a time-series and used to assess patterns of change over time on the beach. Two elevation datums were selected for this step: (1) The local Mean Higher High Water (MHHW) datum (2.68 m above MLLW; COOPS 2022) where an annual cycle of erosion and accretion is commonly observed on sand beaches, was selected to assess annual variability in beach position, and (2) A “dune toe” elevation of 3.74 m MLLW (4.0 m NAVD88) on Hobuck and Tsoo-Yess beaches (Figure 2). This dune toe elevation was derived from a survey of the elevation of dune grass conducted on 23 May 2019 on Hobuck Beach, during which 18 measurements of the elevation of the seaward limit of dense dune grass were made at approximately equal intervals along the length of the beach. The average elevation of dense dune grass during this survey was 3.84 m MLLW (4.12 m NAVD88), and the dune toe was defined as the zone 0.1 m below the dune fringe (Figure 2b). Trends in the position of the dune toe on Hobuck and Tsoo-Yess beaches were evaluated by fitting a linear regression to shoreline positions extracted from all available field survey data for each transect coupled with aerial lidar data.

Historical aerial imagery was used to extend the period of analysis further back in time, and coastline features were delineated on each of twelve sets of aerial imagery collected between 1952 and 2019 (Kaminsky and others 2022). The spatial resolution of the images ranged between 13.8 ft. in 1952 and 1 ft. in 2019, however all images between 1964 and 2019 had a resolution between 1 ft. and 3 ft (Kaminsky and others 2022). The vegetation line was digitized at the seaward extent of stable vegetation, which was defined as terrestrial vegetation or well-established dune grass with greater than 50 percent ground cover. The shoreline was digitized at the average high-water mark, which is the horizontal excursion of water, including wave run-up, during a mean high water (MHW) tide event. Change rates were calculated over two time periods (2009-2019 and 1952-2019) by first extracting the position of the delineated shoreline feature on transects with 1-m spacing and calculating change rates using ordinary least squares linear regression. Rates calculated along every 1-m of beach were then averaged for a set of 12 larger beach clusters on Hobuck and Tsoo-Yess beaches identified with cluster analysis (Kaminsky and others 2022).

Results

Beach topography data were collected on Hobuck and Tsoo-Yess beaches on 25 survey days between June 2017 and March 2022. 13 of those surveys were conducted only on Hobuck Beach, 6 only on Tsoo-Yess Beach, and 6 included data collection on both beaches (Miller and Akmajian 2022). To evaluate the vertical uncertainty of survey and lidar data all measurements made on a gravel pad landward of the south end of Hobuck Beach that fell within 15 cm of each other in the horizontal direction were compared. Across all 33 surveys between 2017 and 2022, and including three lidar datasets from 2010, 2014 and 2016, a total of 182 paired elevation measurements were identified. The difference in elevation across the full set of 182 pairs ranged between 0.32 m and -0.16 m, with a mean of 0.05 m, a median value of 0.02 m and a standard deviation of 0.09 m. We use the standard deviation, ±0.09 m, as a reasonable estimate of the vertical uncertainty of individual data points and derived profiles in this analysis. The uncertainty in elevation measurements was used to calculate an estimated horizontal uncertainty in beach position assuming a uniform beach slope of 0.02 (i.e., error bars in Figure 4c).

Beach accretion around MHHW was observed during the summer on all transects and formed a berm approximately 1 m in height and approximately 20 m in cross-shore length (Figure 4a). The annual cycle of formation and erosion of this berm resulted in an annual cycle in beach position at the MHHW elevation contour of, on average, ~35 m (Figure 4c). On some transects a second, wider (across-shore widths of >50 m) sand deposit formed lower on the beach during the summer, with sand depths of ~0.5 m. No seasonal pattern of erosion and accretion was observed higher on the beach around the dune toe (i.e., around 3.75 m MLLW) at Hobuck and Tsoo-Yess beaches (Figure 4a).

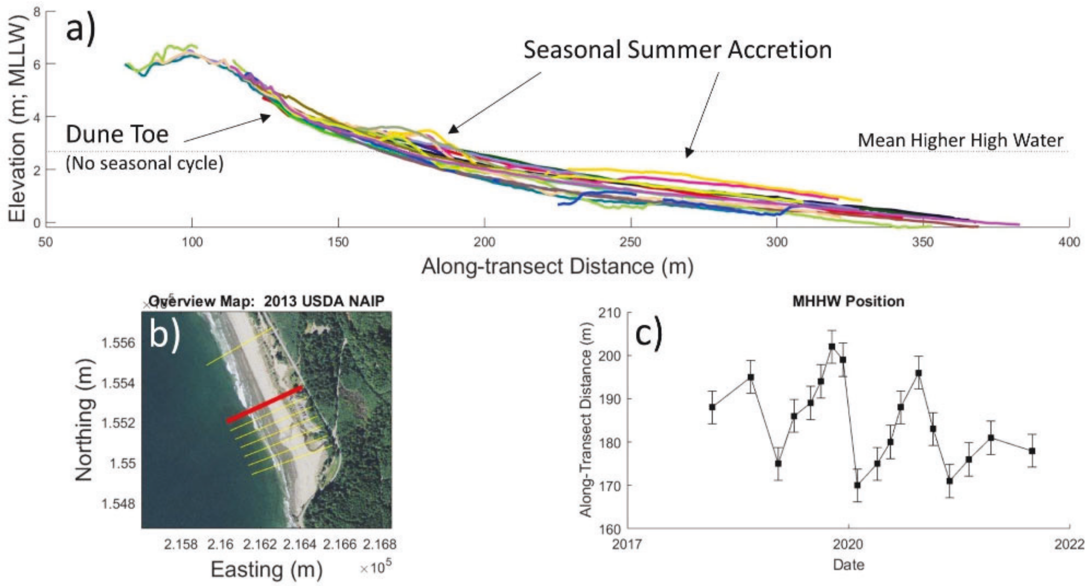

Figure 4. Representative a) beach profiles and c) shoreline position time-series from b) Transect 4 on Hobuck Beach. The different profile colors in (a) are associated with different survey dates. Annotations added to the profiles in a) highlight key morphological features discussed in the text. Time-series of the position of the Mean Higher High Water contour on the beach between 2018 and 2022 (c) shows a seasonal cycle of erosion and accretion.

The dune toe was selected for the evaluation of beach position trends because the presence of a seasonal cycle of erosion and accretion around the MHHW elevation contour (Figure 4c) can complicate the detection of longer-term trends (i.e., over years or decades) in shoreline position, and a seasonal erosion/accretion cycle was not detected on the dune toe. Most of the sampled transects on Hobuck and Tsoo-Yess beaches (transects 1-6 and 10-16) displayed positive trends in dune toe position between 2010-2022, accreting at average rates of ~0.8 m/y (Figure 5). Rates calculated at three transects (6,11 and 12) were not significantly different from zero, but two of those transects (11 and 12) lacked lidar data coverage from 2010, 2014 and 2016, and the linear regression model was fit to data for the relatively short period between 2018 and 2022. Towards the south end of Hobuck Beach the dune toe at transects 7-9 transgressed at rates exceeding 1 m/yr between 2010 and 2022 associated with dune erosion. The dune toe at Transect 10, by contrast, at the very southern end of Hobuck Beach, prograded at a rate of

3.3 ± 0.9 m/yr (Figure 5), the highest rate of beach position change observed in the study.

Trends in both shoreline proxies delineated from aerial imagery follow similar patterns to those observed from profiles derived from GNSS data (Figure 6). Over the period between 2009-2019 both methods identify a general pattern of progradation across both Hobuck and Tsoo-Yess beaches, but transgression on the south end of Hobuck Beach (Figure 6). Analysis of change rates of the vegetation line for the longer period between 1952 and 2019 derived from aerial imagery show seaward trends in the position of the vegetation line of ~0.7 m/yr (Figure 6).

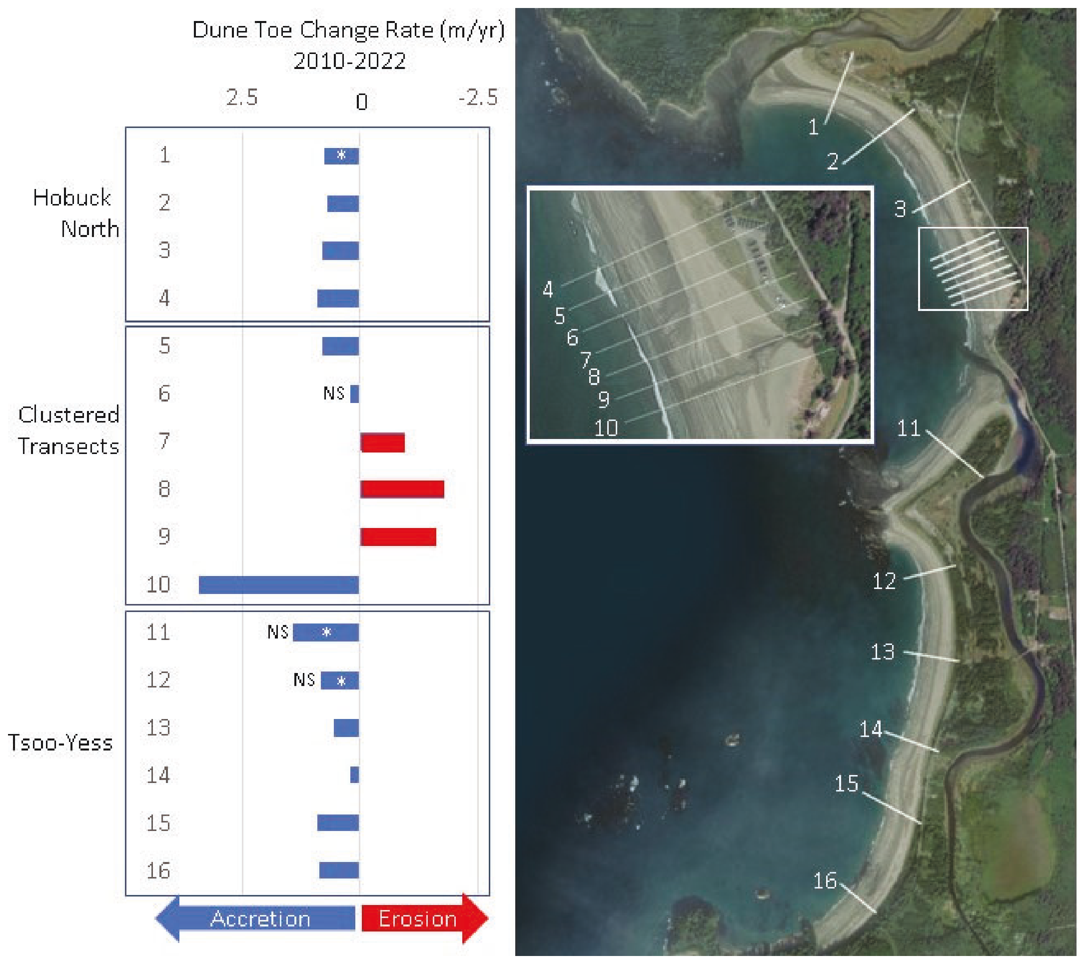

Figure 5. Trends in the position of the dune toe at Hobuck and Tsoo-Yess beaches between 2010 and 2022, based on linear regression. “NS” refers to trends that are not significantly different from zero, and a white star indicates transects for which lidar coverage was not available. In those cases, the calculated trends are for the period 2018-2022.

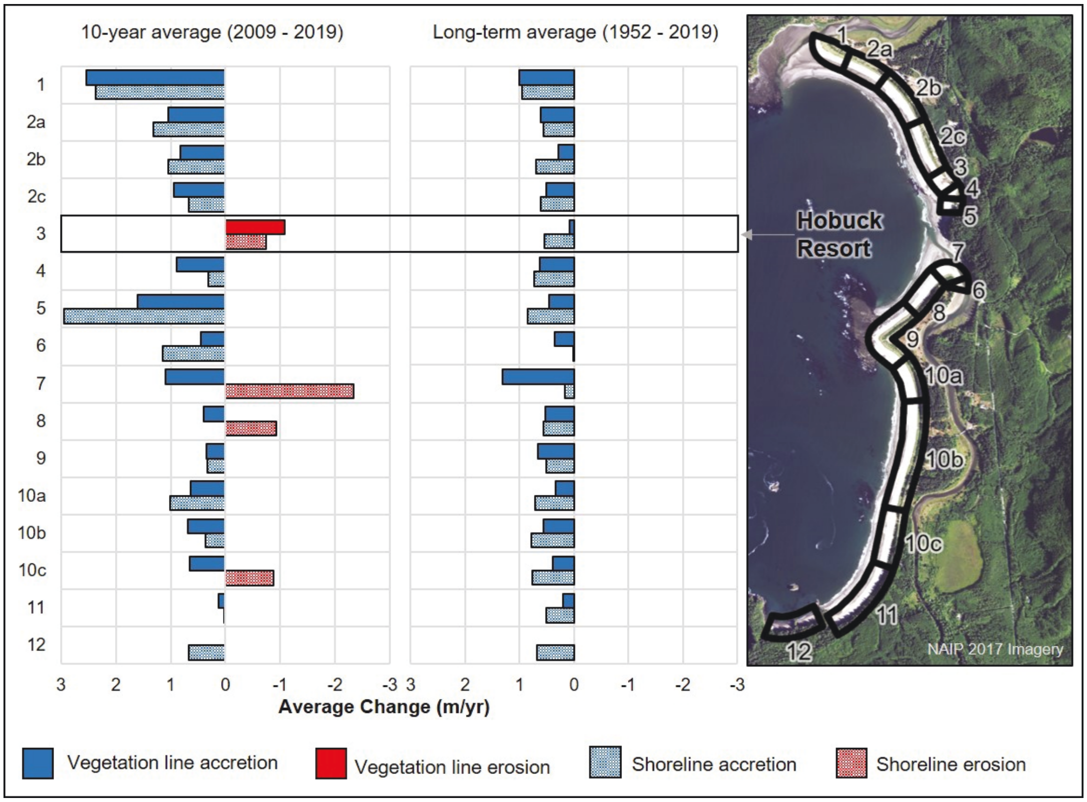

Figure 6. Average rates of shoreline and vegetation line change, in m/yr, in Makah Bay by cluster (see Kaminsky and others 2022 for an explanation of the clustering methodology) beaches for the period 2009-2019 and 1952-2019 based on the analysis of historical aerial photography. Positive change rates (blue) indicate progradation and negative change rates (red) indicate shoreline transgression. Image quality for Cluster 12 was poor, making the delineation of vegetation lines uncertain. The black box around Cluster 3 identifies the known erosion area at the south end of Hobuck Beach.

Discussion

Our results fill a gap in knowledge about long-term change rates and patterns of seasonal beach dynamics along the Olympic Coast of Washington State, which is relatively poorly characterized (Ruggiero and others 2013). Our observations also provide insights about long-term trends and dynamics on beaches where relative sea level is falling. We find significant dune toe progradation trends at most transects on Hobuck and Tsoo-Yess beaches where measurements are made with GNSS and lidar data. A similar progradation trend is observed for proxy shorelines delineated from aerial imagery.

Shoreline progradation is typically associated with large supplies of sediment on to or adjacent to coastal areas, for example in the Columbia River Littoral Cell on the west coast of the United States, where sediment flux from a massive river is associated with modern coastal progradation rates of ~4m/yr (Ruggiero and others

2016). The link between sediment supply and progradation is also illustrated by van IJzendoorn and others (2021) on the coast of Holland, where progradation of the dune toe at rates of ~1m/yr is observed even over time periods during which sea level is rising at rates of 1.9 mm/yr, a pattern that they tentatively attribute to sediments supplied from the continental shelf.

Can sediment supply account for the shoreline progradation in Makah Bay? Makah Bay is a semi-enclosed embayment that may act as an efficient sediment trap for coarse sediments delivered by the two small rivers, and two creeks, draining into the bay (Figure 1). We estimate that 2000-4000 m^3/yr of sand delivered to the upper beach would be required to generate the progradation of the upper beach profile observed in our study (Figure 4a). Kaminsky and others (2022) used two high resolution topo-bathymetric surveys of Makah Bay to suggest a net change in volume in the shoreface and beach of 93,000 m^3 between 2019 and 2021, suggesting a surplus sediment budget more than adequate to explain the observed changes.

It is not clear, though, that the rivers and creeks draining to Makah Bay are the source of this material. Dion and others (1980) estimated a total suspended sediment flux of approximately 6440 metric tons/yr from the Tsoo-Yess and Wa'atch Rivers, based on measurements made between April 1976 and March 1979. Data from comparatively sized rivers on the Olympic Peninsula suggest these annual sediment flux estimates are reasonable. Czuba and others (2011) report an estimated sediment flux of 5440 metric tons/yr on the slightly smaller Big Quilcene River (annual discharge of ~5.1 m^3/s) a basin that lies ~120 km east of our study area, and an sediment flux of 31,750 metric tons/yr on the larger Deschutes River (annual discharge of 11.3 m^3/s) draining into southern Puget Sound ~200km from our study area. Assuming, conservatively, a bulk sediment density of 1000 kg/m^3 (Miller and others 2015), and that the bedload flux is 20% of the suspended sediment load (a value on the upper end of the range reported by Czuba and others [2011]), we derive an upper estimate of the total annual volumetric sand flux into Makah Bay from the Tsoo-Yess and Wa'atch Rivers of just 1300 m^3.

Other unaccounted for sources of sediment are possible. van IJzendoorn and others (2021) and Ruggiero and others (2016) cite sediment deposits on the inner continental shelf as potential sediment sources to explain shoreline progradation. Both study sites featured large rivers relatively nearby, though, that may explain the presence of sediment deposits on the continental shelf adequate to nourish the shoreline. In the case of Makah Bay, no similarly sized sediment source is obvious. Kaminsky and others (2022), based on two topo-bathymetric surveys conducted two years apart, suggest that the deeper zones of Makah Bay are depositional and could represent a source of sediment to the beach. Further analysis would be required to identify the source of that sediment, though, as well as the magnitude and patterns of sediment transfers from the inner continental shelf to the beach in Makah Bay.

The pattern of relative sea-level fall associated with positive vertical land movement (uplift) at Makah Bay may help to explain the observed patterns of shoreline progradation even in the absence of a large sediment supply. Relative sea-level fall could be expected to have a variety of consequences that could contribute to shoreline progradation. First, relative sea-level fall incrementally reduces the reach of tides on the beach face, exposing additional sand area to drying, and facilitating onshore aeolian transport. Second, the reach of the erosive potential of the ocean on the beach is reduced over time, decreasing the opportunity for upper beach and dune erosion associated with extreme events (Bullar et al., 2019). Finally, falling relative sea level should have the effect of lowering the effective depth of closure and exposing stored shoreface sediments to onshore transport. Taken together these processes, coupled with the small supply from the rivers and creeks draining to Makah Bay, may explain the observed patterns of shoreline progradation.

Conclusion

In this study progradation of the dune toe on the sandy, dune-backed beaches of Makah Bay, on the Pacific Ocean shorelines of the reservation lands of the Makah Tribe, were documented for the first time. Estimates derived from GNSS survey data, aerial lidar, and aerial imagery analysis were similar, and suggested progradation rates of 0.7-0.8 m/yr along the 5.5 km length of beach in Makah Bay, except for the ~250m long erosional area that prompted the study. We assess evidence to evaluate whether this pattern of dune progradation can be explained by sediment supplies from watersheds draining to Makah Bay and conclude that local sediment supply cannot explain observed patterns. A variety of shoreline processes associated with relative sea-level fall are discussed and may explain the observed rates of shoreline progradation.

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