Erosive water levels and beach-dune morphodynamics, Wickaninnish Bay, Pacific Rim National Park Reserve, British Columbia, Canada

by

Derek Kenneth Heathfield

B.Sc., University of Victoria, 2009

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of the Requirements for the Degree of

MASTER OF SCIENCE

In the Department of Geography

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Abstract

Increases in the frequency and magnitude of extreme water levels and storm surges are observed along some areas of the British Columbia coast to be correlated with known climatic variability (CV) phenomena, including the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Since a shift to a positive PDO regime in 1977, the effect of ENSO events have been more frequent, persistent, and intense. Teleconnected impacts include more frequent storms, higher surges, and greater coastal erosion. Geomorphic recovery of regional beach-dune systems from erosive events is usually rapid (i.e., within a year) by way of high onshore sand transport and aeolian delivery to the upper beach and dunes. At Wickaninnish Bay on the west coast of Vancouver Island, fast progradation rates (to +1.46 m a^{-1}) have been observed in recent decades, in part due to rapid regional tectonic uplift and a resulting fall in relative sea level of ~ -0.9 mm a^{-1}. The Wickaninnish foredune complex has rapidly extended alongshore in response to a net northward littoral drift and onshore sediment delivery. Bar deposition and welding processes supply sediment to the foredune complex via aeolian processes, and as a result, this is forcing Sandhill Creek northward toward the prograding (+0.71 m a-1) Combers Beach system, in part maintaining active erosion (-1.24 m a^{-1}) of a bluff system landward of the channel. Bluff erosion generates substantial sediment volumes (-0.137 m^3 m^{-2} a^-

^{1}) that feed a large intertidal braided channel and delta system as the creek purges into the Pacific Ocean. As a first step in exploring the interactions between ocean-atmosphere forcing and beach-dune responses on the west coast of Vancouver Island, British Columbia, Canada, the proposed thesis: 1) Examines and assembles the historic erosive water level regime and attempts to draw links to observed high magnitude storm events that have occurred in the Tofino-Ucluelet region (Wickaninnish Bay); and 2) Explores the geomorphic response of local shorelines by examining the geomorphology and historical evolution of a foredune-riverine-backshore bluff complex. Despite rapid shoreline progradation, foredune erosion occurs locally with a recurrence interval of ~1.53 yrs. followed by rapid rebuilding, often in the presence of large woody debris and rapidly colonizing vegetation, which drives a longer-term trend of shoreline progradation. This process is complicated locally, however, by the influence of local geological control (bedrock headlands) and backshore rivers, such as Sandhill Creek, which alter spatial-temporal patterns of both intertidal and supratidal erosion and deposition. This work is necessary to understand mechanisms responsible for erosive water levels and the process interaction responsible for subsequent coastal rebuilding following erosive periods.

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To my friends: you're the reason this took an extra year and the reason I enjoyed the whole process. I love you all.

Dedicated to the wildcards,

for keeping life balanced and bent.

1. Introduction

1.1. Research context

1.1.1. Coastal geomorphology

Coastal geomorphology is the study of wind, wave, and current movements as mechanisms of erosion and accretion of coastal sediments, and the associated landforms that result (Psuty, 2004). The most geomorphically responsive coastal zones are, typically, areas that are wave dominated and have an abundant supply of sand (Short and Hesp, 1982; Psuty, 2004). The influence of ocean-atmospheric energy inputs, or environmental forcing, drives process interaction between ecology and geomorphology, which drives coastal processes that play a significant role in the initiation, evolution, dynamics and geomorphology of beach-dune systems.

Beach-dune morphodynamics refers to: 1) The formation of both incipient (new or developing foredunes) and established foredunes by trapping and storing aeolian sands amongst pioneer vegetation (e.g., *Ammophilla spp.*) and; 2) Erosion of those features by extreme storm events, elevated water levels and high wave run-up (Hesp, 1988; Psuty, 1988; Sherman and Bauer, 1993; Aagaard et al., 2007). Foredunes are shore-parallel dune ridges on the landward end of the backshore and they play an important role in beach dune systems because they occupy the foremost seaward position in the backshore system and thus are the first line of coastal defense during extreme water levels and wave attack (Hesp, 2002). Foredune evolution is controlled by the local aeolian sediment transport regime which is defined by the interaction of several factors including beach type, surface moisture content, wind regime, sand supply, and type, density, and spatial distribution of vegetation (Psuty, 1988; Hesp, 2002). Erosion of foredunes is moderated by controls such as tidal regime, storm regime (frequency and magnitude), storm surge activity, and wave run-up (Aagaard et al., 2007; Sallenger, 2000).

Short and Hesp (1982) framed initial views on beach classification. The authors distinguish three zones of interaction: 1) the transformation of wave energy across the shelf, nearshore and surfzone; 2) the response of sandy coastlines to this transformation, particularly mesoscale beach-dune forms; and 3) the role of onshore winds in transporting wave-deposited sand landward of the swash zone. Unique morphology and geomorphic processes characterize each zone. Pertinent to the following research, the Short and Hesp (1982) beach classification model is primarily interested in wave-dominated sedimentary coasts, as they are the most responsive to oceanographic and atmospheric forcing. Incoming wave energy (high, moderate, low) is directly related to beach form (dissipative, intermediate, reflective). Generally, as beach gradient increases potential aeolian sediment transport decreases and foredune size decreases. As such, dissipative beaches are found in energetic wave environments and are characterized by a wide, low gradient beach face. The high sediment supply and fetch provide high potential aeolian sediment transport and, accordingly, large foredune systems are likely to develop given vegetation with adequate sand-storage capacity (Eamer and Walker, 2010). Intermediate beaches are characterized by moderate wave energy and have a variety of morphodynamic states. Reflective beaches are found in low wave energy environments and have a steep beach face, and as follows, aeolian sediment transport is limited and thus foredunes are typically small.

1.1.2. Environmental forcing

Extra-tropical storms occurring in the northeast Pacific Ocean are known to force meteorological conditions and wave generation with a magnitude to cause erosion on sandy coastlines (Allan and Komar, 2002). Historical research on storm impacts largely focused on hurricane activity in the Atlantic Ocean, particularly along the eastern coast of the United States

(Davis and Dolan, 1993; Dolan et al., 1988; Jensen and Garcia, 1993; Jones and Davis, 1995; Maa and Wang, 1995) and similar analysis focusing on the northeast Pacific Ocean has comparatively less representation in the literature. An early analysis by Danielsen et al. (1957) focused on the frequency and magnitude of extra-tropical storms in the Gulf of Alaska. This research was sparked by the loss of the S.S. Pennsylvania during an extreme storm event where winds persisting from the same direction generated deep-water significant wave heights of 14m. Subsequent research by Earle et al. (1984) analyzed extreme storms and resulting conditions of wave generation and propagation in the Pacific Northwest between January and March of 1983, which coincided with the major 1982-83 El Nino. Over the past 25 years, increases in storm wave height (Allan and Komar, 2000) have been associated with a progressive increase in the frequency and magnitude of cyclonic storms in the northeast Pacific Ocean (Graham and Diaz, 2001). Examining controls responsible for extreme environmental forcing is required to understand the conditions during erosive events on shorelines in the northeastern Pacific Ocean.

Extra-tropical storms are counter clockwise-rotating low pressure cyclonic systems in the northern Hemisphere (Allan and Komar, 2002). Geographically, these storms form at mid-latitudes because of warm, humid air originating from the Tropics mixing with cooler air carried from the Arctic by the polar jet stream (Davis and Dolan, 1993). Tropical air accumulates in the mid-latitudes due to circulation via the Hadley cell (Sturman and Tapper, 1996), and the Coriolis Effect deflects poleword moving air towards the east. This deflection results in westerly winds that are ultimately responsible for the forcing that cross the Pacific Coast of North America (Allan and Komar, 2002). Extra-tropical storms are largely fuelled by the high-level jet stream, which is responsible for cyclogenesis by moving mass away from the storm center. This process allows a storm to intensify as a low-pressure system near the surface, thus the greater the divergence of mass in the jet stream, then the greater the storm intensity at the surface (Ritter et al., 2002; Allan and Komar, 2002).

Wind studies in the northeast Pacific Ocean have generally had a latitudinal approach, focusing on regimes between 20° to 40°N, or parts of northern Mexico and extending north to California. For example, Graham and Diaz (2001) found that in the last 50 years between 25° and 40°N the number of extreme wind events increased 10-15% and average westerly winds had a magnitude increase of 5 to 10 m s^{-1}. These increases may contribute to extreme wave heights and an increase in the magnitude of storms along the West Coast of North America.

Investigations into the interaction between climate variability indices and extreme wind events on the Pacific Coast of North America have attempted to reveal causal relationships between the two. Research by Abeysirigunawardena et al. (2009) used data from three climate stations on British Columbia's south coast to show that La Niña event years are more closely associated with extreme winds as compared to El Niño years. Contrasting research by Allan and Komar (2002) found that on the California coast higher magnitude winds are associated with El Niño event years as compared to La Niña years. These differences are a result of a southward migration of the jet stream that focuses extra-tropical storms on the California coast during El Niño years, whereas during La Niña years the jet stream returns north and focuses cyclonic systems on Canada's west coast (Beaugrand, 2010).

Enhanced storm wave heights in the northeast Pacific over a 20 to 25 year period have been associated with an increase in storm intensities (Allan and Komar, 2006; Graham and Diaz, 2001). Neu (1984) first recognized a trend of increasing wave height in the north Atlantic from 1970 to 1982 based on crude data from visual observations of ships and charts published at 12-hour intervals. More robust pressure sensor data later demonstrated a 40-year increase in wave height in the North Atlantic (Carter and Draper, 1988). Similar trends have been recognized in the north east Pacific Ocean (Allan and Komar, 2000). Buoy data have demonstrated that at mid-latitudes wave height has increased by 1.0 m during a 25-year period, and reached a max rate of 0.042 m a^{-1}. Allan and Komar (2006) analyzed data from 10 wave buoys (period of record from 1975 to 1999) and found significant winter wave height increase of 0.021 m a^{-1} in California, 0.028 m a^{-1} in Oregon, and 0.032 m a^{-1} in Washington. Similar to the wind regime on the west coast of North America, increases of magnitude in wave regime appears to be dependent on latitude, with higher latitudes experiencing a greater increase in wave height (Allan and Komar, 2000).

1.1.3. Erosive water level regime

In recent decades beach-dune systems in many parts of the world have experienced erosion via wave scarping and overwash (Bird, 1985), and more locally in the northeastern Pacific foredune retreat is a major concern for developed coastlines and protected areas management (Beaugrand, 2010). Foredune erosion directly depends on the elevation reached by the water relative to the elevation of the beach-dune system. If a known erosion threshold elevation is reached and/or exceeded by the water elevation, then an erosive event occurred. This simple conceptual model of erosion (Ruggiero et al., 2001; Fig. 1) provides a tool to connect regional environmental forcing and local geomorphic response, a process interaction that remains poorly understood. Demonstrated increases in the frequency and intensity of extreme events (Ruggiero et al., 2001; Allan and Komar, 2006; Walker and Barrie, 2006; Abeysirigunawardena and Walker, 2008; Walker and Sydneysmith, 2008) may translate to higher winds (e.g., Graham and Diaz, 2001), increased sea levels (e.g., Subbotina et al., 2001; Barrie and Conway, 2002), and higher wave heights and peak periods (e.g., Ruggerio et al., 2001; Allan and Komar, 2006). These impacts in turn may contribute to increased extreme total water levels, the dominant control of coastal erosion.

1.2. Thesis structure

1.2.1. Research gap

The controls of environmental forcing in the northeast Pacific Ocean have been well documented. Increased wind and wave regimes are correlated with an increase in the frequency and magnitude of extra-tropical storms, which has links to climate variability phenomenon. Coastal geomorphology literature is rich with research documenting the controls of beach form and the interaction of wind, wave, and tidal regimes with beach-dune morphodynamics. What remains unclear is the variable magnitude of environmental forcing mechanisms, and more specifically which forcing mechanism is responsible for the greatest proportion of erosive water levels. This knowledge gap is further complicated by the presence of localized controls of erosion and deposition, such as coastal fluvial systems, littoral cells, and local nearshore processes.

1.2.2. Purpose and objectives

The following thesis is structured around two independent, but conceptually linked, results sections (Chapters 2 and 3) of data collected and analyzed from the Wickaninnish Bay region of Pacific Rim National Park Reserve on Vancouver Island, Canada. These sections are bound by an Introduction (Chapter 1) that situates the research within a broader context and by a Summary and Conclusions (Chapter 4) that reviews key findings of the research.

The purpose of this research is to improve our understanding of and characterize the local extreme water level regime by examining regional atmospheric and oceanographic controls and beach-dune geomorphic responses. This purpose is explored through the following research objectives. Chapter 2 examines the regional environmental forcing responsible for extreme water levels that exceed a known erosion threshold elevation. By deconstructing the current over-simplified view of atmospheric and oceanographic forcing into the individual contributing mechanisms (i.e., tidal, surge, wave energy) this research will reveal interaction of and spatio-temporal variation of each mechanism. Specifically, the objectives of this chapter are to: i) Explore and examine water level trends and the largest erosive events on record (1909 – 2010) and identify and categorize the mechanisms of formation; ii) Explore correlations between the historical extreme water level record and various environmental forcing mechanisms, including regional climate variability signals (e.g., MEI, PDO, NOI, ALPI); and iii) Synthesize findings to establish a local erosive event regime for beach-dune systems in the region expressed in the context of forcing mechanisms. This chapter has been published as a peer reviewed manuscript in the journal Earth Surface Processes and Landforms (Heathfield et al., 2013).

Chapter 3 examines local landscape response to environmental forcing documented and described in Chapter 2, and further considers the geomorphic influence of nearshore wave, littoral, fluvial, and aeolian forces as agents of erosion and deposition. Specifically, the objectives of this chapter are to: examine changes in historical shoreline positions from aerial photographic coverage, ii) quantify significant volumetric erosion and deposition values within defined geomorphic units, and iii) integrate these results with other similar studies to develop a conceptual model describing the landscape evolution of a wave-dominated delta complex. This model may prove instructive to coastal managers and stakeholders of potential erosion and rebuilding capacity in this type of geomorphic setting.

2. Erosive water level regime and climatic variability forcing of beach-dune systems on southwestern Vancouver Island, British Columbia, Canada.

2.1. Abstract

Increases in the frequency and magnitude of extreme water levels and storm surges are correlated with known indices of climatic variability (CV), including the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), along some areas of the British Columbia coast. Since a shift to a positive PDO regime in 1977, the effects of ENSO events have been more frequent, persistent, and intense. Teleconnected impacts include more frequent storms, higher surges, and enhanced coastal erosion. The response of oceanographic forcing mechanisms (i.e., tide, surge, wave height, wave period) to CV events and their role in coastal erosion remain unclear, particularly in western Canada. As a first step in exploring the interactions between ocean-atmosphere forcing and beach-dune responses, this paper assembles the historic erosive Total Water Level (TWL) regime and explores relations with observed high magnitude storms that have occurred in the Tofino-Ucluelet region (Wickaninnish Bay) on the west coast of Vancouver Island, British Columbia, Canada. Extreme events where TWL exceeded an erosional threshold (i.e., elevation of the beach-foredune junction) of 5.5 m aCD are examined to identify dominant forcing mechanisms and to classify a regime that describes erosive events driven principally by wave conditions (61.5%), followed by surge (21.8%), and tidal (16.7%) effects. Furthermore, teleconnections between regional CV phenomena, extreme storm events and, by association, coastal erosion, are explored. Despite regional sea level rise (eustatic and steric), rapid crustal uplift rates have resulted in a falling relative sea level and, in some sedimentary systems, shoreline progradation at rates approaching +1.5 m a^{-1} over recent decades. Foredune erosion occurs locally with a recurrence interval of approximately 1.53 years

followed by rapid rebuilding due to high onshore sand supply and often in the presence of large woody debris and rapidly colonizing vegetation in the backshore.

2.2. Introduction

Recent increases in the frequency and magnitude of storm events have been observed in the northeastern Pacific Ocean, accompanied by focussed public concern regarding potential increases in coastal erosion and flooding hazards (e.g., Storlazzi et al., 2000; Ruggiero et al., 2001; Graham and Diaz, 2001; Subbotina et al., 2001; Allan and Komar, 2006; Abeysirigunawardena and Walker, 2008; Ruggiero, 2008; Abeysirigunawardena et al., 2009). Regional erosive events are driven largely by strong storms and related increased wave heights and periods that are superimposed on elevated water levels (Allan and Komar, 2002). Recent research has identified strong relationships between occurrences of positive phases of the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) with increased frequency of extreme events on the west coast of North America (e.g., Storlazzi et al., 2000; Ruggiero et al., 2001; Allan and Komar, 2002; 2006; Abeysirigunawardena and Walker, 2008; Abeysirigunawardena et al., 2009). For example, Allan and Komar (2002) found that the succession of a strong El Niño (1997-98) followed by a moderate La Niña (1998-99) favored the formation of strong extra-tropical storms that generated elevated mean water levels, increased storm wave heights, and extensive coastal erosion along the Washington and Oregon coasts. Subbotina et al. (2001) found that, during the strong El Niños of 1997-98 and 1982-83, water levels between California and Alaska were elevated by as much as 100 cm above average, leading to coastal erosion. In British Columbia, these same events caused a mean sea level rise between 10-20 cm (Crawford et al., 1999) and, on the northern British Columbia coast, a seasonal sea level rise of 40 cm above average was associated with as much as 12 m of coastal erosion on Graham Island, Haida Gwaii (Barrie and Conway, 2002).

Recent work has examined the geomorphic impacts of erosive water level events and climatic forcing on sandy beach-dune systems (e.g., Sallenger, 2000; Morton, 2002; Ruz et al., 2009); however, little is known about climatic forcing of coastal erosion in western Canada. The purpose of this research is to address this gap by examining atmospheric and oceanographic forcing of erosive water levels in coastal British Columbia, Canada using a case study from southwestern Vancouver Island and, from this, define the erosive regime (i.e., suite of atmospheric and oceanographic components that force erosive water levels) for beach-dune systems in the region. This study has three specific objectives: i) to determine the nature of water level trends at Tofino, ii) to examine relations between limited shorter-term (1971-1998) total water level (TWL) records and various marine and climatic forcing mechanisms, and iii) to establish a local erosive event regime for beaches in the region expressed in the context of forcing mechanisms.

2.2.1. Erosive water level forcing mechanisms

There are three primary mechanisms that contribute to erosive water level events: i) storm surge, defined as residual water levels superimposed on observed astronomical tides that result from atmospheric pressure drops and wind forcing, ii) wave runup, defined as the shoreward edge of wave setup and swash fluctuations, and iii) seasonal to interannual increases in regional water levels associated with CV phenomena and related oceanographic manifestations including, for example, thermal expansion via increased sea surface temperatures (SST) associated with the warm phase of ENSO. Storm surge combined with astronomical tides defines the observed water level (OWL) and total water level (TWL) is the combination of OWL and wave runup.

2.2.1.1. Surge

OWL represents a combined signal in which astronomical tides are mixed with short- to long-term oceanographic and/or climatologically driven surge signals. More specifically, storm surge is a long-period wave controlled by wind forcing, atmospheric pressure, water temperature, and ocean currents (Komar and Enfield, 1987; Komar, 1998; Rego and Li, 2010). When surges driven by winds from extra-tropical storms occur in phase with high astronomical tides, OWL may be raised to elevations that are potentially erosive. Despite significant storm activity along the western coast of North America, examination of storm surge forcing of coastal erosion is limited. Although it is often assumed that surge magnitudes are far exceeded by wave runup in this region, storm surges observed on the Oregon coast in November 1981 ranged from 0.5 to 1.2 m and increased to heights of 1.6 m during the 1997-99 El Niño/La Niña seasons (Allan and Komar, 2002). On the north coast of British Columbia, Abeysirigunawardena and Walker (2008) documented a historically high storm surge event of 0.7 m that caused significant local coastal erosion. Their analyses also showed that the trend of extreme water level events over the past century (+3.4 mm a^{-1}) is more than twice that of the trend in regional mean sea level (MSL) rise of +1.4 mm a^{-1} and they suggested that this may relate to an increase in the frequency of surge-generating SE storm winds since the mid-1970s.

Extra-tropical storm systems, ultimately responsible for forcing elevated surges, are generally more frequent in winter in the North Pacific Ocean (Mesquita et al., 2010) and, in particular, along the British Columbia coast. The Western Cordillera presents a topographic barrier that impedes and/or deflects the westward motion of many storm systems; this shows up as increased lysis densities (the number of storms decaying in a region) along the northern Pacific coast of North America (Mesquita et al., 2010). This has implications for coastal erosion because, when a storm stalls, storm wind duration along a given coastline can be greatly increased and this, in turn, increases the potential for higher and potentially erosive sea states.

Dynamic surge activity associated with atmospheric forcing and climatic variability contributes to erosive events by elevating wave runup, effectively enhancing TWL to erosive elevations. An understanding of surge controls (e.g., wind forcing, pressure gradient, etc.) may provide a framework with which to better index a local erosive water level regime.

2.2.1.2. Wave runup

In addition to surge and tide components, TWL observed on an open beach includes an additional vertical component resulting from wave runup, which includes wave setup and swash components (Ruggiero, 1997; 2001). Ruggiero (1997) proposed a model to quantify the susceptibility of high-energy beaches to erosion based on the frequency of extreme wave runup elevations (Fig. 1). Essentially, under certain atmospheric and oceanographic conditions, coastal erosion will occur when TWL exceeds the erosional threshold elevation of the beach-dune junction, which can also be defined by the average elevation of an incipient dune front or toe of an established foredune.

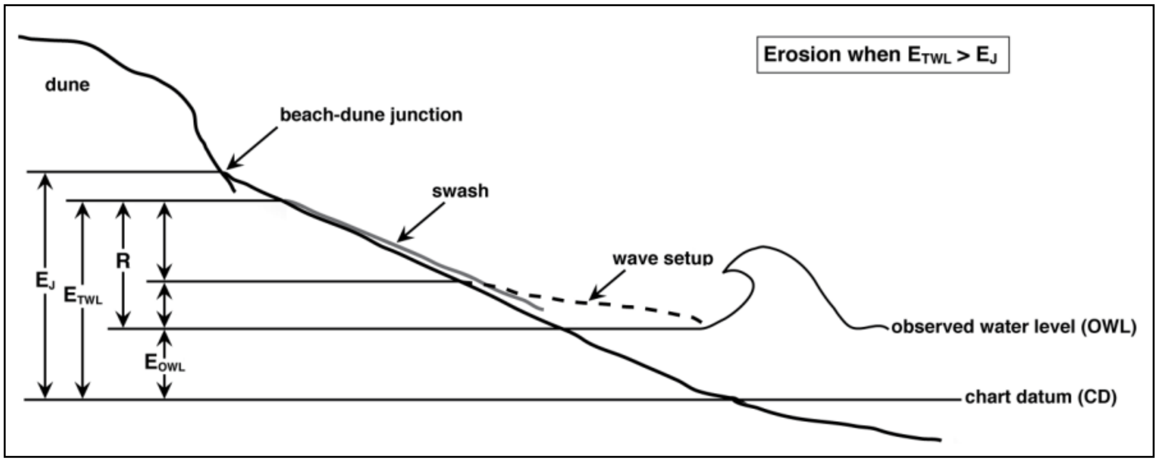

Figure 1. Profile definition of total water level model. Foredune erosion occurs when TWL (observed water level + wave runup) exceeds beyond the erosional threshold elevation (E_J) (beach-dune junction) (Modified from Ruggiero et al., 2001).

Ruggiero et al. (2001) estimated wave runup levels, or the elevation to which wave swash and setup reach during storms on high energy, dissipative beaches, via the following relationship:

$$R_{2\%} = 0.27(SH_sL_o)^{1/2} \qquad (1)$$

where $R_{2\%}$ is the beach elevation above the local reference datum that only 2% of extreme water levels will exceed, S is beach slope, H_s is deep water significant wave height, and L_o is wave length.

Enhanced storm wave heights in the northeastern Pacific Ocean analyzed over a 20 to 25 year period have been associated with increasing storm intensities over the past 50 years (Allan and Komar, 2006; Graham and Diaz, 2001). Per Equation 1 (Ruggiero, 2001), increasing significant wave heights translate to elevated wave runup elevations. Analysis of buoy data in the northeastern Pacific Ocean by Allan and Komar (2000) showed that wave height at mid-latitudes increased by 1.0 m during a 25-year period (1962 to 1986) to a maximum rate of 0.042 m a^{-1}. Allan and Komar (2006) analyzed data from 10 wave buoys between 1975 to 1999 and found significant winter wave height increases of 0.021 m a^{-1} in California, 0.028 m a^{-1} in Oregon, and 0.032 m a^{-1} in Washington. Similar to, and perhaps associated with, the storm wind regime on the west coast of North America, increases in the magnitude of storm waves appear to be latitude dependent and the northeastern Pacific ocean has generally experienced greater increases in wave height (Allan and Komar, 2000; 2006).

2.2.1.3. Climatic variability phenomenon

Variability in sea level and climate conditions in the northeastern Pacific Ocean are forced by known ocean-atmosphere phenomena including the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the strength and position of the Aleutian Low Pressure System (Beamish et al., 1997; Ruggerio et al., 2001; Allan and Komar, 2002, 2006; Barrie and Conway, 2002; Abeysirigunawardena and Walker, 2008). Each phenomenon is indexed by controlling variables, such as sea surface temperature (SST) and sea level pressure (SLP).

ENSO is characterized by warming of the tropical Pacific, which occurs on a cycle of approximately 3 to 7 years and persists for 12 to 18 months. The ENSO phenomenon is driven by a disruption in the trade wind pattern across the equator (Chelton and Enfield, 1986; Wolter and Timlin, 1993), which ultimately results in warmer SST in the equatorial eastern Pacific. In turn, this results in regional to local scale manifestations of climatic variability events including extreme or limited precipitation (floods or droughts) and enhanced storminess. The opposing cold phase of ENSO, La Niña, causes trade winds to strengthen. The Multivariate ENSO index (MEI) is a single value that expresses the effects of ENSO in the tropics (Wolter and Timlin, 1993) while the Northern Oscillation Index (NOI) is meant to express the extra-tropical effects of ENSO in the northeastern Pacific (Schwing et al., 2002).

The Pacific Decadal Oscillation (PDO) is a long-term (20 to 30 year period) mode of climatic variability (Mantua et al., 1997). Although manifest in a completely different region of the

Pacific Ocean (the Aleutian basin in the northeastern Pacific), regional climatic anomalies caused by PDO phases are similar to, yet longer in duration than, those associated with ENSO. Three PDO phases have occurred during the 20th century: 1922 - 1942 (+), 1947 - 1976 (-), 1978 - 1998 (+). The PDO index is derived from SST, such that a positive PDO value indicates colder sea surface temperatures over the north Pacific, while a negative value indicates warmer.

The Aleutian Low Pressure Index (ALPI; Beamish and Bouillon, 1993) is a statistical summary of SLP in the Aleutian basin from December through March. As such, ALPI is a measure of the relative strength of collective winter storms that track through this region, the statistical integration of which indicates the Aleutian Low pressure feature. The strength of the Aleutian Low may be regarded as an indicator of seasonal storm activity and, particularly, favoured storm track locations. That is, because it is an average of SLP over a period of time, the center of the Aleutian Low represents a region where the greatest frequency of storms track during that period. A shift in the position or strength of the Aleutian Low, therefore, indicates that storms may move along a slightly displaced track, or may be generally stronger/weaker, during the storm season. Thus, the Aleutian Low pressure system is linked to wind forcing that, in turn, affects storm surges and OWL in the region. Generally, positive ALPI values indicate a more intense Aleutian Low and *vice versa*. Combined, these four CV indices provide a means to explore associations between oceanographic forcing variables (e.g., surge, TWL) and coastal erosion regimes on the west coast of Vancouver Island.

2.3. Study area

Wickaninnish Bay is located on the southwest coast of Vancouver Island, British Columbia, Canada between the communities of Ucluelet and Tofino in Pacific Rim National Park Reserve, which is managed by Parks Canada Agency (Fig. 2).

Wickaninnish Bay encompasses a 10-km stretch of four embayed, dissipative (wide surf zone) sandy beach-dune systems bound by rock headlands. Beaches have a gradual, shallow bathymetry and experience a mesotidal range (2 to 4 m) and a seasonally variable, energetic wave regime (e.g., average summer significant wave height, H_s, of 1.14 m and period, T, 10.89 s; average winter H_s of 2.47 m and T of 12.07 s; maximum observed H_s of 11.44 m and T of 28.57 s). The 30-year climate normals (1971-2000) derived from observations at Tofino Airport show daily average temperatures ranging from 4.5°C in January to 14.8°C in August, and an average annual precipitation total of 3306 mm a^{-1}. The local wind regime is seasonally bimodal: winter is dominated by strong SE storm winds and summer is dominated by WNW winds (Beaugrand, 2010). Maximum gusts often exceed 100 km hr^{-1}.

Periodic erosive water levels are an integral part of beach-dune morphodynamics in the study area. Frequent dune scarping suggests that high water events exceed the erosive threshold elevation (5.5 m aCD) of the beach-dune junction often (~1.5 years; Beaugrand, 2010) in this high-energy wind and wave setting. Despite frequent erosion, foredunes along Wickaninnish Bay are prograding seaward by as much as 1.5 m a^{-1} (Heathfield and Walker, 2011), which suggests a high nearshore sand supply, competent onshore wind regime (Fig. 3), and rapid dune rebuilding capacity. Dune rebuilding occurs via sand ramp development and incipient dune growth, often in the presence of large woody debris (Heathfield and Walker, 2011). Regional tectonic uplift along the Cascadia Subduction Zone immediately offshore of Vancouver Island of ~2.6 mm a^{-1}

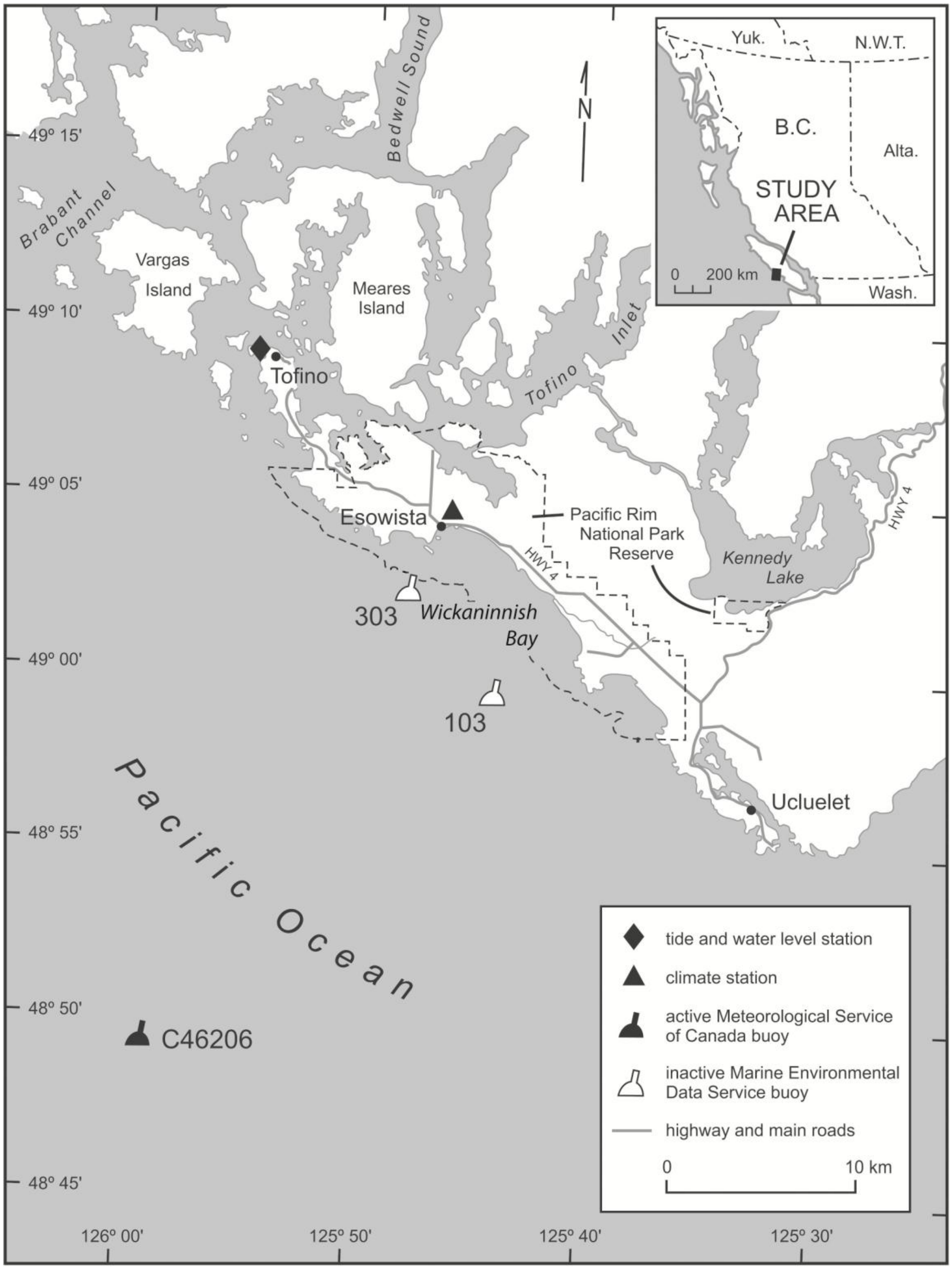

Figure 2. Study region map showing beaches within Wickaninnish Bay between Tofino and Ucluelet on the southwest coast of Vancouver Island, British Columbia, Canada. Data used in this study were obtained from the Department of Fisheries and Oceans (DFO) Tofino tidal station (#8615) and Environment Canada's Marine Environmental Data Service (MEDS) buoy #103.

exceeds a regional absolute (eustatic and steric) sea-level rise of 1.7 mm a^{-1}, which results in a falling relative sea level of -0.9 mm a^{-1} (Wolynec, 2004; Mazzotti et al., 2008) and aids in dune maintenance and progradation (Beaugrand, 2010; Heathfield and Walker, 2011).

Backing the foredunes at Wickaninnish Beach, at the south end of the bay, is the largest active transgressive dune complex on Vancouver Island (~80,000 m^2) that hosts deflation plains, trough blowouts, coppice dunes, and large precipitation ridges that migrate into established forest stands (Heathfield and Walker, 2011). Dunes in this area support a number of plant species that are adapted to survive in nutrient poor, sandy soils, salt spray, and sand scour. Dominant species on the foredune are the introduced American and European beach (marram) grasses (*Ammophila breviligulata* and *A. arenaria*, respectively), which are of particular concern as they compete with the native dune (wildrye) grass (*Leymus mollis*) community, which hosts the provincially endangered Grey beach pea vine (*Lathyrus littoralis*) and the federally endangered Pink sandverbena (*Abronia umbellate var breviflora*). Heathfield and Walker (2011) hypothesized that dense *Ammophila* colonization of the foredune has reduced sand supply to the transgressive dunes at Wickaninnish, which has resulted in increased vegetation colonization and a loss of 28% in active sand surface area between 1973 and 2007. Examining the regional coastal erosion regime is important for ongoing protected areas management and dune restoration initiatives in the study region.

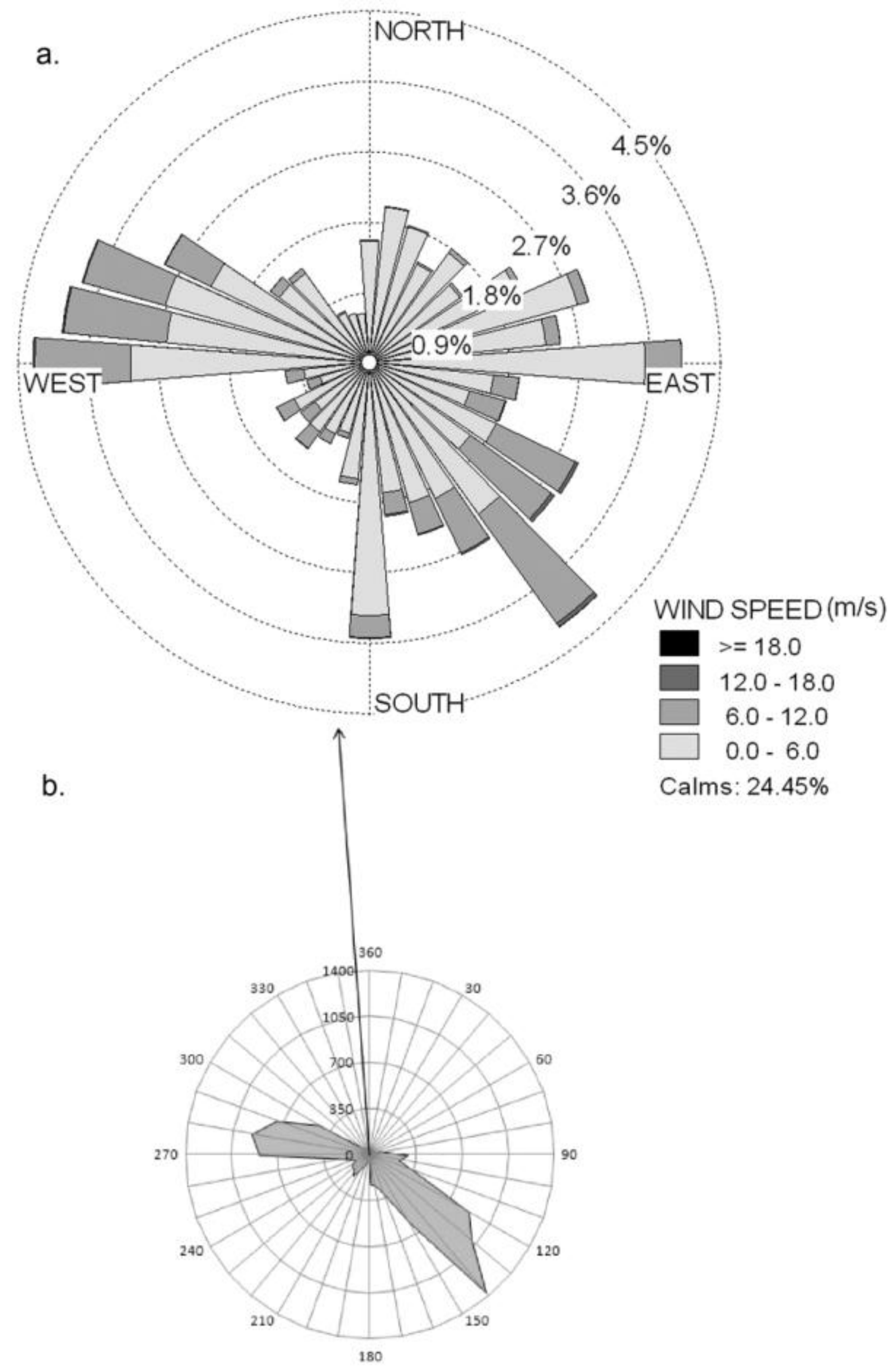

Figure 3. The annual wind rose derived from Environment Canada's Tofino Airport station (1038205) for 1971 to 1977 (the last period during which 24 hour observations were recorded). The southeast mode is associated with winter storms and contains the highest magnitude winds. A secondary mode of lower magnitude winds from the west is associated with summer winds (modified from Beaugrand, 2010).

2.4. Methods

2.4.1. Data

Data used for this research were compiled from several sources. Hourly observed water levels (OWL) and predicted tidal elevations were obtained from the Canadian Hydrographic Service (CHS) database for the Tofino tide gauge (DFO station #8615). A residual surge dataset was derived from these data by subtracting predicted astronomical tides from corresponding OWL values. Annual and monthly average and maximum values for OWL and surge were derived from hourly observations from the beginning of the Tofino tidal gauge record in 1909 forward and adjusted for crustal uplift rates from Mazzotti et al. (2008). The OWL and tidal datasets were incomplete between 1921 and 1939, so only data from 1940 to 2010 were analyzed. All measured water levels are referenced to a geodetic chart datum (CD) determined by CHS.

Deep-water significant wave heights (H_s) and periods (T_s) from 1970 to 1998 were retrieved from Environment Canada's Marine Environmental Data Service (MEDS) database for the nearest buoy (#103), located approximately 44 km offshore of Wickaninnish Beach. From 1970 to 1986 wave data were measured at 3-hour intervals, increasing to hourly from 1987 to 1998. Erroneous data (12.3% of dataset) were removed via quality control fields in the wave dataset provided by MEDS. The La Perouse buoy (C46206) was not used in this analysis because it is further offshore and has a shorter record (1988 – present). All buoy data were coarsened to monthly averages and annual maximum values. Wave data used in this study are spatially and temporally limited. MEDS buoy 103 is located 44 km offshore from Wickaninnish Bay and the buoy was only operational from 1970 to 1998, which limits the period of aggregate wave runup estimates for this study.

Wave runup values ($R_{2\%}$) were calculated using Equation 1, which was developed for beaches in Oregon and assumed to produce representative values for other, similar dissipative beaches in the Pacific Northwest region (Ruggiero, 2001). Beach slope was estimated to be 0.02 m m^{-1} from a topographic profile obtained in summer of 2008 and bathymetric data from 1931 (Beaugrand, 2010), and wave height (H_s) conditions were obtained from MEDS buoy 103. Deep water wavelength is given by $L_o = (g/2\pi)T^2$, where g is the acceleration of gravity and T is wave period collected from MEDS buoy 103. Runup values from 1970-1998 were added to corresponding OWL values to derive TWL estimates. Nearshore bathymetry in Wickaninnish Bay near the location of established dune topographic monitoring profiles is fairly uniform and, thus, only one topographic profile was used to derive beach slope for runup estimates. Bathymetric data for the high-energy, exposed coast at Wickaninnish Bay is also constrained to depths below 5 m aCD due to CHS sampling limitations.

Index values for known CV phenomenon were downloaded from online sources (the US National Oceanic and Atmospheric Administration, NOAA, and the Canadian Department of Fisheries and Oceans, DFO). ENSO variability is described using the global Multivariate ENSO Index (MEI) (Wolter and Timlin, 1993) and the more regionally-derived Northern Oscillation Index (NOI) (Schwing et al., 2002). The MEI is a weighted average of various atmospheric and oceanographic forcing variables such as surface winds, sea level pressure, and percent cloud cover. Negative MEI values correspond to the cold ENSO phase (La Niña) and positive MEI values correspond to the warm ENSO phase (El Niño) (Wolter and Timlin, 1993). The NOI index is a more regional ENSO index that expresses the sea level pressure anomaly between the North Pacific High (NPH) in the northeast Pacific and the equatorial Pacific Low near Darwin, Australia (NPH mean position - 35°N and 130°W). Inverse to the MEI, positive NOI values are associated with La Niña events and negative values with El Niño (Schwing et al., 2002). The Pacific Decadal Oscillation (PDO) reflects regional atmospheric and oceanographic variability in the northeastern Pacific Ocean. The PDO index is derived primarily using interannual variability in average SST in the northern Pacific, and positive (negative) PDO values correspond to warm (cold) phases (Mantua et al., 1997). Finally, the Aleutian Low Pressure Index (ALPI), a measure of North Pacific mean wintertime storm strength, is derived using sea level pressure in the Aleutian Low region, or the sub-arctic Pacific. ALPI corresponds to the mean area (km^2) where SLP is less than, or equal to, 100.5 kPa (Beamish and Bouillon, 1993). Generally, positive ALPI values signal a strong Aleutian Low and *vice versa*.

2.4.2. Sea level trends and climatic variability

Simple linear regression was applied to mean and maximum OWL and surge data from Tofino to identify temporal trends and to highlight variability in extreme water levels. The reliability of the predicted regression model is assessed using 95% confidence intervals, and the strength of dependence in the regression model is assessed using the Coefficient of Determination (r^2).

Correlation analysis (i.e., Pearson’s Product Moment, r) was used to determine the strength of shared covariance between forcing mechanisms (e.g., significant wave height, peak wave period, observed and calculated total water levels, and surge) and CV indices (i.e., MEI, NOI, PDO, ALPI). Significant wave height, peak wave period, and TWL (including runup) data spanned 1970 to 1998, and the OWL and surge data covered a 70-year period from 1940 to 2010. For correlation analysis with ALPI, the monthly data for each variable was coarsened to seasonal

(December through March) in order to align with the period over which ALPI is calculated (Beamish et al., 1997).

2.4.3. Local erosive regime

Erosion occurs when TWL (OWL + $R_{2\%}$) exceeds some locally defined erosive threshold elevation on a beach (Ruggiero et al., 2001). At the study site, the erosive threshold (5.5 m aCD) was determined by averaging the elevation of the seaward extent of the vegetated foredune on three cross-shore transects during the summer when incipient dunes fronting the foredune were fully developed (Beaugrand, 2010)(Fig. 4). Thus, TWL events that exceed this elevation are considered erosional for the purposes of this study.

All TWL events that exceed the erosional threshold elevation of 5.5m aCD between 1970 and 1998 (n = 78) were examined in order to characterize common event types. To do so, hourly time series were plotted to show the timing of peak surge and wave events relative to TWL_{max}. Following graphical analyses (e.g., Figs. 7 and 8), the R statistical package (Ihaka and Gentleman, 1996) was used to identify 'events' as those forced by a single storm with duration of no more than 24 hours before and after TWL_{max} (i.e., 48 hrs total). Associated peak timings of $tide_{max}$, $surge_{max}$, and H_{smax} were organized by the hour to reveal the dominant mechanism forcing the erosive water level. If more than one instance of TWL > 5.5 m aCD occurred within the 48-hour period of analysis, it was considered to be associated with the same event and only TWL_{max} within that time period was analyzed. Review of all events showed that the erosive regime at Wickaninnish Bay involves three types of high water events: 1) tidally dominated (i.e., TWL_{max} phases with high tide); 2) surge dominated (i.e., TWL_{max} phases most closely with $surge_{max}$); and 3) wave dominated (i.e., TWL_{max} phases most closely with H_{smax}).

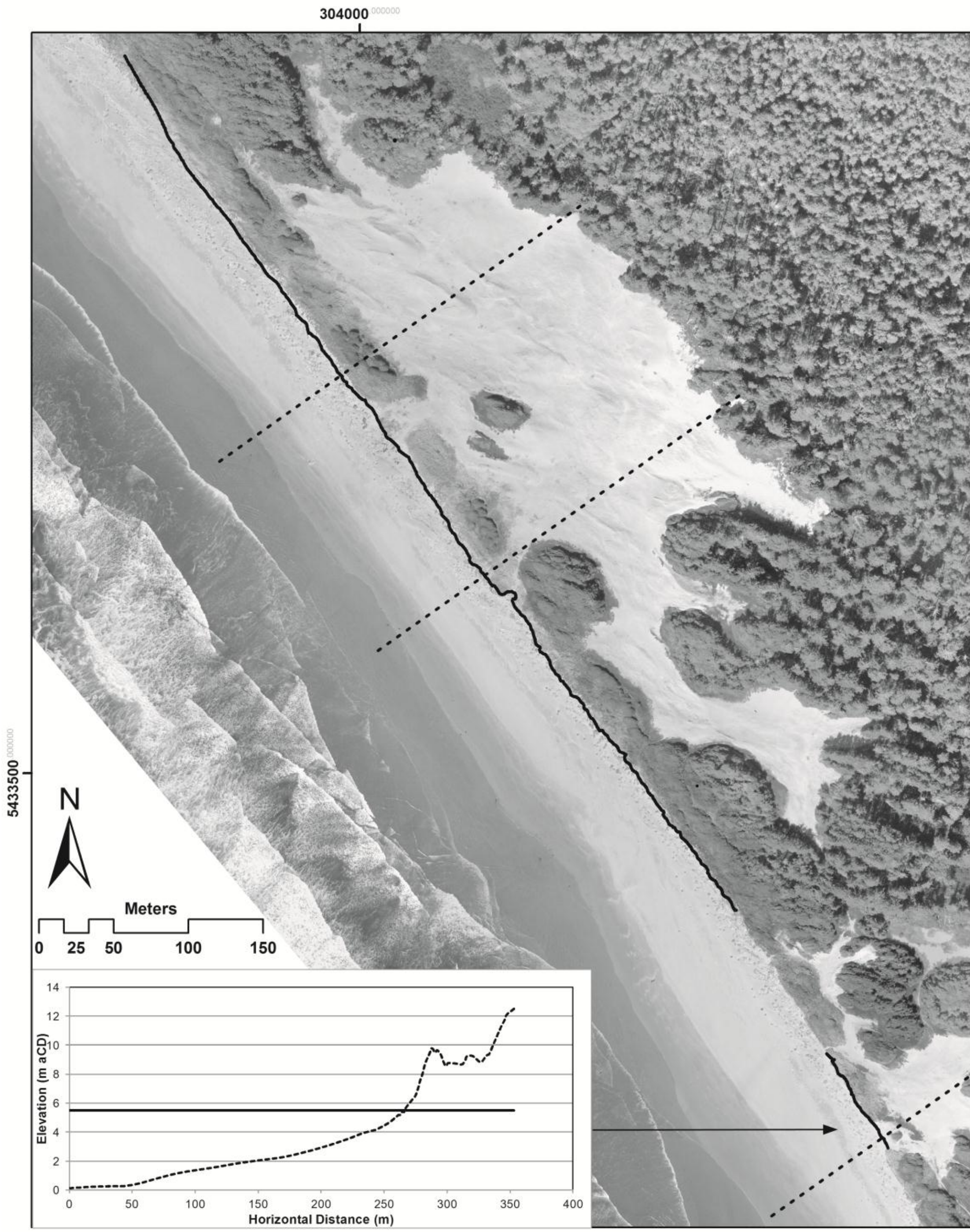

Figure 4. Location of three repeat cross-shore transects (hatched line) on Wickaninnish Beach. Combined, the transects provide an average elevation of the local beach dune junction, or erosive threshold elevation (solid line). Erosion occurs when water levels exceed this elevation (5.5 m aCD), and this event has a recurrence interval of 1.53 years, or a 65% probability of occurring in any given year (Beaugrand, 2010).

2.5. Results

2.5.1. Long term water level trends

Long term (70-year) trend analysis of mean and maximum OWL and surge datasets for the Tofino tidal station are shown below (Table 1, Figs. 5 and 6). Following a correction for crustal uplift and despite strong annual variability, both OWL and surge show an increase in annual values over the period of record. The linear best-fit regression model for annual average OWL at Tofino from 1940 to 2010 yields a statistically significant ($p<0.01$) long-term trend of $+1.04 \pm 1.10$ mm a^{-1} and, for the same period, annual average surge yields a statistically significant ($p<0.01$) long-term trend of $+1.01 \pm 1.05$ mm a^{-1} (Table 1, Fig. 5). Thus, the long-term trends in both observed water levels and residual surge are increasing at similar rates over the period of record.

Simple linear regression models applied to both maximum annual OWL and surge values over the same period show slightly increasing, yet insignificant long-term trends (Table 1, Fig. 6). The best-fit model for annual maximum OWL showed increases of $+1.17 \pm 3.96$ mm a^{-1} and for annual maximum surge showed a rate of $+1.58 \pm 3.99$ mm a^{-1}, slightly higher than the average surge trend. The wide confidence interval corresponds to natural variability within the dataset, particularly with maximum values. This variability is also illustrated in the scatter of points in Figures 5 and 6.

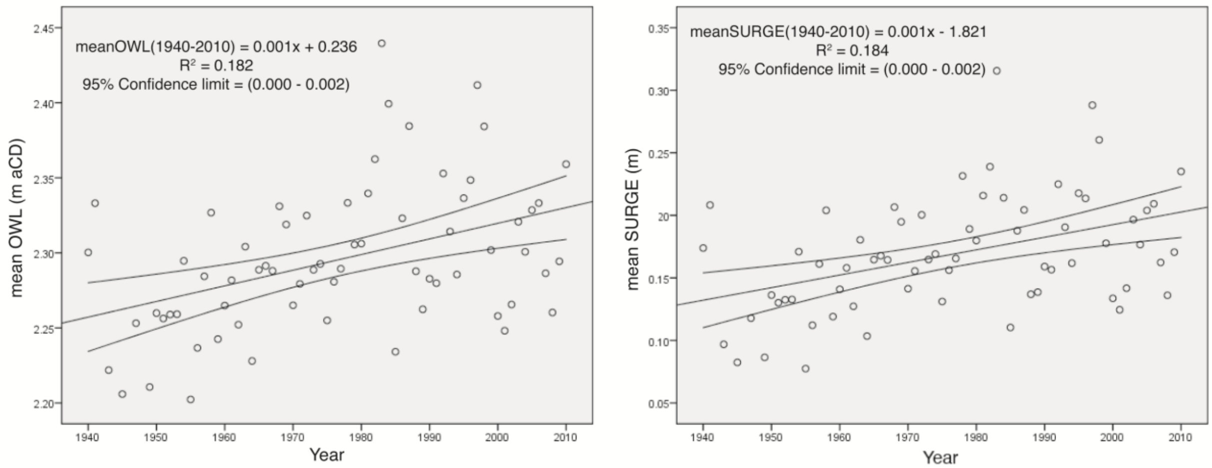

Figure 5. Mean annual OWL (a) and mean annual surge level (b) trends at Tofino, British Columbia from 1940-2010, adjusted for crustal uplift. Long-term trends are increasing for both mean OWL (1.04 mm a^{-1}) and mean surge (1.01 mm a^{-1}).

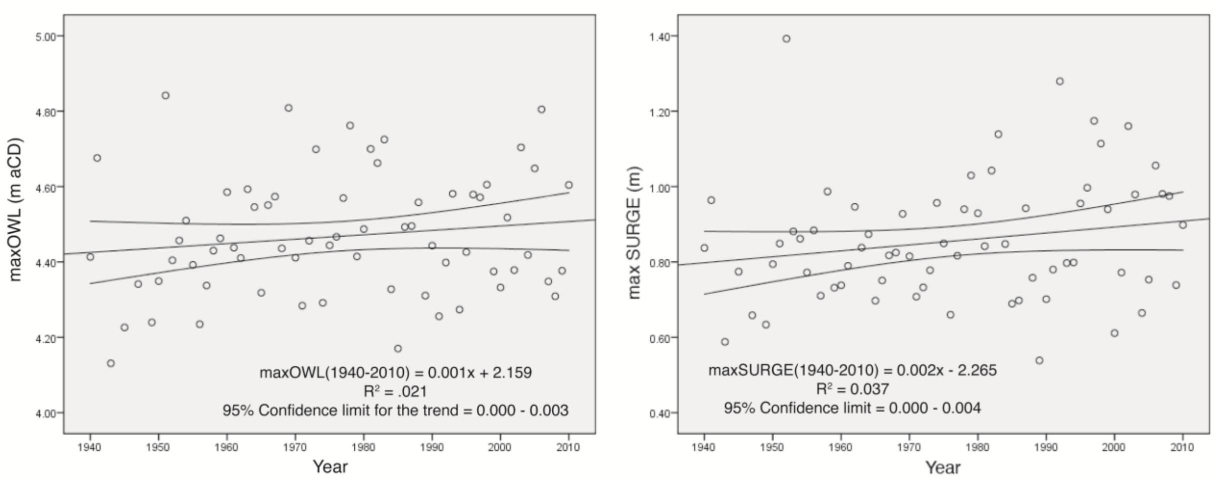

Figure 6. Maximum annual OWL (a) and maximum annual residual surge (b) trends at Tofino, British Columbia from 1940-2010, adjusted for crustal uplift. Linear trendlines show positive (increasing) trends for both variables, with max surge increasing at 1.35 times the rate of max water level (1.17 mm a^{-1} versus 1.58 mm a^{-1}).

Table 1. Summary of simple linear regression results for annual mean and annual max water observed water levels (OWL) and residual surge from Tofino tidal station (DFO#8615).

Variable		R^2	Sig.	t	Confidence Interval		Trend (mm)
					Lower	Upper	
OWL	Mean	0.182	<0.01	3.80	0.000	0.002	1.04±1.10
	Max	0.021	insignif.	1.18	0.000	0.003	1.17±3.96
SURGE	Mean	0.184	<0.01	3.83	0.000	0.002	1.01±1.05
	Max	0.031	insignif.	0.12	0.000	0.004	1.57±3.99

2.5.2. Relations between oceanographic forcing and climatic variability

Values of shared variance between erosive water level forcing mechanisms and CV phenomena (Table 2) show that annual maximum OWL exhibits a statistically significant ($p < 0.01$) correlation with MEI ($r = 0.197$) and with NOI ($r = -0.345$). Annual maximum surge exhibits a statistically significant ($p < 0.01$) poor correlation with MEI ($r = 0.211$) and a moderately strong correlation with NOI ($r = -0.295$).

Table 2 shows that both annual maximum OWL and annual maximum surge exhibit statistically significant ($p < 0.01$) and moderately strong correlations with NOI, but poor correlations with MEI, perhaps due to the regional definition of the NOI vs. the more globally-derived MEI. Annual maximum TWL, which includes wave runup, showed poor correlations with both MEI and NOI (statistically significant at $p < 0.05$). A moderately strong ($r = 0.519$) significant ($p < 0.05$) correlation exists between maximum annual TWL and ALPI. Maximum significant wave height (H_{smax}) did not show a significant correlation with any of the CV indices, while maximum peak wave period (T_{max}) exhibited statistically significant ($p < 0.05$), moderately strong correlations with MEI (r = 0.312) and ALPI (r = 0.545). None of the forcing variables correlated significantly to PDO, which may be due in part to a relatively short period of record.

Table 2. Strength of shared variance between oceanographic forcing variables (OWL, residual surge, TWL, $H_{s\,max}$, T_{max}) and selected CV indices. OWL and surge datasets span 1940 to 2010 from the Tofino tidal station (station 8615), while wave data and TWL datasets are derived from the shorter (1970 to 1998) decommissioned MEDS 103 buoy record. Bold text represents Correlation coefficients (r) significant at the 95% level ($p < 0.05$) (p). r corresponds to Pearson's product-moment coefficient and p corresponds to the significance level.

	MEI		NOI		PDO		ALPI	
	r	p	r	p	r	p	r	p
Maximum Observed WL (1940-2008)	**0.197**	**0.001**	**-0.345**	**0.000**	0.086	0.135	**0.289**	**0.014**
Maximum Surge (1940-2008)	**0.211**	**0.000**	**-0.295**	**0.000**	0.094	0.100	**0.294**	**0.016**
Total Water Level (1970-1998)	**0.168**	**0.003**	**-0.270**	**0.000**	0.060	0.300	**0.519**	**0.005**
Significant Wave Height (1970-1998)	-0.025	0.662	-0.051	0.372	-0.059	0.303	0.060	0.765
Significant Wave Period (1970-1998)	**0.312**	**0.000**	**-0.241**	**0.000**	**0.247**	**0.000**	**0.545**	**0.003**

2.5.3. Erosive Water Level Regime Analyses

Analysis of the 1970 to 1998 TWL dataset revealed 78 events that exceeded the threshold erosive elevation (5.5 m aCD) at Wickaninnish Beach, with a maximum TWL of 6.64 m aCD on 20 January 1981. This translates to about 2.79 erosive events per year or, using a generalized extreme value (GEV) distribution block maxima approach, a recurrence interval of 1.53 years, which translates to a 65% probability of occurrence in any given year (Beaugrand, 2010).

Table 3 summarizes the proportional contributions of each event type in the erosive regime. The majority of erosive events are wave-dominated (61.5%, e.g., Fig. 7) followed by surge-dominated events (21.8%, e.g., Fig. 8). Thirteen events (16.7%) were deemed to be tidally-dominated as they exhibited neither extreme significant wave height nor extreme surge contributions. On closer inspection, the most extreme events (i.e., TWL_{max} > 6.00 m) are largely forced by enhanced wave conditions, as characterized by H_s (83.3%), followed by surge-dominated events (16.7%). Moderate erosive events (i.e., TWL = 5.50 to 5.99 m) are mostly associated with wave dominated forcing (57.6%) while surge and tidally dominated events occupy a much larger proportion (22.7% and 19.7%, respectively).

Table 3. Summary of proportional contributions of erosive event (i.e., TWL_{max} > 5.5 m aCD) types at Wickaninnish Bay between 1970 and 1998. Most erosive events are wave dominated followed by surge dominated events. The most extreme events (TWL_{max} > 6.0 m aCD) have a much stronger association with wave energy as compared to surge.

TWL_{max}	Tide Dominated (type 1) % (n)	Surge Dominated (type 2) % (n)	Wave Dominated (type 3) % (n)	Total % (n)
5.50 – 5.99 m	19.7% (13)	22.7% (15)	57.6% (38)	84.6% (66)
6.0 – 6.65 m	0% (0)	16.7% (2)	83.3% (10)	15.4% (12)
Total TWL Record % (n)	16.7% (13)	21.8% (17)	61.5% (48)	100% (78)

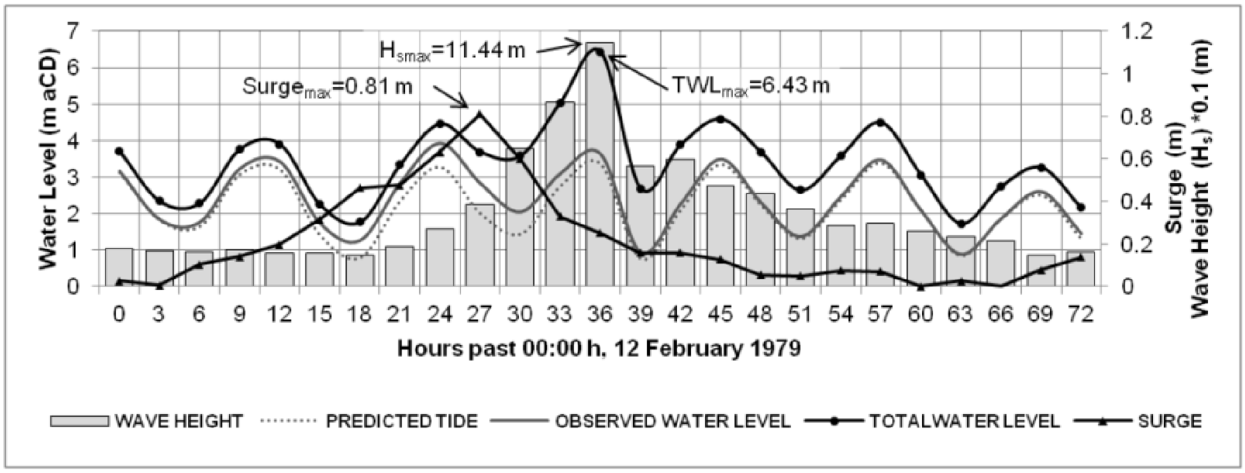

Figure 7. Graphic representation of a 'Type 3' (wave dominated) erosive event. The plot shows that TWL_{max} reached 6.43m aCD (0.93 m above the erosive threshold elevation) which is phased with the peak wave height, whereas the peak surge occurred 9 hours earlier.

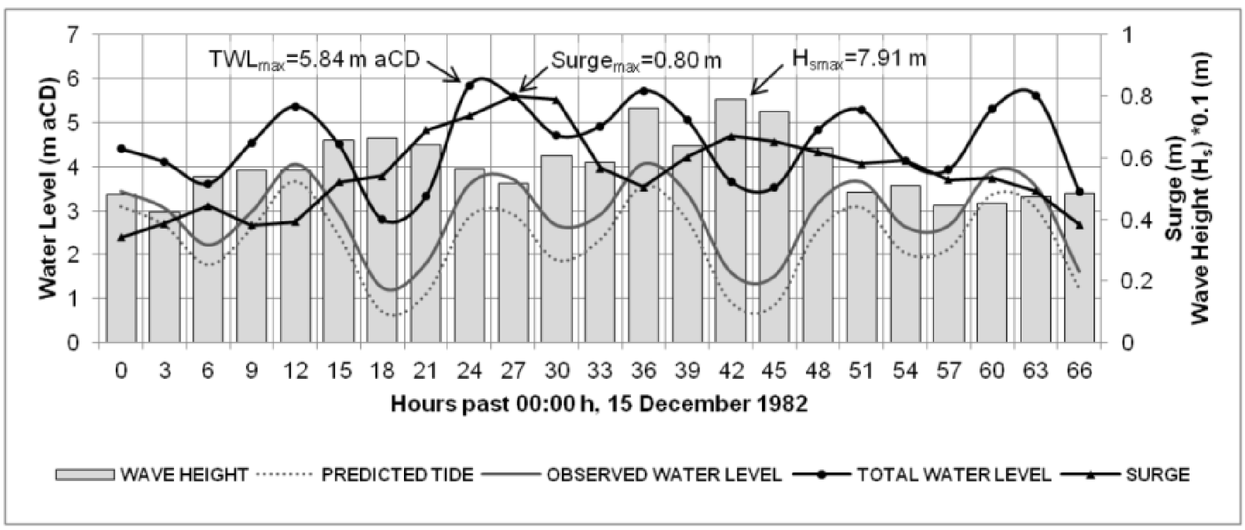

Figure 8. Graphic representation of a sample 'Type 2' (surge dominated) erosive event. The plot shows that TWL_{max} reached 5.84 m aCD (0.34 m above the erosive threshold elevation of 5.50 m aCD) which is phased with peak surge (0.802 m), whereas peak wave height occurred 21 hours later.

2.6. Discussion

2.6.1. Long term water level trends

Simple linear regression models of the 70-year annual mean and max OWL and residual surge databases revealed that all four variables show increasing trends. Although trends are increasing, high confidence ranges reflect extreme natural variability within the dataset (Table 1). Average annual observed water level is increasing at 1.04 mm a-1, which is consistent with other assessments of absolute sea level rise in the Northeast Pacific. Mazzotti et al. (2008) used tidal information for Tofino from 1948 - 2006 to derive a regional absolute sea level rise rate of 1.7 ± 0.8 mm a-1 for the southwest coast of Vancouver Island. The slight difference in magnitude is due to data corrections applied by Mazzotti et al. to eliminate long period signals, such as interannual to decadal-scale processes (e.g., ENSO and PDO), which are explored in this research. Abeysirigunawardena and Walker (2008) estimated that regional mean sea level on the northern coast of British Columbia at Prince Rupert was rising at 1.4 ± 0.5 mm a-1. Local variability in these rates is expected in response to local variations and controls of sea level change (e.g., tectonic or glacioisostatic adjustments). Average annual surge levels also show a similar trend (+1.01 mm a-1) to that of average water level. As the residual between OWL and predicted tides, this is not surprising as annual mean and max storm surge elevations are inherently related to increased OWL. However, on other areas of the coast, the trend of extreme water level events over the past century exceeds that of MSL trends. For instance, Abeysirigunawardena and Walker (2008) found that, over a similar time interval to this study (1945 to 2003), extreme water level events were increasing at a rate (+3.4 mm a-1) more than twice that of the trend in MSL and suggested that this was in response to an increase in the frequency of surge-generating SE storm winds since the mid-1970s associated with the influence of major El Nino events (e.g., 1982–83, 97–98) during this period. These observations agree well with Graham and Diaz (2001), who documented increasing numbers of intense cyclones and related wind speeds, responsible for local surge and wave generation, in the northeastern Pacific (20°N–65°N) over the latter half of the twentieth century. Thus, increases in the frequency and magnitude of storm events in the northeast Pacific Ocean appear to largely influence these trends and may be invoked as an explanation.

Regression models showed that maximum OWL is rising at 1.17 mm a^{-1}. Unlike the TWL event regime, which appears to be most strongly wave dominated (Table 3), most maximum OWL events from the tidal station record are associated with spring tides that occur from November through January. Annual maximum OWL has a strong surge component forced by winter extra-tropical southeasterly storm winds, as is documented elsewhere (e.g., Ruggiero et al., 2001; Graham and Diaz, 2001; Subbotina et al., 2001; Allan and Komar, 2006; Abeysirigunawardena et al., 2009). The trend in $surge_{max}$ is 1.35 times higher than that of OWL_{max} (1.57 vs. 1.17 mm a^{-1}). Albeit slight, the increasing long-term trend in $surge_{max}$ and variability within that trend suggest enhanced wind forcing associated with southeasterly winter storms is responsible for amplified surge forcing on the west coast of Vancouver Island (Abeysirigunawardena et al., 2009). Despite a regional decrease in relative sea level, increasing magnitude of storm surges could result in more frequent erosive events that exceed the threshold elevation for erosion.

Future studies of regional long-term trends and variability of sea level will benefit from more in-depth analysis of contributing factors including steric components, oceanic circulation, and variations in winds and air pressure that contribute to temporarily elevated water levels.

2.6.2. Climatic Variability phenomena and forcing of erosive water levels

Identification of relations between known CV phenomenon and oceanographic responses on British Columbia's coast may help to forecast seasonal to interannual variations in erosive water levels. CV indices are currently used by Environment Canada and NOAA to prepare seasonal forecasts of temperature and precipitation. Statistically significant associations between CV indices and an index of storm activity (e.g., zonal wind anomalies) in the northeastern Pacific Ocean is an initial step toward characterizing the erosive water level regime at Wickaninnish Bay. The strength of shared variance between CV indices (NOI, MEI, PDO, ALPI) and erosive water level forcing mechanisms (maximum OWL, surge, TWL, H_s and T) are assessed below.

2.6.2.1. Maximum observed water level and storm surge

In this study, both OWL_{max} and $surge_{max}$ exhibit stronger correlations with NOI as compared to MEI. This is expected because, while both indices are expressions of ENSO-derived variability, NOI captures the extra-tropical effects of ENSO in the northeastern Pacific Ocean (i.e., regionally-derived). Graham and Diaz (2001) associated increases in storm frequency and intensity in the northeastern Pacific Ocean (20°N–65°N) between 1948 and 1998 to higher SST in the tropical western Pacific Ocean and, thus, a teleconnection with El Niño that results in more intense cyclones and stronger, more persistent winds that generate elevated OWL, surge, and wave conditions regionally. These findings agree with the results of other studies in the region (e.g., Abeysirigunawardena and Walker, 2008; Beaugrand, 2010). Beamish et al. (1997) associated elevated surge and more intense storms in the northeastern Pacific Ocean to forcing of an enhanced Aleutian Low pressure system during El Niño events. In this study, significant correlations between the ALPI storm index and seasonal (December through March) OWL_{max}, $surge_{max}$, and the shorter-term TWL record (that includes wave runup), indeed reflect atmospheric forcing by an enhanced Aleutian Low and associated extra-tropical winter storms in the study region. These findings suggest that ENSO and ALPI forcing, which appear to be teleconnected, exert notable control on the forcing of extreme water levels, storm surge and, by association, coastal erosion potential in the study region.

On the north coast of British Columbia, Abeysirigunawardena and Walker (2008) found seasonal associations between CV and regional MSL in Hecate Strait such that, during winters, MSL responded mainly to ENSO forcing while longer-term summer MSL responses were related more to PDO forcing, perhaps via persistent SST and thermal expansion effects. They suggested that, despite seasonal differences, SST-driven multi-decadal forcing by the PDO best explained overall interannual MSL variability on the northern British Columbia coast. In contrast, the results presented here show poor correlation between PDO and both OWL_{max} and $surge_{max}$ over the period of 1940 to 2010. Unlike in tropical cyclone regions, SST has been found to not be a dominant control of storm strength in the North Pacific (Mesquita et al., 2010); therefore, as PDO is manifest largely as a SST phenomenon (Mantua et al. 1997), it is not surprising that it does not exhibit strong correlations with oceanographic expressions of North Pacific extra-tropical storms.

2.6.2.2. Maximum wave height and peak period

Interestingly, none of the relevant CV indices correlated significantly with maximum significant wave height, H_{smax} (Table 2). As ALPI reflects the intensity of the Aleutian Low pressure system and, thus, the relative strength of winter storms and winds in the region, it seems logical that some correlation would exist between H_{smax} and ALPI. Previous research on wave height variation in California and Oregon (e.g., Seymour, 1996; 1998) documented correlation between ENSO events and the magnitude of wave conditions such that, during El Niño winters, storm waves were greater at more southern latitudes as compared to normal years. Allan and Komar (2002) also found an association between storm wave heights and ENSO and they concluded that wave heights along the Pacific Northwest coast of the United States have strong latitudinal variation depending on the dominant storm track position.

All CV indices considered were correlated with significant wave period, but none of the CV indices showed any correlation with significant wave height (Table 2). A possible explanation for this is as follows. Various major patterns of atmospheric circulation, as expressed by the CV indices, influence where storms tend to track on a fairly broad scale. For example, during La Niña, storms tend to track towards the southern British Columbia - Washington coast rather than the southern half of California (Fig. 9). The largest values for H_{smax} are generated by local wind-waves associated with passage of strong storms. The largest values for T_{max} are associated with swell that is not locally derived. Wave height and period data are obtained from local MEDS buoy 103 (Fig. 2). Storm tracks influenced by CV tend to favor one region versus another, but this does not necessarily translate into an increased frequency of storms tracking past a particular site. Thus, maximum values for H_{smax} will only occur when a storm passes within close proximity to this buoy, placing it under the direct influence of the strongest winds. For this reason, it is suggested that H_{smax} will not necessarily correlate well with CV indices. Conversely, all strong storms generate long-period waves (swell) that propagate away from the local system and eventually affect a much wider region than that influenced by the local storm winds. This means that a given location need not come under the direct influence of a storm to see the effects of its swell, and so a given site is more likely to experience an increased regional frequency of storms through a measure of swell, T_{max} in this case, rather than a more local expression of waves, i.e. H_{smax}. For this reason, T_{max} was observed to correlate much more strongly with CV indices than H_{smax}. More detailed regional analysis of teleconnected CV impacts on storm wave generation and variability is needed. Unfortunately, data from the offshore MEDS buoys and Tofino Airport meteorological station local to the study area were limited (e.g., local wind conditions only recorded 12 hours/day past 1977, short records from decommissioned buoys), hence examination of correlations with CV phenomena with more advanced methods was not explored.

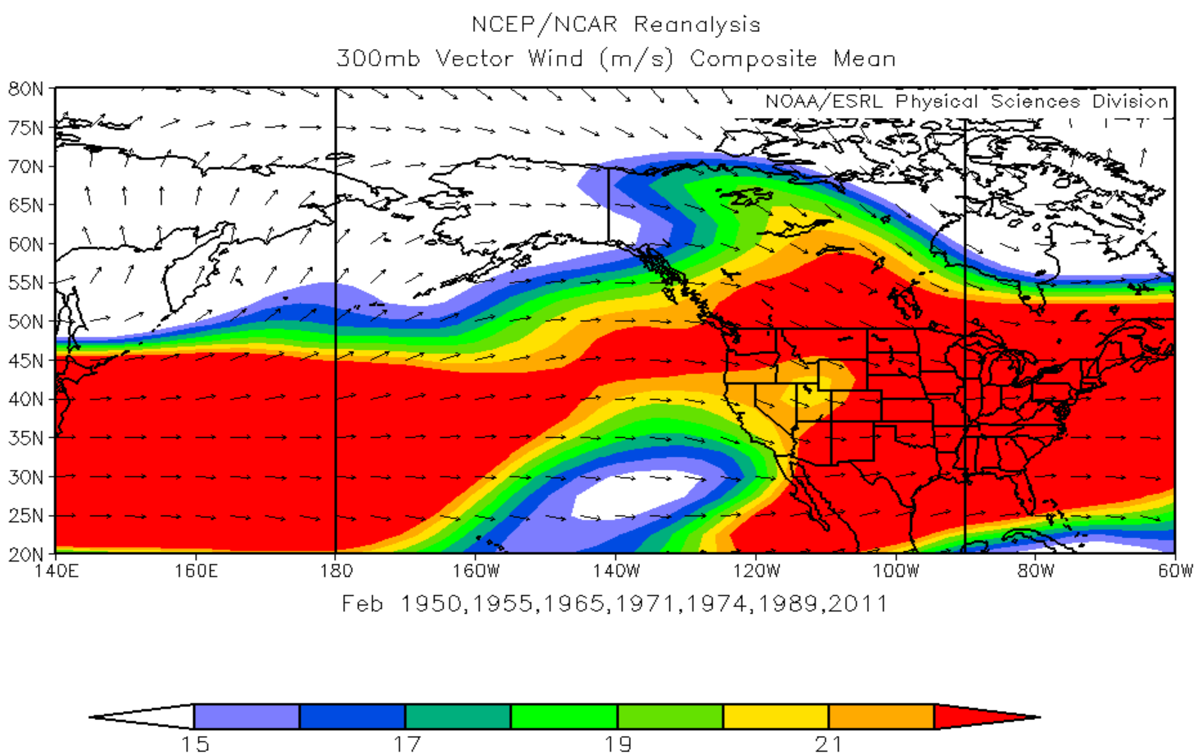

Figure 9. Mean February winds for La Niña years. Arrows indicate direction only. Magnitude contours have a 1 m/s interval and range from 15 to 22 m/s, to emphasize the Pacific Northwest region.

2.6.2.3 Maximum total water level

Annual maximum TWL exhibited significant ($p < 0.01$), yet poor correlations with both MEI ($r = 0.17$) and NOI ($r = -0.27$) but a moderately strong, significant ($p < 0.01$) correlation with ALPI ($r = 0.52$), which reflects the influence of enhanced winter storm conditions on forcing variables subsumed in the TWL dataset, namely surge and runup of larger, longer period waves, particularly when phased with winter spring tides. This association between the strength of the Aleutian Low Pressure system and forcing variables within TWL indicates atmospheric and oceanographic forcing of high water events in the study region and suggests that ALPI may serve as a rough proxy for coastal erosion potential on the west coast of Vancouver Island. Similar to OWL_{max} and $surge_{max}$, TWL_{max} did not show a significant correlation with PDO. Again, this is likely due to SST, the control of PDO, not being a dominant control of extra-tropical storms in the northeastern Pacific Ocean (Mesquita et al., 2010).

2.6.3. Erosive water level regime assessment

Analysis of the historical water level regime at Wickaninnish Bay presented here shows that 78 events exceeded the threshold erosional elevation of 5.5 m aCD between 1970 and 1998 with a probability of occurrence of approximately 65% in any given year (recurrence interval of 1.53 a) estimated using a generalized extreme value distribution (per Gumbel 1958 as in Beaugrand 2010). Classification by forcing mechanism (e.g., tide, surge, or waves) of these events (Figs. 7 and 8, Table 3) reveals that all mechanisms contribute to erosive events, however, one typically dominates. The majority of erosive events are wave-dominated (61.5%) followed by surge-dominated (21.8%) and tidally-dominated events (16.7%). The most extreme events (i.e., $TWL_{max} > 6.00$ m aCD) are forced by elevated wave conditions (83% of TWL_{max} events) while storm surge forcing dominates more moderate erosive events (i.e., 5.5 < TWL < 5.9) (Table 3).

Extreme OWL events are observed when peak astronomical tide occurs in phase with peak surge. During these conditions, there is a high potential for beach inundation and dune scarping with extant wave runup. The mesotidal (2-4 m) environment at Wickaninnish Bay suggests that local bathymetry may be a dominant control of surge propagation and magnitude. Although beyond the scope of this study, further examination of the bathymetry of the coastal shelf, where the magnitude of surge may be reduced in areas of greater water depth, could provide further insight to understanding the local surge-tide relationship.

These findings suggest a strong relationship between regional storm activity and coastal erosion and, more specifically, between wind speed, direction and wave propagation. Hence, the local erosive regime is largely controlled by local wave conditions. Wickaninnish Bay experiences an average of about 3 erosive events per year (65% probability in any given year). This assessment of erosive events at Wickaninnish Bay should be considered as a first order estimate, however, as it is based on a generalized runup model, offshore wave data, and simplified local bathymetric and shoreline characteristics (e.g., nearshore slope, beach aspect and width, etc.). These local factors modify incident wave conditions and runup, thus, the nature of oceanographic forcing that the beach encounters is only approximated with these constraints. Despite this, beach-dune systems at Wickaninnish Bay rebuild rapidly following erosive events through aeolian sediment transport, incipient dune growth, sand ramp infilling of eroded scarps, and subsequent stabilization via large woody debris and vegetation (Heathfield and Walker, 2011). This rebuilding process, combined with high onshore sand supply, rapid crustal uplift and resulting drop in relative sea level, contributes to rapid observed rates of shoreline progradation (to +1.5 m a^{-1}) in the region over recent decades. This longer-term progradation is interspersed with erosive events and the implications of anticipated increases in storminess associated with climate change for beach-dune morphodynamics and local sediment budgets remains unclear.

2.7. Conclusion

This study investigates and analyzes atmospheric and oceanographic forcing mechanisms that define the erosive water level regime for beach-dune systems at Wickaninnish Bay, on the Pacific coast of southwestern Vancouver Island, British Columbia, Canada. This research improves our understanding of regional environmental forcing variables that are responsible for coastal erosion. The key findings of this research are as follows:

1. Between 1940 and 2010, average annual OWL increased at an average rate of 1.04 ± 1.1 mm a^{-1} and average annual surge increased by 1.01 ± 1.05 mm a^{-1}. Maximum surge levels have increased at 1.35 times the rate of maximum OWL (1.57 vs. 1.17 mm a^{-1}), indicating that extreme event forcing by temporarily elevated storm surges are increasing in frequency and magnitude. Ongoing crustal uplift results in a regional regression of relative sea level and rapid shoreline progradation. Foredunes in the region experience extensive, episodic erosion from temporarily elevated water levels followed by rapid rebuilding via high onshore aeolian sand supply.
2. Regionally relevant indicators of climatic variability were found to be correlated to oceanographic variables that contribute to coastal erosion. The strongest correlations exist between the ALPI and TWL ($r = 0.519$; $p <0.01$) and wave period ($r = 0.545$; $p < 0.01$), and more moderately between ALPI and maximum OWL ($r = 0.289$; $p < 0.05$) and surge ($r = 0.294$; $p < 0.05$). Thus, potentially erosive water levels are, in part, forced by

storm activity, the strength of which is characterized by ALPI. The effects of ENSO were also suggested in all oceanographic variables, with the exception of significant wave height. NOI, which describes the regional manifestations of ENSO, showed stronger statistical associations than did MEI. Results suggest that the La Niña phase of ENSO exerts a stronger influence on regional storm events and associated elevated water levels (OWL_{max}) and enhanced surge events ($surge_{max}$).

3. The regime of erosive water levels at Wickaninnish Bay is characterized primarily (61.5%) by high stage, wave-driven events (i.e., TWL_{max} > 5.5 m aCD), then enhanced storm surge events (21.8%), and tidally dominated events (16.7%). The most extreme events (i.e., TWL_{max} > 6.0 m aCD) are clearly dominated by enhanced wave conditions (83%). These results provide preliminary insight into the dominant drivers of local beach-dune erosion. Future examination of local bathymetric effects on surge propagation and geomorphic responses to erosive periods may improve understanding of regional scale ocean-atmosphere forcing components and their specific contributions to landscape evolution.

3. Historic evolution of a foredune-bluff-backshore river complex on a high-energy, drift aligned beach

3.1. Abstract

This research explores the historical evolution of a foredune-riverine-backshore bluff complex on a wave-dominated coastline in Wickaninnish Bay, located within Pacific Rim National Park Reserve on the west coast of Vancouver Island, Canada. Local shoreline positions are generally prograding seaward in response to rapid regional tectonic uplift and a resulting fall in relative sea level of ~ -0.9 mm a^{-1}. Fast progradation rates (to +1.46 m a^{-1}) have been observed in recent decades and the northern end of the Wickaninnish foredune complex has extended rapidly alongshore in response to a net northward littoral drift. Despite these net accretional responses, the beach-dune system experiences relatively frequent (1.53 years) erosive events when total water levels exceed a local erosional threshold elevation of approximately 5.5 m aCD. Geomorphic recovery of the beach-dune system from erosive events is usually rapid (i.e., within a year) by way of high onshore sand transport and aeolian delivery to the upper beach and dunes. This response is complicated locally, however, by the influence of local geological control (bedrock headlands) and backshore rivers, such as Sandhill Creek, which alter spatial-temporal patterns of both intertidal and supratidal erosion and deposition. Historic landscape changes are explored by examining shoreline progradation/erosion rates derived from 1973, 1996, 2007, 2009, and 2012 digital orthophotography using the USGS Digital Shoreline Analysis System (DSAS). Significant volumetric change estimates are also derived using aerial LiDAR-derived DEMs in 2005, 2009, and 2012 and their spatial dynamics are interpreted using a statistically constrained geomorphic change detection method. Results suggest that overwash bar deposition and welding processes are forcing the Sandhill Creek channel alongshore, followed by alongshore extension of the foredune

complex, all in response to northward beach drift alignment. In turn, this is forcing Sandhill Creek northward toward the prograding (+0.71 m a^{-1}) Combers Beach system and, in doing so, maintains active erosion (-1.24 m a^{-1}) of a bluff system landward of the channel. Bluff erosion generates substantial sediment volumes (-0.137 m^3 m^{-2} a^{-1}) that feed a large intertidal braided channel and delta system as the creek purges into the Pacific Ocean. These results provide context for a conceptual model of the evolution of wave-dominated, drift-aligned beach-foredune systems that interact with backshore rivers. This model also provides useful information to park managers at the site as erosion and sedimentation hazards threaten visitor safety and park infrastructure.

3.2. Introduction

This paper examines the geomorphology of a wave-dominated, drift-aligned beach-foredune system, wherein process-response morphodynamics are controlled by the joint interactions between fluvial, littoral, and aeolian processes. The objectives of the paper are to: examine changes in historical shoreline positions from aerial photographic coverage, ii) quantify significant volumetric erosion and deposition values within defined geomorphic units, and iii) integrate these results with other similar studies to develop a conceptual model describing the landscape evolution of a wave-dominated delta complex. This model provides important information that could better inform coastal managers and stakeholders of potential erosion and rebuilding capacity in this type of geomorphic setting.

Evolution of this landscape is explored by examining historical shoreline movements and quantifying significant sediment volumetric changes (erosion and deposition) within distinct geomorphic units. Resulting trends and values will be used in conjunction with qualitative geomorphic assessment to inform a conceptual model describing the landscape evolution of wave dominated, drift aligned beach-dune systems. This model will better inform coastal managers and stakeholders of potential erosion and rebuilding capacity in this type of geomorphic setting.

3.2.1. Morphodynamics of wave-dominated, drift-aligned beaches and foredune systems

A wave-dominated coast is a shoreline characterized by long-term coastal evolution dominantly shaped by erosion, deposition, and transport via high energy wave processes and wave-generated currents (Davidson-Arnott, 2011). Coastal geomorphology in the wave dominated environment is characterized by elongate shore-parallel sedimentary forms including longshore bars, beaches, beach ridges and foredunes (Wright, 1977; Short and Hesp, 1982; Hesp, 2002; Masselink and Hughes, 2003). On wave-dominated coasts, process-response morphodynamics typically depend on how dominant, high stage wave energy combines and interacts with other environmental forcing mechanisms such as tides, surge, and/or wind energy. In addition, the geomorphology of wave-dominated beaches reflects nearshore sediment transport and supply. Davies (1980) distinguishes drift-aligned coasts, which are oriented obliquely to an incident wave approach that generates strong, alongshore sediment transport gradients, from swash-aligned coasts that are oriented essentially parallel to the incident wave approach and have comparatively negligible net alongshore transport rates. On drift-aligned coasts, beach-dune systems will often achieve equilibrium and typically exhibit the net result of drift alignment in the direction of barrier deposits (Sherman and Bauer, 1993; Anthony and Blivi, 1999). Beach-dune morphology exhibits a dominant shore parallel alignment, where alongshore transport deposits elongate swash bars and levees that can weld to the beach, providing an onshore sediment source for shore parallel foredune growth and establishment.

Foredune development is common on high-energy coasts with high onshore sediment supply and competent winds (Hesp, 2002). Foredune morphology can vary in complexity, height, and volume depending on a number of variables such as i) sand supply; ii) vegetation type and density; iii) rates of aeolian deposition/erosion; iv) the frequency and magnitude of environmental forcing mechanisms (e.g., storm erosion, wave, wind, tidal forcing); v) shoreline movement state (i.e. net-progradation or net-retrogradation); vi) anthropogenic impact (Hesp, 2002). Foredunes on high energy, dissipative beaches typically have the largest foredunes, due to high potential wave-induced sand transport and aeolian sand transport (Short and Hesp, 1982). Compared to environments with moderate wave energy, such as tidally dominated or tidally modified beaches, wave dominated beaches provide the largest volume of sediment necessary for dune formation. On beaches with oblique wave approach, a resultant dominant alongshore drift direction can be setup, preferentially depositing nearshore and intertidal bars. These forms develop into an alongshore ridge that, due to wave runup, can grow beyond overwash elevation and deposit amongst vegetation and debris (e.g., LWD) (Carter et al., 1992). This process seeds the initial development of incipient dunes, supplying sediment that is transported and deposited amongst vegetation and flotsam, forming shadow dunes (Carter et al., 1992; Hesp, 2002). Given a low occurrence of storm wave erosion and overwash that would otherwise limit vegetation persistence, the incipient foredune zone can develop into an established foredune, distinguished by a greater height/volume, position (landward of incipient zone), and the establishment of woody plant species (Hesp, 2002). On a drift-aligned beach, in addition to building upward and outward (volumetrically), established foredunes can extend alongshore and build upon subaqueous levees deposited as swash bar deposits into the supratidal incipient dune plain, partially in response to the preferential down-drift deposition of sediments (Wright, 1977).

3.2.2. Riverine – delta systems on high energy coasts

River outflows on high-energy coasts are modified by varying contributions from wave, tide, and surge forcing (Wright, 1977; Carter et al., 1992; Cooper, 2001; Psuty, 2004), which are the main drivers of sediment dispersal and accumulation in marine deltas. More specifically, these marine processes alter fluvial outflow by: i) promoting rapid mixing and momentum exchange between river discharge and ambient waters, which also influences sediment transport, and ii) redistributing and reshaping river mouth morphology following initial deposition and formation of the channel.

The role of coastal form and process in relation to fluvial dynamics has been explored by previous research. Carter et al. (1992) described the geomorphic sequence of river mouth closure to the subsequent development and establishment of coastal dunes (Fig. 10). The sequence model illustrates fluvial – marine sediment interaction and the role of foredunes to buffer the coast by providing a large sub-aerial store of sediment. As it relates here, the key point of this research is the link between coastal fluvial systems and foredunes, where, on a wave dominated shoreline, migration or closure of a fluvial outlet will be opportunistically followed by foredune growth and extension in response to an increased sediment supply. Related research by Cooper (2001) examined over 300 coastal river mouths and estuaries and, while the article is largely focussed on estuary classificiation, relevant sediment transport processes and pathways responsible for channel infilling and migration are discussed.

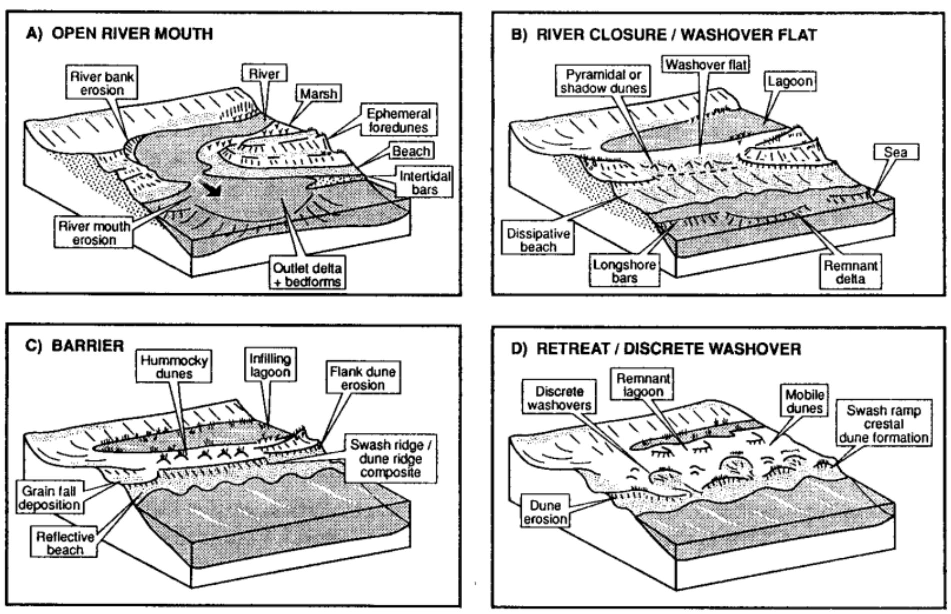

Figure 10. The geomorphological sequence proposed by Carter et al. (1992) showing foredune establishment following river mouth closure. In A) the channel mouth is open and sediment deposits to a bar in the outlet delta. B) shows the closure of the channel via onshore delivery of nearshore bedforms. C) shows the growth and development of the barrier via wave and aeolian deposition. D. Shows the barrier evolved to a more reflective form, leading to dune erosion and overwash.

Specifically, the geomorphic evolution of over 300 fluvial deltas is assessed, wherein barrier development can lead to extensive shore-parallel foredune extension at the coast following outlet migration.

Psuty (2004) described foredune morphology in the presence of a river mouth as a continuum of sediment balance (Fig. 11). The model describes sediment discharge is higher at the river mouth and is continually reduced with added proximity from the outlet (i.e., onshore sediment supply is negligible). As a result, beach accretion near the river mouth is relatively rapid and foredune development here is equally rapid, developing into several small foredune ridges close to the river mouth. With added proximity from the river mouth and reduced sediment supply, a single foredune ridge develops. Rapid accretion near the river mouth is such that new foredunes are built in relatively rapid succssion seaward of developed foredunes, which are ultimately abandoned. Sediment delivery decreases with increasing distance away (alongshore) from the river mouth, increasing the duration of sediment delivery to the foredune.

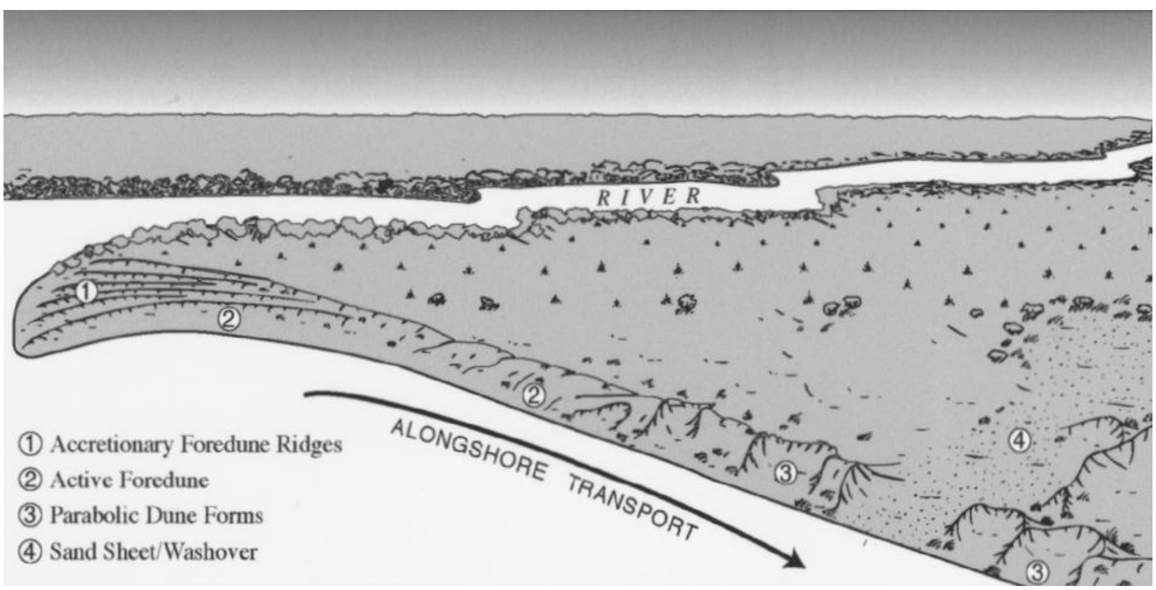

Figure 11. Psuty's (2004) proposed coastal foredune continuum on a wave dominated shoreline. Sediment deposition is decreased with increasing distance from the river mouth, resulting in rapid accretion and multiple small dune ridges close to the river mouth and a single large foredune ridge further away from the river mouth.

Wave energy has been identified as an important process that controls delta morphology and growth (Bhattacharya and Giosan, 2003; Ashton and Giosan, 2011; Nardin et al., 2013). Wright (1977) explored delta and subaqueous bar and levee formation, highlighting the importance of oceanographic forcing mechanisms (wave, surge, tide energy) to determining the delta morphology. The author identified incident wave angle as a first-order control of marine delta evolution (Fig. 12). Normal wave incidence increases thalweg jet deceleration and causes rapid deposition at the river mouth, resulting in symmetric delta morphology (Fig. 12A). However, oblique incident waves will result in asymmetric delta morphology, where sediment is preferentially deposited down drift of the channel in response to longshore drift (Fig. 12B). More recently, related research by Ashton and Giosan (2011) quantitatively produced similar results using numerical modelling. Their study also described how dominant oblique wave approach can seed the formation of off-shore extending spits and alongshore sand waves. What remains unclear is asymmetric delta evolution can influence erosion and deposition on backshore bluff and foredune complexes.

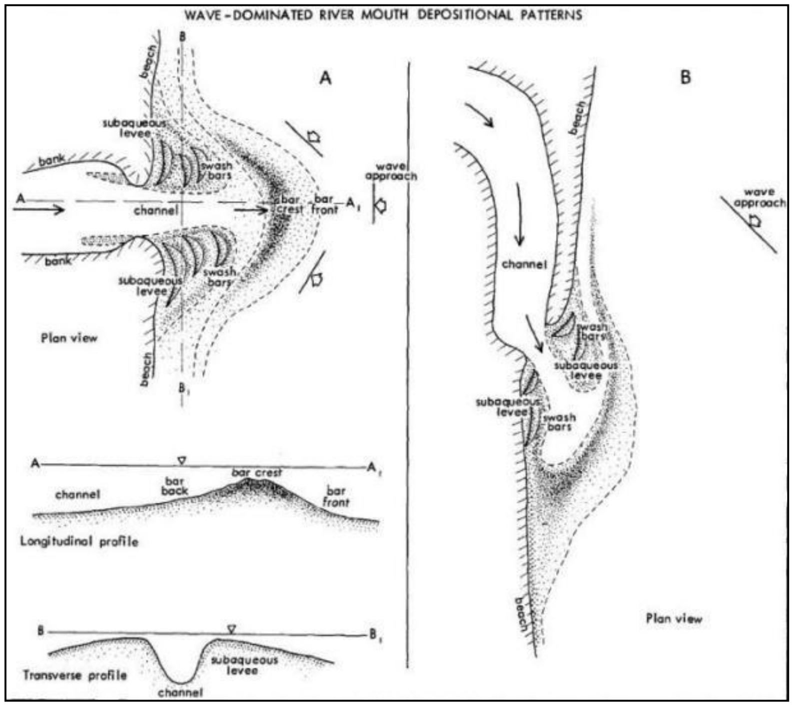

Figure 12. Conceptual model proposed by Wright (1977) of the depositional pattern effect of waves at a river mouth. A. Shows the morphology of a wave-dominated river mouth modified by normal wave approach. Swash bar formation is the result of increased deceleration and rapid deposition. B. shows the morphology of a wave-dominated river mouth modified by oblique wave approach. Alongshore swash bar formation is manifest of similar processes in A., but oblique wave approach and associated littoral drift laterally deflect deposition and the resultant delta morphology.

3.3. Study Site

Wickaninnish Bay is a 10 km wide embayment that is located between Ucluelet and Tofino on the west coast of Vancouver Island, British Columbia, Canada (Fig. 13). The bay is open to the Pacific Ocean and hosts four embayed, sandy beaches bound by rock headlands including: Wickaninnish Beach, Combers Beach, Long Beach, and Schooner Cove. Beaches at Wickaninnish and Combers beaches are barred, dissipative (wide surf zone) with gradual, shallow bathymetry, mesotidal range (2 to 4 m) and all are subject to a seasonally variable, energetic wave regime (e.g., average summer significant wave height, H_s, of 1.14 m and wave period, T, 10.89 s; average winter H_s 2.47 m and T of 12.07 s; maximum observed H_s of 11.44 m and T of 28.57 s). The regional wind regime is seasonally bimodal (Fig. 13, inset) and frequently competent to transport local sands with an estimated aeolian sand transport potential of 9984.31 m^3 m^{-1} (beach width) a^{-1} with a net resultant value of 3268.28 m^3 m^{-1} a^{-1} toward the north (356°) (Beaugrand, 2010). Despite stronger winds in the winter months, the more moderate summer mode towards the SE reflects dune alignment at Wickaninnish Bay, ultimately resulting in transgressive dune form. During winter, sediments remain wet and difficult to transport, whereas dry summer winds are more competent. Combined, a high onshore sand supply and a competent wind regime make for very dynamic beach, foredune, and transgressive dune systems in the region.

Periodic erosive water levels are an integral part of beach-dune morphodynamics in the study area. Frequent dune scarping suggests that high water events exceeding the erosive threshold elevation of the beach-dune junction (~5.5 m aCD) occur often (i.e., with a recurrence interval of approximately 1.5 years; Beaugrand, 2010). Despite frequent erosion, foredunes along Wickaninnish Bay are prograding seaward by as much as +1.5 m a^{-1} (Heathfield and Walker, 2011), which suggests a high nearshore sand supply and rapid dune rebuilding capacity.

Elevated total water level (TWL) capable of beach-dune erosion are driven by three forcing mechanisms: storm surge, wave runup, and CV phenomena (Heathfield et al., 2013). At Wickaninnish Bay, Heathfield et al. (2013) observed that 61.5% of historical erosive events were driven principally by high stage wave energy, followed by 21.8% of erosive events driven by enhanced storm surge events. More regionally, recent research has identified strong associations between the magnitude of environmental forcing mechanisms and known ocean-atmosphere phenomena, such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the Aleutian Low Pressure System (Ruggerio et al., 2001; Allan and Komar, 2002, 2006; Barrie and Conway, 2002; Abeysirigunawardena and Walker, 2008; Heathfield et al., 2013). For example, the ENSO phenomenon, which ultimately results in warmer sea surface temperature (SST) in the equatorial eastern Pacific, can trigger regional and distal changes in weather phenomena (termed "teleconnections") along the coast of North America. This can result in regional to local scale manifestations of CV events including enhanced storminess. Contrary to several articles (e.g., Crawford et al., 1999; Storlazzi et al., 2000; Subbotina et al., 2001; Allan and Komar, 2002) which identify the warm phase of ENSO, El Niño, as a driver of erosion on the westcoast of North America, Heathfield et al. (2013) found a stronger correlation between the cold phase of ENSO, La Niña, and storm activity on the westcoast of Vancouver Island. This is because during the La Niña phase, storms tend to track towards the south coast of BC and the north coast of Washington.

Figure 13. Location of study area showing the intersection of Wickaninnish Beach, Sandhill Creek, and Combers Beach in Wickaninnish Bay on western Vancouver Island, British Columbia, Canada. Inset, top right, is the annual wind rose derived from Environment Canada's Tofino Airport station (1038205). The local wind regime is bi-modal, with the highest magnitude winds, associated with winter storms, coming from the southeast and lower magnitude summer winds coming from the west.

Regional bedrock geology controls modern embayment and beach geomorphology as it influences nearshore currents, wave dynamics, and littoral sediment transport pathways. Tectonic uplift occurs along the Cascadia subduction zone, which lies immediately offshore of western Vancouver Island. As the Juan de Fuca plate subsides under the North American plate, crustal uplift occurs at rates of 2.9 to 2.6 mm a^{-1}, which is offsetting absolute (i.e., eustatic and steric) sea level rise in the Tofino region of 1.7 mm a^{-1} to produce a fall in relative sea level of -0.9 mm a^{-1} (Wolynec, 2004; Mazzotti et al., 2008). Combined with an energetic wind regime and high onshore sediment supply, these conditions result in local beach-dune systems exhibiting a general trend of accretion and seaward progradation. However, the intersection of Wickaninnish Beach, Combers Beach, and Sandhill Creek provides a notable exception. Sandhill Creek flows alongshore as a backshore fluvial system behind a prograding foredune system on Wickaninnish Beach. Over time, the river's course has migrated to the NW, contributing in part to erosion of a former elevated coastal plain deposit and formation of a backshore bluff on the landward side of the river. This site hosted a parking lot managed by Parks Canada and a former historic hotel site that have since been eroded by fluviomarine processes. Combers Beach is sheltered from wave action via rocky islets, islands, and headlands. Nearshore transport of sediments and large woody debris (LWD) within coastal circulation cells is altered by outcrop and headland wave refraction, which protects these regions of Wickaninnish Bay.

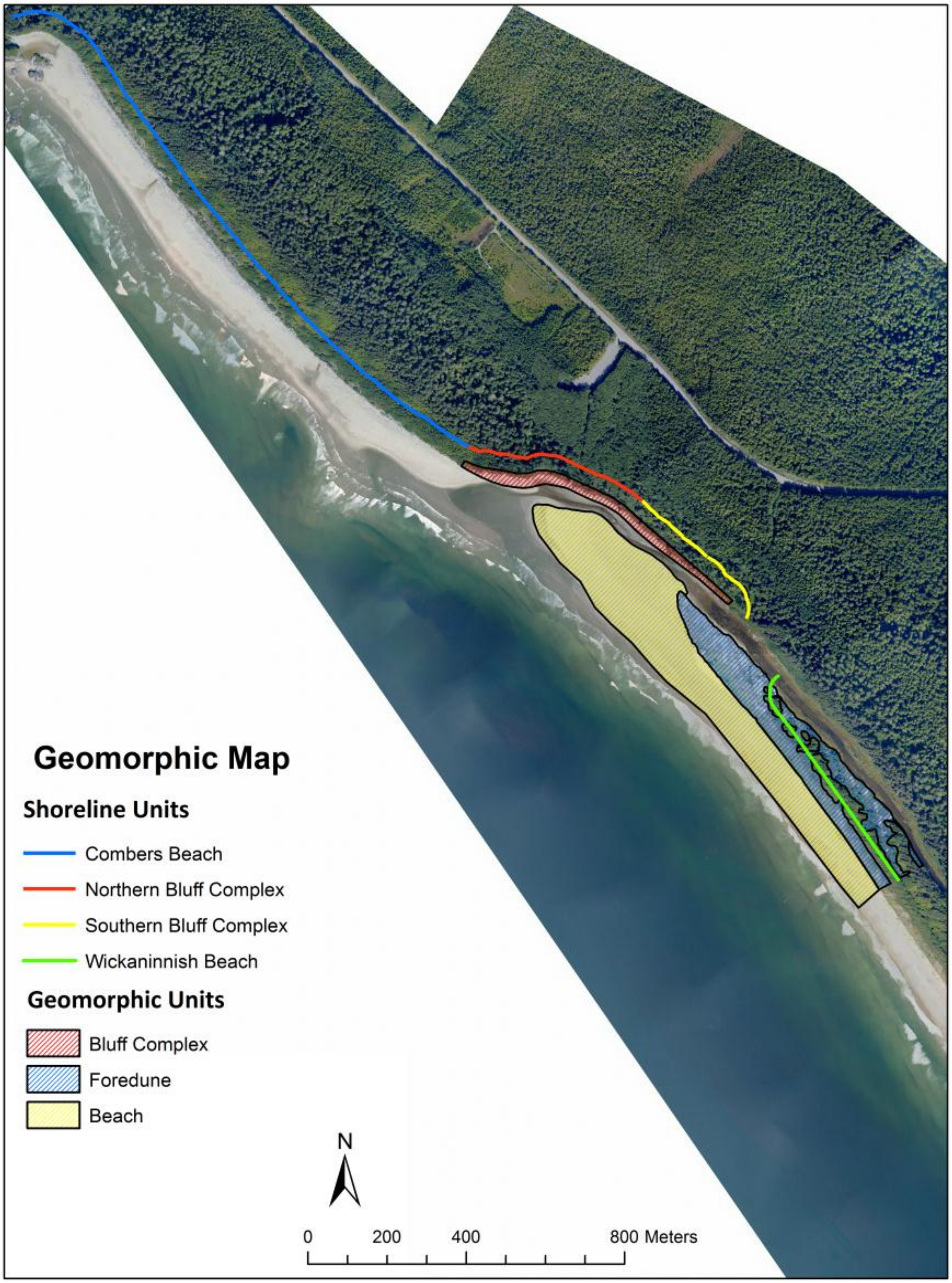

Figure 14. Study site map showing the areas of analysis superimposed on a 2012 orthophoto mosaic. Four shoreline units were delineated and used for the DSAS analysis, and three geomorphic units were delineated and used for the GCD analysis.

3.4. Data and Methods

3.4.1. Aerial Photography and Pre-processing

Historical aerial photographs spanning 39 years (1973 to 2012) were selected to create digital orthomosaics of the study region. Only photo coverage that was of relatively small scale (i.e., < 1:15,000) and that provided complete coverage of the study site was selected. Additional photo coverage dating back to 1938 was available, however, the imagery was unsuitable for analysis due to low image quality and/or large-scale coverage limitations. Contact prints of vertical aerial photographs from 1973 and 1996 were acquired from the Province of British Columbia. These prints were scanned as uncompressed TIFF files (to avoid reduced pixel accuracy resulting from data compression) at a resolution of 1200 dpi, providing a pixel resolution of 0.31 m and 0.30 m (or a scale of ~1:15,000), respectively, following the method described by Nelson et al. (2001). More recent digital orthophotographic coverage of the study site was flown by at a pixel resolution of 0.30 m in 2007 and at 0.15 m resolution in 2009 and 2012 (Table 4).

Geometric distortions introduced to aerial photography by aircraft attitude (roll, pitch, and yaw) and/or altitude changes were corrected for using ground control points and the OrthoEngine® photogrammetry module of PCI Geomatica®. Image-image transformations for the 1973, 1996, and 2007 coverage and subsequent georeferencing of the imagery was conducted using a thin plate spline (TPS) model. A minimum of 15 ground control points (GCPs) was collected for each image to geographically coordinate the orthorectification. Where possible, roads and buildings were used, however, as the study region is relatively undeveloped and forested, rocky outcrops and headlands were also used. Following the collection of GCPs, an orthorectification was run using the NAD83 Canadian datum and GRS 80 reference ellipsoid.

Table 4. Summary of data used in this research, including airphotos and LiDAR. Nominal scales are expressed for airphotos that were scanned and orthorectified, NA applies to pre-orthorectified imagery. Imagery sources include the provincial government of British Columbia (BC Gov.), Integrated Mapping Technologies Inc. (IMTI), and Terra Remote Sensing Inc. (TRSI).

	Year	**Source**	**Nominal Scale**	**Month**	**Scan Resolution (dpi)**	**Ground Resolution (m)**
Airphotos	1973	BC Gov.	1:15000	unknown	1200	0.31
	1996	BC Gov.	1:15000	July	1200	0.30
	2007	IMTI	1:30000	May	NA	0.30
	2009	TRSI	NA	August	NA	0.15
	2012	TRSI	NA	September	NA	0.15
	Year	**Source**	**Point Density (m^{-2})**	**Month**		
LiDAR	2005	TRSI	0.83	July		
	2009	TRSI	0.86	August		
	2012	TRSI	1.02	September		

3.3.2. Airborne LiDAR and pre-processing

Airborne LiDAR coverage of the study site was flown in 2005, 2009, and 2012 at varying point densities (Table 4). LiDAR point clouds were classified to extract ground points that were then used to generate bare-earth DEM surfaces in Surfer (Golden Software©) using ordinary Kriging at a density of 1 m. This spacing was chosen as representative to capture morphological and volumetric changes within coastal sedimentary systems on an annual timescale (per Woolard and Colby, 2002). The bare earth DEMs were then used to detect significant geomorphic changes and corresponding sediment volume estimates using the methods described in the following sections.

3.3.3. Shoreline Change Analysis

Rates of change were calculated in ESRI software using the Digital Shoreline Analysis Software (DSAS) version 4.3 provided by the United States Geologic Survey (USGS) (Thieler et al., 2009). Shore-normal transects were created at 5 m intervals in DSAS from a manually generated shore-parallel baseline located deeper in the backshore. Deviations in shoreline positions from this baseline were then used to calculate shoreline change statistics from each profile, including net shoreline movement (NSM - a measure of the distance in meters between oldest and youngest shorelines) and end point rate (EPR - an annualized rate of the time elapsed between the oldest and youngest shoreline positions expressed in m a^{-1}). These statistics can be averaged to provide information on net responses within broader landscape units over time and plotted spatially to provide a visual representation of the alongshore variability in shoreline position.

For the purposes of this study, DSAS transects were compartmentalized into four shoreline units: 1) Combers Beach; 2) Northern Bluff Complex; 3) Southern Bluff Complex; and 4) Wickaninnish Beach (Fig. 14). These units were delineated based on geomorphic distinction and controlling sedimentary processes (e.g., bluff vs. beach, etc.) and, as such, served to reduce bias in estimates of average shoreline changes. For example, the Combers Beach unit is geomorphically distinct from the adjacent Bluff Complex (North and South) units as it has prograded historically (Heathfield and Walker, 2011) while the bluff complex has remained erosional. Thus, the erosional bluff complex units were kept distinct from the beach units so as not to skew shoreline change estimates negatively.

Shoreline change estimates derived from two-dimensional aerial orthophotography contain a certain amount of error that results from a combination of positional and measurement uncertainty (e.g., Stojic et al., 1998; Moore, 2000; Fletcher et al., 2003). Positional uncertainty is incurred from data limitations (e.g., digital pixel size) that reduce the precision in determining a spatial position. Measurement uncertainty results from user-based error in the operation of vector generation during onscreen delineation. Based on an arbitrary uncertainty threshold of three pixels, positional uncertainty for 1973, 1996, and 2007 orthomosaics was assigned a value of 0.9 m, while for 2009 and 2012 coverages, a value of 0.45 m was assigned. A measurement uncertainty value of 2.5 m, based on repeat trials of onscreen shoreline delineation, was also assigned to all orthophoto years. Combined, a total uncertainty value of ± 3.4 m was derived for NSM and processed in DSAS to calculate annualized EPR confidence interval value of ± 0.09 m a^{-1} (Table 5).

3.3.4. Geomorphic Change Detection and Volumetric Change Estimation

Within the central study area, three geomorphic units (beach, foredune, and bluff complex) were delineated (Fig. 14) using a combination of orthophoto interpretation and field truthing. Similar to the shoreline units described above, these units were delineated based on distinct formative processes so as to more accurately detect and analyze changes in their morphodynamics and sediment volumes. These particular units were delineated only in the region of the foredune-bluff-riverine complex (to isolate sedimentary processes related to Sandhill Creek) and were held fixed over the three time periods of LiDAR coverage (2005, 2009, 2012) so as to provide spatially and temporally normalized significant volumetric change estimates.

Clipped DEMs for each geomorphic unit were imported to the Geomorphic Change Detection (GCD) package (Wheaton et al., 2010), which was used to identify statistically significant volumetric changes within geomorphic units. Each LiDAR dataset contained inherent vertical uncertainty (±0.15 m) that was also included in the calculation. Output from the GCD method included statistically significant volumetric change estimates based on the student's *t* distribution and a test statistic (Wheaton et al., 2010):

$$t = \frac{|zDEM_{new} - zDEM_{old}|}{\sigma DoD} \tag{3}$$

where $zDEM_{new}$ and $zDEM_{old}$ are the interpolated elevations in a specific grid cell of subsequent surveys and σ_{DoD} is the characteristic error in this case represented by propagated errors:

$$\sigma_{DoD} = \sqrt{(\epsilon_{new})^2 + (\epsilon_{old})^2} \tag{4}$$

where ε_{new} and ε_{old} are the individual survey errors.

Volumetric change uncertainty is accounted for by the t-test and allows for a confidence interval to be calculated based on assumed LiDAR vertical uncertainty (± 0.15 m) + interpolation error as determined by cross-validation. Only statistically significant values were reported at a p-value of 0.05. Resulting maps visualize spatial patterns of significant volumetric change (both erosional and depositional) throughout each geomorphic unit. Change detection maps were imported into ESRI and superimposed onto the 2012 orthomosaic for ease of interpretation.

3.4. Results

All measured shoreline positions and volumetric change estimates are presented in Tables 5 and 6 and are conveyed visually in Figures 15 and 16 to demonstrate both spatial variability and temporal trends in the results. Sequential aerial photographs in Figure 17 are presented to qualitatively complement these results within the Sandhill Creek region where all geomorphic units intersect.

Table 5. Summary of shoreline change values derived from DSAS for each time period at each shoreline unit. Net shoreline movement (NSM) distance values and annualized end point rate (EPR) values are provided for each unit over the 39-year study period, with an associated uncertainty of ± 3.4 m and ± 0.11 m, respectively.

Time Period	**Shoreline Change Rate (m a^{-1} ± 0.09)**			
Beach Unit	**Combers Beach**	**Northern Bluff Complex**	**Southern Bluff Complex**	**Wickaninnish Beach**
1973-1996	0.78	-1.26	0.14	1.75
1996-2007	0.76	-1.26	0.09	0.95
2007-2009	0.30	-0.40	0.49	2.36
2009-2012		-1.63	0.23	0.49
NSM (m ± 3.4)	**27.89**	**-48.50**	**5.89**	**56.97**
EPR (m a^{-1} ± 0.09)	**0.715**	**-1.244**	**0.151**	**1.461**

3.4.1. Changes in Shoreline Positions

The shoreline change analyses show a general trend of progradation at Wickaninnish and Combers Beaches while the North Bluff complex at Sandhill Creek is rapidly eroding. Since 1973, Combers Beach experienced a net shoreline movement (NSM) of +27.9 m with an average progradation rate (EPR) of +0.72 m a^{-1} and the highest maximum rate (+0.78 m a^{-1}) occurring between 1973 and 2007 (Table 5). Spatially, the highest rates of progradation (exceeding 1.0 m a^{-1}) occurred on the northern end of Combers Beach furthest away from Sandhill Creek (Fig. 15a). There are no change values for Combers Beach between 2007 and 2009 due to the limited spatial extent of 2009 orthophoto mosaic.

Wickaninnish Beach prograded (seaward advance) an average of +56.97 m at a mean EPR of +1.46 m a^{-1}, however, this average does not completely represent the rapid rates of lateral extension (alongshore advance) at the northern end of the beach at the study site near Sandhill Creek, which serves to skew the mean trend rate. By analyzing Wickaninnish Beach in two zones, much faster rates of lateral extension are found at the northern tip of Wickaninnish foredune (~3.48 m a^{-1}) while the remaining established foredune is advancing seaward at a more modest rate (+1.05 m a^{-1}) (Fig. 15b). Between the two rapidly prograding beach systems, the bluff complex at Sandhill Creek had an average net shoreline movement of -48.5 m over the observed period (EPR -1.24 m a^{-1}). The highest rates of erosion within the bluff complex exceeded -1.5 m a^{-1} and were concentrated along the last (seaward-most) 200 m of Sandhill Creek where a substantial deposit of large woody debris exists between the bluff base and the channel. Temporally, erosion rates were fastest (-1.63 m a^{-1}) within the last three years (2009 to 2012) of the study period, which corresponds with a period of historically high water events and a recent La Niña phase of ENSO (Heathfield et al., 2013).

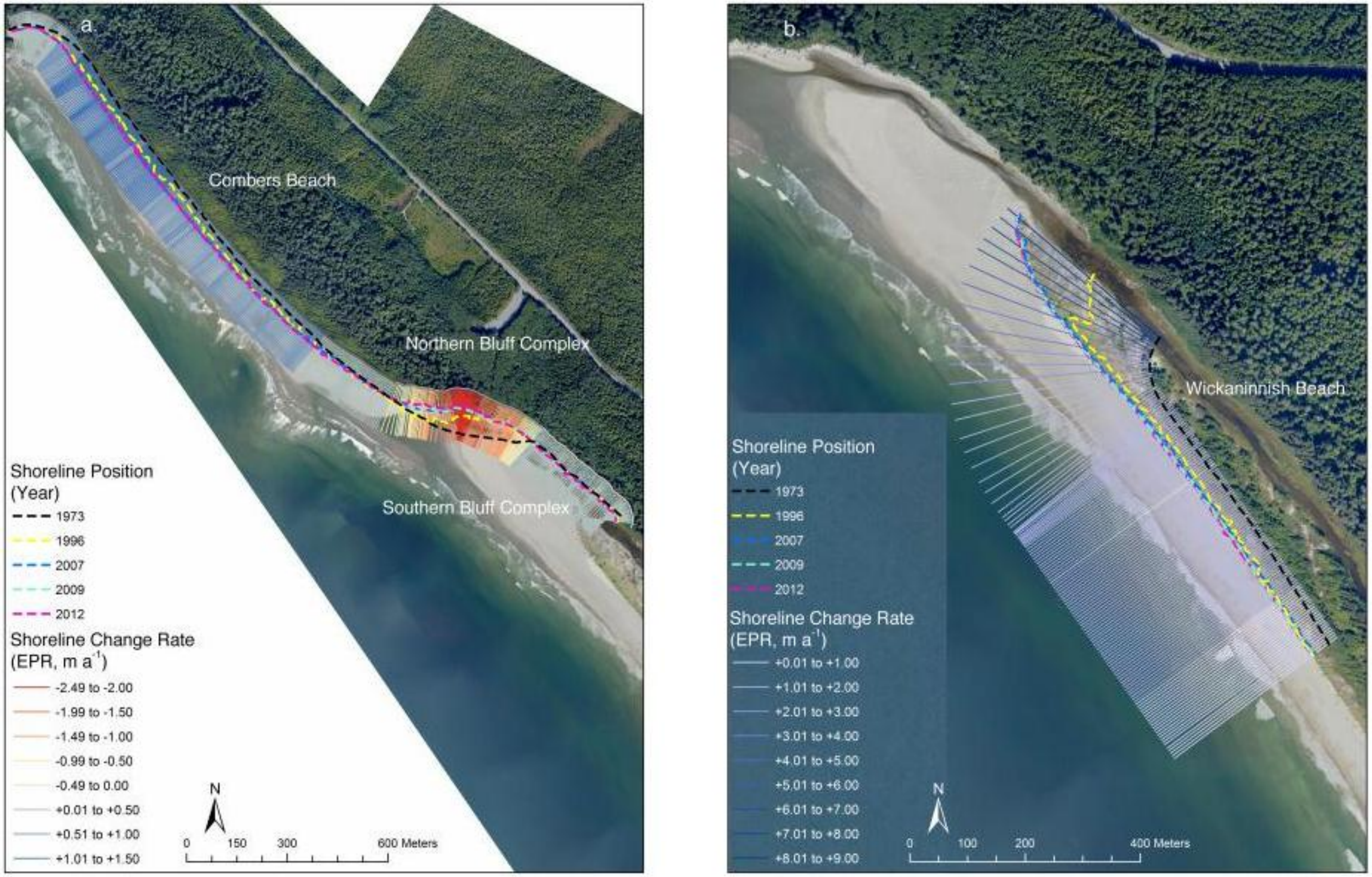

Figure 15. DSAS maps showing shoreline change transects and related change rates (EPR). Figure 15a shows Combers Beach where the highest rates of progradation occurred at the northern end. The most rapid rates of erosion occurred at the intersection of Combers and Wickaninnish Beaches near Sandhill Creek (-1.24 m a^{-1}). Figure 15b shows the northern end of Wickaninnish Beach where lateral (northward) extension of the foredune complex result in rapid average rates of progradation (3.48 m a^{-1}). For comparison, the rate of seaward progradation of the southern portion of Wickaninnish Beach is comparatively slower (1.05 m a^{-1}).

3.4.2. Significant Volumetric Changes and Geomorphic Responses

Statistically significant volumetric changes derived from the LiDAR-derived bare earth DEMs are shown in Table 6. Generally, the Sandhill Creek bluff complex showed increasing sediment losses and the highest net (negative) volumetric change rate over the period of analysis. Net sediment losses are expected for an erosive landform. The Wickaninnish Beach unit showed a more variable response with a modest (though significant) net sediment loss during the 2005-2009 period followed by an appreciable gain of sediment between 2009-2012. Overall, the beach unit experienced the highest total positive net volumetric change and change rate. Normalised by surface area, however, the bluff unit yielded the highest normalized (negative) values. The Wickaninnish foredune unit experienced comparatively minimal net volumetric change over the period of analysis, with net accretion between 2005 and 2009 followed by net erosion in 2009-2012 and the lowest area-normalized volumes, which suggests this unit remained fairly stable in terms of its sediment budget during the period of observation.

The Sandhill Creek bluff unit lost 18,658 m^3 (-0.13 $m^3 m^{-2} a^{-1}$) of sediment during the observation period. The rate of erosion accelerated from -0.086 $m^3 m^{-2} a^{-1}$ between 2005 and 2009 to -0.190 $m^3 m^{-2} a^{-1}$ between 2009 and 2012. Figure 16 visualizes the spatial distribution of erosion within the Combers bluff complex for both intervals and shows that the highest rates of sediment loss were concentrated along the final reach of Sandhill Creek.

Table 6. Statistically significant volumetric change estimates from the region where Sandhill Creek intersects Wickaninnish and Combers beaches. Total erosion and deposition values for each period and geomorphic unit are presented in addition to net change normalized by area ($m^3 m^{-2}$) and over time ($m^3 m^{-2} a^{-1}$).

Geomorphic Unit (Area m^2)	**Time Period**	**Total Volume of Erosion m^3**	**Total Volume of Deposition m^3**	**Net Volumetric Change m^3 ($m^3 m^{-2}$)**	**Net Volumetric Change Rate $m^3 m^{-2} a^{-1}$**
Bluff (20,417)	2005-2009	-8,072.1	1,033.9	-7,038.2 (-0.345)	-0.086
	2009-2012	-12,517.8	897.5	-11,620.3 (-0.569)	-0.190
	Total	**-20,589.9**	**1,931.4**	**-18,658.5 (0.914)**	**-0.131**
Beach (145,152)	2005-2009	-6,586.4	1,127.8	-5,458.6 (-0.038)	-0.009
	2009-2012	-3,891.5	32,338.5	28,446.9 (0.196)	0.065
	Total	**-10,477.9**	**33466.3**	**22,988.3 (0.158)**	**0.023**
Foredune (66,587)	2005-2009	-1,635.7	3,400.4	1,764.7 (0.027)	0.007
	2009-2012	-2,845.6	1,352.7	-1,492.9 (-0.022)	-0.007
	Total	**-4,481.3**	**4753.1**	**271.8 (0.004)**	**0.001**

Wickaninnish Beach experienced a volumetric net gain of 22,988.3 m^3 (+0.023 $m^3 m^{-2} a^{-1}$) over the same period with slight erosion between 2005 and 2009 (-0.038 $m^3 m^{-2}$) followed by distinct shift toward a net volumetric gain from 2009 to 2012 (+0.196 $m^3 m^{-2}$). Between 2009 and 2012, intertidal bar welding on the landward edge of the supratidal plain and deposition on the intertidal beach along the channel margin at the tip of the Wickaninnish foredune complex. This is expected as the beach unit is intertidal and thus subject to substantial morphologic change on daily to seasonal scales.

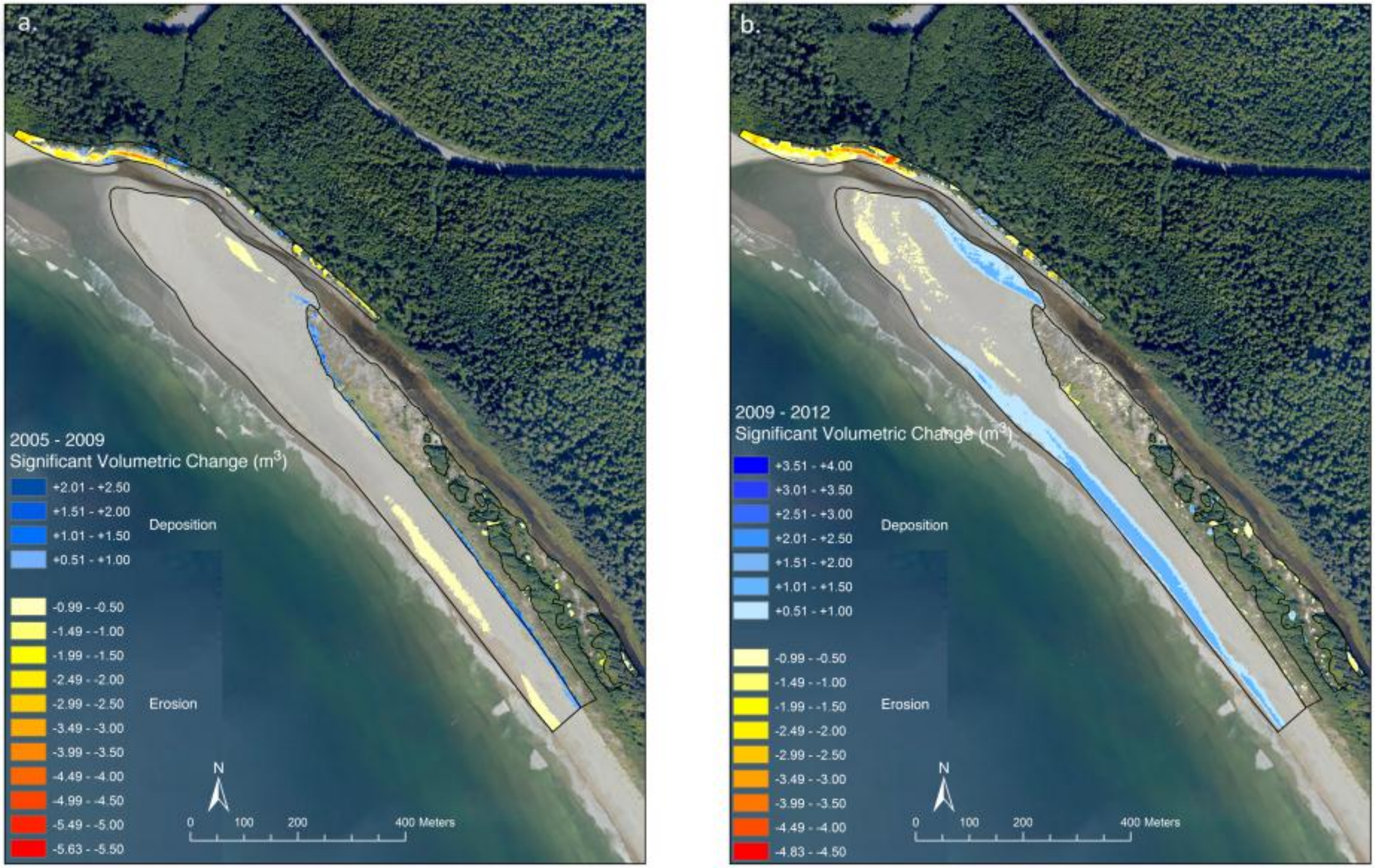

Figure 16. Geomorphic change detection maps showing statistically significant patterns in surface erosion or deposition (red or blue, respectively) shown for 2005-2012 (a) and for 2009-2012 (b).

The Wickaninnish foredune unit experienced relatively little change in sediment budget over the observation period with only a slight net gain of 271.8 m^3 (-0.003 $m^3\ m^{-2}\ a^{-1}$). This change resulted from a relatively low volumetric gain (0.027 $m^3\ m^{-2}$) between 2005 and 2009 followed by a proportionate loss (-0.022 $m^3\ m^{-2}$) between 2009 and 2012. Analysis of the GCD map (Fig. 16), however, shows notable and fairly continuous accumulation along the seaward toe of the foredune. As above, intertidal bar welding evident in the beach unit upon the supratidal overwash plain (Fig. 16b) promotes growth and extension of the incipient dune zone and the Wickaninnish foredune unit by providing an onshore sediment supply.

3.5. Discussion

3.5.1. Shoreline dynamics

Between 1973 and 2012, shoreline positions throughout the study area exhibited variable rates of change, signalling a dynamic regime of geomorphic processes influencing a relatively small area. Combers and Wickaninnish Beaches are prograding rapidly in response to high on-shore sediment supply, regressing regional sea level, a frequently competent wind regime, and the presence of LWD accumulations that serve to stabilize aeolian sands on the supratidal beach (Heathfield and Walker, 2011). If these accumulations remain undisturbed by erosive water levels and, in particular, if they become stabilized by vegetation, LWD deposits can promote foredune growth and shoreline progradation (Walker and Barrie, 2006; Eamer and Walker, 2010; Heathfield and Walker, 2011). This process is most evident on Combers Beach where LWD is abundant amongst incipient, established, and stabilized foredunes in the backshore.

In addition to local geomorphic processes, tectonic uplift contributes to promoting shoreline advance. Mazzotti et al. (2008) found that crustal uplift occurring along the Cascadia

Subduction Zone, which lies immediately offshore of western Vancouver Island, at rates of +2.6 to 2.9 mm a^{-1}, which is offsetting absolute (i.e., eustatic and steric) sea level rise in the Tofino region of +1.7 mm a^{-1} to produce a fall in relative sea level of –0.9 mm a^{-1} (Wolynec, 2004; Mazzotti et al., 2008). Other research (e.g. Ruz and Allard, 1994; Hesp, 2002) has shown that, given a moderate to high onshore sediment supply, a regressing sea level will promote vegetation colonization and foredune development, ultimately driving shoreline advance.

Despite net shoreline progradation rates, frequent erosion occurs at the toe of the foredune along both Combers and Wickaninnish Beaches and more persistent erosion maintains the Sandhill Creek bluffs. Long-term shoreline change is evident throughout the 39-year study period (1973 – 2012) (Fig. 17), illustrating the results of long-term process interaction. Bluff erosion here is most likely in response to the combined influences of longer-term fluvial, littoral, and internal slope processes. Qualitative site assessments (vantage photos [Fig. 18], anecdotal accounts, field surveys) combined with variability in EPR estimates suggest that local sediment loss is associated with episodic erosive events driven by extreme storms (see also Heathfield et al., 2013). The braided channel outflow of Sandhill Creek (Fig. 18b) modifies the intertidal to subaerial beach creating a wide floodplain of incised channels and general deflation. During high water events, wave setup and runup submerge the supratidal beach and water progressively floods the deflated river channel during tidal encroachment. If surge and/or increasing wave conditions persist, water levels may not retreat in phase with the tides, as is the case on adjacent dissipative beaches backed by buffering foredunes. High storm surges combined with storm wave action at the base of the bluff system combine to destabilize and erode the bluff by three combined processes: i) mobilization and thrusting of LWD against the bluff, ii) direct wave erosion and undercutting, and iii) saturation of basal bluff sediments and internal failure from pore water pressure effects (Fig. 18a).

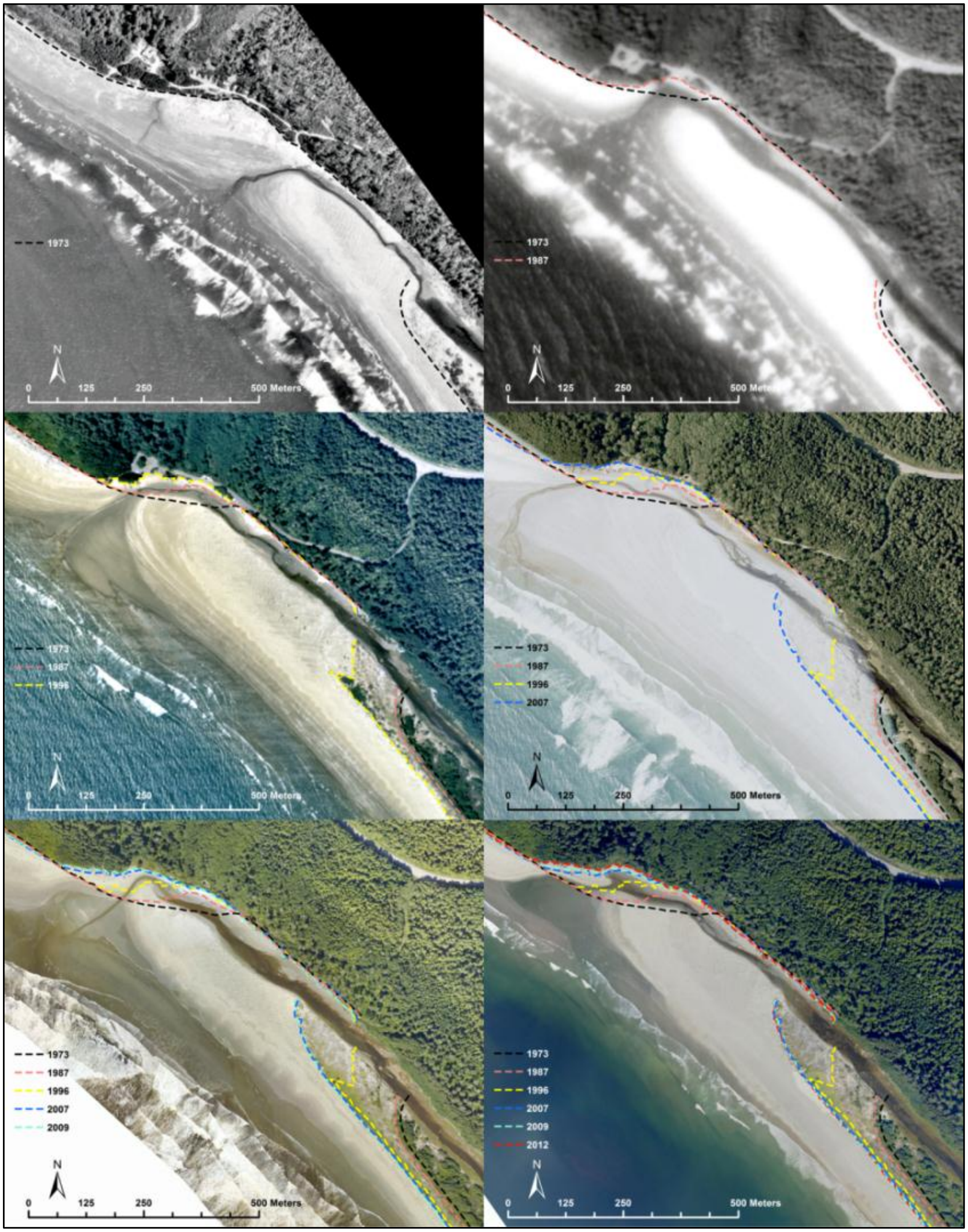

Figure 17. Orthorectified photo mosaics of the study area between Wickaninnish and Combers Beaches showing historical evolution in shoreline position over a 39-year period (1973, 1987, 1996, 2007, 2009 and 2012).

Over longer time periods, broader landscape-scale processes also contribute to erosion at the Sandhill Creek bluff system (Figs. 15,17). Lateral extension of the Wickaninnish foredune complex has occurred continually in response to northward littoral drift and high on-shore sediment supply. Aeolian activity and vegetation colonization promote incipient dune development at the leading edge of the Wickaninnish foredune and on the supratidal zone, further driving lateral extension and foredune establishment. Combined, these deposition processes act to barricade Sandhill Creek and promote a northward migration of the channel, resulting in incision into pre-existing coastal plain deposits that back the southern extent of Combers Beach. Oblique wave approach results in littoral drift that, in part, stimulates alongshore migration of subaqueous bars and beach extension, as described by Wright's (1977) conceptual model (Fig. 12), Carter et al. (1992) (Fig. 10) and locally at Wickaninnish Beach (Figs.15b,18c). The rate of shoreline position change at the Sandhill Creek southern bluff complex is slowest (+0.15 m a^{-1}), but has accelerated recently (from +0.09 m a^{-1} in 1996-2007 to +0.49 m a^{-1} in 2007-2009). With this rapid alongshore extension, the Wickaninnish foredune complex provided an effective buffer for the southern portion of the bluff system against erosive high water events and storm wave attack.

Figure 18. Composite of site photos displaying geomorphically distinct areas. Photo a. displays the rapidly eroding bluff complex and LWD accumulation backing Sandhill creek. Photo b. shows the eroding bluff complex from a different perspective, including a destroyed bridge. Photo c. shows the Wickaninnish foredune complex with Sandhill creek in the backshore. Overwash deposits are seen in the top left corner protruding into the channel. LWD at the leading seaward edge acts to trap Aeolian sands and stabilize the foredune, effectively promoting lateral alongshore extension. (Photo A&B, D. Heathfield; Photo C, PR-NPR)

3.5.2. Geomorphic responses

Maps of significant surface changes within the three geomorphic units (Fig. 16) reflect the highly dynamic and interrelated nature of sediment exchange between different components of the coastal landscape. Given the limited temporal extent of the LiDAR data sets (i.e., only two time intervals over seven years), it is difficult to discern seasonal or episodic process-response dynamics. As such, the spatial variability of erosion and deposition patterns and the association between geomorphic units reflect general process-response dynamics and environmental forcing at the study site. The broader bluff unit experienced a substantial net loss of sediment over the period of observation (2005-2012), while the adjacent beach unit had a proportionally less substantial net gain of sediment, and the backing foredune unit remained fairly stable in terms of volumetric change. The high rates of volumetric loss, and spatial concentration of erosion at the Sandhill Creek bluff complex (Fig. 16), further suggests that erosion here is a combined result of nearshore and fluvial sediment mixing and oceanographic forcing related to storm activity. Increased rates of volumetric change at the Sandhill Creek bluff system (-0.086 $m^3\,m^{-2}\,a^{-1}$ to -0.190 $m^3\,m^{-2}\,a^{-1}$) are consistent with the findings of Heathfield et al. (2013), who documented recent increases in the frequency and magnitude of regional storms and associated oceanographic forcing mechanisms (e.g., significant wave height, surge magnitude). Focussed patterns of local erosion on the bluff complex (Fig. 16) suggest that the interaction of fluvial and nearshore littoral processes at Sandhill Creek modify intertidal beach and delta morphology that can, in turn, amplify oceanographic forcing during storm events.

Despite shoreline analysis showing rapid lateral extension and seaward progradation (Fig. 15b), the Wickaninnish foredune unit exhibited relatively small fluctuations in significant volumetric change over the observed period. This is likely in response to deposition at the dune toe and within the incipient dune zone fronting the established foredune (Fig. 14). Between 2005 and 2009, approximately 3,400 m^3 of sediment contributed to accretion and extension of the Wickaninnish foredune complex, and in the following period (2009-2012), slightly less overall sediment was deposited on average. Visual evidence (Fig. 16b) of erosion at portions of the seaward margin of the foredune are consistent with a documented increase in regional erosive events during that period (Heathfield et al., 2013). Volumetric growth of the foredune is the result of vegetation trapping and sub aerial storage of aeolian sands in the backshore, building the foredune upward and outward. Despite pulses of erosive events, the foredune can become established and prograde seaward and extend laterally, as is evident in shoreline change results (Table 5, Fig. 15b).

As an intertidal geomorphic unit influenced by multiple variables (e.g., tides, waves, littoral drift, aeolian transport), Wickaninnish Beach is subject to highly variable sediment fluctuations that operate on daily to seasonal scales. As such, the temporally limited volumetric change estimates presented here are only indicative of interannual to decadal scale responses. Following only slight change between 2005 and 2009, Wickaninnish Beach experienced appreciable deposition between 2009 and 2012. Most of the deposition was concentrated on the mid-beach, typical of a summer beach morphology (August-September data acquisition) where sediment delivery from offshore bars to the beach-face occurs during lesser wave conditions. Hine (1979) identified that growth and accumulation towards the leading tip of a spit is a result of decreasing alongshore transport in response to changing shoreline orientation. Similar to nearshore processes at Wickaninnish Bay, Hine (1979) discusses how an oblique wave approach sets up a longshore transport system. Waves are refracted closer to the leading tip of the spit, altering the breaker angle and slowing longshore transport to the point that deposition is accelerated. An intertidal/supratidal terrace develops, upon which swash bars are deposited and weld to the beach, leading to supratidal berm-ridge development. Figure 18c provides evidence at Sandhill Creek of this process, where at the tip of the Wickaninnish foredune complex sits a supratidal plain hosting swash bar deposits. Furthermore, figure 14b shows significant deposition occurred in the form of intertidal bar welding and berm development at the landward edge of the supratidal overwash plain between 2009 and 2012. Despite higher winds coming from the SE in the winter, most local aeolian onshore movement occurs during summer months towards the SE due to drier winds. Interestingly, this is opposite to the dominant N littoral drift direction, resulting in transgressive dune form.

3.5.3. Foredune-fluvial interactions on a drift-aligned beach

Previous models of coastal foredune development and nearshore / fluvial interaction identify and describe specific processes and forms that characterize the wave dominated coastal delta complex. Here, the proposed model attempts to build on existing models by characterizing foredune-fluvial interactions on a drift-aligned beach. The model proposed by Wright (1977) provided a strong basis for characterizing the formation of coastal deltas and subaqueous levees as they relate to incident wave energy. The model specifically discusses how incident wave energy/direction influences river-mouth morphologies and depositional patterns (Fig. 12). While instructive to identifying process interactions on a drift-aligned beach, this model does not integrate the role of beach-dune interaction with the fluvial channel, nor does it ascribe intertidal responses to subaerial foredune morphodynamics. A more integrated work by Carter et al. (1992) examined the sequence of coastal dune development following fluvial channel closure, with a primary focus on overwash and sediment infilling. The model describes how outlet delta bedforms and intertidal bars are transported onshore to form a supratidal plain, effectively barricading and infilling the fluvial channel. This process sequence stimulates further growth and expansion of the barrier into a dune ridge that eventually takes on a reflective form, ultimately resulting in the dunes erosion and retreat. The sequence described by Carter et al. (1992) is useful to understanding sediment interactions between fluvial and beach-dune systems; however, nearshore processes (i.e., wave energy, alongshore transport) that influence the sequence and have a central role in onshore sediment delivery are not included. Finally, a coastal foredune continuum model proposed by Psuty (2004) briefly addressed the long-term evolution of foredune development and associated sediment transport at river mouths (Fig. 11). The model posits that beach accretion and foredune development is rapid closer to the river mouth, and the rate of accretion slows with greater proximity away from this point. While conceptually this model makes sense, the assumption that a) the dominant point source for sediment input is the river and, b) alongshore transport moves away from the extending spit, does not necessarily apply to all cases, particularly at Wickaninnish Bay. Furthermore, the models scope is limited to foredune development and ignores interactions between wave energy and nearshore transport pathways, the result of which a key component to beach form.

Figure 19 presents a conceptual model that summarizes the case study results of nearly 40 years of historic shoreline movements, significant sediment volume changes, and related geomorphic responses on a high-energy, drift-aligned beach. The model describes the interactions between littoral, fluvial, and aeolian processes acting on an accreting coast that control the morphodynamics and decadal-scale evolution of a laterally extending foredune complex and active bluff system. The model also considers concepts and elements of models proposed by Wright (1977), Hine (1979), Carter et al. (1992), Hesp (2002), and Psuty (2004) so as to expand on existing research for wave-dominated deltas and riverine-foredune interactions.

Foredune stabilization and progradation processes are driven by a high onshore sediment supply that accumulates on the upper beach and is readily transported by competent winds (Hesp, 2002). On drift aligned beaches, sediment is preferentially transported and deposited in a net alongshore littoral drift direction that results from dominant oblique nearshore wave approach, which often promotes lateral migration of swash bars and subaqueous levees and drift-oriented extension of deltas and spits in the proximity of river outflows (Wright, 1977; Hine, 1979). Adjacent to the established foredune complex and adjoining the river is a relatively flat, supratidal sand plain. Overwash and wave action are ephemeral in this supratidal zone and vegetation is able to colonize seasonally and may persist during years with infrequent high water events to promote further storage of aeolian sands via incipient dune development (Carter et al., 1992). The onshore movement of sediment deposits on the supratidal overwash plain in the form of overwash deposits and swash bars, over time, can alter the outflow of the fluvial channel. Deposition amongst the supratidal plain can develop into an incipient foredune zone, which can be transported via aeolian activity to the foredune complex and drive seaward progradation (Hesp, 2002) and lateral extension. Foredune growth and extension effectively barricades the river, the continual process of supratidal sedimentation stimulates a lateral channel migration (Hine, 1979; Hesp, 2002). Fluvial incision occurs at the river mouth, causing the beach to be somewhat deflated from a supra- to a sub-tidal elevation. Given a period of elevated surge and storm waves, total water levels can preferentially enter the backshore via the fluviomarine channel and erode the beach and bluff deposits adjacent to the river system. In areas where

LWD accumulates, this process is potentially amplified, as mobilized LWD can substantially increase erosion by way of battering and undercutting backshore sedimentary deposits.

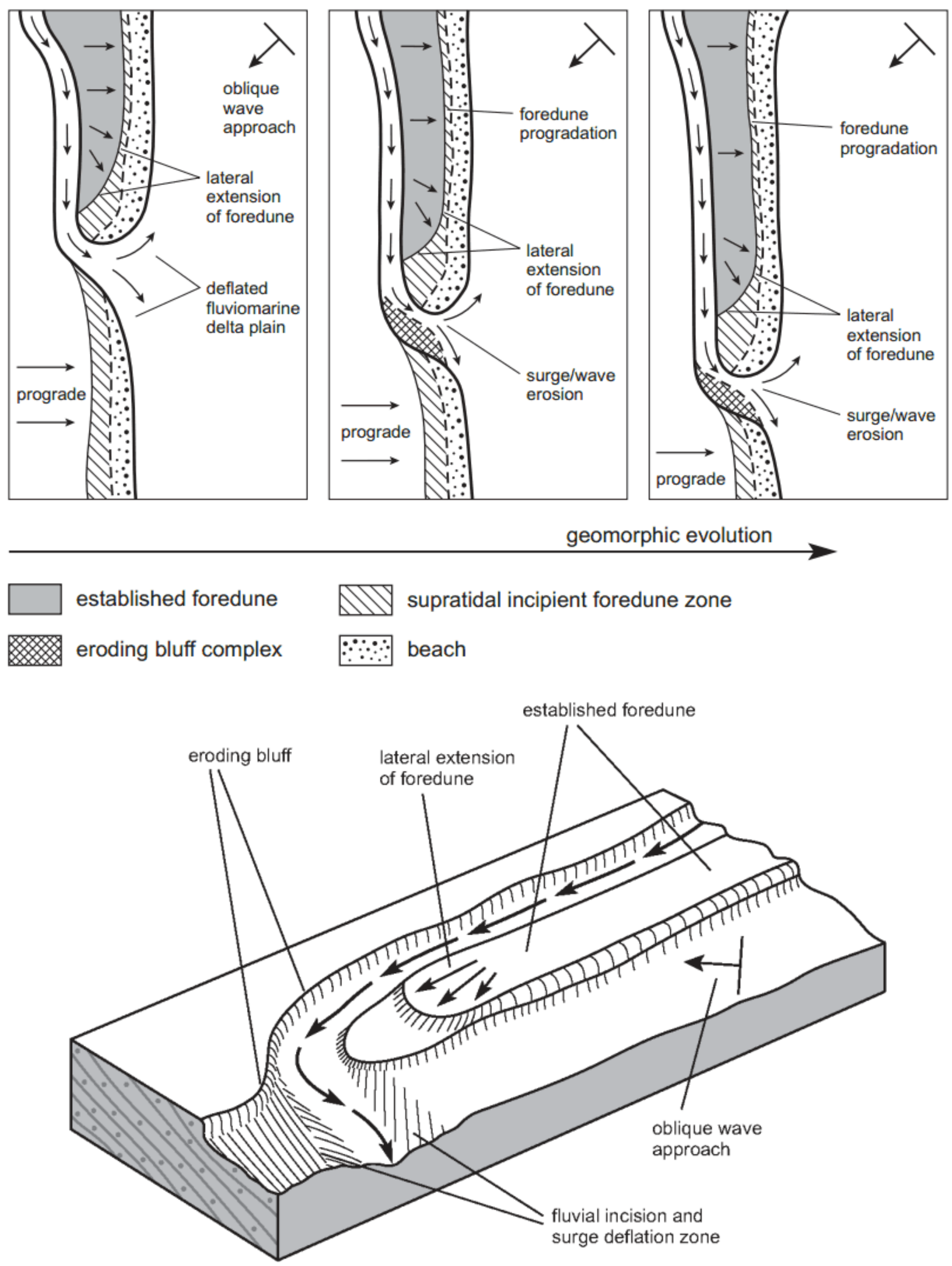

Figure 19. Conceptual model describing the geomorphic evolution of a wave dominated beach-dune complex and backshore river system. Figure 19A describes in plan-view the landscape

features and processes found in this type of setting. Overwash deposits and bar welding on the supratidal zone feed sediment to LWD and incipient vegetation, promoting seaward advance and lateral extension of the established foredune complex. This process is promoted by oblique wave approach and resultant net-littoral drift, which provides sediment downdrift and subsequent shoreline progradation. Fluvial processes modify the river mouth such that a zone of deflation develops, allowing for erosive water levels to penetrate into the backshore and erode the bluff-complex. Figure 19B describes the same process-response dynamic in 3D.

The proposed conceptual model is informed by previous research and models of coastal delta and foredune development (Wright, 1977; Hine, 1979; Carter et al., 1992; Hesp, 2002; Psuty, 2004) and is based on nearly 40 years of shoreline change and significant volumetric and related geomorphic response. On sedimentary coastlines exposed to high-energy, oblique wave conditions, high rates of onshore sediment delivery combined with fluvial channel incision can have substantial geomorphic implications for adjacent and backing beach-dune systems. Swash bar deposition and incipient dune development promoting foredune progradation and alongshore extension of the down drift foredune complex can enhance the spatial punctuation of fluvial outflow. The result is fluviomarine processes concentrated in relatively small area, creating a zone of lower beach elevation that lacks the storm-wave buffering capacity of adjacent shorelines, and hence this is the principal cause of amplified coastal erosion in this zone. The proposed model is admittedly site specific, but serves to incorporate the interaction of a wide range of processes and forms. In order to properly assess other similar sites, all relevant processes and resulting landforms should be considered, from regional wave forcing to fluvial – marine sediment interaction to foredune morphodynamics.

3.6. Conclusion

This study examines and interprets the historical landscape evolution of a wave-dominated drift-aligned beach-dune complex at the outflow of a backshore river on the westcoast of Vancouver Island, BC. Shoreline position and significant volumetric change analysis reveal a highly dynamic environment that has persistent long-term trends of both erosion and deposition, but also exhibits pulses of erosion and deposition related regional storm activity. Results are synthesized into a conceptual model that may be applied to other energetic drift-aligned sedimentary coasts to better understand beach-dune-fluvial dynamics and future coastal impacts of storm forcing. Key results are as follows:

1. Shorelines in the study region exhibit a general trend of progradation over the study period (1973 – 2012) as a result of a high on-shore sediment supply, a competent wind regime, and regional crustal uplift. Combers and Wickaninnish Beaches are advancing seaward at appreciable rates of +0.715 and +1.461 m a^{-1}, respectively. Located at the intersection of these two beaches, the bluff system backing Sandhill Creek is rapidly eroding at -1.244 m a^{-1} due to the alongshore migration of the river in response to high rates of onshore sediment deposition at the supratidal plain. Swash bar depositions on the supratidal plain are transported to the foredune complex via aeolian winds, driving foredune progradation and alongshore extension. This has concentrated oceanographic forcing to the outflow of Sandhill Creek and punctuated erosion amongst an otherwise accreting coastline. The extreme variability of shoreline change rates in the study area reflect the geomorphic impact of fluvial systems on high-energy sedimentary coastlines.
2. Three selected geomorphic units examined over the observed period (2005 – 2012) exhibited significant volumetric change rates which reflect the interaction of fluvial,

nearshore, and beach-dune sedimentation processes and feedback. The bluff complex backing Sandhill Creek had a net loss of 18,658.5 m^3m^{-2} at a rate of -0.131 $m^3m^{-2}a^{-1}$, substantiated by shoreline retreat rates and field observations of bluff undercutting and slumping. Volumetric analysis of both the foredune and beach units reveal a long-term trend of dune growth and alongshore extension due to appreciable sediment deposition at the leading edge of the dune and bar attachment to the beach at the supratidal incipient dune zone. Continued trends of sedimentation in the beach and foredune units will continue to force Sandhill Creek to the northwest and contribute to erosion of the bluff unit.

3. A proposed conceptual model of the morphology, process-feedback dynamics, and evolutionary trends of a drift-aligned wave dominated foredune-riverine complex is presented. The model, informed by historical shoreline position and volumetric change analysis, and by previous research provides a dynamic process interaction based explanation of the geomorphic evolution of this specific environment. Its principal aim is to provide a conceptual framework, whereby similar sites may be better understood and characterized based on assessment of local process-feedback regimes and their resulting geomorphology.

4. Conclusion

4.1. Summary and conclusions

This thesis provides a comprehensive analysis of local erosion at Wickaninnish Bay, from the regional environmental forcing regime and the manifest mechanisms responsible for driving erosion, to the geomorphic response of local beach-dune systems to erosive water levels. Results were used to identify an erosive water level regime and to understand how local beach-dune systems respond to erosive periods. Thesis structure is based on two results sections (chapters 2 and 3) that describe the aforementioned queries at Wickaninnish Bay, Pacific Rim National Park Reserve, British Columbia, Canada. Each chapter is independently structured to be submitted for publication in a peer-reviewed journal. Chapter 2 identified an erosive water level regime by identifying dominant drivers of erosion based on analysis of regional environmental forcing mechanisms (i.e., tide, surge, wave energy) and their association with known climate variability indices (i.e., ENSO, PDO, ALPI). Chapter 3 explored the geomorphic evolution of a foredune-bluff-backshore river complex quantified historical shoreline change using historical aerial photography and significant volumetric change estimates based on LiDAR generated DEMs. These chapters are bound with an introduction (Chapter 1) that sets the research context and this section that summarizes key findings of the research.

The purpose of chapter 2 was to investigate and analyze atmospheric and oceanographic forcing mechanisms that define the erosive water level regime for beach-dune systems at Wickaninnish Bay within Pacific Rim National Park Reserve, British Columbia. Historical (1940 – 2010) water level data measured at the Tofino tide station was analyzed for long-term tide and surge trends, as well as erosive signals. Shorter-term (1970 – 1998) deep-water significant wave height and period data was analyzed for trends and maximums, and combined with tide data to calculate wave runup and total water level values. Associations between all variables and climate variability indices were explored. Results show that maximum surge levels are increasing at 1.35 times the rate of maximum observed water level (1.57 versus 1.17 mm a^{-1}), indicating that extreme event forcing by temporarily elevated storm surges are increasing in frequency and magnitude. Despite ongoing crustal uplift which results in a regional relative sea level fall and shoreline progradation, local foredunes experience extensive, episodic erosion from temporarily elevated water levels. Regionally relevant indicators of climatic variability were found to be correlated to oceanographic variables that contribute to coastal erosion, the strongest association existing between ALPI and TWL ($r = 0.519$; $p < 0.01$) and wave period ($r = 0.545$; $p < 0.01$). This result suggests that potentially erosive water levels are, in part, forced by storm activity, the strength of which is characterized by ALPI. Results also suggest that the La Nina phase of ENSO exerts a stronger influence on regional storm events and associated elevated water levels (OWL_{max}) and enhanced surge events ($surge_{max}$), as compared to El Nino. The final key result of this research found that the majority of erosive water levels (61.5%) at Wickaninnish Bay are driven, primarily, by enhanced wave energy, followed by enhanced storm surge events (21.8%), and tidally dominated events (16.7%).

The purpose of chapter 3 was to document and describe local erosion and deposition process interaction in response to environmental forcing at Wickaninnish Bay, Pacific Rim National Park Reserve, British Columbia. The chapter explores the historical evolution of the foredune-riverine-bluff complex at the intersection of Wickaninnish Beach, Sandhill Creek, and Combers beach by examining shoreline progradation/erosion rates derived from sequential historical digital orthophotography using the USGS Digital Shoreline Analysis System (DSAS). Significant volumetric change estimates were derived using aerial LiDAR-derived DEMs and their spatial patterns interpreted using a statistically constrained geomorphic change detection system.

Results show that shorelines in the region are generally prograding (Combers Beach = +0.715 m a^{-1}; Wickaninnish Beach = +1.461 m a^{-1}) as a result of a high on-shore sediment supply, a competent wind regime, and regional crustal uplift. The bluff system backing Sandhill Creek, however, is rapidly eroding (-1.244 m a^{-1}) due to storm wave attack and fluvial outflow modification via alongshore transport and onshore sediment deposition. The bluff complex backing Sandhill Creek had a net loss of 18,658.5 m^3m^{-2} sediment at a rate of -0.131 $m^3m^{-2}a^{-1}$, a process substantiated by shoreline retreat rates and field observations of bluff undercutting and slumping. Nearly 40 years of historic shoreline movement, significant sediment volume changes, and associated geomorphic responses were combined with qualitative field observations to characterize the study site. These results were combined with elements of previous, related models to inform and develop a conceptual model of the morphology, dynamics, and evolutionary trends of a drift-aligned wave-dominated delta complex on an accreting coast. The model provides a dynamic process based explanation of the geomorphic evolution of this type of system.

4.2. Research contributions and future directions

The principal contribution of this research is a detailed characterization of the process dynamics at Wickaninnish Bay, and a deeper understanding of the causes and effects of erosive water levels on sedimentary beaches on the westcoast of Vancouver Island, British Columbia. Previous research on the mechanisms responsible for forcing erosive water levels was somewhat limited, in that mechanisms responsible for driving erosive process were not addressed individually to identify the variation of influence. By analyzing individual oceanographic forcing mechanisms during historical erosive events (TWL > erosive threshold elevation), an erosive water level regime may be characterized and developed for other locations, which can translate to a more thorough understanding of local erosion. Beach-dune rebuilding capacity in the context of fluvial-marine process interaction is better understood. The proposed model describes a coastal process sequence that characterizes historical geomorphic evolution within beach-dune-riverine systems. The model provides a framework to link processes responsible for rapid rates of simultaneous erosion and deposition, from nearshore oblique wave energy, to littoral transport, to swash bar development and fluvial buffering, to aeolian transport of sediment to the foredune complex.

Digital shoreline analysis system (DSAS) software and geomorphic change detection (GCD) software are effective methods for building upon the causes of erosion in order to understand the landscape response. Both quantitative methods can be used to analyze digital orthophotographs and bare earth DEM's to identify landscape response trends. Overall, the suite of methods used in this research, when utilized in concert, can build an integrated understanding of the local erosive water level regime. This may be instructive to planners, managers, and stakeholders of potential coastal hazards to property and infrastructure.

Similar studies in the future should consider including an examination of local near-shore bathymetric effects on wave and surge propagation, either through direct measurement or modelling techniques. Future research on wave dominated delta systems may consider sediment analysis in order to identify the interaction between fluvial and marine sedimentation. This may be insightful to understanding how nearshore bathymetry and beach-dune form at fluvial outflows is altered and how this influences incident wave energy (height and approach) and surge propagation responsible for erosive water levels.

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