# Is the Intensifying Wave Climate of the U.S. Pacific Northwest Increasing Flooding and Erosion Risk Faster Than Sea-Level Rise?

Peter Ruggiero[1]

**Abstract:** The relative contributions of sea-level rise (SLR) and increasing extratropical storminess to the frequency with which waves attack coastal features is assessed with a simple total water level (TWL) model. For the coast of the U.S. Pacific Northwest over the period of wave-buoy observations (approximately 30 years), wave height (and period) increases have had a more significant role in the increased frequency of coastal flooding and erosion than has the rise in sea level. Where tectonic-induced vertical land motions are significant and coastlines are presently emergent relative to the mean sea level, increasing wave heights result in these stretches of coast being possibly submergent relative to the TWL. Although it is uncertain whether wave height increases will continue into the future, it is clear that this process could remain more important than, or at least as important as, SLR for the coming decades, and needs to be taken into account in terms of the increasing exposure of coastal communities and ecosystems to flooding and erosion. **DOI: 10.1061/(ASCE)WW.1943-5460.0000172.** *© 2013 American Society of Civil Engineers.*

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## Introduction

In light of the control that Earth's changing and variable climate has on the multiple atmospheric and oceanic processes that combine to enhance coastal hazards, there is a need to reevaluate procedures used to quantify flooding and erosion risk to better protect coastal populations, infrastructure, and ecosystems. Most recent attention has been directed toward potential acceleration in the global mean rise in sea levels (Church and White 2006; Bindoff et al. 2007; Rahmstorf 2010). This problem has received considerable scientific, public, and political attention, and research has focused not only on predicting the magnitude and time scales associated with sea-level rise (SLR) but also on studies quantifying the merits of various mitigation and adaptation strategies (Nicholls and Tol 2006).

A second important phenomenon that has been speculatively linked to (Graham and Diaz 2001; Seymour 2011), but not formally attributed to (Knutson et al. 2010), global climate change is increasing storm intensities and the heights of the waves they have generated. An increase in North Atlantic wave heights was first documented by measurements off the southwest coast of England that began in the 1960s (Carter and Draper 1988; Bacon and Carter 1991). Wang and Swail (2006) and Wang et al. (2009) suggest that the changes in the North Atlantic wave climates, a rate of increase in annual mean significant wave heights (SWHs) of about 2.2 cm/year, are associated with the mean position of the storm track shifting northward. Comparable increases have been found in the northeast Pacific documented by measurements from a series of the National Oceanic and Atmospheric Administration (NOAA) buoys along the United States and Canadian West Coast (Allan and Komar 2000, 2006; Méndez et al. 2006; Menéndez et al. 2008; Ruggiero et al. 2010b, Seymour 2011) and from satellite altimetry (Young et al. 2011). Analyses by climatologists of North Pacific extratropical storms have concluded that their intensities (wind velocities and atmospheric pressures) have increased since the late 1940s (Graham and Diaz 2001; Favre and Gershunov 2006), implying that the trends of increasing wave heights perhaps began in the midtwentieth century, earlier than could be documented with the direct measurements of the waves by buoys.

However, the results of studies relying solely on buoy measurements have recently been called into question after careful analyses of modifications of the wave measurement hardware as well as the analysis procedures since the start of the observations have demonstrated inhomogeneities in the records (Gemmrich et al. 2011). Accounting for these changes in trends for the corrected data are smaller than the apparent trends obtained from the uncorrected data. Of interest, the most significant of the nonclimatic step changes in the buoy records occurred prior to the mid-1980s. Menéndez et al. (2008) analyzed extreme significant wave heights along the eastern North Pacific using data sets from 26 buoys over the period 1985–2007; not including the more suspect data from the earlier buoy records. Application of their time-dependent extreme value model to SWHs showed significant positive long-term trends in the extremes between 30 and 45° N near the western coast of the United States. Méndez et al. (2010) extended this work by using two time-dependent extreme value models and three different datasets from buoys, satellite missions, and hindcast databases. They concluded that the extreme wave climate in the northeast Pacific was increasing in the period 1948–2008 at a rate of about 1 cm/year (using

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reanalysis data) and 2–3 cm/year in the period 1985–2007 (using buoy data).

Research on trends in midlatitude extratropical storms in the eastern North Pacific have confirmed that there has been an increase in storm intensity and has documented a decrease in storm frequency, possibly because storm tracks have shifted poleward during the latter half of the twentieth century. McCabe et al. (2001) showed a statistically significant decrease in the frequency of storms over the years 1959–1997. However, Geng and Sugi (2003) found that the decrease in annual numbers of storms is typically of the weak-to-medium strength variety, while the stronger storms have actually increased in frequency. Young et al. (2011) recently demonstrated that over the (relatively short) altimetry record both wind speeds and wave heights—particularly the extremes—are increasing along much of the coast of North America. These documented changes in storms are thought to be primarily caused by changes in baroclinicity, which in turn has been linked to changes in atmospheric temperature distributions as a result of increased greenhouse gas emissions. Yin (2005) used the output of 15 coupled general circulation models to relate the poleward shift of storm tracks to forecasted changes in baroclinicity in the 21st century. Although these studies were conclusive that storminess has changed over the last several decades and may continue to change in the future, uncertainties regarding natural variability and model limitations remain.

Although the exact cause of the increasing wave heights in portions of the Northeast Pacific is still uncertain, the impacts of this phenomenon, particularly in regard to assessments of coastal hazards along the west coast of North America, remain largely uninvestigated. In this paper, the hypothesis is quantitatively tested over the historical record (approximately the last 30 years) that increasing wave heights (and periods) have been more important than sea level changes in terms of increasing the vulnerability of the U.S. Pacific Northwest (PNW) coast to erosion and flooding. Predictions are then made, under various ranges of future SLR and rates of wave height increase, regarding the relative roles of SLR and increasing extratropical storminess on an increased frequency of flood events and erosion potential over coastal management time scales of decades.

## Total Water Level Modeling

The connection between climate change and the potential for increased exposure to coastal hazards is established through application of a total water level (TWL) model (Ruggiero et al. 2001) that involves the summation of the predicted astronomical tides, the nontidal factors that alter the measured tides from those predicted (most important in the PNW being elevated water levels during major El Niños), and the runup levels of the waves on the beach. Estimates of the (hourly) TWL achieved on beaches are taken as

$$\mathrm{TWL} = \mathrm{MSL} + \eta_A + \eta_{\mathrm{NTR}} + R \quad (1)$$

where the local mean sea level (MSL) can be treated as either a constant tidal datum or as a variable with a rate of change, $\eta_A$ = astronomical tide, $\eta_{\mathrm{NTR}}$ = nontidal residual (NTR) water level, and $R$ = vertical component of the wave runup, which includes both the wave setup (a superelevation of the water level caused by wave breaking) and swash oscillations around the wave setup. Here, an extreme wave runup statistic, $R_{2\%}$ (Holman 1986)—the 2% exceedance value of wave runup maxima—is used because it is the highest swash events in a wave runup distribution that are initially responsible for erosion and overtopping. Simple empirical formulas have been developed for the application of this statistic; for example, Stockdon et al. (2006) combined data from 10 nearshore field experiments and derived an expression for $R_{2\%}$ applicable to natural sandy beaches over a wide range of morphodynamic conditions. Their relationship relates deepwater wave characteristics and beach morphology to wave runup on the beach

$$R_{2\%} = 1.1\left\{0.35\tan\beta(H_0L_0)^{1/2} + \frac{\left[H_0L_0\left(0.563\tan\beta^2 + 0.004\right)\right]^{1/2}}{2}\right\} \quad (2)$$

where $\tan\beta$ = foreshore beach slope; $H_0$ = deepwater significant wave height; and $L_0$ = deepwater wavelength given by Airy (linear) wave theory as $(g/2\pi)T^2$, where $g$ = acceleration of gravity and $T$ = spectral peak wave period. Because it is the most widely applicable available formula for wave runup (RMS error = 0.38 m) based on the majority of available field data including from the PNW (Ruggiero et al. 2004), the Stockdon et al. (2006) relationship will be used here.

The elevation of a particular backshore feature (BF)—for example, the base of sand dunes or the toe of a sea cliff or shore protection structure—relative to the TWL determines the frequency with which it can be reached by waves, and thus governs its susceptibility to erosion or overtopping (Ruggiero et al. 1996, 2001; Sallenger 2000). This TWL modeling approach has been demonstrated to be a good predictor of the erosion of weakly lithified coastal bluffs at the interannual-to-decadal scale (Ruggiero et al. 2001; Collins and Sitar 2008; Hapke and Plant 2010), dune erosion at the annual scale, and the event-scale dune response to hurricanes along the U.S. gulf and Atlantic coasts (Stockdon et al. 2007).

Of primary interest for assessing the impact of climate change on both the historical and future exposure of a coastline to flood and erosion hazards is the time rate of change of the TWL

$$\frac{\Delta\mathrm{TWL}}{\Delta t} = \frac{\Delta\mathrm{MSL}}{\Delta t} + \frac{\Delta\eta_A}{\Delta t} + \frac{\Delta\eta_{\mathrm{NTR}}}{\Delta t} + \frac{\Delta R}{\Delta t} \quad (3)$$

where $\Delta\mathrm{MSL}/\Delta t = \mathrm{RSLR} = \mathrm{SLR}_G + \mathrm{SLR}_R + \mathrm{VLM}_R$ and the local relative SLR (RSLR) rate can be either positive or negative because it combines the rate of vertical water motions as a result of global processes, $\mathrm{SLR}_G$ (e.g., increased water temperatures and melting glaciers and ice caps), regional processes that cause variations from the global mean, $\mathrm{SLR}_R$ (e.g., changes to Earth's gravitational field), and vertical land motions, $\mathrm{VLM}_R$ (e.g., local tectonics, isostasy, and compaction). While there is some evidence indicating that the range of astronomical tides may be evolving (Flick et al. 2003), of the terms in Eq. (3) both $\Delta\eta_A/\Delta t$ and the $\mathrm{VLM}_R$ component of the RSLR can be considered unaffected by a changing climate at the time scales relevant to this study.

The NTR component of the TWL is composed of a complex interplay of processes often dominated by storm surge (atmospheric pressure effect and wind setup) and also including effects of local water density variations and coastal trapped waves (Enfield and Allan 1980). Climate-induced changes in any of these processes could lead to measurable changes in local water levels observed at tide gauges. While this meteo-oceanographic noise is often minimized in tide gauge analyses meant to assess regional or global SLR rates, here the interest is in trends in local TWLs and $\Delta\eta_{\mathrm{NTR}}/\Delta t$ is treated as a component of $\mathrm{SLR}_R$ and subsumed within long-term estimates of the RSLR. Therefore, the time rate of change of the TWL achieved on beaches can be simplified to being primarily a function of the RSLR as directly determined from tide gauges and the rate of change of offshore wave characteristics (SWH and peak



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period) for a particular beach morphology through their control on the wave runup [Eq. (2)]. Any trends or variability in these parameters will directly influence the frequency that backshore properties experience erosion or flooding.

As in several previous investigations (Allan and Komar 2006; Méndez et al. 2006; Ruggiero et al. 2010b), the increase in wave characteristics off the PNW is first documented with data from National Data Buoy Center (NDBC 2008) Wave Buoy 46005, located about 400 km west of the mouth of the Columbia River. This buoy became operational in the mid-1970s and is one of the longest quality wave records in the world. The corresponding hourly $R_{2\%}$ wave runup computations are derived from the buoy data, for representative PNW foreshore beach slopes. The computed RSLR rates are based on the measured tide levels from various National Ocean Service (NOS 2009) tide gauge records, and recent investigations have derived updated and improved values for trends in the relative sea levels (RSLs) for each of the gauges (Komar et al. 2011).

Predictions regarding the relative importance of accelerated SLR and increases in storminess to enhanced future coastal vulnerability were made by examining the influence of these factors on a bulk statistic derived from a 10-year TWL time series. This hourly time series, extending from July 1, 1994, to June 30, 2004, has been constructed using the methods developed by Allan et al. (2012) and Harris (2011). Data gaps in NDBC Wave Buoy 46005 were filled with NDBC Buoys 46089 and 46050, which are landward of the edge of the continental shelf. Hourly estimates of $R_{2\%}$ computed from wave characteristics were simply added to hourly measured water levels from NOS Tide Gauge 9435380 in Yaquina Bay, Oregon, to generate hourly estimates of the TWL. The average number of hours per year [impact hours per year (IHPY)] in which the TWL for a particular beach slope reaches or exceeds a particular backshore elevation serves here as a proxy for the probability of beach erosion or backshore flooding (Ruggiero et al. 2001). The 10-year time period used to compute this proxy included the major El Niño of 1997/1998 (Komar 1998a, b; Kaminsky et al. 1998) and the La Niña of 1998/1999 (Allan and Komar 2002) as well as subsequent mild years, and is taken here as representative of a typical PNW TWL decade. This gap filling approach allows for a 10-year time series that is approximately 94% complete.

## Results

In the subsequent sections the primary components comprising the TWL during the recent historical period, captured by wave buoy and tide gauge observations, are first compared and contrasted. Then, the relative influence of possible SLR and increasing storminess on predictions of the future risk of coastal flooding and erosion is explored.

### *Historical Changes in Total Water Level*

Variations in VLM rates along the PNW coast as a result of its tectonic setting (Burgette et al. 2009) result in alongshore variations in rates of the RSLR. Along the southern and northern stretches of the PNW coast, tectonic uplift rates exceed recent rates of regional SLR and land is emergent. By separately analyzing summer-averaged water levels for robust estimates of multidecadal PNW RSLR, Komar et al. (2011) found that the Crescent City, California, tide gauge is experiencing a RSLR rate of approximately $-1.1 \pm 0.50$ mm/year. Along the central-to-northern Oregon coast sea level is rising relative to the land; for example, the Yaquina Bay tide gauge is experiencing approximately $1.33 \pm 0.79$ mm/year of RSLR [Fig. 1(a)]. Along the Oregon/Washington border the Astoria, Oregon, tide gauge suggests emergence, while at the Toke Point, Washington, tide gauge, about 50 km north of the Columbia River, sea level is again rising relative to land at a rate of $1.48 \pm 1.05$ mm/year, similar to the rate documented for the Yaquina Bay tide gauge.

Ruggiero et al. (2010b) found that at NDBC Wave Buoy 46005 the annual average SWH is increasing at rate of $1.5 \pm 1$ cm/year [Fig. 1(b)]. Of more concern in regard to coastal hazards, winter waves observed at this buoy are increasing at a rate of $2.3 \pm 1.4$ cm/year. In fact, the rate of increase of the wave climate depends on the exceedance percentile of the SWH cumulative distribution function (CDF) because the bigger waves are getting bigger faster. Annual averaged spectral peak wave periods have been increasing at a rate of approximately 0.015 s/year.

When the wave height and wave period are combined to compute the wave runup [Eq. (2)], a direct comparison can be made between the sea level and wave-induced components of the TWL at the multidecadal scale. Fig. 1(c) illustrates that the long-term trend in annual mean wave runup is approximately 3.4 mm/year when using a representative PNW foreshore beach slope of 0.05 (1Vertical:20Horizontal). The early part of NDBC Wave Buoy 46005 record, as called into question by Gemmrich et al. (2011), is not used in this calculation of trends in runup because the wave period was not recorded by the buoy until the early 1980s (Fig. 1). Therefore, for north-central Oregon beaches with this beach slope (on average), wave-induced processes have been over 250% more important than RSLR in producing multidecadal changes in TWLs. The relative importance of wave-induced versus sea level–induced impacts on the TWL as a function of foreshore beach slope is illustrated in Fig. 2 over a wide range of (average) beach slopes. Only where beach slopes are very mild have wave-induced processes and changes in RSL been of approximately equal importance in the rate of change of the TWL. For beaches with relatively steep foreshores, winter wave height increases have been as much as a factor of 6 times more important than the RSLR during the recent historical period. Allowing beach slopes to vary seasonally (Ruggiero et al. 2005) has little impact on the results presented in Fig. 2 (data not shown).

Performing the same set of analyses as previously described for NDBC Wave Buoy 46002, located seaward of the southern Oregon/northern California coast, reveals that the annual rate of change of wave runup is again positive (approximately 1.8 mm/year) during the observational record. Therefore, while the coastline is emergent relative to processes that affect local MSL, this southern stretch of the PNW may, in fact, be submergent relative to the TWL caused by the impact of an increasing wave climate. Fig. 3 conceptually illustrates the magnitude and alongshore variability of both the RSLR and time rate of change of wave runup during the historical observational period. While the alongshore resolution of the wave runup computations is poor (only two long-term buoys), it is clear that for at least most of the Oregon coastline, increases in wave runup have made more of a contribution to changes in the TWL than the RSLR.

### *Predicting Future Changes in Total Water Level*

To assess the relative impacts of continued wave height increases and SLR on future flood probability and erosion potential along the PNW coast, how often TWLs impact the backshore was first computed (e.g., the toe of a sea cliff) under current conditions (Fig. 4). The proxy IHPY computed using the 10-year TWL time series previously described depends on the foreshore beach slope and on the elevation of the BF of interest. As a result of the wave runup dependence on foreshore beach slope, the model predicts higher values of IHPY for steep intermediate to reflective beaches than for





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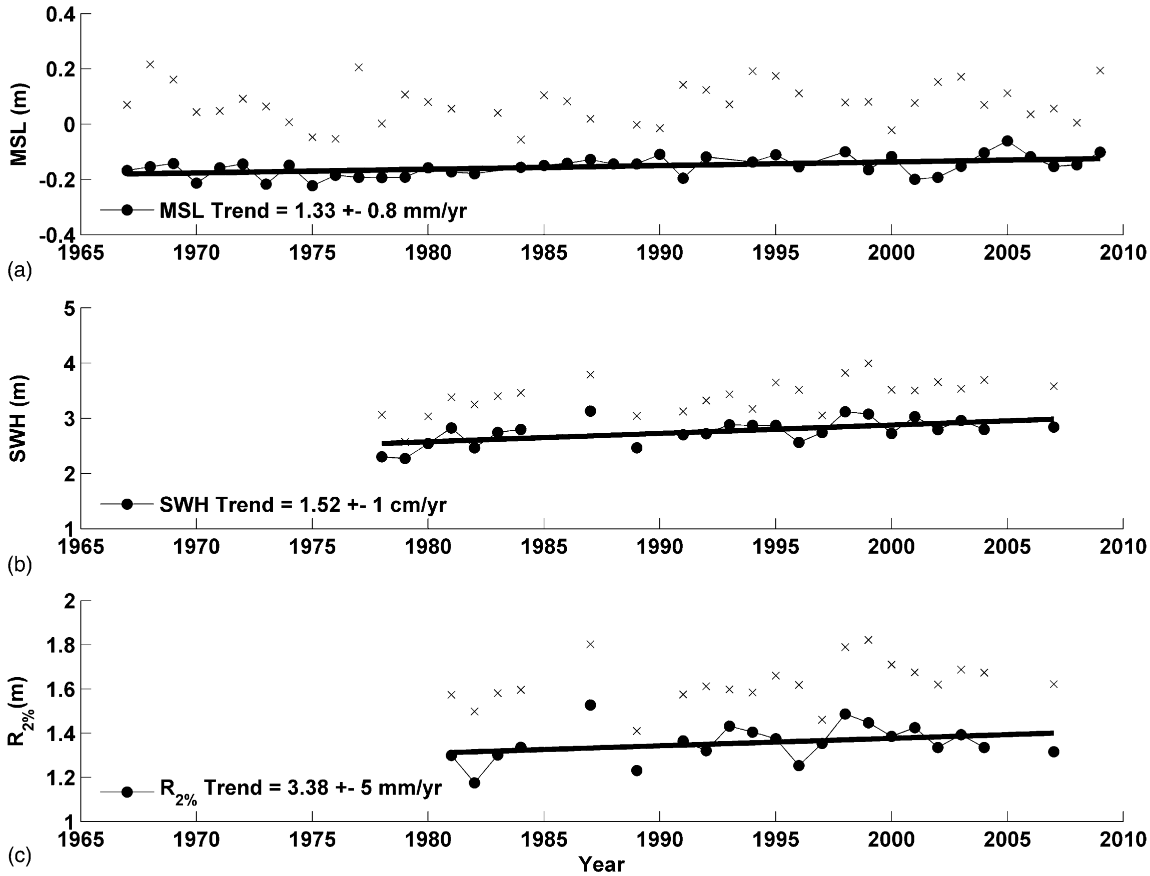


**Fig. 1.** (a) Trends and variations in summer average (solid line) and winter average (symbols only) RSLs for the Yaquina Bay tide-gauge record; (b) trends and variations in annual average significant wave heights (solid line) and winter average wave heights (symbols only) from NDBC Buoy 46005; (c) trends and variations in annual average (solid line) and winter average (symbols only) 2% exceedance wave runup values computed using Eq. (2) and a representative foreshore beach slope of 0.05

shallower sloping dissipative beaches. For a given beach slope, the average number of IHPY decreases with increasing BF elevation (Fig. 4). For example, for a representative beach slope of 0.05 the TWL modeling approach suggests that water levels exceeded an elevation of 6 m (relative to the approximate mean lower low water) only about 5 h/year while reaching 4 m more than 600 h/year during the representative decade centered on 2000.

Once the current conditions are known, both SLR and various projections of continued increases in storminess can be incorporated directly into the representative 10-year TWL time series yielding predictions of the expected future increase in the probability of flooding/erosion events. In Fig. 5, the percent increase in IHPY as a result of RSLR only is computed for a range of possible future conditions. Here, the RSLR projections can be thought of either as a range of possible changes by a certain time period, say by 2025 (25 years from year 2000), or simply a magnitude of change not associated with a particular time frame but one that may eventually be reached. Recent projections of multidecadal SLR magnitudes (Bindoff et al. 2007; Rahmstorf 2010) of approximately 0.1–0.2 m, assuming the Intergovernmental Panel on Climate Change's (IPCC) A1B Special Report on Emissions Scenarios (SRES) climate scenario and a stationary wave climate, would result in an increase in IHPY between 20 and 140%, depending on the elevation of the backing feature (shown in Fig. 5 for a beach slope of 0.05). The IPCC A1B scenario describes a more integrated world characterized by rapid economic growth, technological innovation, increased globalization, and a balance across energy sources such that the reliance is not solely on fossil fuels (Nakicenovic et al. 2000). These curves shift downward for higher sloping beaches and upward for lower sloping beaches where the relative effect of SLR is more important. More extreme estimates of multidecadal sea level change, up to as much as 0.5 m (Fig. 5), could cause an increase in IHPY of as much as 100–400%.

While uncertain, the ability to predict RSLR is more advanced than the ability to predict future trends in wave climate. Therefore, a simple assumption is first made that the linear rate of increase observed in the wave height record will continue and the predictions are restricted to 25 years from the midpoint of the 10-year time series (2000–2025). Because the storms responsible for the highest wave runup events occur during the winter it is important to distinguish between the rates of increase of waves as a function of season. Applying the same analysis techniques employed to create Fig. 1(b) to just the winter (summer) wave heights and periods, it is found that their rates of increase are 0.024 m/year (0.013 m/year) and 0.0072 s/year (0.0214 s/year), respectively. As previously described, the rate of increase in wave heights is, in fact, dependent on the exceedance percentile of the SWH CDF. Therefore, the most appropriate method for incorporating predicted increases in wave heights into the 10-year TWL time series is as a function of exceedance percentile. Here, the CDF is discretized into 1% probability bins and the rate of increase for each bin is computed.



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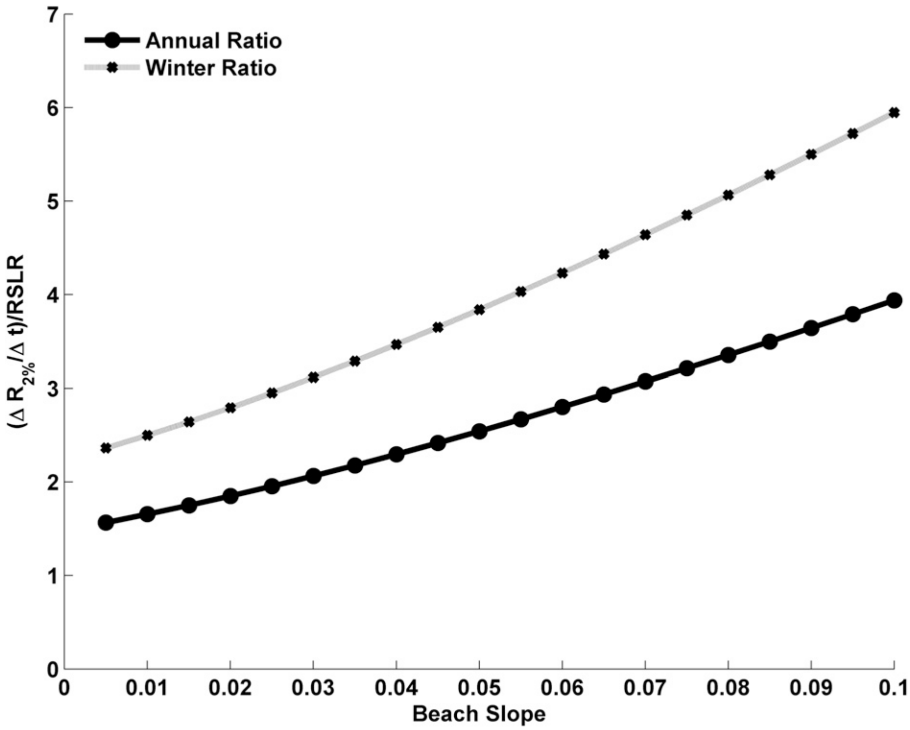


**Fig. 2.** Ratio of the annual average time rate of change in wave runup [computed using NDBC 46005 wave data and Eq. (2)] versus RSLR (from the Yaquina Bay tide gauge) as a function of average foreshore beach slope (dashed line is the ratio of winter average runup change rate versus RSLR)

Waves that are exceeded only 1% of the time in any given year have increased by a rate of approximately 4.3 cm/year.

Fig. 6 illustrates the impact of both a range of RSLR and a continued increase in the intensity of the wave climate on the frequency with which the TWL exceeds various backshore elevations. It is clear that the impact of the combination of RSLR and increasing waves is significantly different from that with RSLR alone (Fig. 5). The relative importance of increasing wave heights and periods depends on the magnitude of the RSL change, foreshore beach slope, elevation of the backing feature, and the method by which the wave height increases are incorporated into the TWL time series (Fig. 7). For RSLR magnitudes of up to 0.15 m by 2025, increasing wave heights contribute more to the increase in IHPY than does SLR. Wave heights become relatively more important with increasing beach slopes and increasing BF elevations. Incorporating the increase in wave heights as a function of exceedance percentile has a more significant impact than simply incorporating seasonal or annual increases into the wave height time series (Fig. 7).

Fig. 7 indicates that a RSLR of between 0.15 and 0.3 m would be more important than wave height increases by approximately 2025. While wave height increases were incorporated using a variety of approaches, in each case the rate of increase was similar to that observed in the recent historical time period. In Fig. 8 the RSLR value that will have equal impact on changes to IHPY as increasing wave heights is computed for a variety of changes in the rate of increase in waves. The rate of increase is varied between 20 and 200% of the observed values.

## Discussion

The objective of this paper has been to develop a primary impression of the roles of the various climate controls on coastal hazards, particularly SLR versus increasing wave heights, and to assess their relative importance along the PNW coast with its variability in land elevation changes. Based on approximately 30 years of recorded waves and tides, and good documentation of the morphologies of PNW beaches, it has been possible to model these relative impacts for any combination of SLR, VLM, or projected increases in storminess and generated waves through assessments of the TWLs from the combined processes. However, this simple approach suffers from two primary limitations. First, the analyses have not accounted for morphological feedbacks; e.g., the toe of the BF is not adjusted to a new equilibrium elevation under changing sea level and erosion by waves. The significance of excluding this negative feedback depends on the resistance of the backshore to erosion. The toe elevation of sea cliffs composed of resistant rock (or shore protection structures) may have a considerable lag in its response to increased impacts, whereas IHPY at the toe of retreating sand dunes may remain approximately constant over the long term in a condition of dynamic equilibrium. Regardless of whether these contrasting erosional responses had been included in the analyses, the quantification of the increase in IHPY can be thought of as a proxy for this retreat, and therefore still represents an enhancement of coastal vulnerability. A second limitation in the approach is the scientific community's present lack of ability to predict either SLR or the behavior of regional wave climates over the coming decades without significant uncertainty. Here, a likely conservative approach has been taken by simply extrapolating historical rates into the future. As knowledge of the physics responsible for these climate controls increases, analyses like these can be refined.

Changes to the TWL are just one way in which increasing wave heights (and periods) impact coastal hazards. Volumetric sediment transport rates are often formulated as nonlinear functions of wave height (Komar 1998a, b), and therefore small increases in wave heights can have significant impacts on transport rates, gradients in transport rates, and resulting morphological changes. Slott et al.



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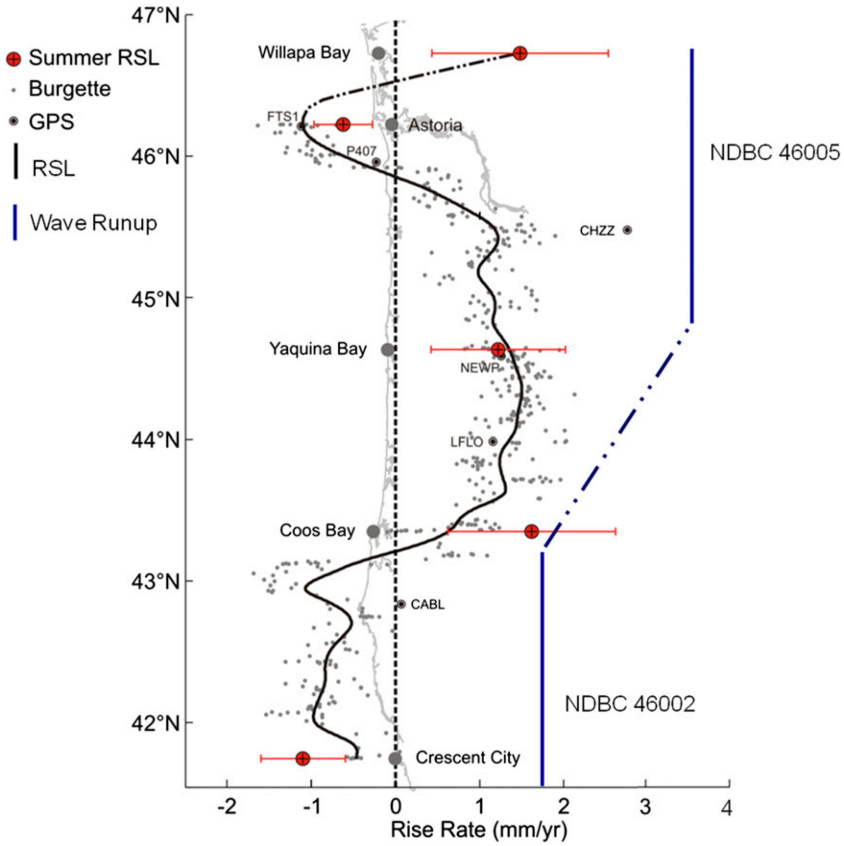


**Fig. 3.** Alongshore variability of rate of change of wave runup [computed using the wave data from NDBC Buoys 46005 and 46002, Eq. (2), and a foreshore beach slope of 0.05] versus RSLR for the Oregon coast; assessments of changes in RSLs are based on tide-gauge records compared with benchmark and GPS measurements of land-elevation changes (after Burgette et al. 2009), with their corresponding RSL rates obtained by adding 2.28 mm/year as an estimate of the regional PNW rise in sea level (modified from Komar et al. 2011)

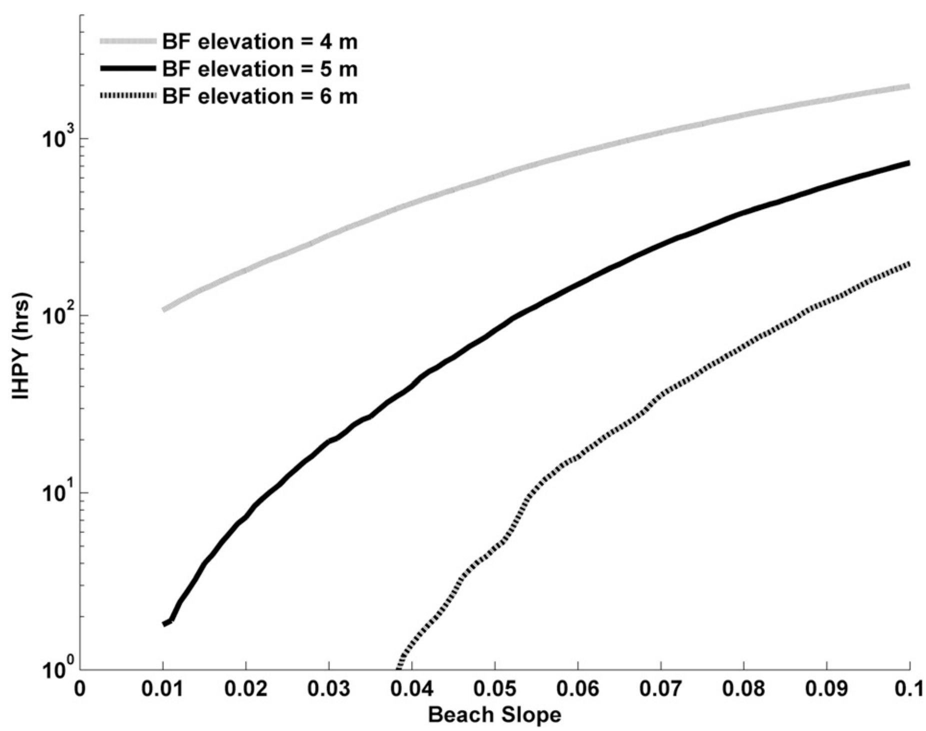


**Fig. 4.** IHPY of the TWL for a range of foreshore beach slopes and three BF elevations (e.g., sea cliff toe or dune crest elevation)



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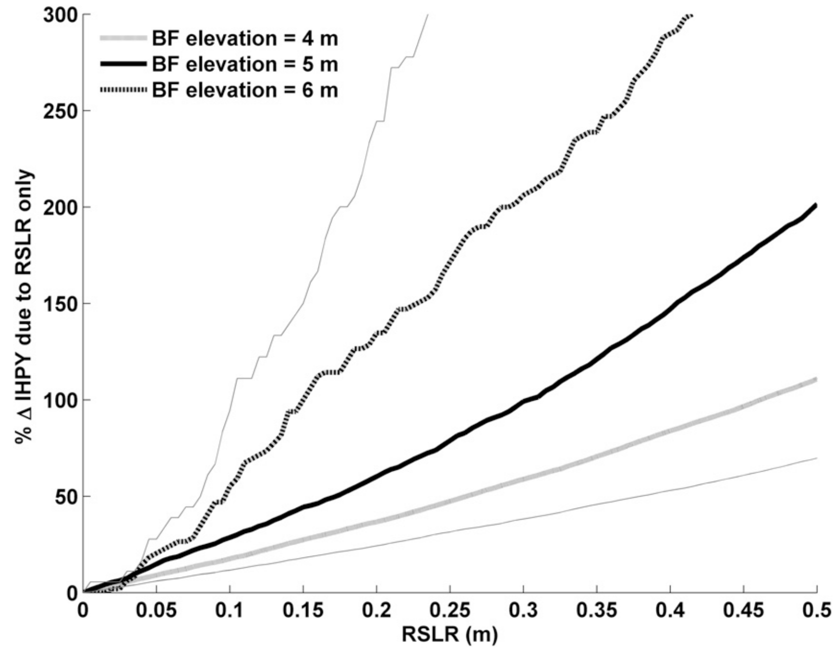


**Fig. 5.** Percent increase in IHPY as a result of SLR only relative to approximately year 2000 for a range of RSLR magnitudes and three BF elevations; thick lines show computations for a beach slope of 0.05, whereas the thin black lines show the influence of various beach slopes for BF = 5 m (higher line for slope = 0.01 and lower line for slope = 0.1)

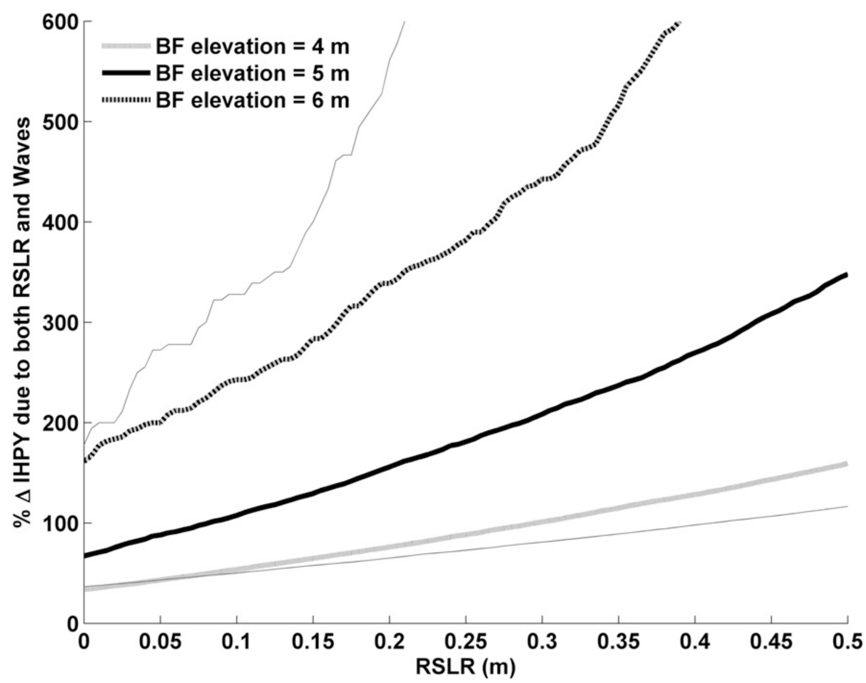


**Fig. 6.** Percent increase in IHPY as a result of both SLR and wave height increases relative to approximately year 2000 for a range of RSLR magnitudes and three BF elevations; thick lines show computations for a beach slope of 0.05, whereas the thin black lines show the influence of various beach slopes for BF = 5 m (higher line for slope = 0.01 and lower line for slope = 0.1)

(2006) found that moderate shifts in storminess patterns and the subsequent effect on wave climates could increase the rate at which shorelines recede or accrete to as much as several times the recent historical rate of shoreline change. On complex-shaped coastlines, including cuspate-cape and spit coastlines, they found that the alongshore variation in shoreline retreat rates could be an order of magnitude higher than the baseline retreat rate expected from SLR alone over the coming century.

Working on a straight, sandy coastline just north of the Columbia River, Ruggiero et al. (2010a) applied a deterministic one-line



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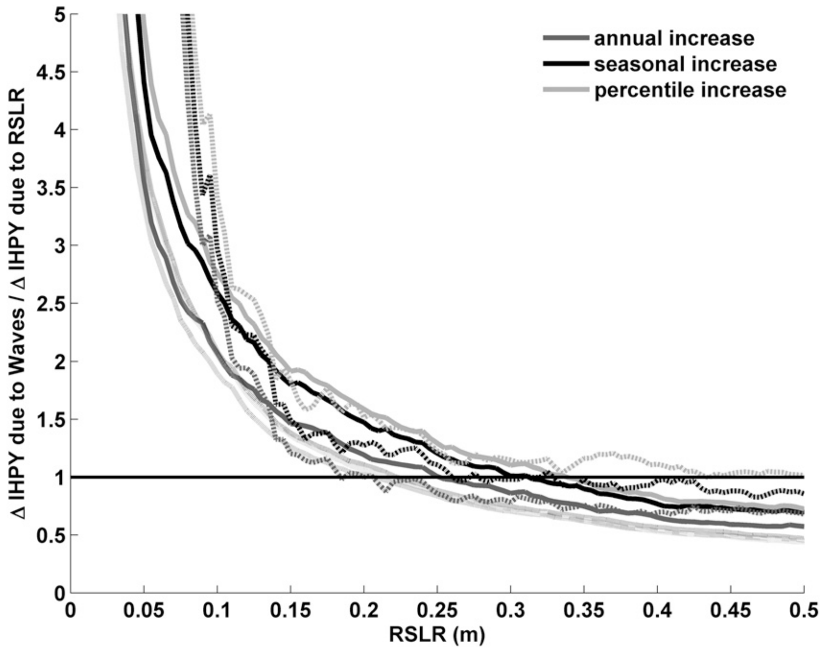


**Fig. 7.** Ratio of the increase in IHPY as a result of wave height changes only to IHPY increases owing to SLR only for a range of SLR scenarios by approximately 2025 (relative to 2000) and three BF elevations (line types same as in Fig. 6); dark gray lines represent annual increases in wave heights incorporated into the TWL, whereas the black lines represent inclusion of seasonal trends and the light gray lines represent rates of increase of various percentiles, respectively

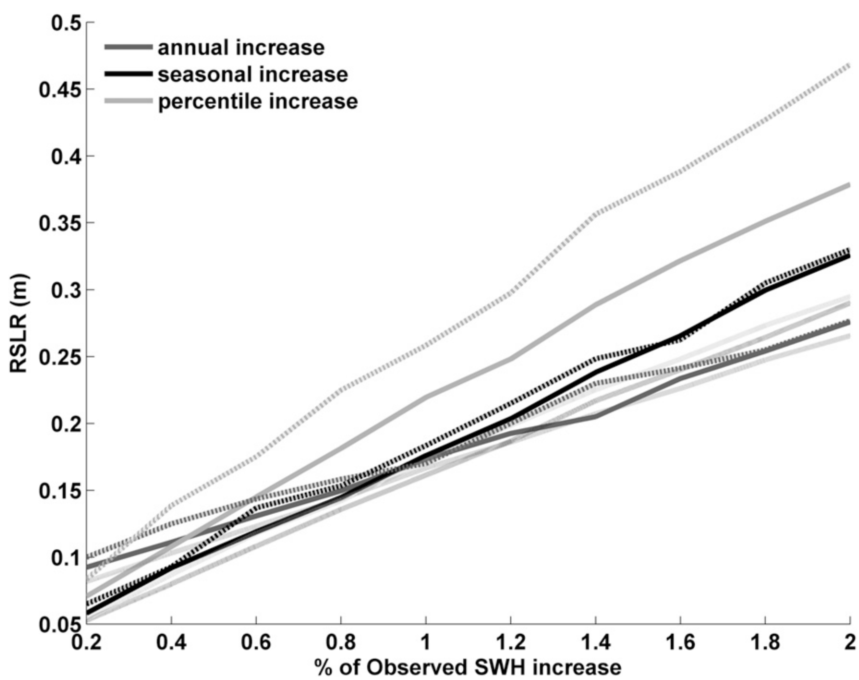


**Fig. 8.** RSLR magnitude that would have the same impact on IHPY as wave height increases for a range of possible future wave climates; the wave climate is allowed to vary between 20 and 200% of observed recent historical rates; line symbols and shading represent the same combinations of BF elevations and approach for inclusion of wave height increases into the TWL as in Figs. 6 and 7

shoreline change model in a quasi-probabilistic manner to test the effects of both wave climate and sediment supply variability on decadal-scale hindcasts and forecasts. Although their modeling exercises indicated that shoreline change is most sensitive to changes in wave direction, the effect of an increasingly intense future wave climate was significant. A wave climatology incorporating increasing winter wave heights and periods resulted in as much as 100 m more erosion than a baseline prediction in which the wave climate remained stationary. As with the TWL modeling, the magnitude of these differences depended on whether the increase in the severity of wave conditions is distributed evenly throughout the entire year or enhanced during the winter storm season. To achieve the same magnitude of additional shoreline change caused by increasing wave heights, approximately 100 m, a simple Bruun rule calculation (Bruun 1962) indicates that sea level would have to rise over 0.5 m by approximately 2025.

## Conclusions

The primary outcome of this work is a direct assessment of the relative contributions of various climate controls on coastal exposure to high water levels. Over the historical period of observations (since the early 1980s), the buoy-measured increases in deepwater wave heights and periods have been more responsible for increasing the frequency of coastal erosion and flooding events along the PNW coast than changes in sea level. Although this is true for stretches of the PNW coast in which RSL change is approximately the same as global SLR (north-central Oregon coast), trends in wave-induced processes have been potentially more important along the southern Oregon coast where VLMs are significant. Under a range of future multidecadal climate change scenarios, increasing storm wave heights may continue to increase the probability of coastal flooding/erosion more than SLR-induced changes alone. The combination of each of these climate controls on the TWL occurring simultaneously could cause an increase of as much as a factor of 5 in the erosion/flood frequency over the coming decades.

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