# Is the intensifying wave climate of the U.S. Pacific Northwest increasing flooding and erosion risk faster than sea level rise?

**Peter Ruggiero**[1]

[1]*College of Earth, Oceanic, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA;* voice: 541-737-1239, fax: 541-737-1200, *ruggierp@geo.oregonstate.edu*

## Abstract

The relative contributions of sea level rise (SLR) and increasing extra-tropical 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 (PNW) over the period of wave-buoy observations (~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 mean sea level, increasing wave heights results in these stretches of coast being possibly submergent relative to the TWL. While 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.

**Key words:** coastal erosion; coastal flooding; coastal hazards; Oregon; Pacific Northwest; sea level rise; storminess; total water level; vertical land motions; wave height increases

## *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 re-evaluate 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 (e.g., 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 (e.g., Nichols and Tol, 2006).

A second important phenomenon that has been speculatively linked to (e.g., Graham and Diaz, 2001; Seymour, 2011), but not formally attributed to (e.g., 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 et al. (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 (SWH) 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 NOAA buoys along the U.S. and Canadian West Coast (Allan and Komar, 2000, 2006; Mendez et al., 2006, Menendez et al., 2008a; Ruggiero et al., 2010a, Seymour, 2011) and from satellite altimetry (Young et al., 2011). Analyses by climatologists of North Pacific extra-tropical 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 mid-20th century, earlier than could be documented with the direct measurements of the waves by buoys.

The results of studies relying solely on buoy measurements have, however, 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 trends for the corrected data are smaller than the apparent trends obtained from the uncorrected data. Of interest, the most significant of the non-climatic step changes in the buoy records occurred prior to the mid 1980s. Menendez 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 earlier in the buoy records. Application of their time-dependent extreme value model to SWHs showed significant positive long-term trends in the extremes between 30–45° N near the western coast of the US. Mendez 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 conclude that the extreme wave climate in the NE Pacific is increasing in the period 1948-2008 at a rate of about 1 cm/yr (using reanalysis data) and 2-3 cm/yr in the period 1985-2007 (using buoy data).

Research on trends in mid-latitude extra-tropical storms in the Eastern North Pacific have confirmed that there has been an increase in storm intensity, but has documented a decrease in storm frequency, possibly since storm tracks have shifted poleward during the latter half of the 20th 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-medium strength variety, while the stronger storms have actually increased in frequency. Young (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 due to changes in baroclinicity, which in turn has been linked to changes in atmospheric temperature distributions due to 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. Though 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.

While the exact cause of the increasing wave heights in portions of the Northeast Pacific is still uncertain, the impacts of this phenomenon, particularly in regards to assessments of coastal hazards along the west coast of North America, remain largely uninvestigated. In this paper we quantitatively test the hypothesis that over the historical record (~the last 30 years) 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 extra-tropical 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 non-tidal factors that alter the measured tides from those predicted (most important in the PNW being elevated tides 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

$$TWL = \mathbf{MSL} + \eta_A + \eta_{NTR} + \mathrm{R} \tag{1}$$

where MSL is the local mean sea level (which can be treated as either a constant tidal datum or as a variable with a rate of change), $\eta_A$ is the astronomical tide, $\eta_{NTR}$ is the non-tidal residual (NTR) water level, and $R$ is the vertical component of the wave runup which includes both the wave setup (a super elevation of the water level due to wave breaking) and swash oscillations around the wave setup. Here we employ an extreme wave runup statistic, $R_{2\%}$ (e.g., Holman, 1986), the two percent exceedance value of wave runup maxima, since it is the highest swash events in a wave runup distribution that are initially responsible for erosion and overtopping. Simple empirical formulae 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

$$R_{2\%} = 1.1\left( .35\tan\beta(H_0 L_0)^{1/2} + \frac{\left[H_0 L_0 (0.563\tan\beta^2 + 0.004)\right]^{1/2}}{2} \right) \quad (2)$$

relates deep-water wave characteristics and beach morphology to wave runup on the beach; where *tanβ* is the foreshore beach slope, $H_0$ is the deep-water significant wave height, $L_0$ is the deep-water wave length, given by Airy (linear) wave theory as $(g/2\pi)T^2$ where $g$ is the acceleration of gravity and $T$ is the spectral peak wave period. Being the most widely applicable available formula for wave runup (rmse = 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, 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 interannual- to decadal-scale (e.g., Ruggiero et al., 2001, Collins and Sitar, 2008, Hapke and Plant, 2010), dune erosion at annual scale, and event-scale dune response to hurricanes along the U.S. Gulf and Atlantic coasts (e.g., 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

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

where $\frac{\Delta MSL}{\partial t} = RSLR = SLR_G + SLR_R + VLM_R$ and RSLR is the local relative sea level rise rate. RSLR can be either positive or negative as it combines the rate of vertical water motions due to global processes ($SLR_G$, e.g., increased water temperatures and melting glaciers and ice caps), regional processes that cause variations from the global mean ($SLR_R$, e.g., changes to earth's gravitational field), and vertical land motions ($VLM_R$, e.g., local tectonics, isostasy, and compaction). While there is some evidence indicating that the range of astronomical tides may be evolving (e.g., Flick et al., 2003), of the terms in Eq. 3 both $\frac{\Delta \eta_A}{\Delta t}$ and the $VLM_R$ component of 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) but also including effects of local water density variations and coastal trapped waves (e.g., Enfield and Allan, 1980). Climate-induced changes in any of these processes could lead to measurable changes in local water levels observed at tide gages. While this meteo-oceanographic 'noise' is often minimized in tide gage analyses meant to assess regional or global SLR rates, here we are interested in trends in local TWLs and $\frac{\Delta \eta_{NTR}}{\Delta t}$ is treated as a component of $SLR_R$ and subsumed within long-term estimates of RSLR. Therefore, the time rate of change of the TWL achieved on beaches can be simplified to being primarily a function of RSLR as directly determined from tide gages and the rate of change of offshore wave characteristics (significant wave height (SWH) and peak period), for particular beach morphology, via 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 (e.g., Allan and Komar, 2006, Mendez et al. 2006, Ruggiero et al., 2010a), the increase in wave characteristics off the PNW is first documented with data from National Data Buoy Center (NDBC) 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. Computed RSLR rates are based on the measured tide levels from various National Ocean Service (NOS) tide gage records, and recent investigations have derived updated and improved values for trends in the 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 are 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 1 July 1994 to 30 June 2004, has been constructed using the methods developed by Allan and Ruggiero (2010) and Harris (2011). Data gaps in NDBC wave buoy #46005 are 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 are simply added to hourly measured water levels from NOS tide gage 9435380 in Yaquina Bay, OR to generate hourly estimates of the TWL. The average number of hours per year (impact hours per year, hereinafter 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 (e.g., Ruggiero et al., 2001). The 10-year time period used to compute this proxy includes the major El Niño of 1997/1998 (Komar, 1998; 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 following sections the primary components comprising the TWL during the recent historical period, captured by wave buoy and tide gage observations, are first compared and contrasted. Next, the relative influence of possible SLR and increasing storminess on predictions of future risk of coastal flooding and erosion is explored.

### Historical changes in TWL

Variations in VLM rates along the PNW coast due to its tectonic setting (e.g., Burgette et al., 2009) result in along-coast variations in rates of 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 multi-decadal PNW RSLR, Komar et al. (2011) found that the Crescent City, CA tide gage is experiencing a RSLR rate of approximately -1.1 ± 0.50 mm/yr. Along the central to northern Oregon coast sea level is rising relative to the land, for example, the Yaquina Bay, OR tide gage is experiencing approximately 1.33 ± 0.79 mm/yr of RSLR (Figure 1, top panel). Along the Oregon/Washington border the Astoria, OR tide gage suggests emergence, while at the Toke Point, WA tide gage, about 50 km north of the Columbia River, sea level is again rising relative to land at a rate of 1.48 ± 1.05 mm/yr, similar to the rate documented for the Yaquina Bay, OR tide gage.

Ruggiero et al. (2010a) found that at NDBC wave buoy #46005 the annual average SWH is increasing at rate of 1.5 ± 1 cm/yr (Figure 1, middle panel). Of more concern in regards to coastal hazards, winter waves observed at this buoy are increasing at a rate of 2.3 ± 1.4 cm/yr. In fact, the rate of increase of the wave climate depends on the exceedance percentile of the SWH cumulative distribution function (CDF) as the bigger waves are getting bigger faster. Annual averaged spectral peak wave periods have been increasing at a rate of approximately 0.015 seconds per year.

Of importance, when wave height and period are combined to compute wave runup (Eq. 2), a direct comparison can be made between the sea level and wave induced components of the TWL at multi-decadal scale. Figure 1 (bottom panel) illustrates that the long-term trend in annual mean wave runup, using a representative PNW foreshore beach slope of 0.05 (1V:20H), is approximately 3.4 mm/yr. The early part of NDBC wave buoy #46005's record, as called into question by Gemmrich et al., 2011, is not used in this calculation of trends in runup as wave period was not recorded by the buoy until the early 1980s (Figure 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 multi-decadal 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 Figure 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 six times more important than RSLR during the recent historical period. Allowing beach slopes to vary seasonally (Ruggiero et al., 2005) has little impact on the results presented in Figure 2 (not shown).

Performing the same set of analyses as described above 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 (~1.8 mm/yr) during the observational record. Therefore while the coastline is emergent relative to processes that affect local mean sea level, this southern stretch of the PNW may in fact be submergent relative to the TWL due to the impact of an increasing wave climate. Figure 3 conceptually illustrates the magnitude and alongshore variability of both RSLR and the 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 RSLR.

### *Predicting future changes in TWL*

To assess the relative impacts of continued wave height increases and SLR on future flood probability and erosion potential along the PNW coast, I first compute how often TWLs impact the backshore (e.g., the toe of a sea cliff) under 'present' conditions (Figure 4). The proxy IHPY computed using the 10-year TWL time series described above depends on the foreshore beach slope and on the elevation of the backshore feature of interest. Due to the wave runup dependence on foreshore beach slope, the model predicts higher values of IPHY for steep intermediate to reflective beaches than for shallower sloping dissipative beaches. For a given beach slope, the average number of IHPY decreases with increasing backshore feature elevation (Figure 4). For example, for a representative beach slope of 0.05 our TWL modeling approach suggests that water levels exceeded an elevation of 6 m (relative to ~ Mean Lower Low Water) only about 5 hours per year while reaching 4 m over 600 hours per year during the representative decade centered on 2000.

Once present 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 Figure 5, the percent increase in IHPY due to 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 multi-decadal SLR (Bindoff et al., 2007, Rahmstorf, 2010) magnitudes of approximately 0.1 m to 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 of between 20% to 140%, depending on the elevation of the backing feature (shown in Figure 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 so that we are not solely reliant 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 multi-decadal sea level change, up to as much as 0.5 m (Figure 5), could cause an increase in IHPY of as much as 100% to 400%.

While uncertain, our ability to predict RSLR is more advanced than our ability to predict future trends in wave climate. Therefore, we first make the simple assumption that the linear rate of increase observed in the wave height record will continue and we restrict our predictions to 25 years from the midpoint of our 10 year time series (2000 to 2025). Since 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 Figure 1 (middle panel) to just the winter (summer) wave heights and periods, it is found that their rates of increase are respectively 0.024 m/yr (0.013 m/yr) and 0.0072 s/yr (0.0214 s/yr). As described above, 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 we discretize the CDF into 1% probability bins and compute the rate of increase for each bin. Waves that are exceeded only 1% of the time in any given year have increased by a rate of approximately 4.3 cm/yr.

Figure 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 than that with RSLR alone (Figure 5). The relative importance of increasing wave heights and periods depends on the magnitude of

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 (Figure 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 backshore feature elevations. Incorporating the increase in wave heights as a function of exceedance percentile has a more significant impact than simply incorporating seasonal increases or annual increases into the wave height time series (Figure 7).

Figure 7 indicates that a RSLR of between 0.15 m 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 Figure 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% of 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 documentations 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 via 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 backshore feature 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 while IPHY at the toe of retreating sand dunes may remain approximately constant over the long term in a condition of dynamic equilibrium. Regardless of whether or not 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 representing 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 I have taken what is likely a conservative approach 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, 1998) 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. (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 sea level rise alone over the coming century.

Working on a straight, sandy coastline just north of the Columbia River, Ruggiero et al. (2010b) applied a deterministic one-line 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. While 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 deep-water 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. While 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 multi-decadal 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 as much as a factor of five increase in erosion/flood frequency over the coming decades.

## ***Acknowledgements***

The author gratefully acknowledges the support of NOAA's Sectoral Applications Research Program (SARP) under NOAA Grant# NA08OAR4310693 and NOAA's National Sea Grant College Program under NOAA Grant's #NA06OAR4170010.

## **References**

Allan, J.C. and Komar, P.D., 2000. Are ocean wave heights increasing in the eastern North Pacific? *EOS, Trans. AGU*, 47, 561-567.

Allan, J. C. and P. D. Komar. 2002. Extreme storms on the Pacific Northwest Coast during the 1997-98 El Niño and 1998-99 La Niña. Journal of Coastal Research, 18, 175-193.

Allan, J. C., and P.D. Komar, 2006. Climate controls on US West Coast erosion processes: *J. Coastal Res.*, 22, 511-529.

Allan, J.C., Ruggiero, P., and Roberts, J., 2010. Coastal Flood Insurance Study, Coos County, Oregon, Oregon Department of Geology and Mineral Industries Report to the Federal Emergency Management Agency, Portland, Oregon, 131 pp.

Bacon, S. and Carter, D. J. T., 1991. Wave climate changes in the North Atlantic and North Sea, *Int. J. of Climatol.*, 11, 545-558.

Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan, 2007. Observations: oceanic climate change and sea level. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Avery, M. Tignor, and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, UK and New York, pp. 385-432.

Bruun, P. 1962. Sea-level rise as a cause of shore erosion.  Journal of Waterways Harbors Division, American Society of Civil Engineers, 88, 117-130.

Burgette, R.J., Weldon, R.J II, and Schmidt, D.A, 2009. Interseismic uplift rates for western Oregon and along-strike variation in locking on the Cascadia subduction zone, *J. Geophys. Res.*, 114, B01408, doi:10.1029/2008JB005679.

Carter, D., and L. Draper, 1988. Has the north-east Atlantic become rougher?, *Nature*.

Church, J. A., and N. J. White, 2006. A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

Collins, B. and Sitar, N., 2008. Processes of coastal bluff erosion in weakly lithified sands, Pacifica, California, USA, *Geomorphology*, 97, 483-501.

Enfield, D.B., and Allan, J.S., 1980. On the structure and dynamics of monthly mean sea level anomalies along the Pacific coast of North and South America, J. Phys. Oceanogr., 10, 557-578.

Favre, A., and A. Gershunov. 2006. Extra-tropical cyclonic/anticyclonic activity in North-Eastern Pacific and air temperature extremes in Western North America. Climate Dynamics, 26, 617–629.

Flick, R.E., Murray, J.F., and Ewing, L.C., 2003. Trends in United States Tidal Datum Statistics and Tide Range. J. Waterway, Port, Coastal, Ocean Eng. 129, 155, doi:10.1061/(ASCE)0733-950X(2003)129:4.

Gemmrich, J., Thomas, B., and Bouchard, R., 2011. Observational changes and trends in northeast Pacific wave records, Geophysical Research Letters, 38, L22601, doi:10.1029/2011GL049518.

Geng, Q., and Sugi, M. 2003. Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols: Study with a high-resolution AGCM, J. Clim., 16, 2262–2274.

Graham, N.E., and H.F. Diaz, 2001. Evidence for intensification of North Pacific winter cyclones since 1948: *Bulletin of the American Meteorological Society*, 82, 1869-1893.

Hapke, C. and Plant, N, 2010. Predicting coastal cliff erosion using a Bayesian probabilistic model, Marine Geology, 278, 140-149, doi:10.1016/j.margeo.2010.10.001.

Harris, E.L., 2011. Assessing physical vulnerability of the coast in light of a changing climate: An integrated, multi-hazard, multi-timescale approach, unpublished MS thesis, Oregon State University, Corvallis, OR, 77 pp.

Holman, R.A., 1986. Extreme value statistics for wave run-up on a natural beach, *Coast. Eng.*, 9, 527-544.

Kaminsky, G., Ruggiero, P. and Gelfenbaum, G., 1998. Monitoring coastal change in Southwest Washington and Northwest Oregon during the 1997/98 El Niño, *Shore and Beach*, 66 (3), 42-51.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nature Geoscience*, *3*(3), 157–163, doi:10.1038/ngeo779.

Komar, P. D.  1998.  The 1997-98 El Niño and erosion of the Oregon coast.  Shore & Beach, 66, 33-41.

Komar, P.D., 1998. Beach processes and sedimentation, Second edition, Prentice Hall, Saddle River, N.J., 544 pp.

Komar, P.D., Allan, J.C., and Ruggiero, P., 2011. Sea level variations along the US Pacific Northwest coast: tectonic and climate controls, *Journal of Coastal Research*, (27) 5, 808-823, DOI:10.2112/JCOASTRES-D-10-00116.1.

McCabe, G. J., M. P. Clark, and M. C. Serreze.  2001.  Trends in northern hemisphere surface cyclone frequency and intensity.  Journal of Climate, 14, 2763–2768.

Méndez, F.J., Menéndez, M., A. Luceno, and I. J. Losada, 2006. Estimation of the long-term variability of extreme significant wave height using a time-dependent Peak Over Threshold (POT) model, *J. Geophys. Res.*, 111, C07024, doi:10.1029/2005JC003344.

Mendez, F. J., M. Menendez, A. Luceno, and I. J. Losada, 2006. Estimation of the long-term variability of extreme significant wave height using a time-dependent Peak Over Threshold (POT) model, *J. Geophys. Res*., 111, C07024, doi:10.1029/2005JC003344.

Menéndez, M., Méndez, F.J., Losada, I. J., and Graham, N.E., 2008. Variability of extreme wave heights in the northeast Pacific Ocean based on buoy measurements, *Geophys. Res. Lett*, *35*(22), doi:10.1029/2008GL035394.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, N. Nakicenovic and R. Swart (eds). Cambridge University Press, Cambridge, United Kingdom, 570 pp.

National Data Buoy Center (NDBC), 2008. National Data Buoy Center, National Oceanographic and Atmospheric Administration. http://seaboard.ndbc.noaa.gov/ (accessed April 1, 2008).

Nichols, R.J. and Tol, R.S.J., 2006. Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century, *Phil. Trans. R. Soc. A*, doi: 10.1098/rsta.2006.1754, 364 (1841), 1073-1095.

National Ocean Service (NOS), 2009. NOAA Tides and Currents: Center for Operational Oceanographic Products and Services. http://www.co-ops.nos.noaa.gov/ (accessed

April 1, 2010).

Rahmstorf, S., 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise *Science*, 315 (5810), DOI: 10.1126/science.1135456.

Rahmstorf, S. 2010. A new view on sea level rise. Nature, 4, 44-45.

Ruggiero, P., Komar, P.D., McDougal, W.G. and Beach, R.A., 1996. Extreme water levels, wave runup, and coastal erosion, *Proceedings 25th Coastal Engineering Conference, ASCE*, 2793-2805.

Ruggiero, P., Komar, P.D., McDougal, W.G., Marra, J.J., and Beach, R.A., 2001. Wave runup, extreme water levels and the erosion of properties backing beaches, *J. Coastal Res.*, 17(2), 407-419.

Ruggiero, P., Holman, R.A., and Beach, R.A., 2004. Wave runup on a high-energy dissipative beach, *Journal of Geophysical Research*, Vol. 109, C06025, doi:10.1029/2003JC002160, 2004.

Ruggiero, P., Kaminsky, G.M., Gelfenbaum, G., and Voigt, B., 2005. Seasonal to interannual morphodynamics along a high-energy dissipative littoral cell, *Journal of Coastal Research*, 21(3), 553-578.

Ruggiero, P., Komar, P.D., Allan, J.C., 2010a. Increasing wave heights and extreme-value projections: the wave climate of the U.S. Pacific Northwest, *Coastal Engineering*, 57, 539-552, doi:10.1016/j.coastaleng.2009.12.005.

Ruggiero, P., Buijsman, M.C., Kaminsky, G., and Gelfenbaum, G., 2010b. Modeling the effect of wave climate and sediment supply variability on large-scale shoreline change, *Marine Geology*, 273, 127-140, DOI:10.1016/j.margeo.2010.02.008.

Sallenger, A. H. 2000. Storm impact scale for barrier islands. Journal of Coastal Research 16:890-895.

Seymour, R.J., 2011. Evidence for Changes to the Northeast Pacific Wave Climate Journal of Coastal Research, 27(1), 194-201, DOI: 10.2112/JCOASTRES-D-09-00149.1

Slott, J.M., Murray, A.B., Ashton, A.D., Crowley, T.J., 2006. Coastline responses to changing storm patterns, Geophys. Res. Lett., 33, 33(L18404): DOI0.1029/2006GL027445.

Stockdon, H.F., R.A. Holman, P.A. Howd, and A.H. Sallenger, 2006. Empirical parameterization of setup, swash, and runup, *Coast. Eng.*, 53(7), pp. 573-588.

Stockdon, H.F., Sallenger, A.H., Holman, R.A., and Howd, P.A., 2007. A simple model for the spatially-variable coastal response to hurricanes, *Mar. Geol*., 238, 1-20.

Wang, X.L., Zwiers, F.W., and Swail, V.R. (2004). " North Atlantic ocean wave climate change scenarios for the twenty-first century". J. Climate, 17, 2368-2383.

Wang, X.L. and Swail, V.R. (2006). " Climate change signal and uncertainty in projections of ocean wave heights". Climate Dyn., 26, 109-126.

Yin, J. H. 2005. A consistent poleward shift of the storm tracks in simulations of 21st century climate, Geophysical Research Letters, 32, L18701.

Young, I.R., Zieger, S., and Babanin, A.V., 2011. Global trends in wind speed and wave height, *Science* 332, 451, DOI: 10.1126/science.1197.

Figure1
Click here to download high resolution image

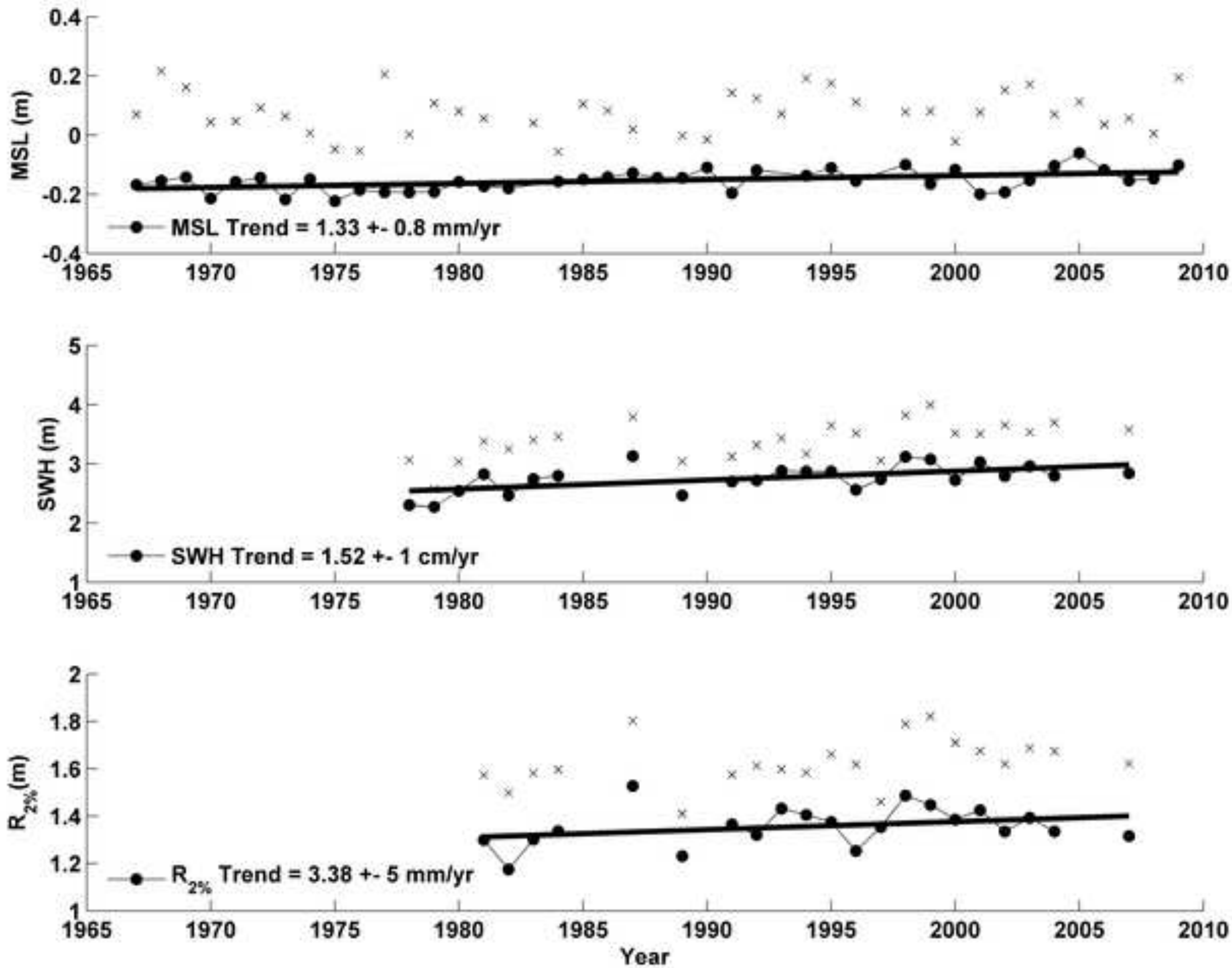


Figure2



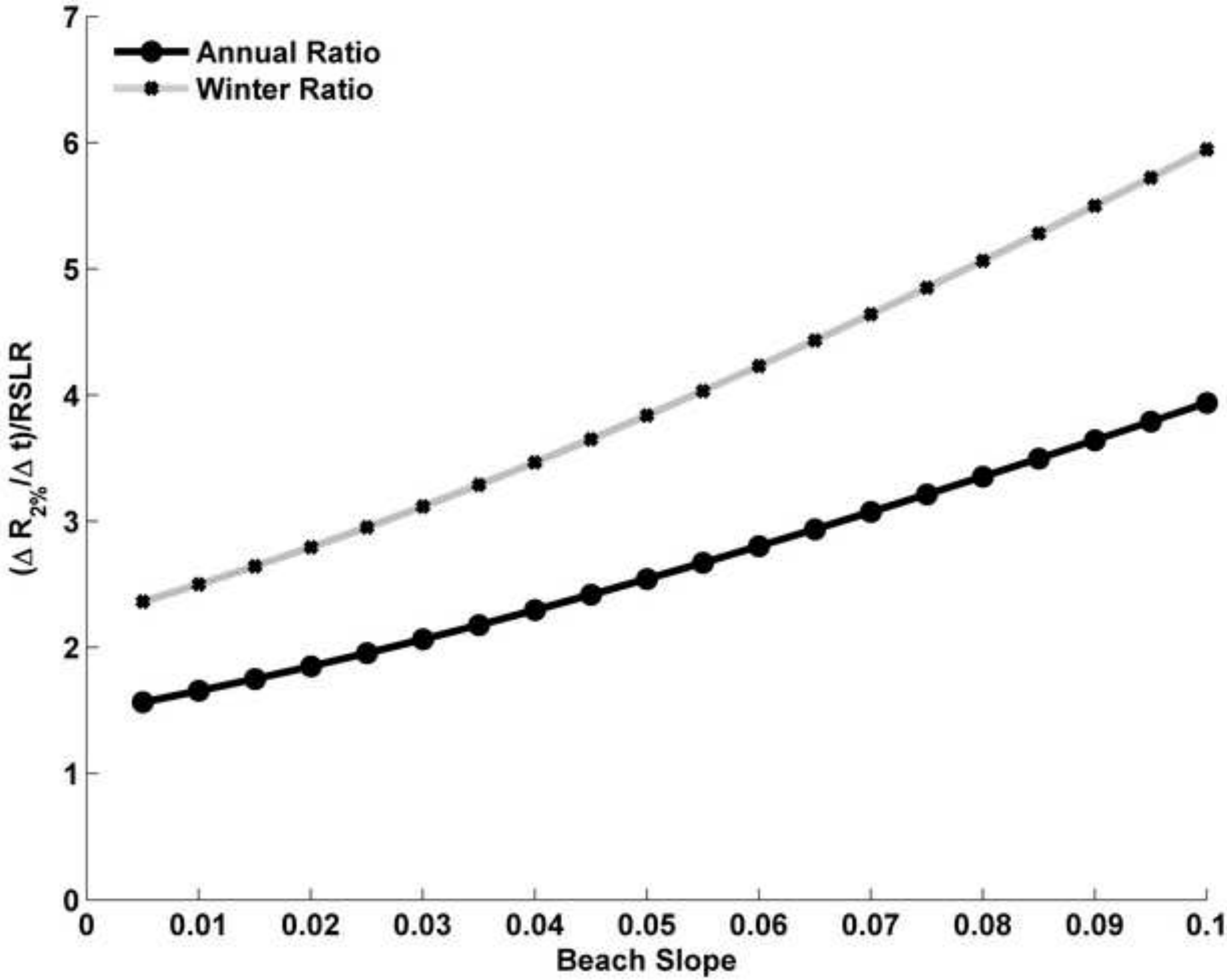

Annual Ratio
Winter Ratio
(Δ R2% /Δ t)/RSLR
Beach Slope
0
1
2
3
4
5
6
7
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1

Figure3
Click here to download high resolution image

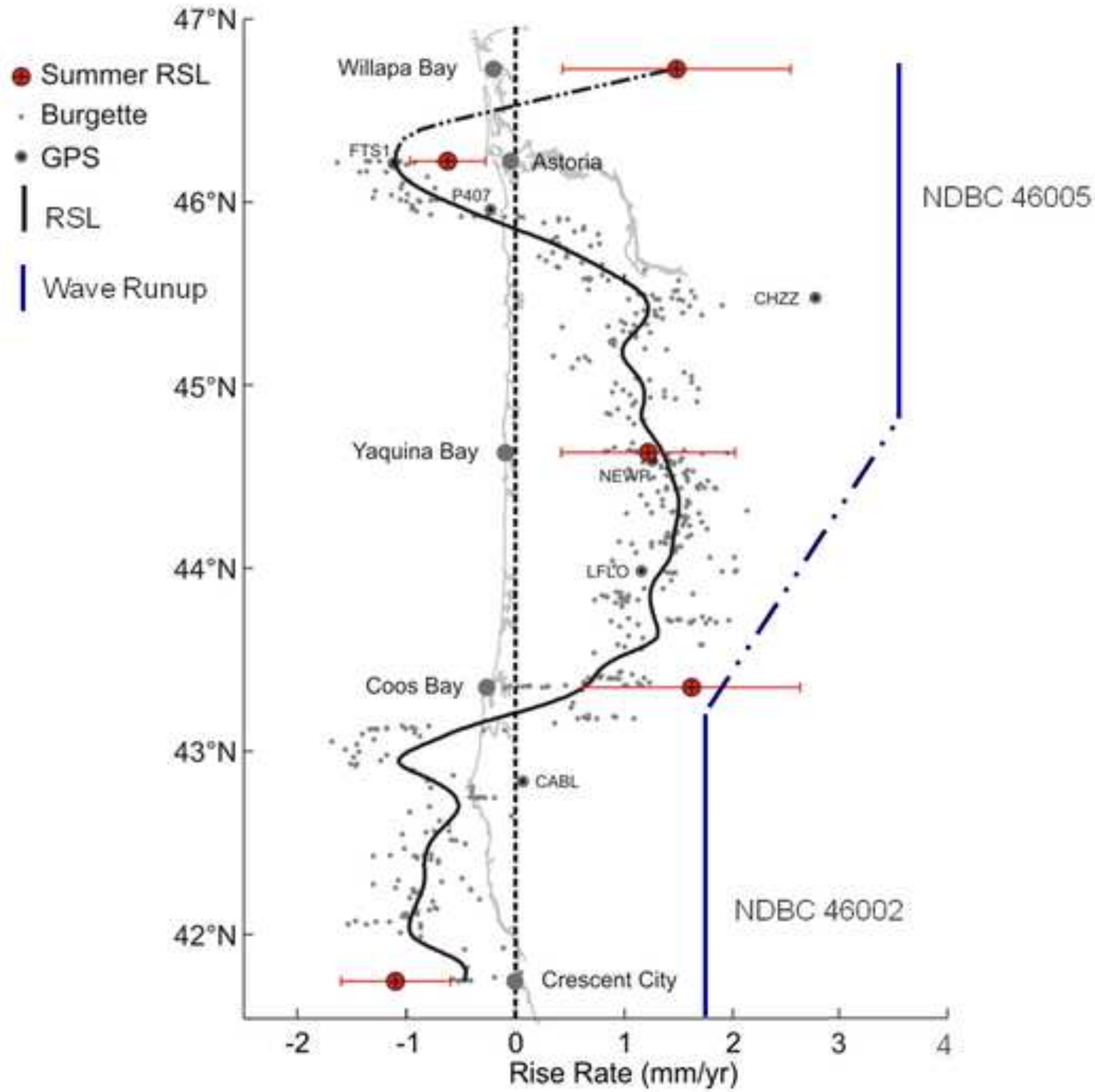


Figure4

Click here to download high resolution image

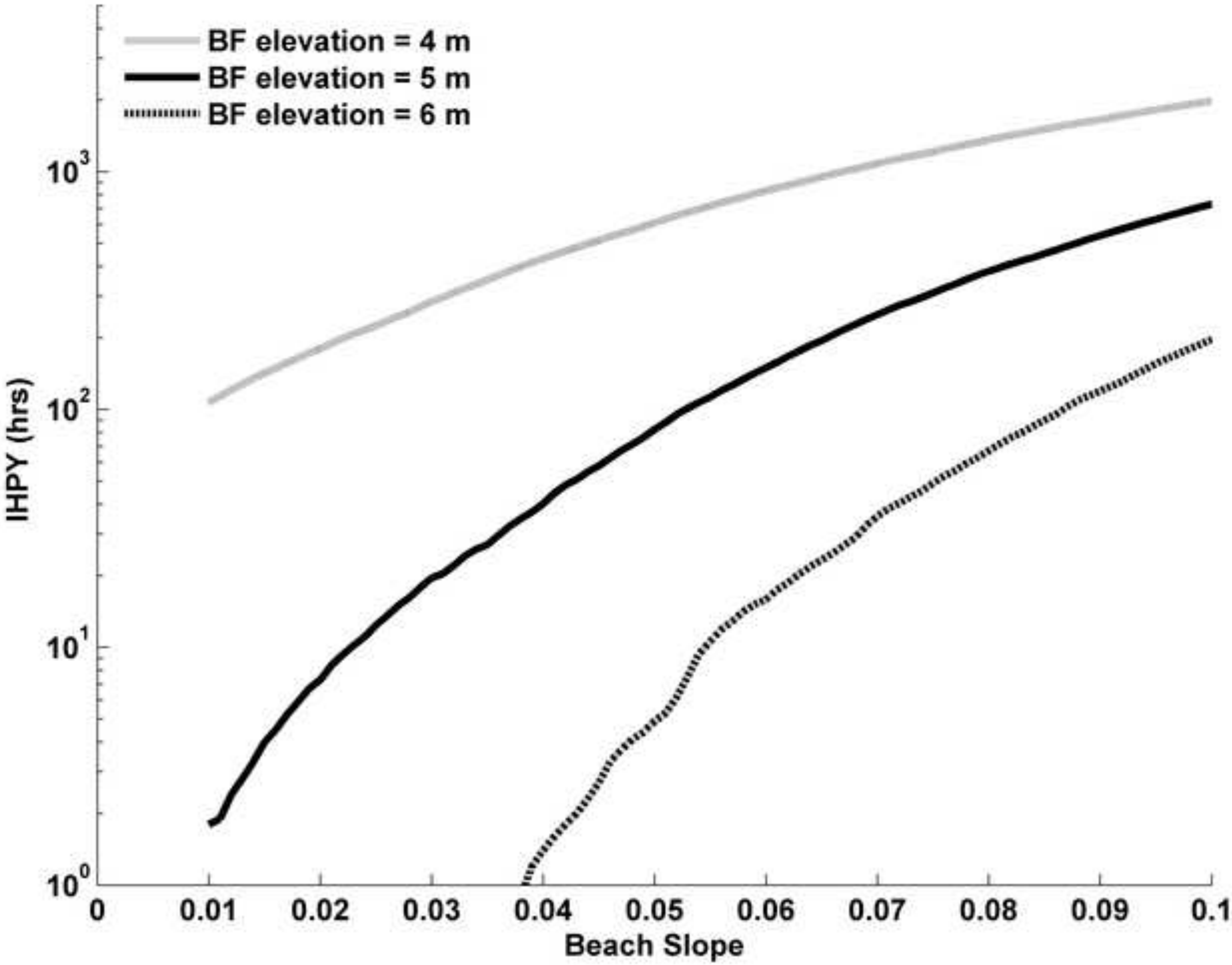


Figure5
Click here to download high resolution image

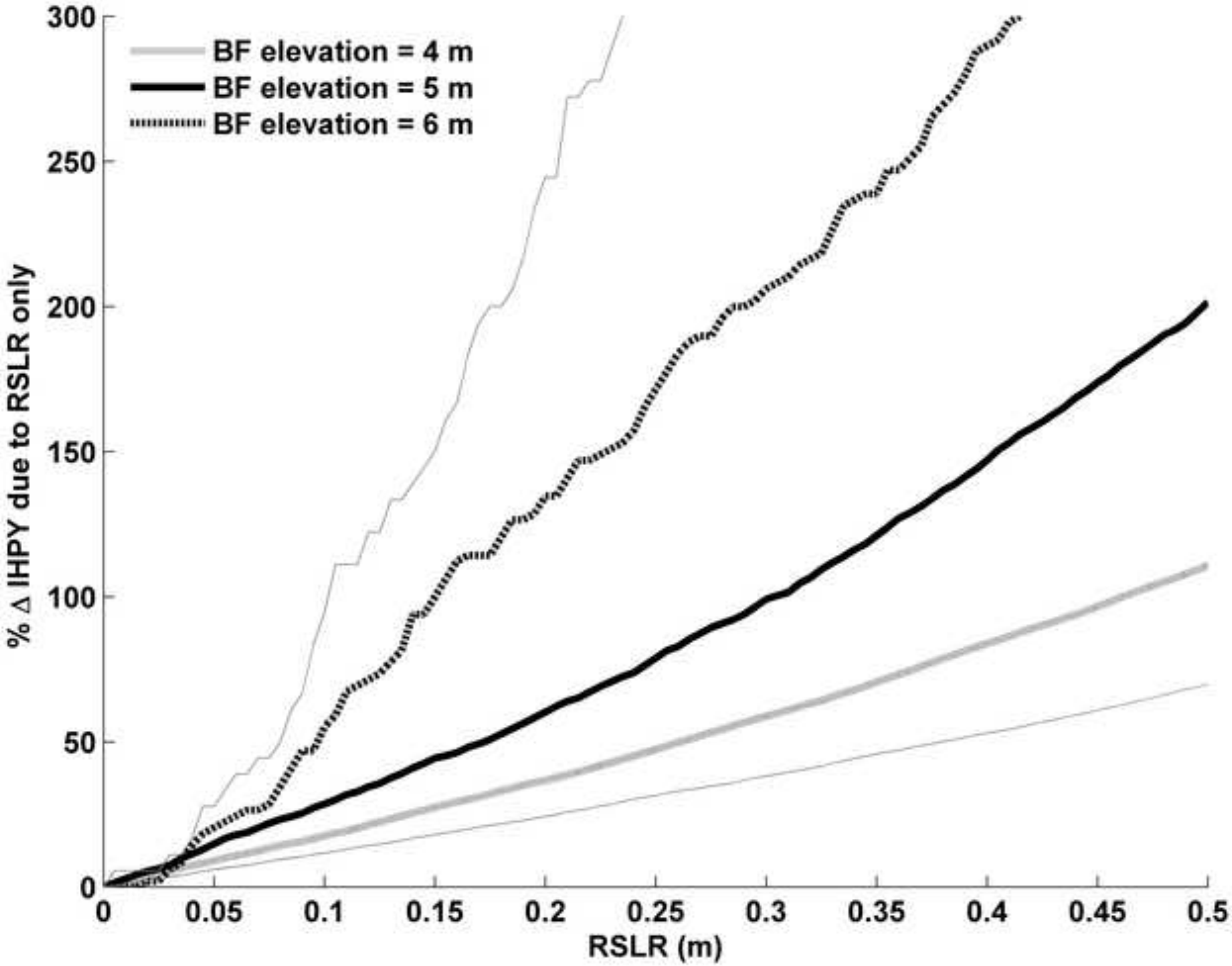


Figure6

Click here to download high resolution image

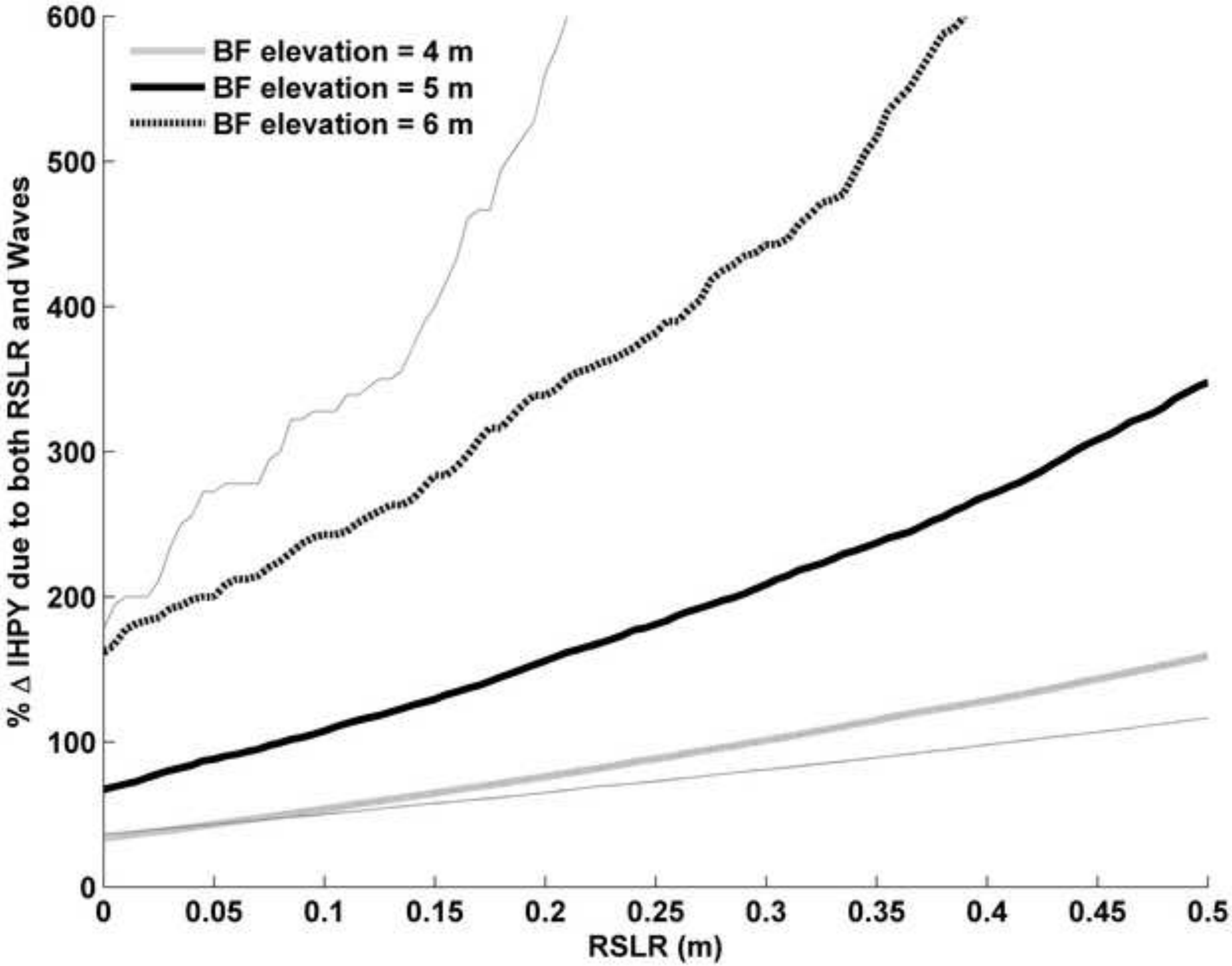


Figure7
Click here to download high resolution image

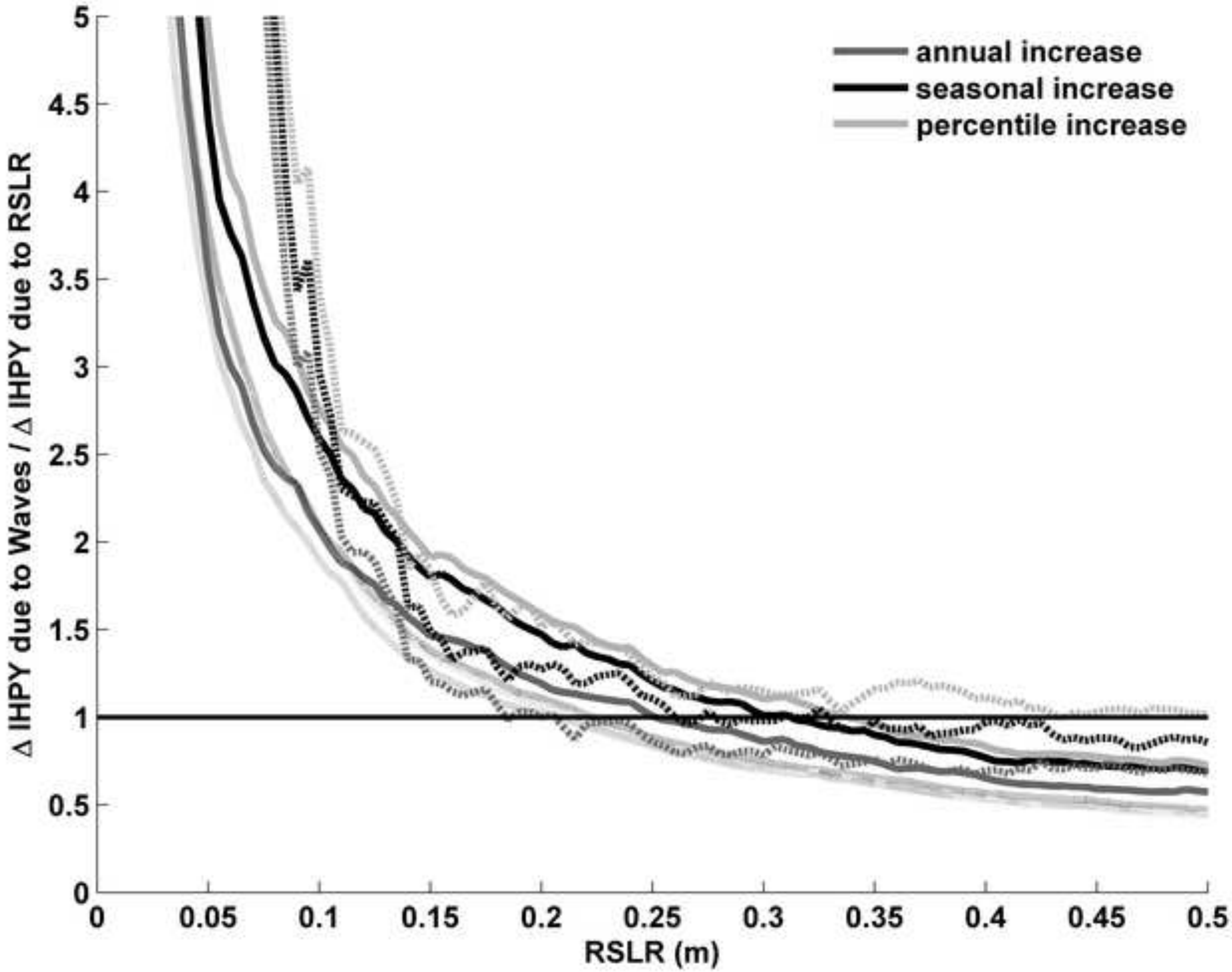
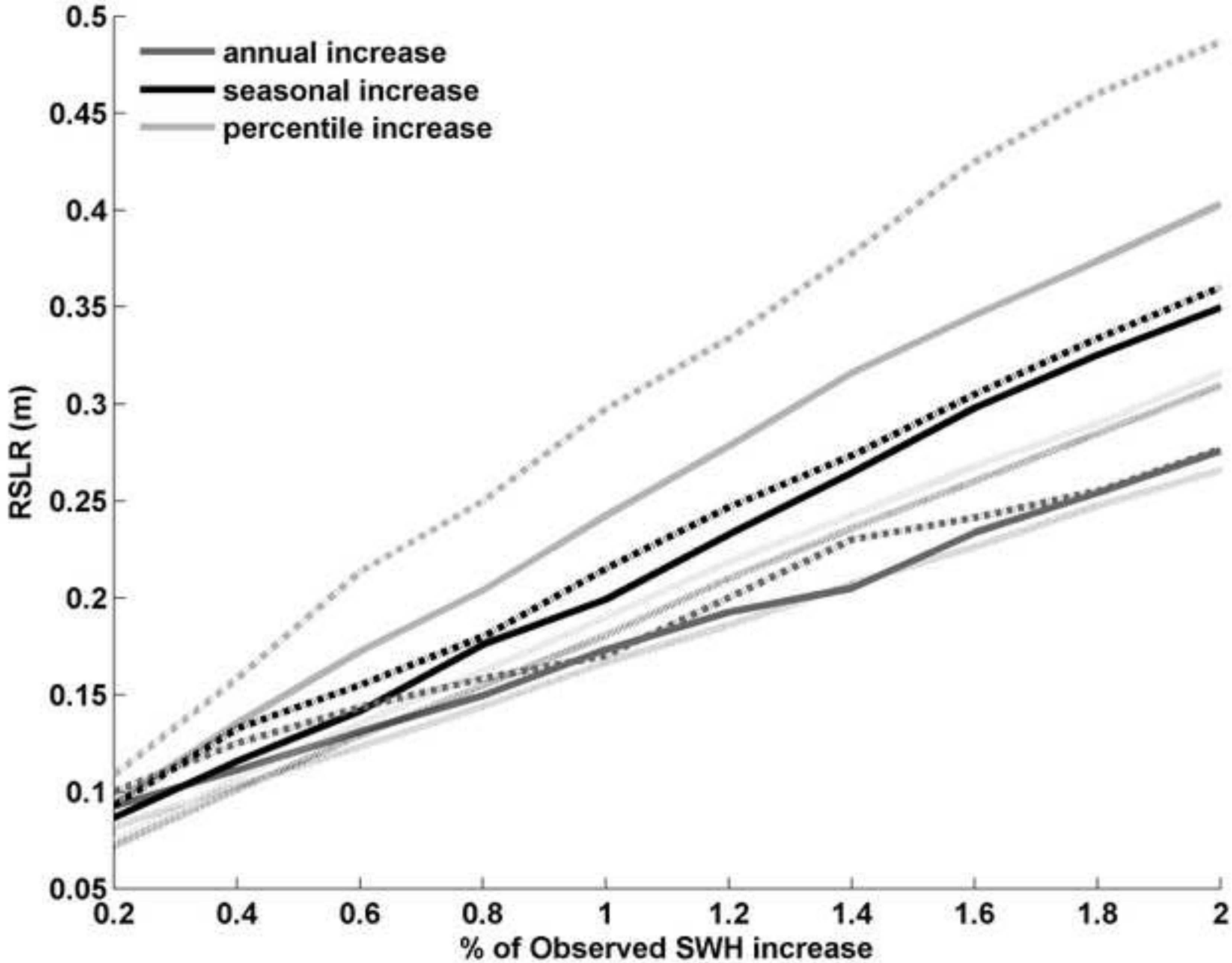


Figure8

Click here to download high resolution image



## *Figure Captions*

Figure 1. top panel) Trends and variations in summer average (solid line) and winter average (symbols only ) RSLs for the Yaquina Bay tide-gauge record. Middle panel) Trends and variations in annual average significant wave heights (solid line) and winter average wave heights (symbols only) from NDBC buoy 46005. Bottom panel) Trends and variations in annual average (solid line) and winter average (symbols only) two percent exceedance wave runup values computed using equation 2 and a representative foreshore beach slope of 0.05.

Figure 2. Ratio of the annual average time rate of change in wave runup (computed using NDBC 46005 wave data and Equation 2) versus RSLR (from the Yaquina Bay tide gage) as a function of average foreshore beach slope. The dashed line is the ratio of winter average runup change rate versus RSLR.

Figure 3. Alongshore variability of rate of change of wave runup (computed using wave data from NDBC buoys 46005 and 46002, Equation 2, and a foreshore beach slope of 0.05) versus RSLR for the Oregon coast (blue lines). 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/y as an estimate of the regional PNW rise in sea level. (modified from Komar et al., 2011)

Figure 4. Impact hours per year (IHPY) of the TWL for a range of foreshore beach slopes and three backshore feature (BF) elevations (e.g., sea cliff toe or dune crest elevation).

Figure 5. Percent increase in IHPY due to SLR only, relative to approximately year 2000, for a range of RSLR magnitudes and three backshore feature (BF) elevations. Thick lines show computations for a beach slope of 0.05 while 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).

Figure 6. Percent increase in IHPY due to both SLR and wave height increases, relative to approximately year 2000, for a range of RSLR magnitudes and three backshore feature (BF) elevations. Thick lines show computations for a beach slope of 0.05 while 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).

Figure 7. Ratio of the increase in IHPY due to wave height changes only to IHPY increases due to SLR only for a range of SLR scenarios by approximately 2025 (relative to 2000) and 3 backshore feature elevations (line types same as Figure 6). The dark grey lines represent annual increases in wave heights incorporated into the TWL, while the black lines represent inclusion of seasonal trends and the light grey lines represent rates of increase of various percentiles respectively.

Figure 8. The 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 colors represent the same combinations of BF elevations and approach for inclusion of wave height increases into the TWL as in Figures 6 and 7.