

IMPACTS OF CLIMATE CHANGE ON COASTAL EROSION AND FLOOD PROBABILITY IN THE US PACIFIC NORTHWEST

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Abstract: A simple total water level (TWL) model is employed to investigate the relative importance of various climate controls on the potential for an increased probability of coastal erosion and flooding on sandy beaches of the US Pacific Northwest. Model results suggest that if decadal-scale increases in storm intensity (wave height) continue into the future, this process will have a greater impact on increasing the probability of coastal hazards, via the relationship between wave height and wave runup, than even relatively high estimates of relative sea level rise (RSLR) rates over the next century. RSLR appears to be more important to potential hazards than an increase in the frequency of major El Niño events (from approximately one to two events per decade). The combined effect of each of these climate controls operating simultaneously is predicted to increase erosion/flood frequency by as much as an order of magnitude for some beach slopes and dune crest elevations. These results confirm the need to incorporate climate-controlled processes in methodologies designed to assess the risks of enhanced coastal hazards to humans and infrastructure.

INTRODUCTION

Recent natural disasters such as Hurricane Katrina and the Indian Ocean Tsunami have focused public awareness on the catastrophic consequences of the range and magnitude of coastal hazards. The magnitude of these events, and the scale of human suffering associated with them, suggests an urgent need to re-evaluate current coastal hazard risk assessment procedures to ensure the safety of both coastal populations and infrastructure. The most common coastal hazard risk indicator in the United States is the 1% annual chance total water level (i.e. the 100 year event). Along the West Coast of the United States the total water level (TWL) is due to the combined effects of astronomical tides, tidal residuals (e.g., storm surges and the enhanced monthly-mean water levels during El

Niños), wave runup (setup plus swash), and tsunamis. This indicator is used in a variety of coastal hazards assessments that in turn dictate planning decisions such as coastal setback distances, zoning laws, and flood insurance distributions.

It is recognized that Earth's changing and variable climate exerts control on several of the processes that combine to generate extremes in the TWL (Allan and Komar, 2006), and therefore exerts control on coastal flooding and property damage probabilities. Climate change impacts include rising sea levels (Church and White, 2006; IPCC, 2007) increased storm frequency and intensity (Allan and Komar, 2000, Graham and Diaz, 2001, Allan and Komar, 2006, Mendez et al., 2006), and the potential for an increased frequency of major El Niños associated with global warming (Trenberth and Hoar, 1997). An understanding of the relative importance of these climate-controlled processes and their inclusion in methodologies to assess the resulting risk of coastal hazards to human life and coastal infrastructure are critical to both prioritizing future research programs and to the sound management of the coast.

We are developing new methodologies for extending coastal erosion and flood risk assessments along the US West Coast, with particular focus on the sandy beaches of the Pacific Northwest (PNW), models that directly account for climate change and variability. In this paper we apply a simple TWL model to quantify the relative roles of various climate controls on the potential for an increased frequency of erosion and/or flood events, without allowing for morphological feedback. Ultimately, the goal of this research is to provide a scientific basis for sound coastal zone management decisions in light of a variable and changing climate.

METHODOLOGY

The connection between climate change and variability and the potential for increased coastal erosion and flood probability will be established through application of the TWL model developed by Ruggiero et al. (1996, 2001), which involves the summation of the tides, the sea-level controlling factors, and the runup levels (wave setup plus swash) of the waves on the beach (Figure 1). Estimates of the TWL achieved on beaches are taken as

$$TWL = Z_T + R_{2\%} \quad (1)$$

a combination of the measured tidal level including storm surge, Z_T , and the two percent exceedence value of wave runup, $R_{2\%}$. Although this model is conceptually simple (Figure 1), its establishment and initial application involved quantitative assessments of the individual water-level components. This required our having undertaken investigations of the processes that have caused measured tides to at times be well above predicted levels, and a program where we collected measurements of runup elevations on Oregon beaches and related them to wave heights, periods, and beach morphology (Ruggiero et al., 2004). Only then could this otherwise simple model be used in practical applications (e.g., Ruggiero et al., 1997, Sallenger, 2000). The elevation of a particular backshore feature, the base or crest of the dunes or toe of a sea cliff (Figure 1), governs

the frequency with which it can be reached by waves during a year, and thus governs its vulnerability to erosion or overtopping.

Here we slightly modify the approach of Ruggiero et al. (1996, 2001) by taking advantage of an updated empirical relation for extreme wave runup (Stockdon et al., 2006) based on analyses of data from 10 dynamically diverse field experiments (including data from PNW beaches). Estimates of the TWL using the Stockdon et al. (2006) relation are applicable on natural beaches over a wide range of hydrodynamic and morphological conditions and can be taken as

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

where $\tan \beta$ is the foreshore beach slope, H_0 is the offshore wave height, L_0 is the offshore wave length, given by linear theory as $(g/2\pi)T^2$ where g is the acceleration of gravity and T is the peak wave period. Equation 2 can be applied anywhere with readily available measurements of waves, tides, and beach morphology.

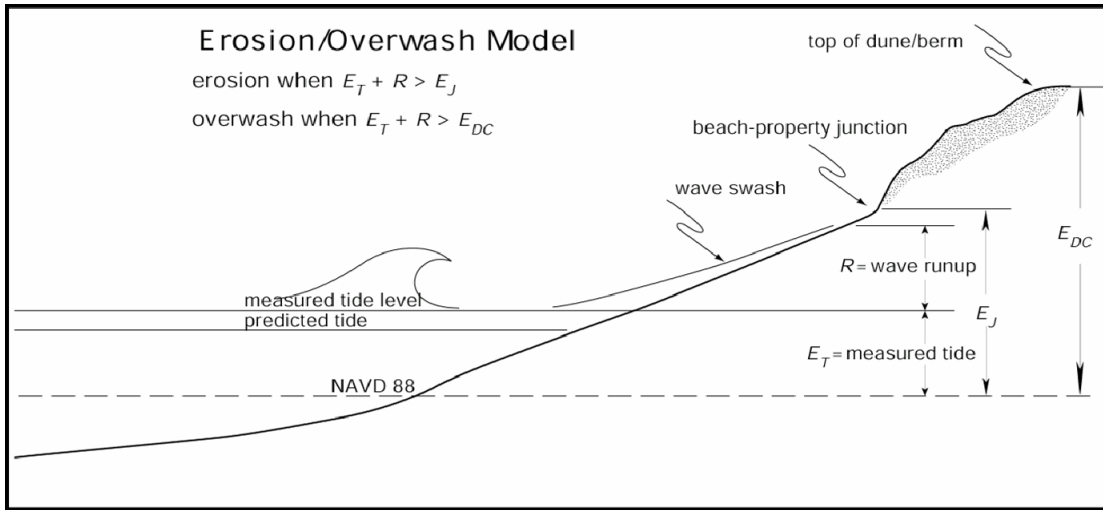


Fig 1. Definition sketch of the total water level model. Dune/sea cliff erosion occurs when the TWL exceeds the elevation of the beach face junction and overtopping/flooding occurs when the TWL exceeds the elevation of the dune crest (after Ruggiero et al., 2001).

Since the TWL is a function of measured tide levels, offshore wave conditions, and beach morphology in the form of the foreshore beach slope, any trends or variability in these parameters will directly influence the frequency that backshore properties experience erosion or flooding. Beach morphology and wave forcing conditions are derived from existing PNW regional monitoring programs (Ruggiero et al., 2005) and the suite of long-term records from offshore and onshore gages measuring waves (NDBC, 2007 and SCRIPPS, 2006) and water levels (NOAA, 2007), always employing the closest sources of those data.

We quantify the relative importance of sea level rise, increasing wave heights, and variations in the frequency of major El Niños to the probability of coastal flooding and erosion by examining the influence of these factors on a 10-year total water level time series (Figure 2). This time series, extending from 1 July 1994 to 30 June 2004, is constructed by computing hourly estimates of $R_{2\%}$ (using eq. 2) from measured significant wave heights and peak periods and adding those estimates to hourly measured water levels. The wave and period time series is constructed primarily from the Coastal Data Information Program buoy 036 offshore of Grays Harbor, WA. Gaps in the time series have been filled using the National Data Buoy Center buoy 46029 offshore of the Columbia River to generate as complete of an hourly time series for the ten years as possible. For many of the results presented below we use a ‘typical’ PNW foreshore beach slope of $\tan\beta=0.04$ when applying Equation 2, however we will discuss the sensitivity of model results to beach slope variability below. Hourly measurements of water level (relative to the North American Vertical Datum of 1988, NAVD88) are taken from NOAA tide gage 9440910 at Toke Point, WA (Figure 2) and are added to the hourly estimates of $R_{2\%}$ to generate the TWL time series shown in the bottom panel of Figure 2.

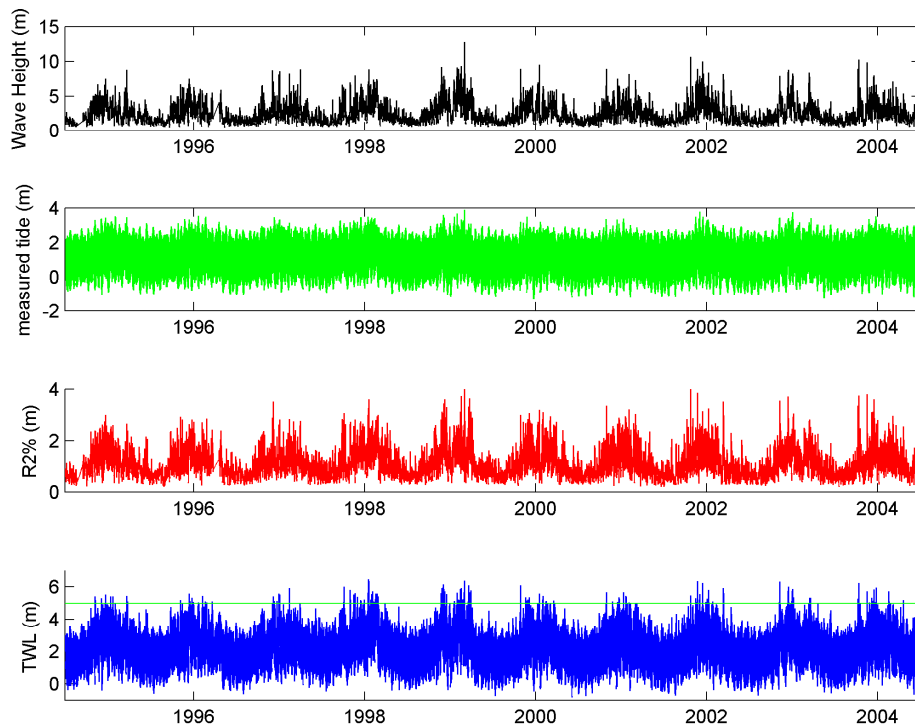


Fig 2. 10-year time series of wave height (combination of CDIP buoy 36 and NDBC buoy 46029), measured tide (Toke Point, WA), computed $R_{2\%}$, and the total water level (using Equation 2 and a foreshore beach slope of 0.04). The horizontal line in the bottom panel represents a backshore feature elevation (e.g., sea cliff toe or dune height) of approximately 5 m allowing for a visual representation of the frequency with which waves reach or exceed that elevation during the 10-year period.

A progressive rise in global sea level, and the local relative sea level affected by land-

elevation changes, can be added directly to the Ruggiero et al. (1996; 2001) model, this simply being another factor that governs the total water levels, acting progressively in the long term. Its addition leads to quantitative predictions of the expected future increase in the probability of erosion events and/or overtopping of foredunes, accounting for a range of climate change on the ocean processes. Here we first examine the impacts of various sea level rise scenarios on coastal hazard probability by the year 2100. Typical predictions of sea level rise for that year are in the range of approximately 0.2 to 0.6 m (IPCC, 2007). Presently the sea level at Toke Point is rising at a rate of 2.82 millimeters per year so even without an increase in the rate of sea level rise the Toke Point sea level trend will fall within the IPCC (2007) range.

We also apply the TWL model to investigate the effect of increasing storm intensities and wave heights as documented by Allan and Komar (2000; 2006) and Graham and Diaz (2001). Offshore of the PNW, the annual average winter significant wave height has been increasing at a rate of approximately 0.03 m/yr (Allan and Komar, 2006). Winter peak wave periods have also increased over the last several decades, increasing at a rate of approximately 0.025 s/yr (Allan and Komar, 2006). Since wave runup is a function of both wave heights and periods (via wave length in Equation 2), the elevation of swash on beaches has no doubt increased due to this climate control. Allan and Komar (2002; 2006) exploited this relationship to demonstrate that the average winter runup elevation, along most West Coast beaches, has actually been increasing at a faster rate than relative sea level rise for the last two decades. Here we apply the TWL model in forecast mode to examine the impact of increasing wave heights relative to a variety of sea level rise scenarios.

On the US West Coast, severe episodic beach erosion is typically associated with the occurrence of a major El Niño (e.g., Komar, 1986, Kaminsky et al., 1998, Ruggiero et al., 2005). The importance of El Niños to beach and property erosion was first recognized during the major 1982-83 event, with that recognition reinforced by a repeat of the impacts during another strong El Niño in 1997-98. Subsequent research has shown that the erosion resulted primarily from temporarily elevated mean water levels, coupled with increased storm intensities and the heights of the waves they generated. Since both wave heights (and therefore wave runup) and water levels are enhanced during El Niños, two components of the TWL are super-elevated during these climate events. Most importantly, these processes considerably increase the probability that the runup of storm waves will reach or exceed backshore properties, resulting in their erosion or flooding. Dating back to the mid 1970s, El Niños have occurred on average every three to seven years with the two major events in that span being the 1982-1983 and 1997-1998 events. In a similar manner, as described above, we examine scenarios in which the future wave climate will bring more frequent El Niños.

To examine the relative impact of the three climate controls described above, we manipulate the 10-year times series of TWL (Figure 2, computed based on observations) with a variety of climate change scenarios. We then compare the annual probability of erosion/flooding computed from the initial 10-yr time series with the probability of erosion/flooding computed from the manipulated 10-yr time series meant to represent a

climate scenario in the decade centered on the year 2050. In this initial effort at attempting to quantify the relative strength of the various climate controls we do not include feedbacks between the hydrodynamics and the local beach morphology. Obviously this is a simplification as sandy beach morphology and the backing sand dunes or sea cliffs will respond (via a variety of negative feedback mechanisms) but one that allows for a direct comparison of the various climate controls. Future work will attempt to incorporate the effects of evolving beach morphology (e.g, sea cliff and dune erosion) in light of a changing climate.

RESULTS

The average number of hours per year (impact hours) in which the TWL, computed from the 1994 to 2004 observations, reaches or exceeds a particular elevation, for various beach morphologies, serves as a proxy for the probability of beach erosion/backshore flooding. Figure 3 illustrates the dependence of impact hours on foreshore beach slope and elevation of the backshore feature. Due to the runup dependence on beach slope (Equation 2), increases in beach slope increase the number of impact hours per year for a given backshore feature elevation. For example, the model predicts that for the ten years between 1994 and 2004 the TWL reached or exceeded an elevation of 5 m approximately 54 hours per year on beaches with foreshore slopes of 0.04, but only approximately 6 hours per year on beaches with beach slopes of 0.01. For a given beach slope, an increase in backshore feature elevation decreases the number of impact hours per year (Figure 3).

The results in Figure 3 depict the analysis results for the past decade, while the analyses in Figure 4 project the increases in impact hours for a range of relative sea-level rise projections. The model projections indicate that typical predictions of RSLR by 2100 (approximately 0.2 m to 0.6 m) could cause a doubling to tripling of the frequency with which waves impact sea cliffs and dunes along the Oregon/Washington coast. Extreme estimates of sea level rise by the century's end (on the order of 1 meter and therefore still not accounting for the potential catastrophic melting of ice sheets) can cause an order of magnitude increase in flood frequency for some beach geometries (Figure 4).

Model results also indicate that future climate change scenarios in which wave heights continue to increase at rates similar to those observed over the last several decades will have a more significant impact on coastal erosion and flood probabilities than even relatively extreme sea level rise scenarios (Figures 5 and 6). In those model analyses we applied the observed rate of increase in the average winter wave heights (Allan and Komar, 2006) to the wave runup component of the total water level model, having analyzed the impact of increasing winter waves for a decade centered on the year 2050. For that decade the average winter wave heights will be approximately 1.6 m higher than at present and peak wave periods will be 1.4 s longer.

Figure 5 gives the model results for four 10-year time series centered around 2050, for various climate change scenarios. The relation of the TWL curve to the horizontal line at 5 m elevation gives a clear visual demonstration of the relative impacts of the various scenarios. For example, in 2050 a scenario of 0.25 m of RSLR causes a doubling of the

probability with which water will reach an elevation of 5 m, changing the frequency from 54 hours per year to 104 hours per year. However, the impact of increasing wave heights and periods causes the frequency of wave impact to increase to 214 hours per year, having twice as much impact as RSLR (for a foreshore beach slope of 0.04).

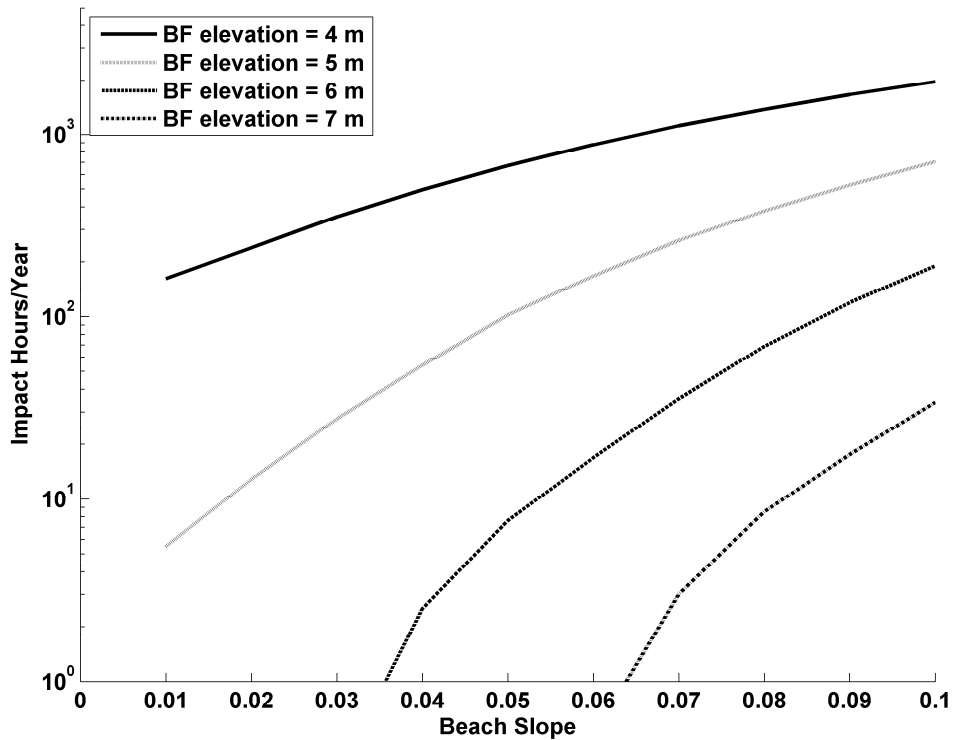


Fig 3. The number of hours per year in which the total water level exceeded a particular beach feature elevation during the decade from 1994 to 2004 for a range of beach slopes. Computations are shown for a variety of sample elevations of beach feature elevations (e.g., the dune toe or the dune crest elevation).

We also examined the impact of an increased frequency of major El Niño events on erosion/flood probabilities. The initial TWL time series (Figure 3) contains one major El Niño, the 1997/1998 event that caused significant erosion problems along the PNW coast (Komar, 1998, Ruggiero et al., 2005). For simplicity the TWL for a ‘normal’ year within the 10-year record (in this case the wave year beginning in July 1994) is replaced with the same wave and water level record measured during the extreme event. For this scenario our 10-year time series in effect now has two major El Niño events of equal magnitude and duration. The impact this has on the resulting backshore-impact probability in 2050 is due to the fact that we are replacing a year in our 10-year time series in which the TWL reached 5 m approximately 30 hrs with an El Niño year in which it reaches that elevation approximately 113 hours (Figure 6). A decade with two major El Niños increases the average annual frequency of waves reaching a beach feature elevation of 5 m approximately 15%.

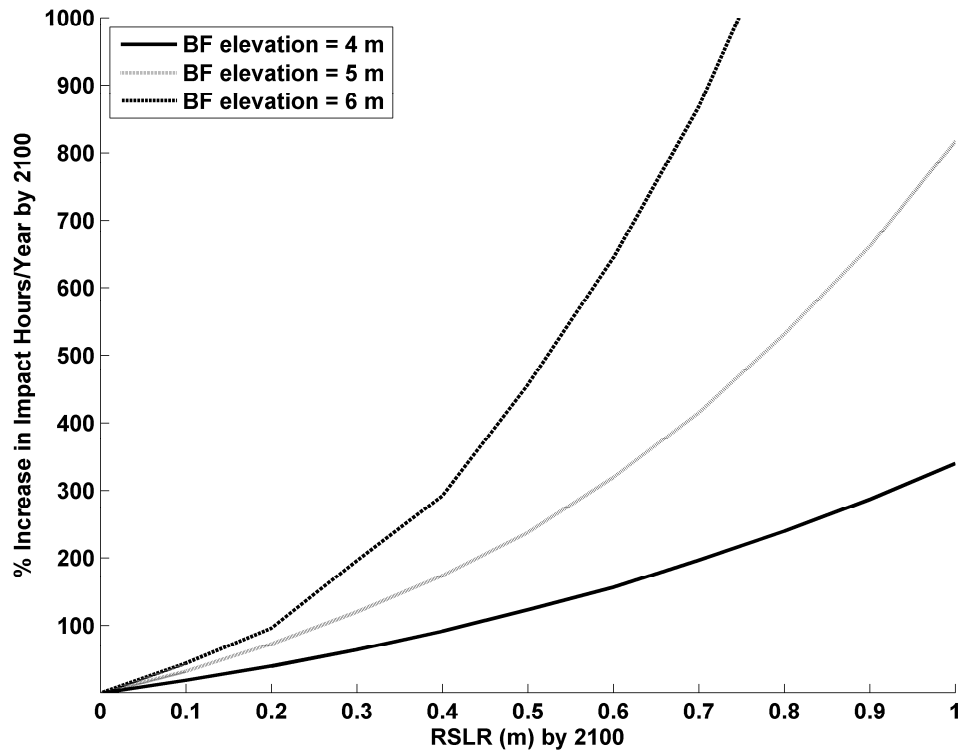


Fig 4. Percent increase, relative to year 2000, in the number of hours per year in which the total water level exceeds a particular beach feature elevation for a range of relative sea level rise scenarios by 2100. Computations are for a foreshore beach slope of 0.04 and are shown for a variety of sample elevations of backing feature elevations (e.g., the dune toe or the dune crest elevation).

Finally, we examine the impact of each of the climate controls affecting the TWL simultaneously with the results included in Figures 5 and 6. The model predicts that if in 2050 there would be 0.25 m of RSLR, a 1.6 m and 1.4 s increase in wave height and period respectively, and there would be a doubling of the frequency of major El Niño events, the rate at which a beach backing feature of 5 m will be exceeded will increase from 54 hours per year to approximately 370 hours per year. This represents almost a 700% increase in impact hours (for this particular elevation and beach slope) as compared to the current situation and a 350% increase as compared to the effects of sea level rise alone. Figure 7 quantifies this ratio of the impact of all climate controls occurring simultaneously versus the impact of sea level rise only for a wide range of beach morphologies; emphasizing the point that sea level rise is only a fraction of the problem when it comes to increased probabilities of coastal impacts and hazards as a result of future changes in the climate.

DISCUSSION AND CONCLUSION

The primary outcome of this work is a direct assessment of the relative contribution of various climate controls on coastal change and flood probability. The application of a simple total water level model under various climate change scenarios suggests that increasing storm wave heights may increase the probability of coastal erosion/flooding

twice as fast as sea level rise alone and up to four times as fast as a doubling of the frequency of occurrence of major El Niño events. The combination of each of these climate controls on the total water level occurring simultaneously could cause as much as an order of magnitude increase in erosion/flood frequency as compared with the present rate of those processes occurring. These results confirm the need to incorporate climate-controlled processes in methodologies designed to assess the risks of enhanced coastal hazards to humans and infrastructure

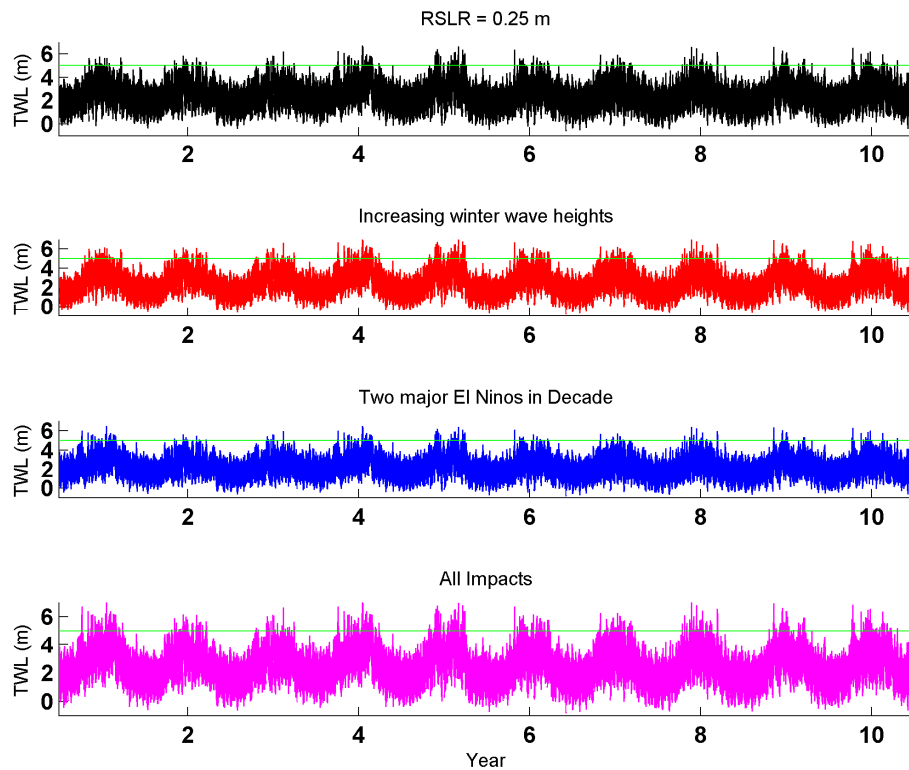


Fig 5. 10-year TWL time series for various climate change scenarios at 2050 including; a 0.25 m increase in sea level, a 1.6 m and 1.4 s increase in wave height and period respectively, a doubling of the frequency of major El Niños, and all of these climate impacts occurring simultaneously.

Coastal zone managers are at present operating without quantitative knowledge of the effects of climate change and variability and coastal hazards at planning time scales of decades. The results presented in this paper provide an initial assessment of the relative importance of various climate controls applicable to coastal zone decision making. While promising, these results are being refined by examining model sensitivity to the various input parameters, by varying the methodology of computing the joint tide and wave runup time series, and by addressing the impacts of potential morphological feedbacks associated with climate change.

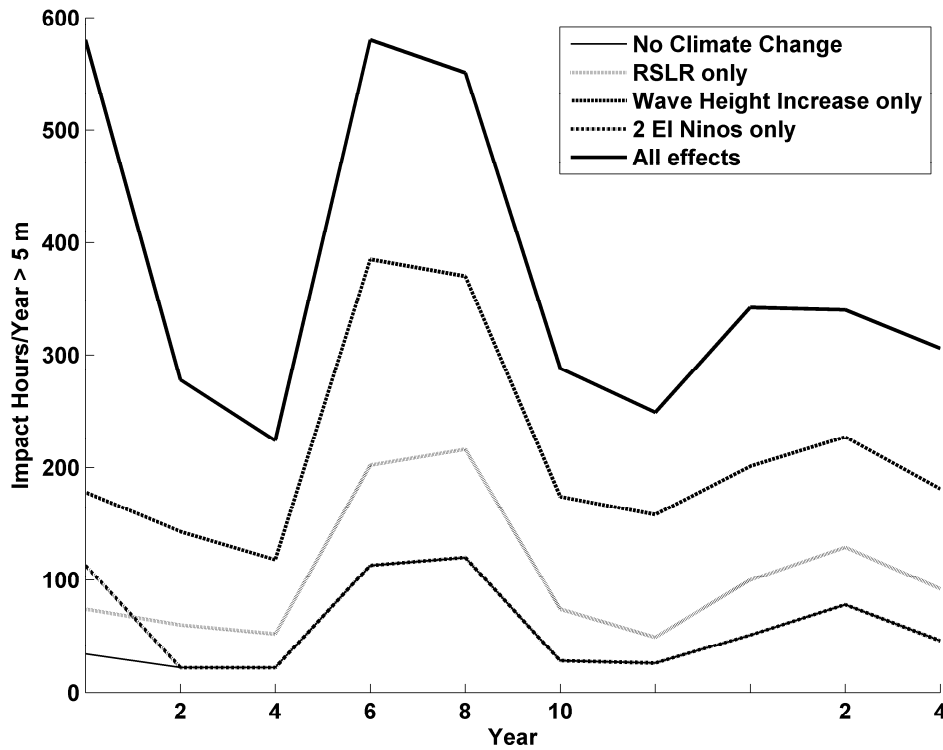


Fig 6. The number of hours in each year of various 10-year time series of TWL (centered on 2050) that exceed an elevation of 5 m for climate scenarios that include; a 0.25 m increase in sea level, a 1.6 m and 1.4 s increase in wave height and period respectively, a doubling of the frequency of major El Niños, and all of these climate impacts occurring simultaneously.

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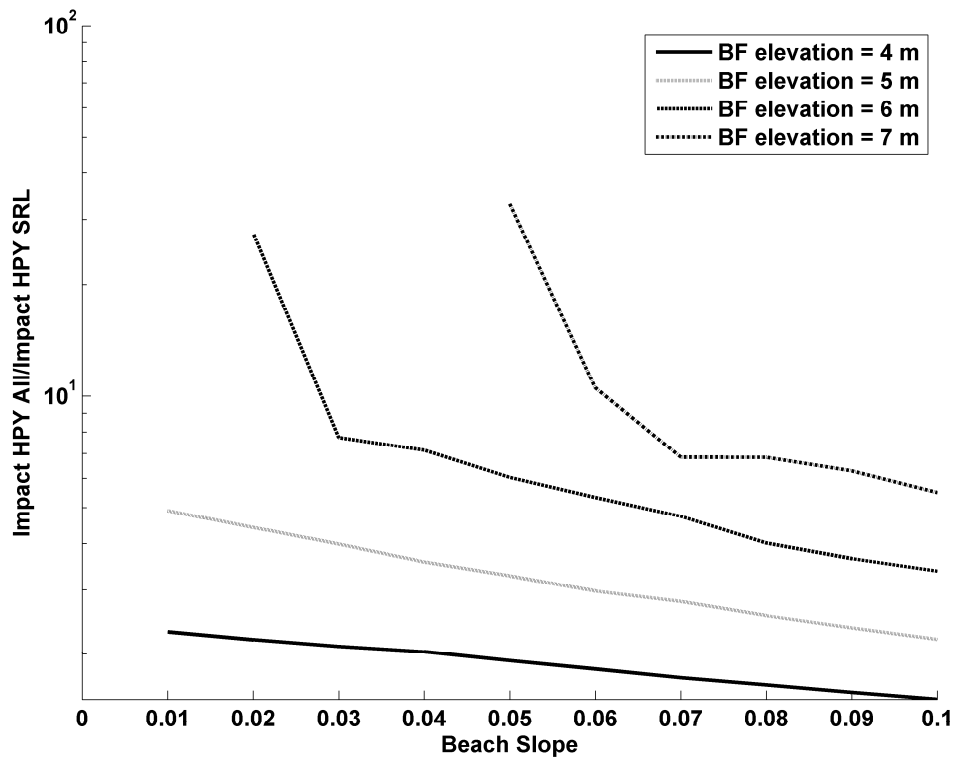


Fig 7. Ratio of the impact hours per year with all climate scenarios operating simultaneously versus the impact hours per year with only sea level rise of 0.25 m occurring by 2050.

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