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2010 IOP Conf. Ser.: Earth Environ. Sci. 11 012033

(http://iopscience.iop.org/1755-1315/11/1/012033)

17th National Conference of the Australian Meteorological and Oceanographic Society IOP Publishing
IOP Conf. Series: Earth and Environmental Science **11** (2010) 012033 doi:10.1088/1755-1315/11/1/012033

Estimating 21st century changes in extreme sea levels around Western Australia

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Abstract. Extreme sea levels are likely to increase in the future with an expected accelerated rise in mean sea level and through possible changes in storminess. Society is becoming more vulnerable to extreme sea levels due to considerable growth in human populations and economy at the coastal zone and this is particularly true for Western Australia, the fastest growing Australian state or region. This paper describes a novel approach used to estimate future changes in extreme sea level around the southwest coastline of Western Australia. Probabilities of extreme sea level for the present climate have been estimated using a 60 year hindcast of sea levels. The impact of climate change has been explored by adding a range of mean sea level rise projections to these probabilities. Estimates of possible future changes in recurrence intervals every decade over the 21st century are presented, showing that climate change has the potential to significantly reduce current average recurrence intervals and that the amount of reduction varies significantly around the coastline.

1. Introduction

Globally, mean sea levels (MSL) are rising [1] and the rate of rise is predicted to accelerate over the 21st century [2]. This will lead, along with possible changes in storminess (i.e. more intense cyclones [3]), to more extreme sea levels and hence an increased likelihood of coastal flooding and erosion. Society is becoming more vulnerable to extreme flooding events because of the growing human populations and economy in the coastal zone [4]. This is especially true for Western Australia (WA), the fastest growing Australian state or region for the last two years [5]. Some of the areas experiencing the largest population growth in the state are in flood prone areas (e.g. Rockingham, Mandurah, Bunbury and Busselton) and it has been estimated that between about 19,000 and 29,000 houses will be at risk of inundation in WA from a sea-level rise of 1.1 m, if flood defence measures are not upgraded. Hence there is an urgent need to provide accurate projections of possible future changes in extreme sea levels around WA to aid current coastal management and for future planning.

A simple estimate of future changes in extreme sea levels can be obtained by just adding projections of MSL to current recurrence intervals, estimated from existing sea level measurements [6] (we term this the ‘MSL offset method’). However, there are problems with calculating current recurrence intervals from existing tide-gauge measurements. Firstly, the observational records vary in length at each site and have different periods of missing data. This can bias the calculation of current recurrence intervals. Secondly, the sea level observations are only available at discrete locations

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around the coastline. The WA coastline is long (approximately 20,000 km) and characteristics of the astronomical tide and storm surges vary significantly around it. Therefore, a simple interpolation of current recurrence intervals, between the existing network of 28 tide-gauges in the state, is not likely to capture accurately the spatial variation in sea levels around the coastline.

An alternative method, first applied in 1998 [7], is to calculate recurrence intervals using multi-decadal hindcasts of sea level, created by driving hydrodynamic models, validated against observations, with meteorological fields. This has the advantage that maps of recurrence intervals can be estimated across the whole model domain. This method has recently been applied to estimate the frequency of sea level extremes and the impact of climate change in southeast Australia [8].

The aims of this paper are to: (1) briefly describe a 60 year hindcast of sea levels that has been created for the coastline of WA; and (2) use the results of this modelling exercise to provide an initial estimate of possible future changes in extreme sea level around the coastline of southwest Australia.

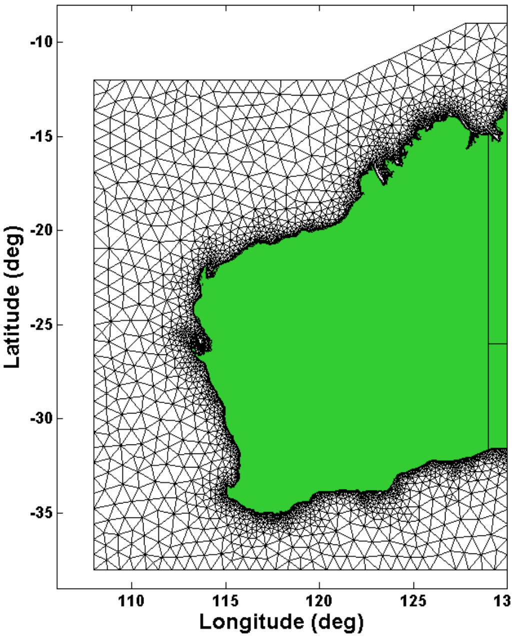

Figure 1. Model grid

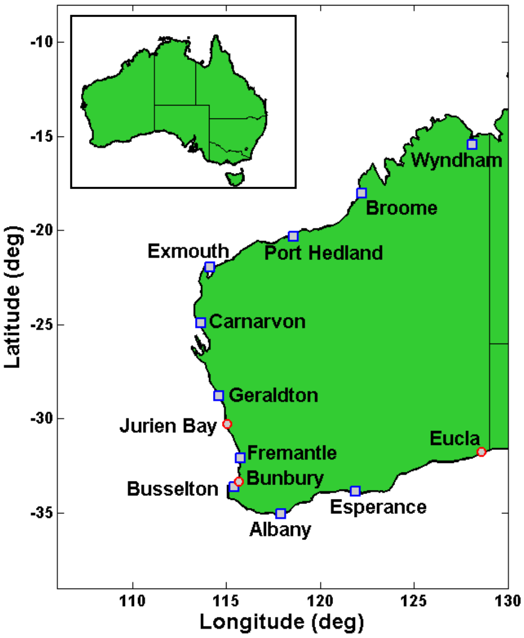

Figure 2. Tide-gauge locations (blue squares)

2. A 60 year hindcast of sea levels

Hydrodynamic numerical models have been used since the 1960's to improve understanding of sea level characteristics. Until recently, most of the past studies simulated sea levels over a particular storm event or for a few tidal cycles. It is only over the last decade that hydrodynamic models have been used to simulate multi-decadal hindcasts of sea level [9].

In this study, a depth-average tide-surge model has been created for the entire WA coastline using the Danish Hydraulic Institute's Mike21 FM (flexible mesh) suite of modelling tools. The Mike21 FM modelling system is based on the numerical solution of the incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and hydostatic pressure [10]. The spatial discretization of the primitive equations, over the flexible mesh, is performed using a cell-centred finite volume method.

The model mesh, configured for WA, is shown in figure 1. It has a resolution of about 60 km at the open boundaries, increasing to 10 km along the entire coastline of WA. The bathymetric data, interpolated onto the model grid, was obtained from Geoscience Australia. In order to generate the astronomical tidal component of sea levels, the open model boundaries were driven with sea levels derived from 10 tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_f, M_m), obtained from the Oregon State University Tidal Inversion Software [11]. To generate the surge component of sea levels, the model has been forced with atmospheric pressures and u and v components of wind, obtained from the US National Center for Environmental Prediction's (NCEP) global reanalysis [12]. These meteorological fields were available every 6 hours from 1949 to present and have a horizontal resolution of 2.5^o.

The model has been validated against observations from 10 tide-gauges (Esperance, Albany, Busselton, Fremantle, Geraldton, Carnarvon, Exmouth, Port Hedland, Broome and Wyndham), the locations of which are shown in figure 2. The tide-gauge records were obtained from the WA Department of Transport. Validation was undertaken for the year 2003, as this was one of the stormiest years on record.

Two separate model simulations were undertaken. The model was first driven only with tidal forcing at the open boundary. In the second simulation the model was also forced with winds and surface air pressures. The first simulation provided only the astronomical tidal component of sea levels. The second simulation predicted the total sea level (i.e. tide + surge). By subtracting the second simulation from the first, the storm surge component of sea levels was obtained. The predicted total, tidal and surge levels were compared with the observed record and the derived tidal and storm surge components of the observed record (which were calculated by performing harmonic tidal analysis on the measured record at each site).

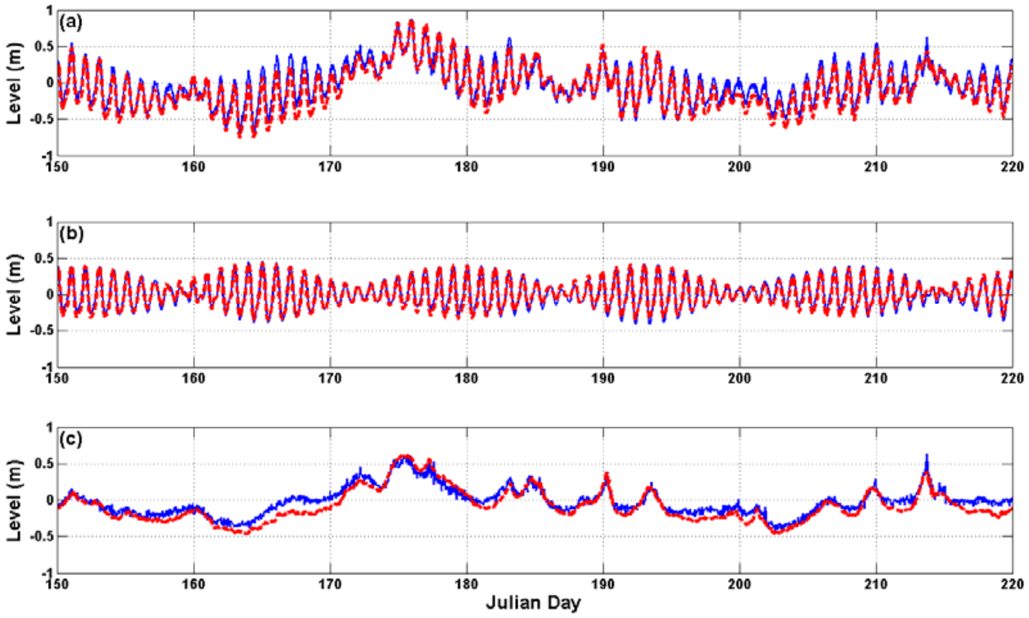

Figure 3. A comparison of the observed (solid blue) and model (dotted red) (a) total sea levels; (b) astronomical tidal levels; and (c) surge levels, for Fremantle during June and July 2003.

At each of the 10 sites, there is good agreement between the observed and modelled astronomical tidal component (root mean square errors are typically within 10 cm). However, the total sea levels and storm surge component of the sea levels only show good agreement (again root mean square errors are typically within 10 cm) for the southwest region of WA (Geraldton southwards). The poor agreement along the northwest part of the coastline is due the low spatial and temporal resolution of the NCEP air pressure and wind fields, which are not adequate to simulate the storm surge generated by tropical cyclones. A comparison of the measured and modelled total sea levels, tidal and surge levels is shown in figure 3 for Fremantle. Root mean square errors of the observed and modelled total, tidal and surge components of sea level are less than 5 cm at this site.

3. 21st century changes in extreme sea levels

Following the validation stage, the model was run for the 60 year period from 1949 to 2008. Results were saved every hour for each model grid cell. The 60 year simulated time-series of total sea levels were extracted for each model grid point around the coastline of southwest Australia (Eucla to Geraldton) and were then used to calculate current recurrence intervals. (At this stage in the study, we limit the analysis to the southwest region, as this is where there was good agreement between the model and observational dataset. Future work will address extending this analysis along the northwest shelf by using higher resolution wind and pressure fields, capable of more accurately predicting surges associated with cyclones in these regions.) The recurrence intervals were estimated by fitting an extreme value Gumbel distribution to the annual maximum sea level at each point [13]. The MSL offset method was then used with sea-level rise projections from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) to provide an estimate of possible future changes in extreme sea level every decade from 1990 to 2100 around the southwest coast of WA.

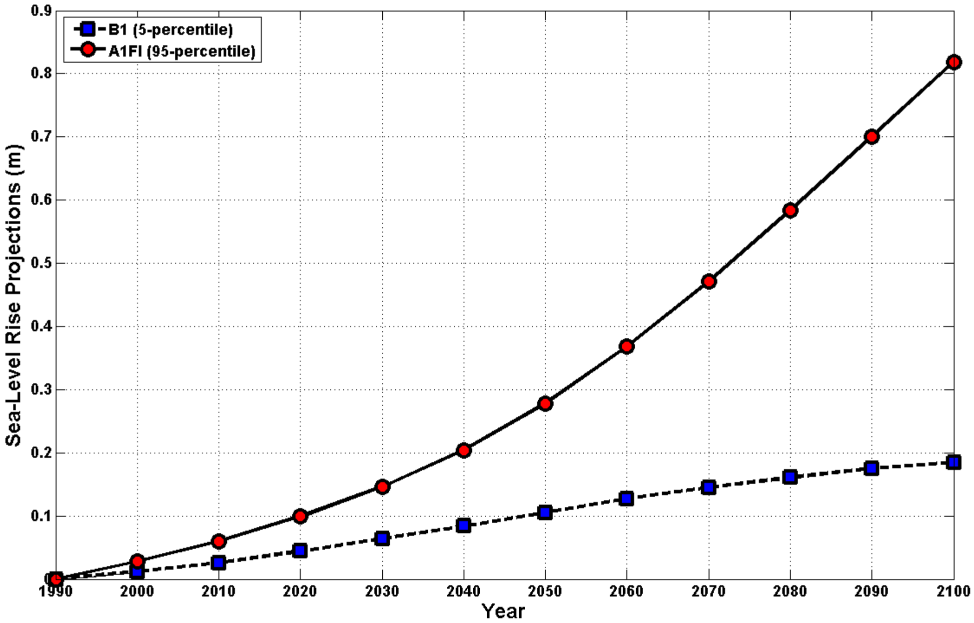

Figure 4. Lower and upper sea-level rise projections from the IPCC AR4. The lower projection corresponds to the 5th percentile of the low emissions scenario (B1) and the upper projection corresponds to the 95th percentile of the high emissions scenario (A1FI).

The IPCC's AR4 provided global projections of MSL rise at 2095 relative to 1990 for six SRES (Special Report on Emissions Scenarios) [2]. The sea-level rise projected by the models was between 18 and 79 cm for this period. The AR4 only provided projections of sea-level rise for 2095, unlike the IPCC's Third Assessment Report (TAR) which provided projections throughout the 21st century. Hunter [14] fitted the time series from the TAR to the AR4 projections to calculate sea-level rise projections at decadal resolutions for the different scenarios. We consider the 5th percentile of the B1 (low emission) and 95th percentile of the A1FI (high emission) sea-level rise scenarios (figure 4), to sample the range of change. The low scenario is approximately consistent with a continuation of the 17 cm of global change observed by tide-gauges over the 20th century [1], while the upper scenario represents a significant acceleration on 20th century rates of rise.

At each model grid point around the coastline of southwest Australia, and for each 10 year period from 1990 to 2100, the estimated current recurrence intervals have been increased by the lower and upper sea level projection for that specific decade. A cubic interpolation was then used, for each

10 year period, to find the recurrence interval associated with the level in 1990 that had a 100 year recurrence interval.

Results for the lower projection are shown in figure 5. Between Eucla and Albany, the level associated with a 100 year event in 1900 is predicted to occur about every 2 to 3 years by 2100, about a 50 fold increase in exceedence frequency. Between Albany and Bunbury, on the southwest corner of WA, the change in the recurrence interval becomes less dramatic. The level in 1990 associated with a 100 year event is predicted to occur about every 10 years by 2100, a 10 fold increase in exceedence frequency. Between Jurien Bay and Geraldton, there is a 100 fold increase in exceedence frequency. These results illustrate the dramatic changes in recurrence intervals of extreme high sea levels that can occur due simply to a small change in MSL and highlight the considerable spatial variation in the change around the coastline.

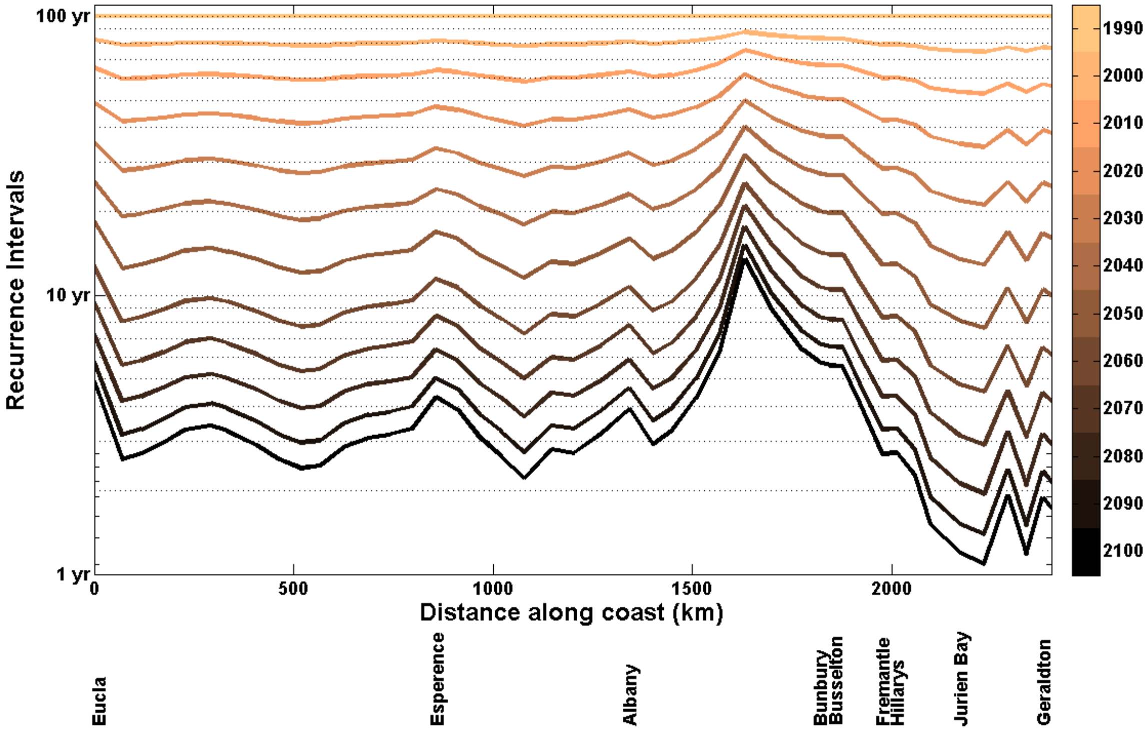

Figure 5. Recurrence intervals (years), every 10 years from 1990 to 2100, associated with a return level with a 100 year return period in 1990, for the lower sea-level rise projections.

For the upper sea-level rise projection (results not shown), the pattern of change around the coastline is similar to the lower projection, but the increase in exceedence frequency is significantly more pronounced. Between Eucla and Albany, the level associated with a 100 year event in 1990 is predicted to occur about every 2 to 3 years by 2050 (i.e. 50 years earlier than the lower projection). By 2100, the level associated with the 100 year event in 1990, is likely to occur at least once every spring/neap tidal cycle by 2100 along almost the entire southwest stretch of WA coastline (i.e. more than a 2,500 fold increase in exceedence frequency).

4. Conclusions

This paper has presented a 60 year hindcast of sea levels around Western Australia. This modelled sea level dataset has been used to map current recurrence intervals around the coastline of southwest Australia. Future changes in extreme sea levels throughout the 21st century have been estimated by increasing the current recurrence intervals by a low (18 cm) and upper (79 cm) sea-level rise projection. Results have shown that the predicted rise in sea level over the 21st century has the potential to significantly reduce current average recurrence intervals around southwest Australia and that the increase in exceedence frequency varies significantly around the coast. These estimates could increase further with enhanced storminess and this will be investigated in the next stage of the study.

Acknowledgments

We would like to thank the Department of Transport for providing the tide-gauge data. This study is being funded through the Western Australian Marine Science Institution.

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