Assessing the Impact of Climate Change on Storm Surges in Southern Australia

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EXTENDED ABSTRACT

Global warming induced increases in mean sea level and possible changes to weather patterns that drive extremes of sea level such as storm surges are likely to increase the frequency and severity of coastal flooding and erosion in the future. Information about the present threat of storm surges and how this threat will change in the future is essential to assess the impact of climate change on the coast and to subsequently formulate adaptation responses to changing climate conditions.

Tide gauge data provides an opportunity to evaluate the average recurrence intervals of extreme sea levels. However the often short duration of records collected at many gauges prevents a reliable analysis of extreme event probabilities. Furthermore, the limited number of tide gauges means that large stretches of coastline are without direct data coverage to enable an assessment of this hazard even under present climate conditions let alone future conditions due to greenhouse warming.

Along Australia's south coast, storm surge events are driven by severe weather events such as cold fronts and mid-latitude storms. The strong winds and falling pressure elevate sea levels in the vicinity of the coast. Many of the events affect large stretches of coastline leading to a high coherence of the storm surge signal in the available tide gauge records. This aspect has been exploited in the design of an approach to quantify the storm surge hazard over a large stretch of coastline.

The severity and frequency of storm tide events in the future will increase with rising sea levels and additionally, climate change may also change the frequency and intensity of the meteorological drivers of storm surge. The modelling framework for assessing the current climate storm surge hazard must be flexible enough to allow exploration of future climate change scenarios and their associated uncertainty, bearing in mind that estimates of future climate change are undergoing constant refinement and revision.

The modelling approach described here has been developed with these issues in mind. In this paper it has been used to estimate the impact of climate change on storm surge return periods over the southeastern Australian coastline. The approach requires the identification of a large population of extreme sea level events from tide gauge records along the stretch of coastline of interest, and modelling each event with a hydrodynamic model. Extreme value analysis is then applied to the modelled events to enable the generation of event probabilities and return periods for storm surge. Joint probability analysis is then used to combine the tide with the storm surge to produce storm tides. The impact of climate change on storm surge return periods and inundation extent is investigated by considering the wind speed changes simulated by a range of climate models, as well as projected increases in mean sea level.

The results indicate that under current climate conditions, the modelling approach yields results at the locations of tide gauges that are consistent with results obtained by directly analysing the tide gauge data. Under future climate conditions it is found that a 1 in 100 year storm tide level estimated for the late 20th century would occur every 10 years or less under a 2030 high sea level rise scenario once every 4 years or less for a 2070 high sea level rise scenario. Wind speed changes over the region of interest may increase or decrease but will have a considerably smaller impact than sea level rise.

In ongoing work the approach will be extended to broader coastal regions by including additional tide gauge data for selection of extreme sea level events and using the model to develop tidal information over the same coastal region.

1. INTRODUCTION

Coastal populations around the world are increasing significantly. It is estimated that currently, over 150 million people live within 1 metres of the high tide (Church et al., 2007).

As coastal communities increase in size, their exposure to extreme sea level events increases. Combined with the increase in frequency and or intensity of the hazard itself, as the climate changes, there is an urgent need to evaluate the likely future threat from sea level extremes. In doing so, coastal communities can assess their vulnerability, their adaptation options and implement appropriate management strategies.

This study provides a methodology that combines hydrodynamic modelling and statistical analysis to quantify the storm surge hazard under current and future climate conditions. The methodology is applied to the eastern Victorian coastline in Australia.

The remainder of this study is organised as follows. The next section describes the methodology, the model and the climate change scenarios. This is followed by results and finally a summary and brief discussion of future work.

2. STUDY REGION AND METHOD

The approach adopted in this study exploits the fact that extreme sea level events are highly coherent along the Australian south coast. In other words, an event recorded at one tide gauge will usually register at the other gauges in the region because the dominant forcing mechanism is the west to east moving cold front which brings westerly to southwesterly winds to the region (McInnes and Hubbert, 2003).

2.1. Selection of extreme sea level events

The data from three tide gauges located at Portland, Point Lonsdale and Lakes Entrance (Figure 1) were used to identify extreme sea level residual events due to their length, completeness and spatial coverage of the northern coastline of Bass Strait. The data were filtered using the method of Godin (1972) to remove the tidal signal. Data gaps in the records were then filled by developing linear regression relationships between these records and other available records and selecting the most highly correlated gauge for which data was available.

The events were defined as episodes during which sea level residuals exceeded a threshold, μ m. A μ value of 0.20 m was selected for Point Lonsdale and linear relationships between the Point Lonsdale time series and the other two time series indicated that appropriate thresholds for Portland and Lakes Entrance were 0.15 and 0.14 m respectively.

Since a single weather event may elevate the sea levels at a number of tide gauges as it propagates through the region, the events identified at each of the three tide gauges were checked for overlapping dates and merged into a single set which encompassed the earliest start date (minus 24 hours to allow for model spin-up) and the latest completion date. A total of 489 events were selected from an effective 38 years of data, the duration of each event ranging from 2 to 11 days.

The modelling of the individual events rather than the entire 38 year time period and subsequently identifying extreme events in the modelled data was adopted to maximise computational efficiency and minimise data storage.

2.2. Hydrodynamic modelling

The model used in this study is a two-dimensional hydrodynamic model known as GCOM2D (Hubbert and McInnes, 1999) which solves the depth-averaged hydrodynamic equations for currents and sea levels. The regions over which the model is run in this study are shown in Figure 1; the entire region comprising the outer grid at 1 km resolution and the two rectangles defining the Corner Inlet and Gippsland Lakes grids at 100 and 50 m respectively.

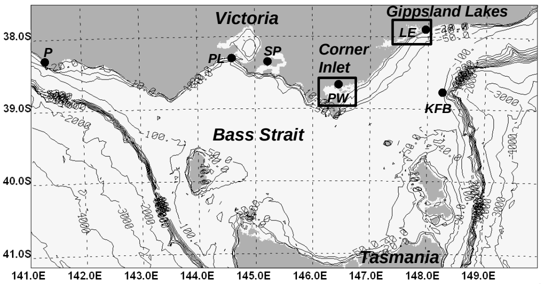

Figure 1. The region covered by the 1 km resolution Bass Strait storm surge model with rectangles indicating the Corner Inlet and the Gippsland Lakes grids. P=Portland, PL=Point Lonsdale, SP=Stony Point, PW=Port Welshpool, LE=Lakes Entrance, KFB=Kingfish B platform.

Topographic and bathymetric data for the 1 km grid were obtained from the AUSLIG 9 second DEM (Version 1) (http://www.ga.gov.au/nmd/products/digidat/dem_9s.htm) and the Geoscience

Australia (formerly AGSO) 30 second bathymetry data set. Higher resolution Digital Elevation Models were available for Corner Inlet and the Gippsland Lakes and these data were used to define the elevations on the high resolution model grids as well as refine the 1km grid elevation data in these locations.

The currents and sea levels modelled on the 1km grid, are stored at hourly time intervals, to provide boundary conditions for the higher resolution grids using a one-way nesting technique.

The simulation of storm surges requires that the hydrodynamic model be forced with 10 m winds and surface pressure. These were obtained from the U.S. National Center for Environmental Prediction (NCEP) reanalyses (Kalnay et al., 1996). Wind fields at 10 m above the surface were available on a 1.875°×1.875° global grid and the mean sea level pressure fields were available on a 2.5°×2.5° global grid every 6 hours from 1958 onwards. The NCEP data were interpolated spatially and temporally to the GCOM2D grids.

At the conclusion of each storm surge simulation, the maximum sea level simulated by the model at each grid point was stored yielding an array of peak sea levels for each event.

2.3. Extreme event analysis

Since the population of events identified in the tide gauge records represents only a 38 year period, extreme value statistical methods were applied to the set of modelled extremes to estimate return levels over longer time intervals. Two approaches are commonly used in the analysis of extremes. The first uses the Generalised Extreme Value (GEV) distribution in which the extreme events are grouped into regular (e.g. annual) time intervals and the GEV is fitted to the maximum value from each interval. A common criticism of this approach is that much of the available data is not used in the fitting procedure. The second approach is the extremes-over-threshold approach using the Generalised Pareto Distribution (GPD) in which the GPD is fitted to data in a sample that exceeds a certain high threshold. Both methods were investigated for their suitability in this study and found to produce similar results for selected locations (not shown). The implementation of the GPD required a number of subjective decisions in the fitting procedure and so was difficult to automate across the spatial domain of the hydrodynamic model. It was decided therefore to adopt a modified GEV approach known as the 'r-largest' approach (see Coles, 2001) in which the r-highest values per year are used in the fitting procedure. A value of r=4 was found to yield optimal results.

2.4. Estimation of Storm Tide Levels

Storm tides are the combination of the storm surge with astronomical tide. The peak storm tide to occur during a storm surge event depends upon the tidal variation during the surge which range not only from low to high tide but also from a smaller tidal range at neap tides to a larger range at spring tides.

The method applied for combining surge and tide distributions follows the approach described in Pugh and Vassey (1980). Probability density histograms were developed for the tidal heights by running a tide model (Foreman, 1977) over a full astronomical (18.6 year) cycle and binning the tide values. The data from tide gauges at Stony Point in Westernport Bay, Port Welshpool in Corner Inlet and Lakes Entrance were used for this purpose. Tidal constituents for these gauges, evaluated by the National Tidal Centre (Australian Bureau of Meteorology), were used to predict the tides and develop tide height frequency distributions.

A tide randomly sampled from the high tide distribution was added to a surge randomly sampled from the GEV probability distribution and summed to produce a storm tide at each grid point of the storm surge model. A total of 10,000 combinations of surge and tide were sampled, summed and ranked from largest to smallest. The return levels were calculated using $R = N / r$ where R is the return level, N is the number of random samples and r is the rank of the event.

2.5. Estimation of Inundation

Dynamic inundation algorithms described in Hubbert and McInnes (1999) are not suitable in the present study because the total sea level from surge, tide and sea level rise are not modelled implicitly but combined separately. Therefore a simpler method for estimating inundation was devised in this study for use after the total sea level was calculated.

Dry land points were reclassified as inundated points by carrying out sweeps across the model grid from east to west, west to east, north to south and south to north and comparing the height of the coastal sea level to the adjacent land point. If the sea level exceeded the land height, the land point was inundated to the level of the adjacent sea point. The advantages of this simple approach are; (1) the area of inundation for a range of storm tide return levels can be easily estimated once the extreme value and joint probability analyses are complete; (2) it is computationally inexpensive to explore a range of future sea level rise scenarios and (3) the inundation can be estimated on a higher resolution grid than that used for the storm tide modelling and also easily revised if and when more accurate terrain data becomes available.

2.6. Climate Change Scenarios for Wind and Sea Level Rise

Projections of future wind speed changes were developed from an analysis of climate models in which the range of responses between different climate models were extracted using the pattern scaling technique of Whetton et al., (2005). In this, the time series of wind speed at each model grid point is linearly regressed against the model's globally averaged temperature time series to yield a map of wind speed change per degree of global warming. Thirteen models were selected from a larger set of models on the basis that they most accurately reproduced the observed seasonal temperature, rainfall and mean sea level pressure patterns over the 1961 to 1990 time interval (see McInnes et al., 2005 for more details). The model response patterns were interpolated to a common 0.5×0.5°lat/long grid for the purpose of ranking the models to identify the highest and lowest responses of the models to greenhouse gas forcing (in practice only the second highest and second lowest climate responses were used to avoid the influence of significant outliers in the estimation of the range of possible change). Once the range of spatial response was evaluated, scenarios of future wind speed changes were developed for two future years by multiplying the patterns by the range of global warming projected by the IPCC (2001) at the particular future year. The projections developed in this way take into consideration three sources of uncertainty: (1) that of future emissions of greenhouse gases, as deemed plausible by the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (IPCC, 2000); (2) the uncertainty in the sensitivity of the climate system to greenhouse gas emissions, as represented by the thirteen models; and (3) the spatial variations of change simulated by the different models. Scenarios of annual mean wind speed changes, expressed as a percentage change relative to average wind speeds over the period from 1961 to 1990, are presented in Table 1.

These indicate a change of 1±2% for 2030 and approximately 3±7% for 2070. Similar mid-range changes are estimated for the annual 95th percentile wind speed, which are approximately 1±3% for 2030 and 3±8% for 2070, indicating that the variations across climate models for the 95th percentile wind speeds were only slightly larger than for the mean wind speeds. Therefore, the mean wind speed changes were applied as a uniform change to the wind speeds forcing the storm surge model. More details on the climate change responses including the seasonal changes can be found in McInnes et al (2005). Sea level rise scenarios obtained from IPCC (2001) are also shown in Table 1.

Table 1: Projected annual and winter wind speed changes for the Bass Strait expressed as a percentage relative to climatological wind speeds for the 1961 to 1990 period. The low and high values are obtained from the lowest and highest ranked responses of thirteen climate models.

Variable	Low	Mid	High
2030			
Wind Speed (m/s)	-1	1	3
Sea Level Rise (m)	0.03	0.10	0.17
2070			
Wind Speed (m/s)	-5	3	10
Sea Level Rise (m)	0.07	0.25	0.49

3. RESULTS

3.1. Model Performance

We focus briefly here on the agreement between the entire population of modelled and observed event peaks since this will indicate the degree of similarity between return levels estimated from observed and modelled event peaks. A more detailed analysis (not presented here) of the storm surge model performance has indicated that both the NCEP winds and the surge model are performing well for the purposes of this study. Figure 2 shows a regression between the ranked peak sea levels from the model simulations and those from the observations. Clearly the modelled and observed event populations show close agreement with each other indicating that the modelling approach applied in this study will be suitable for the purpose of developing event probabilities and return levels.

3.2. Storm surge

Return levels for storm surge based on the model results for the 10, 20, 50 and 100 year levels are presented in Table 2. The results for Stony Point were obtained from the low resolution Bass Strait simulations while the results for Port Welshpool and Lakes Entrance were obtained from the high resolution Corner Inlet and Gippsland Lakes simulations.

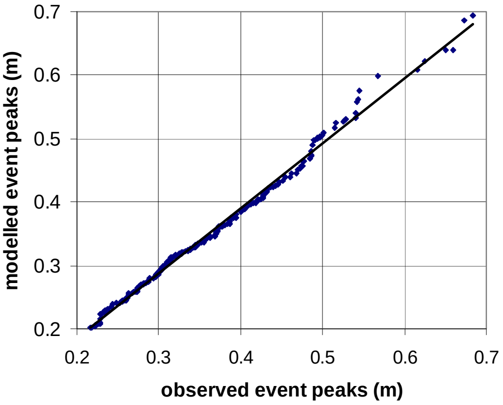

Figure 2: Regression of ranked observed versus ranked modelled maximum sea level residuals for each event at Stony Point.

Table 2: Storm surge return levels and 95% confidence intervals for locations along the coast. All heights are relative to mean sea level.

	Return Level (m)			
Location	**10 yr**	**20 yr**	**50 yr**	**100 yr**
Stony Point	0.62 ±0.04	0.65 ±0.05	0.69 ±0.06	0.71 ±0.07
Port Welshpool	0.46 ±0.04	0.49 ±0.04	0.52 ±0.05	0.54 ±0.06
Lakes Entrance	0.59 ±0.02	0.62 ±0.02	0.64 ±0.03	0.65 ±0.03

The spatial pattern of storm surge height across Corner Inlet and the Gippsland Lakes is illustrated in Figure 3. There is considerable variation in height along the coastlines. In Corner Inlet, Port Welshpool has a 1 in 100 year level of 0.54±0.06m compared with Port Franklin to the west (0.81±0.12m) and Port Albert to the east (0.63±0.04m). In general, storm surges are highest in the north of the inlet with values exceeding 0.7 m. This is due to wind set up when the wind direction is from a southerly direction such as occurs when a low pressure system is in the southern Tasman Sea. Similarly in the south of Corner Inlet, wind can cause local set up during periods of pre-frontal northeasterly winds. Relatively low sea levels of between 0.4 and 0.5 m occur along the coast to the east of Port Welshpool in the lee of the islands in the entrance to the inlet. Sea levels increase to between 0.5 and 0.6 m from Port Albert eastwards.

Elevated sea levels along the open coastline adjacent to the Gippsland Lakes are most commonly caused by the southwesterlies that accompany the passage of cold fronts. These produce sea level elevations on the open coastline that exceed 0.7 m at the 100 year return level (Figure 3b). The narrow entrance to the Gippsland Lakes significantly limits the transfer of water from Bass Strait. This is evidenced by the strong attenuation of particularly the high frequency constituents, across the entrance to the Lakes.

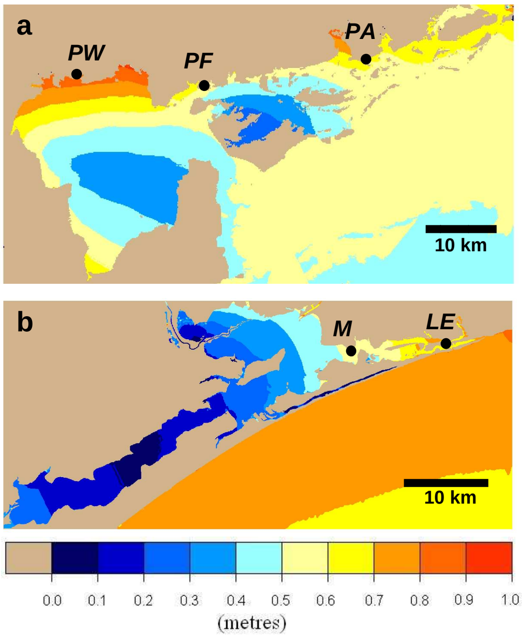

Figure 3: The spatial pattern of the 1 in 100 year storm surge heights (m) for (a) Corner Inlet and (b) Gippsland.

Within the Lakes, sea levels are highest in the northeast with values exceeding 0.6 m just inside the entrance. The amplification of sea levels in the northeast occurs as a result of wind setup from the prevailing southwesterly winds that occur in the majority of events. Throughout the Lakes, sea levels decrease towards the southwest. The maintenance of relatively high sea levels just inside the entrance due to wind setup means that only small differences in height occur across the entrance to drive down-gradient flow from the open coastline into the Lakes. This implies that the dynamics within the Lakes may be relatively independent of the sea levels occurring on the open coastline during such events.

3.3. Storm tides

The storm tide return levels are shown in Table 3. The tidal range is greatest at Stony Point and diminishes further to the east. It is interesting to compare the results of this study with those of an earlier unpublished study by Tawn and Mitchell (hereafter referred to as TM, Bill Mitchell, Pers.

Comm.) (see Table 3). In that study the GEV (r=1) approach was used to evaluate the 100 year storm tide return periods directly (as opposed to analysing the surge and tide components separately as is done here) at a number of Australian tide gauges. The TM values are slightly lower than those of the present study and this is likely due to the shorter records available at the time that the TM analysis was undertaken.

Table 3: Comparison between 100 year storm tide heights estimated in the present study and those estimated by Tawn and Mitchell (1990) for locations along the coastline of eastern Victoria.

100 year storm tide	Stony Point	Port Welshpool	Lakes Entrance
This study	2.08 ± 0.07	1.62 ± 0.06	0.96 ± 0.03
TM	2.00 ± 0.05	1.60 ± 0.07	0.96 ± 0.04

The estimated future storm tide values based on changes to both sea level and wind speed are given in Table 4 for 2070 and show that even under a worst case wind speed scenario (that of more severe wind speeds in the future), the increase in storm surge height due to the stronger winds will be smaller overall than the projected worst case rise in sea level. Under the best case of decreasing wind speed, the reductions in storm surge height will be cancelled out by the low range of projected sea level rise. These results point to a change of extreme sea level events in 2070 along this coastline that range from; at best, little change from current climatology to at worst, more severe storm surge events.

Table 4: Storm tide return levels under current climate and 2070 low, mid and high scenarios of wind and mean sea level rise.

Location	Current Climate (m)	2070 Low (m)	Mid (m)	High (m)
Stony Point	2.08	2.13	2.43	2.72
Port Welshpool	1.62	1.65	1.92	2.24
Lakes Entrance	0.96	1.00	1.27	1.59

Figure 4 illustrates the return period curves at Port Welshpool under high sea level rise and wind speed scenarios for 2030 and 2070. These show that a current climate 100 year event becomes a 20 year event in 2030 and a 4 year event in 2070.

The inundation over Corner Inlet resulting from the 2030 and 2070 high scenarios is greatest across the mangrove islands and northern coastline of the inlet, although due to the low-lying coastal terrain, much of the flooding occurs under a current climate 1 in 100 year event (Figure 5). The inundation in the vicinity of the towns of Port Franklin, Port Welshpool and Port Albert increases by between 15% and 30% by 2070 under a high wind speed change, high mean sea level rise scenario.

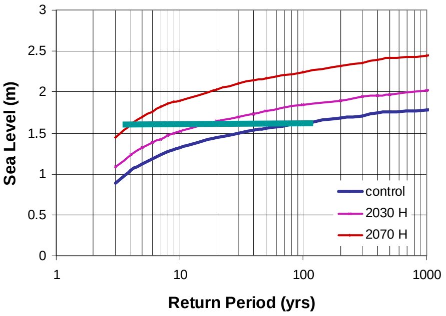

Figure 4: The 1 in 100 year storm surge heights at Port Welshpool under current and future conditions.

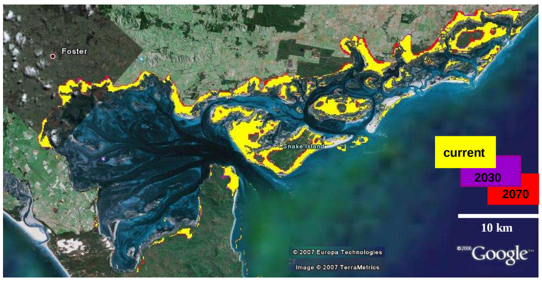

Figure 5: The spatial pattern of inundation over Corner Inlet under present and high wind and sea level rise scenarios for 2030 and 2070.

4. SUMMARY AND FUTURE WORK

This study describes a methodology that has been developed for estimating extreme sea levels under current and future climate conditions. Storm tide return periods for current climate conditions are found to agree well with comparable studies of tide gauge data in this region. The key features of the methodology are (1) the modelling of historical events to establish a reliable baseline from which to estimate the effects of climate change, (2) the use of hydrodynamic modelling to provide information along the entire modelled coastline and (3) its flexibility in enabling the exploration of a range of climate change scenarios on storm tide height and inundation.

Future work includes using the hydrodynamic model to also model the tides to enable statistics on tide heights to be generated spatially (as opposed to simply generating results in the vicinity of tide gauges where tidal constituents are known). The procedure involves using the hydrodynamic model to simulate several tidal cycles. These are then analysed using standard tidal analysis procedures to extract the tidal constituents which can then be used to predict tides over longer time intervals so that tide height distributions can be estimated for the joint probability analysis. Preliminary results from this procedure which have enabled the estimation of a spatial map of 99th percentile tide heights is shown in Figure 6. This illustrates the complex tidal pattern in Bass Strait whereby the westward propagating tidal wave enters at the eastern boundary and also propagates around Tasmania to enter from the west about three hours later. The net effect is that the flood tide enters Bass Strait from both the east and the west producing tidal maxima across the centre of the Strait. Future work will focus on refining the tide heights for the joint probability analysis.

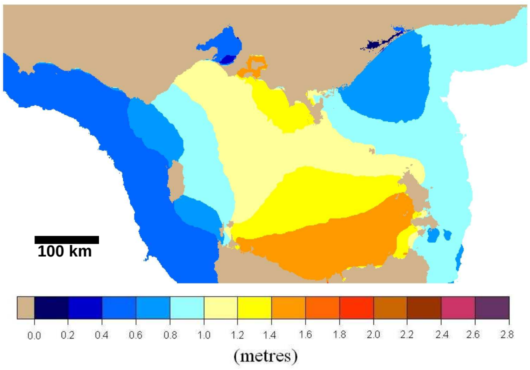

Figure 6: The spatial pattern for the 99th percentile high tide heights (m).

Work has also commenced on increasing the spatial coverage of the modelled storm surges. The modelling of storm surges on the 1 km Bass Strait particularly to the west requires that the events also be modelled over a larger region, to provide lateral boundary conditions for the 1 km grid. Figure 7 illustrates a 5 km grid used for this purpose. When the selected events are simulated on this grid and the return periods evaluated, a storm surge signature can be seen at locations further to the west of Bass Strait and along Tasmania's south coast. This is because extreme sea levels along these coastlines are mostly generated by the eastward moving cold fronts which influence this broader geographical region also. It should be noted however, that the 100 year storm tide patterns shown in Figure 7 are reliable only along the northern Bass Strait coast where the three tide gauges used for selection of surge events are located. Outside the region spanned by these gauges, additional weather events may contribute to severe storm surges. This will be addressed in future work by increasing the number of tide gauges from which extreme events are selected for modelling.

The preliminary results presented here illustrate that the approach developed in this study will be applicable over a more extensive coastal region. It therefore offers a potentially valuable method for evaluating storm tide risk over large coastal regions to provide information to coastal planners of the relative vulnerability of different stretches of coastline to extreme sea level events both now and in the future.

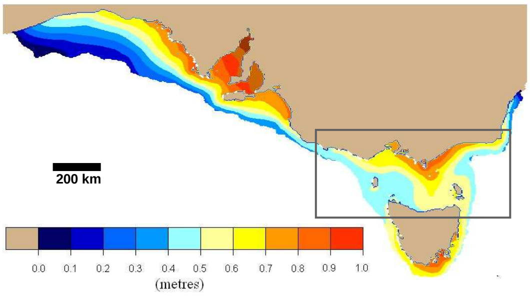

Figure 7: The pattern of the 1 in 100 year storm surge heights (m) for the 5 km grid in which the 1 km grid, indicated by the rectangle is nested.

5. REFERENCES

Church, J.A., Nicholls, R., Hay, J.E. and Gornitz, V., 2007: Ice and Sea-level Change, in Global Outlook for Ice and Snow, Ed. Joan Eamer, United Nations Environment Programme, 235pp (ISBN: 978-92-807-2799-9).

Coles, S.G., 2001: An Introduction to Statistical Modeling of Extreme Values. Springer.

Foreman, M. G., 1977: Manual for tidal heights analysis and prediction. Institute of Ocean Sciences, Victoria, B. C., Canada, 98pp.

Godin, G., 1972: The Analysis of Tides. University of Toronto Press.

Hubbert, G.D., and McInnes, K.L., 1999: A storm surge inundation model for coastal planning and impact studies., J. Coastal Research, 15,168-185.

IPCC, 2000: Special Report on Emission Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press.

IPCC, 2001: Climate Change 2001: The Science of Climate Change. Summary for Policymakers and Technical Summary of Working Group I Report. Intergovernmental Panel on Climate Change. Cambridge University Press, v+ 98 pp.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, B. Reynolds, M. Chelliah, W. Ebisuzaki, W.Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R.Jenne, and D. Joseph, 1996: The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc., 77, 437–471.

McInnes, K.L., and Hubbert, G.D., 2003: A numerical modelling study of storm surges in Bass Strait. Aust. Met. Mag. 52, 143-156.

McInnes, K.L., Macadam, I., Hubbert, G.D., Abbs, D.J., and Bathols, J.A., 2005: Climate Change in Eastern Victoria Stage 2 Report: The effect of climate change on storm surges. CSIRO Report for the Gippsland Coastal Board. 37pp.

Pugh and Vassey 1980: Application of the joint probability method for extreme sea level computations. Proc.Instn.Civ.Engrs, 69: 959-975.

Whetton, P.H., McInnes, K.L., Jones, R.N., Hennessy, K.J., Suppiah, R., Page, C.M., Bathols, J.A., and Durack, P., Climate change projections for Australia for impact assessment and policy application: A review. CSIRO Technical Paper.