QUANTIFYING CLIMATE CHANGE AND DETERMINING FUTURE COASTAL DESIGN STORMS FOR EASTERN AUSTRALIA

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Coastal inundation has both potential marine and inland contributions. Using a suite of Global Circulation Models, their skill in representing the key fundamental coastal engineering design forcings (mean sea level pressure, wind and precipitation) has been quantified at the 20 year ARI. Skill is assessed by comparison with measured and assembled data along the temperate east Australian coast. Clear extreme distributions are available from GCM output which show no sign of saturation within the tails of extreme distributions. Extreme surface pressures and winds are comparable with the available data giving confidence to the coastal engineering community that GCMs provide data that is suitable for coastal engineering design. GCMs also provide much longer and more detailed data than is available from equivalent measured records. When changes under the A2 scenario are considered, the consensus of the models is that little change in 20 year extreme surface pressures and rainfall are anticipated over the next 100 years with an accompanying 10% decrease in design wind.

Keywords: climate change; coastal inundation; design

INTRODUCTION

Peak loadings due to wind at the coast are reasonably straightforward to determine. These are based on characterisations of the atmospheric boundary layer and statistical distributions based on wind data that are part of routine meteorological observations (e.g. AS/NZS 1170.2:2011). However, determining impact due to coastal inundation is a much more complex process as there are potentially both maritime and hinterland contributions which are more difficult to determine.

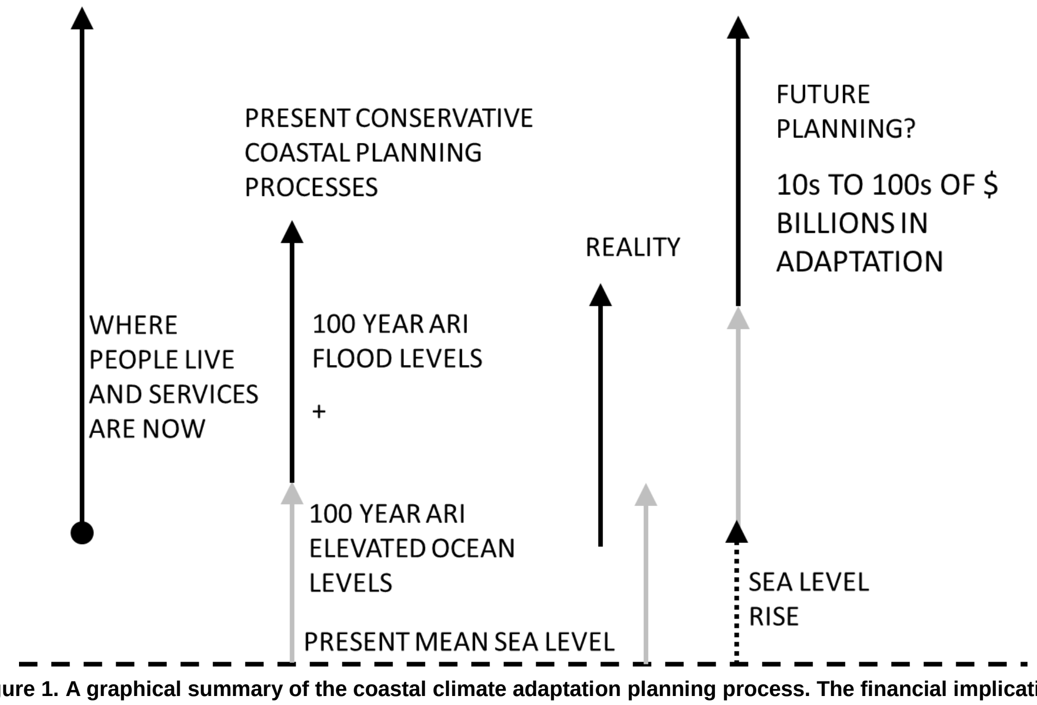

Figure 1. A graphical summary of the coastal climate adaptation planning process. The financial implications of climate adaptation in Australia are significant. Some existing development is already regularly impacted by coastal inundation and methods of determining the frequency of coastal inundation due to floods and elevated coastal ocean water levels are required.

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Water levels at the coast become elevated by a complex combination of high astronomic tides, reduced atmospheric pressure, onshore winds and wave breaking at coast (CEM, 2006, Part II-5). Storm waves are wind-generated. Especially during cyclonic conditions, there is a tendency for extreme low pressures, strong winds and high waves to occur concurrently and cause extreme inundation. Coastal-generated surges can propagate many tens of kilometres inland either via direct overland inundation or via the estuarine systems that drain coastal river basins.

Interaction between intense coastal storms and coastal topography also triggers precipitation within coastal river basins. Runoff from these storms will elevate river and estuary water levels as flood waters drain from the catchment to the coastal ocean. Consequently, flooding can arise from storm effects coming from both within the catchment and the adjacent ocean with possible conjunction of the contributions, especially during low pressure events.

Determining the conjunctive probability of the relative contributions of rainfall runoff, coastal extreme water levels and storm wave attack remains a longstanding coastal engineering problem. One conservative approach has been to assume coincident occurrence of contributing factors at a specified recurrence interval or annual exceedance probability. An additional freeboard allowance may also be specified for design (e.g. DECCW, 2009).

Coastal guidelines developed in the late 20th century recognised past rises in sea level (NCCOE, 1991), anticipated that this would continue and recommended that appropriate allowances be made over the life of any coastal development project. More recently, the possibility of accelerated sea level rise has been raised (see Watson, 2014 for a recent summary of this debate), highlighting to coastal communities and governments that increased adaptation of coastal settlements and infrastructure may be required to ameliorate the risk of coastal inundation. Questions are now being raised regarding the adaptive capacity provided by existing coastal design guidelines and the level of risk faced by coastal development that may have been constructed with and without proper consideration of possible sea level rise.

These questions are particularly relevant to Australia where around 85 per cent of the population now live in the coastal region and it is of immense economic, social and environmental importance to the nation. All Australian state capital cities are located within the coastal zone. Up to $63 billion of existing residential buildings are potentially at risk of inundation from a projected sea-level rise of 1.1m (DCC, 2009). Australia's most populous state, New South Wales with the bulk of its major cities and commercial centres within the coastal strip is particularly vulnerable. Present levels of adaptive capacity to climate change in Australia are unknown and development of suitable quantitative assessment methods are required.

The principal issues are summarised in Figure 1 and are as follows:

1. Present development reflects past (and sometimes poor) planning such that some settlements and infrastructure may be regularly impacted by coastal flooding.
2. Improved guidelines, developed since the 1970s, now incorporate an appropriately conservative approach to coastal planning. At their most fundamental level, risk is addressed by assuming that rare flood and coastal inundation events occur simultaneously.
3. Although there tends to be some degree of correlation between flooding and coastal inundation, they are not identically correlated (e.g. Zheng *et al*., 2013).
4. As mean sea level rises, the financial implications for coastal adaptation are potentially economically crippling.

The development of global climate and other general circulation models (GCMs) has provided opportunities to resolve this issue. However, shortcomings in their ability to depict tropical cyclonic formation and intensification are well established (Emmanuel et al., 2008). In addition, such models exhibit different skill levels for critical primary state variables (e.g. central pressure, maximum pressure gradient, precipitation, wind speed see (Lambert & Fyfe, 2006; Bengtsson et al., 2007; Caron & Jones, 2008). Nonetheless, it is anticipated that GCM resolution and internal physics will steadily improve over coming decades.

Whilst Emmanuel et al. (2008) have developed a technique to address issues associated with tropical cyclone formation (noting that these are extremely computationally intensive), many highly populated areas (particularly the east coasts of the United States and Australia) are primarily impacted by larger-scale extratropical systems (Shand *et al*., 2010). Extratropical low pressure systems are of sufficiently large scale to be resolved by GCMs and global reanalysis data sets (NCAR-NCEP and ERA-40, Sinclair and Watterson, 1999; Wernli and Schwierz, 2006).

GCMs offer a means of augmenting numerically the limited available recorded historical data. A major concern associated with GCM application is the degree to which storm intensity is attenuated by the limited spatial resolution and the computational economy in key storm intensification processes of the GCMs.

A variety of downscaling techniques have been proposed (e.g. Wilby & Wigley, 1997; Mearns et al., 1999). In general, these are computationally intensive and all may inherit weaknesses of the utilized GCM estimates, as these estimates are required source data for the downscaling process.

This contribution describes a preliminary assessment of the performance of Global Circulation Models (GCMs) as a function of latitude along the temperate east coast of Australia. The eventual purpose of this work is to resolve the conjunctive probability of the maritime and land-based contributions to flooding and coastal storm damage (Peirson et al., 2012). This present contribution begins by describing the available data (both measurement and numerical model), the methodology adopted and associated processing techniques. The study results are then presented with discussion of their significance. Conclusions and recommendations for future investigations presented within the final section.

METHOD

Measured Data Sources

Surface pressure, precipitation and wind observational data has been sourced from several long-term stations along the Australian temperate East Coast covering the range of latitudes 25° to 45°S (Figure 2). Meridional spacing between the stations is approximately 2°. Selection was made based on recorded data quality for the period between 1960 and 2000. Although the available data may be recorded at a higher frequency than a daily interval, in each case the data was averaged to a daily interval to provide comparable temporal resolution to the GCM outputs.

The wind data was vectorised into its zonal (u) and meridional (v) directions and onshore easterly winds (also termed to be in a –u direction) were selected for comparison as these approach the coast in an approximately shore normal direction.

Figure 2. The selected Australian east coast observation stations

Global Circulation Model Data

Global Circulation Models are numerical representations of the climate system, which are used to increase the understanding of past and current climates, and to provide projections of future climates (e.g. Perkins and Pitman, 2009). GCMs aim to solve the fundamental equations of physics at each grid cell subject to the relative parameters, at each incremental time step, in order to capture the climatic interactions resulting from complex atmospheric and oceanic physical processes including energy, momentum and mass conservation as well as associated equations of state.

Table 1. CMIP3 GCMs used in present assessment

Model ID	Sponsor, Country	Horizontal Resolution (°)
CSIRO-Mk3.0	Commonwealth Scientific Industrial and Research Organisation, Australia	~ 1.9° x 1.9°
CSIRO-Mk3.5	Commonwealth Scientific Industrial and Research Organisation, Australia	~ 1.9° x 1.9°
GFDL-CM2.0	Geophysical Fluid Dynamics Laboratory, United States of America	2.5° x 2.0°
GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory, United States of America	2.5° x 2.0°
GISS-ER	NASA/ Goddard Institute for Space Studies, United States of America	5.0° x 4.0°
NCAR-CCSM3	National Centre for Atmospheric Research, United States of America	~ 1.4° x 1.4°
MIUBEG ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model & Data Group, Germany/ Korea	~ 3.9° x 3.9°

Daily data for comparison with the observations has been sourced from the seven GCMs listed in Table 1 climate models used within the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report (AR-4). All relevant model data covering the scenarios and regions of interest has been obtained from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl et al., 2007). Daily precipitation, mean surface level pressure and wind speed were extracted at the land and ocean cells zonally adjacent to each observation location. Land and their adjacent ocean cells were sampled to assess whether there is significant difference in the modelled variables at the coastal boundary.

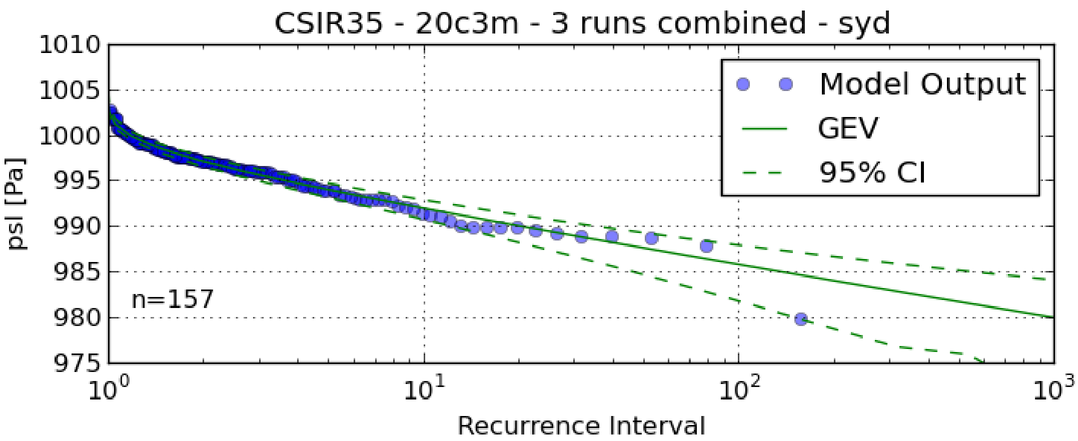

Figure 3. Extreme value distribution of mean sea level pressure at Sydney obtained from the run ensemble 20th Century (20c3m) GCM land cell results obtained from the CSIRO-Mk3.5 model. Points indicate the model values, the lines indicate the fitted extreme value distribution and 95% confidence limits.

Model results from two scenarios were used. These include the Climate of the 20th Century experiment (20c3m) and the 21st Century SRES A2 experiment (sresA2). The 20c3m model is a representation of 20th Century development and observed increases carbon dioxide (CO2) emission rates while the 21st Century models represent various socio-economic storylines with consequent changes in CO2 emission rates. The A2 scenario assumes that economic development is primarily regionally oriented and slower per capita economic growth and technological change (IPCC, 2007). This scenario predicts medium to high increase in CO2 emissions with climate models generally predicting higher increases in global temperature and sea level (IPCC, 2007). The 20th Century scenario produces results for the 1960 – 2000 period and the 21st century sresA2 scenario produces results for two output periods: 2044 – 2065 and 2080 – 2099.

Each 20th Century model comprises a number of Runs corresponding to differing initialisation times from a pre-industrial control experiment (PIcntrl). These initialisation times differ by between 10 and 20 years depending on the model. For example, the CSIRO-Mk3.0 20c3m Run 1 is initiated at from PIcntrl at the year 1870, Run 2 in 1880 and Run 3 in 1890 (Program for Climate Model Diagnosis and Intercomparison; http://www-pcmdi.llnl.gov/). The individual runs were combined to form an ensemble in each case.

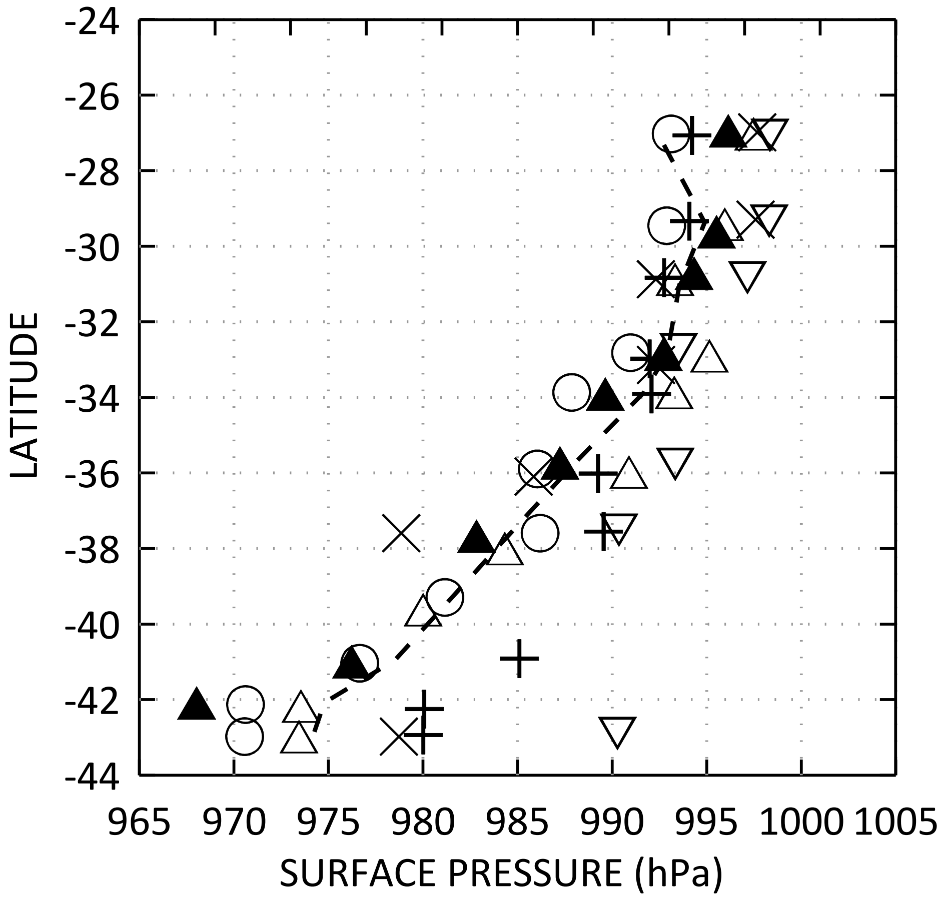

Figure 4. GCM coastal ocean predictions of 20 year ARI minimum surface pressure along the Eastern Australian coast from latitude 26°S to 44°S. CSIRO3.0: upright hollow triangle, CSIRO3.5: upright solid triangle, GISSER: downward pointing hollow triangle, GFDL2.0: hollow circle, GFDL2.1: +, MIUBEG: x. Measurements are indicated by the dashed line.

RESULTS AND DISCUSSION

This present investigation was focussed on answering three key questions that are central to the application of GCM data for coastal engineering design. These are as follows:

1. Do GCMs show signs of numerical saturation? Specifically, do extreme pressures, winds, precipitation reach ceiling levels that are not exceeded due to resolution or physics?
2. To what degree do GCMs replicate observed latitudinal variation in extreme values?
3. What changes in extreme values can be observed between climate of the 20th century (c30m) and plausible future climates (SRES A2)?

These questions are addressed in turn in the following sections.

Numerical Saturation

A representative data set from this investigation is shown in Figure 3 – in this case, mean sea level pressure from a CSIRO model. Three ensembles of model runs have been combined to generate an annual series of data equivalent to 157 years of record.

As shown, the extreme value distribution is well defined with no evidence of saturation of the model behaviour. This is representative of all models and all available state variables apart from the precipitation estimates provided by the GISS-ER model. These extreme value distributions were used to compare models with measured data.

Latitudinal variations in extreme values

As shown in Figure 3, to quantify extreme behaviour between measurements and models, there is a tradeoff between the size of the recurrence interval (or exceedance probability) and the degree of confidence in the estimate. As the recurrence interval increases, the uncertainty of the estimate also increases. For the purposes of this investigation, it was judged that 20 year ARI provided an appropriate balance of a sufficiently extreme event while maintaining an acceptable level of uncertainty. This is the basis of all comparisons presented subsequently in this paper.

Sea level pressures

As shown in Figure 4, there is a systematic decrease in the 20 year ARI 20c3m mean sea level pressure with increasing latitude (~1.25hPa/°). There are some differences of detail between the models but, in general, the meridional distribution of extreme storm intensity predicted by the models closely replicates the observations.

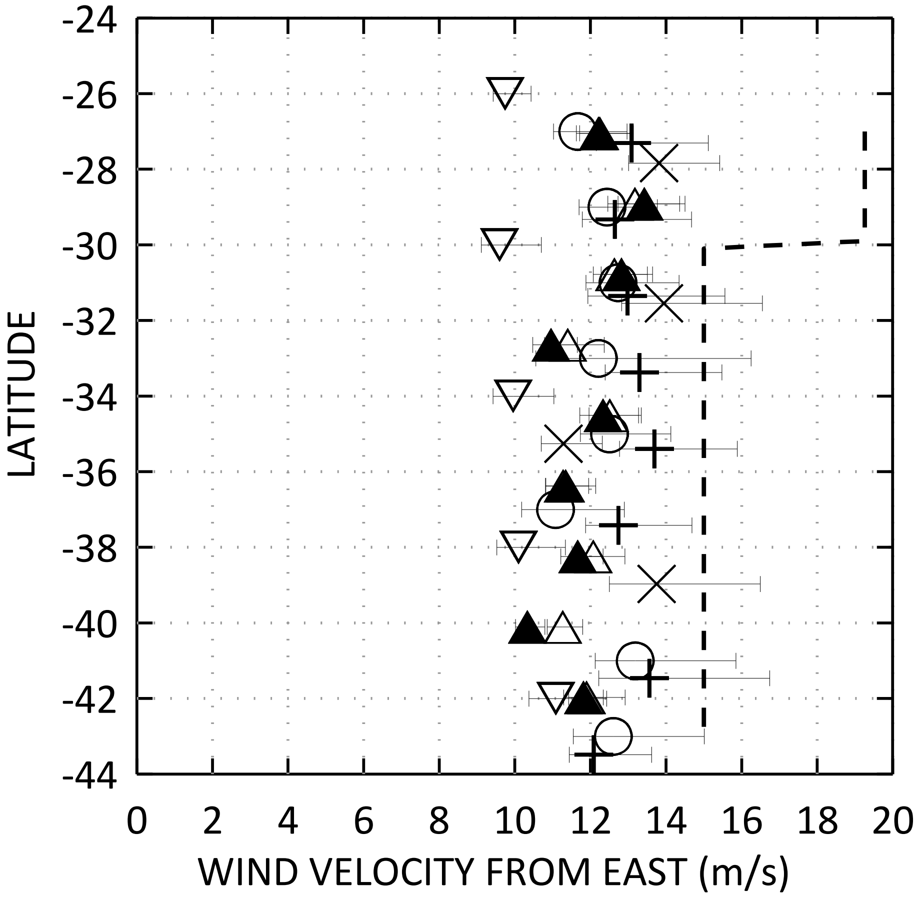

Figure 5. GCM coastal ocean predictions of 20 year ARI maximum mean daily wind speed along the Eastern Australian coast from latitude 26°S to 44°S. The error bars show the 90% confidence interval. Symbols are as shown in Figure 4. Design values derived from AS1170:2011 adjusted using CEM (2006) Figure II-2-1 are shown as the dashed line.

Winds

Winds over land are systematically lower than those over water, reflecting the relative smoothness of the sea. This was reflected in the model results over sea and land.

Longer term anemometer records usually only contain 9am and 3pm observations. This makes comparison of anemometer statistics with daily average model winds questionable. In addition, differences in air and sea drag as well as topographic steering can generate directional effects in coastal anemometer records.

Consequently, to assess the extreme winds estimated by GCMs we adopted an alternative approach. Design easterly winds from AS1170:2011 were transformed to 24 hour 20year ARI design values using Figure II-2-1 in CEM (2006). These were compared with the 20 year ARI 20c3m daily winds available from the GCMs. These results are summarised in Figure 5.

The change in the design velocity at 30°S reflects AS1170:2011 partition between cyclone and temperate wind design regions. The results are encouraging with the average of the model 20 year ARI wind intensities approximately 80% of the design code values. The absence of a significant meridional gradient in extreme wind south of 30° assumed by the code is also indicated by the models.

Precipitation

Precipitation biases in GCMs are well known (e.g. Perkins and Pitman, 2009). Similarly, the modelled 24 hour, 20 year ARI precipitations are up to a factor of 3 smaller than those recorded indicating systematic attenuation of the rainfall distribution tails.

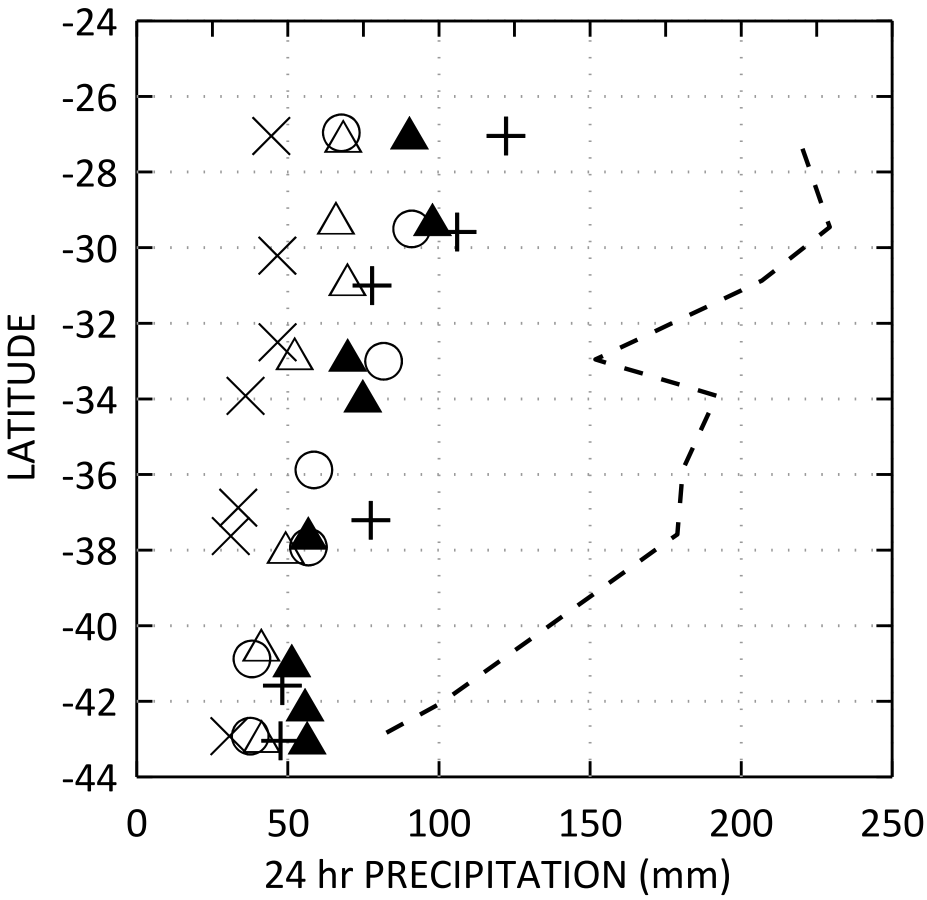

Figure 6. The change in GCM coastal ocean predictions of 20 year ARI maximum 24 hour precipitation along the Eastern Australian coast from latitude 26°S to 44°S. Symbols are as shown in Figure 4. Measurements are indicated by the dashed line.

Changes in extreme values with changing climate

Global warming anticipates a more unstable atmosphere and therefore more intense extreme storms. However, it is the net shift in (extreme) values at a given ARI/AEP that are crucial to engineering design.

During this present investigation, identical processing was applied to surface pressure, winds and precipitation available from the GCMs for the scenarios of AR2 2046-2065 and AR2 2081-2100. The 90% confidence intervals were also computed. A consequence of the differencing is that the size of the confidence interval becomes large relative to the size of the change. Summary findings are as follows:

1. No systematic change amongst the models or statistically significant change in 20 year ARI mean sea level pressure from 20th century climate up to 2100 A2 emission scenario can be discerned.
2. No systematic change amongst the models or statistically significant variation in 20 year ARI precipitation can be discerned up to 2100 horizon under an A2 emission scenario.
3. No systematic change amongst the models or statistically significant change in 20 year ARI mean winds under A2 emission scenario can be discerned to 2050.

However, over a 100 year time horizon, a systematic decrease in the onshore component of wind velocity between 0 and 2ms^{-1} is predicted at the 20 year ARI as shown in Figure 7. The computed 90% confidence intervals are large and the apparent asymmetry arises from the extreme value determinations. All these values should be amplified. Figure 5 indicates that a small bias correction (approximately 113%) should be applied to these results.

Nonetheless, the shift in wind speed is systematic across the GCMs investigated and encourages overall confidence in the findings. An overall reduction of order 10% in design wind speeds is anticipated.

As wind stress and fully-developed deep water wave height (CEM, 2006, p. II-2-44ff) both increase quadratically with wind speed, wind set up and initial coastal breaking wave heights are anticipated to *decrease* by ~20% under an A2 emission scenario. At 90% confidence, it is not anticipated that they will increase or decrease by more than a factor of 50%.

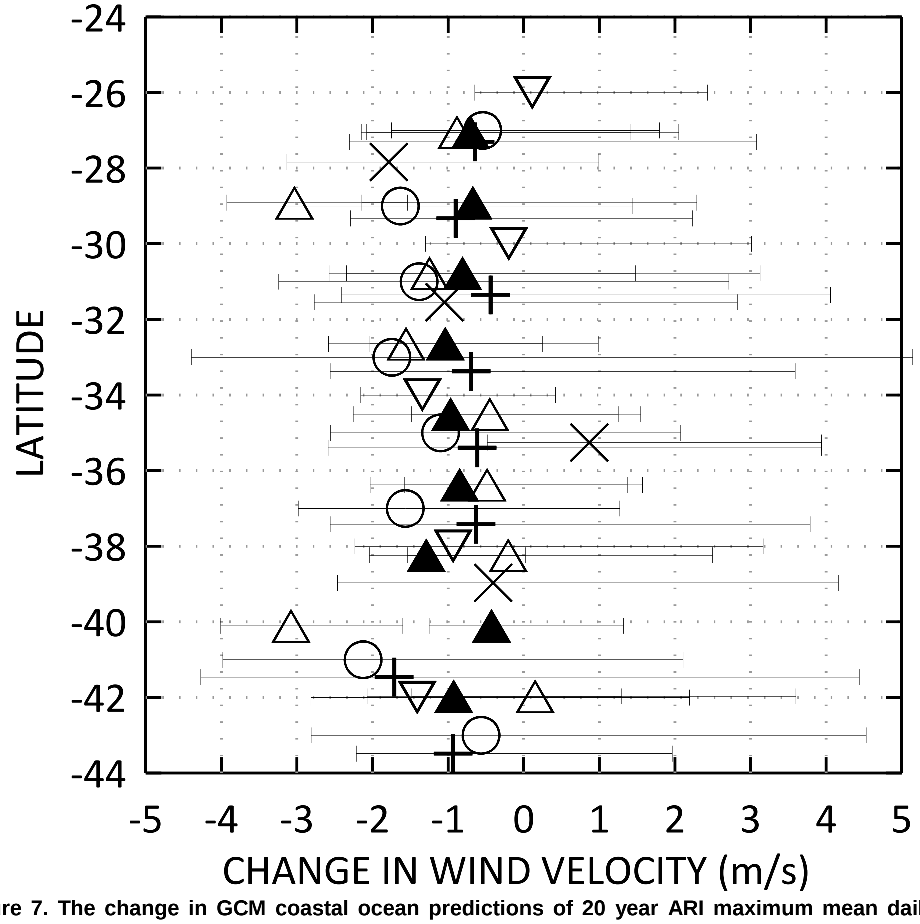

Figure 7. The change in GCM coastal ocean predictions of 20 year ARI maximum mean daily wind speed along the Eastern Australian coast from latitude 26°S to 44°S. The difference is between SRESA2 2080 to 2099 and 20c3m predictions. The error bars show the 90% confidence interval. Symbols are as shown in Figure 4.

CONCLUSIONS AND RECOMMENDATIONS

Coastal inundation has both potential marine and inland contributions. Using CMIP3 GCM outputs, skill in representing 20 year ARI mean sea level pressure, wind and precipitation has been quantified by comparison with measured and assembled data.

Clear extreme distributions of the state variables relevant to larger-scale coastal inundation are available from GCM output. These show no sign of saturation within the tails of extreme distributions derived from surface pressure, wind and precipitation.

The extreme value distributions of both surface pressure and wind on the temperate east Australian coast are comparable with the available measured data. This gives the coastal engineering community confidence that GCMs provide data that is suitable for coastal engineering design. A second important outcome for coastal engineering is the availability of large synthetic data sets containing coastal storms that are potentially much longer and more detailed than is available from equivalent recorded data.

As anticipated, there is significant bias in GCM-derived coastal rainfall which needs to be corrected by suitable correction schemes.

When changes under the A2 scenario are considered, the consensus of the models is that little change in 20 year extreme surface pressures and rainfall are anticipated over the next 100 years. The GCM consensus is an order 10% decrease in design wind is predicted. In spite of suggestions that storm intensity will increase under climate change, quantitative evidence is that little change is anticipated at a given design ARI of 20 years. The predicted systematic reduction in design wind indicates some small but developing adaptive capacity within that design facet.

This present study has not investigated changes in wind direction but robust determinations are likely to be elusive. Future investigations are focussed on investigating the joint probabilities of the individual contributions and overall adaptive capacity.

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