Towards a Coordinated Ocean Storm Surge Model Intercomparison Project

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(1) Introduction

Storm surges are the major cause of extreme sea levels and devastating coastal impacts along many coastlines around the world. Impacts of storm surges are realised though significant human tolls and economic impacts. Recent examples include the storm surge from Typhoon Nargis in Myanmar in 2008, which killed 138000 people (IPCC, 2012) and Hurricane Katrina in 2004 for which the US Federal government flood damage payouts totalled around $16.1 Billion.

Despite the significant impacts that storm surges cause, recent scientific assessments of future projections of storm surges have low confidence due to (1) the relatively small number of assessments, (2) the different methods and models used to investigate future changes and (3) the limited regional coverage of these assessments (see for example IPCC, 2012; Church et al, 2013).

This paper discusses the merits and challenges of building a collaborative global project for storm surges. We note benefits that global storm surge climatology studies would have to assess future storm surge hazards. This would not be without significant numerical modelling and data challenges given the need for relatively high spatial resolution and forcing variables over the continental shelf regions of the world, where storm surges manifest. However, it would provide a powerful tool for investigating how and where changes in storm surge hazard may emerge due to changes in circulation patterns and synoptic weather systems in the future. Such a global database will strongly complement existing and emerging global sea-level and wave-climate projections for identifying coastal regions exposed to greatest future hazards.

(2) Numerical and Logistical Challenges

Modelling the combination of storm surges and tides at global scale is challenging because of the significant computational resources that are required. However, recent studies show significant progress in this regard. For example, Pickering (2014) uses the global hydrodynamic model of Egbert et al. (2004) with model resolution of 1/8 x 1/8 degree (approximately 14 x 14km at its coarsest equatorial resolution) to investigate the impact of sea-level rise on tides (see also Pickering et al., 2015). Applying sea-level rise scenarios of 0.5m, 1m and 2m SLR to a model with fixed coastlines it was found that MHW changes exceed ±10% of the SLR at 13, 13 and 10 of the 136 coastal cities that have populations greater than 1 million, respectively. Allowing for coastline adjustment to the SLR scenarios led to a stronger and increasingly negative MHW response.

The Global Storm Surge Forecasting and Information System (GLOSSIS) developed by Verlaan et al., (2015) is an unstructured global modelling system for the simulation of tides and storm surge using the Delft3D Flexible Mesh (D3D-FM) [4]0. The flexible mesh approach allows coastal areas to be represented at up to 5 km resolution while open oceans areas have lower resolution of around 50 km resolution yielding a total of nearly 1 million computation cells. The main purpose of this model system is to provide operational storm surge guidance where no official warnings exist, as well as provide potentially improved boundary conditions for regional and local storm surge modelling systems.

Climate change impacts and assessment modelling requires the consideration of a number of future greenhouse gas emission scenarios, and the modelled climate and weather response from a large number of climate model realizations to characterise the range of possible responses to the climate system. For example, the latest IPCC report considered four emission scenarios – the so-called Representative Climate Pathways (RCPs) that ranged from RCP 8.5, a business-as-usual high end scenario, to RCPs 6.0, 4.5 and 2.6, the latter being a strong mitigation scenario (van Vuuren et al., 2011). As part of the Coupled Model Intercomparison Project Phase 5 (CMIP5), twenty eight modelling centres across the globe undertook future climate simulations with global ocean and atmosphere climate models using these emission scenarios. Some centres submitted simulations from several differently configured climate models. Thus, approximately 60 different climate models have contributed to CMIP5 to use for climate change impact studies (http://cmip-pcmdi.llnl.gov/cmip5/availability.html). Furthermore, of these 60 models, many have been used to carry out multiple ensemble runs to assess internal variability within the climate scenarios.

Collectively the different emission scenarios, CMIP5 climate models, and ensemble simulations available from the CMIP5 models pose a significant computational challenge for modelling future storm surge change given the sheer number of potential input conditions that need to be considered and which collectively represent a major contribution to the range of uncertainty of project future conditions. However, the additional step of simulating storm-surges carried out using different methods introduces another level of uncertainty in the projected conditions. Additional uncertainty arises due to the differences between different hydrodynamic models, differences in how a research group deals with bias adjustment, of tropical cyclones for example as discussed below, and between dynamical and statistical methods for modelling storm surges or their forcing condition. Similar challenges are being addressed by the ocean wind-wave climate community through the collaborative project COWCLIP (Coordinated Ocean Wave Climate Project), from which this final 'downscaling' step appears as the dominant source of uncertainty in the projected 21st Century wind-wave conditions. COWCLIP has progressed international efforts to coordinate both global and regional scale wave model simulations to investigate the role of anthropogenic climate change on future wave climate in both the former CMIP3 models (e.g. Hemer et al., 2013; Fan et al., 2014) and CMIP5 models (e.g., Dobrynin et al., 2012; Wang et al., 2015). Many of the challenges faced through COWCLIP are common to developing 21st Century projections of storm surges. COWCLIP provides a valuable framework for the international storm surge modelling community to come together and share efforts to address these challenges.

(3) Regional changes and uncertainties

Regions within the world that are currently susceptible to large storm surges are well known due to significant historical events and their impacts. However, large-scale circulation patterns may potentially undergo changes in the future as a result of climate change and this in turn may open up new regions where significant storm surge impacts could occur in the future. Regions where events have not occurred historically are particularly vulnerable. Potential locations of large future changes are near the boundaries of circulation patterns where morphological characteristics of the coastline are also particularly conducive to storm surge development. For example, a hydrodynamic modelling study of Australia with surface pressure and wind forcing taken from the ACCESS climate model under the RCP 8.5 emission scenario revealed potentially large localised changes in sea level and potential coastal impacts arising from circulation changes only (i.e. no tides or sea-level rise). The changes in the average of the DJF maximum sea level (Figure 1a) reveal that while changes are generally small for much of the continent, relatively large changes are seen in the northern Gulf of Carpentaria in 2080-2099 relative to 1980-1999. Investigation of the changes revealed an increase in wind variability (Figure 1b) together with an eastward shift in the zero contour of the zonal wind speed in the 2080-2099 DJF (Figure 1c). This, together with the shallow and semi-enclosed coastline of the Gulf of Carpentaria, means it is particularly susceptible to relatively large changes in sea level compared to elsewhere along the coastline (Colberg et al., 2015).

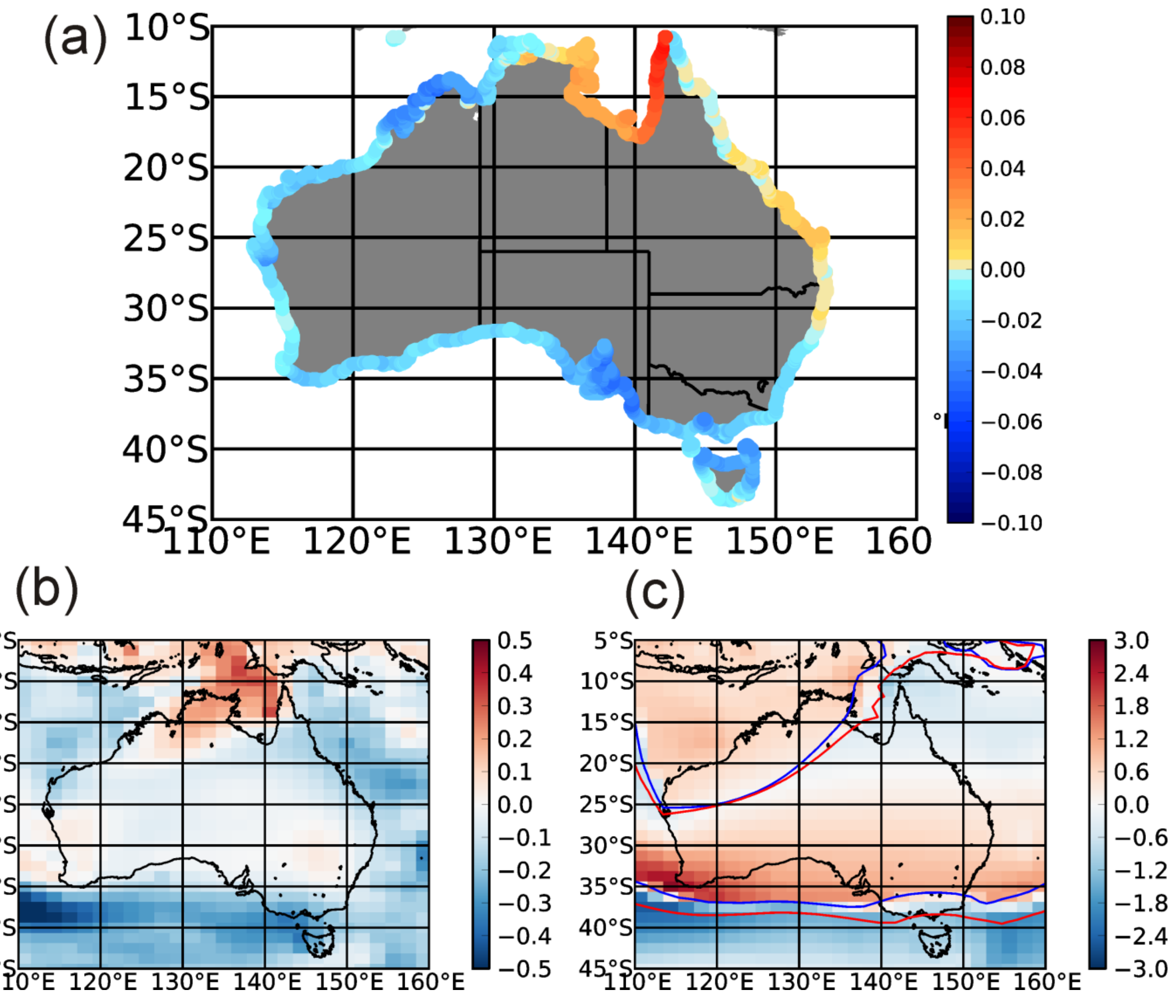

Figure 1: (a) the change in the average DJF maximum sea level (m) between 2080-2099 and 1980-1999 calculated from a hydrodynamic simulation of the region shown using the ROMS ocean model forced by the CSIRO and Bureau of Meteorology ACCESS GCM under RCP 8.5. (b) the change in the standard deviation of wind speed for DJF and (c) change in wind speed for DJF with zero of zonal wind speed shown as a contour in blue for current climate and red for future climate.

In addition to extreme sea levels, other coastal impacts such as changes in littoral transport, coastal erosion and accretion may also occur as a result of circulation changes. In the southeast of Australia, the southward movement of the subtropical ridge has been investigated in O'Grady et al. (2015) using wind driven currents from this hydrodynamic simulation and a wave model simulation forced by the same GCM (Hemer and Trenham, 2015). They show that the change in both wind-driven currents and waves in this region may lead to complex seasonal changes in longshore sediment transport with subsequent impacts on the near shore region. The development of global storm surge modelling for climate applications will provide the ability to assess at the global scale such potential ‘hotspots’ for future coastal change, which can then be investigated in more detail using higher resolution regional models.

(4) Uncertainties associated with small scale and relatively infrequent weather drivers

A particular challenge for future global storm surge modelling efforts will be the low resolution of present climate models and their inability to simulate the intensity or frequency of small scale weather systems such as tropical cyclones that lead to potentially large storm surges. Various regional studies have employed different techniques for investigating the effect of projected future changes in tropical cyclones on storm surges. For example, in the Gulf of Mexico, Mousavi et al., (2011) developed a simple relationship between hurricane-induced storm surges, SLR and hurricane intensification through increased SST’s to investigate climate change due to both sea level rise and hurricane intensity changes. Lin et al. (2012) used a synthetic cyclone approach to scale up the number of tropical cyclones (hurricanes) in global climate models to realistic numbers in order to study the impact of their future changes for New York City. (McInnes et al., 2014, 2015) used a synthetic cyclone technique and perturbed the extreme value statistical relationships describing cyclone frequency and intensity to simulate the storm surge response to future tropical cyclone changes.

The GLOSSIS model (Verlaan et al., 2015) features a technique for enhancing the winds around tropical cyclones. This is achieved by a Wind Enhancement Scheme in which a (Holland, 1980) cyclone vortex is used to simulate the wind field and this is introduced into the GLOSSIS model via a user-defined ‘spider-web grid’ that enhances the resolution in the vicinity of the cyclone and moves with the cyclone track. Such techniques combined with GCM tropical cyclone scaling techniques (e.g. Walsh et al. (2007) and other synthetic cyclone approaches offer a range of techniques that could be explored to address the future changes to tropical cyclones in a global storm surge model.

(5) Incorporating impact of waves

While storm surges are the largest cause of weather-related extreme sea level elevation along continental shelf regions, wind-wave contributions are known to be a significant contributor to extreme sea levels through nearshore wave breaking processes such as wave setup and runup in areas with narrow continental shelves, particularly at oceanic islands (e.g. Hoeke et al., (2013). Hoeke et al., (2015) demonstrate that wave setup can further enhance the 1-in-100 year sea levels due to storm surge and tide by more than a factor of two within scales of a few kilometres along typical island morphologies fronted by coral reefs (Figure 2). The sea levels at the 'tide' gauge location (see Figure 2 right) are similar to those modelled without the inclusion of waves indicating that the tide gauge location in the deep-water harbour is protected from wave-induced sea level variations. However, elsewhere along the coast, and particularly shoreward of the offshore reefs, the edge of which is delineated by the marked reduction in offshore wave heights in excess of 8 m to less than 2 m (Figure 2, left), coastal sea levels exceed twice the height of the sea levels at the tide gauge due to the additional effect of wave setup. Although global-scale storm surge modelling will not address the significant issues posed by waves in typical island-scale locations, indeed the high-resolution bathymetric data required for such studies is not generally available, global scale storm surge model data together with analogous global wave data simulated within COWCLIP will support higher resolution studies by providing information on large scale changes relevant to the locations of interest.

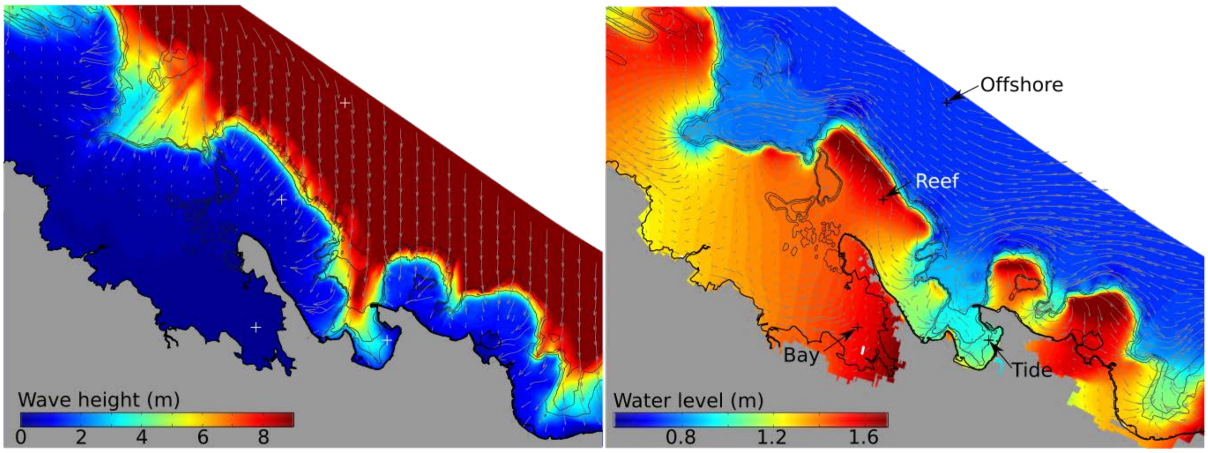

Figure 2: Simulated significant wave height (left) and water levels and depth-averaged current vectors (right) simulated by the Delft3D flow-wave-coupled hydrodynamic modelling system for Apia, Samoa under tropical cyclone forcing conditions

(6) Conclusions

With about half a billion people living at the coast below 10 m elevation and 270 million people exposed to the 1-in-100-year coastal flood (Wong et al., 2014), guidance on how both SLR and weather and circulation changes influence coastal extreme sea levels is critical to underpin climate change adaptation. Recent developments in hydrodynamic modelling, high performance computing and emerging global storm-surge simulation efforts, along with our current understanding of weather and coastal extremes suggest that timing is opportune to consider developing a global storm surge modelling capability for future climate change investigations.

(7) References

Church J.A., Clark P.U., et al (2013) Sea Level Change., in: T. F. Stocker, et al. (Eds.), In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2012) Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, in: C. B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.) (Ed.). pp. 582 pp.

Colberg F., McInnes K.L., Hoeke R.K. (2015) Atmospheric Circulation Changes and their Impact on Extreme Sea Levels and Coastal Currents in Australia. Journal of Geophysical Research (under revision).

Dobrynin M., Murawsky J., Yang S. (2012) Evolution of the global wind wave climate in CMIP5 experiments. Geophysical Research Letters 39:L18606. DOI: 10.1029/2012gl052843.

Egbert G.D., Ray R.D., Bills B.G. (2004) Numerical modeling of the global semidiurnal tide in the present day and in the last glacial maximum. Journal of Geophysical Research: Oceans (1978–2012) 109.

Fan Y., Lin S.-J., Griffies S.M., Hemer M.A. (2014) Simulated global swell and wind-sea climate and their responses to anthropogenic climate change at the end of the twenty-first century. Journal of Climate 27:3516-3536.

Hemer M.A., Trenham C.E. (2015) Evaluation of a CMIP5 derived dynamical global wind wave climate model ensemble. Ocean Modelling submitted.

Hemer M.A., Fan Y., Mori N., Semedo A., Wang X.L. (2013) Projected changes in wave climate from a multi-model ensemble. Nature Clim. Change advance online publication. DOI: http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1791.html#supplementary-information.

Hoeke R.K., McInnes K.L., O'Grady J.G. (2015) Wind and wave setup contributions to extreme sea Levels at a tropical high island: A stochastic cyclone simulation study for Apia, Samoa J. Marine Science and Engineering 3:1117-1135. DOI: 10.3390/jmse3031117.

Hoeke R.K., McInnes K.L., Kruger J.C., McNaught R.J., Hunter J.R., Smithers S.G. (2013) Widespread inundation of Pacific islands triggered by distant-source wind-waves. Global and Planetary Change 108:128-138. DOI: http://dx.doi.org/10.1016/j.gloplacha.2013.06.006.

Holland G.J. (1980) An Analytic Model of the Wind and Pressure Profiles in Hurricanes. Monthly Weather Review 108:1212-1218. DOI: 10.1175/1520-0493(1980)108<1212:aamotw>2.0.co;2.

Lin N., Emanuel K., Oppenheimer M., Vanmarcke E. (2012) Physically based assessment of hurricane surge threat under climate change. Nature Clim. Change 2:462-467. DOI: http://www.nature.com/nclimate/journal/v2/n6/abs/nclimate1389.html#supplementary-information.

McInnes K.L., Hoeke R.K., Walsh K.J.E., O'Grady J.G., Hubbert G.D. (2015) Application of a synthetic cyclone method for assessment of tropical cyclone storm tides in Samoa. Natural Hazards (submitted).

McInnes K.L., Walsh K.J.E., Hoeke R.K., O'Grady J.G., Colberg F., Hubbert G.D. (2014) Quantifying storm tide risk in Fiji due to climate variability and change. Global and Planetary Change 116:115–129.

Mousavi M., Irish J., Frey A., Olivera F., Edge B. (2011) Global warming and hurricanes: the potential impact of hurricane intensification and sea level rise on coastal flooding. Climatic Change 104:575-597. DOI: 10.1007/s10584-009-9790-0.

O'Grady J.G., McInnes K.L., Colberg F., Hemer M.A., Babanin A.V. (2015) Longshore wind, waves and currents: climate and climate projections at Ninety Mile Beach, southeastern Australia. International Journal of Climatology:n/a-n/a. DOI: 10.1002/joc.4268.

Pickering M. (2014) The impact of future sea-level rise on the tides, Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, Southampton. pp. 347pp.

Pickering M.D., Horsburgh K.J., Blundell J.R., Hirschi J.J.-M., Nicholls R.J., Verlaan M., Wells N.C. (2015) The impact of future sea-level rise on the global tides. Progress in Oceanography (in press).

van Vuuren D.P., Edmonds J., Kainuma M., Riahi K., Thomson A., Hibbard K., Hurtt G.C., Kram T., Krey V., Lamarque J.F., Masui T., Meinshausen M., Nakicenovic N., Smith S.J., Rose S.K. (2011) The representative concentration pathways: an overview. Climatic Change 109:5-31.

Verlaan M., De Kleermaeker S., Buckman L. (2015) GLOSSIS: Global storm surge forecasting and information System, Australasian Coasts and Ports Conference, Auckland, New Zealand.
Walsh K., Fiorino M., Landsea C., McInnes K. (2007) Objectively determined resolution-dependent threshold criteria for the detection of tropical cyclones in climate models and reanalyses. Journal of Climate 20:2307-2314.
Wang X.L., Feng Y., Swail V.R. (2015) Climate change signal and uncertainty in CMIP5-based projections of global ocean surface wave heights. Journal of Geophysical Research: Oceans.
Wong P.-P., Losada I.J., Gattuso J.P., Hinkel J., Khattabi A., McInnes K.L., Saito Y., Sallenger A. (2014) Coastal Systems and Low-Lying Areas, Climate Change 2014:Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, (in press).