Please find our response to reviewers below. Our responses to the reviewers comments are in red text.

Reviewer 1

The duration (20 years) of the analyed time periods is lower than 30 year minimum duration often recommended. Effects of multidecadal variability could in this case hide a climate change signal that is not sufficiently strong. I think that is should be investigated wheather using longer time slices could have produced more robuts results.

The choice of twenty-year time slices was to align the hydrodynamic model output to wave model simulations carried out using the same climate models over the same time period that was published in Hemer and Trenham (2016). Our aim was to be able to couple hydrodynamic extremes with wave-induced extremes (e.g. wave setup or runup) in future work. We acknowledge that 20 years may be too short to assess the role of future changes to interannual variability (i.e. ENSO) on weather events that cause extreme sea levels such as tropical cyclones, but as we already note, the GCMs do not adequately resolve TCs anyway so the focus of our study is on the contribution of large scale circulation changes to extreme sea levels. We feel that 20-year time slices are adequate for assessing how large scale circulation changes will affect drivers of sea levels around much of Australia's coast where seasonally varying weather systems are a major cause of extreme sea levels.

(Hemer, M. A. and C. E. Trenham, 2016: Evaluation of a CMIP5 derived dynamical global wind wave climate model ensemble. Ocean Modelling, 103, 190-203, doi:https://doi.org/10.1016/j.ocemod.2015.10.009.)

We have added a brief discussion on this at the end of paragraph 1 of section 2.3

Abstract

The abstract should state more clearly the main conclusions. I think the present one is not satisfactory on this respect. The text at lines 15-16 is too generic and not informative on atmospheric circulation changes, while they, being mentioned in the title, should be a main focus of the manuscript. The last lines mention a large increase in extreme sea level during austral summer in the Gulf of Carpentaria (note that it is difficult to locate it for those not familiar with Australian geography and it is not mentioned in the map of figure 1). However, this conclusion is rather uncertain because only 2 of the 4 models used show such increase (fig.9). Further, the abstract mentions a small reduction of sea level extremes along the southern coast. However, the four models (fig.11) agree only on a relatively small central fraction of the southern coast and on its westernmost tip. A limitation of this study is, in my view, that it is unable to identify significant change in surge extremes (there is very little agreement among models).

We removed the sentence in question. We understand that there is a limited amount of agreement between the different modle simulations and changed our wording around it, we give more detailed information regarding the SSH changes in the abstract.

Overall we argue that the disagreement in responses between the differently forced model simulations and the difference in seasonality in their response is in itselft is a valuable result. It may emphasize that we need to work towards a better understanding of parametrized physics in climate models. These unresolved phyics may very well drive a large amount of uncertainty and may lead to large intra-model differences. We have changed the manuscript to put a stronger emphasize on this aspect.

The Gulf of Carpenteria (GoC) is now indicated in Figure 1.

Introduction

page 1, line 24 it is not clear what authors mean here. Do they mean that storm surges are superimposed to low frequency modulation of sea level (forced by large scale patterns) or that the synoptic forcing of extremes is, in turn, modulated by large scale circulation patterns?
We have reworded this part of the manuscript to clarify our meaning here.

It seems to me that the author do not summarize adequately the existing literature.
Page1, line 33 to page 2, line16, This paragraph looks rather incomplete to me. Only the last four lines refer to Australia. Is it reasonably complete list of available studies for Australia ? After a quick search with google scholar have found also

3) it seems to me that the author do not summarize adequately the existing literature. Page1, line 33 to page 2, line16, This paragraph looks rather incomplete to me. Only the last four lines refer to Australia. Is it reasonably complete list of available studies for Australia ? After a quick search with google scholar have found also –
McInnes, K.L., Macadam, I., Hubbert, G.D. et al. Nat Hazards (2009) 51: 115. –
Church JA, Hunter JR, McInnes KL, White NJ (2006). Aust Meteorol Mag 55:253–260 Are they not relevant?
The rest is for European Seas and it looks a very incomplete reference to a very rich literature, with many studies published for the North and the Mediterranean Seas. Again, just searching with scholar, I have found
Vousdoukas, M.I., Voukouvalas, E., Annunziato, A. et al. Clim Dyn (2016) 47: 3171. https://doi.org/10.1007/s00382-016-3019-5
Woth, K., Weisse, R. & von Storch, H. Ocean Dynamics (2006) 56: 3. https://doi.org/10.1007/s10236-005-0024-3
Conte D.and LionelloP. (2013) https://doi.org/10.1016/j.gloplacha.2013.09.006 Androulidakis YS et al.(2015) https://doi.org/10.1016/j.dynatmoce.2015.06.001
Lionello P.et al (2017) https://doi.org/10.1016/j.gloplacha.2016.06.012
Debernard J, Røed L (2008) Tellus 60:427–438. doi:10.1111/j.1600– 0870.2008.00312.x R.Weisse et al (2012) https://doi.org/10.1016/j.ocecoaman.2011.09.005 . . . and this list does not mean to be complete
The fact that the authors do not adequately summarize the existing literature applies also to the following paragraphs on interactions between storm surge and sea level rise and on tropical cyclones
We have updated and extended our literature review with additional relevant references

Page 3 lines 12 to 19.Should be better explained what is new in this study. Which new information is missing and authors aim at providing?
We have strengthened the introduction (paragraph 1 and 7) to emphasize what is new in this modelling study. SSH changes driven by synoptic weather changes for the whole australian coastline have not been investigated before.

Section 2.1. which fraction of the total tidal amplitude is explained by using only 8 components?
We follow the common convention used for shelf-scale models, which is to apply the 8 major tidal constituents at the deep water model boundaries. These major constituents are obtained from global tide models. It is not necessarily possible to obtain higher order tidal constituents from global tidal models due to their low coastal resolution, nor is it necessary to do anyway since the tidal heights are applied as a deep water boundary condition where overtides would not occur anyway. The dominant tidal constituents are the semidiurnal constituents M_2, S_2, N_2, and S_2 and the diurnal constituents, K_1, O_1, P_1, Q_1, and S_1, (Wollanksi, and Elliot, 2016). Other constituents that typically may contribute non-trivially to overall tidal amplitudes at the coast include higher-frequency non-linear shallow water “overtides” and annual and semiannual constituents (which are typically due mainly to seasonal oceanographic and meteorological variability, rather than astronomical forcing). The ROMS model is capable of dynamically reproducing both of these types contituents (at least to some degree).

Section2.3 the problem with introduction of tides in model adopting 360 day long year does not appear relevant because tides are not included in the climate change experiments (authors write this a few lines below)
Yes, we agree with the reviewer and removed this paragraph from manuscript.

Page 5 , lines 11-13, RMSE, STDE and correlation are weak metrics for validation of extremes in a time-series. High correlation and low RMSE can be obtained also if extremes are poorly reproduced. Further, to validate a model percent errors should be considered, particularly for extremes. To compare magnitude of the error to the magnitude of the observed value is important.
We are aiming to compare the analyses to that given by Haigh et al, 2014a. The aim thus was to show that the model captures atmospheric driven variability generally well. We asses extremes via qq plots in Figure 4.

Page 5, lines 4.It is not clear to me how is the seasonal variability component defined and computed in this study
We follow the methodology of Haigh et al,2014a. The seaosnal component is calculated by using a 30day running mean over the detided and detrended time series. This removes basically the high frequency (weather driven) variability. We changed the paragraph to make this clearer.

Page 5, line 31. If the 30-day running mean is subtracted to the signal, I expect that the steric contribution on the residual is small
We are not quite sure what the reviewer means. We use the 30 day running mean to tease out the seasonal signal. This follows the method of Haigh et al, 2014a. The line in question is discussing the findings of Forbes and Church 1983 who used measurements to show that the strong seasonal signal in sea level in the Gulf of Carpentaria comprises a barotropic component (northwest monsoon winds that produce wind setup in the gulf) and a steric component due to seasonal changes in temperature and salinity of the water column and these both have a maximum postive effect on sea levels in January. Our model is barotropic so can only capture the barotropic component of sea level variations.

Sea level residuals.
It is not clear to me what we learn from the considered examples. What have been the criteria for their selection
The examples have been selected to illustrate the main weather systems that cause storm surges along different coastal regions in Australia. The year 1997 was selected as it contained examples of extreme sea levels along each coastal region examined. We have reworded the relevant paragraphs to make this clearer .

Page 6, lines 33-34 to blame the inaccurate meteorological forcing is often correct, but it is also an easy way out. Can the authors provide an argument to support this?
Yes, this is true. Arguably there are a couple of reasons why the model is not able to reproduce SSH anomalies correctly (1) representation error of model and atmospheric forcing (i.e. grid resolution, bathymetry errors, coastlines not resolved properly, errors in the atmospheric forcing, limited temporal resolution), (2) model physics - a 2D model will only ever resolve the first barotropic mode of coastally trapped waves. Higher order modes may be necessary to properly account for all the variability.
We have added discussion on these points (see next point).

Page 7, line 13. It is not clear why in this specific location wave set up is expected to be a relevant contribution and could explain the underestimated sea level by the model. This should

be explained in terms of location of the gauge and morphology of the sea bottom (including depth).
We agree with the reviewer and changed the paragraph. In fact what appears to happen here is explained by the following:
The missing peak may be explained by an insufficiently resolved modelled coastally trapped wave (CTW). Studies like Woodham et al, 2013 suggest speeds of CTW between 2-4m/s. CTW travel anticlockwise around Australia. It takes about 5-6 days for CTW to travel the distance from Port Kembla to Rosslyn Bay. On the 10th may a coastal low produced a surge in Port Kembla that excited a CTW. According to Woodham et al, CTW can cause sea level elevations of 0.25m which is in the order of what has been observed at Rosslyn Bay about 5-7 days later. The ROMS model does not capture this elevation,. This may potentially be due to its barotropic nature which does not allow higher order (bariclinic) modes of CTW to develop. Unresolved bathymetric features over the Great Barrier Reef are also candiates for explaining the model behaviour. We have amended the text to discuss these possible explanations.

Page 8 lines 6-11. To which figures do these sentences refer?
These sentences refer to Figure 6. We made appropriate changes in the text.

Authors consider the total sea level ZTM , Its tidal ZT and meteorological ZM components, all computed separately by independent simulation. Defining the residual ZR= ZTM - ZT, they find that peaks (ranks) of ZR and ZM agree and conclude that time-surge interaction is negligible. However, this is in contrast with the lack of agreement between ZTM and ZT + ZM , which shows that tides substantially decrease the importance of the meteorological contribution to sea level extremes. Therefore, to me it seems that tides are not relevant for computing correctly the maxima of the storm surge, but actual sea level maxima are affected (decreased) by tide-surge interaction (practically high tidal levels reduce the contribution of the surge to the maxima). Further, the whole analysis applies at the location of the tide gauge. I suspect that at the actual coastal line, at the shore, analysis can produce different results.
We agree with the assertion by the reviewer which is what we wrote in the manuscript. We have slightly revised the paragraph to make this clearer.

The statement that "climate models overall perform well" is too positive, considering the tendency of all simulations to underestimate high quantiles is some locations (fig.7).Such underestimate is particularly large for inmcm (note that the annotation in the figure is not consistent with the text which refers to this simulation as CC-I). Model simulations substantially underestimate extremes at several locations.
We have revised this paragraph to more explicitly describe the performance of the climate models. We have revised the figures to make naming of the climate models consistent with elsewhere in the paper.

Seasonal mean maximum sea level change

I find this part should be improved in several aspects 16.1) It discusses the multimodel mean at annual scale, and only individual models at seasonal scale.

The shown multimodel mean for the annual average is to compare results from CFSR forced surge model with observations and to show that the CMIP5 forced models show similar results in terms of overall distribution. The individual climate model results are broken into seasons to better understand the role that seasonal weather and circulation changes have on the results.

There is no indications whether changes are statistically significant for individual models. I suggest to mask in figure 11 (central panel) values when models do not agree on the sign of the change or add, anyway, an indication of the level of consensus among models.
We have modified the figure to have hatching where the multi-model ensemble is not in agreement on the sign of the change.

There is a discussion of the link of the observed changes of extremes with changes of wind speed. However, it is not clear why changes of mean speed are relevant for extremes and whether figure 10 is a multimodel mean or it represents the winds driving the CC-A simulations.
Yes, we agree with the reviewer and clarified this. Figure 10 demonstrates a possible mechanism that may explain the observed increase in extremes seen for ACCESS-R and HadGEM forced model simulations. Stronger mean monsoonal winds will cause more wind setup over the GoC. This in turn will increase the likelihood of extremes to happen.

Reviewer 2
Their conclusion is that tide-surge interaction is strong (at least at some parts along the coast) for individual extremes but may be neglected for statistics over longer periods. For me, this is not very conclusive as potential changes in tides are also not taken into account.
Yes – the author is correct we conclude 2 things in this section: (1) surges occur more often during low tide for some locations when tides are included thus leading to smaller total sea levels. This means the timing of the surge and tides is interlocked at times owing to non-linear interactions. However, we also show (2) that the height of the surge regardless of including tides or not does not change when looked at it in a ranked sense (or only to a small degree). We argue that because of point (2) we do not need to include tides in the future climate scenarios as our main interest is the effect of change in coastal surge driven by atmospheric forcing.

I understand somehow that changes in the met. forcing alone may be visible in a surge-only run and potential changes may (roughly) be inferred thereof but only if relative changes in he met induced component are investigated.
We are not sure what the reviewer is suggesting here.

Climate change will also affect the base water level (MSL) which has not been considered in your experiments, right? From SLR, the propagation of the surge will be affected influencing the timing (and hights) of surge events.
Yes we agree with the reviewer that e.g. SLR has the potential to change the speed of the gravity tidal wave and thereby also has the potential to change the distribution of tidal phases/ amplitutdes around the globe. However, in order to add such an effect into a surge model we would need to have access to newly generated tidal constituents (calculated by inverse modelling). Such a dataset is not available do date (to our knowledge). Also consider the large uncertainty in regional sea level rise projections that one needs to take into account. Furthermore changes due to SLR are in the order of meters which is small compared to errors/ uncertainty in the bathymetric datasets. I can see that one could change bottom topography to model such an effect to understand the sensitivity but this is beyond the scope of our study.

Furthermore, also the tidal propagation may/will change with SLR having the potential to further increase water levels and partly compensate for the "mostly" negative trend in ESL changes you reported stemming from the met. only approach
Yes, MSL and RSL both have the ability to increase current tidal propagation. To a first approximation components are often linearly added which leads to different exceedence probability thresholds. Note, however, that in our manuscript we only consider atmospheric driven changes in SSH. We added a paragraph discussion SLR scenarios.

The period of 20 yrs you consider for the future climate conditions are too short to draw robust conclusions. Usually a period of 30yrs is used to estimate changes in the met. forcing. Please consider extending your modelling or discuss why you chose this short period, how it affects your results.
The choice of twenty-year time slices was to align the hydrodynamic model output to wave model simulations carried out using the same climate models over the same time period that was published in Hemer and Trenham (2016). Our aim was to be able to couple hydrodynamic extremes with wave-induced extremes (e.g. wave setup or runup) in future work. We acknowledge that 20 years may be too short to assess the role of future changes to interannual variability (i.e. ENSO) on weather events that cause extreme sea levels such as tropical cyclones, but as we already note, the GCMs do not adequately resolve TCs anyway so the focus of our study is on the contribution of large scale circulation changes to extreme sea levels. We feel that 20-year time slices are adequate for assessing how large scale circulation changes will affect drivers of sea levels around much of Australia's coast where seasonally varying weather systems are a major cause of extreme sea levels.

(Hemer, M. A. and C. E. Trenham, 2016: Evaluation of a CMIP5 derived dynamical global wind wave climate model ensemble. Ocean Modelling, 103, 190-203, doi:https://doi.org/10.1016/j.ocemod.2015.10.009.)

page 3, line 30: 1' x 1', x missing
Fixed that

page 7, line 26: Due to computational constraints, we demonstrate that... From my point of view, this is not a good argumentation
Yes we agree and changed this

page 9, line 8: BM covers 1981-2012, right? so the common period is '81-'99. Should be clear
This has been fixed

page 9, line 18: Albany not shown in Figure 1
The reference to Albany in the text should have been Esperance. This has been fixed

Fig1: Could be helpful to show the average tidal range (e.g. based on TPXO) over the entire area

Fig.2: Please define the dots (semi- and diurnal)
We explain the dots in the figure caption.

Fig.4: All R2s show values of ~1. This is a bit misleading, as most stations over- and/or underestimate the extremes. Also the R2 is not mentioned
We agree and have removed the R2 values.

Fig. 6: Units missing; please highlight meaning of surge and residual again; for me, the figure shows a clear tide-surge interaction which cannot be neglected. Also for the largest events as e.g. in Rosslyn Bay or Darwin
Units have been added. More information has been added to the figure caption

Fig. 8: Portland not given in the Fig. , what is happening at the northern part (Milner Bay)
Have added Portland. We assume the reviewer is referring to the large difference between the Milner Bay observations and model results. They may be explained by the fact that the Milner Bay tide gauge is located at the south side of Groote Island which is not very well resolved in the model.

All figures would benefit from detailed captions.
We have added more information to the figure captions as necessary.

Atmospheric Circulation Changes and their Impact on Extreme Sea Levels around Australia

Frank Colberg[1], Kathleen L. McInnes[2], Julian O'Grady[2] and Ron Hoeke[2]

[1]Bureau of Meteorology,
f.colberg@bom.gov.au

[2]Climate Science Centre,
CSIRO Marine and Atmospheric Research,
Aspendale, 3195, Australia
kathleen.mcinnes@csiro.au
julian.ogrady@csiro.au
ron.hoeke@csiro.au

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Abstract

Projections of sea level rise (SLR) will lead to increasing coastal impacts during extreme sea level events globally, however, there is significant uncertainty around short-term coastal sea level variability and the attendant frequency and severity of extreme sea level events. In this study, we investigate drivers of coastal sea level variability (including extremes) around Australia by means of historical conditions as well as future changes under a high greenhouse gas emissions scenario (RCP 8.5). To do this, a multi-decade hindcast simulation is validated against tide gauge data. The role of tide-surge interaction is assessed and found to have negligible effects on storm surge characteristic heights over most of the coastline. For future projections, twenty-year long simulations are carried out over the time periods 1981-1999 and 2081-2099 using atmospheric forcing from four CMIP5 climate models. Changes in extreme sea levels are apparent but there are large inter-model differences. On the southern mainland coast all models simulated a southward movement of the subtropical ridge which led to a small reduction in sea level extremes in the hydrodynamic simulations. Sea level changes over the Gulf of Carpentaria in the north are largest and positive during Austral summer in 2 out of the 4 models. In these models, changes to the northwest monsoon appear to be the cause of the sea level response. These simulations highlight a sensitivity of this semi-enclosed gulf to changes in large scale dynamics in this region, and indicate that further assessment of the potential changes to the northwest monsoon in a larger multimodel ensemble be investigated, together with its effect on extreme sea levels.

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1. Introduction

Extreme sea levels (ESLs) are a significant hazard for many low-lying coastal communities [*Hanson et al.*, 2011; *Nicholls et al.*, 2011] and with rising global mean sea level, extreme events are expected to rise [*Menéndez and Woodworth*, 2010]. ESLs are largely driven by storm surge superimposed on the astronomical tides (storm tides). The severity of these ESLs can be further enhanced by larger-scale atmospheric and oceanic circulation patterns that operate on seasonal to interannual time scales.

ESL hazards are typically represented as probability-based exceedance levels with associated uncertainties. These uncertainties may be significantly larger than uncertainties in projected SLR itself [*Wahl et al.,* 2017]. Many studies have attempted to quantify ESL uncertainties using historical tide gauge information combined with global SLR projections [e.g. *Hunter, et al*., 2013], or by spatially extrapolating tide gauge observations using a hydrodynamic model [e.g. *Haigh et al*., 2014a]. In the present study, we assess the performance of a hydrodynamic model for the Australian region and examine atmospheric drivers of ESL and how they may change under future climate conditions.

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A number of studies have used a similar approach, i.e. investigating ESL changes using hydrodynamic models forced by global climate models (GCMs) or regional climate models (RCMs). Lowe et al. [2009] developed projections of storm surge change for the UK using climate forcing from an 11-member perturbed physics ensemble of the Hadley Centre GCM downscaled to 25 km resolution with the RCM HadRM3 [*Murphy et al.*, 2007] under a mid-range SRES [*Nakićenović and Swart*, 2000] emission scenario. Results indicated that the changes in the 2 to 50-year storm surge height associated with projected changes in weather and storms would increase by no more than 0.09 m by 2100 anywhere around the UK coast. [*Sterl et al.*, 2009] concatenated the output from a 17-member ensemble of a mid-range SRES emissions scenario from the ECHAM5/MPI-OM climate model [*Jungclaus et al.*, 2006] to estimate 10,000-year return values of surge heights along the Dutch coastline. No statistically significant change in this value was projected for the 21st century because projected wind speed changes were associated with non-surge generating south westerlies rather than surge-conducive northerlies. *Vousdoukas et al,* (2016) used a hydrodynamic model to downscale storm surge changes in an 8-member ensemble of climate models under RCP 4.5 and 8.5 and found increases in storm surges over the model domain north of 50°N whereas there was minimal to slightly negative change south of 50°N except under RCP 8.5 towards the end of the century. In southern Europe, *Marcos et al.* [2011] assessed changes in storm surges in the Mediterranean Sea and Atlantic Iberian coasts using climate model forcing from the ARPEGE-v3 global, spectral stretched-grid climate model under a high, medium and low SRES emissions scenario [*Jordà et al.*, 2012]. Findings revealed a general decrease in both the frequency and magnitude of storm surges with up to a 0.08 m reduction in the 50-year return levels. In southern Australia *Colberg and McInnes* [2012] found both positive and negative changes in 95th percentile sea level height across the southern half of the Australian continent in surge model simulations forced by the high SRES emission scenario of the CSIRO Mark 3.5 GCM

[*Gordon et al.*, 2010] and two simulations of the CCAM stretched grid global model [*McGregor and Dix*, 2008]. The ESL changes were small, mostly negative along the southern mainland coast but with wintertime increases over Tasmania. These resembled the changes in wind patterns to some degree, although there were large inter-model differences.

Several studies have also examined the non-linear effect of rising sea levels on tide and surge propagation. Using a global tide model, *Pickering* [2017] found that changes in mean high tide levels exceeded ±10% of the SLR at approximately 10% of coastal cities when coastlines were held fixed, but a reduction of tidal range when coastlines were allowed to recede due to resulting changes in the period of oscillation, *Arns* et al. [2015] investigated the non-linear impact of SLR on maximum storm surge heights in the North Sea, focussing on the German Bight. They found that maximum storm surges relative to the imposed background sea levels were amplified by up to 20% when the background mean sea levels were elevated by around 0.5 m. The positive increases in extreme water levels were caused by nonlinear changes in the tidal component, which were only partially offset by a reduction in the storm surge component.

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Coastal regions affected by tropical cyclones have been the focus of several recent studies. For example, *Unnikrishnan et al.* [2011] used RCM simulations to force a storm-surge model for the Bay of Bengal and found that the combined effect of mean SLR of 4 mm yr^{-1} and RCM projections for the high emissions scenario (2071–2100) gave an increase in 1-in-100 year heights in the range of 15–20% compared to the 1961–1990 baseline. For east Asia, *Yasuda et al.* [2014] applied a hydrodynamic model based on a 20-km resolution climate model and found that storm surge heights increased in the future for much of the coastline considered. For New York, Lin et al. [2012] investigated the change in extreme sea levels arising from hurricanes over 2081-2100 relative to 1981-2000 in four GCMs run with the SRES medium emission scenario by generating synthetic cyclones under the background conditions provided by the GCMs. Accounting for hurricane forcing only, results differed markedly between the four climate models ranging from overall increases to decreases in storm surge level. *McInnes et al.* [2014, 2016a] used a synthetic cyclone technique to investigate the effect of a 10% increase in cyclone intensity and a frequency reduction of 25% (consistent with tropical cyclone projections for the region) on storm tides over Fiji and Samoa and found a reduction in storm tides with return periods of less than 50 years and an increase for return periods longer than 200 years.

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In new studies, the contribution of waves to extreme sea levels as well as storm surge and sea level rise has also been examined. For Europe, *Vousdoukas et al*, (2017) using a 6-member ensemble of climate models to assess changes in extreme sea levels, found that by 2100, under RCP 8.5, Changes in storm surges and waves enhance the effects of RSLR along the majority of northern European coasts by up to 40% whereas for southern Europe, decreases in storm surges and waves tend to offset the increases in extreme sea levels due to mean sea level rise. For the Mediterranean, *Lionello et al*, (2017) used a 7-member ensemble of regional climate model simulations under the SRES A1B scenario to examine sea level changes by 2050 and found that the positive contribution to sea level extremes of the positive trend in thermal expansion would be largely offset by the declining trend in storms and hence storm surges and waves over this time period. In a global study, *Vousdoukas et al*, (2018) shows that under RCP4.5 and RCP8.5, the global average 100-year extreme sea level arising from mean sea level, tides, wind-waves and storm surges is very likely to increase by 34-76 cm and 58-172 cm, respectively between 2000 and 2100.

Numerical modelling studies of the non-linear interactions between sea level rise and cyclone-induced extreme water levels due to tides, storm surge and waves have also been undertaken. Smith et al. [2010] showed that sea level rise altered the speed of propagation of tropical cyclone-induced storm surges on the south-eastern Louisiana coast and amplified the extreme water levels under SLR although the amount of amplification varied significantly along different parts of the coast. Hoeke et al. [2015] found that SLR reduced wave setup and wind setup by 10-20% but increased wave energy reaching the shore by up to 200% under cyclone conditions along the Apia, Samoa coastline.

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Australia extends from the tropics to the mid-latitudes with a variety of meteorological systems responsible for extreme sea levels along its coastline [*McInnes et al.*, 2016b]. The range of weather systems, and more particularly their associated spatial scales means that it is challenging to obtain meteorological forcing that consistently represents all weather systems responsible for sea level extremes. *McInnes et al*, [2009, 2012, 2013] used joint probability methods to evaluate ESLs in southeastern Australia. *Haigh et al.*, [2014a; 2014b] extended such modelling and analysis of ESLs to the entire Australian coast using two approaches. In Haigh et al., (2014a), the water levels arising from weather and tides were investigated over the period 1949 to 2009 using 6-hourly meteorological forcing obtained from the NCEP reanalyses while in Haigh et al., (2014b), ESLs were simulated using a synthetic cyclone approach. As expected, extreme sea levels over the tropical northern coastlines were underestimated in the first study compared to the second one because of the low resolution of tropical cyclones in the reanalysis data set.

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The present study assesses the performance of a medium resolution barotropic hydrodynamic model for the Australian region to investigate extreme sea levels for the current climate and examines for the first time over the entire Australian coastline the potential changes in a future climate scenario in a four-member ensemble of climate model simulations. The model described by *Colberg and McInnes* [2012] is extended to cover the entire Australian coastline at 5 km resolution. A current climate (baseline) simulation is undertaken with tide and atmospheric forcing over the period 1981-2012 using reanalyses from the NCEP Climate Forecast System Reanalyses (CFSR) [*Saha et al.*, 2010]. The performance of the model is assessed with respect to tides, weather driven sea levels, and tide-surge interaction. Finally, changes are investigated in storm surge and seasonal sea levels around the coastline based on forcing from an ensemble of four CMIP5 models forced with the RCP 8.5 emission scenario [*Taylor et al.*, 2012].

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The paper is organised as follows. Section 2 describes the model setup, input data sets and procedure for assessing model performance. Section 3 assesses the model performance and the baseline simulations are used to investigate tide-surge interaction around the Australian coastline and the meteorological causes of ESLs. Section 4 presents the results from simulations forced by climate models and section 5 discusses the results, conclusions and further work.

2. Model Description and Method

2.1 Model Configuration

As with Colberg and McInnes [2012], the model used in this study is the Rutgers version of the Regional Ocean Modeling System (ROMS) [*Shchepetkin and McWilliams*, 2005] configured to run in barotropic or 'depth-averaged' mode. The model grid spans the region shown in Figure 1 at 5 km resolution. Bathymetry for the model is obtained from the 1'x1' resolution General Bathymetric Chart of the Oceans data set [GEBCO, *Jakobsson, et al.,* 2008].

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For simulations including tides, the tidal currents and heights were derived from the TPXO7.2 global model (*Egbert et al.,* 1994; *Egbert and Erofeeva,* 2002) and applied to the open model boundaries. TPXO7.2 best fits (in a least-squares sense) the Laplace Tidal Equations and along track-averaged data from the TOPEX/Poseidon and Jason altimetry missions, obtained with OTIS (Oregon State University Tidal Inversion Software). Eight primary tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1) are provided on a 1/4 of a degree resolution full global grid. A combination of Flather/Chapman boundary conditions was used in applying the tidal forcing [*Flather*, 1976; *Chapman*, 1985]. The Flather condition was applied to the normal component of the barotropic velocity and radiates deviations from the values at exterior grid points out of the model domain at the speed of the external gravity waves. The corresponding Chapman condition for surface elevation assumes all outgoing signals leave at the shallow-water wave speed. Meteorological forcing is discussed in the next section.

2.2 Baseline experiment

In the first part of the study, we assess the ability of the Australia-wide ROMS model to simulate historical tides and meteorologically-driven water levels. The model experiments performed are also used to investigate non-linear tide-surge interactions as well as the meteorological causes of extreme sea levels around the Australian coastline. Three baseline experiments are run over the period 1981-2012. The first experiment, B-TM, includes tidal and meteorological forcing, the second, B-T, tide-forcing only and the third, B-M, meteorological forcing only. Meteorological forcing for these experiments is obtained from the Climate Forecast System Reanalyses

(CFSR) dataset [*Saha et al.*, 2010, *Saha et al.*, 2014], which provides meteorological variables across the globe at hourly temporal resolution and approximately 38 km spatial resolution from 1979 to 2012.

2.3 Climate change experiments

Finally, a set of simulations with meteorological forcing from four GCMs from the 5th Phase of the Coupled Model Intercomparison Project (CMIP5; [*Taylor et al,* 2012]) is undertaken to assess how climate change will affect sea levels around the Australian coast. The various experiments are described in Table 1. The four models were chosen by subjectively evaluating performance metrics reported by *Hemer & Trenham* [2016], computational considerations and data availability. The twenty-year time slices were chosen to align the hydrodynamic model output to wave model simulations described in *Hemer and Trenham* [2016] with the aim to combine hydrodynamic extremes with wave-induced extremes (e.g. wave setup or runup) in future work. The 20-year time slices are deemed adequate for assessing how large scale circulation changes will affect the drivers of ESLs around much of the Australian coast where seasonally varying weather systems are a major cause of extreme sea levels. The various experiments are described in Table 1.

Tides were not included in the simulations forced by climate models. This was primarily because of the large computational overhead required to undertake two simulations for each time slice (current and future) consisting of one simulation with tides only and one with tides and atmospheric forcing in order to calculate non-tidal residuals. As will be discussed in section 3.3, the decision to omit tidal forcing from the climate runs is somewhat justified because non-linear tide surge interaction is evident around parts of Australia and therefore may impact substantially on an individual surge event it does not change the surge statistics over a period of years to decades [*Williams et al.,* 2016], which is the main focus of the experiments. In the following we refer to the climate change simulations as CC (see also Table 1).

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3. Baseline results and model performance

Here we assess the baseline experiments (forced by CFSR and/or tides) in terms of how well the model-generated sea levels compared with observations. In the first sub-section, we address the contribution of seasonal and interannual variability in sea level in the modelled and observed data. The following sub-sections examine the performance of the model in representing astronomical tides, the high frequency variability in sea levels including extremes, and the meteorological drivers of ESLs around the coast. Finally, we examine tide-surge interaction.

The model is assessed against hourly tide measurements from fourteen high quality tide gauges from the Australian Base Line Sea Level Monitoring Network with data available from 1993 to 2012 (Figure 1). We decompose both the tide gauge measurements and the simulated sea levels at corresponding model grid points in the B-TM simulation into components consisting of the (a) seasonal and interannual variability, (b) the tidal signal and (c) the residual signal (the remaining signal after the removal of the seasonal and tidal components from the total sea level) using the approach of *Haigh et al.* [2014a]. In order to facilitate a fair comparison between modelled and observed time series we apply the same methodology to both. Firstly, sea levels are linearly de-trended at each station. The seasonal and interannual component is then derived by applying a 30-day running mean to the detrended time series. The running mean is removed in the next step and a harmonic tidal analysis is carried out using T-Tide [*Pawlowicz et al.*, 2002]. This yields the tidal signal. Removing the tidal signal from the time series gives the residuals which include the storm surge signal.

These component time series, as well as the total sea level, are compared by means of root mean square errors (RMSE), The mean difference in standard deviation between observations and simulation (STDE) and linear correlations between the modelled and observed time series over the period from 1993 to 2012 (the shorter assessment period is determined by the availability of tide gauge data at the selected sites). In addition, a 1-day running mean filter was applied to the de-tided modelled and observed sea levels for the locations of Darwin and Broome because these locations display high frequency intra-daily to daily variability in sea surface height after applying the filtering techniques described above. This variability may be a consequence of the large tidal signal in the area propagating over a fairly shallow and wide shelf. The nature of the high frequency variability is such that at times it would mask surge events related to atmospheric weather patterns.

3.1 Seasonal and interannual variations in sea level

Table 2 compares the differences between the seasonal signal in the observations and the model via RMSE, STDE and correlation coefficients. For most of the coastline, the RMSE values are 0.07 m or less with lowest values along the southeast coast. Higher values of RMSE occur on the northern and western coastline from Milner Bay (0.15 m) to Hillarys (0.10 m). Similarly, STDE indicate that the model underestimates the seasonal component by a larger amount in these locations. The reason for the poorer model performance in these locations may be attributed to seasonal and interannual variations since these regions feature a relatively large steric component, which is not simulated by barotropic models [*Haigh et al.*, 2014a].

In Milner Bay, a large seasonal cycle in sea level occurs in part due to the transition from the prevailing north-westerly winds during the December to April monsoon to the dry season southeasterly trade winds from May to November [*Oliver and Thompson*, 2011; *Green et al.*, 2010] and steric effects from seasonal variations in ocean temperature and salinity. Variations in barotropic and steric sea level components are approximately in phase, are at a maximum in January and are highest in the southeast of the Gulf of Carpentaria [*Forbes and Church*, 1983].

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The range of the seasonal signal from tide gauge measurements for Milner Bay is estimated here to be 0.67 m. This is lower than the range of approximately 0.8 m reported in *Tregoning et al.* [2008] based on five years of data and the difference may be a result of interannual variations in the seasonal cycle in the longer record that is analysed here. The range of the seasonal signal in the barotropic model is 0.27 m, also smaller than the barotropic range of 0.4 m estimated by *Tregoning et al.* [2008]. Nevertheless, the results highlight that the steric component contributes to about half of the seasonal variation in sea levels in the Gulf of Carpentaria.

A relatively large steric component is also present in the seasonal signal from Darwin to Hillarys and this is related to seasonal variations in the strength of the southward flowing Leeuwin Current, which is weakest in October to March as it flows against maximum southerly winds and is strongest between April and August when southerly winds are weaker [*Godfrey and Ridgway*, 1985]. This produces an annual cycle in sea levels at Hillarys of about 0.22 m with maximum levels occurring in May-June and minimum levels in October-November [*Pattiaratchi and Eliot*, 2008]. The range of the seasonal signal from the Hillarys tide gauge is estimated here to be 0.34 m whereas in the model it is 0.09 m, the difference being of a similar order to the steric effect, which is not captured by the model.

3.2 Tides

A comparison of the amplitudes of the eight major tidal constituents derived from the measured and modelled sea levels over 1993-2012 is presented in Figure 2 for each of the tide gauge locations. For most locations there is reasonably good agreement between constituents estimates from model and observations. The largest differences in the M2 and S2 constituents occur along the south coast at Thevenard and Port Stanvac. At Port Stanvac in particular, this may be related to poor resolution of tidal waves propagating into the Gulf of St. Vincent. Milner Bay in the Gulf of Carpentaria is also showing poor agreement, with the leading O1 and K1 constituents largely underestimated by the model. The RMSE values in Table 2 also reflect larger differences and lowest correlations at Port Stanvac and Thevenard. Locations with large tidal amplitudes such as Broome and Darwin display the largest RMSE errors (30 and 40cm respectively). On average RMSE, STDE and correlation across all locations is 0.17 m, -0.05 m and 0.94 respectively indicating generally good model skill overall.

3.3 Sea Level Residuals

The sea level residuals, obtained after removal of the tides and seasonal signal are indicative of short-term fluctuations such as storm surge. Table 2 shows error statistics for the sea level residuals over the period 1993 to 2009 and in Figure 3 data is plotted for selected sites for the year 1997. This particular year is selected because it contained examples of storm surges at each of the tide gauge locations across the Australian region. The lowest RMSE errors of around 0.06 m are generally located along the east coast and within Bass Strait. The largest RMSE errors of 0.11 m are found at Milner Bay in the Gulf of Carpentaria and at Thevenard and Port Stanvac along the south coast. Correlations are highest at gauges across the south coast stretching from Hillarys to Spring Bay with values exceeding 0.8 at all locations except Burnie where a slightly lower correlation of 0.77

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was found. Correlations are lowest in macro-tidal areas with large shelves and/or complex bathymetry, with the lowest values of 0.55 and 0.39 at Darwin and Broome respectively. The poorer performance in these areas are further demonstrated using quantile-quantile plots shown in Figure 4. It can be seen that the ESLs tend to be more systematically underestimated along this coastline than in the southern mid-latitudes. For example, at Milner Bay the 99.9th percentile values are underestimated by approximately 0.5 m. At Port Stanvac, the underestimation of the high percentiles is likely a result of the 5 km grid spacing of the model inadequately resolving the Gulf of St. Vincent in which Port Stanvac is located.

To provide further insights into the type and scale of the the synoptic weather systems responsible for the storm surge events identified by arrows in Figure 3 (note that for Burnie, the synoptic map for Portland applies), Figure 5 presents the mean sea level pressure (MSLP) and 10 m wind vectors at the time of the peak sea levels. At Spring Bay, the peak residual of 0.4 m on 8 July 1997 is associated with the passage of a frontal trough that brings low pressure and southwesterly winds along the eastern Tasmanian coast (Figure 5a). *McInnes et al.* [2012] found that daily maximum sea levels at Spring Bay were highly correlated with those in Hobart (r=0.98) and Portland (r=0.80) indicating the strong influence of frontal systems on sea level extremes in this part of the country. Indeed relative peaks in residuals are evident at other south mainland coast stations for this event (Figures 5g-j).

At Port Kembla a relative peak in residual sea level of 0.3 m at around 10 May 1997 is the result of an east coast low that brings southeasterly winds to the coast. These systems are the cause of the majority of elevated sea level events along this coastline [*McInnes and Hubbert*, 2001]. A tropical cyclone off the northeast coast around 9 March (Figure 3c and 5c) and in the Gulf of Carpentaria on 28 December are responsible for sea level residuals of up to 0.4 at Rosslyn Bay and 1.0 m at Milner Bay respectively (Figure 3d and 5d). A second residual peak at Rosslyn Bay of up to 0.4 m around 13 May was not captured by the model.

The cause of this peak in the observations is not easily explained by the synoptic winds and SLP fields. However, some evidence points towards this peak being generated by a coastally trapped wave (CTW). Coastally trapped waves travel anticlockwise around Australia with speeds between 2-4m/s and amplitudes in the order of 0.25m (Woodham et al., 2013). On May 10th a coastal low produced a surge in Port Kembla that may have excited such a CTW. The timing and measured elevation height for the peak at Rosslyn Bay matches well with theoretical values of a passing CTW. The barotropic hydrodynamic model used in this study does not allow higher order (baroclinic) modes of CTW to exist and this may contribute to the failure of the model to capture this extreme sea level. Also unresolved bathymetric features over the Great Barrier Reef may alter the modelled sea surface height signal at this location.

At Darwin, a small relative peak of about 0.2 m around 22 February is associated with a burst of northwest monsoon winds (Figures 3e and 5e). At this time sea levels are also elevated to 0.5 m at Milner Bay (Figure 3d) by the northwesterly winds that are also directed into the Gulf of Carpentaria. At Hillarys, a sea level peak around 18 May is associated with a low pressure system off the southwest of the continent directing

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northwesterly flow onto the southwest coast. The final sequence of figures (Figures 4g-i) show the passage of a cold front that travels from west to east bringing southwesterly winds to the south coast of Australia and producing elevated sea levels in Esperance on 04 June (Figure 3g and 5g), Thevenard on 05 June (Figure 3h and 5h) and Portland and Burnie on 06 June (Figures 3i-j, 5i). Events of this type have been discussed in previous studies such as *McInnes and Hubbert*, [2003] and *McInnes et al.*[2009].

3.4 Tide-surge interaction

Understanding tide-surge interaction is important since it can alter timing, severity and intensity of storm surges [*Olbert et al.*, 2013; *Haigh et al.*, 2014b, *Antony and Unnikrishnan*, 2013]. In the context of the present study, a better understanding of the potential non-linear interaction between tides and surges contributes to an understanding of the uncertainty associated with the CMIP5-forced ocean model simulations.

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Tide-surge interaction has been studied previously for parts of the Australian coast. In Bass Strait, the occurrence of strong westerly winds leads to a phase shift in the timing of the surge [*McInnes and Hubbert*, 2003; *Wijeratne et al.*, 2012]. On the northern shelf, the combination of strong tropical cyclone winds together with tides alters the amplitude of the water column [*Haigh et al.*, 2014b]. Both of these observed effects are in line with the notion of [*Rossiter*, 1961] that the interaction of tides and surges is one of mutual alteration. Simply put, depending on the size of the tide and the water depth the presence of tides alters the generation of the surge signal because the wind is more effective at creating a surge over lower sea levels. They conclude therefore that surges produced during low tide are generally larger [*Horsburgh and Wilson*, 2007] than those produced during high tides. Furthermore, since the tide and surge signals propagate as shallow water waves the presence of a surge increases the speed of the tidal wave so that the high tide arrives sooner than predicted. Therefore, when predicted tides are removed from tide gauge observations, the residuals can contain variations that are not driven by meteorological effects [e.g. *McInnes and Hubbert,* 2003].

To examine tide-surge interaction, sea level components (ζ) from the three baseline simulations are analysed (see Table 1). The first is forced by meteorology (B-M, i.e. atmospheric winds and pressure only) yielding surge only, ζ_M; the second (B-T) is forced by tides only, $\zeta_{T;}$ and the third (B-TM) combines tide and meteorological forcing, ζ_{TM}. Subtracting the ζ_T from the ζ_{TM} yields a time series of residuals ζ_R. By definition, differences between the time series of residuals and surges (i.e. ζ_R and ζ_M) are a result of tide-surge interaction.

The potential amplitude changes arising from tide-surge interactions around Australia are first examined by selecting the four largest surges and and the four largest residuals (separated by a 3-day window) per year from the 20-year ζ_M and ζ_R time series respectively and ranking the values (Figure 6). Although ranking of events removes the one-to-one relationship between the events in the surge and residual time series, it clarifies the relationship between the two. Figure 6 suggests the relationship between the surges and residuals (red points and axes on top and right) are close to one, indicating that across the population of extremes the height of the surge is not systematically affected by the presence of tides in B-TM. Exceptions are Broome, where the largest

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residuals (those greater than 0.6 m) are higher than the equivalent surges and Darwin and Burnie where residuals tend to be consistently higher than the surges by about 1-2cm.

To examine the effect of non-linear interaction on the timing of the surge maximum, we also examine the total water level at the time of the four largest annual maxima from the ζ_R and $\zeta_{M.}$ In order to do so we add the predicted tide height to the surge and residuals at the times that the respective peaks occurred and again ranked the two groups and plot their relationship (black points and bottom and left axes on Figure 6). In this case near one to one relationships are now only seen for eight of the fourteen stations. Tide-surge interaction is evident for Cape Ferguson, Rosslyn Bay, Broome, Darwin, Burnie and Stony Point. With the exception of Broome, the interaction is such that the total sea level at the times of the maximum ζ_R is smaller than the total sea level at times of maximum $\zeta_{M.}$. In other words when tides are included in the model simulations, the interaction between tides and surges causes the maximum sea levels to occur during lower tides. The density distribution of the tides at the time of the 4-largest surges and residuals (not shown) indicates that the reason for the difference is that maximum residuals tend to occur on low waters for these locations. This 'phase locking' phenomenon may occur because the presence of a surge increase the water depth and this changes the speed of the tidal wave due to the reduced bottom friction [e.g *Arns et al*., 2015]. As shown by *Horsburgh and Wilson* [2008] in observations, a first order effect of this is that the peak surge occurs before the maximum water level due to tides only.

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From the above analysis we conclude (1) that tide-surge interaction does exist, particularly over the shallow shelf areas in the northwest, northeast and Bass Strait where large tidal amplitudes enhance these interactions. The interactions in these locations affect both the timing and height of the surge. The effect on timing is particularly important for operational forecasting considerations. However, our analysis also shows (2) that there is little overall difference in the magnitudes of the highest weather-driven events (i.e. ζ_R and ζ_M). This suggests that for the remainder of this study in which we are dealing with future changes in weather conditions and their effects on sea levels the omission of tidal forcing in the hydrodynamic simulations forced by climate models is not likely to alter the overall conclusions regarding changes to extreme sea levels [*Williams et al.,* 2016].

4. Climate change results

In this section, the primary focus is on changes in ESLs simulated by the climate change experiments listed in Table 2. First, quantile-quantile plots between the current climate (1980-1999) CC simulations and the B-M simulation are undertaken to examine the comparative performance of the different climate models under present climate conditions. Then the differences between the present and future climate conditions are examined.

4.1 Comparison with current climate

Figure 7 displays quantile-quantile sea level plots. They are used to compare the performance of the four CC experiments over the current climate period with those from the baseline (B-M) simulation. The figure suggests that the different climate models perform reasonablyin modelled sea levels for the lower percentile ranges. The sea level response across the upper percentile range from the climate models over the current climate period is only on par with the baseline experiment for Spring Bay while Port Kembla, Cape Ferguson and Portland. Rosslyn Bay, Milner Bay, Broome, Thevenard, Port Stanvac and Stony Point display lower sea levels. For Darwin the lower percentiles are also overestimated by all models. Out of the four simulations CC-I performs the worst for Broome, Milner Bay, Thevenard and Port Stanvac. CC-H performs the best for Port Stanvac and Thevenard.

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The average annual maximum sea levels from the B-M simulation are shown in Figure 8a together with values from the tide gauges residuals over 1980-1999. From Portland to Broome (counter clockwise), the B-M model is able to represent both magnitude and spatial variation in ESLs well. However at Hillarys on the west coast and Albany on the southwest coast the model underestimates the extremes. This underestimation may be partly due the contribution of wind-waves to ESLs (i.e. through wave setup), which is not considered in this study. A second, potentially larger contributor is sea level variably associated with baroclinic forcing and the Leeuwin Current [*McInnes et al*., 2016]. ESLs were also underestimated in this same region in the study of [*Haigh et al.*, 2014a], which, like this study, did not consider wave-driven or baroclinic processes influencing sea level. Model values are also underestimated at Port Stanvac and this may be due to poor model resolution of Gulf of St Vincent in which Port Stanvac is located.

Figure 8b shows the ensemble-average annual maximum sea levels of the four CC simulations. Results show that the climate model forcing leads to overall lower sea level extremes around the coastline of Australia compared to the baseline (B-M) simulation. This is likely to be at least partially due to the lower spatial and temporal resolution in the CC forcing (Table 1) compared to B-M. However, the variation in the ESL magnitude around the coastline is generally well captured with higher sea levels in the Gulf of Carpentaria and the southeastern coastline and Tasmania compared to the east and west coast regions.

We note that the skill of eight CMIP5 models in reproducing variables of surface temperature, precipitation and air pressure over continental areas by *Watterson et al*, [2014], including the four used here, led to model skill rankings which were markedly different to those determined by *Hemer and Trenham* [2015] in assessing global wind-wave climate skill using wind forcing from the same models. This highlights the need to assess the skill of the GCMs according to the task to which they are being used.

4.2 Seasonal mean maximum sea level change

To understand how seasonal changes in atmospheric forcing affect both the seasonal/ interannual and short-term (storm surge) sea level variations, the average of the largest sea level events per season over each set of 20 seasons is calculated and the 1980-1999 average values are subtracted from those of the 2080-2099 (Figure 9) for each of the CC simulations. The largest positive anomalies of up to 0.1 m are seen in the Gulf of Carpentaria in DJF in the CC-A and CC-H simulations. The positive anomalies extend to MAM in CC-A, are also positive in CC-C but are negative by up to -0.1 m in CC-H. Along the southern mainland coastline, the changes are generally small and mostly negative consistent with results reported in *Colberg and McInnes* [2012]. However, positive changes are evident in CC-H in SON and CC-I in DJF and MAM over the southeast of the mainland and Tasmania. On the east and west coastal regions, the changes across models are typically small and within the range of ±0.04 m.

To better understand the atmospheric forcing changes responsible for these changes in sea level variability seen in the CC-A simulation between present and future time slices, the change in the seasonal mean and standard deviation (STD) of the wind speed from the ACCESS1.0 is shown in Figure 10. Also shown on Figure 10a is the zero contour line of the zonal wind speed from 1980-1999 (blue) and 2080-2099 (red). This contour line identifies the delineation between the monsoon north-westerlies and tradewind easterlies over northern Australia during DJF and the subtropical ridge separating trade easterlies from mid-latitude westerlies over southern Australia throughout the year.

During DJF the eastward shift in the zero contour of the zonal wind in the 2080-2099 DJF is accompanied by a general increase in wind speed across tropical Australia and wind STD within the Gulf of Carpentaria. This suggests there is a greater influence of northeast monsoon winds on the Gulf of Carpentaria, which provide favourable conditions for increased sea levels in the Gulf [*Oliver and Thompson*, 2008]. The CC-H simulations produce a similar increase in sea levels in the Gulf during DJF, also related to northwest monsoon winds penetrating further east and increased variability in this region. The reasons for the positive anomalies in the ACCESS1.0 and the CC-C simulations in MAM are less clear since both simulations show a decrease in mean winds and variability in the Gulf of Carpentaria (not shown).

Along the southern coastline of the continent and Tasmania there is a tendency for a decrease in ESLs in most seasons of the models. As illustrated in figure 10 for CC-A, this is related to the southward movement of the subtropical ridge, reduced wind variability and the greater frequency of non-storm surge producing easterly winds. In CC-H in SON, positive anomalies in sea level are seen and this is related to both an increase in westerlies over Tasmania and a strong increase in STD (not shown). The weak increase in CC-I in DJF is related to the minimal southward movement of the mid-latitude storm belt together with an increase in the STD in that model.

The overall projected changes to maximum ESL events around Australia are summarised in Figure 11. These ensemble differences are generated by finding the difference between the maximum sea level for 1990-1999 and 2080-2099 time periods for each of the CC ensembles members. Since each time period is 20 years, this equates to the (empirical) change in 1 in 20 year average recurrence interval; the minimum, average and maximum of these ensemble differences are shown in the upper, middle and lower subplot of Figure 11 and give an indication of uncertainty. Additionally, the values of ESL are hatched where the model solutions differ

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in sign indicating inter-model variability. The minimum changes are negative around the entire coastline indicating an average decrease in the approximate 20-year average recurrence interval in the range of 0 to 0.2 m. The largest projected decreases are on the northwestern shelf, the central west and south coasts. The average change across the four models is weakly negative around most of the coastline with weak positive anomalies evident along parts of the north, the GoC and southern Tasmania. The ensemble maximum changes show weak positive anomalies of up to 0.04 m along the southeast and east coast. The largest positive changes of up to 0.15 m occur on the eastern side of the Gulf of Carpentaria, the central north coast and parts of the northwest and west coast. Negative anomalies occur on the central south and southwest coasts. Overall, model results are fairly robust over the southern coastline where all models suggest a decline in maximum sea levels. Large areas particularly over the north exist where changes in maximum ESL could go either way depending on the atmospheric model used. This may indicate possible uncertainties in parameterizing atmospheric convection in climate models over the tropics, which in turn strongly influences monsoonal winds and sea level setup in the Gulf of Carpentaria. It is worth noting that *Vousdoukas et al,* [2018] project changes for the Australian coastline in a 6-member ensemble containing one model in common with the present study (ACCESS1.0) and find for 2100 under RCP 8.5 largely uncertain changes in the Gulf of Carpentaria, mostly negative changes around the eastern, southern and western coastlines, positive changes across Tasmania and southeastern Australia and uncertain changes along the southwestern mainland coastline and the Gulf of St Vincent.

5. Summary and Concluding Discussion

In order to investigate characteristics of extreme sea levels (ESLs), a depth-averaged hydrodynamic model covering Australia was implemented at 5 km spatial resolution and baseline simulations carried out over the period 1981 to 2012 with hourly atmospheric and tidal forcing. Overall, simulations of longer-term (seasonal and interannual) and short-term (weather-driven) variations in sea level compare well with those measured at tide gauges, with differences largely reflecting the absence of baroclinic forcing in the model. The modelled tides agree well with observations in all except the Gulf of Carpentaria where the O1 and K1 constituents were underestimated by the model and the southwestern coast where the M2 and S2 constituents were underestimated. The effect of tide-surge interaction on the amplitude of the meteorological component of sea level extremes (e.g. storm surge) was found to be small for much of the coastline; the main effect of the interaction being on the timing of the peak sea levels rather than the annual maximum surges/residuals. This suggested that in climate model-forced hydrodynamic simulations that assess how atmospheric circulation changes affect ESLs, tidal forcing could be neglected. This is further supported by the finding (across a large number of north Atlantic tide gauges) that while tide-surge interaction may affect the timing of maximum water levels, tides have no direct effect on the magnitude of storm surge [*Williams et al.,* 2016].

Hydrodynamic simulations were carried out over the periods 1980-1999 and 2080-2099 using forcing from four CMIP5 climate models run with the RCP 8.5 emission scenario. Changes in ESLs were generally small and mostly negative along much of the coastline. However, in some areas ESL changes were sensitive to the

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movement of major atmospheric circulation patterns. This was because of factors such as bathymetric depths and coastline orientation in relation to the weather forcing that favoured the occurrence of certain sea level extremes. For example, the Gulf of Carpentaria exhibited relatively large increases in ESLs in the climate models that simulated eastward movement of the northwest monsoon during the DJF season. However, since only two of the four climate model simulations simulated this change in the future climate, the finding is uncertain. Along the mainland south coast, there was a greater tendency for the models to indicate a reduction of ESLs in the future, particularly during winter which is also consistent with the finding of *Colberg and McInnes* [2012] using CMIP3 and regional climate models for the atmospheric forcing and somewhat similar to the study of *Vousdoukas et al.*, [2018] regional climate models for the atmospheric forcing..

With regards to the projected ESL changes, we note several caveats. First, the changes are subject to large uncertainty due to the small number of CMIP5 models used to force the hydrodynamic model. Furthermore, certain important drivers of ESLs are poorly represented in climate models in general (e.g. tropical cyclones). Future studies may address these uncertainties by considering a larger ensemble of hydrodynamic simulations forced with higher resolution climate models that better capture important small-scale meteorological features, or by perturbing characteristics of historical storms to produce plausible future synthetic storm libraries [*McInnes et al.*, 2014]. We also note that wind-waves contribute to sea level extremes and these effects and their potential changes need to be assessed for a more complete understanding of the changes to sea level extremes [*e.g. Hoeke et al*., 2015]. The increasing availability of wave climate change assessments [e.g. *Hemer et al.*, 2013; *Hemer and Trenham*, 2015] will facilitate future efforts in this regard. Also, while previous studies similar to this one have focused on changes to ESLs and coastal inundation [e.g. *Colberg and McInnes*, 2012;. *McInnes et al.*, 2013], consideration of changes to other variables, including currents is emerging [e.g. *Lowe et al.*, 2009]. Changes to wind-driven coastal currents, which could be considered using the modelling framework presented in this study (but is beyond the scope of this paper), is also potentially important in the context of coastal erosion and shoreline change [*Gornitz*, 1991; *O'Grady et al.*, 2015].

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