Estimation of regional departures from global-average sea-level rise around New Zealand from AOGCM simulations

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Abstract

Quantifying future increases in sea level around New Zealand arising from climate change is a key factor for determining decisions on adaptation, yet most projections are expressed in terms of a global-mean rise in sea level. The work presented here makes use of the data from the Atmosphere-Ocean General Circulation Models (AOGCM) used in the 4th Intergovernmental Panel on Climate Change Assessment Report (IPCC AR4) of 2007 to estimate the possible regional changes in absolute sea level for the SW Pacific for the middle and end of this century for three future climate SRES scenarios (A1B, A2, B2). The AR4 models are initially assessed against satellite altimetry data and while the time mean characteristics of the dynamic topography are represented well, the representation of higher frequency variability is poor. Regional steric changes, determined from averaging several AR4 climate-ocean models, indicate departures of up to an additional 0.05 m, relative to the global average rise, may be applicable to the New Zealand region by the end of the century (2080–2099 relative to 1980–1999). The highest departures from the global mean rise in steric sea level would occur to the west of New Zealand (Tasman Sea) with the lowest departures in the deeper ocean areas (not the coast) to the south-east of the South Island (south of Chatham Rise). Of the three scenarios considered, the largest projected regional departures in sea-level rise around New Zealand for 2030–2049 occur in the A1B scenario and for 2080–2099 in the A2 scenario. However, the analysis presented here shows the projected regional increase in eustatic sea level will be relatively small compared to the global mean sea-level rise and supports earlier statements about departures in the region in more detail. Additionally, further regional contributions to sea-level rise will be influenced by future spatial changes in the gravitational field as melting of the Earth's polar ice sheets accelerates, producing a south-to-north gradient in sea-level rise for New Zealand from this process, with a lower contribution in the south relative to the north. It remains unclear what effects climate change will have on oceanic current circulation in the New Zealand region, and therefore on regional and local changes in sea-surface height. Locally, around the New Zealand coast, relative sea-level rise will also be influenced by spatial and temporal variations in rates of vertical land motion arising primarily from tectonic processes, such as the subsidence currently being experienced in the Wellington region.

Keywords: Sea level rise, New Zealand, IPCC AR 4 climate models.

1. Background: Climate effects on global and regional sea-level rise

Increasing sea levels and associated coastal hazards will be important considerations for coastal communities to adapt to during this century and beyond. This applies to a significant proportion of New Zealanders, where sixty-five percent of the population lives within 5 km of the sea (Statistics NZ, 2008), including twelve of our fifteen largest towns and cities.

The three main contributors to climate-driven sea-level rise (SLR) are: i) a net increase in total mass of ocean water (mostly associated with ablation of grounded ice sheets, ice caps and glaciers); ii) increases in ocean volume due to thermal (thermosteric) or salinity (halosteric) changes that change ocean water density; and iii) geophysical responses of the Earth's crust and oceans to past, ongoing and future adjustments to the gravitational field due to loss of land-based ice to the ocean. With regard to the latter, recent studies have shown that gradually additional regional variability in the sea-level signature will arise from changes in the gravitational field as polar ice-sheet mass is re-distributed throughout the oceans as melt water (Mitrovica et al., 2011; Spada et al., 2013). The complex combination of all these three main processes is producing an absolute (eustatic) rise in the ocean sea level (that varies regionally) and also regional and local variability in relative sea level, due to changes in landmass movement and gravitational changes (Cazenave and Llovel, 2010; Church et al., 2010; Cazenave and Remy, 2011; Meyssignac and Cazenave, 2012; Slangen et al., 2012). While much of the focus has been on projections for the global average sea-level rise, the uncertainty in the regional variability of sea-level change is likely to impact individual countries differently, depending on their geographic location, through regional oceanic responses to buoyancy fluxes (heat and freshwater), shifts in wind stress, potential changes in oceanic circulation and changes in the gravitational field, and locally, through vertical movement of the land due to tectonics, subsidence of sedimentary basins or extraction of groundwater.

Bindoff et al. (2007) have shown that globally, sea level has risen at an average rate of 1.8 ±0.5 mm yr^{-1} for 1961–2003. By summing the estimated values for each contributor to the sea-level budget (thermal expansion, glaciers, ice caps, polar ice sheets, changes in terrestrial water storage), Church et al. (2011) revisited the global sea-level budget for the modern era from 1972 to 2008. The observed sea-level rise (1.8 ±0.2 mm yr^{-1} from tide gauges alone and 2.1 ±0.2 mm yr^{-1} from a combination of tide gauges and satellite altimeter observations) reasonably matches their independent sum of contributions to global sea-level rise (1.8 ±0.4 mm yr^{-1}). The largest contributions come from ocean thermal expansion (0.8 mm yr^{-1}) and the melting of glaciers and ice caps (0.7 mm yr^{-1}), with Greenland and Antarctica contributing about 0.4 mm yr^{-1} (Church et al., 2011).

Research aimed at closure of the global sea-level budget has made significant progress in resolving shortfalls in budgets from earlier reviews (e.g., Bindoff et al., 2007) by addressing sources of uncertainty for the various contributors. Improved closure has been achieved for the more recent period (e.g., the last 50 years since 1961 and more so since 1993) for which there is a reasonably good heat budget (Church et al., 2013). Challenges remain at the global level, particularly: i) the closure between process-based models and sea-level observations further back in time covering the entire 20th century (Church et al., 2013); and ii) the inclusion of ice sheet contributions, which in terms of forward predictive capability of process-based models will also need to include the potential for accelerating ice-sheet loss. Despite this on-going progress in closing the global sea-level budget, patterns in sea-level response at regional ocean scales are still only partly understood, despite steric effects dominating regional variability in most regions (Slangen et al., 2012).

Historic long-term trends in New Zealand sea-level records were initially estimated by Hannah (1990) at four primary gauge locations (Auckland, Wellington Lyttelton and Dunedin) for the twentieth century period 1899–1988. Hannah (2004), extended the observation period up to 2000, revising the New Zealand mean rate of relative sea-level rise to 1.6 ±0.24 mm yr^{-1}. Hannah et al. (2010) updated the average relative sea-level rise up to end of 2008 to be 1.7 ±0.1 mm yr^{-1}. The same average rate of 1.7 mm yr^{-1} was obtained independently for an additional six regional tide-gauge sites (Whangarei, Moturiki Island, Port Taranaki, Nelson, Timaru, Bluff) by Hannah and Bell (2012). When the average glacial isostatic adjustment (GIA) of 0.3 mm yr^{-1} crustal rebound across New Zealand is included to derive an absolute sea-level rise, the average absolute rate for New Zealand is 2.0 mm yr^{-1}, which is within, but towards the upper range for the global average 1.8 ±0.5 mm yr^{-1} observed over the twentieth century (Bindoff et al., 2007). This means historically over the 20^{th} century, sea levels around New Zealand have been tracking upwards at a similar rate to the global mean.

The recent trend in global-average sea-level rise over the relatively short satellite-altimetry period from 1993 to 2009 of 3.2 ±0.4 mm yr^{-1} is around 65% higher than the longer-term rate from 1961–2009 (Church and White, 2011), with the same rate of rise (3.2 mm yr^{-1}) extending up to March 2013 (White, 2013). However, behind this global-average trend lies substantial regional variability, with the southern oceans and the western Pacific waters contributing most to this recent increase in global sea-level rise, primarily through long-period variability in winds and climate modes (Bindoff et al., 2007; Merrifield, 2011; Merrifield and Maltrud, 2011; Meyssignac and Cazenave, 2012; Zhang and Church, 2012) and spin-up of the deep South Pacific subtropical gyre near New Zealand (Roemmich et al., 2007). This recent short-term increase in sea-level rate is also present in New Zealand coastal waters with short-term rates of 4–5 mm yr^{-1} calculated from trends over the satellite altimetry period (1993–2011) from the annual-mean datasets of relative sea-level processed by Hannah and Bell (2012) for four long-term gauges at Auckland, Mount Maunganui (Moturiki), Wellington and Lyttelton. This range of short-term rates also matches with absolute sea-level trends in the merged altimeter record over New Zealand waters (Zhang and Church, 2012; Fig. 1) for a slightly shorter period 1993–2009.

This recent global and regional increase in SLR rates in the last two decades, since the start of the altimetry era in 1993, attracted attention due to a possible link to climate change. Natural variability in climate forcing predominates at similar decadal scales, due to, for example, changes in wind stress in the southern Pacific leading to the switch in the Inter-decadal Pacific Oscillation in 1998–2000 (Sasaki et al., 2008; Hannah and Bell, 2012) and decadal spin-up of the deep South Pacific subtropical gyre near New Zealand (Roemmich et al., 2007). Natural decadal variability explains a substantial proportion of this recent increase in the western and South Pacific as shown by Sasaki et al. (2008); Meyssignac and Cazenave (2012) and Zhang and Church (2012), although there remains an underlying contribution from anthropogenic radiative forcing at the global scale (Church et al., 2013). Understanding such regional variability in the recent-past sea-level response, together with isolating these regional variations from underlying long-term trends in ongoing monitoring of how sea level is tracking, are important considerations when planning coastal adaptation in countries bordering the Pacific Ocean, such as New Zealand.

Changes in surface heat and freshwater fluxes and wind stress will also affect ocean circulation (Bindoff et al., 2007). Alteration of circulation patterns is another mechanism for regional sea-level change in the SW Pacific, particularly the subtropical western boundary currents arising from a potential increase in the flow of warmer waters to the poleward extent of these boundary currents and changes in circulation and fronts within the Antarctic Circumpolar Current (Roemmich et al., 2007; Sokolov and Rintoul, 2009; Wu et al., 2012; Hill et al., 2011). Several studies of ocean circulation in the wider New Zealand region have highlighted the variability in sea-surface heights at interannual to decadal timescales e.g., mid Tasman Sea with a sea-surface height variability range of 0.2 m, mainly an increase, from 1993 to 2004 (Sutton et al., 2005) and a similar decadal response to the east of New Zealand in the Wairarapa Eddy between 1993 to 2003 (Chiswell, 2005). There remains considerable uncertainty about trends and changes in oceanic circulation in the New Zealand region at centennial timescales due to climate change (Phil Sutton, NIWA, personal commmunication.).

For coastal land-use and hazard planning, it is the local sea-level rise (i.e., implicitly including local vertical land movement due to tectonic and sediment-basin processes) that is the main consideration rather than a sole focus on the absolute sea-level rise including regional effects (MfE, 2008). However, future global projections are couched in terms of absolute (eustatic) values, so both types of sea-level rise need to be considered in the context of local coastal adaptation to climate change. The gaps in future projections of sea-level rise for New Zealand are understanding the regional influences on sea-level trends in the SW Pacific and estimating the departures of long-term regional sea-level projections from the global-average projections. The main aim of this paper is to address some of these gaps in the wider New Zealand region focusing on regional eustatic sea-level rise and briefly introducing the effect gravitational finger-printing could have on sea levels. While there are indications that the East Australia Current may strengthen with ongoing climate warming (Hill et al., 2011), multi-decadal to centennial time-scale changes in regional sea levels in the New Zealand region arising from changes in oceanic circulation are not considered any further as changes in circulation patterns over and above the considerable decadal variability are not yet clear (Phil Sutton, NIWA, pers comm.). This study uses projections of absolute (eustatic) sea level from the Atmosphere-Ocean General Circulation Models (AOGCMs) used in the 4th Assessment Report (AR4) of the Inter-governmental Panel on Climate Change (IPCC). Despite the presence of interannual and inter-decadal variability, the studies show that there has been a consistent long-term increase in sea-level during the twentieth century, which has carried on into the twenty-first century. Therefore, this study provides estimations of the likely change (departure) in absolute steric sea level in the New Zealand region relative to global-average sea level projections, leaving aside potential changes to the dynamics of ocean circulation.

Section 2 discusses the datasets used from the AR4 models and satellite altimetry. Section 3 provides a comparison to spatial patterns in the satellite altimetry data as an initial quality control. Section 4 provides a further quality control measure, based on historical trends in the altimetry data, and then contains the analysis of the model output from the AR4 models. Finally, the results are discussed in Section 5 in context of the known uncertainties and variability, including possible effects on regional sea level of gravitational changes, to provide estimates of future regional sea-level rise for New Zealand coasts in the context of global projections.

2. Data

2.1 AOGCM data

The projected sea-level rise data from Atmospheric-Ocean General Circulation Models (AOGCMs) used in this analysis were taken from the Coupled Model Intercomparison Project 3 (CMIP3) experiment used in the IPCC AR4 report (see Chapter 10, Meehl et al., 2007). For this analysis we used the "sea surface height above the geoid" as is defined by PCMDI at http://www-pcmdi.llnl.gov/ipcc/standard_output.html#overview:

"As defined here, "the geoid" is a surface of constant geopotential that, if the ocean were at rest, would coincide with mean sea level. Under this definition, the geoid changes as the mean volume of the ocean changes."

Essentially, if the volume of the ocean is changing then the height of the geoid from the centre of the earth is changing too. Therefore, by estimating the global mean value of the geoid during the 'control' period (1980–1999, see later) it is possible to estimate the deviation from this value as the change in sea level from the 'control' period out to the future projection. The surface height above the control-period geoid will be referred to as '*zos' (the variable name used in the PCMDI archive)*. This parameter from the coupled AOGCMs accounts for steric changes in eustatic sea level and estimates of the contribution from ablation of ice caps, ice sheets and glaciers but not the gravitational fingerprint (discussed later).

Three future scenarios from the Special Report on Emissions Scenarios (SRES) were used in this study along with simulations of the twentieth century, for all available models. The future scenarios are denoted as A1B, A2 and B1 and the twentieth century run from ~1850 to 2000 as 20c3m. Details of each of these scenarios can be found in Houghton et al. (2001), Meehl et al. (2007), Nakićenović and Swart (2000) and Randall et al. (2007). The models used for each scenario can be seen in Table 1 and details of all the models can be found in Table 8.1 of Randall et al. (2007)

Model	20c3m	A1B	A2	B1
bccr_bcm2_0	X	X	X	X
giss_model_e_h	X	X		
giss_model_e_r	X	X	X	X
gfdl_cm2_0	X	X	X	
gfdl_cm2_1	X	X	X	X
cccma_cgcm3_1	X	X	X	X
iap_fgoals1_0_g	X	X		X
miroc3_2_hires	X	X		X
miroc3_2_medres	X	X	X	X
mpi_echam5	X	X	X	X
mri_cgcm2_3_2a	X	X	X	X
ncar_ccsm3_0	X	X	X	X
ncar_pcm1	X	X	X	X
ukmo_hadcm3	X	X	X	X
giss_aom	X	-	-	-
miub_echo_g	X	-	-	-
ukmo_hadgem1	X	-	-	-

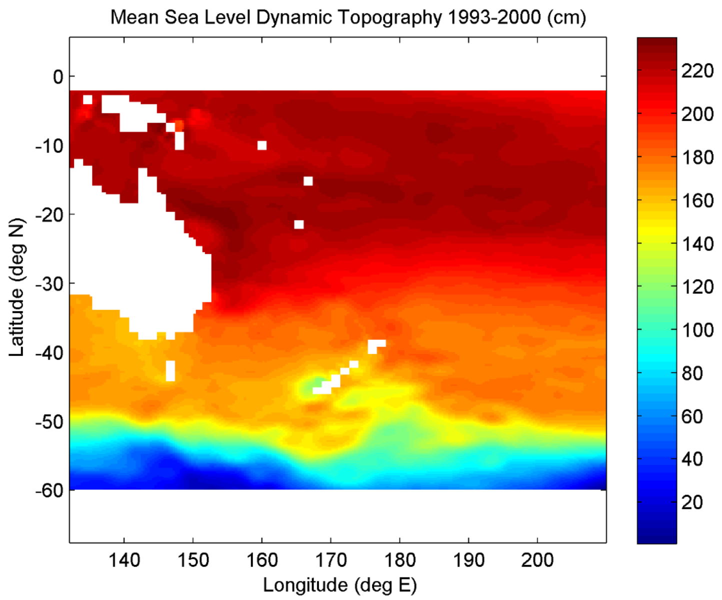
Table 1: Model data availability from the AR4 database. X represents scenario availability, a space implies data are not available for that model and '-' implies the model was not used beyond the 20c3m phase (~1850 to 2000) for failing the quality control.

2.2 Satellite altimeter data

Satellite altimetry data were taken from TOPEX/Poseidon, Jason-1, ERS-1 and ERS-2, specifically the "SSALTO/DUACS Gridded Absolute Dynamic Topography" dataset. The data are distributed by AVISO at http://www.aviso.oceanobs.com/. Details of corrections applied to the altimetry datasets can be found in the AVISO/CNES User Handbook (2011). These satellite data are used to provide a quality control for the future sea-level projections from the model data.

3. Comparison of climate-ocean modelling to satellite altimetry data

Maps of the mean and standard deviation of the dynamic sea-level topography as measured by satellite altimetry can be seen in Figures 1(a) and (b) for the Southwest Pacific region. These maps use monthly data from the period 1993-2000. The data is not de-trended before calculation of the standard deviation, because we are interested in total variability of the dynamic sea-level topography, on timescales from monthly up to decadal. The dynamic sea-surface topography, using the CLS09 mean sea surface (Rio et al., 2011), is the permanent stationary component of ocean-surface topography. It is derived from hydrography and drifting buoy velocities, satellite altimetry and other gravity data sources to be relative to the Earth's geoid and is therefore synonymous with *zos* provided by the coupled climate-ocean models. The highest mean values are generally close to the equator with lower values at high latitudes. The largest variability (standard deviation) in the dynamic topography corresponds with strong ocean currents such as the Antarctic Circumpolar Current (ACC) in the Southern Ocean, the East Australian Current (EAC) off New South Wales and to a lesser extent, the Tasman Front east of the EAC and associated East Auckland Current that flows east and then south-east around the top of the North Island of New Zealand.



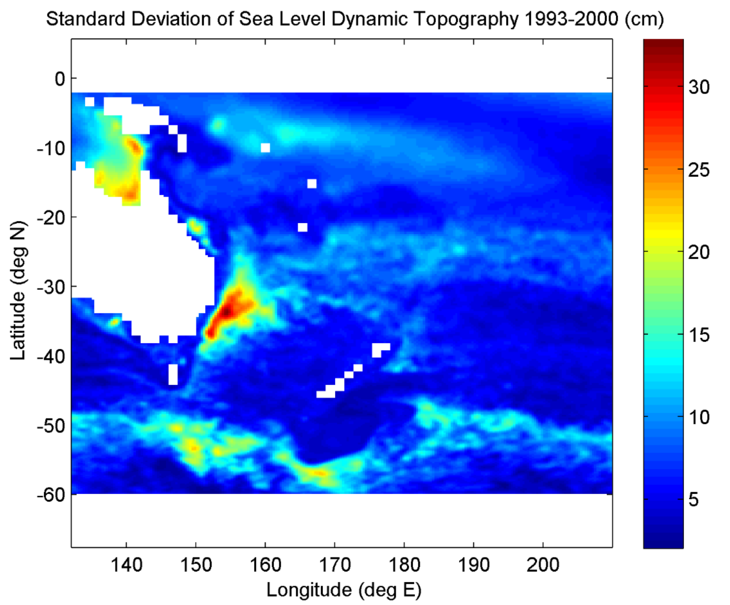


Figure 1: Mean sea level dynamic topography (top) and the standard deviation of the sea level dynamic topography from the satellite altimetry data (bottom) (discussed in Section 2) from 1993 – 2000 (cm).

The 17 models given in Table 1 were compared to the satellite altimetry data given in Figures 1(a) and (b) for the same period 1993–2000. To achieve this, we calculated spatial maps of mean and standard deviation using monthly data from each model (i.e., model equivalents of Figures 1a;b), and interpolated these onto a common grid with the satellite altimetry data. A correlation value was then calculated for each model, for both the mean and the standard deviation, using a point-by-point linear correlation between the model and satellite maps. This approach tests the models' ability to reproduce the patterns in the mean and standard deviation of the dynamic sea-level topography. The correlations for each model are for the SW Pacific region shown in Figures 1(a) and (b) and can be seen in Figure 2.

For the mean sea level over the SW Pacific, all of the models show a high degree of spatial correlation (>0.9) with the altimetry data, except for miub_echo_g. However, the correlations for the standard deviation in sea level (the variability of sea level over the 8-year period 1993–2000) are not well reproduced for any of the models. This suggests that, while the CMIP3 models are capable of reproducing the spatial pattern of long-term changes in mean sea level, they are not capable of representing the higher frequency and smaller-scale variability in the SW Pacific. For example, if a model had a bias in the location of the atmospheric jet stream and strongest surface winds, then high variability in the model's ACC would be at the wrong latitude and have a poor correlation with Fig 1b. Therefore, this study focuses on long-term changes in sea level and disregards decadal and interannual variations. Based on the analysis in Figure 2, we will also remove miub_echo_g from further consideration as it is particularly poor at representing the mean state relative to the other models.

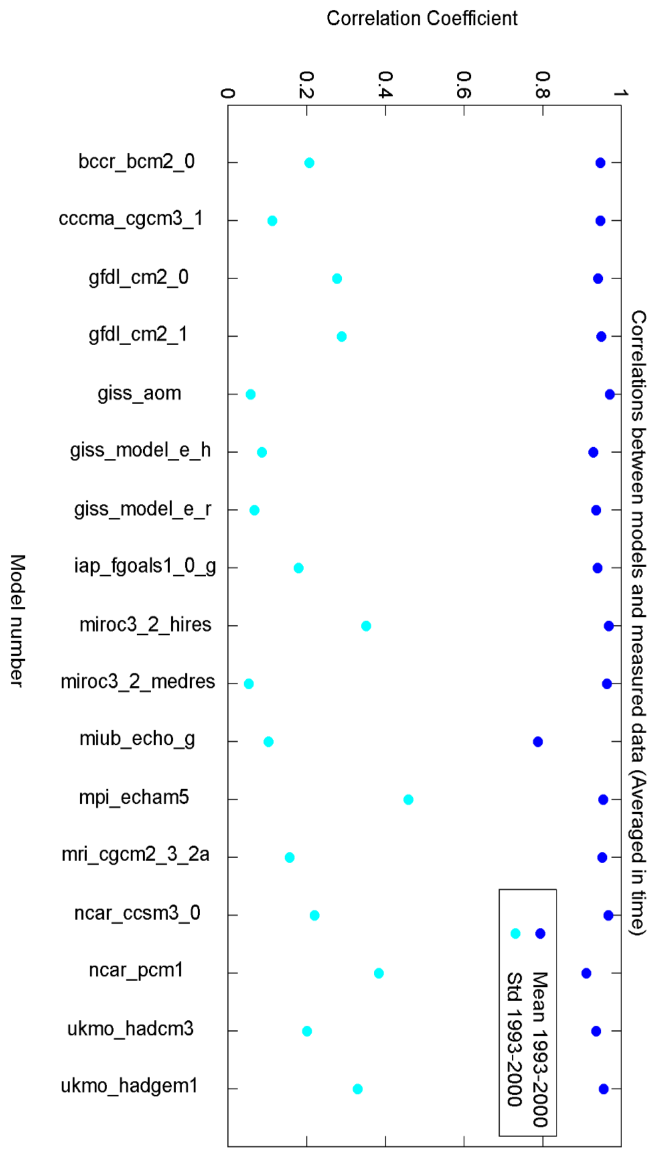


Figure 2: Spatial correlations, for the Southwest Pacific region in Figure 1, between the mean and standard deviation (1993-2000) of the satellite derived dynamic topography and zos for each of the models.

4. Projections of sea-level change

4.1 Quality Control

Following the initial comparison to the satellite altimetry observations, a further quality control was run on the twentieth-century 20c3m phase of each of the 16 remaining atmosphere-ocean models. The global annual mean value of *zos* was calculated for each year of the 20c3m simulations and plotted (not shown). From this analysis, two of the models (giss_aom and ukmo_hadgem1) were found to have a strong negative trend. The negative trend in ukmo_hadgem1 has been noted in other work (Siobhan O'Farrell, CSIRO, personal communication) and giss_aom has a low horizontal grid resolution compared to the other models. Due to the negative trends in global mean *zos* for giss_aom and ukmo_hadgem1, which are counter to the measured historic rates of sea-level rise, they have been removed from the analysis.

4.2 Changes in sea level for the Southwest Pacific region

The ensemble mean change (departure) in regional *zos*, relative to the global mean change, for each of the three SRES scenarios and time-slices can be seen in Figures 3 – 5. To produce the ensemble means, each of the 14 retained models was re-gridded to a common grid and then averaged (the land surface of the re-gridded fields is overlaid in white with an outline of the land surface surrounding those points purely to aid in visualizing the location of the land). The values in each figure are for the change in *zos* for either 2030–2049 or 2080–2099 relative to a 1980–1999 baseline, minus the global mean change in *zos*. The yellow / red colours indicate a higher regional departure in sea level and the green / blue colours a reduction, relative to the global mean change.

For all three future climate scenarios, the largest increases in *zos* (relative to the global mean) are along the EAC and the subtropical front, with positive anomalies around New Zealand. This suggests that sea levels will rise by more than the global mean increase in the SW Pacific centred on the New Zealand region. All scenarios indicate that sea level departure from the global mean will rise for 2030–2049 relative to 1980–1999 and increase further by 2080–2099, which can also be seen in the bottom panels of Figures 3 – 5.

The largest projected regional departure in *zos* increases around New Zealand for 2030–2049 occur in the A1B scenario (Figure 3(a)) and changes over to the A2 scenario for 2080–2099 (Figure 4(b)). This changeover in scenario matches the projected pattern for surface temperatures, which directly links with sea-level response through thermal expansion rather than any subtle form of ocean response. The smallest increases in sea level relative to the global mean occur in the B1 scenario at both 2030–2049 and 2080–2099 (Figures 5(a) and (b)). The rise in sea level around New Zealand at 2030–2049 is approximately 0 – 4 cm above the global mean and at 2080–2099 approximately 1 – 7 cm above the global mean (across all three SRES scenarios). To assess these values further, we have identified three sub-regions surrounding New Zealand (see Figure 6) to investigate the changes in sea level around the eastern and western seas.

4.3 Changes in sea level for New Zealand waters

The three sub-regions used to estimate the steric sea-level change close to New Zealand can be seen in Figure 6 and are defined as:

1. West of New Zealand (W)
2. Northeast of New Zealand (NE) and
3. Southeast of New Zealand (SE).

These sub-regions encompass much of New Zealand's surrounding ocean and several islands. The area mean changes in *zos* (μ, relative to the global mean) can be seen in Table 2 along with the standard deviation (σ) between the area averages of each model.

To the west of New Zealand (W sub-region), steric sea levels are projected to rise by 2.1 cm, 1.1 cm and 1.2 cm more than the global mean (averaged over several models) for A1B, A2 and B1 scenarios, respectively for 2030–2049. The values increase further for all scenarios by 2080–2099 with the largest increase of 4.9 cm above the global mean of the A2 scenario. This increase in departure from the global-mean estimates implies a slightly higher rate of regional sea-level rise during the latter part of the century compared to the rise in the global-average from these models, although the regional departure is still small.

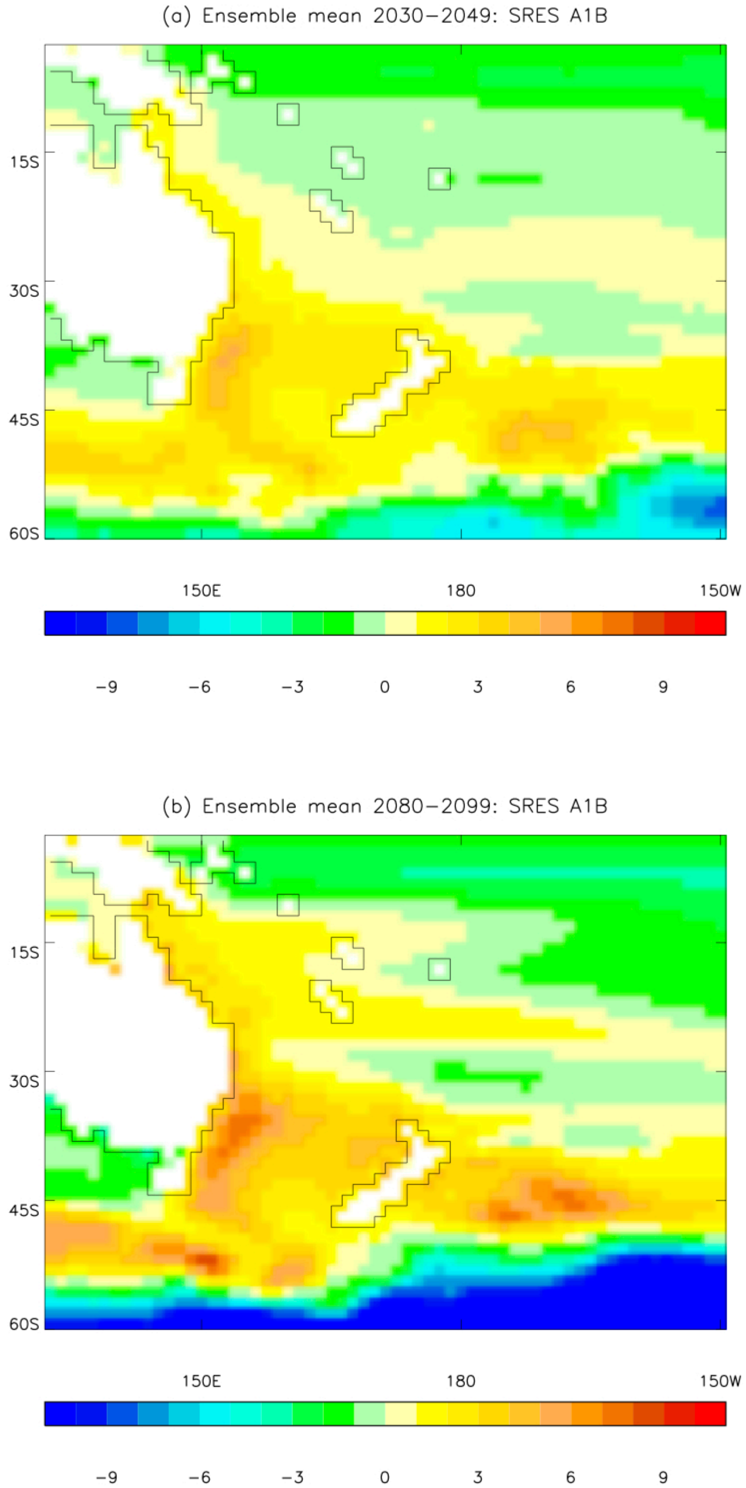


*Figure 3**:** The A1B scenario, ensemble mean change in the grid box zos relative to the global mean change in zos (cm) for (a) 2030 – 2049 and (b) 2080 – 2099 relative to the 1980 – 1999 mean.*

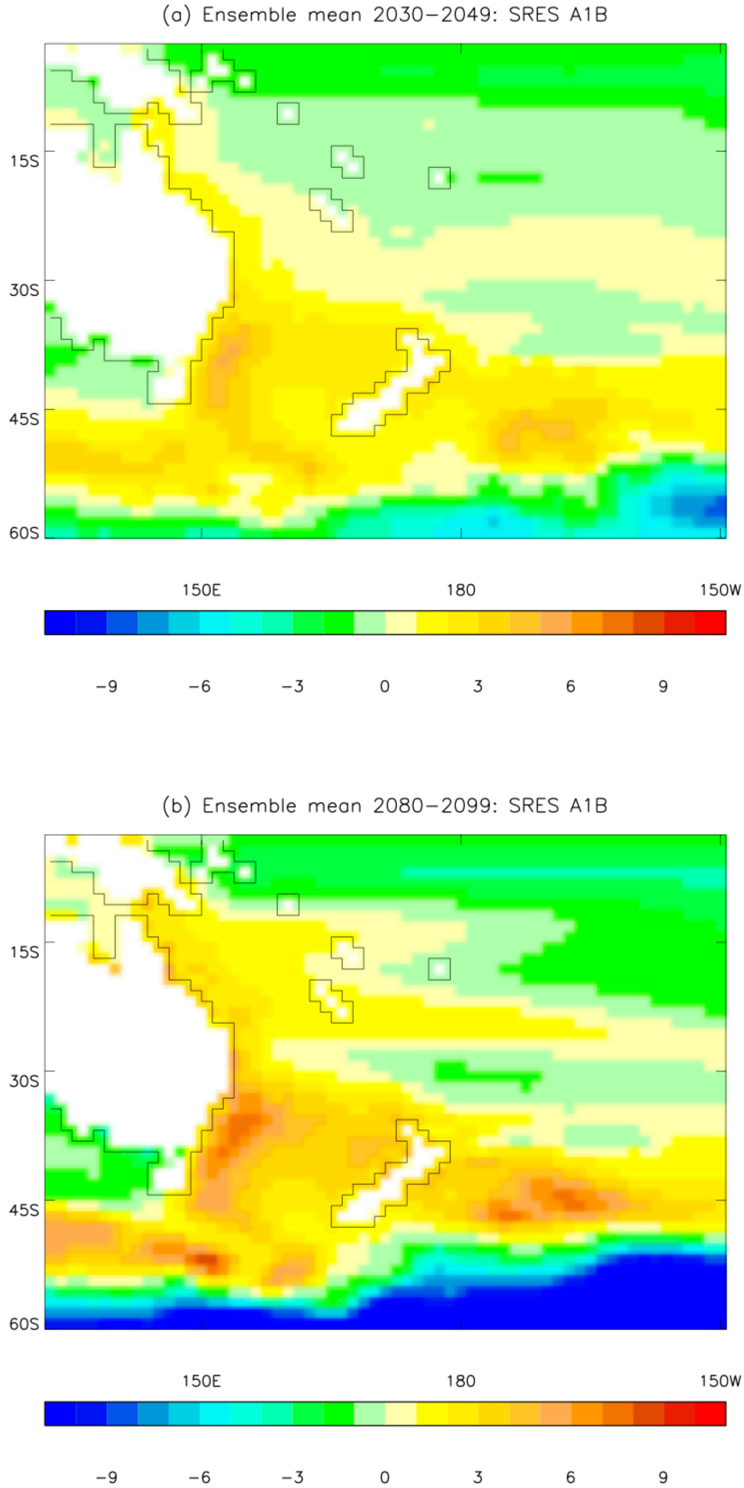


Figure 4: The A2 scenario, ensemble mean change in the grid box zos relative to the global mean change in zos (cm) for (a) 2030 – 2049 and (b) 2080 – 2099 relative to the 1980 – 1999 mean.

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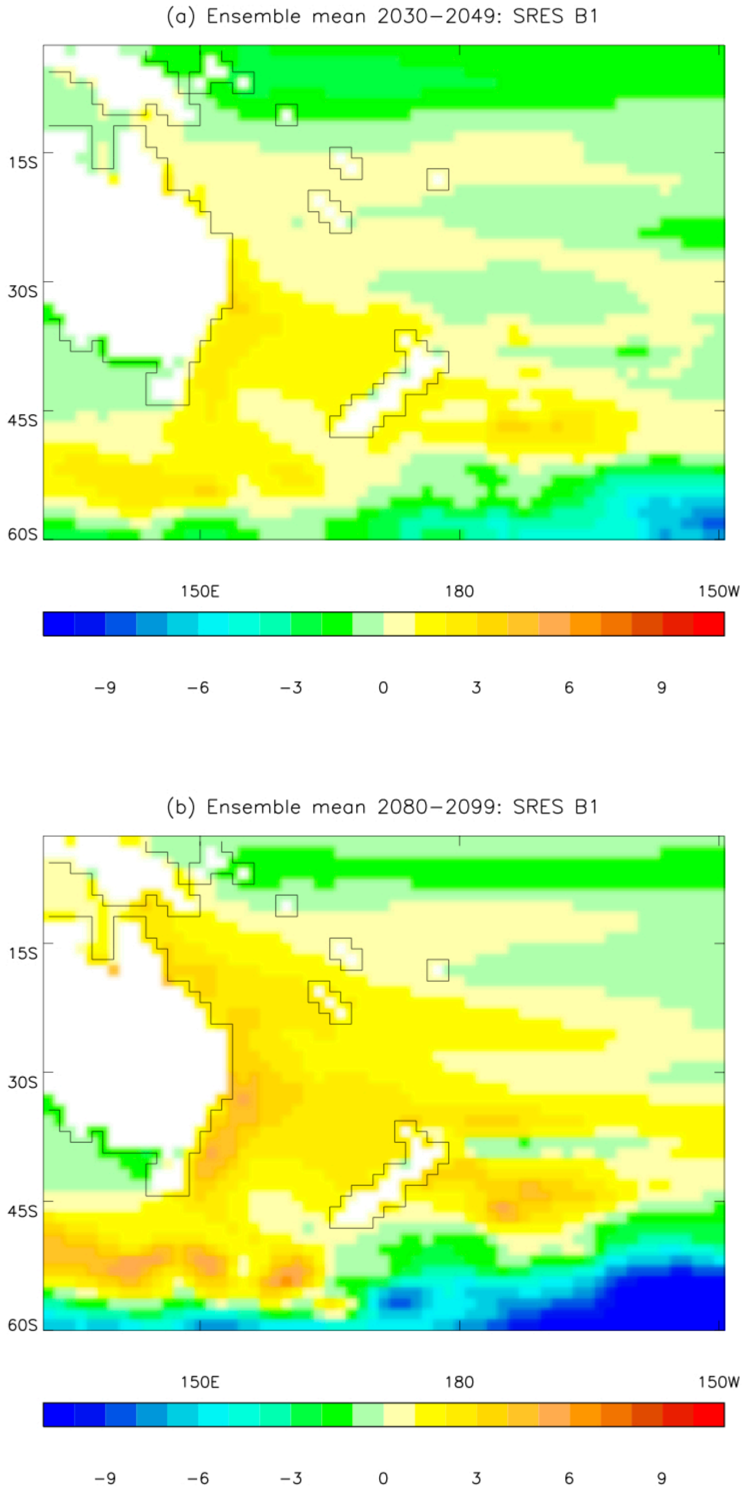

Figure 5: The B1 scenario, ensemble mean change in the grid box zos relative to the global mean change in zos (cm) for (a) 2030 – 2049 and (b) 2080 – 2099 relative to the 1980 – 1999 mean.

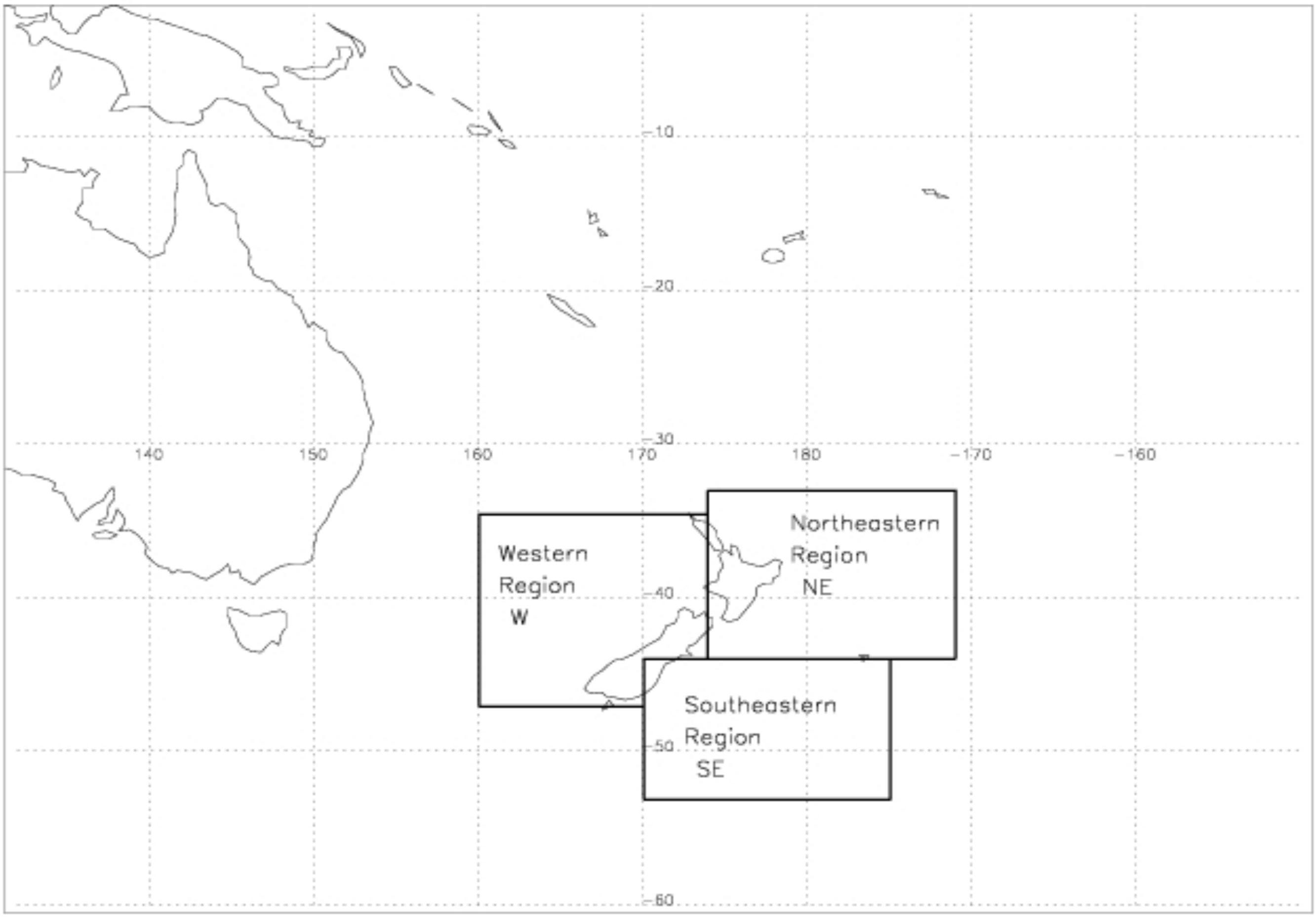

Figure 6: Domains of the sub-regions used for the average sea-level departures given in Tables 2–3.

Scenario	2030-2049			2080-2099		
	W	NE	SE	W	NE	SE
A1B μ	**2.1**	**1.2**	**1.7**	**3.1**	**2.6**	**0.9**
A1B σ	2.4	3.3	3.2	5.1	5.5	5.9
A2 μ	**1.1**	**1.1**	**-0.1**	**4.9**	**4.1**	**2.9**
A2 σ	5.2	4.4	4.7	5.1	5.3	3.6
B1 μ	**1.2**	**0.7**	**0.7**	**1.8**	**2.0**	**-0.2**
B1 σ	1.4	2.7	2.3	3.3	3.7	4.3

Table 2: The ensemble mean (μ) change in zos (cm) for 2030 – 2049 and 2080 – 2099 relative to 1980 – 1999 for each SRES and averaged throughout the sub-regions given in Figure 6 (minus the global mean). Also included is the standard deviation in the regional means across the models (σ).

Scenario	2030-2049			2080-2099		
	W	NE	SE	W	NE	SE
A1B μ	**3.9**	**4.3**	**2.5**	**3.5**	**6.7**	**-1.4**
A2 μ	**4.4**	**6.9**	**1.0**	**6.3**	**7.1**	**1.0**
B1 μ	**2.8**	**4.3**	**0.1**	**2.2**	**5.9**	**-2.4**

Table 3: The mean (μ) change in zos (cm) from the gfdl_cm2_1 model for 2030 – 2049 and 2080 – 2099 relative to 1980 – 1999 for each SRES and averaged throughout the sub-regions given in Figure 6 (minus the global mean).

For the NE sub-region (as with W), all scenarios result in an increase in steric sea level above the global mean increase at 2030–2049 and 2080–2099. The increases in the regional departure of sea-level rise by 2080–2099 are more than double the rises for 2030–2049, exhibiting a similar pattern of increasing departures by the end of this century as in the W sub-region. Again, as with the W region, the largest increases in *zos* above the global mean are projected to occur for the A2 scenario for the 2080–2099 period.

The SE sub-region differs from the W and NE regions as the regional mean change in sea level is slightly less than the global mean value in 2030–2049 for A2 and also in 2080–2099 for the B1 scenario. It is likely that in this sub-region, there will be a greater areal extent of lower changes in sea-level rise compared to higher changes, relative to the global mean sea-level rise (see Figures 4(a) and 5(b)). Despite the lower values for the mean departure of sea-level rise from the global average in the SE sub-region, Figures 4 and 5 show that on the continental shelf of the South Island, sea levels should rise by a similar amount to those seen in the NE sub-region.

There is however an important caveat associated with the values in Table 2. The standard deviation across models in the values of sea-level change (relative to the global mean change), is larger than the mean value and agrees with Figure 10.32 in Meehl et al. (2007) for the A1B scenario. This indicates that the CMIP3 model estimates exhibit high variability in inter-model differences in each of these sub-regions and should be considered with caution.

In an attempt to reduce the uncertainty in the values given in Table 2, we also analysed the regional mean changes in *zos* in a single model (gfdl_cm2_1) which is regarded as highly reliable (Table 3). According to the work by Russell et al. (2006), the gfdl_cm2_1 model simulates "the strength and position of the ACC for approximately the right reasons" (for example salinity and the location of the maximum wind stress for the 'present day' situation). Assuming gfdl_cm2_1 has the best representation of present and further assuming it is reliable for future projected values of *zos*, implies that the ensemble mean projected values are slightly low for W and NE at both 2030–2049 and 2080–2099, and slightly high for SE.

The gfdl_cm2_1 model shows strong increases above global mean *zos* throughout the Tasman Sea and to the east of the North Island in a similar manner to Figures 3–5, albeit stronger. Similarly, the rise in sea level in sub-Antarctic waters is less than the global mean rate in gfdl_cm2_1 and less than the values for the ensemble means given in Figures 3–5 and leads to the negative values for A1B and B1 in Table 3 (i.e., the rise is lower than the global average). Despite the differences between gfdl_cm2_1 and the global mean values, the patterns in Figures 3–5 are very similar to those for gfdl_cm2_1 (not shown) and the differences in the magnitude of regional mean departure for *zos* only differ by approximately 0 – 3 cm (see Tables 2 and 3).

Based on this appraisal, the current estimate of sea-level rise (excluding gravitational and local tectonic effects) around New Zealand coasts is likely to be similar to the global mean change or slightly higher, except possibly in the far southeast of New Zealand EEZ waters (which may be slightly lower than the global mean). From the results in this section, the departures in sea level from the global mean are likely to be slightly higher in northeastern and western waters of New Zealand than in southeastern waters.

5. Discussion of modelling results and uncertainties in regional context.

The previous sections have assessed the AOGCM CMIP3 models used and the projected regional changes in sea level around New Zealand. In this section, a discussion of the uncertainties and projections of sea level rise, along with a possible regional variability arising from changes in gravitational loading, is undertaken to provide context for the results.

Current New Zealand guidance on selecting an appropriate sea-level rise estimate is based on a risk-assessment framework that includes consideration of the consequences on a specific objective or project of a range of sea-level rise estimates by the 2090s (2090–2099), starting the assessment with a 0.5 m rise and at least considering at least a 0.8 m rise (MfE, 2008). This guidance manual included a preliminary estimate of an additional 0.05 m for the departure in regional absolute (eustatic) sea-level rise for the New Zealand region. The more detailed analysis from this paper given in Table 2, comprising an additional regional departure from the global mean of 0.01 – 0.02 m for the 2030–2049 period and an extra 0.03 – 0.05 m for the 2080–2099 period, confirms the validity of the 0.05 m allowance by the 2090s for the regional departure incorporated into the current sea-level rise guidance for New Zealand (MfE, 2008). However, these changes only represent an approximate 10% change in the estimates in MfE (2008) and the uncertainty in the model estimates in Table 2 is greater than the actual mean change.

A major source of uncertainty comes from the location of the strongest Southern Hemisphere (SH) wind stress imparted upon the ocean. Compared to reanalysis data (see Randall et al., 2007) the AR4 AOGCMs generally simulate the maximum SH wind stress too far northward and subsequently the Antarctic Circumpolar Current (ACC) is located too far north (also see Russell et al., 2006). The location of the ACC in each model and the representation of oceanic mixing are likely to be the main causes of the substantial spread in sea-level estimates in the New Zealand region amongst the AR4 models (see Table 2). Meehl et al. (2007) indicate that the increases in sea level for the South Pacific could be associated with a southward shift in the circumpolar front (also see Suzuki et al., 2005 and Sallée et al., 2008). However, if the circumpolar front (like the ACC) is generally located too far north in some of the AR4 models (Russell et al., 2006; Fig.1), some of the estimated regional sea-level rise departures around New Zealand may be overestimated, leaving aside any effect on sea-level rise from a shift in the circumpolar front on the stability of the West Antarctic Ice Sheet.

Despite a possible over-estimate in the sea-level rise over and above the global mean in the New Zealand region from the AR4 models in relation to the position of the ACC, progressively more pronounced contributions to both global-mean sea-level rise and regional departures are likely to arise towards the end of this century and beyond from increased melting of Greenland and Antarctic ice sheets (Meehl et al., 2007) and associated regional variations to the gravitational sea-level fingerprint.[1] The latter arises from changes in

[1] A large ice sheet exerts a gravitational attraction on the surrounding ocean. As the ice sheet melts, the net volume of water in the oceans increases, but the gravitational force exerted by the (now smaller) ice sheet on the ocean decreases. The latter leads to a migration of water from the near field of the ice sheet to the far field. Within 2000 km of the ice sheet, this migration dominates the sea level redistribution and the net result is a fall in sea level from that contribution. In the far field the migration due to the altered gravitational field adds to the general increase in ocean volume, leading to a sea-level rise in excess of the eustatic SLR (Mitrovica et al., 2011).

the gravitational field due to a re-distribution of mass from polar ice sheets to the wider ocean with consequential changes to regional patterns of SLR (Mitrovica et al., 2011; Bamber and Riva, 2010), in addition to the underlying increase in ocean volume from melt water.

Church et al. (2008) highlight that the current ice-sheet models used in the AR4 AOGCMs do not provide an adequate representation of dynamical processes on these ice sheets to provide an accurate assessment of the future contribution of ice sheets to sea-level rise or the uncertainty in that value. In an attempt to provide a value in AR4, Meehl et al. (2007) suggested the addition of 0.1 – 0.2 m by 2090-2099 to the upper limit of the modelled sea-level rise estimates, based on the assumption that glacier mass balance scales with surface air temperature change (this may not be the case however). This extra 0.2 m was also incorporated into the New Zealand guidance manual (MfE, 2008), although the expert-panel assessment by Bamber and Aspinall (2013) indicates that this future contribution from ice sheets may be an underestimate.

Recent studies have also shown that eustatic sea-level rise may be higher than AR4 projections due to the aforementioned uncertainties and potential future collapse of polar ice sheets (see review by the Royal Society of New Zealand, 2010), with plausible sea-level rises of more than 1 m possible by 2100. Pfeffer et al. (2008) carried out an analysis of upper sea-level rise bounds based on kinematic constraints governing ice-sheet and glacier loss, concluding that glaciological conditions required for a rise of 2 m by 2100 are very unlikely to occur (i.e., physically possible but only if all variables quickly accelerate to extremely high limits) and that a more plausible, but still accelerating ice-sheet contribution, would lead to a sea-level rise of about 0.8 m by 2100. The latter estimate is comparable to the 0.8 m by 2090s to at least be considered when applying a risk assessment under the current New Zealand guidance (MfE, 2008). A recent comparison of observations up to 2011 with previous IPCC climate projections (Rahmstorf et al., 2012) has shown that the AR4 sea-level projections of Meehl et al. (2007) may be biased low, particularly as the AOGCMs do not adequately represent the melting processes of the polar ice sheets (Randall et al., 2007). So uncertainty on a plausible upper bound on sea-level rise projections by the end of the century remains.

The modern theory of sea-level change from gravitational fingerprinting associated with ice-mass redistribution globally was developed in the mid-1970s but has only been further developed and given more focus recently e.g., Bamber and Riva, 2010; Mitrovica et al., 2011; Spada et al., 2013., There has been little information specifically on its effect on the New Zealand region, relative to global-average projections. Gravitational sea-level fingerprinting, so called because a specific ice sheet produces a distinct spatial geometry of sea-level change, has largely been based on particular scenarios. Once such scenario based on a 50:50 contribution to ice-sheet ablation from Greenland and Antarctica is shown in Figure 7 (as calculated by Dan Zwartz, Victoria University, personal communication). This combination ice-sheet melt scenario indicates that regionally in New Zealand a south-to-north gradient would result, with sea-level rise from this gravitational finger-print around 10% less at the south end of New Zealand compared with the northern end. A similar gradient also occurs for other specific polar ice-sheet melt combinations. For example, a similar, but slightly enhanced, south-north difference in the sea-level fingerprint across New Zealand was also obtained by Bamber et al. (2009; Fig. 3) and Mitrovica et al. (2011; Fig. 1), although this was for a unrealistic scenario that just considered a West Antarctica Ice Sheet collapse in isolation. The south-north gradient in the sea-level fingerprint (Figure 7) arises predominantly from the relaxation of the gravitational field in southern latitudes from

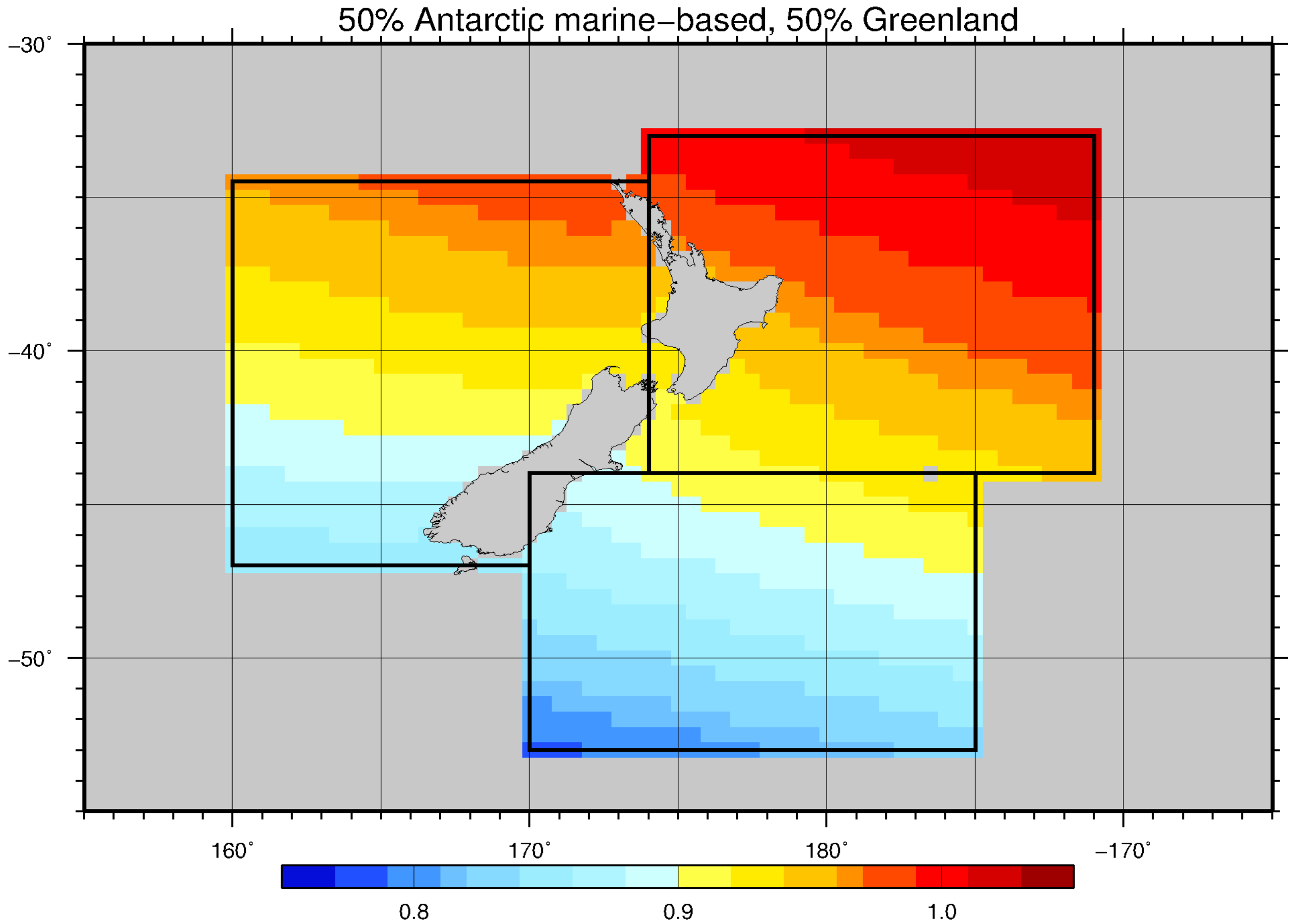

Figure 7: *Gravitational sea-level fingerprint for the New Zealand region for a single scenario where global ice-sheet melt is divided 50:50 between Greenland and Antarctica ice sheets. The scalar is normalized by the eustatic sea-level change from those ice sheets. The same sub-regions shown in Figure 6 are annotated.*

loss of ice mass from nearby Antarctica balanced off by the influence of the far-field increase in sea-level rise from Greenland Ice Sheet losses (Mitrovica et al., 2011). However, for most of this century, ice-mass contributions from the Greenland Ice Sheet and glaciers will be significantly larger than from Antarctica. Consequently, modelling by Slangen et al. (2012; Fig. 5) and Spada et al. (2013; Fig. 1) to combine and demonstrate the relativity between the effects of ice-sheet losses versus thermosteric effects shows the relative contribution of sea-level finger-printing to regional SLR in the SW Pacific (New Zealand region) is not prominent for a mid-range scenario by the end of this century. However, as Antarctic ice-sheet discharges become a more dominant contributor to global sea-level rise, as expected beyond the end of this century, regional variability of sea-level change in New Zealand from the more direct climate-ocean effects may be increasingly modified by the gravitational effect on sea-level fingerprint, particularly in southern New Zealand (Spada et al., 2013) Further research is now required to develop quantitative regional estimates for New Zealand of the gravitational influence of ice-sheet melting from various ice-sheet ablation scenarios and their interaction with thermosteric effects and associated changes in oceanic circulation.

At local scales within New Zealand, spatial and temporal differences in the rate of vertical land motion will lead to variations in relative sea-level rise. Given New Zealand's active tectonic geological setting, historic trends in relative sea-level rise have been remarkably consistent across 10 long-term tide-gauge sites

(Hannah and Bell, 2012). However, ongoing research is required to improve the spatial coverage of trends in vertical land movement through increasing coverage of the continuous GPS (cGPS) network operated by GeoNet (GNS Science and Land Information NZ). cGPS records are still relatively short (< 10 years at present). Nevertheless, local effects on relative sea-level rise are becoming evident, particularly in the lower North Island (greater Wellington region), where slow slip events on the plate subduction interface have resulted in general subsidence averaging 2 mm yr^{-1} over the past decade (Beavan and Litchfield, 2012). If such tectonic subsidence persists, future rates of local relative sea-level rise may be considerably higher in the lower North Island than the relative sea-level rise across other more stable parts of the New Zealand region.

6. Conclusion

In conclusion, some additional regional influences on projected absolute sea-level rise for marine waters surrounding New Zealand have been determined. Regional steric changes, determined from averaging several AR4 climate-ocean models, indicate departures of up to an additional 0.05 m, relative to the global average rise, may be applicable to the New Zealand region by the end of the century (2080–2099 relative to 1980–1999). The highest departures from the global mean rise in steric sea level would occur to the west of New Zealand (Tasman Sea) with the lowest departures in the south-east region (below Chatham Rise). Of the three climate scenarios considered, the largest projected regional departures in sea-level rise around New Zealand for 2030–2049 occur in the A1B scenario and for 2080–2099 in the A2 scenario. The regional increase is still relatively small compared to the projected global sea-level rise and the uncertainties in this value.

Limited information on the gravitational fingerprint arising from redistribution of ice-sheet mass indicates that regional sea-level rise may increasingly exhibit a south-north gradient with around 10% lower relative sea-level rise from this process in southern New Zealand, than northern New Zealand. Clearly, further research and improvements to coupled atmosphere ocean cryosphere and gravitational modelling are needed to constrain future projections on global-average rise in sea level and determine how these estimates can be downscaled regionally (Willis and Church, 2012), including incorporating relative vertical land movements at the local level from continuous GPS monitoring and regional gravitational changes from redistribution of polar ice-sheet mass.

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