Comments on GWRC Draft Climate Change Strategy

1. I have been asked by CRU to comment on the science underpinning the GWRC Draft Climate Change Strategy. My comments predominantly address aspects related to coastal hazards, which includes changes in weather extremes and particularly the assessment of past and future sea level rise for the Wellington region that appears in section 3.2.1 of the Draft Climate Change Strategy (DCCS) (Figure 1). However, as a general comment, the DCCS is based on the IPCC AR4 projections. The more recent IPCC AR5 projections differ from the earlier ones, particularly with respect to extreme events, where the IPCC AR5 Chapter 2 analysis indicates that the AR4 report tended to overstate both the magnitude of projected changes and their associated confidence. This document will first address the assessments of sea level rise, and then weather extremes.

Sea level rise: historic changes and future projections

2. The sea level rise part of section 3.2.1 is interesting in that it appears to avoid specifying IPCC projections, unlike the other climate parameters discussed, and is based on the Ministry for the Environment (MfE) guidelines[1]. Further, it refers to the IPCC projections published in the AR4 report as predictions, implying a more rigorous analysis of certainty than is the case. The section also conflates relative and absolute sea level rise. For management purposes, only relative sea level should be considered.

> *Sea level rise – currently tracking towards a 0.8m rise by the 2090s or ~1m by 2115 compared to 1990.*
>
> The Wellington region has a more complicated spatial and temporal pattern of long-term relative sea-level rise than other parts of New Zealand due to its geographical position astride a complex network of faults.
> These faults are associated with the convergence of the Australian and Pacific crustal plates some 20-40km beneath the surface. Recently Wellington city has been subject to slow-slip events that have produced an average subsidence of 1.7mm per year since 2000. Records over 6 years up to 2012 show subsidence varies across the region from around 1mm per year on the Kapiti coast up to between 2 to 3mm per year along the Wairarapa coast.
> Wellington Harbour has experienced an average rise in relative sea level of 0.2m in the last 100 years, which is relative to the inner-city land mass. Sea level monitoring in Wellington Harbour since 1990 shows that relative sea level is currently tracking towards a 0.8m rise by the 2090s or ~1m by 2115.
> Recent sea-level rise in Wellington (and in other main ports in New Zealand) is consistent with the trajectory being taken by the global average sea-level rise, which is tracking close to the upper end of the range of sea level rise predictions published in the IPCC's AR4 report.

Figure 1 – Text from the Draft Climate Strategy section 3.2.1 on projected climate change that summarises projected sea level rise.

3. Considering the first two paragraphs of Figure 1, the Wellington region does have a complicated pattern of relative sea level rise associated with vertical land movements[2], but not more so than many other areas along the New Zealand coast. These vertical movements can mitigate or exacerbate the effects of absolute (or eustatic) sea level changes. The draft strategy highlights the effects of recent short-term subsidence, but ignores the effects of uplift such as occurred in

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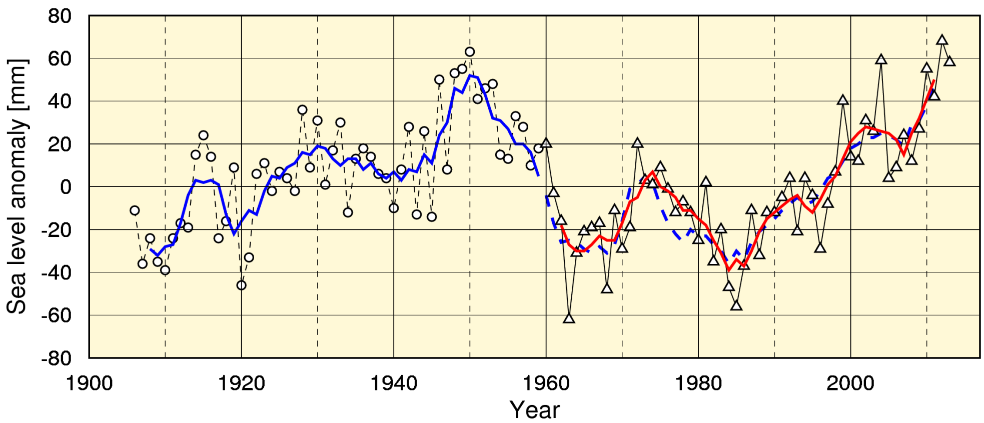
[1] Ministry for the Environment. 2008. Climate change effects and impacts assessment: A guidance manual for local government in New Zealand. http://www.mfe.govt.nz/publications/climate/climate-change- effect-impacts-assessments-may08/index.html

[2] National Institute of Water and Atmospheric Research Ltd (NIWA). 2012. Sea level variability and trends- Wellington region. Prepared for Greater Wellington Regional Council.

the Wellington Region during the 1855 West Wairarapa Earthquake. The well known sequences of raised beaches along the Wellington Coast, such as at Turakirae Head, are evidence of long-term episodic uplift. While it is difficult to predict when future uplift will occur, the probability of it occurring with centennial time-scales is comparable to the extreme scenarios of ice sheet collapse incorporated in the MfE guidelines for sea level rise.

4. Relative sea level changes in areas associated with subduction can show time varying rises and falls that do not correlate at all with global absolute sea level changes. One example highlighted in the IPCC AR5 assessment report is the Japanese coast, where there has been no detectable sea level trend since 1900 (Figure 2), excluding areas affected by coseismic vertical land movements during major historic earthquakes. The Japanese sea level data highlight long-term fluctuations due to natural internal variability of the ocean-atmosphere system. Numerical simulations of the effect of internal variability based on the CIMP5 climate models indicate that the ensemble spread of centennial scale dynamic sea level projections are the same magnitude as the global average steric component of sea level rise[3]. This indicates that internal variability should be included in sea level projections, which was not the case for the IPCC AR4 projections used by the DCCS, or the IPCC AR5 projections that should have been used.



5.

Figure 2 – Composite sea level anomaly for Japan between 1906 and 1959 for 4 tidal stations (blue) and 1960 and 2013 for regional averages. Only areas considered to be unaffected by coseismic relative sea level changes have been included[4]. The observed fluctuations correlate well with changes in wind stress and ocean temperatures linked to the Pacific Decadal Oscillation (PDO).

6. It is clear that sea levels for New Zealand, including the Wellington region, are affected by internal variability[2]. Figure 3 shows the cumulative residual departures from the long-term trends for (A) Auckland and (B) Wellington. This type of analysis highlights the longer period fluctuations due to the Pacific Decadal Oscillation, and tends to reduce the apparent influence of shorter duration events such as the El Niño – Southern Oscillation (ENSO). The Auckland data are consistent with most other tide gauge records around New Zealand.

7. In addition to internal variability, long-term vertical land movements affect the rate of relative sea level rise. Comparison of the rates of sea level rise assuming a linear trend (Ordinary Least-squares Regression) show differences between the main tide gauges around the New Zealand coast. The analysis of Wellington sea level by NIWA incorporates an estimate of the vertical changes associated with glacio-isostatic adjustments (GIA) of the crust and the tectonic movement recorded by continuous GPS measurements[2]. This indicates that the absolute rate of sea level rise for Wellington is 0.33 ± 0.26 mm.y^{-1}. A separate analysis of the same data[5] estimated the absolute rate for Wellington as 0.4 ± 0.3 mm.y^{-1}, compared to an average absolute rate for New Zealand of 1.1 ± 0.3 mm.y^{-1}. However, it was recognised that there are different underlying tectonic vertical motions depending on whether the coastal region was predominantly on the Australian Plate (-1.4 mm.y^{-1}) or the Pacific Plate (+0.5 mm.y^{-1}), and the distance from the plate boundaries. Therefore, the mean rate for New Zealand may not be

[3] Bordbar, M. H., Martin, T., Latif, M. & Park, W. Effects of long-term variability on projections of twenty-first century dynamic sea level. *Nature Clim. Change* **5,** 343–347 (2015).
[4] http://www.data.jma.go.jp/gmd/kaiyou/english/sl_trend/sea_level_around_japan.html
[5] Tenzer, R. & Gladkikh, V. in Earth on the Edge: Science for a Sustainable Planet (eds. Rizos, C. & Willis, P.), International Association of Geodesy Symposia Volume 139, 135–139 (Springer Berlin Heidelberg, 2014).

meaningful, even though it is close to the range of mean global absolute sea rise rates of 0.39-1.03 $mm.y^{-1}$ derived using nonstationary statistical methods for time series data[6].

8. NIWA used a GIA of -0.3 $mm.y^{-1}$, based on the modelling of Peltier (2004)[2]. However, studies that have used geodetic data to constrain GIA have consistently found that the Peltier model results only are valid for Fenno-scandinavia. A review of these studies has indicated that the Peltier model values for New Zealand are not valid[7] and geodetic assessment of vertical land movement is more useful.

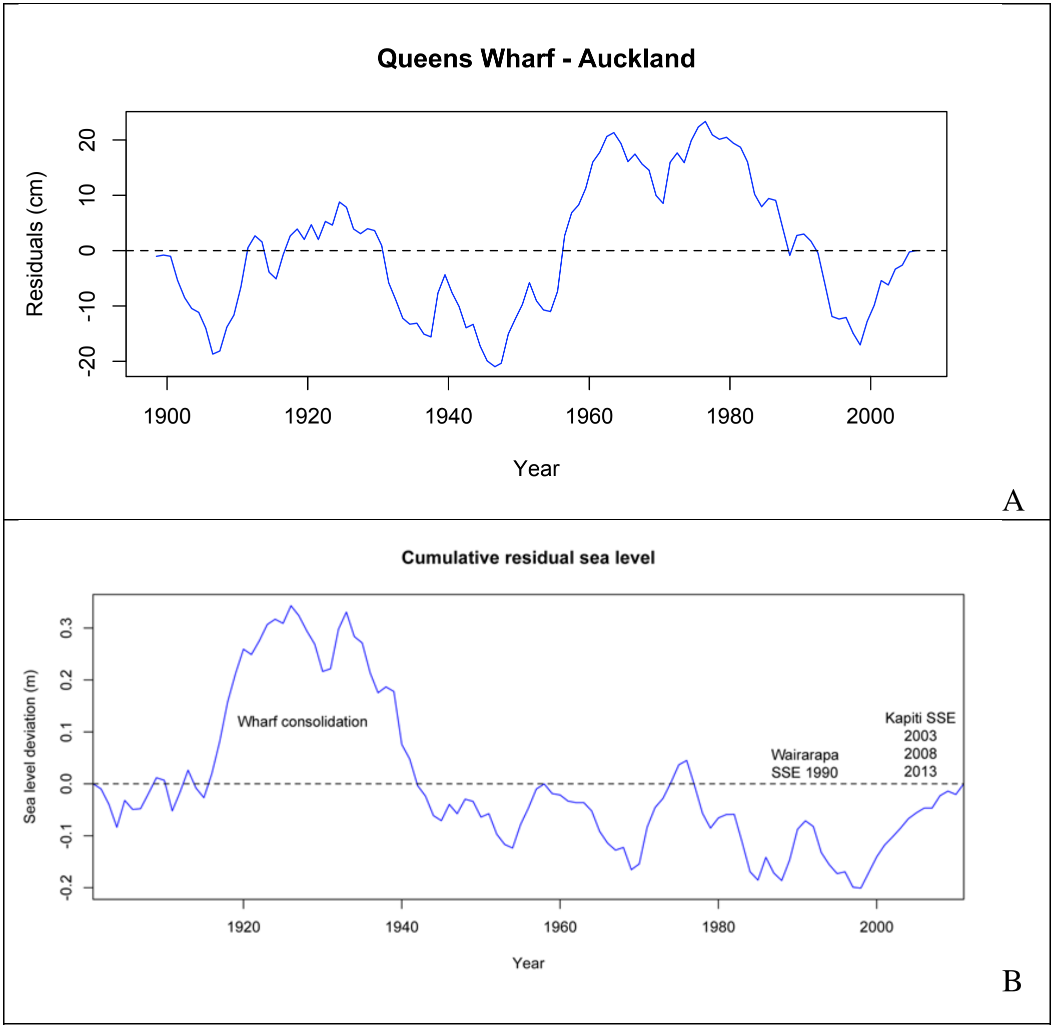


Figure 3 – Cumulative residual sea level departures from the long-term sea level trends determined from tide gauge observations at (A) Auckland and (B) Wellington. Indicated on the Wellington record (B) are periods associated with land reclamation and subsequent construction (Figure 4).

9. Further it is unclear from the NIWA report cited by the DCCS, why the GIA (*b* in their table 7.2) was added to the average NZ relative sea level rate to derive a corrected *relative* rate of sea level rise that was compared to the global average *absolute* rate of sea level rise of 1.7 ± 0.3 $mm.y^{-1}$. The comparison should be between *absolute* rates: in other words with 0.33 ± 0.26 $mm.y^{-1}$. This indicates that the rate of absolute sea level rise determined for Wellington does not “fit well” with the best global estimates cited by NIWA. The average absolute for NZ is also not a good fit. It is also clear that during the period of observations, the absolute rate of sea level rise was less than the global average cited by NIWA.

10. While there is good evidence for the influence of internal variability at Wellington[2], the determination of a low rate of absolute sea level rise suggests the observed relative sea level rise is predominantly due to local vertical movements. The cumulative residuals also indicate that tectonic (slow-slip events) and neotectonic (consolidation) effects are important. In

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[6] 1.Beenstock, M., Felsenstein, D., Frank, E. & Reingewertz, Y. Tide gauge location and the measurement of global sea level rise. Environ Ecol Stat 22, 179–206 (2014).

[7] Ostanciaux, É., Husson, L., Choblet, G., Robin, C. & Pedoja, K. Present-day trends of vertical ground motion along the coast lines. Earth-Science Reviews 110, 74–92 (2012).

particular, it is clear that large departures between 1920 and 1940 coincided with the large 70 ha reclamation at Thorndon adjacent to the tide gauge (Figure 4). Also evident are spikes associated with slow-slip events in the early 1990s, since 2000 (as mentioned in the DCCS), and possibly in the 1960s and 1970s. Further, the consequential heteroscedastic behaviour exhibited by the residuals (Figure 3) for both Auckland and Wellington indicate that the linear trends determined by OLS are unreliable. It is also recognised that there are high rates of tectonic subsidence in the Wellington region that are not well defined by short duration continuous GPS data, so that sea level trends determined at Wellington may be unrealistic[5].

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Figure 4. Land reclamation at Thorndon between 1924 and 1927, involving a total area of 70 ha[8] and forming Aotea Wharf. The tide gauge was located on older reclaimed land adjacent to this reclamation, although the exact location is unclear[2].

11. The third paragraph in Figure 1 claims that sea level observations obtained at Wellington since 1990 show that it is tracking towards the MfE guidelines for the upper limit that should be considered for planning purposes[1] (although this is not specifically stated). This claim is based on the NIWA report on Wellington sea levels[2], which includes a graph in their Figure 8-2 to illustrate the basis for this claim (Figure 5). The graph starts in 1900 and not 1990, which tends to obscure the recent trends, and includes 4 projected trends for future sea level of unknown origin. However, the low and mid scenarios are consistent with the base and planning trajectories in the MfE guidelines[1].

12. The 4 scenarios are supposed to be referenced to the 1990 Wellington sea level (zero line and red cross)[2]. However, a visual examination shows this is not true (the blue sea level curve is about 0.05 m above the zero line and centre of the cross). Instead the scenarios appear to be base-lined to the average sea level over some period such as 1985-1995. This forces the observed sea level to initially track the scenarios. Figure 6 shows the same sea level data compared to the MfE guidelines adjusted to start at the average sea level for the 1989-1999 period. For comparison, the observed sea level has also been mover downwards by 0.05 m so that the guidelines are baselined to the 1990 sea level as claimed for Figure 5. It is clear from both Figure 5 and Figure 6 that the observed sea level at Wellington is tracking below the MfE planning projections, and also below the base projections although the deviation is less. The only time that sea level really matches the projections is during the spike in 1999 that coincided with the PDO shift (labelled IPO shift 1999 in Figure 5). Finally, the observed sea level in 2011 (0.796 m) is similar to the level in 1990 (0.790 m).

13. Matching the start of the MfE curves to a single point on the sea level time series will significantly affect the apparent agreement. Baselining to a decadal average will reduce this effect. In Figure 6 the chosen period was between 1989-1999, which corresponds to 11 years and is better at removing the effects of interannual sea level variations than a 10-year period. If

[8] http://www.stuff.co.nz/dominion-post/capital-life/67623142/150-years-of-news-how-reclamations-shaped-wellington

the period from 1985-1995 were used, the starting sea level would be 0.730 m compared to the 0.741 m used in Figure 6. The 11 mm difference would not substantially affect the appearance of the graph. The MfE projections are relative to the average for 1980-1999 (20 years), which corresponds to 0.725 m at Wellington[9]. Again a 16 mm difference would not substantially affect the appearance. Changing the starting year will have a much more noticeable effect. For example, starting at 2000 instead of 1990 would provide a much better fit between the observed sea level at Wellington and the MfE projections.

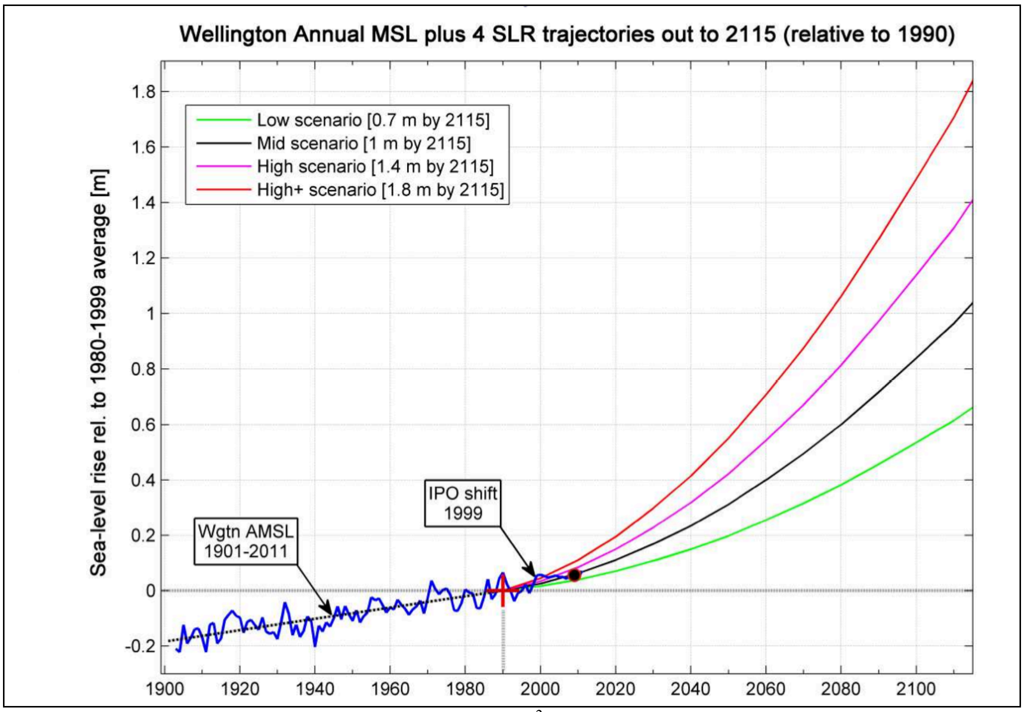

Figure 5 – Copy of Figure 8-2 from the NIWA report[2] cited by the DCCS. This graph appears to be the basis for the claim Wellington sea levels are tracking towards 0.8 m by the 2090s.

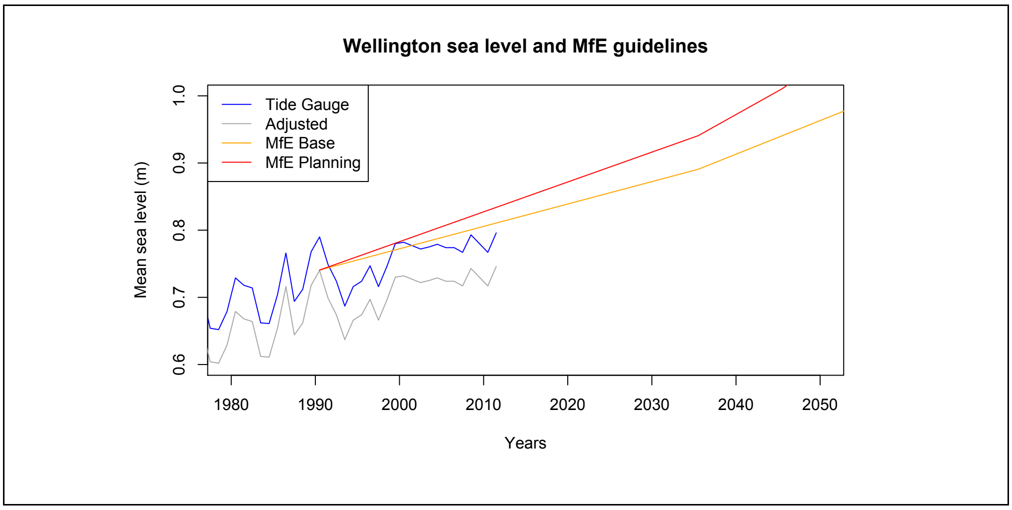

Figure 6 – Comparison between measured sea levels at Wellington and the MfE guidelines for projected sea level rise. The MfE curves are straight lines between the levels specified in the guidelines and have been baselined to a starting sea level of 0.741 m, which is the average for the period 1989-1999. The grey curve is the observed sea level minus 0.05 m to indicate the effect of starting the MfE curves at the actual 1990 sea level.

14. A slightly better impression of agreement could also be achieved in Figure 6 if the initial MfE sea levels were joined by a smooth curve as used in Figure 5. However, the MfE projections do not follow a smooth curve as shown in Table 1. Table 1 also indicates that the assumed rate of

[9] I think this is the most likely value used for the NIWA graph in Figure 5, but at the scale drawn a 5 mm difference between the decadal and bidecadal average is not detectable.

sea level rise between now and the 2030s decade is significantly higher than the long-term historical rate at Wellington (2.1 ± 0.1 $mm.y^{-1}$)[5]. The projected base sea level rise rate is not much higher than the average rate between the base period of 1980-1999 and the 11 year period from 2001-2011 (3.3 $mm.y^{-1}$), but this period was affected by the PDO interval variability (labelled as IPO shift 1999 in Figure 5) and the effects of slow-slip events that temporarily increased the rate of sea level rise[2].

Table 1 – MfE baseline sea level rise projections relative to 1980-1999 average[10].

Timeframe	Base sea level rise (m)	Average annual rate ($mm.y^{-1}$)	Planning sea level rise (m)	Average annual rate ($mm.y^{-1}$)
		3.8		5.0
2030-2039	0.15		0.20	
		5.0		7.0
2040-2049	0.20		0.27	
		5.0		9.0
2050-2059	0.25		0.36	
		6.0		9.0
2060-2069	0.31		0.45	
		6.0		10.0
2070-2079	0.37		0.55	
		7.0		11.0
2080-2089	0.44		0.66	
		6.0		14.0
2090-2099	0.50		0.80	
Beyond 2100		10.0		10.0

15. Overall it is clear that the observed sea level is not tracking towards the MfE planning sea level rise of ~0.80 m by 2090-2099 or ~1 m by 2115 as stated in the DCCS. The NIWA report (sections 8.5.1 and 8.5.2) also identifies various reasons why it is very unlikely that there will be a sudden acceleration in the rate of sea level rise to the levels that are necessary to achieve the MfE projections. The discussion in section 8.5.1 concludes by stating "*Even extrapolating the higher 'satellite-period' trend of a constant 3.1 mm/year for another 40 years would mean a sea level rise of only ~0.2 m by 2050, relative to 1990 (lower curve of Figure 8.5). Therefore, it is clear that a substantial acceleration is now required, possibly through an ice-sheet tipping-point response, to achieve any projected rise of more than 1.2 m by 2115. The lack of such a signal in present day tide gauge data suggests that a measure of caution before higher-end sea level rise scenarios be adopted in statutory plans*". In my opinion, this conclusion is valid, although I consider it applies equally to 1 m by 2115 given that the IPCC AR5 assessment of tipping points or catastrophic consequences of "climate change" occurring within the 21st Century is that they are *very unlikely* or *exceptionally unlikely* and/or have *low confidence*. In particular, Table 12.4 on page 1115 of Chapter 12 of the WGI report reports that it is "*Exceptionally unlikely* that either Greenland or West Antarctic Ice sheets will suffer near-complete disintegration (*high confidence*)", and even partial collapse is not considered *likely*. This means that the high rates assumed by the MfE projections (Table 1) are *not likely.*

16. The final paragraph makes similar assertions to the third paragraph, but compares the observed *relative* average New Zealand sea level rise with the *absolute* sea level projections from the IPCC AR4 report. The papers cited by the NIWA report compared a reconstructed global sea level record obtained by developing a statistical model between tide gauge data and satellite altimetric data to estimate past sea levels in areas where insufficient tide gauge exists. The resulting estimated sea level records were then averaged to provide the reconstructed tidal record. A GIA was applied during the process to estimate *absolute* sea level. However, this appears to have been from the Peltier (2004) model and it was noted that the GIA applied to satellite data differed to those applied to tide gauge data for the same locations[11].

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[10] http://www.mfe.govt.nz/publications/climate-change/preparing-coastal-change-guide-local-government-new-zealand/part-one

[11] Church, J. A., & White, N. J. (2011). Sea-Level Rise from the Late 19th to the Early 21st Century. Surveys in Geophysics, 32(4-5), 585-602

17. Regardless of any issues about the procedures followed to produce the graphic used in the NIWA report (Figure 8.6 page 53), which are not clearly explained in the original source[12], the comparison of *relative* sea levels with *absolute* projections is not valid. Within the period of overlap in Figure 6, the satellite trend was 3.2 ± 0.4 $mm.y^{-1}$ and the tide gauge trend was 2.8 ± 0.8 $mm.y^{-1}$ according to a separately published analysis[11]. While these *absolute* trends are consistent with the 3.3 $mm.y^{-1}$ *relative* trend between 1990 and 2006 at Wellington, the *absolute* trend at Wellington was approximately half assuming an average vertical land movement of -1.7 ± 0.3 $mm.y^{-1}$ determined for Wellington from continuous GPS measurements[5]. This is not consistent, and the long-term *absolute* sea level trend (0.4 ± 0.3 $mm.y^{-1}$) is even less so. This indicates that the *absolute* sea level trend for Wellington is not consistent with IPCC AR4 projections, and to quote the NIWA report this "*suggests that a measure of caution before higher-end sea level rise scenarios be adopted in statutory plans*".

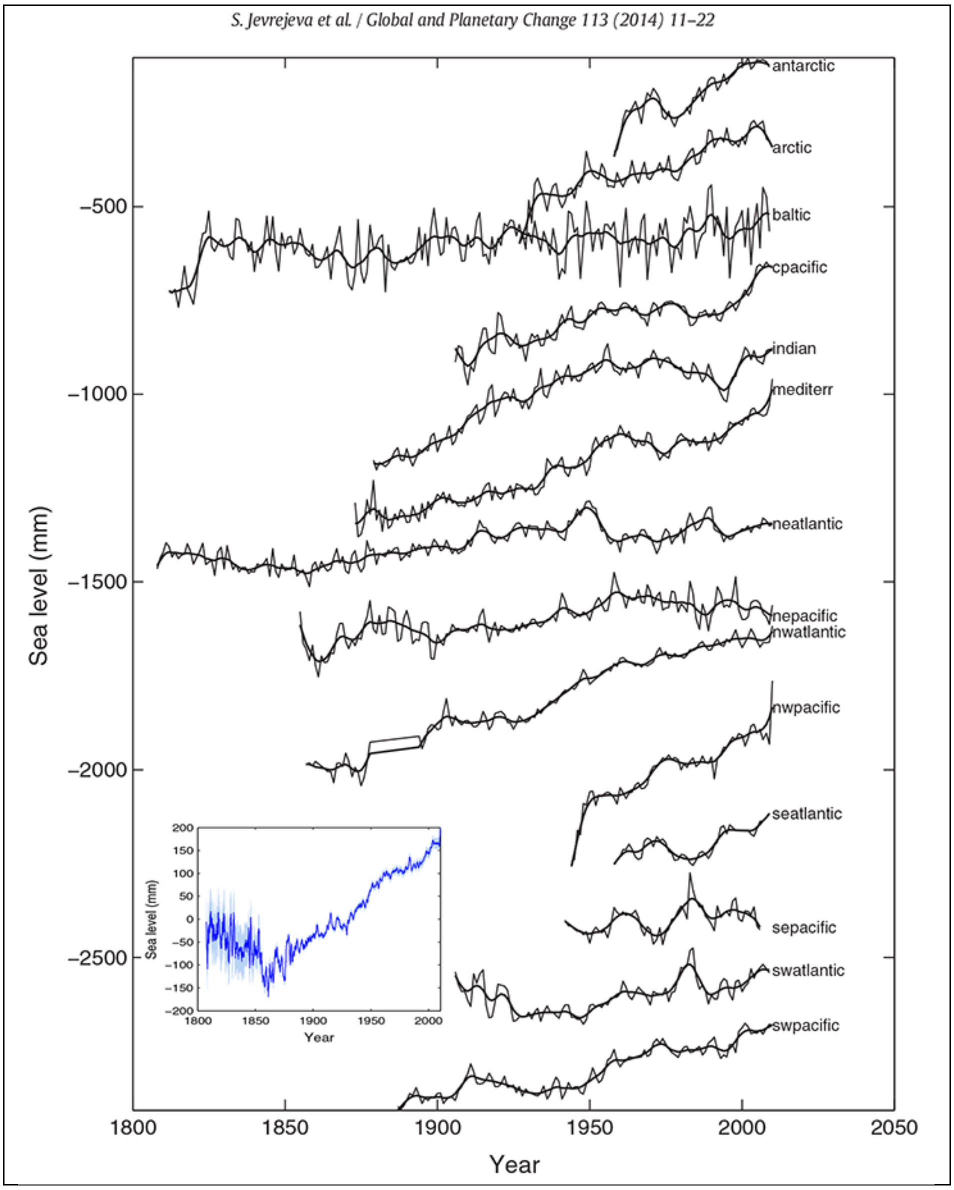

Figure 7 – Regional sea levels determined from tide gauges within 14 ocean "basins" covering ~30,000,000 km^2 (except for the 73,000,000 km^2 Indian basin) from Jevrejeva *et al* (2014)[13], and their global reconstruction combining all sites (inset graph).

18. There have been several recent papers that have examined the behaviour of sea level rise during the 21st Century that are relevant to the assertions discussed above (summarised in Figure 1). Jevrejeva *et al* (2014) re-evaluated the sea level trends for 1277 tide gauge records

[12] Church, J. A., Gregory, J. M., White, N. J., Platten, S. M., & Mitrovica, J. X. (2011). Understanding and projecting sea level. Oceanography, 24(2), 130-143.

(including Wellington) for the period 1807-2009 (Figure 7)[13]. Their reconstruction shows sea level rise following a fall in sea level during the Little Ice Age, and predicts a slightly higher rate of sea level rise during the 20th Century (1.9 ± 0.3 mm.y^{-1}) than the 1.7 ± 0.3 mm.y^{-1} discussed above (based on the 1.7 ± 0.2 mm.y^{-1} derived from the Church and White reconstruction[11]). Considering the rate of acceleration of sea level rise between 1880 and 2009, Jevrejeva *et al* (2014) found an increase of 0.001 ± 0.010 mm.y^{-2}, compared to 0.009 ± 0.003 mm.y^{-2} for the period 1900-2009 reported by Church and White (2011). The difference is attributed to the inclusion of more tide gauge locations (1277 versus 290), particularly from the Arctic and Antarctic that were omitted from the earlier reconstruction. It was also noted that it is debatable whether the small acceleration found in the 20th Century can be attributed to anthropogenic climate change[13].

19. Apart from finding no significant acceleration in the long-term rate of sea level rise, the key aspect of the Jevrejeva *et al* (2014) study is confirmation of the large variation between different coastal regions (Figure 7). The NIWA report used as the basis for the Draft Climate Change Strategy assumes that the global sea level projections from the CIMP5 simulations can be downscaled to the New Zealand region. Comparing the Southwest Pacific trend (bottom right SLR curve in Figure 7) with the global reconstruction (inset of Figure 7) indicates that the overall pattern of sea level changes are not the same. There is less agreement between the global reconstruction and the Wellington sea level curve due to the local effects discussed above. Therefore, scaling the projected global sea level curve to “predict” future sea level at Wellington is not a reliable approach.

20. More recently, Watson *et al* (2015) re-examined satellite derived reconstructions of global sea level (1993 to mid-2014)[14]. They focussed on the calibration of the satellite altimetry data against tide gauge measurements (known as *bias drift estimation*). Their analysis initially considered 122 tide gauges globally, including Wellington. However, some were removed from the analysis due to the effects of earthquake deformation during the analysis period (eg. Lyttelton), or obvious non-linear vertical land movement (eg. Dunedin), leaving between 90 and 110 calibration tide gauges depending on the methodology they used. It is surprising that the non-linear vertical land movement associated with the slow-slip events (Figure 1) discussed above did not result in the removal of the Wellington record from the analysis (the longer Auckland record was not included in the initial data set).

21. The reanalysis produced revised bias drift estimates for each of the main satellite data series that are combined to produce the satellite global sea level record. The revisions are summarised in Figure 8a, along with their impact on the estimated trend of Global Mean Sea Level (GMSL). The GMSL trend marked with the ‘x’ symbol corresponds to 3.2 ± 0.3 mm.y^{-1} as reported by IPCC AR4 for the late 20th Century (without GIA correction of 0.3 mm.y^{-1}). The revised trend incorporating no adjustment for vertical land movement (VLM) is indicated by the ‘•‘ symbol, and it does not differ significantly from the AR4 “consensus” value. The inverted grey triangle is an updated version of Church and White (2011) for the period 1993 to 2012, with GPS derived VLM adjustments to individual tide gauges. Figure 8a indicates that GPS derived bias estimate corrections give a GMSL trend of 2.6 ± 0.2 mm.y^{-1}, which is consistent with: the GPS adjusted tide gauge trend of 2.7 ± 0.7 mm.y^{-1}; and the adjusted (based on a revised model of the time varying strength of Earth’s gravitational field[15]) Envisat satellite trend for 2002-2011 of 2.9 ± 0.2 mm.y^{-1} and the ERS-2 satellite trend for 2002-2011 of 2.6 ± 0.2 mm.y^{-1}. All of these values are below the 3.8-5.0 mm.y^{-1} assumed for this period in the MfE guidelines (Table 1).

22. Watson *et al* (2015) also estimated the effect of applying the new bias drift estimates on any underlying acceleration in the rate of sea level rise. The effect of reducing the GMSL trend for TOPEX-A and TOPEX-B and increasing it for Jason-2 (GMSL trend changes are the opposite sign to the bias drift estimates in Figure 8a), is to change the acceleration from -0.057 ± 0.058 mm.y^{-2} to 0.041 ± 0.058 mm.y^{-2}. It was noted that neither estimate is significantly different from zero[14]. The acceleration was determined by fitting a combined linear trend and quadratic polynomial to the data using unweighted least squares, and doubling the quadratic coefficient

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13 Jevrejeva, S., Moore, J. C., Grinsted, A., Matthews, A. P. & Spada, G. Trends and acceleration in global and regional sea levels since 1807. *Global and Planetary Change* 113, 11–22 (2014).

14 Watson, C. S. et al. Unabated global mean sea-level rise over the satellite altimeter era. *Nature Climate Change* advance online publication, (2015).

15 Rudenko, S. et al. Influence of time variable geopotential models on precise orbits of altimetry satellites, global and regional mean sea level trends. *Advances in Space Research* 54, 92–118 (2014).

(Figure 8b). The initial deceleration reported is consistent with other studies that used the same methodology[14].

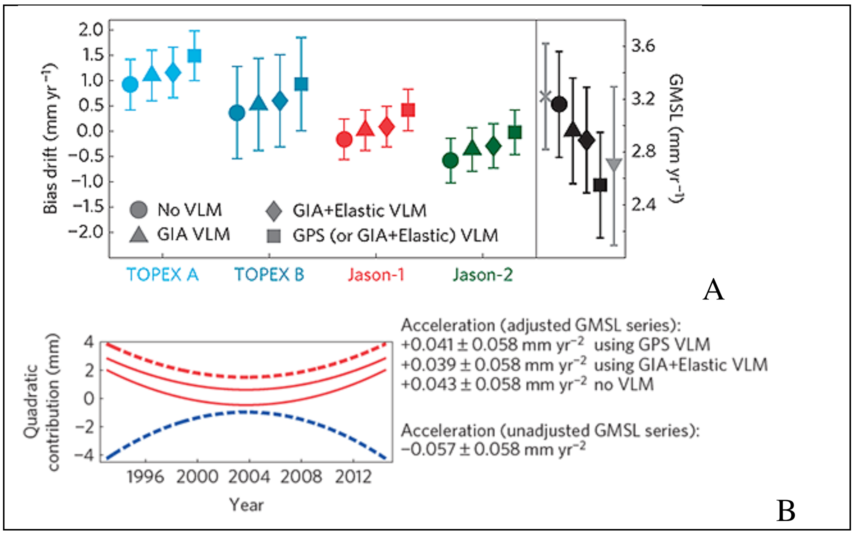

Figure 8 – (A) Bias drift estimates for the main satellite sea level datasets determined used different corrections for VLM and GIA, and the resulting estimated trends in GMSL for the period 1993 to mid-2014. (B) Quadratic components of GMSL and estimated acceleration for the 4 GMSL datasets in (A)[14].

23. There are different approaches to estimating sea level rise acceleration that do not assume a specific functional shape, and arguably better capture the effect of climatic oscillations such as the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO), and the changing influence of steric effects (temperature and salinity) and mass effects (meltwater). For example, Chen *et al* (2014) applied Empirical Mode Decomposition (EMD) to the satellite GMSL data for the period 1993-2012[16]. Their analysis also considered the steric sea level rise determined from estimates of ocean density, and the sea level component due to changes in the total ocean mass determined by the Gravity Recovery and Climate Experiment (GRACE). Figure 9 shows the EMD trend functions fitted to the raw AVISO data for GMSL, steric sea level estimated from the EN3 ocean density data, and mass-equivalent sea level estimated from JPL RL05 version of GRACE data. Trend functions represent the long-term changes in behaviour and therefore fulfil the same purpose as linear trends or linear plus quadratic trends more commonly used. Multiple analyses are presented, with the black trends covering 1993-2010 and coloured trends representing monthly increments of data until the data covers 1993-2012. This was done to assess the effect of the developing El Niño conditions in 2012, and it was found that it did not significantly alter the behaviour of the trend functions, although it did affect the shorter period fluctuations extracted by EMD, particularly at ENSO frequencies.

24. The first derivative of the trend functions provides a time series of the rate of sea level rise, while the second derivative provides an estimate of acceleration. Figure 10 shows the first derivative determined by Chen *et al* (2014). This indicates that the rate of GMSL rise increased between 1993-2003, with an average rate of 3.2 ± 0.4 mm.y^{-1} consistent with the AR4 report, and then decreased to a rate of 1.8 ± 0.9 by the end of 2012[16]. Figures 9 and 10 do not show any acceleration consistent with anthropic forcing, as has been demonstrated by previous analyses of the long-term tide gauge record[14,17]. This result is unsurprising, as analyses of the Time of Emergence (ToE) consistently indicate that the anthropic sea level signature will be indistinguishable from natural variability for 20-80 years depending on location and CIMP5 RCP projection[181920]. The delayed ToE also suggest it is unlikely that the observed sea level at Wellington, which includes natural variability, should match the sea level projections that do not.

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[16] Chen, X., Feng, Y. & Huang, N. E. Global sea level trend during 1993–2012. *Global and Planetary Change* 112, 26–32 (2014).
[17] Meyssignac, B., Salas Y Melia, D., Becker, M., Llovel, W., and Cazenave, A., 2012, Tropical Pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature?: *Climate of the Past*, 8: 787-802
[18] Richter, K., & Marzelon, B., 2014. Earliest local emergence of forced dynamic and steric sea-level trends in climate models. *Environmental Research Letters* 9: 114009, 7pp.
[19] Little, C. M., Horton, R. M., Kopp, R. E., Oppenheimer, M. & Yip, S. Uncertainty in Twenty-First-Century CMIP5 Sea Level Projections. J. Climate 28, 838–852 (2014).

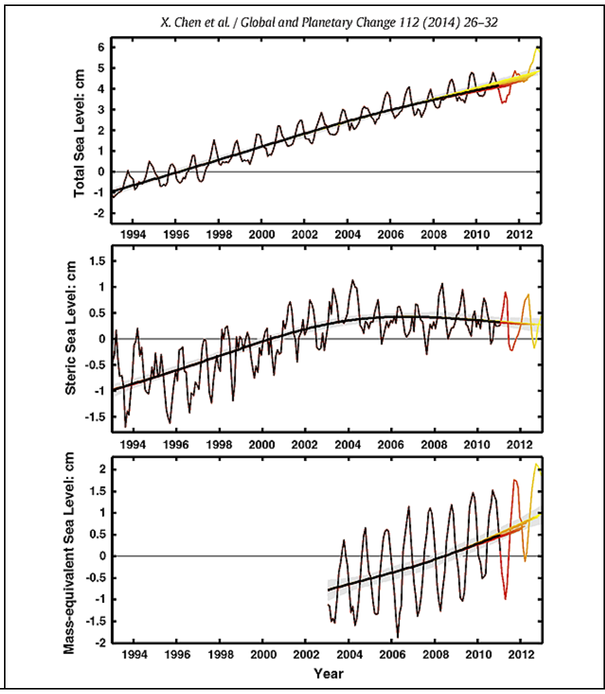


Figure 9 – EMD trend functions for (top) AVISO GMSL, (middle) steric sea level using the EN3 data set for upper 5000 m of the oceans, and global-mean mass-equivalent sea level from the JPL RL05 dataset obtained from GRACE. Black trends are for 1993-2010 and coloured trends representing monthly increments of data until the data covers the full period 1993-2012[16].

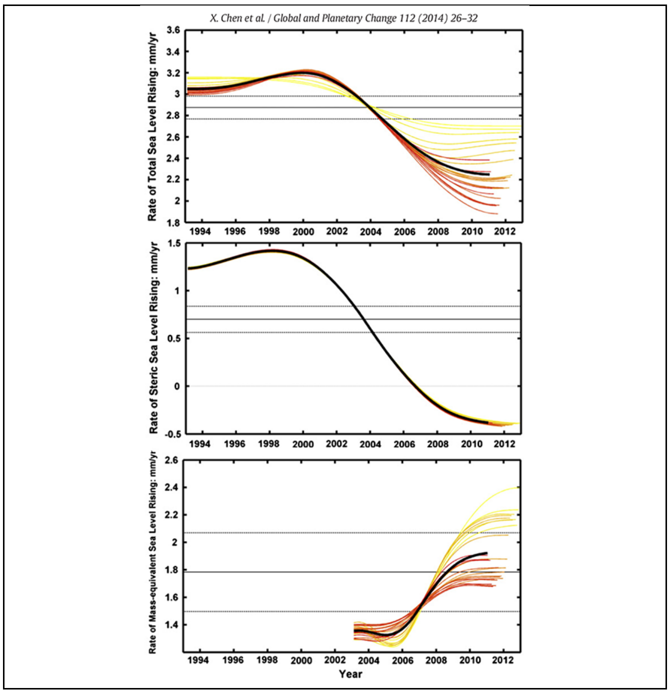


Figure 10 – First derivatives (rates of sea level change) of the trend functions in Figure 9[16].

25. Figure 10 also shows a change in the relative influence of steric and mass contributions to GMSL, albeit with less certainty about the mass contribution due to the length of the GRACE record. Jevrejeva *et al* (2014) concluded that over the time period 1807 to 2009, steric components contributed an acceleration of 0.003 $mm.y^{-1}$, while ice melt (mass) contributed 0.006 $mm.y^{-2}$. They suggested that the steric component is driven primarily by natural variability at decadal scales, and noted that numerical simulations suggest the ice melt component may

[20] 1.Lyu, K., Zhang, X., Church, J. A., Slangen, A. B. A. & Hu, J. Time of emergence for regional sea-level change. *Nature Climate Change* 4, 1006–1010 (2014).

have an anthropic component[13]. Figure 10 indicates that steric component of GMSL has been decreasing since 1998, and the mass component shows a step change around 2005.

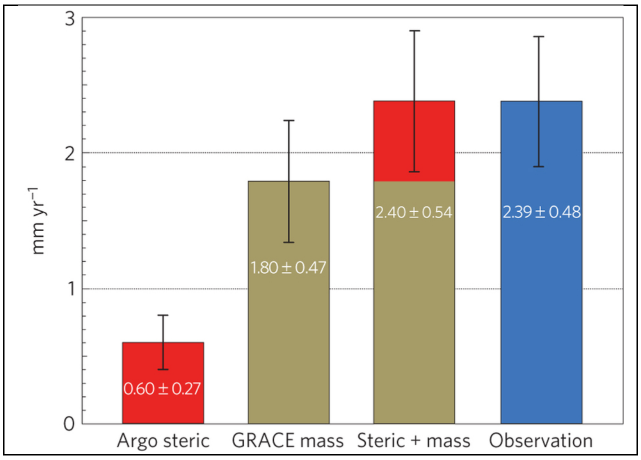


Figure 11 – GMSL rise budget combining estimates of the steric component based on ARGO observations and GRACE estimates of ice melt[21].

Table 13.1 | Global mean sea level budget (mm yr^{-1}) over different time intervals from observations and from model-based contributions. Uncertainties are 5 to 95%. The Atmosphere–Ocean General Circulation Model (AOGCM) historical integrations end in 2005; projections for RCP4.5 are used for 2006–2010. The modelled thermal expansion and glacier contributions are computed from the CMIP5 results, using the model of Marzeion et al. (2012a) for glaciers. The land water contribution is due to anthropogenic intervention only, not including climate-related fluctuations.

Source	1901–1990	1971–2010	1993–2010
Observed contributions to global mean sea level (GMSL) rise			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.54 [0.47 to 0.61]	0.62 [0.25 to 0.99]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.15 [0.10 to 0.19]	0.06 [0.03 to 0.09]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	–0.11 [–0.16 to –0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	**–**	**–**	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**1.5 [1.3 to 1.7]**	**2.0 [1.7 to 2.3]**	**3.2 [2.8 to 3.6]**
Modelled contributions to GMSL rise			
Thermal expansion	0.37 [0.06 to 0.67]	0.96 [0.51 to 1.41]	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.63 [0.37 to 0.89]	0.62 [0.41 to 0.84]	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.07 [–0.02 to 0.16]	0.10 [0.05 to 0.15]	0.14 [0.06 to 0.23]
Total including land water storage	**1.0 [0.5 to 1.4]**	**1.8 [1.3 to 2.3]**	**2.8 [2.1 to 3.5]**
Residual[c]	**0.5 [0.1 to 1.0]**	**0.2 [–0.4 to 0.8]**	**0.4 [–0.4 to 1.2]**

Notes:

[a] Data for all glaciers extend to 2009, not 2010.

[b] This contribution is not included in the total because glaciers in Greenland are included in the observational assessment of the Greenland ice sheet.

[c] Observed GMSL rise – modelled thermal expansion – modelled glaciers – observed land water storage.

Figure 12 – Table 13.1 from IPCC AR5 WGI report summarising the estimates of different contributions to the GMSL budget based on observational data and CIMP5 model results

26. Chen *et al* (2014) assessed the relative contributions of steric sea level rise and ice melt to the measured GMSL between 2005 and 2011[21]. They demonstrated that the ice melt contribution was approximately 75% of the observed trend over this period (Figure 11). Their estimated contribution from Greenland (0.69 ± 0.05 mm.y^{-1}) was consistent with other studies, and the contribution from Antarctica (0.50 ± 0.26 mm.y^{-1}) was at the lower end of the range estimated by other studies. The balance of the ice melt was derived from glaciers. For comparison, the IPCC AR4 report estimated that the steric and ice melt contributions to GMSL rise between 1993 and 2003 were roughly equal (~1.6 ± 0.5 mm.y^{-1} and ~1.2 ± 0.5 mm.y^{-1} respectively). The AR5 report also estimated roughly equal contributions, although the balance differs between observational and model estimates (Figure 12).

[21] Chen, J. L., Wilson, C. R. & Tapley, B. D. Contribution of ice sheet and mountain glacier melt to recent sea level rise. *Nature Geoscience* 6, 549–552 (2013).

Projected sea level rise

27. As discussed above, the projected sea levels on with the Draft Climate Change Strategy are based come from the MfE guidelines, which in turn are based on the IPCC AR4 projections. The more recent IPCC AR5 projections should be more appropriate, depending on how much the projections have changed. The underlying scenarios defining future possible radiative forcing, and the methodology for assessing the ranges of sea level projections was changed for the AR5 assessment, which makes it difficult to directly compare the 2013 projections with the earlier values. Importantly, the mid-point rise is now quoted instead of the most likely or median rise. Since the distribution of values for each scenario is asymmetrically distributed (most projections cluster towards the minimum rise in the range), the mid-point rise is higher than both the mean and median. Further, the IPCC AR5 projections are based on emission scenarios and not economic activity scenarios. However, for the purposes of comparison, the IPCC AR5 report included the AR4 projections for scenario SRES A1B in the WGI report (Figure 13), which were close to the values adopted by the MfE guidelines.

28. Figure 13 highlights the key differences between the 4 sea level projections based on the RCP scenarios. The main difference is the magnitude of the thermal contribution (the salinity component of steric sea level is ignored), and the melt contribution is very similar for RCPs 2.6, 4.5, and 6.0 (slightly lower for RCP2.6). RCP8.5 includes more glacial melt and an increased contribution from the Greenland ice sheet. It is clear that the patterns of sea level contributions from the CIMP5 models are very different to that based on observations in Figures 9, 10 and 11.

29. The IPCC sea level projections are preferentially based on deterministic modelling of assumed processes contributing to sea level rise based on the global temperature projections produced by models based on radiative forcing derived directly from emissions scenarios (AR5) or indirectly from economic scenarios (earlier assessments). The results are referred to as projections because they strictly do not have any associated likelihood of occurrence, which is inherent to predictions. There are several issues that arise from the dependence of projecting sea level rise on the projected global temperature.

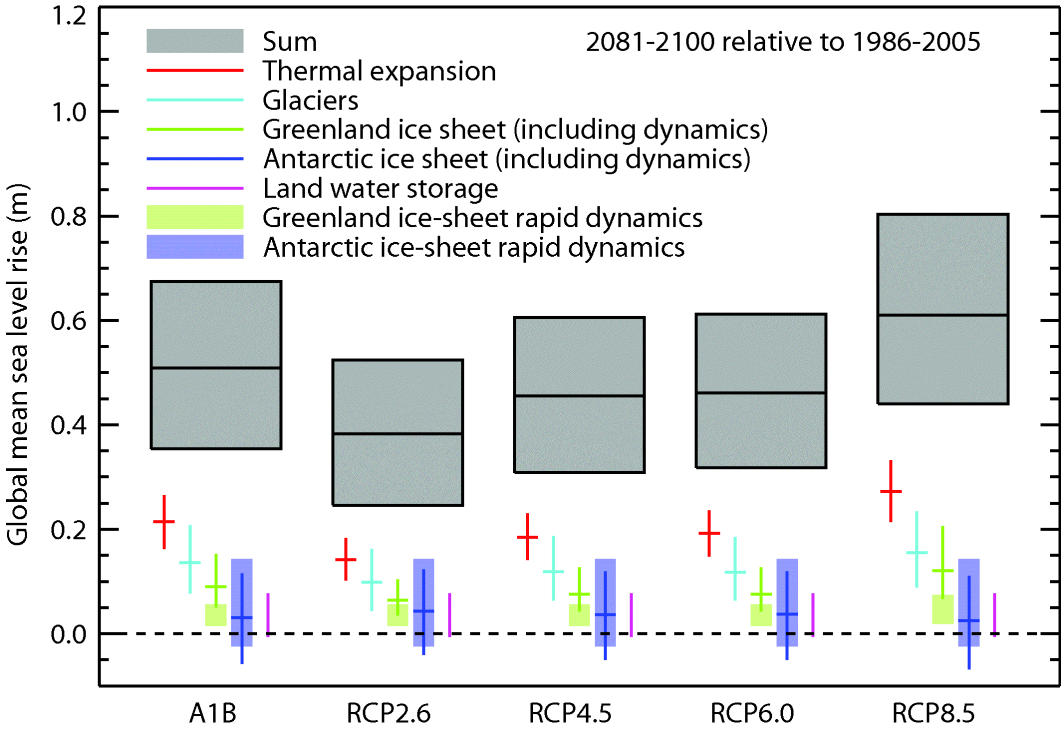
30. In particular, the review by Gregory *et al* (2012) found a poor relationship between global temperature and sea level that results in *low confidence* in semi-empirical models that directly predict sea level from global temperature. The IPCC AR5 assessment in 2013 also concluded that there is no consensus on the reliability of semi-empirical methods that project higher sea levels and assigns low confidence to their projections. The same problem arises for deterministic models, although it is argued that there is higher confidence in process-based deterministic modelling. It is clear from the published literature that there is ongoing disagreement between different studies about the relative magnitude of different contributions to observed sea level rise (Gregory *et al*, 2012), which in part accounts for the range of sea level projections for any particular emissions scenario. If the observed changed from predominantly steric sea level rise during the 20th Century continues to switch to predominantly melt driven sea level rise this Century, the current CIMP5 projections are of little practical value.

31. As discussed above, there is significant decadal scale variability in GMSL, which is more pronounced at a regional scale[22]. Recently the CIMP5 results were compared against the Kiel Climate Model (KCM) that combines a general circulation model (ECHAM5) with an ice response model (OASIS) and an ocean circulation model (NEMO), to examine the effects of natural variability on the regional departures from the centennial projects of GMSL[23]. The KCM results indicate that natural variability is of the same order of magnitude or larger than the steric component of sea level rise, and for New Zealand is likely to produce a 0.40 m drop offsetting the projected 0.25 m steric sea level rise. Therefore, it was concluded that natural variability must be included in modelling of future sea level. Some CIMP5 models have variability resulting from random fluctuations that approximates natural variability. However, the KCM simulations also showed it was necessary to initialise the simulations with the correct initial ocean state, which was not done for all CIMP5 simulations and raises questions about their regional projections. Bordbar *et al* (2015) noted that their findings introduce additional uncertainties about the evolution of future regional sea level[23]. Finally, they reassessed the ToE (Figure 14) relative to 2 or 3 standard deviations of natural regional variability, which indicates that it will

[22] Chambers, D. P., Merrifield, M. A., & Nerem, R. S. (2012). Is there a 60-year oscillation in global mean sea level? *Geophysical Research Letters*, 39(18).

[23] Bordbar, M. H., Martin, T., Latif, M. & Park, W. Effects of long-term variability on projections of twenty-first century dynamic sea level. *Nature Climate Change* 5, 343–347 (2015).

take at least 100 years before an anthropic sea level rise signal can be detected around New Zealand.



SCENARIO	Minimum rise (cm)	Maximum rise (cm)	Mid-point rise (cm)
SRES A1B	36	59	47
RCP2.6	26	55	40
RCP4.5	32	63	47
RCP6.0	33	63	48
RCP8.5	45	82	63

Figure **13** – IPCC AR5 2013 sea level projections for different emission scenarios (RCP), compared to the IPCC AR4 2007 SRES A1B scenario used to set the MfE (2008) planning sea level projections. The graph also shows the range of CIMP5 projections for the components contributing to the projected sea levels.

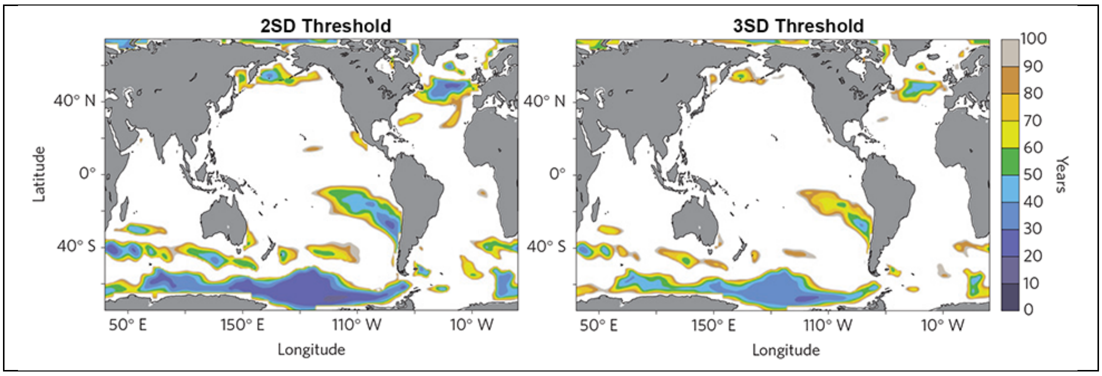


Figure 14 – Time of emergence (ToE) for CO_2 forced sea level rise signal from natural regional variability. White areas correspond to a ToE greater than 100 years[23].

32. The predicted values for the ToE, the changing balance between steric and melt contributions to GMSL, the identification of problems with the methodologies used to make CIMP5 projections, the mixing of *relative* and *absolute* sea level, and all published estimates of recent sea level rise trends being below those assumed for the MfE guides, makes it very difficult to accept the claim

made in the Draft Climate Change Strategy: "*Sea level rise – currently tracking towards a 0.8m rise by the 2090s or ~1m by 2115 compared to 1990.*"

Weather extremes

33. Like the sea level rise projections discussed above, the projections of future extreme weather are is based on the Ministry for the Environment (MfE) guidelines[1]. The key projections relate to wind, precipitation and temperature, and the highlighted statements in the Draft Climate Change Strategy are replicated in Figure 15. Section 3.2.2 also introduces additional extreme weather risks derived from the Regional Policy Statement, including an "*increased frequency and intensity of storm events, adding to the risk from floods, landslides, severe wind, storm surge, coastal erosion and inundation*".

> ***Wind*** *– the frequency of extreme winds over this century is likely to increase by between 2 and 5% in winter, and decrease by a similar amount in summer.*
> ***Precipitation*** *– overall there is expected to be a small increase in rainfall in the west of the region and a decrease in the east. Very heavy rainfall events are likely to become more frequent.*
> ***Temperature*** *– average temperatures are likely to be around 0.9℃ warmer by 2040 and 2.1℃ warmer by 2090, compared to 1990.*

Figure 15 – Text from the Draft Climate Strategy section 3.2.1 on projected climate change that summarises projected changes to extreme weather.

34. Considering the first two paragraphs of Figure 1.

35. There is a growing deviation between projected and observed global temperatures; with models projecting greater warming than has been observed over the last 2 decades (Fyfe *et al*, 2013; Fyfe and Gillett, 2014; Santer *et al*, 2014; Schmidt *et al*, 2014). This suggests that the projected temperatures based on the models, and hence projected sea levels derived by deterministic models, are too high. This was demonstrated by Houston (2013), who compared observed sea levels between 1993 and 2012, as measured by satellite altimetry, with the IPCC AR4 projections for the same period, and found that by 2012 observed sea level fell within the lowest 50% of the projections.

36.