Comments on GWRC Draft Climate Change Strategy – Dr Willem de Lange

1. I have been asked by Coastal Ratepayers United Incorporated to provide comments on the science underpinning the GWRC Draft Climate Change Strategy (DCCS). 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 DCCS (Figure 1). However, as a general comment, the DCCS is based on the Ministry for the Environment (MfE) guidelines[1], which are largely based on 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 based on a NIWA report[2] that largely updates and restates Ministry for the Environment (MfE) guidelines[3]. 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 DCCS 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 DCCS highlights the effects of recent short-term subsidence, but ignores the effects of uplift such as occurred in the

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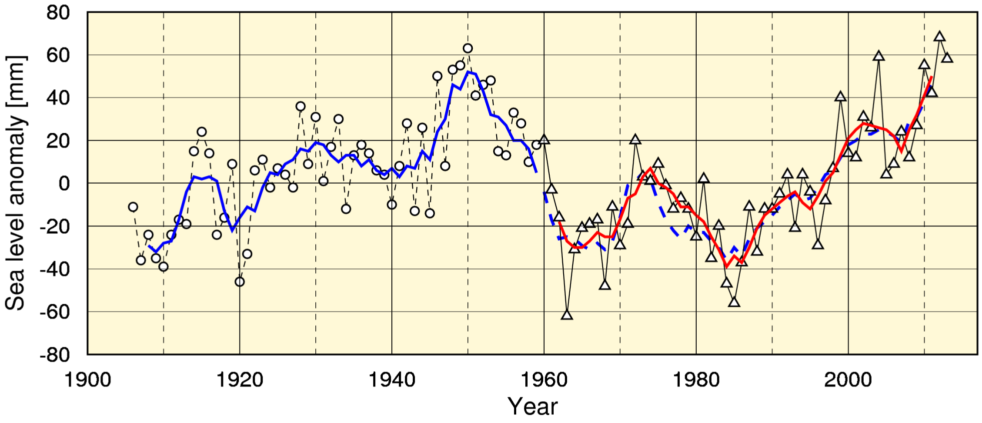
[1] Ministry for the Environment. 2008. Climate change effects and impacts assessment: A guidance manual for local government in New Zealand. http://www.mfe.govt.nz/publications/climate/climate-change- effect-impacts-assessments-may08/index.html

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

[3] Ministry for the Environment, 2008. Coastal hazards and climate change: A guidance manual for local government in New Zealand. http://www.mfe.govt.nz/publications/climate/coastal-hazards-climate-change-guidance-manual

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[3] 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 CMIP5 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[4]. 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[5]. 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[6] 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

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[4] 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).

[5] http://www.data.jma.go.jp/gmd/kaiyou/english/sl_trend/sea_level_around_japan.html

[6] 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[7].

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[8] and geodetic assessment of vertical land movement is more useful.

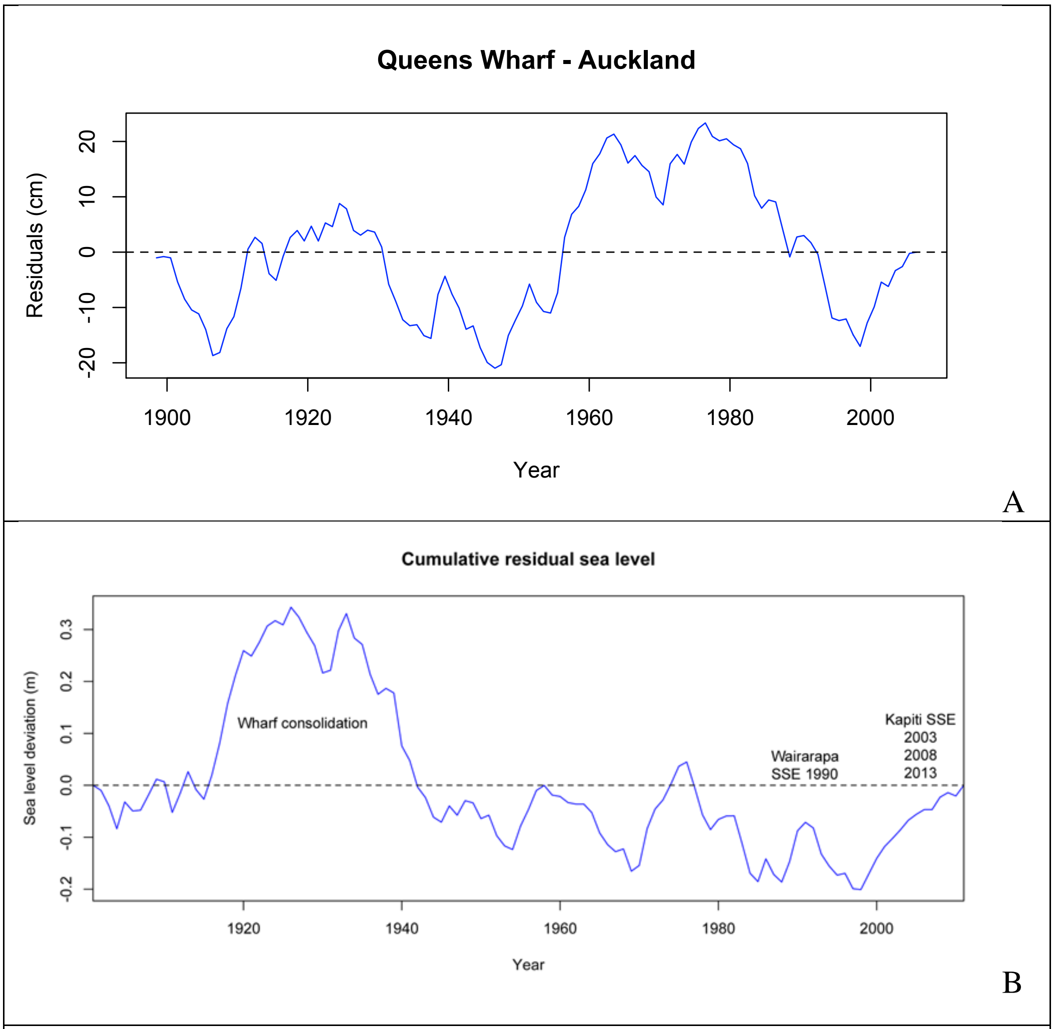

Figure 3 – Cumulative residual sea level departures from the long-term sea level trends determined from tide gauge observations at (A) Auckland and (B) Wellington. Indicated on the Wellington record (B) are periods associated with land reclamation and subsequent construction (Figure 4).

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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[7] 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).

[8] 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 Ordinary Least-Squares regression (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[6].

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Figure 4. Land reclamation at Thorndon between 1924 and 1927, involving a total area of 70 ha[9] 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[3] (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[3].

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 moved 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

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

and is better at removing the effects of interannual sea level variations than a 10-year period. If 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[10]. This 16 mm difference also 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.

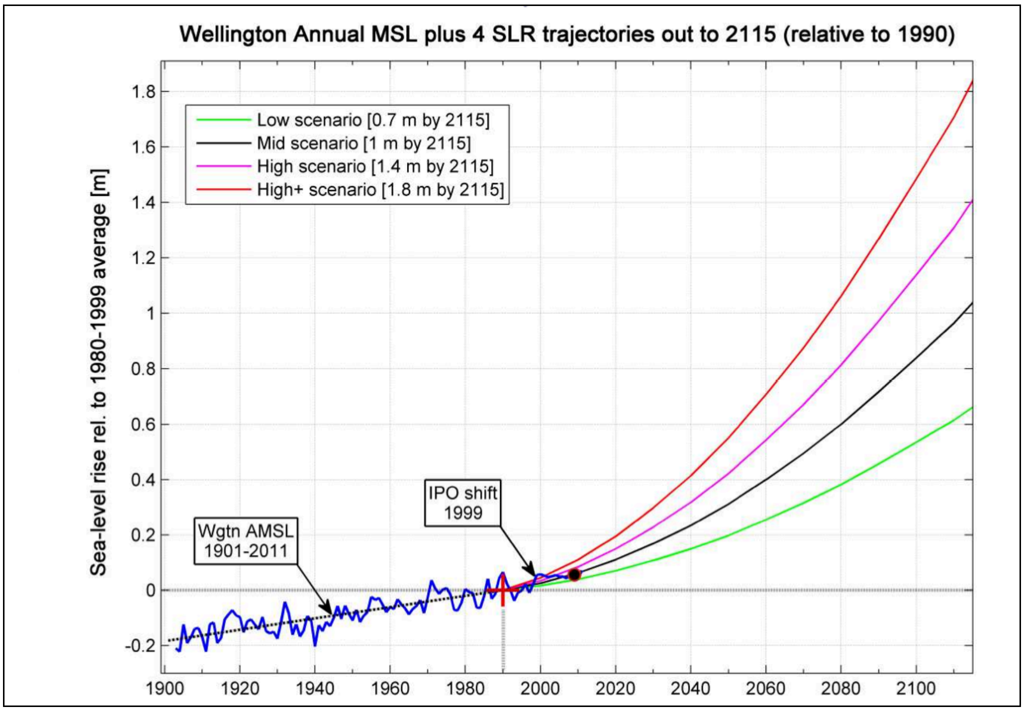

Figure 5 – Copy of Figure 8-2 from the NIWA report[2] cited by the DCCS. This graph appears to be the basis for the claim Wellington sea levels are tracking towards 0.8 m by the 2090s.

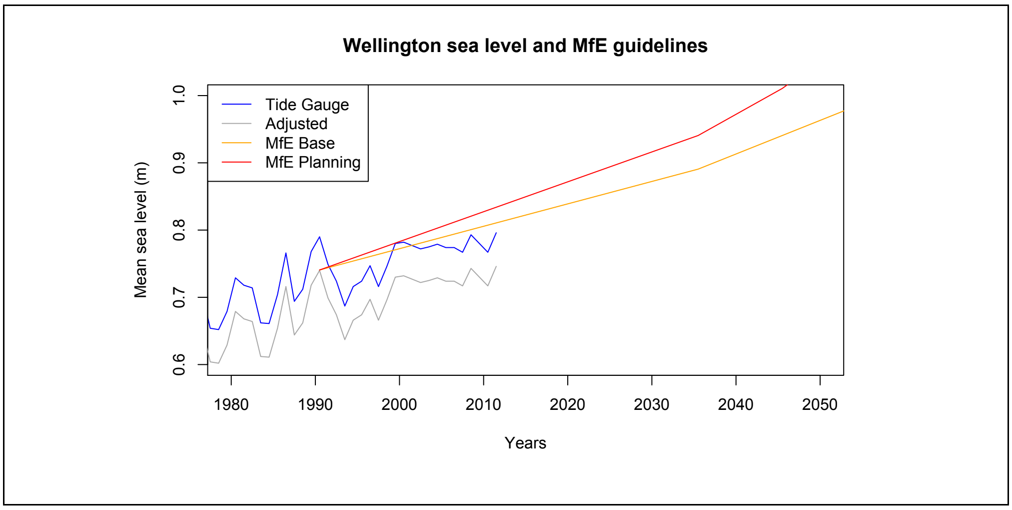

Figure 6 – Comparison between measured sea levels at Wellington and the MfE guidelines for projected sea level rise. The MfE curves are straight lines between the levels specified in the guidelines and have been baselined to a starting sea level of 0.741 m, which is the average for the period 1989-1999.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

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[10] 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.

not follow a smooth curve as shown in Table 1. Table 1 also indicates that the assumed rate of 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})[7]. 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 relative sea level rise[2].

Table 1 – MfE baseline sea level rise projections relative to 1980-1999 average[11].

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 unlikel*y or *exceptionally unlikely* and/or have *low confidence*. In particular, Table 12.4 on page 1115 of Chapter 12 of the Working Group I report states 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 of the DCCS extract in Figure 1 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[12].

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

[12] 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[13], 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[12]. 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[6]. 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*".

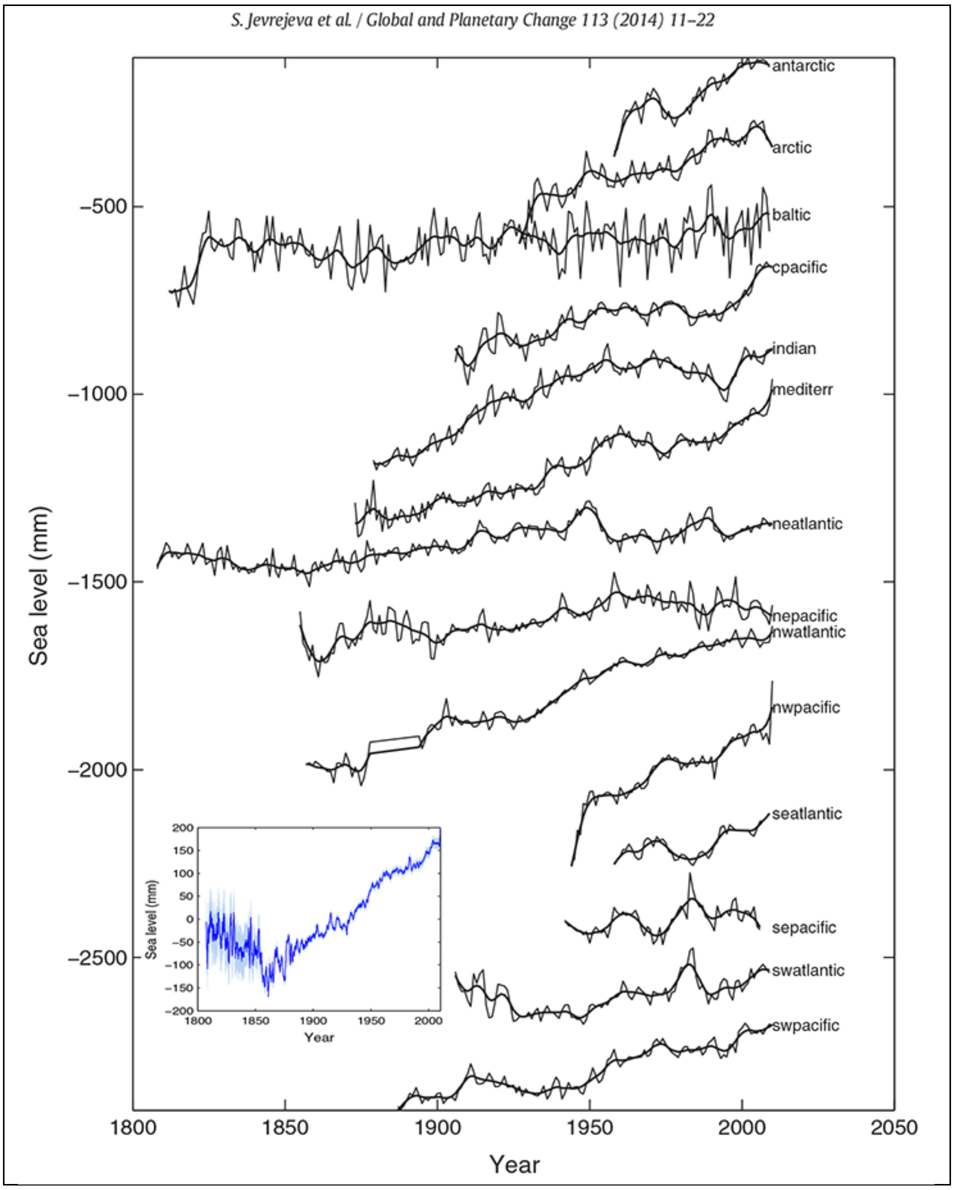
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Figure 7 – Regional sea levels determined from tide gauges within 14 ocean "basins" covering ~30,000,000 km^2 (except for the 73,000,000 km^2 Indian basin) from Jevrejeva *et al* (2014)[14], and their global reconstruction combining all sites (inset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

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[13] 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)[14]. 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[14].

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 DCCS assumes that the global sea level projections from the CMIP5 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)[15]. 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[16]) 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, although they incorrectly suggest the difference between the estimates is statistically significant[15]. 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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[14] 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).

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

[16] 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[15]. However, an analysis of the modified statistical approach used by Church and White (2011) to derive their GMSL time series has demonstrated that the methodology significantly smooths the data, resulting in a poor reconstruction of natural variability, particularly at interannual to decadal time scales[17].

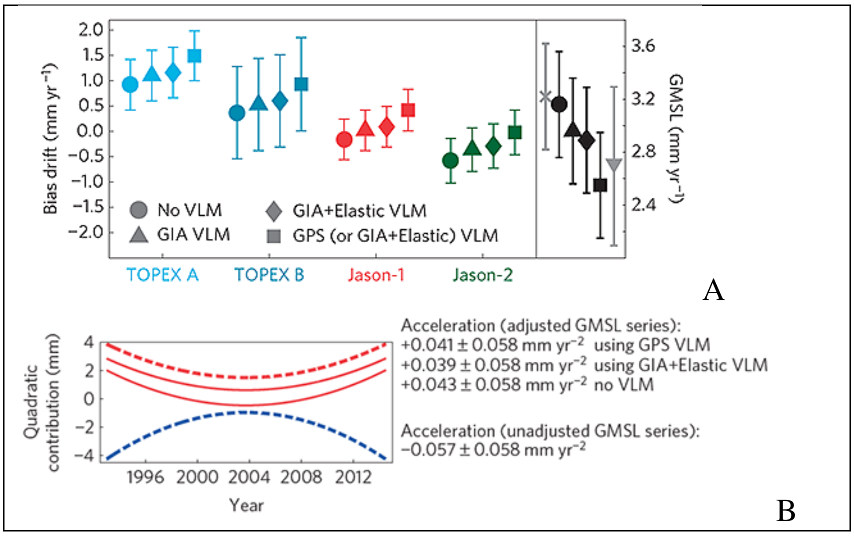

Figure 8 – (A) Bias drift estimates for the main satellite sea level datasets determined used different corrections for VLM and GIA, and the resulting estimated trends in GMSL for the period 1993 to mid-2014. (B) Quadratic components of GMSL and estimated acceleration for the 4 GMSL datasets in (A)[15].

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[18]. 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[18]. 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[15,19]. 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 CMIP5 RCP

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[17] Calafat, F.M., Chambers, D.P., & Tsimplis, M.N., 2014, On the ability of global sea level reconstructions to determine trends and variability, Journal of Geophysical Research: Oceans, 119: 1572-1592.

[18] Chen, X., Feng, Y. & Huang, N. E. Global sea level trend during 1993–2012. *Global and Planetary Change* 112, 26–32 (2014).

[19] 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

projection[20,21,22]. 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.

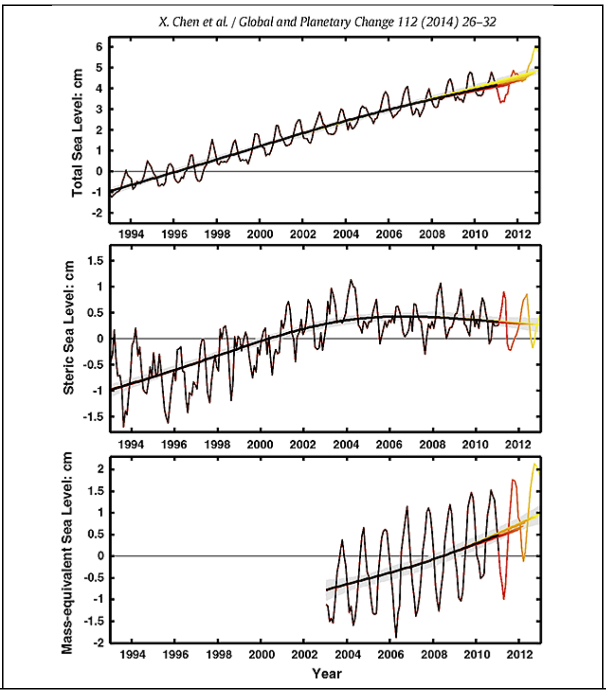
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Figure 9 – EMD trend functions for (top) AVISO GMSL, (middle) steric sea level using the EN3 data set for upper 5000 m of the oceans, and global-mean mass-equivalent sea level from the JPL RL05 dataset obtained from GRACE. Black trends are for 1993-2010 and coloured trends representing monthly increments of data until the data covers the full period 1993-2012[18].

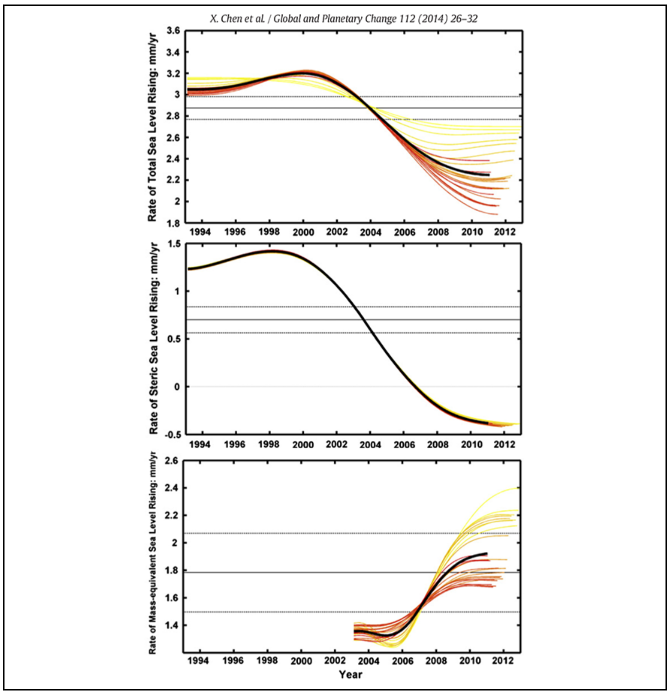
X. Chen et al. / Global and Planetary Change 112 (2014) 26–32

Figure 10 – First derivatives (rates of sea level change) of the trend functions in Figure 9[18].

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[20] 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.

[21] 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).

[22] 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).

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 have an anthropic component[14]. Figure 10 indicates that steric component of GMSL has been decreasing since 1998, and the mass component shows a step change around 2005.

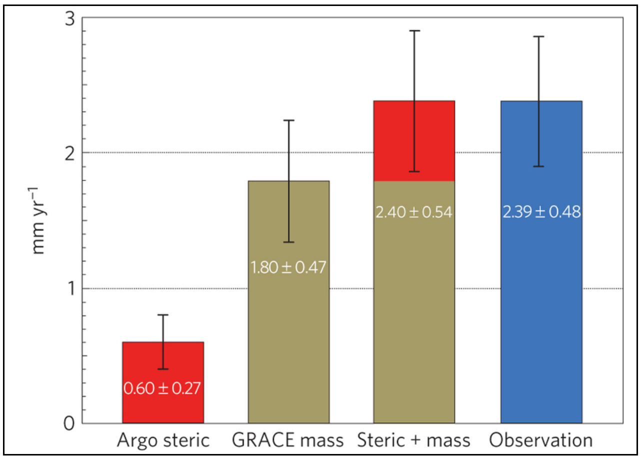

Figure 11 – GMSL rise budget combining estimates of the steric component based on ARGO observations and GRACE estimates of ice melt[23].

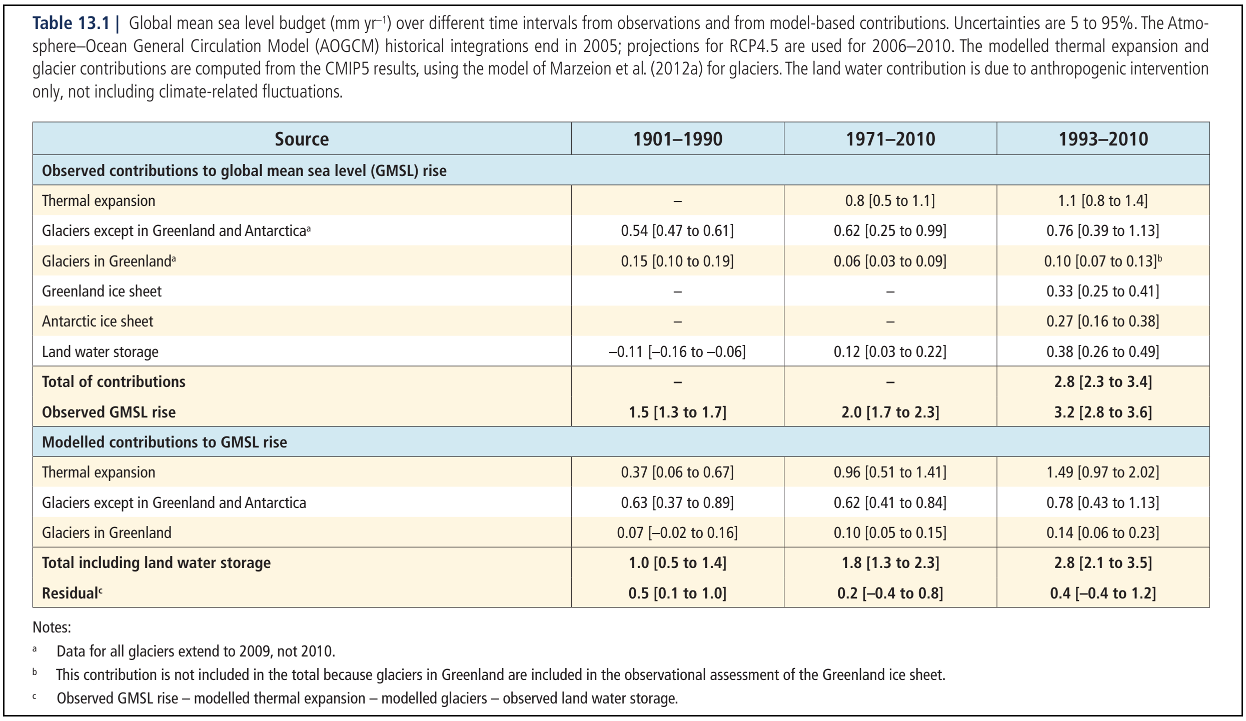

Table 13.1 | Global mean sea level budget (mm yr^{-1}) over different time intervals from observations and from model-based contributions. Uncertainties are 5 to 95%. The Atmosphere–Ocean General Circulation Model (AOGCM) historical integrations end in 2005; projections for RCP4.5 are used for 2006–2010. 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 CMIP5 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[23]. 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

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[23] 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).

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).

Projected sea level rise

27. As discussed above, the projected sea levels within Section 3.2 of the DCCS are based on the MfE guidelines[3], 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 were 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 CMIP5 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 change from predominantly steric sea level rise during the 20th Century continues to predominantly melt driven sea level rise this Century, the current CMIP5 projections are of little practical value, and the semi-empirical models are even less so.

31. As discussed above, there is significant decadal scale variability in GMSL, which is more pronounced at a regional scale[24]. Recently the CMIP5 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 projections of GMSL[25]. 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 over the 21st Century. Therefore, it was concluded that natural variability must be included in modelling of future sea level. Some CMIP5

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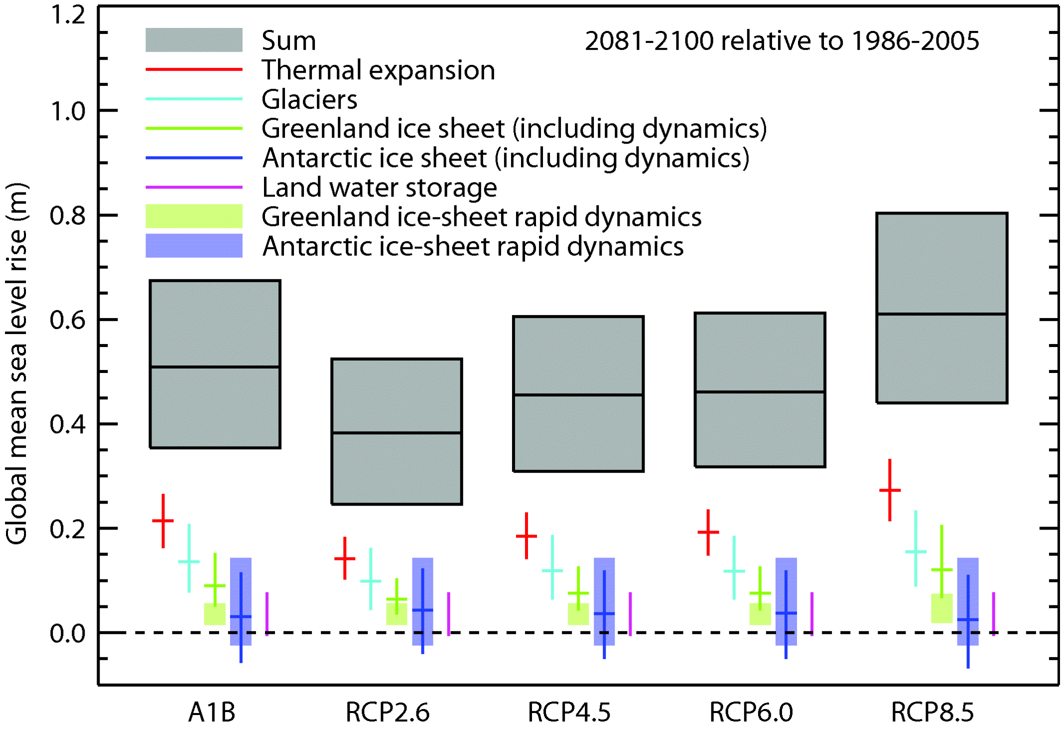
[24] Chambers, D. P., Merrifield, M. A., & Nerem, R. S. (2012). Is there a 60-year oscillation in global mean sea level? *Geophysical Research Letters*, 39(18).

[25] 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).

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 CMIP5 simulations and raises questions about the regional projections based on the CMIP5 results.



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 CMIP5 projections for the components contributing to the projected sea levels.

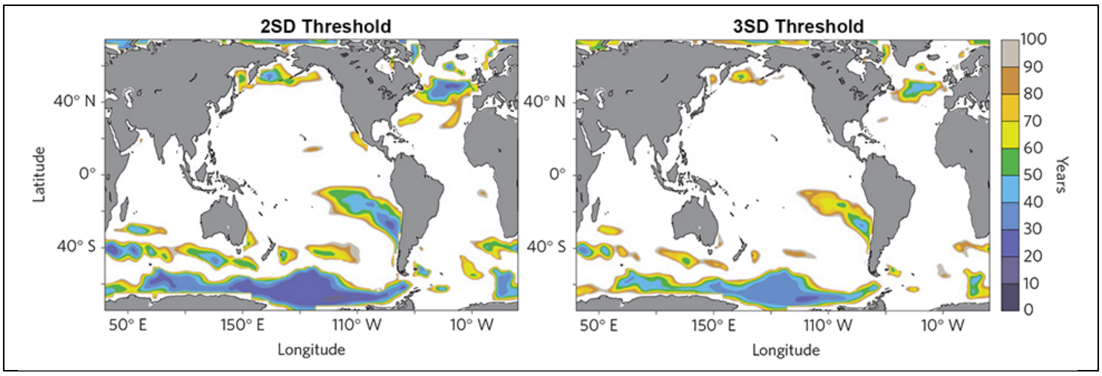


Figure 14 – Time of emergence (ToE) for CO_2 forced sea level rise signal from natural regional variability. White areas correspond to a ToE greater than 100 years[25].

32. Bordbar *et al* (2015) noted that their findings introduce additional uncertainties about the evolution of future regional sea level[25]. Finally, they reassessed the ToE (Figure 14) relative to 2

or 3 standard deviations of natural regional variability, which indicates that it will take at least 100 years before an anthropic sea level rise signal can be detected around New Zealand.

33. Parker (2014) assessed the growing deviations between CMIP5 projections and observed GMSL, and in particular the changing balance between components of GMSL rise that are inconsistent with CMIP5 assumptions[26]. He found that "*The true measurements are in marked contrast to theoretical reconstructions and simulations*". He also considered the implications of the observed discrepancies for coastal management in Australia, and concluded that management strategies should be "*based on observationally derived forecasts rather than 'projections' of models lacking validation*".

34. 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 CMIP5 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 guidelines, makes it very difficult to accept the claim made in the DCCS: "*Sea level rise – currently tracking towards a 0.8m rise by the 2090s or ~1m by 2115 compared to 1990*". Further, the regional variations in vertical land movement within the Wellington Region indicate that trends at the Port tide gauge should not be treated as representative of the entire coast.

Weather extremes

35. Like the sea level rise projections discussed above, the projections of future extreme weather are based on Ministry for the Environment (MfE) guidelines[1]. The key projections relate to wind, precipitation and temperature, and the highlighted statements in the DCCS 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*". The projections presented in Figure 15 were obtained by downscaling of a subset of projections for the A1B SRES scenario prepared for the IPCC AR4 reports[1], using a simple approach developed after the IPCC TAR report[27].

> ***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 DCCS section 3.2.1 on projected climate change that summarises projected changes to extreme weather.

36. Before considering the projections, it is useful to contextualise them in terms of the climate of the Wellington Region. Figure 16 is a summary of the average annual distribution of the parameters referred to in Figure 15 for Wellington City. Like the rest of New Zealand, Wellington City is a typical maritime or oceanic climatic zone, where the surrounding oceans, particularly the Tasman Sea, influence the climate. This means that there is a relatively narrow temperature range, which is around 8.5°C for the annual mean temperature range, with warm summer and mild winter conditions. The daily temperature range does not vary much with season, as indicated by the average maximum and minimum temperatures plotted in Figure 16. The lags between temperature and indicators of insolation (day length and average sunlight hours) also indicate that sea surface temperatures affect temperatures.

37. Precipitation is relatively uniform throughout the year, without a distinct dry season, although Wellington does display some seasonality with an increased winter precipitation and reduced late summer precipitation. This appears to be due to the seasonal distribution of mid-latitude cyclones, although intense rainfall events are associated with mesoscale convective events, particularly in spring and autumn. Therefore, precipitation patterns in the Wellington region tend to follow North Island patterns, and differ from South Island patterns. However, there is

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[26] Parker, A., 2014, Present contributions to sea level rise by thermal expansion and ice melting and implication on coastal management. *Ocean & Coastal Management* 98: 202-211.

[27] Mullan, A.B., Wratt, D.S., & Renwick, J.A., 2002. Transient model scenarios of climate changes for New Zealand. *Weather and Climate* 21:3-34.

considerable variability within the Wellington region due to the effects of topography. Overall, the daily probability of rainfall in Wellington ranges from 32-58% depending on the month, with an annual average of 43%.

38. Finally there is a slight seasonal variation in average wind speed, with the highest average wind speeds in spring. Wind speed is highly variable throughout the region, but Wellington City is considered the windiest city in New Zealand, with an average speed of 29 km.h^{-1} at the Airport[28]. More significantly, Wellington City experiences more days (175 at the airport) with wind gusts exceeding gale force (75 km.h^{-1}) than any other city in New Zealand, or world wide. However, this is quite variable, with the windiest year involving 233 days exceeding the gale force threshold. The maximum-recorded wind gust was 248 km.h^{-1} observed in 1959 and 1962.

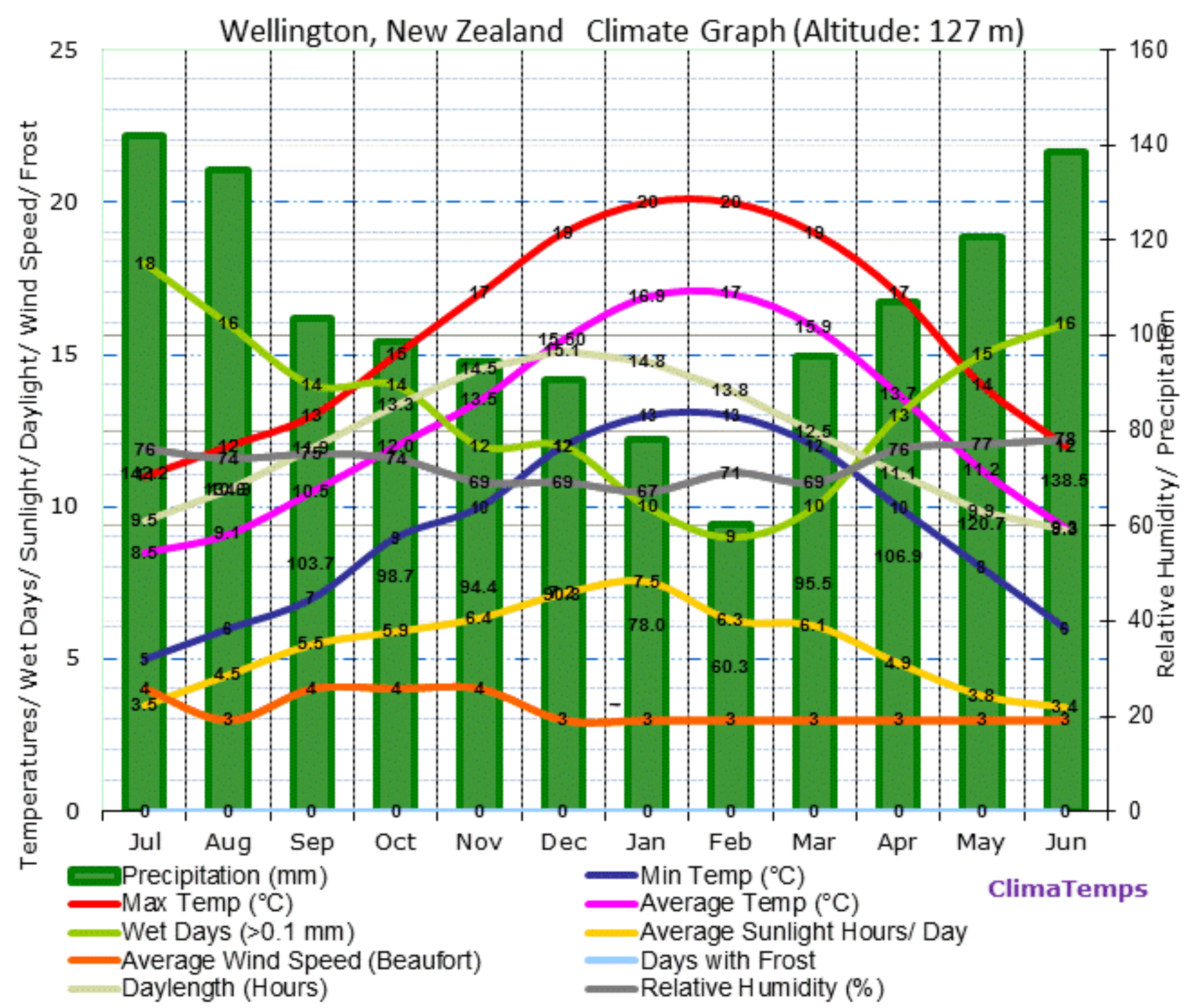

Figure 16 - Summary of average monthly climate parameters for Wellington City[29], including temperature, precipitation and wind.

39. With a maritime climate, New Zealand tends to be sensitive to changes in atmospheric and oceanic circulation in the Pacific region, particularly through changes in sea level pressure (SLP) and sea surface temperature (SST)[30]. A number of quasi-periodic changes involving inversely correlated sub-regions around the Pacific have been recognised, and generally are referred to as oscillations. Most vary over periods less than the 30 years[31] and are strictly weather oscillations, while some are longer than 30 years and are strictly climate oscillations. Neither are well simulated in current climate models, although some suggest that the random unforced noise in model simulations are an approximation of natural oscillations[32]. The

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[28] http://www.stuff.co.nz/dominion-post/capital-life/6111069/How-windy-is-Wellington-really

[29] http://www.wellington.climatemps.com/

[30] Ummenhofer, C. C. & England, M. H. Interannual Extremes in New Zealand Precipitation Linked to Modes of Southern Hemisphere Climate Variability. *Journal of Climate* 20, 5418–5440 (2007).

[31] A Conference in Warsaw in 1935 defined 30 years as the standard period for characterizing climate – the climate normal. At that time oscillations with periods of 30-100 years had not been identified.

[32] Brown, P. T., Li, W., Cordero, E. C. & Mauget, S. A. Comparing the model-simulated global warming signal to observations using empirical estimates of unforced noise. *Scientific Reports* 5: 9957, 9 pp., (2015).

oscillations that appear to strongly influence or appear in New Zealand weather include[30]; the El Niño – Southern Oscillation (ENSO); the Pacific Decadal Oscillation (PDO), which is also known as the Interdecadal Pacific Oscillation (IPO); the Southern Annular Mode (SAM), and the Antarctic Circumpolar Wave (ACW).

40. Section 3.2 in the MfE guidance note[1] summarises ENSO and PDO impacts on New Zealand. This summary was written before it became clear that the PDO changed to a negative phase around the start of the 21st Century, and so there is some speculation about whether observed changes represent a PDO phase shift or the effects of anthropic Climate Change[33]. There is ongoing debate about the causes of the PDO, and whether it is a real physical phenomenon. However, there is agreement that the positive phase is associated with an increased frequency and magnitude of El Niño events, while the negative phase is associated with fewer and weaker El Niño events and, therefore, a more frequent La Niña state.

41. It has been suggested that El Niño has also changed in behaviour since the late 20th Century, morphing into a Central Pacific centre of activity, rather than an Eastern Pacific feature. This "new" type of El Niño has been called a CP El Niño, or more popularly an El Niño Modoki[34]. While the appearance of El Niño Modoki has been attributed to global warming, the patterns associated with an El Niño Modoki are the same as those associated with the PDO[35]. This appears to include the precipitation changes attributed to El Niño Modoki, such as those reported for Australia[36].

42. The SAM is a ring of climate variability centred on the south pole, that consists of variations in SLP and associated wind patterns between high (50-70°S) and mid latitudes (40-50° S). This indicates that it directly affects the South Island of New Zealand. The pattern associated with SAM is highly variable and tends to flip between positive and negative states over a 1-2 week cycle. However, there are longer-term (decadal) trends between predominantly positive and predominantly negative states. It is argued that during the late 20th Century SAM has trended towards a predominantly positive state due to the effects of ozone depletion[37], although numerical models predict the same behaviour due to increasing greenhouse gases[38]. Long term records of SAM are based primarily on tree-ring proxies, and it is possible that the deviation since 1950 is also partially driven by rising CO_2 levels directly affecting growth or a response to trends in precipitation since the Little Ice Age[37].

43. The ACW differs from the other oscillations in that is not attributed to atmospheric circulation, but is linked primarily to SST anomalies located within the Antarctic Circumpolar Current, that is manifest as a wave-like feature that travels westward against the current[39], taking 8-9 years to complete a circuit. The SST anomalies then force an atmospheric response through changes in convection. Since there are two pairs of cold-warm SST anomalies in the ACW, it has been linked to a 4-5 year cycle of precipitation (rainfall and snowline elevation) in New Zealand[30,39]. However, the ACW was defined from a relatively short data-set, and numerical model simulations suggest that the ACW corresponds to the longer-term fluctuations of SAM[30].

44. For New Zealand, the El Niño extreme of ENSO is associated with stronger than normal south-westerly wind flow, which tends to produce lower seasonal temperatures in New Zealand (mostly in the late spring and summer), and reduced precipitation in the northwest of the country (Figure 17A)[1]. The La Niña extreme produces more north-westerly to north-easterly wind flows, which increases seasonal temperatures (mostly in late summer and autumn), and increases precipitation in the north and east of the North Island and reduces precipitation over the South Island[1].

45. As already discussed above, the PDO appears to correlate well with the observed step-like pattern of sea level rise around New Zealand. Although, there is an established link between ENSO and both SST and air temperatures[40], there is not a clear pattern associated with the PDO (Figure 18). A higher frequency of El Niño events during a positive PDO, such as between

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[33] The IPCC define "Climate Change" as only being a consequence of human activities, which leads to confusion with climate change that considers all possible drivers of climate variability. It is not always clear which definition the MfE guidance notes are using.

[34] Ashok, K. & Yamagata, T. Climate change: The El Niño with a difference. *Nature* **461,** 481–484 (2009).

[35] Di Lorenzo, E. *et al*. Central Pacific El Nino and decadal climate change in the North Pacific Ocean. *Nature Geoscience* **3,** 762–765 (2010).

[36] Taschetto, A. S. & England, M. H. El Niño Modoki Impacts on Australian Rainfall. *Journal of Climate* **22,** 3167–3174 (2009).

[37] Villalba, R. *et al*. Unusual Southern Hemisphere tree growth patterns induced by changes in the Southern Annular Mode. *Nature Geoscience* **5,** 793–798 (2012).

[38] Thompson, D. W. J. et al. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience* 4, 741–749 (2011).

[39] White, W. B., & Cherry, N. J. (1999). Influence of the Antarctic circumpolar wave upon New Zealand temperature and precipitation during autumn-winter. *Journal of Climate, 12*(4), 960-976.

1978 and 1998, should result in below average temperatures, and vice versa for the negative PDO (between 1948 and 1978). There is some evidence that a negative PDO results in higher SST in the Tasman Sea[30], but this is not well supported by reconstructed time series of SST around New Zealand apart from upwards steps in SST around 1960[40] and 1996[41]. Nonetheless, the PDO is often given as the cause of decadal scale temperature fluctuations for New Zealand, with a negative PDO phase associated with warming[42].

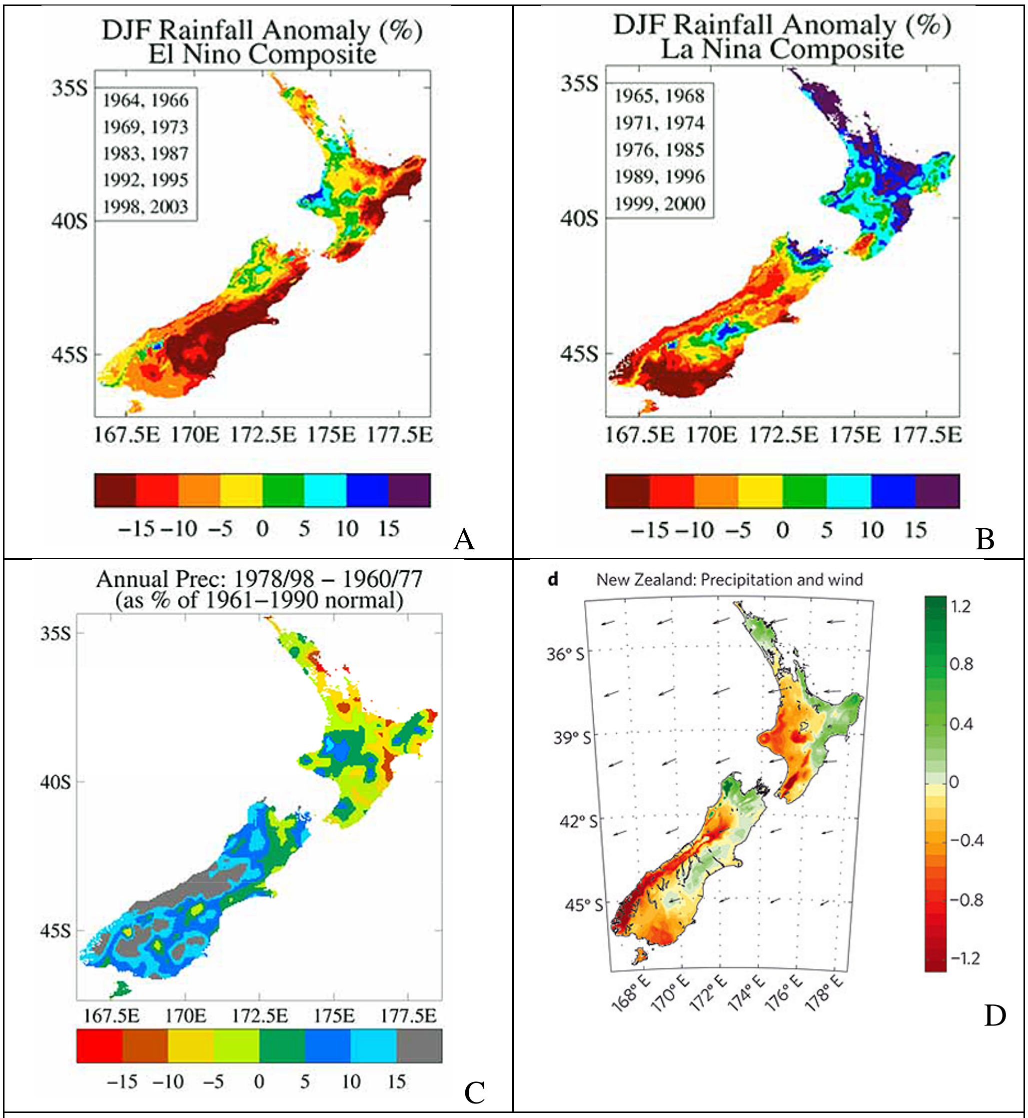

Figure 17 – Summary of precipitation changes associated with (A) El Niño, (B) La Niña, (C) PDO, and (D) SAM. (A) and (B) are summer anomalies, and (C) is a decadal comparison between a positive PDO (1978/98) and the preceding negative PDO (1960/1977)[1]. (D) is the correlation between the phase of SAM and precipitation[30].

46. There does appear to be a clear relationship between PDO state and precipitation patterns (Figure 17C), and a weaker relationship with wind patterns. The positive phase of the PDO is associated with stronger westerly winds, with increased rainfall in the southwest, and decreased rainfall in the northeast, of New Zealand. The opposite occurs during the negative phase, although less data were available for the negative phase when the patterns were first recognised, making the effects less certain.

47. The pattern of changing precipitation associated with the PDO has also been attributed to long-term variations in SAM (Figure 17D), with up to 80% of North Island and 20-50% of South Island

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[40] Folland, C. K. & Salinger, M. J. Surface temperature trends and variations in New Zealand and the surrounding ocean, 1871–1993. *International Journal of Climatoly*, **15,** 1195–1218 (1995).

[41] Uddstrom. M.J. & Oien, N.A., 1999. On the use of high-resolution satellite data to describe the spatial and temporal variability pf sea surface temperature in the New Zealand region. *Journal of Geophysical Research* 104(C4): 20,729-20,751.

[42] Mullan, B., Tait, A. & Thompson, C., 2012. *Climate - New Zealand and global climate patterns*, Te Ara - the Encyclopedia of New Zealand, updated 13-Jul-12 . URL: http://www.TeAra.govt.nz/en/climate/page-3

decline in summer rainfall since 1979 linked to an increased positive SAM state[43]. This interpretation contradicts other research that suggests that the impact of SAM is predominantly in the lower South Island, and not the North Island. However, if it is correct then the observed changes in precipitation would be linked to ozone depletion and increasing radiative forcing due to greenhouse gases[38], and not natural variability as represented by the PDO. Over the next few decades it will be interesting to see if the rainfall pattern continues to change to one consistent with a negative PDO or follows the proposed SAM pattern.

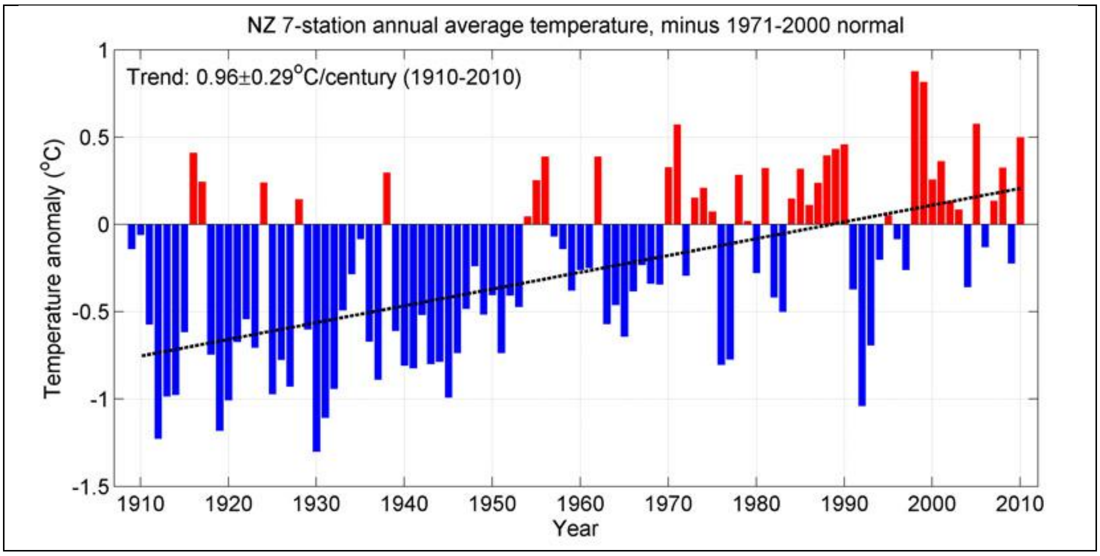

Figure 18 – Time series of the estimated air temperature anomaly for New Zealand determined from 7 homogenised station records considered representative of New Zealand[44].

48. There doesn't appear to be published data on the contributions of different types of storm systems to the observed precipitation patterns. In particular, the relative importance of high intensity mesoscale convective storms versus larger scale, lower intensity frontal systems or extratropical storms. However, there are data on the frequency and magnitude of landslides, which is often linked to the frequency and magnitude of high intensity rainfall[45]. These data indicate that that there has been considerable variability at different time scales within the instrumental record[44], and the longer proxy record[46], with no long-term trends evident[47].

49. Both the PDO and SAM oscillations have been linked to an increase in westerly winds for New Zealand for the late 20th Century, through trends in zonal climate indices (Z1 and Z2) that reflect north-south gradients in SLP. However, like precipitation, there is considerable local and regional variability in wind patterns due to topography. This means that for many locations within New Zealand there is a poor correlation between SLP and extreme winds[48]. Considering only locations that do not show an obvious local topographic effect, an analysis of extreme SLP differences and winds across New Zealand for the period 1966-2003 found an increase in both westerly and easterly winds for southern New Zealand and further south, which is consistent with the trend in SAM state[41]. However, only the trend in extreme (>99% percentile) westerly winds for latitudes between Christchurch and Campbell Island (Z2 index) was statistically significant at the 90% confidence limit. This equates to a trend to 0.6 days more extreme wind days per decade. It is unclear how this has been extended to an increase in westerly winds for all of New Zealand. It should be noted that the pattern of increasing westerly winds now attributed to global warming, is largely the opposite to that also attributed to global warming during the previous negative PDO phase. Trenberth (1976) stated "*Trends in both P1 and P2 since the 1940s are related to the rising temperature trend in New Zealand. There has been a trend for less westerly especially between 25 and 45°S, some increase in westerly south of 45°S and less southwesterly or more northeasterly component to the flow across the whole of*

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[43] Ummenhofer, C. C., Sen Gupta, A. & England, M. H., 2009. Causes of Late Twentieth-Century Trends in New Zealand Precipitation. *Journal of Climate* **22:** 3–19.

[44] https://www.niwa.co.nz/our-science/climate/information-and-resources/clivar/pastclimate

[45] Reid, L. M. & Page, M. J. Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology* **49,** 71–88 (2003).

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New Zealand as a result of the increased tendency for anticyclones to persist to the east of New Zealand rather than over Australia and the Tasman Sea, and their preference for higher latitude blocking” [49].

50. Figure 19 summarises the annual number of windy days (>60 km.h^{-1}) for the period 1966-2014 and also compares the monthly values for 2014 against the average monthly distribution. Comparing the annual number of windy days with the average for 1981-2010 (39 days) indicates that there is no trend, but significant interannual variability.

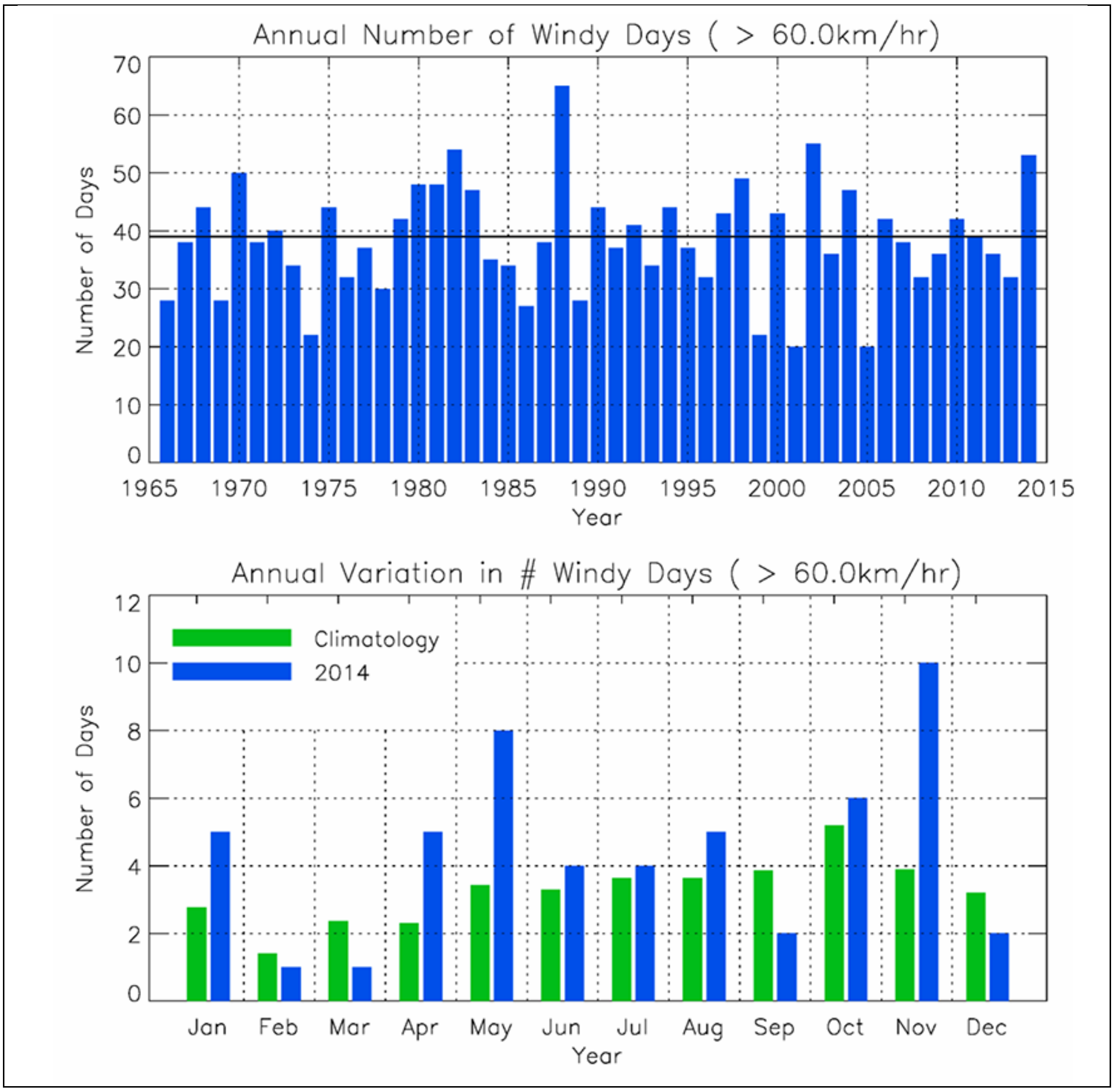

Figure 19 – (Top) Summary of annual number of windy days for 1965-2014, with the horizontal line representing the 1981-2010 average (39 days); (Bottom) Comparison of the monthly number of ‘windy days’ by month, in 2014 (blue) with the 1981-2010 average (green)[50].

51. Comparing the observed variability, without accounting for the local effects of topography, with the projected changes in Figure 15 indicates that the projections are well within the existing variability of the climate within the Wellington Region.

Projected future weather extremes

52. The projections in Figure 15, and the Regional Policy Statement were obtained by downscaling the projections from global simulations. For many regions around the world, this downscaling is achieved by running regional climate simulations forced by the selected global simulations (the coarse resolution global model provides the boundary conditions for a higher resolution regional model) [51]. The IPCC TAR report identified two main problems with this approach for downscaling: the effects of systematic errors in the driving fields provided by global models; and

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[51] IPCC TAR WGI report – Sections 10.2.3 and 10.2.4

lack of two-way interactions between regional and global climate models. These issues still exist with the recent CMIP5 models and their downscaled regional projections. Therefore a common caveat arising from assessments of model hindcasts of regional climate is that "the predictability is not enough to drive impact models at decadal timescales and to influence the policy and decision making"[52].

53. The downscaling for New Zealand as summarised in Figure 15 did not use a regional climate model. Instead it used an alternative approach, generally referred to as statistical downscaling[51]. The methodology used is summarised in the MfE guidance note appendices[1], and a paper in the journal published by the NZ Meteorological Society[53]. This approach assumes that the regional climate is primarily a response to two factors: the large-scale global climatic state; and regional or local physiographic features. Under this assumption, the global projections are downscaled by determining a statistical model that relates global climate variables to regional and local variables. Then the projections from a global simulation are fed into this statistical model to estimate the corresponding local and regional climate responses[51]. For New Zealand this was intially done for selected locations that had sufficient climate data for analysis, and for the 2008 MfE guidelines an interpolated grided statistical model for the whole of New Zealand was used[1]. OLS regression was used to develop the relationships between the selected stations, or the individual grid cells, and 12 global simulations driven by the SRES A1B scenario. The slope of each regression equation was then used as a scale factor or multiplier to adjust the global projections to the local projection. For the MfE guidance note, the individual grid cells within a regional council area were combined into a single value, as well as an overall value for all of New Zealand[1].

54. As noted by the IPCC TAR[51], this approach is suffers from a major weakness because "*their basic assumption is not verifiable, i.e., that the statistical relationships developed for present day climate also hold under the different forcing conditions of possible future climates. In addition, data with which to develop relationships may not be readily available in remote regions or regions with complex topography. Another caveat is that these empirically-based techniques cannot account for possible systematic changes in regional forcing conditions or feedback processes. The possibility of tailoring the statistical model to the requested regional or local information is a distinct advantage. However, it has the drawback that a systematic assessment of the uncertainty of this type of technique, as well as a comparison with other techniques, is difficult and may need to be carried out on a case-by-case basis.*"

55. Comparing the projections developed in 2002, with those summarised in the MfE guidance note and Figure 15, there is no significant change in the projections despite improvements in climate modelling. This is not surprising since the gridded statistical model is largely determined by interpolating between the individual stations used for the earlier assessment, and the same global climate model projections were used. The IPCC AR5 report includes projections for Australasia, including specific projections for New Zealand. These are summarised in Table 25-1 of the WGII report. For the climate parameters summarised in Figure 15, Table 25-1 presents the results from the MfE guidance note[1]. It appears that the original scaling factors derived from the AOGCM model projections from IPCC TAR have not been updated using either the CMIP3 or CMIP5 global model results, or to include changes in the regional and local climate associated with the PDO or SAM that are considered to affect the relationship between local climate and global projections[54].

56. Dean and Stott (2009) did compare higher resolution climate models used for IPCC AR4 with the NIWA 7-station temperature series (Figure 18)[54], with New Zealand represented by 2-13 grid cells. The comparison mostly considered the period from 1960-1999 (predominantly a positive PDO phase), although one model considered extended the analysis to 2006. This study is quoted in IPCC AR5 as providing evidence for an anthropic signal in the New Zealand temperature record. However, this evidence only appeared after components of natural variability were removed from the analysis, as the abstract explains, "*For a simple detection analysis it is not possible to separate the observed 30- and 50-yr temperature trends from the distribution created by internal variability in the model control simulations. A pressure index that*

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[52] Mehrotra, R., Sharma, A., Bari, M., Tuteja, N. & Amirthanathan, G. An assessment of CMIP5 multi-model decadal hindcasts over Australia from a hydrological viewpoint. *Journal of Hydrology* 519, Part D, 2932–2951 (2014).

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[54] Dean, S. M. & Stott, P. A. The Effect of Local Circulation Variability on the Detection and Attribution of New Zealand Temperature Trends. *Journal of Climate* 22, 6217–6229 (2009).

is representative of meridional flow (M1) is used to show that the models fail to simulate an observed trend to more southerly flows in the region. The strong relationship between interannual temperature variability and the M1 index in both the observations and the models is used to remove the influence of this circulation variability from the temperature records." The M1 index is the pressure difference between Hobart, Tasmania, and the Chatham Islands, and is a measure of the north-south flow, with positive values corresponding to flow from the south[54]. The M1 index probably reflects the north-south SST gradient in the Tasman Sea, and it is clear from Dean and Stott (2009) that the climate models are not simulating regional circulation very well. It should also be noted that the other studies discussed previously found that the zonal SLP difference (eg. Z2) was more important than the meridional difference (M1) identified in this study,

57. Table 25-1 does include temperature projections for Southern Australia and New Zealand derived from the CMIP5 models as summarised in Chapter 14 of the AR5 WGI in addition to the MfE guideline estimates. These are also expressed as temperature ranges for different time periods and, therefore, difficult to compare with the MfE projections. Table 14.1 in Chapter 14 of AR5 WGI provides more information although it combines New Zealand with South Australia. This table projects temperature to increase to 0.9-2.4°C with a mean value of 1.8°C by AD 2100 (*cf.* 2.1°C by AD 2090), and precipitation to change by -17-7% with a mean value of -2% by AD 2100 (*cf.* ~0% by AD 2900). Chapter 14 also summarises the projections for New Zealand as "*It is very likely that temperatures will continue to rise over New Zealand. Precipitation is likely to increase in western regions in winter and spring, but the magnitude of change is likely to remain comparable to that of natural climate variability through the rest of the century. In summer and autumn, it is as likely as not that precipitation amounts will change*".

58. It appears likely that a reanalysis of the relationship between local climate in New Zealand and global climate models will produce a different result to that obtained previously.

59. There is a growing deviation between projected and observed global tropospheric temperatures; with models projecting greater warming than has been observed so far in the 21st Century[55,56,57,58]. More recently it has also been reported that there is a growing deviation between model projections and stratospheric temperatures[59]. A wide range of hypotheses have been proposed to explain the deviations, including decadal cooling in the tropical Pacific, intensifying trade winds, changes in El Niño activity, increasing volcanic activity and decreasing solar irradiance[60]. Increasingly, it is suggested that the current slower rate of observed warming is predominantly a result of "internal climate variability", particularly the PDO[60]. This variability is also considered as the cause of previous decreases and increases in the rate of global warming since 1920.

60. A consequence of the reduced rate of warming at the start of 21st Century is that observation estimates of Transient and Equilibrium Climate Sensitivity (TCS and ECS respectively), which represent the short-term and long-term change in mean global temperature due to an effective doubling in the concentration of CO_2, have been revised downwards[61,62,63]. Lower values of TCS and ECS result in lower projections for future temperature. Further, recently it has been reported that the maximum cooling effect of aerosols, assumed to reduce the impact of greenhouse gases during the period 1950-1978 for example, is much lower than some models assume[64]. This also indicates that models that have assumed strong aerosol cooling during the 20th Century will over-estimate temperatures during the 21st Century[65].

61. By the end of 2012, considering CMIP3 and CMIP5 models forced by scenarios SRES A1B and RCP4.5, which were considered to most closely match the historical emission history, the

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[55] Fyfe, J. C., Gillett, N. P., & Zwiers, F. W. (2013). Overestimated global warming over the past 20 years. *Nature Climate Change, 3*(9), 767-769.

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[65] Storch, H. V., Barkhordarian, A., Hasselmann, K., & Zorita, E. (2013). Can Climate Models explain the recent stagnation in Global Warming. *Institute for Coastal Research*.

observed temperature trend lay below the 98% "confidence limits" for the model projections[64]. Three possible explanations were suggested for the observed deviation: "*1) the models underestimate the internal natural climate variability; 2) the climate models fail to include important external forcing processes in addition to anthropogenic forcing, or 3) the climate model sensitivities to external anthropogenic forcing is too high*" [65].

62. During the final stages of approving the IPCC AR5 WGI report, the likely (>66%) range projections for AD 2016-2035 were adjusted from those originally projected by the CMIP5 models (Figure 20). Several reasons were suggested to explain the observed deviation between the observations and the CMIP5 projections. Firstly internal climate variability was recognised as causing temperatures to increase faster or slower than the model projections at decadal scales. Secondly, the radiative forcings used by the CMIP5 models after 2005 are from the RCP scenarios, rather than as observed. The observed radiative forcings have been lower than assumed in the scenarios. Thirdly, the real world climate sensitivity (TCS for the model projections) may be below or at the low end of the CMIP5 models range. Finally, the exact position of the observations within the CMIP5 range depends slightly on the reference period chosen. A combination of some of these factors was consider to be responsible, with internal climate variablility being used to justify an abrupt return to the trajectory of the CMIP5 projections after AD 2035.

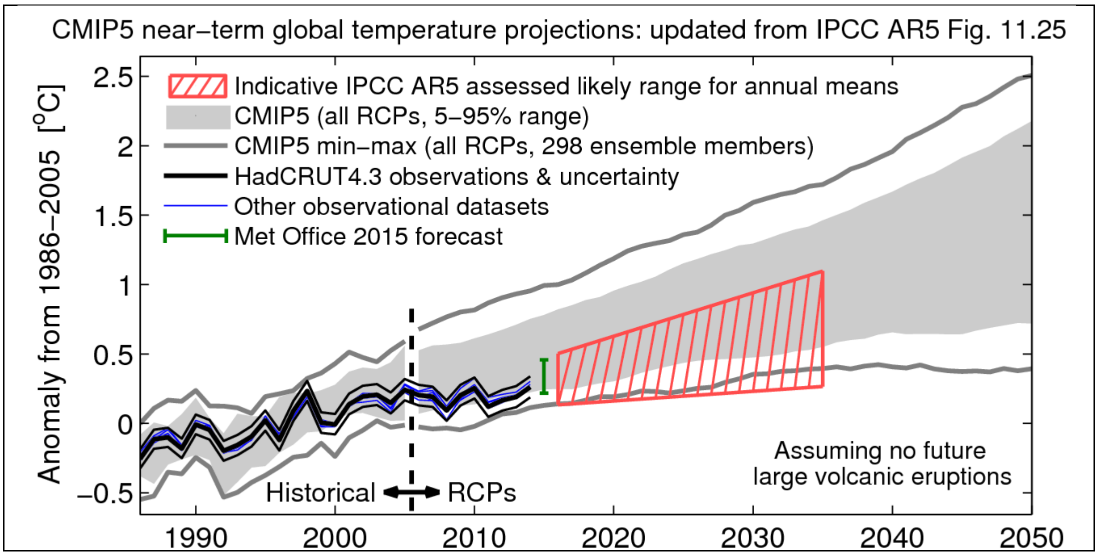

Figure 20 - Figure 11.25 from IPCC AR5 WGI report updated to reflect the adjustment to projected warming made at the final meeting before the report was published. Shown is the full range of projections and the central 90% range, along with HadCRUT4 (black) global temperature time-series. The CMIP5 model projections are shown relative to 1986-2005 (light grey). The red hatching is the IPCC AR5 assessed likely range for global temperatures in the 2016-2035 period. The blue lines represent other observational datasets (Cowtan & Way, NASA GISTEMP, NOAA NCDC, ERA-Interim, BEST)[66].

63. The projections for other climate variables (including sea level rise) based on the CMIP5 temperature projections were not adjusted in the IPCC AR5 reports to reflect the later adjustment illustrated in Figure 20. This appears to have been justified by the assumption that there would be an abrupt climatic shift around AD 2035, which returns the climate trajectory to the projections. However, if factors other than internal climate variability contributed to the observed deviations (as suggested by IPCC AR5 and Storch *et al*, 2013), then it is unlikely that there will be an abrupt return to the projected trajectory, as demonstrated by Brown *et al* (2015)[32].

64. The divergence between the observed response to increasing greenhouse gases and the projected behaviour, the known and unknown uncertainties with the downscaling methodologies used to derived local and regional estimates from CMIP5 projections, and the magnitude of the projected changes relative to the natural climatic variability makes it very difficult to accept that the projections summarised in the DCCS (Figure 15) are appropriate for making strategic planning decisions. The consequences of the projections indicated by the Regional Policy Statement do not appear to be supported by the IPCC AR5 reports. It is likely that there will be no detectable effect of increasing greenhouse gases on storms, floods, landslides and other climate related phenomena outside the observed variability during the 21st Century.

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[66] http://www.climate-lab-book.ac.uk/comparing-cmip5-observations/

Summary

65. Considering the sea level projections adopted by the DCCS, the key points are:

a) Due to vertical land movements, the magnitude of *relative* sea level changes around the coast of the Wellington region varies significantly, and at centennial scales the effects of a major earthquake and the cumulative effect of slow-slip events are likely to dominate over the effects of global *absolute* sea level changes.

b) It is evident that historic *absolute* sea level changes observed at Wellington do not agree with estimated historic global *absolute* sea level changes, or with CMIP5 projections for the available period of overlap this Century. Therefore, it is unlikely that projections of future global *absolute* sea levels provide a useful estimate of future sea levels in Wellington.

c) *Relative* sea level changes at Wellington are not tracking either the CMIP5 projections for *absolute* sea level rise, or the MfE guidelines for planning purposes.

    1. This is predominantly due to the lack of any statistically significant acceleration, which is an underlying assumption in both the projections and the guidelines.
    2. Further, the CMIP5 models do not account for regional-scale variability in the processes driving sea level changes. It is clear that major ocean sub-basins experience different sea level changes at different times, which do not accord with the global average modelled by the sea level projections. Within the sub-basins there are also significant variations. This variability indicates that an anthropic sea level signal is unlike to be detectable at Wellington this Century.
    3. Finally, it is clear that the relative contributions of the different components of sea level rise have been changing over the last few decades, which means the processes driving sea level changes are different to those assumed by the projections.

d) As identified by the NIWA report on sea level trends and variability for the Wellington, it is unlikely that sea level rise will abruptly accelerate to the rates required to achieve the MfE guidelines. Therefore, the MfE guidelines are an over-estimate of potential sea level rise over the next century, and the values specified should be considered *very unlikely*.

66. Considering the climate extreme projections adopted by the DCCS, the key points are:

a) The projected changes in the frequency and magnitude of extreme wind and precipitation events are smaller than the natural variability of these events at any specific location or between locations within the Wellington region. This is due to the effects of local topography and the scale of the systems associated with extreme events. The projected changes are very unlikely to be detectable during this Century.

b) The climate for the Wellington Region is strongly influenced by sea surface temperatures, the local topography, and a range of climate oscillations including ENSO, SAM and PDO. None of these is adequately incorporated into CMIP5 projections (and even less so in earlier projections). It is very unlikely that projections of global mean surface air temperature will provide any useful estimates of future climate for specific locations in the Wellington Region.

c) The MfE guidelines utilise downscaled climate projections produced for the IPCC TAR. Apart from being more than a decade out of date, the methodology used was identified by the IPCC TAR as being flawed. The downscaled projections are also provided as a regional “average”, which is very unlikely to provide any useful estimate of future climate for any specific location.

d) There appears to be fundamental disagreement over the relative influence of key climate oscillations on the climate of the Wellington Region, particularly the relative affects of ENSO, SAM and PDO on extreme events. Without a better understanding of the influence of these on the present climate of the Wellington Region, it is difficult to accept any projections based on assumed changes to their behaviour in the future.

e) There is strong evidence that the CMIP5 models have over-projected future temperature changes, although there is on-going disagreement as to why this has occurred. The same problems are also evident to the earlier models used to produce the MfE guidelines. Until the discrepancies between the out-of-sample observations and model projections are resolved it would be imprudent to rely on model projections for planning purposes.