Review of coastal process impacts of proposed Tuahine Crescent Seawall Addendum

20 September 2022

Introduction

In the 2 years since I wrote the review included as Appendix 1 of the S.42A report on the Tuahine Crescent (Cave) seawall, there have been several studies and reports on sea level rise that have some relevance to the potential coastal process impacts of, and on, a seawall. This addendum summarises the relevant literature, and the recently released SeaRise online tool for predicting sea level rise.

Sea level rise projections

The IPCC AR6 WGI report released in 2021 reviews available literature on sea level rise, and summarises projections of future sea level derived from the CMIP6 global climate models (IPCC, 2021). Figure 1 and Table 1 summarise the sea level projections from the AR6 assessment report (IPCC, 2021). The most plausible scenario presented is SSP2-4.5, which predicts median *likely* (>66% probability) *medium confidence* sea level rises relative to the 1995-2014 baseline of 0.56 m by AD 2100 and 0.93 by AD 2150. The SSP5-8.5 scenario was considered to be implausible in the AR6 report. The report also included the even less plausible low-likelihood, high-impact storyline in summary figures and tables, although it was acknowledged as having *low confidence*.

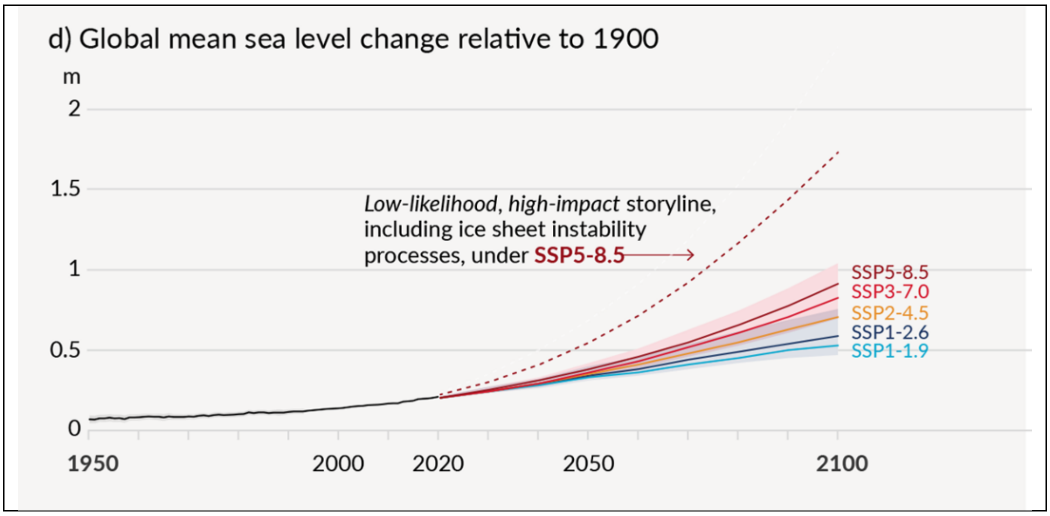

Figure 1 – IPCC AR6 WGI projected eustatic sea level changes relative to AD 1900 for 5 storylines (IPCC, 2021). The corresponding data are summarised in Table 1. The data for 1950-1992 are from tide gauges, satellite altimetry for 1992-2014, and CMIP6 models from 2014. Data are adjusted upwards to allow for 0.158 m sea level rise from 1900 to the 1995-2014 baseline used for simulations.

Table 1 – Eustatic sea level projections (m) relative to a 1995-2014 baseline for 6 storylines summarised from Table 9.9 (IPCC, 2021), and the NZ RCP8.5 H+ projections (MfE, 2017). The projections are from *likely* (>66% probability) ranges with *medium confidence.* Low, median and high values are provided for each scenario. The data up to AD 2100 are plotted in Figure 1.

	By AD 2100			By AD 2150		
Scenario	Low	Median	High	Low	Median	High
SSP1 – 1.9	0.28	0.38	0.55	0.37	0.57	0.86
SSP1 – 2.6	0.32	0.39	0.62	0.46	0.69	0.99
SSP2 – 4.5	0.44	0.56	0.76	0.66	0.93	1.33
SSP3 – 7.0	0.55	0.68	0.90	0.92	1.21	1.89
SSP5 – 8.5	0.63	0.77	1.01	0.98	1.35	1.88
SSP5 – 8.5 *Low confidence*	0.63	0.88	1.60	1.02	1.99	4.83
NZ RCP8.5 H+		1.05			1.88	

The AR6 report did not clearly indicate that the underlying methodology for producing the values from model ensembles displayed in summary tables and figures had changed. Subsequent publications by the modellers and authors involved have clarified the situation (*viz*. Hausfather *et al*, 2022). It was recognised that some models either projected to much warming, or warmed too quickly, or both. The results of these models were considered implausible and the models were excluded from further analyses. Figure 2 is from Hausfather *et al* (2022) and indicates the ranges of temperature changes determined by including all model projections, excluding models deemed to be too hot, and the results finally included in the AR6. It is evident that further selection and/or adjustment beyond excluding 'hot models' has occurred, as indicated by the statement on Figure 2 that excluding 'hot models' is a shortcut approximation to the AR6 average. It is not clear what this involved, but the AR6 results reported (as in Table 1), give a range including 66% of the ensemble results between the 17% and 83% percentiles, while the ranges in Figure 2 include 90% of the ensemble results between the 5% and 95% percentiles. Hence, AR6 has less emphasis on the extreme tails of the ensemble distributions.

From Figure 2 and Hausfather *et al* (2022) it is evident that the choice of CMIP6 models affects the results for all future projections based on the CMIP6 models, and this includes sea level projections. As far as can be determined from the AR6 reports, the sea level results in Figure 1 and Table 1 are subjected to the same weighting processes as the temperature projections in Figure 2. Little *et al* (2015) also demonstrated that the ensemble results from 16 CMIP5 AOGCM models used to project future sea levels were distorted by 4 outliers regardless of the scenario and temperature model. It is not known if this is still an issue for CMIP6 AOGCM models.

Included in Table 1 are the NZ RCP8.5 H+ sea level projections that MfE (2017) recommended as being used to assess sea level rise impacts particularly Category A. The NZ RCP8.5 H+ values are based on the RCP 8.5 pathway within the SSP5-8.5 storyline, and represent the median of the 18% highest ensemble values. The IPCC AR6 report indicates that SSP5-8.5 is implausible, while SSP2-4.5 is considered the most plausible. Table 1 shows that the NZ RCP8.5 H+ sea level projections are too high. For the Tuahine Crescent seawall, the proposal initially reviewed was based on the MfE (2017) guideline of 1 m, which is consistent with the 83% levels for the SSP2-4.5 storyline beyond AD 2100, and well beyond the design life of the structure.

In my review, I discussed the influence of vertical land movement on relative sea level at Tuahine Crescent. Geomorphic, sedimentological and continuous GPS (GNSS) evidence indicated that Wainui Beach was rising at rates comparable to the global eustatic sea level rise (1-2 mm/y). I suggested that, as a consequence, the seawall should be designed to the Category D transitional sea level of 0.65 m (MfE, 2017). This value is consistent with the median (50%) projections for the SSP2-4.5 storyline beyond AD 2100, and well beyond the design life of the structure.

Denys *et al* (2020) undertook an analysis of relative sea level and vertical land movement at 5 ports around New Zealand, and used these data to determine the underlying eustatic sea level rise for New Zealand for the period 1900-2013. Their results indicate an average rate of eustatic sea level rise of 1.45 ± 0.36 $\mathrm{mm.y^{-1}}$, and they did not detect any acceleration in the rate over time, which agrees with an earlier assessment by Fadil *et al* (2013) that found an average rate over the period 1900-2011 of 1.46 ± 0.10 $\mathrm{mm.y^{-1}}$. Garrett *et al* (2022) present a re-analysis of proxy measures of

New Zealand relative sea level for the last millennium. Their reconstructed sea level agrees well with the Denys *et al* (2020) analysis of tide gauge data, and shows an acceleration in the rate of sea level rise in the early 20th Century, peaking in the 1940s and slowing since then. There is no evidence of a recent acceleration. As shown in Figure 1, all of the AR6 sea level projections assume sea level rise has accelerated since 2005 and will continue to do so until at least AD 2150.

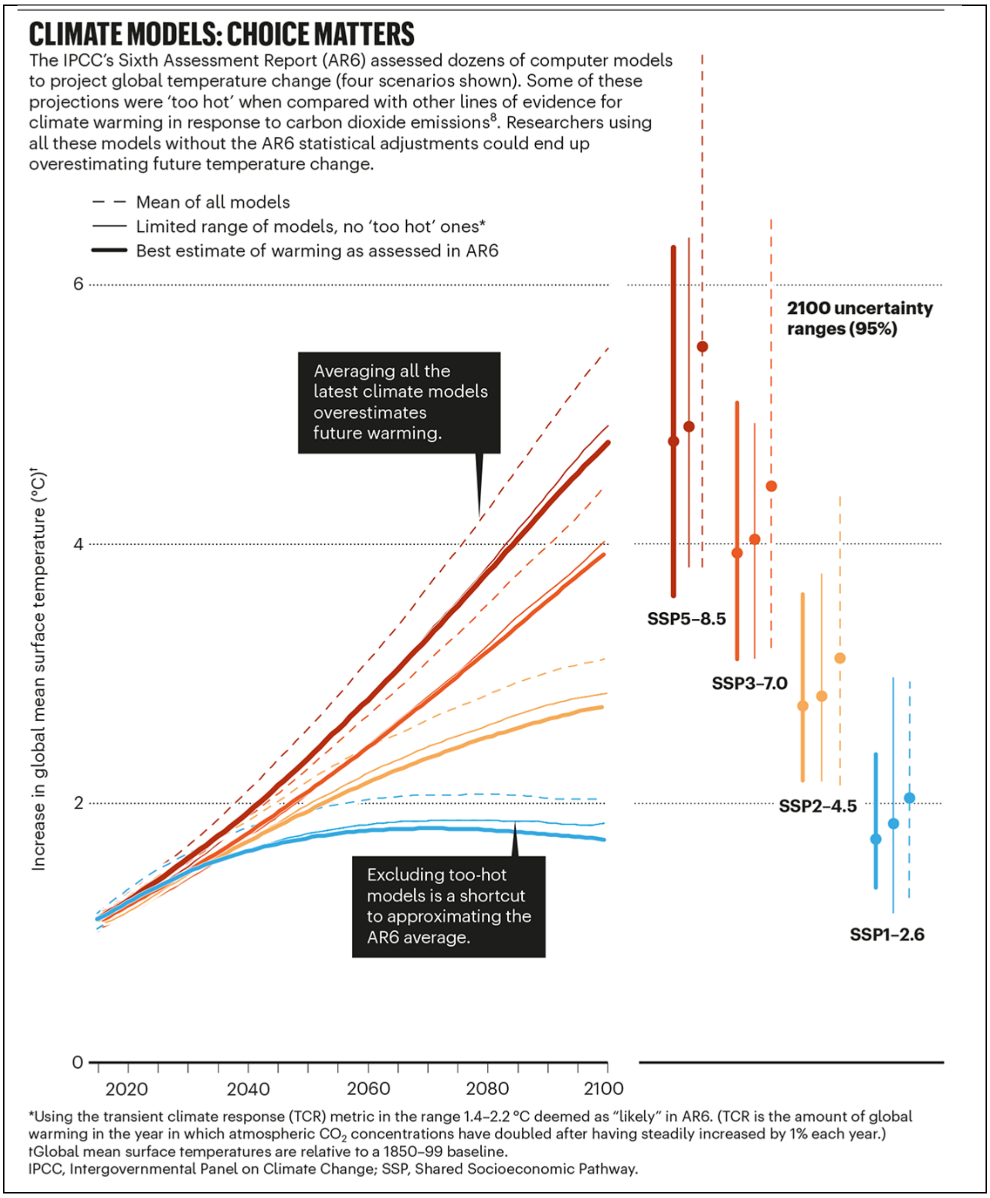

Figure 2 – Comparison of ensemble CMIP6 model medians and ranges for the projected increase in global mean surface temperature: including all models; excluding 'hot models'; and as reported by IPCC AR6 (Hausfather *et al*, 2022).

Recently (May 2022), the SeaRise online tool became available that combines vertical land movement and projections of eustatic sea level rise approximately every 2 km along the New Zealand coastline. The website points to an article written for the New Zealand Coastal Society to explain the methodology used (Levy *et al*, 2020). This article provides little detail about the methodology: particularly about potential errors and uncertainties. There is also no validation of the sea level predictions presented in the article. It is clear, however, that the online tool consists of a database of estimated rates of vertical land movement for all the sites, and a single set of sea level rise projections consisting of decadal estimates of sea level rise from AD 2020 to AD 2300 for 5 storylines. The sea level rise estimates are baselined to zero in AD 2005, and the SeaRise website indicates that the predictions should be offset by the mean observed sea level for the period 1995 to 2014 at the location of interest.

Vertical land movement

Considering the database of vertical land movement estimates, the Levy *et al* (2020) article doesn't provide much detail about the methodology used to derive the estimates. However, Hamling *et al* (2022) do provide a good description of the methodology used to estimate vertical land movement for the New Zealand coastline, and their datasets available online include the 2 km coastal vertical land movement data used by the SeaRise online tool. Hamling *et al* (2022) note that the dataset was restricted to 8 years between 2003 and 2011 with minimal large seismic events causing vertical land movement; data associated with the Fiordland 2009 and Darfield 2010 events were dropped from the analysis. Uplift associated with the Matata earthquake swarm between 2005 and 2011 in the Bay of Plenty was also adjusted to reduce the estimated uplift rate for that area.

The Hamling *et al* (2022) dataset involved combining Interferometric Synthetic Aperture (InSAR) data with continuous GPS measurements (GNSS) collected by GeoNet. The InSAR data measures deformation as result of volcanic, tectonic, and anthropogenic sources: anything that changes the elevation of the dominant radar reflector in an area, so it may not reflect the actual vertical land movement. They also note that the Synthetic Aperture Radar data used to estimate deformation was predominantly derived from ascending satellite tracks, "*making it* [the InSAR data] *largely unusable for deriving a long-term rate*". The issues raised by Hamling *et al* (2022) imply that their estimated rates are not suitable for projecting vertical land movement, and hence relative sea level, out to AD 2300. Levy *et al* (2020) also note that "*the evolution of coastal vertical land movement will pose an ongoing challenge*".

Table 2 summarises the occurrence of earthquakes with magnitudes greater than M_w 4.0 between 1960 and 2021. Given the location of Wainui Beach within the Hikurangi Deformation Front, it is *exceptionally likely* that there will be vertical movement due to at least one earthquake before AD 2300.

Table 2 – Frequency of New Zealand between 1960 and 2021. Data from https://www.geonet.org.nz/earthquake/statistics_long

Magnitude	Annual average	Annual minimum	Annual maximum	"In general"
4.0 - 4.9	360.74	124	1,178	1 per day
5.0 - 5.9	30.05	6	109	2 per month
6.0 - 6.9	1.68	0	9	3 per 2 years
7.0 - 7.9	0.27	0	2	1 per 4 years
8.0 or over	0	0	0	1 per century

Figure 3 shows the estimated rates of vertical land movement for the SeaRise sites between Gisborne and Tatapouri. For Wainui Beach near the proposed seawall, the rates vary from -0.770 mm/y at Tuahine Point to -0.730 mm/y at the beach access near the Pare St and Wairere Road intersection. The maximum subsidence rate is -0.850 mm/y near Sponge Bay. These rates of subsidence contradict the uplift rates determined by previous studies using longer term indicators of vertical land movement as summarised in my initial review. Considering all of the sites in Figure 3, there is no pattern to the estimated rates that is consistent with published studies of the overall tectonic deformation of the region, which are summarised by Clark *et al* (2010) as discussed below. It is possible that the vertical deformation rates determined by InSAR reflect shoreline erosion, landslides and anthropogenic sources; not the actual underlying vertical land movement. Alternatively, the vertical movement is also a consequence of aseismic processes, or slow slip events.

Figure 4 shows an updated plot of the vertical component of ground movement at the Makorori GNSS site (MAKO) that was included in my initial review, and a similar plot for the Gisborne GNSS site (GSIB). The InSAR data for the area around Gisborne would have been adjusted using the GISB GNSS data as it is the only nearby GNSS site that has data for the 2003-2011 period considered. That site lies inland within an area of subsidence under the Poverty Bay flats, and is not representative of the coast around Wainui Beach (Figure 3). Both records show vertical land movement occurring in response to slow slip events.

Figure 3 – Estimated rates of vertical land movement between Gisborne and Tatapouri from the SeaRise online tool. Also shown are the locations of the GISB and MAKO continuous GPS sites, and the location of the proposed seawall.

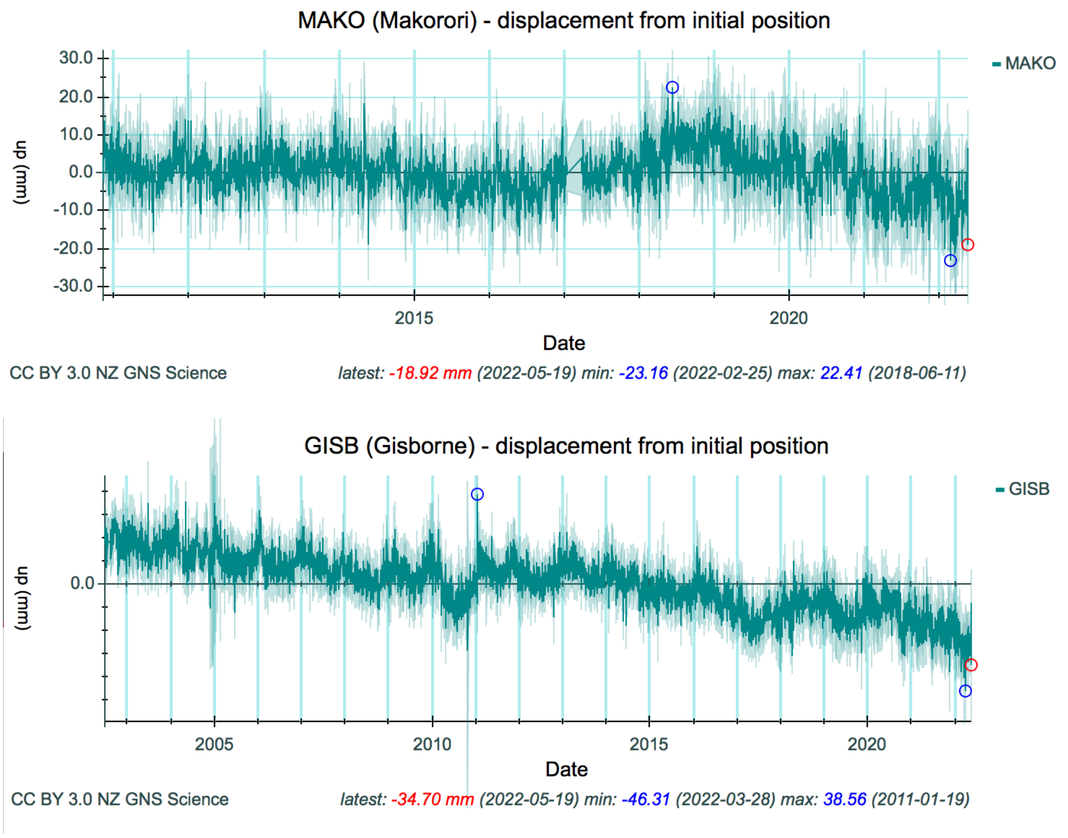

Figure 4 – Continuous GPS (GNSS) records for sites MAKO at Makorori, and GISB in Poverty Bay. The latest, minimum, and maximum values are labelled with coloured circles, and their corresponding values listed below the plot.

Perez-Silva *et al* (2022) analysed slow slip events for the Hikurangi Deformation Front between Anaura Bay and Porangahau for the period from 2004 to 2020. Figure 5 shows the distribution of slow slip events over this period. This shows that Wainui Beach experiences deformation due to slow slip events almost every year, but the frequency during 2003-2011 was lower than subsequently. All of the slow slip events recorded at the GISB station were associated with uplift at the MAKO station; with the strongest response evident for the 2017 event.

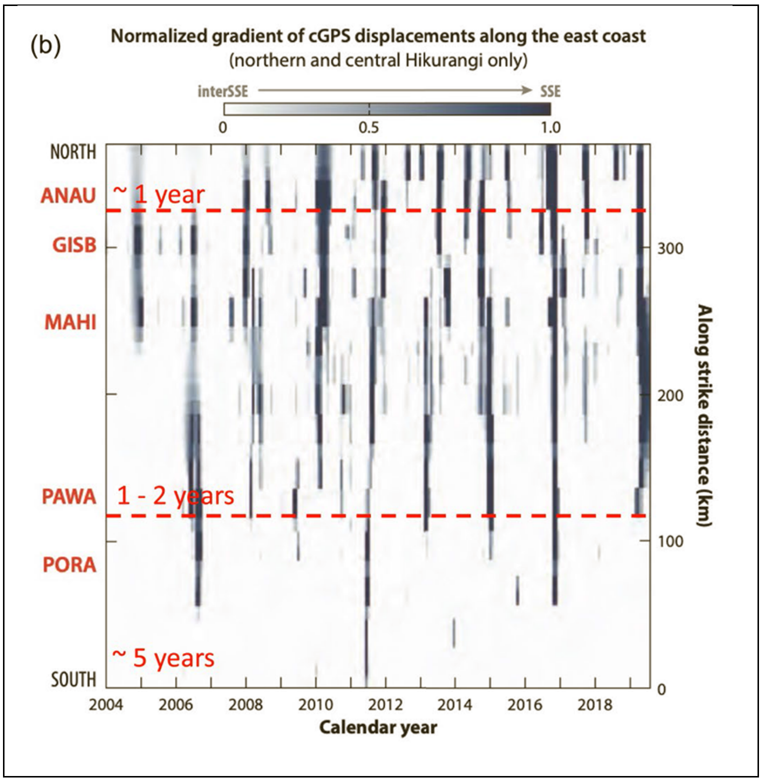

Figure 5 - Change in rate of motion of GeoNet continuous GPS stations as a normalized gradient. Darker colours represent the fastest rate change, which is indicative of slow slip events. The white colour indicates intervals between slow slip events. (Figure 1b from Perez-Silva *et al*, 2022).

Figure 6 is a combination of figures 4 and 6 from Clark *et al* (2010) and shows:

A. A schematic cross-section through the Raukumara Peninsula to indicate the changing processes at depth that are driving coastal deformation, including uplift and subsidence. Wainui Beach lies in an intermediate zone where deformation is changing from being driven primarily by episodic large earthquakes (intermittent deformation zone) to being driven by gradual uplift due to crustal thickening (gradual uplift zone). Within the intermediate zone, causes of deformation vary and are not well understood. However, for the Wainui Beach region it is considered that slow slip events are a significant contributor to deformation;

B. A map of the Raukumara Peninsula and Hikurangi Trough showing the location of the 3 deformation zones, major structures contributing to deformation, and coastal rates of vertical land movement. The map highlights a lack of identified faults in the Poverty Bay region, which is still evident in the active fault database for New Zealand released in May 2022 (Seebeck *et al*, 2022); the abrupt transition from uplift at the coast near Wainui Beach (MAKO site), and subsidence in the western Poverty Bay region (GISB site); and the location of subducted seamounts that are considered to contribute to seismic tremor and the formation of slow slip events; and

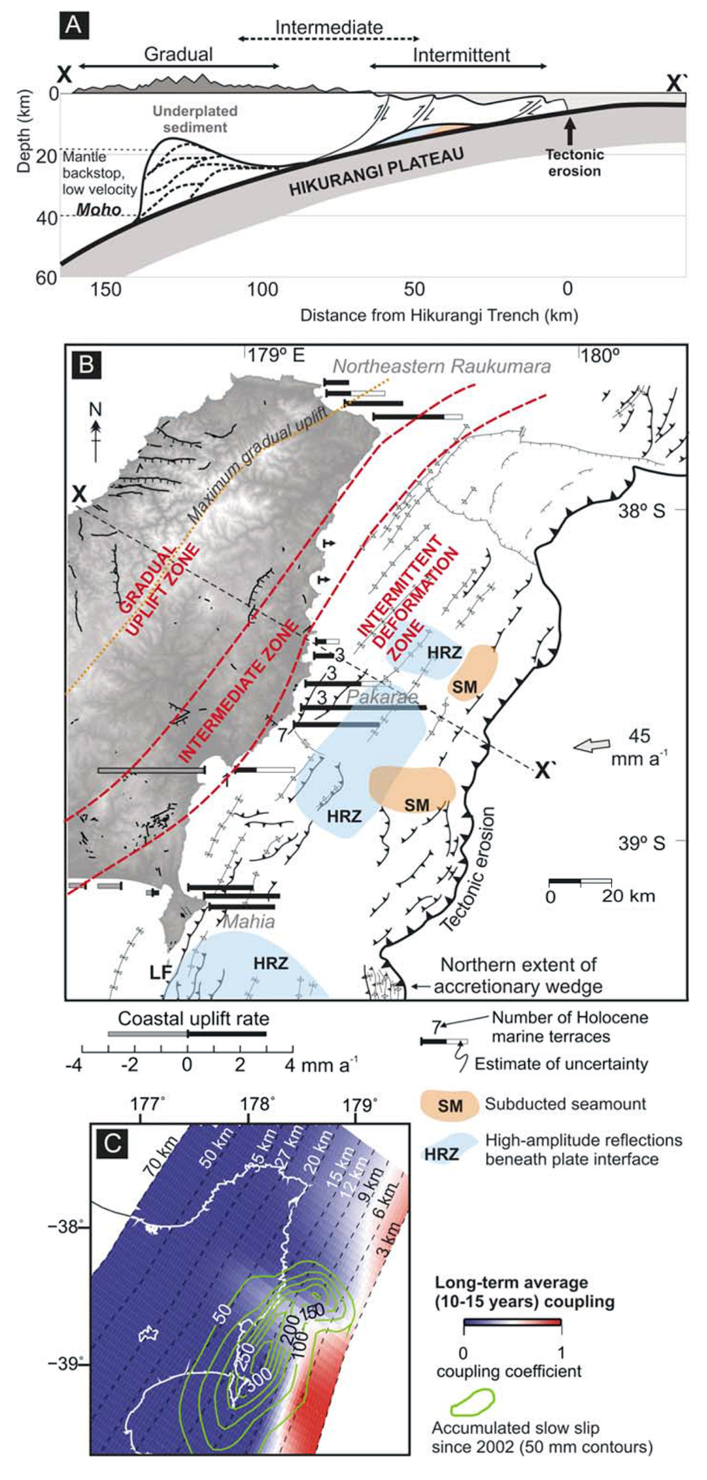

Figure 6 - Summary of the coastal deformation mechanisms of the Raukumara Peninsula. (A) Cross-section across the Raukumara Peninsula showing the tectonic processes responsible the coastal deformation. (B) Map showing relationship between the coastal deformation zones of the Raukumara Peninsula, the upper plate structure and topography and the physical properties of the plate interface. Dotted lines delineate the approximate boundaries of the margin-parallel zones of intermittent and gradual deformation along with the intermediate zone in between. Estimated rates of uplift are shown(C) Interseismic plate coupling along the northern Hikurangi margin derived from geodetic data, and the distribution of plate interface slow-slip since 2002. Dashed lines represent depth contours on the plate interface. Modified from figure 6 of Clark *et al* (2010) by adding the key for coastal uplift from figure 2 in the same publication below panel B.

C. A map showing the amount of coupling between the Pacific and Indo-Australia Plates between seismic events, and the total slow slip deformation between 2002 and 2010. This shows the local concentration of slow slip events associated with subducting submarine seamounts. Barker *et al* (2018) examined the deformation occurring offshore from Wainui Beach associated with Ariel Bank and the Tuaheni Basin, and linked the September to October 2014 slow slip event to a 40 km long, 15 km wide, and 2.5 km thick lozenge-shaped buried ridge on the descending plate.

Overall, the published evidence for ongoing uplift of the Wainui Beach area due to slow slip events and episodic large earthquakes is compelling and indicates that the extrapolation of short-term estimates of vertical land movement from the InSAR observations between 2003 and 2011 is not a reliable predictor of future vertical land movement.

SeaRise eustatic sea level projections

Levy *et al* (2020) state that the eustatic projections are the projected rates from the IPCC Special Report on the Ocean and Cryosphere Change (Oppenheimer *et al*, 2019) combined with extra sea level rise due to ice sheet melt determined by expert elicitation. It further indicates that the median and *likely* range (17% to 83% percentiles) values from Oppenheimer *et al* (2019) were used to define the central region of the sea level projection distributions, and expert elicitation was used to define the extreme tails (upper and lower 17%). The source of the expert elicitation was not specified. Therefore, the methodology is based on adjusted CMIP5 model results and it is unclear if the outlier AOGCM models identified by Little *et al* (2015) were included or excluded.

However, the SeaRise website provides projected sea level rise using the median (p50), lower 17% percentile (p17) and upper 83% percentile (p83) values based on the CMIP6 models. This means that the expert elicitations of the extreme tails for the CMIP5 model projections should not be included in the online tool projections. Comparison of the SeaRise sea level rise projections with those from the IPCC AR6 WGI report summarised in Table 1, show that they agree up to AD 2030, but increasingly deviate over time depending on the storyline: SSP1-1.9 is essentially unchanged; while SSP5-8.5 shows the largest change.

Table 2 – Eustatic sea level projections (m) relative to a 1995-2014 baseline for the 5 storylines used in the SeaRise online tool.

	By AD 2100			By AD 2150		
Scenario	Low	Median	High	Low	Median	High
SSP1 – 1.9	0.25	0.38	0.57	0.34	0.58	0.89
SSP1 – 2.6	0.30	0.42	0.62	0.43	0.67	1.00
SSP2 – 4.5	0.44	0.57	0.78	0.68	0.96	1.35
SSP3 – 7.0	0.59	0.73	0.96	0.99	1.31	1.74
SSP5 – 8.5	0.67	0.83	1.10	1.09	1.47	2.02

As mentioned above, Denys *et al* (2020) analysed relative sea levels and vertical land movements for ports around New Zealand with a sufficiently long record; reporting an average rate of eustatic sea level rise of 1.45 ± 0.36 mm/y. This rate is based on observations that overlap with the start of the SeaRise projections between AD 2005 and AD 2030. For this overlap period, SeaRise projections assume a rate of eustatic sea level rise of 3.2 mm/y for p17, 4.4 mm/y for p50, and 5.6-6.0 mm/y for p83 depending on the storyline (lower rates for higher emission storylines). These rates are more than double the observed long-term rate around New Zealand based on coastal tide gauges. The SeaRise p50 and p83 eustatic sea level rise rates are also higher than the global eustatic sea level rise rate determined by satellite altimetry of 3.0 ± 0.4 mm/y for the period AD 1992 to AD 2022 (this rate excludes the estimated glacial isostatic adjustment for the increasing depth of the ocean basins of 0.2-0.5 mm/y) reported by the NOAA/NESDIS/STAR Laboratory for Satellite Altimetry (https://www.star.nesdis.noaa.gov/socd/lsa/).

The SeaRise projections, therefore, start with a higher rate of eustatic sea level rise than observed for New Zealand, or globally, and assume continual acceleration of the rate of rise until AD 2300. As discussed above, there is currently no evidence for long-term acceleration of the rate of sea level rise for New Zealand. There is evidence that the rate of sea level rise varies at annual to decadal time scales, so it is necessary to analyse time series of sufficient length to average out these variations. The minimum time period required is considered to be 60-70 years, which means that satellite altimetry data are too short to provide a reliable estimate of long-term rates. Therefore, the global eustatic sea level rise rates should be reduced by at least 50% to match the observed rates for the New Zealand coast.

Levy *et al* (2020) also point out that there are latitudinal differences in the rate of eustatic sea level rise, which they illustrate with an extreme example of a large release of water from the Greenland and Antarctic ice caps. Table 3 summarises the results from Denys *et al* (2020) for the ports analysed, and they indicate that there is a latitudinal variation in the rate of eustatic sea level rise for the New Zealand coast; although the value for Dunedin appears anomalous. Despite the differences being small, they are the same magnitude as the glacial isostatic adjustment the Local Government Guidance Note (MfE, 2017) added to eustatic sea level rise projections, and therefore should be considered for 100-year projections (and longer).

Table 3– Summary of the results from Denys *et al* (2020) of rates of relative sea level rise (RSL), vertical land movement (VLM), and eustatic sea level rise (ASL) for 5 New Zealand ports.

Port	RSL (mm.y^{-1})	VLM (mm.y^{-1})	ASL (mm.y^{-1})
Auckland	1.57 ± 0.15	-0.16 ± 0.10	1.41 ± 0.18
New Plymouth	1.46 ± 0.54	-0.04	1.42 ± 0.54
Wellington	2.18 ± 0.17	-0.62 ± 0.31	1.56 ± 0.36
Lyttelton	1.91 ± 0.13	-0.27 ± 0.23	1.64 ± 0.26
Dunedin	1.35 ± 0.15	-0.14 ± 0.31	1.21 ± 0.35
mean	1.69 ± 0.28		1.45 ± 0.36

Figure 7 shows the measured monthly and annual relative mean sea level at Gisborne (station 1613) as provided by the Permanent Service for Mean Sea Level (PSMSL) website (https://www.psmsl.org/), and the SeaRise relative sea level predictions for site 2130 located within Eastland Port with a vertical land movement of -0.020 mm/y (Figure 3). Sea level data for Gisborne before 2010 are sparse and unreliable, so they have not been plotted. The SeaRise predictions have been baselined using the procedure given by SeaRise. This has the effect of forcing the SeaRise projections to overlap the observed sea level for the period 1995-2014. In this case data were not available for the full period, so the mean was based on data for 2007, 2008, and 2010-2014). As plotted, Figure 7 indicates sea level rose faster than predicted until 2016, and then has gradually fallen until the observed mean relative sea level is in close agreement with the predicted sea level in 2020.

Figure 4 shows the vertical land movements at the GISB and MAKO sites approximately equidistant from site 2130, and a comparison with Figure 7 indicates that vertical land movement has had a minor impact on the measured sea level (~10%). The influence of vertical land movement does vary over time, with the largest impact occurring during 2010-2011 period when there was strong slow slip event deformation (Figure 5). Overall, the observed rise and then fall of relative sea level cannot be attributed solely to vertical land movement at site 2130.

Figure 8 shows the measured monthly relative mean sea level at Gisborne and the eustatic sea level measured by satellite altimetry at 38.75°S 178.08°E, which is approximately 10 km south-southeast of the Gisborne tide gauge at 38.68°S 178.02°E. The satellite altimetry data were obtained from the Sea Level Explorer website (https://ccar.colorado.edu/altimetry/index.html). Despite not correcting the Gisborne relative sea level data for vertical land movements, it is generally a good match with the satellite eustatic sea level data. This suggests that sea level at Gisborne (and therefore Wainui Beach) predominantly responded to changes in eustatic sea level offshore from the coast over the period plotted. The main deviations between the two data sets occurs for 2010-2011 when there were larger vertical land movements.

Figure 8 also shows that the rate of sea level rise at Gisborne varies over time, with intervals of acceleration and deceleration. The is no obvious evidence of an overall acceleration or deceleration in the rate of sea level rise in the available data, but the record duration is too short to undertake a reliable analysis. The pattern of sea level variations in Figure 8 also suggest that sea level at Gisborne will soon drop below the SeaRise predicted sea levels (Figure 7).

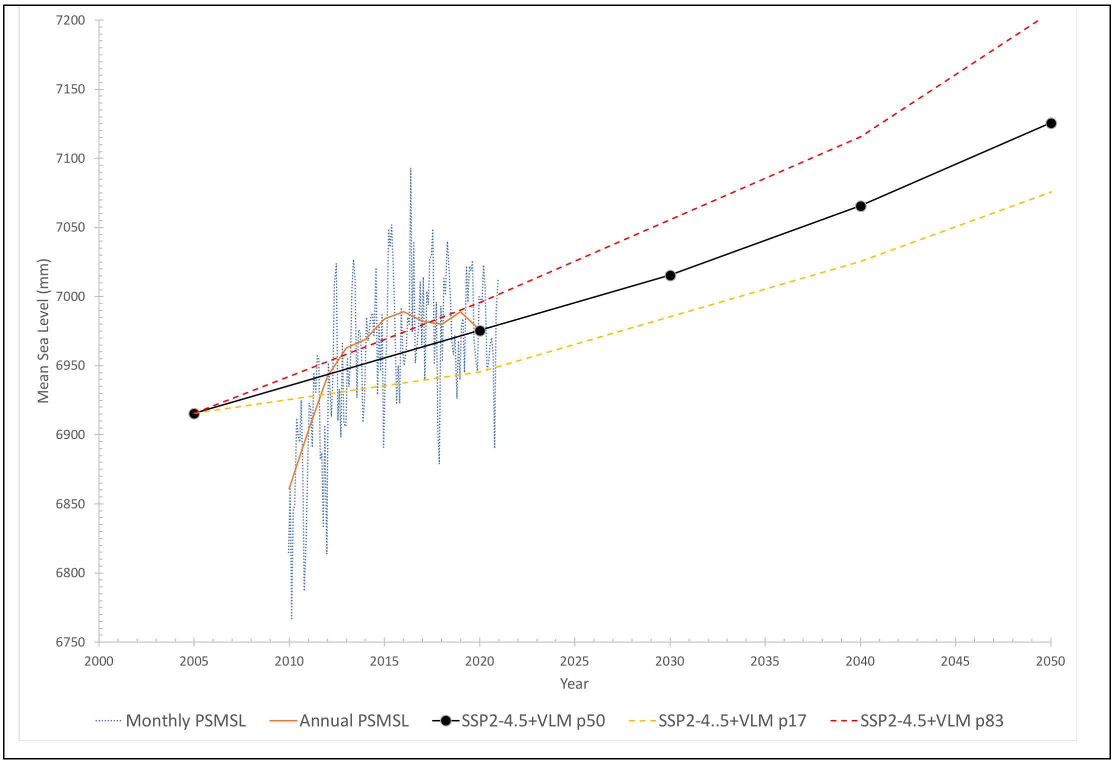

Figure 7 – Measured mean annual and monthly relative sea level at Gisborne for 2010-2020 as reported by PSMSL, and the SeaRise predicted sea level from 2005 to 2050 at site 2130. The SeaRise data have been baselined to the mean of the annual observations for 1995-2014 (6915.6 mm).

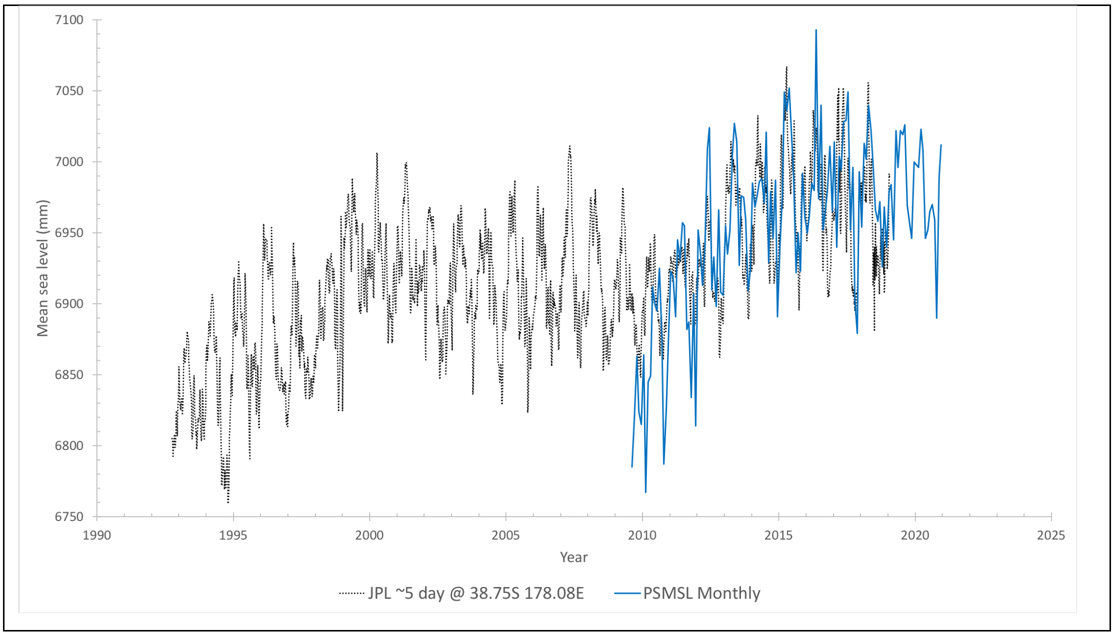

Figure 8 – Measured monthly relative sea level at Gisborne for 2010-2020 as reported by PSMSL, and the satellite altimetry measured eustatic sea level offshore at 5-day intervals as provided by the Sea Level Explorer Website.

Normally La Niña conditions tend to result in an elevated mean sea level around New Zealand, particularly on the east coast of the North Island (areas affected by the East Auckland Current transporting warm tropical water towards polar regions). In contrast El Niño conditions tend to result in lowered mean sea levels. Since 2016, La Niña conditions have dominated, including a prolonged event underway at present (https://www.cpc.ncep.noaa.gov/data/indices/soi). Even though the ocean surface temperatures have increased during the La Niña events, Figure 8 shows that sea level has fallen. When the next El Niño event occurs, it is *likely* that sea level will fall faster.

Overall, the limited sea level data for the Gisborne region indicates that the SeaRise predictions, while currently matching observations after baselining, are *very likely* to overestimate future sea levels at Wainui Beach, particularly over longer time periods (after 2030-2050).

Summary

The additional information on historic sea level changes and new future sea level projections/predictions has not significantly changed my original review. The key findings are:

- Since the predicted sea level is *very likely* to less than assumed for the initial review, the proposed replacement seawall is still *likely* to have the same effect on coastal processes as the existing structure, which is minimal.
- Sea level rise is *very likely* to be less than assumed for the initial proposal reviewed. The RCP 8.5 H+ sea level projections applied then, which were *exceptionally unlikely* at the time, are recognised as not plausible. The new sea level predictions from the SeaRise online tool are not reliable, and a *very likely* to overestimate future sea level, particularly after 2030-2050 depending on the storyline used. Hence, I would still suggest that there is scope to reduce the size of the proposed replacement seawall, and hence the impact, if it is treated as a Category D development following the Ministry for the Environment (2017) guidance with a lower assumed future sea level.

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