The significance of vertical land movements at convergent plate boundaries in probabilistic sea-level projections for AR6 scenarios: The New Zealand case.

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Abstract

Anticipating and managing the impacts of sea-level rise for nations astride active tectonic margins requires rates of sea surface elevation change in relation to coastal land elevation to be understood. Vertical land motion (VLM) can either exacerbate or reduce sea-level changes with impacts varying significantly along a coastline. Determining rate, pattern, and variability of VLM near coasts leads to a direct improvement of location-specific relative sea level (RSL) estimates. Here, we utilise vertical velocity field from interferometric synthetic aperture radar (InSAR) data, calibrated with campaign and continuous Global Navigation Satellite System (GNSS), to determine the VLM for the entire coastline of New Zealand. Guided by existing knowledge of the seismic cycle, the VLM data infer long-term, interseismic rates of land surface deformation. We build probabilistic RSL projections using the Framework for Assessing Changes to Sea-level (FACTS) from IPCC Assessment Report 6 and ingest local VLM data to produce RSL projections at 7435 sites, thereby enhancing spatial coverage that was previously limited to tide gauges. We present ensembles of probability distributions of RSL for *medium confidence* climatic processes for each scenario to 2150 and *low confidence* processes to 2300. For regions where land subsidence is occurring at rates >2mm yr^{-1} VLM makes a significant contribution to RSL projections for all scenarios out 2150. Beyond 2150, for higher emissions scenarios, the land ice contribution to global sea level dominates. We discuss the planning implications of RSL projections, where timing of threshold exceedance for coastal inundation can be brought forward by decades.

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The significance of vertical land movements at convergent plate boundaries in probabilistic sea-level projections for AR6 scenarios: The New Zealand case.

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Key Points:

- Anticipating impacts of sea-level rise for active tectonic margins requires location-specific knowledge of vertical land movement (VLMs).
- We ingest VLMs measured continuously along a tectonically-dynamic coastline into IPCC AR6 projections to provide relative sea-level.
- Downward VLM > 2 mm y^{-1} makes a significant contribution to RSL projections bringing forward adaptation decision thresholds by decades.

Abstract

Anticipating and managing the impacts of sea-level rise for nations astride active tectonic margins requires rates of sea surface elevation change in relation to coastal land elevation to be understood. Vertical land motion (VLM) can either exacerbate or reduce sea-level changes with impacts varying significantly along a coastline. Determining rate, pattern, and variability of VLM near coasts leads to a direct improvement of location-specific relative sea level (RSL) estimates. Here, we utilise vertical velocity field from interferometric synthetic aperture radar (InSAR) data, calibrated with campaign and continuous Global Navigation Satellite System (GNSS), to determine the VLM for the entire coastline of New Zealand. Guided by existing knowledge of the seismic cycle, the VLM data infer long-term, interseismic rates of land surface deformation. We build probabilistic RSL projections using the Framework for Assessing Changes to Sea-level (FACTS) from IPCC Assessment Report 6 and ingest local VLM data to produce RSL projections at 7435 sites, thereby enhancing spatial coverage that was previously limited to four tide gauges. We present ensembles of probability distributions of RSL for *medium confidence* climatic processes for each scenario to 2150 and *low confidence* processes to 2300. For regions where land subsidence is occurring at rates >2mm yr^{-1} VLM makes a significant contribution to RSL projections for all scenarios out 2150. Beyond 2150, for higher emissions scenarios, the land ice contribution to global sea level dominates. We discuss the planning implications of RSL projections, where timing of threshold exceedance for coastal inundation can be brought forward by decades.

Plain Language Summary

This study is the first to outline an approach for deriving projections of relative sea-level change that account for changes in land surface elevation continuously along a coastline. Previous sea-level projections that included vertical land movements (VLMs) were restricted to tide gauge locations. In order to increase spatial-resolution, required by practitioners for effective adaptation planning, we have combined elevations measured using satellite radar data with measurements from land-based Global Navigation Satellite System (GNSS) receivers to build a continuous VLM database showing land uplift and subsidence (sinking) for the entire coastline of New Zealand. We input this data into latest probabilistic projection methodology used in Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 (AR6) for the range of future climate scenarios. Our approach should be applied to any region of the world where the coastline is affected by active tectonic processes. Downward land movement > 2 mm y^{-1} makes a significant contribution in sea-level projections for all climate scenarios out to the end of this century. This means that adaptation planning decision thresholds, such as those linked to the impacts of coastal flooding and inundation, may be brought forward by decades.

1 Introduction

1.1 Background

Sea-level rise is one of the clearest planet-wide consequences of climate change. It impacts our communities and ecosystems, both through permanent inundation of the lowest-lying areas and by increasing the frequency of storm surge affecting the wider coastal environment. Future global mean sea-level (GMSL) rise will be controlled primarily by the thermal expansion of ocean water and mass wasting of land ice from glaciers, ice caps, and ice sheets, the latter is already dominating GMSL rise at an accelerating rate (Fox-Kemper et al., 2021).

New Zealand is one of many countries with extensive coastlines that sit astride a convergent tectonic plate boundary (Fig. 1), where large changes in land surface elevation can dramatically reduce or increase the rate of climate change driven sea-level rise. The magnitude and direction of vertical land motion (VLM) can change across short distances, resulting in highly variable rates of relative sea level (RSL) and different impacts across short sections of coastline (Conrad, 2013; Douglas, 2001; Milne et al., 2009; Stammer et al., 2013; Wöppelmann & Marcos, 2016). Accurately determining the rate and pattern of VLM along coastlines can improve location-specific RSL estimates (Cazenave et al., 1999; Ray et al., 2010; Santamaría-Gómez et al., 2017) and projections (Kopp et al., 2014) with significant implications for adaptation planning and risk management.

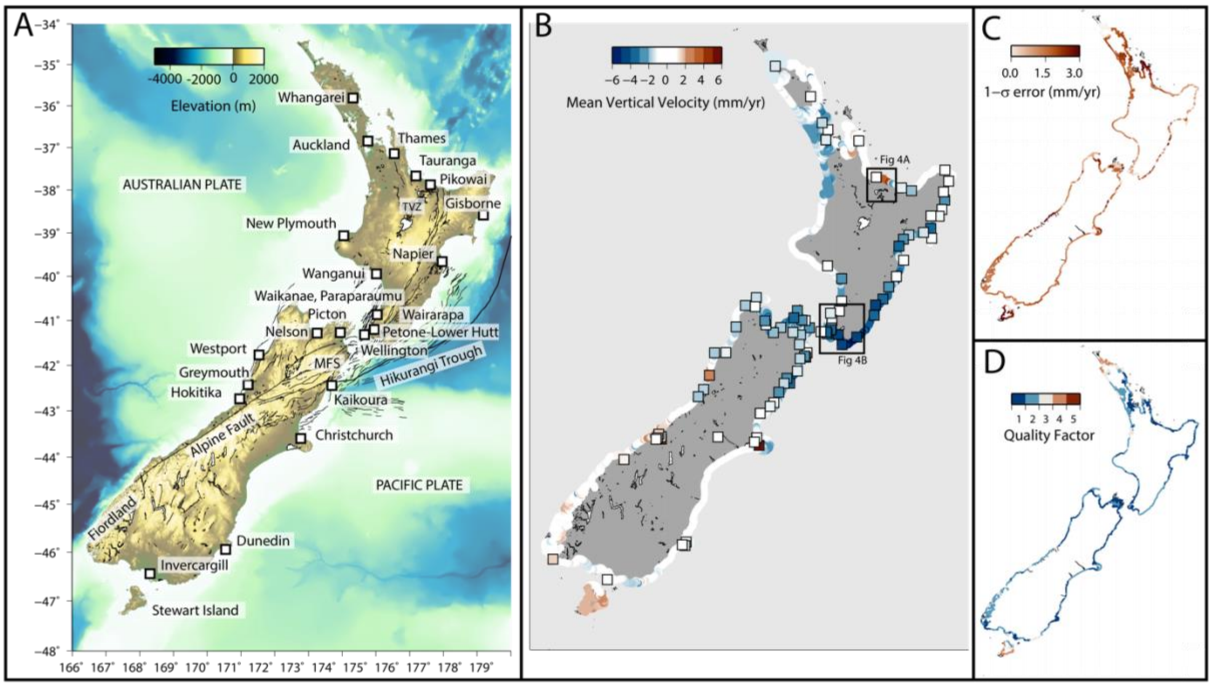


Figure 1. (A) Major tectonic features of the New Zealand convergent plate boundary setting and locations mentioned in text. MFZ = Marlborough Fault Zone. TVZ = Taupo Volcanic Zone. (B) Mean vertical velocity of the (positive upwards) land surface derived from InSAR data (Hamling et al., 2022) averaged for 2 km-spaced sites around the coastline of New Zealand. Boxes show the location of GNSS sites used to calibrate InSAR data. Note that parts of the coastline (50%) coloured white are relatively stable and LSL projections are less affected by VLM. (C) One sigma uncertainty for vertical velocity of the land surface derived from InSAR data averaged for 2 km-spaced sites. (D) Quality factor for vertical velocity of the land surface derived from InSAR data averaged for 2 km-spaced sites (1=good, 5=poor).

1.2 The role of VLM in RSL changes

The spatial variability of RSL change arises from climatic drivers and non-climatic geological processes (Gregory et al., 2019). Climatic processes include non-uniform changes in sea-surface height due to: (i) atmospheric circulation that affects air pressure (Hamlington et al., 2020; Royston et al., 2018), (ii) ocean dynamics that affect salinity and heat content (Levermann et al., 2005; Yin et al., 2009), and (iii) perturbations in the Earth's gravitational field, rotational axis, and crustal height through viscoelastic deformation (referred to as GRD), in response to contemporary redistribution of mass between ice sheets and the ocean (Kopp et al., 2014; Kopp et al., 2010; Mitrovica et al., 2011; Riva et al., 2017; Slangen et al., 2014). Processes listed in (iii) are also referred to as the sea-level fingerprint (Mitrovica et al., 2011) or static-equilibrium effects (Kopp et al., 2014).

Non-climatic processes include: (i) isostatic adjustment following erosion (England & Molnar, 1990; Small & Anderson, 1995), (ii) sediment loading (Ivins et al., 2007), (iii) changes in mantle flow or dynamic topography (Faccenna & Becker, 2010; Hoggard et al., 2016; Kreemer et al., 2020; Moucha et al., 2008; Müller et al., 2018), and (iv) tectonic processes (Beavan & Litchfield, 2012; Hamling et al., 2022; Houlié & Stern, 2017). Shorter-term unsteady non-climatic VLM changes can also arise due to subsidence from extraction within aquifers (Erban et al., 2014; Galloway & Burbey, 2011; Herrera-García et al., 2021) and hydrocarbon reservoirs (Chaussard et al., 2013; White & Morton, 1997), the weight of cities (Han et al., 2020; Jiang et al., 2021; Parsons, 2021) and sediment compaction (Carbognin & Tosi, 2002; Dixon et al., 2006; Johnson et al., 2018). For cratonic continental margins in the Northern Hemisphere, the most significant non-climatic contribution to VLM is the viscoelastic response of the crust arising from glacial isostatic adjustment (GIA) to the loss of continental ice sheets since the Last Glacial Maximum (LGM; c. 18 ka) (Caron et al., 2018; Farrell & Clark, 1976; Milne & Mitrovica, 1998; Peltier et al., 2015).

For convergent margin coastlines in the far-field of the polar ice sheets, where the effect of GIA is small, tectonic processes are the greatest influence on VLM, and therefore RSL variability. These processes cause rapid, non-linear VLM changes during and just following earthquakes. Longer-term steady uplift or subsidence occurs through elastic deformation between seismic events (Burgette et al., 2009; Denys et al., 2020; Mazzotti & Stein, 2007) and/or aseismic creep or slow slip events (SSEs) associated with subduction zones (Wallace, 2020; Wallace & Beavan, 2010; Wallace et al., 2012). These long-term interseismic tectonic VLMs may continue with the same sign (up or down) for decades to centuries and in some cases at rates that exceed the GMSL rise projected for the coming decades (IPCC AR6). A previous assessment of VLM around the New Zealand coastline (Beavan & Litchfield, 2012) noted the probability that a high-magnitude earthquake will cause large vertical displacement at any given point along the coastline over the next 100 years, is low due to historic lengths of the earthquake cycle (Stirling et al., 2012). Therefore, the interseismic rate is dominant across decadal time scales and is most useful when estimating sea-level rise over the next century. Nevertheless, the effect of potential future vertical land-level changes due to earthquake cycle processes and coseismic displacement should be considered. This is particularly important for high probability events including an Alpine Fault rupture (Fig. 1) and large subduction event on the Hikurangi subduction zone, which respectively have a 75% and 26% likelihood of producing a large earthquake in the next 50 years (Howarth et al., 2021; Pizer et al., 2021). However, we note that the amount and direction of any VLM associated with these events is difficult to predict and that historical fault ruptures on the Alpine Fault are predominantly strike-slip and produce very little VLM in the South Island. Whereas the earthquake 'effect' on future sea level should be evaluated in a probabilistic sense, similar to the way that probabilistic seismic hazard models are implemented (Gerstenberger et al., 2020), such work is beyond the scope of this study.

Traditionally, sea-level projections in guidance documents used by coastal zone planners and practitioners did not account for local VLM (Church et al., 2013; Gornitz et al., 2019; Horton et al., 2011; Katsman et al., 2011; Lawrence et al., 2018; Ministry for the Environment, 2017; National Research Council, 2012; Perrette et al., 2013; Slangen et al., 2014; Slangen et al., 2012). More recently, probabilistic sea-level projections that characterize plausible Bayesian probability distributions of future climate scenarios (Meinshausen et al., 2020) to estimate GMSL and RSL (Fox-Kemper et al., 2021; Jackson & Jevrejeva, 2016; Kopp et al., 2014; Kopp et al., 2016) include VLMs extracted from historical tide-gauge data (Kopp et al., 2014). However, users are more frequently demanding high-resolution, spatially resolved RSL projections, particularly along coastlines where VLMs are significant and highly variable (e.g., New Zealand where rates vary from –8 to +10 mm y^{-1}) (Hamling et al., 2016; Hamling et al., 2022; Houlié & Stern, 2017; Lamb & Smith, 2013). By utilizing space-borne geodetic techniques, to include installing permanent Global Navigation Satellite System (GNSS) antenna at or near tide gauges, we have revolutionised our ability to separate terrestrial drivers of relative sea level change from climate and ocean signals (Blewitt et al., 2010; Denys et al., 2020; Poitevin et al., 2019). However, most permanent GNSS stations are not co-located with the tide gauges (Hamlington et al., 2016; Santamaría-Gómez et al., 2017) and GNSS information is spatially limited. In order to increase spatial-resolution, InSAR velocity data calibrated by high-precision campaign and continuous GNSS measurements are being used to build velocity fields of land deformation along the coastal strip (Biggs & Wright, 2020). This approach is providing unprecedented granularity with significantly reduced uncertainties (Hamling et al., 2022; Poitevin et al., 2019).

1.3 Aims of this study

This study was designed in response to a need for relative sea level projections at high spatial resolution that accommodate highly variable rates of vertical land movement along New Zealand's coastal margin. We utilise a high-resolution vertical velocity field generated for the period 2003-2011 from Envisat InSAR data that are calibrated with campaign and continuous GNSS time series through the same interval (Hamling et al., 2022). These data are used to establish VLM estimates for 7435 sites spaced ~2 km apart around the New Zealand coastline. We generate probabilistic RSL projections for each site using the Framework for Assessing Changes to Sea-level (FACTS) (Fig. 2) (See Methods in Supporting Information). FACTS is based on the projection methodology (Garner et al., 2021; Kopp et al., 2014; Kopp et al., 2016) and was used for the Intergovernmental Panel on Climate Change WGI 6th Assessment Report (Fox-Kemper et al., 2021). Here we replace the non-climatic background module of Kopp et al. (2013; 2014) with VLM data from Hamling et al., (2022). We use the IPCC AR6 approach and present an ensemble of probability distributions of RSL for *medium confidence* processes for Shared Socioeconomic Pathways (SSP) scenarios to 2150 and *low confidence* processes in SSPs to 2300 (see Methods in Supporting Information). These new local "NZSeaRise" projections can be accessed through a web-based GIS-visualisation tool (www.searise.nz/maps-2).

New Zealand's coastal hazard and climate change guidance for local government (Lawrence et al., 2018; Ministry for the Environment, 2017) currently uses four sea-level rise scenarios that are drawn from the probabilistic projections of Kopp et al. (2014) and apply a regional sea-level departure from GMSL. These projections indicate that sea level could rise by as much as 1.2 m by 2110 under a high emissions scenario (the 83rd percentile of RCP8.5). However, the guidance does not provide specific allowances for local, non-climatic/oceanic factors due to tectonics, land compaction, or sediment accumulation, and it cautions that "users will also need to factor in a local component for VLM…" (p. 102). As discussed in Section 1.2, VLMs contribute considerably to the magnitude of RSL rise this century, with subsidence rates in some localities as much as 8 mm y^{-1} (Hamling et al., 2022). While the primary purpose of this paper is to outline a methodology for the inclusion of high-resolution, high-precision, satellite-borne geodetic VLM data into probabilistic sea-level projections and their use, we also provide a scientific basis for a new set of location-specific sea-level projections utilising IPCC AR6 WGI for use by practitioners (insert link to MfE interim guidance website here) that will underpin adaptation planning decisions in New Zealand.

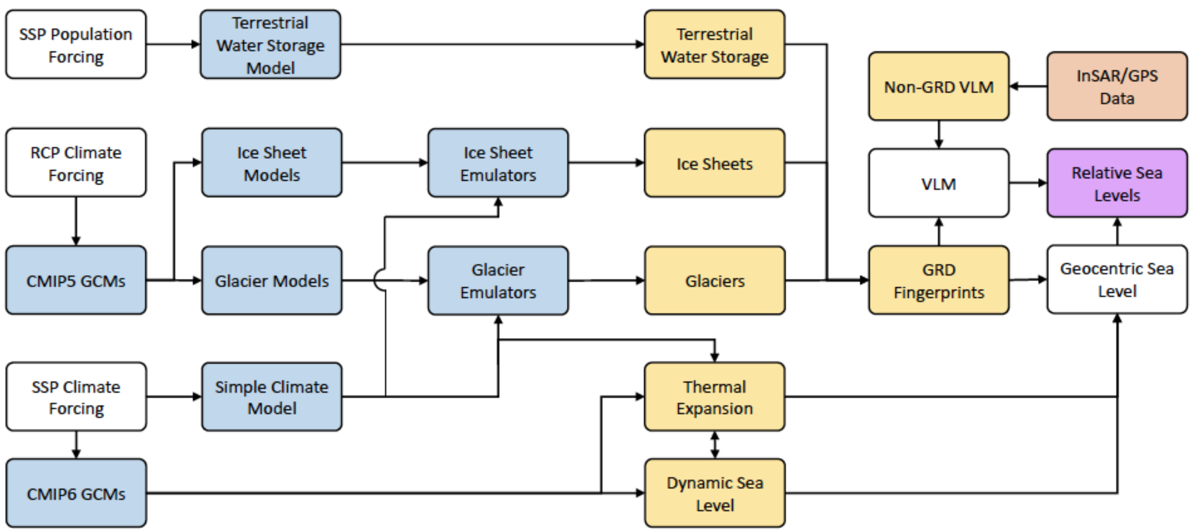


Figure 2. Logical flow of sources of information within the Framework for Assessing Changes to Sea-level (FACTS) to estimate RSL projections (explained in Methods in Supporting Information).

2. Regional Geological and Geographical Context

2.1 Plate tectonic setting and influence on VLM

Oblique convergence between the Pacific and Australian plates at rates of 30 - 40 mm y^{-1} has produced a complex plate boundary with a variety of tectonic regimes operating on a range of temporal and spatial scales that affect the length of New Zealand in different ways (Fig. 1A). In the North Island, tectonics and contemporary deformation are dominated by westward subduction of the Pacific plate along the Hikurangi trough (Nicol et al., 2007; Wallace et al., 2004). Along the Hikurangi margin, block modelling of campaign GNSS data suggests a that the northern Hikurangi margin is dominated by aseismic creep and slow slip, while deep interseismic coupling occurs on the southern Hikurangi margin, to depths of 30 - 40 km (Wallace & Beavan, 2010; Wallace et al., 2004). Plate interface coupling drives long-term regional subsidence of the east and south coasts of the lower North Island at rates up to 8 mm y^{-1}. Episodic, aseismic Slow Slip Events (SSEs) on the subduction zone produces short term reversals (mm to multi-cm) in VLM ranging from weeks to years (Wallace & Beavan, 2010; Wallace et al., 2012). Uplift due to SSEs is difficult to constrain due to limited continuous GNSS (cGNSS) across the Wellington region (Fig. 1A, 1B; see section

2.2), but is estimated to have offset approximately one third of the secular subsidence between 1996-2016 in regions where they occur (Denys et al., 2020). Average long-term (net) VLMs between -2 to -5 mm y^{-1} are estimated for this region (Hamling et al., 2022) (Fig. 3A).

In the northern South Island, 80% of plate motion is taken up along four major strike slip faults through the Marlborough Fault Zone (MFZ, Fig.1A) (Holt & Haines, 1995; Langridge & Berryman, 2005; Van Dissen & Yeats, 1991; Wallace et al., 2007). Further south, 70-75% of the Pacific-Australia relative motion is taken up along the Alpine Fault with the remainder accommodated across the South Island (Wallace et al., 2007). The convergent component of motion has led to the growth of the Southern Alps at rates of between 5-9 mm y^{-1} (Beavan et al., 2010; Beavan et al., 1999; Little et al., 2005; Michailos et al., 2020; Norris & Cooper, 2001; Sutherland et al., 2006).

Along at least half of New Zealand's ~15,000 km coastline from Christchurch clockwise to Hokitika and from Whanganui clockwise to Tauranga (except for Auckland/Waikato segment) estimates of VLM rate from geological archives (spanning the last 125,000 years) are relatively low (<2 mm y^{-1}) and are consistent within error of the GNSS rates (Beavan & Litchfield, 2012; Hamling et al., 2022; Houlié & Stern, 2017; Lamb & Smith, 2013; Pillans, 1986; Ryan et al., 2021). In contrast, along ~40% of the coastline including eastern and southern lower North Island and upper South Island, geodetic data show land surface subsidence has been high this century with rates between 3 to 8 mm y^{-1} (Fig. 3A). However, on longer (millennial) geological timescales these regions have generally been uplifted due to convergence and shortening across the plate boundary and the long-term aggregate effect of large earthquakes (Berryman et al., 2011; Clark et al., 2019; Howell & Clark, 2022). The remaining sections of New Zealand's coastline display complex short-wavelength variations in VLM. For example, high rates of uplift (episodically reaching 10 mm y^{-1}) occur along 30 km zone of coastline in Bay of Plenty, near Matata at the eastern margin of the TVZ rift (Fig. 3B). This rapid uplift is suggested to be associated with a transient earthquake swarm attributed to an off-axis magma body (Hamling et al., 2016; Hamling et al., 2022).

The most significant and damaging earthquake events that have affected New Zealand VLM this century include: (i) September 2010, Mw 7.1 Darfield earthquake, (ii) 22 February 2011, Mw 6.3 Christchurch earthquake, (iii) 13 June 2011, Mw 5.9 Godley Head earthquake, (iv) a sequence of earthquakes in Christchurch on 23 December 2011 (Kaiser et al., 2012), and (v) the 14th November 2016, Mw 7.8 Kaikoura earthquake (Hamling et al., 2017). The latter caused a rapid ~10 mm of subsidence at the Wellington tide-gauge cGNSS followed by a phase of uplift, which appears to have peaked during a series of SSEs on the Hikurangi margin triggered by the earthquake (Wallace et al., 2018). All these events caused rapid shifts in VLM at the Lyttleton tide gauge (Fig.1A). Two strike-slip earthquakes (Cook Strait, Seddon) on the 21st July and 16th of August 2013 respectively, had no apparent effect on the vertical component (Hamling et al., 2014) in tide guage records. Whereas, the next earthquake rupture in Christchurch (Canterbury) could be a long way off as paleoseismological data suggest the penultimate rupture on the Greendale fault (Darfield) occurred between 20 - 30 kyr ago (Hornblow et al., 2014) and that the Christchurch events are a once in 10-kyr occurrence (Mackey & Quigley, 2014).

Southwest New Zealand is also an active seismic region where the Australian plate subducts beneath the Pacific plate along the Puysegur Trench. Whereas the Dunedin tide gauge is 200 – 300 km from the region, it has been affected by recent significant large earthquakes in Fiordland including the George Sound 2007 (Petersen et al., 2009) and Dusky Sound 2009 (Beavan et al., 2010) earthquakes. In addition, the Mw 8.1 Macquarie Island 2004 event (Watson et al., 2010) affected the whole of New Zealand, but largely via horizontal deformation.

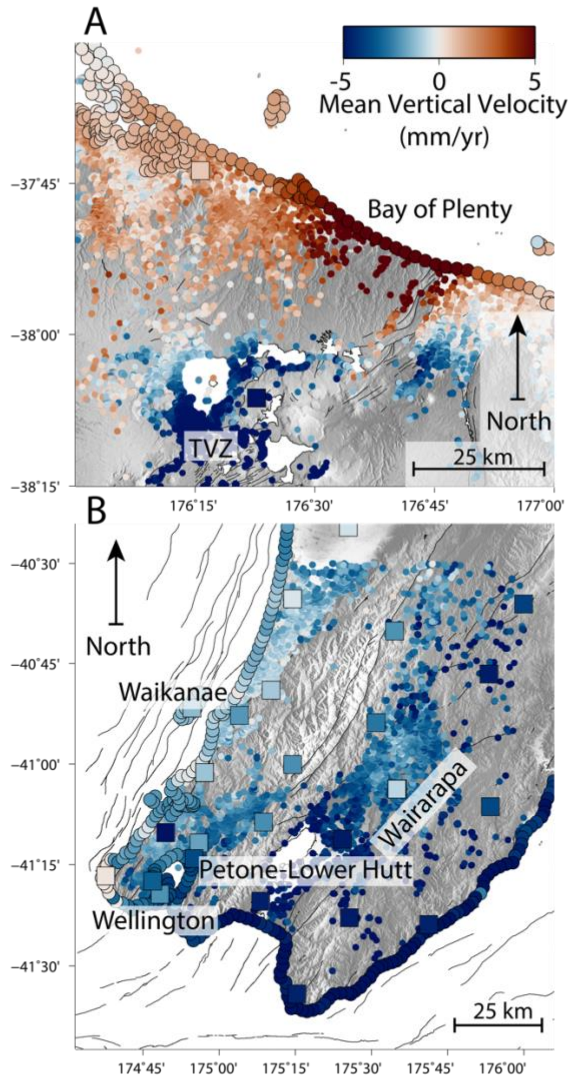


Figure 3. Mean vertical velocity (positive upwards) of the land surface derived from InSAR data averaged for 2 km-spaced sites around the coastline of (A) the Lower North Island showing high rates of subsidence and (B) eastern North Island, central Bay of Plenty showing high rates of uplift (see Fig. 1B). Boxes show the location of GNSS sites used to calibrate InSAR data.

To reduce potential temporal biases introduced by local earthquakes, the period of 2003 and 2011 was selected in this study as it largely preceded many of the Mw>6 earthquakes which have struck New Zealand since late 2009, and is therefore representative of the VLM between the seismic events. The large earthquakes in the Christchurch region in 2010 and 2011 were removed from the

InSAR time series. The inter-seismic rate is considered appropriate for the extrapolation of VLM used in the RSL projections, because over the next 100 years the probability of a high-magnitude earthquake with large local vertical displacement is low due to the historic lengths of the earthquake cycle (Beavan & Litchfield, 2012). Notwithstanding this, seismic hazard risk (Stirling et al., 2012) and the potential for rapid subsidence and/or uplift, while difficult to predict, should always be considered. For example, a major event on the ~600 km long Alpine Fault is likely (75% probability) to occur in the next 50 years (Howarth et al., 2021), but historical fault rupture data suggest little VLM will occur in the South Island. The majority of the southern east coast margin of the North Island is currently experiencing subsidence, largely due to coupling along the plate interface. Model simulations of a rupture of the entire Hikurangi margin shows the intersesimically-coupled zone beneath Wellington would experience up to 2m of subsidence, while the southern Wairarapa coast would experience uplift (Wallace et al., 2014). The spatial distribution of coseismic uplift and subsidence is highly variable and dependent on which fault or faults rupture. While parts of the margin may get a reprieve from the accumulated interseismic subsidence, other areas may have to contend with additional supporting subsidence as a result of any earthquake. In addition, large post-seismic transient deformation may follow a major event temporarily amplifying the local VLM before returning to interseismic rates in as little as 10 years (Hamling et al., 2017; Hussain et al., 2018). Consequently, in some parts of the Christchurch region post-earthquake subsidence rates are significantly higher than the pre-earthquake VLM time series. In view of these various uncertainties surrounding co-seismic VLM events, in particular their long cycles and stochastic unpredictability, secular trends for VLMs used in this paper represent long-term interseismic uplift and subsidence and are appropriate to use for shorter term (decadal) RSL projections.

2.2 Sea-level rise since 1900

Global mean sea level has risen approximately 0.18 m since 1900 and there is robust evidence that GMSL rise has accelerated over the past several decades (Dangendorf et al., 2019; Dangendorf et al., 2017; Frederikse et al., 2020). The rate of GMSL rise has doubled since 1993 (start of the satellite era) to a current global-mean estimate of 3.69 ± 0.48 mm y^{-1} (Nerem et al., 2018). The most likely cause for this acceleration is an increase in the rate of mass loss from Earth’s mountain glaciers and large ice sheets (Bamber et al., 2018; Fox-Kemper et al., 2021; Shepherd et al., 2018; Velicogna et al., 2014).

Sea-level rise data for New Zealand are derived from long-term tide gauges (TG) that are co-located with continuous GNSS at four main ports (Auckland, Wellington, Lyttleton, and Dunedin). These sites provide baseline records (~ 120 years, Figs. 1A) that show an average increase in RSL of 0.21 ± 0.60 m (1.8 ± 0.5 mm y^{-1}) from 1900-2018, with a doubling since 1960 (Bell & Hannah, 2019; Hannah & Bell, 2012). The cause of this doubling remains equivocal due to complications from atmospheric and ocean dynamic influences (e.g., Interdecadal Pacific Oscillation) (Hannah & Bell, 2012). Adjustments for long-term VLM at each TG (see section 4.2) give a best estimate of absolute regional sea-level rise rate for New Zealand of $+1.45 \pm 0.28$ mm y^{-1} for the period from 1891 to 2013, with a trend increase at the Auckland TG of 0.23 ± 0.15 mm y^{-1} since 1990 (Denys et al., 2020).

Whereas the observed century scale increase of ~0.18 m in sea level may seem small and potentially inconsequential, this historical rise in GMSL has increased the frequency of coastal flooding events around the world (Lin et al., 2016). Importantly, relatively modest (0.30-0.45 m) increases in sea level over the coming decades will dramatically increase the frequency of inundation for many sections of the New Zealand coastline. For example, coastal inundation that today occurs at the 1% annual exceedance probability, will become annual events in several of New Zealand's largest cities (Paulik et al., 2020).

2.2 Primary sources of uncertainty in global mean sea-level projections

Up to 2050, GMSL projections for the range of SSPs exhibit little scenario dependence. Beyond 2050, the scenarios increasingly diverge. The AR6 projections show that processes known with at least *medium confidence*, GMSL will rise between 0.33 m and 1.02 m (17th - 83rd percentiles) above a baseline period (1995 to 2014) by 2100 for all scenarios between SSP1-2.6 and SSP5-8.5 (Fig. 4). However, the assessment also notes "that there is a substantial likelihood that sea level rise will be outside the likely range for *medium confidence* processes, and that Supporting processes, for which there is presently *low confidence*, may also contribute to (the likely range) of sea level change". Consequently, the AR6 projections also include *low confidence* projections intended to reflect contributions from these additional processes under high-emissions scenarios. In these projections GMSL for SSP5-8.5 will rise between 0.6 - 1.6 m (17th - 83rd percentile range) with the 5th - 95th percentile range extending to 0.5 - 2.3 m, leading the IPCC's Summary for Policymakers to state, that "2 m GMSL rise by 2100 cannot be ruled out".

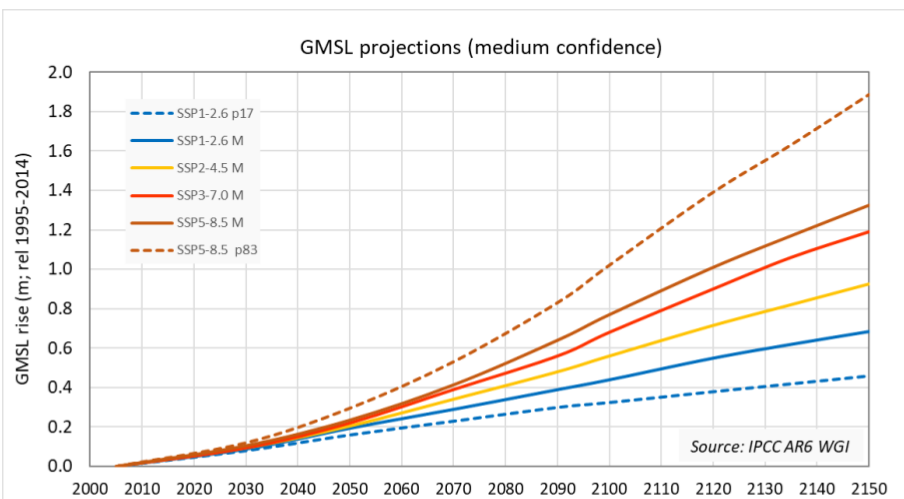


Figure 4. Median and *likely* (17th-83rd percentile) range for GMSL estimated for processes known with *medium confidence* to 2150: SSP1-2.6 (blue), SSP2-4.5 (yellow), SSP3-7.0 (red); SSP5-8.5 (magenta). Baseline reference period follows AR6 and is the mean of 1995 - 2014.

The increasing spread in the likely range of GMSL projections beyond 2050 is due in part to (a) uncertainty related to future emissions scenarios and (b) deep uncertainty due to a lack of scientific understanding of the key rate-determining processes that should be represented in dynamic ice sheet (ISM) and earth system (ESM) models and their couplings. For example, AR6 *medium* *confidence* projections utilise outputs from a standardised ensemble of ISMs from the Ice Sheet Model Intercomparison Project Experiment 6 (ISMIP6) (Edwards et al., 2021; Goelzer et al., 2020; Nowicki et al., 2016; Seroussi et al., 2020) and the Linear Response Model Intercomparison Project (LARMIP2) (Levermann et al., 2020). In contrast, the IPCC AR6 characterization of *low confidence* processes use a smaller set of studies that adopt more heterodox approaches and incorporate a single ISM output that represents Marine Ice Cliff Instability (MICI) (DeConto et al., 2021) (referred to in this paper as DP21) as well as estimates from a structured expert judgement (SEJ) (J. L. Bamber & Aspinall, 2013; Jonathan L. Bamber et al., 2019).

GMSL beyond 2100 continues to rise under all SSPs. Projections to 2300 based on conservative extensions of *medium confidence* ISM output leads to a GMSL rise of 0.8m to 2.0 m under SSP1-2.6, and 1.9 to 4.1 m under SSP5-8.5 (IPCC AR6). Using Antarctic results from a model with MICI (DP21; *low confidence*) and using global warming levels equivalent to SSP1-2.6 and SSP5-8.5, leads to GMSL ranges of 1.40 m to 2.10 m and 9.50 m to 15.90 m, respectively. A further unstable process, known as Marine Ice Sheet Instability (MISI) is considered to cause self-sustaining collapse of marine-based sectors of Antarctica's ice sheet once they begin retreating into deep bedrock basins below sea-level. Models incorporating MISI imply the threshold for irreversible loss is crossed at global warming above 1.5-2°C, resulting in long-term commitment to millennial-duration GMSL rise (Clark et al., 2016; DeConto et al., 2021; Golledge et al., 2015; Van Breedam et al., 2020). This tipping point may be avoided if global warming is stabilised in line with the Paris Climate Agreement (SSP1-2.6) (DeConto et al., 2021; Golledge et al., 2015).

4 Results: RSL Projections for New Zealand (2854 words)

4.1 Large-scale patterns of sea-level change around New Zealand to 2150

Our results provide the first continuous estimates of the RSL around the entire New Zealand coastline (Fig. 1) for processes known with at least *medium confidence* following AR6 for emission pathways SSP1-2.6, SSP2-4.5, SSP3-7.0 SSP5-8.5 to 2150 (Fig. 4). The estimated rates and magnitudes show some interesting variations due to VLM in different parts of the country (section 2.1). In Table S1 (Supporting Information) we provide examples of sites (Fig. 1A) that are representative of the 5 highest subsidence and 5 highest uplift regions around the New Zealand coastline to demonstrate the influence of VLM on LSL projections. The highest rate and magnitude of RSL rise is along the eastern North Island, southern Wairarapa coast at Tora - Oroi Stream (Fig. 1B). Here, the likely range (17th to 83rd percentile) of RSL for all scenarios by 2150 is 1.54 m to 3.24 m. The near-future likely range of RSL rise by 2050 is 0.49 m to 0.72 m. In this region interseismic tectonic subsidence associated with subduction coupling (section 2.1) effectively doubles the decadal rate and magnitude of RSL compared with GMSL change. As noted in sections 2.1 & Methods (in Supporting Information), slow slip events and earthquakes on the Hikurangi margin may reverse up to one third of the tectonic subsidence experienced by lower North Island over the next century, and this is not accounted for in the RSL projections. Other regions where tectonic subsidence significantly increases RSL rise were discussed in section 2.1 and examples include northwest Nelson (eastern Tasman Bay), Kaikoura Peninsula (east coast South Island), eastern Marlborough (northeast South Island) and the city of Napier (eastern. North Island) (Fig.1B).

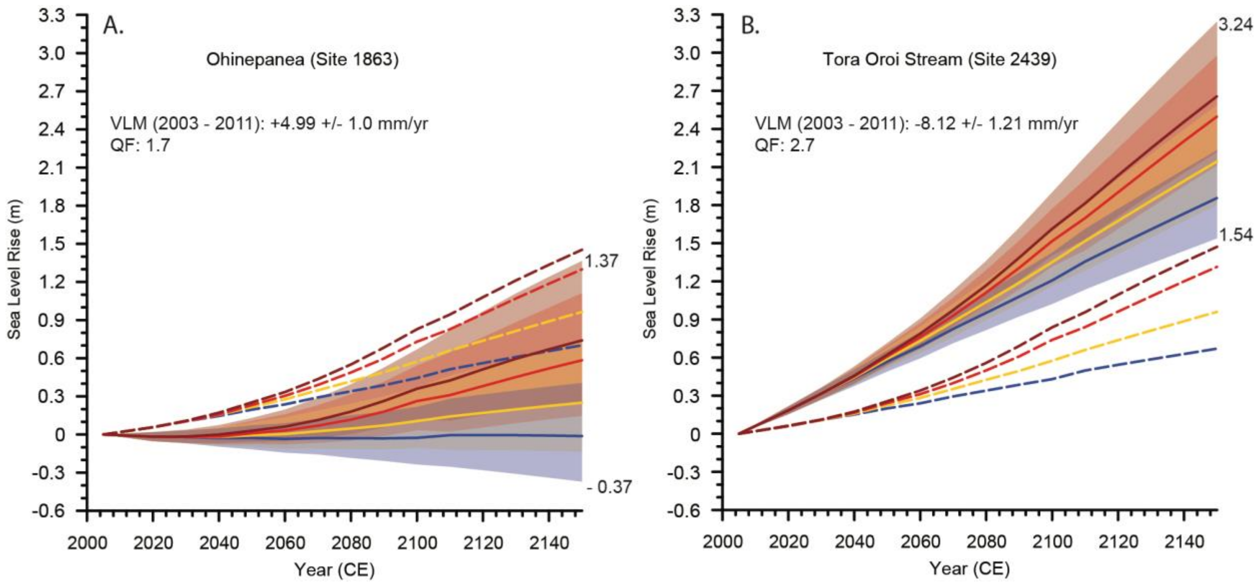


Figure 5. Projected RSL change from 2005 to 2150 at (A) Pikowai - Ohinepanea (Site 1863), the highest rate of land uplift and (B) Wairarapa Tora - Oroi Stream (Site 2439) the highest rate of land subsidence on the New Zealand coastline showing the influence of VLM for the likely range (17th-83rd percentile) for SSP1-2.6 (blue), SSP2-4.5 (yellow), SSP3-7.0 (red) SSP5-8.5 (magenta). See Fig. 1A for site locations. QF = Quality Factor (see section 3.4). Baseline reference period follows AR6 and is the mean of 1995-2014). QF = quality factor (see Supporting Information).

In contrast the lowest rate of RSL rise is along the eastern North Island, Bay of Plenty coastline near the small settlement of Ohinepanea (Fig. 5). Here, the likely range (17th to 83rd percentile) of RSL for all scenarios by 2150 is -0.37 m to 1.37 m. The near-future likely range of RSL rise by 2050 is -0.12 m to 0.13 m. In this region localised tectonic uplift associated with magmatic activity (section 2.1) largely offsets the rate and magnitude of GMSL rise over the next 50 years, and halves it over the next 100 years. Other regions where tectonic uplift significantly decreases RSL rise include lower west coast of the South Island (Fiordland), western Coromandel (North Island), and East Cape of the North Island (Fig.1A). While over longer timeframes (e.g., out to 2300) and for higher emissions scenarios, VLMs have comparatively less influence on RSL rise compared to the growing land ice contribution, they are still a significant contributor to the amplitude and rate of RSL change to 2150.

4.2 Comparing long-term tide gauge records with space-borne geodetic observations and RSL projections.

Historical tide gauge (TG) records are routinely used to determine RSL over the past century and offer a mechanism to compare with our projections where time series overlap. Here we plot TG records at Auckland (Queens Wharf), Tauranga (Moturiki), Wellington (Queens Wharf), Christchurch (Lyttleton) and Dunedin with RSL projections to 2150 (Fig. 6A). Recent analysis of the TG records used cGNSS data and inferences regarding seismic activity to estimate average VLM rates for each of the TG over the past century (Denys et al., 2020). This analysis suggests that most of the TGs have subsided at lower rates over the past century than indicated by our VLM analysis for the period between 2003 and 2011. These differences contribute to the fact that historical sea-level trends determined from TG data are less than indicated by our probabilistic projections, a feature that is most obvious at Wellington. However, observed TG trends and our sea level projections are similar over more recent periods (e.g., 1980 to 2020) (Fig. 6B). This observation suggests either our projections overestimate the long term VLM contribution to relative sea level (at century time scales), that subsidence rates have increased over the past several decades, that the TG records have been incorrectly adjusted for local subsidence, that there may be processing and trend analysis errors, incorrect assumptions in local and global reference frame calibration, or some combination of all these factors. Future studies will provide new centennial-scale salt marsh records (Garrett et al., 2022), and together with the incorporation of recent and future observations, will lengthen time-series, reduce uncertainties, and ultimately help reconcile past, present a future VLM datasets.

Here we explore the differences between long-term and short-term TG VLM estimates in more detail. TG data from Queens Wharf in Auckland indicate an average rise in RSL of 1.57 ± 0.15 mm y^{-1} between 1900 and 2015 with a trend increase of 0.23 ± 0.15 mm y^{-1} since 1990 (Denys et al., 2020). Denys et al., (2020) calculated an average vertical velocity at the Auckland TG of -0.16 mm y^{-1} over the past century, significantly lower than the absolute vertical velocity of -0.62 ± 0.1 mm y^{-1} they measured at the co-located cGNSS unit for the interval from 2000 to 2015. The difference in short-term vs long-term rate is due to adjustments made for Glacial Isostatic Adjustment and Solid Earth Deformation (see section 3). The absolute vertical velocity determined for cGNSS stations (v_{GNSS}) by Denys et al., (2020) are relative to the ITFR08 reference frame (Collilieux & Wöppelmann, 2011; Wöppelmann et al., 2007). Here we use the updated reference frame ITRF14 (Altamimi et al., 2016) and estimate an absolute vertical velocity of -1.09 ± 0.12 mm y^{-1} at the Auckland TG for the period from 2003 to 2011 and -1.21 ± 0.03 mm y^{-1} for the period from 2001 to 2022 (Fig. 8). Hamling et al., 2022 used ITRF14 calibrated cGNSS velocities and InSAR data to estimate a VLM rate of -1.28 ± 0.07 mm y^{-1} for the region within a ~0.7 km sampling radius around the Auckland TG, which is consistent with our TG v_{GNSS} data. Whereas these velocity data indicate that reference frame choice can make a difference, they all show that the Auckland TG has been subsiding at significantly higher rates for the past 21 years than inferred for the previous century.

Our estimates of VLM at locations away from the TG and around Waitemata harbour are highly variable and have a significant influence on relative sea level projections. For example, Viaduct Basin (Port of Auckland, Site 1231; Supporting Information Table S2) is a highly developed commercial and residential area located ~ 1 km from the TG with a VLM estimate of -2.9 ± 1.1 mm y^{-1}. RSL projections for this location indicate that sea level will rise between 0.81 and 2.50 m by 2150 for the likely range of all scenarios. In contrast, our VLM estimate for the residential area at the eastern end of St Heliers Bay (Site 1249) located ~10 km from the TG, is -0.37 ± 1.5 mm y^{-1}. Assuming the VLM rate remains constant, RSL rise at this location will be ~30 to 40 cm less than at Viaduct Basin, increasing between 0.40 and 2.16 m by 2150 for the likely range of all scenarios. In general our VLM estimates suggest the Auckland region has been subsiding between ~1 and 3 mm y^{-1} over the past two decades, a range that is supported by other InSAR studies (Wu et al., 2022). The cause for this apparent relatively recent increase in subsidence and its spatial variability requires further investigation but contributing processes may include ground water extraction (Wu et al., 2022) and the increasing influence of urbanisation (Parsons, 2021).

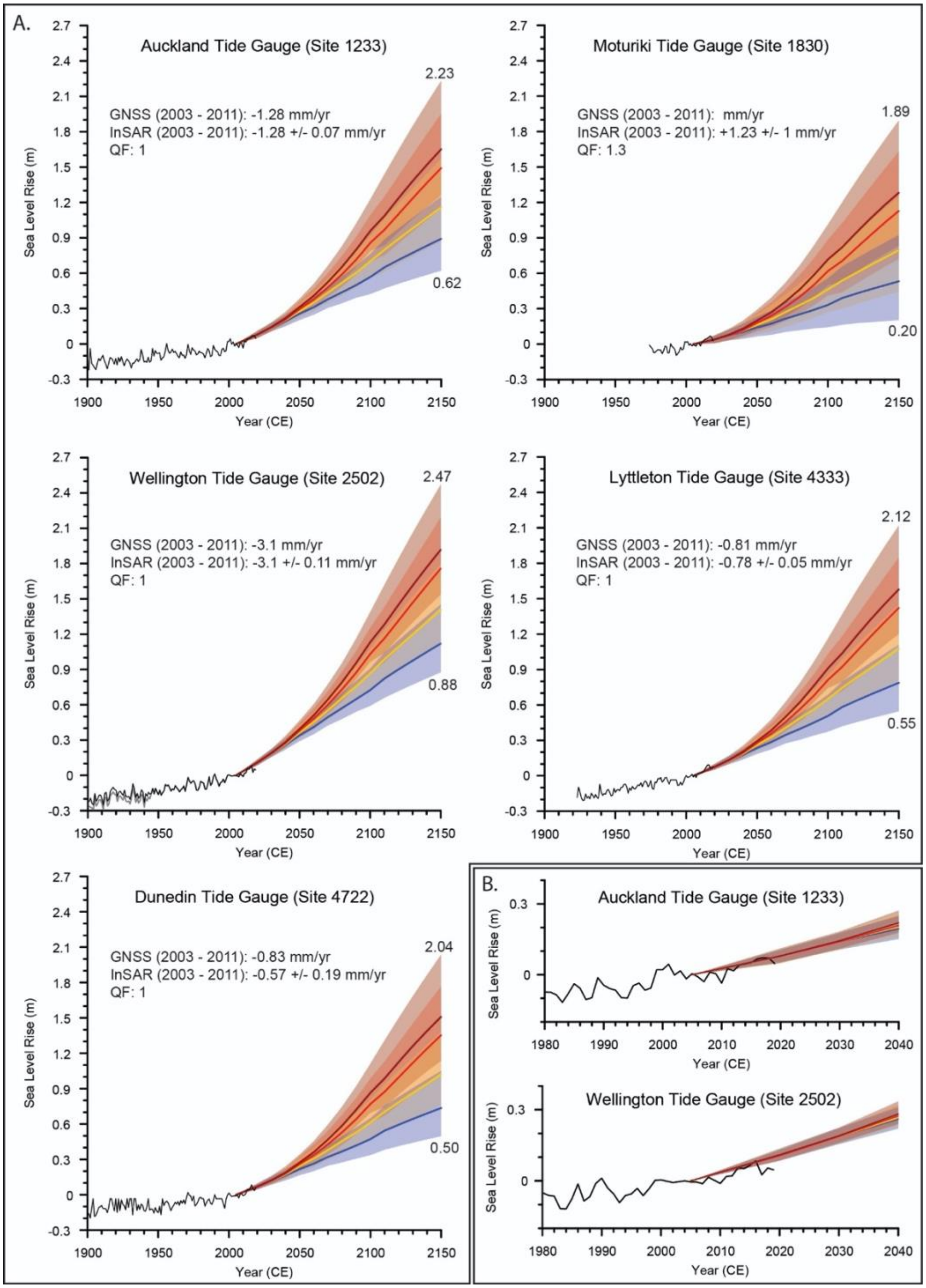


Figure 6. A. Historical records from 1900 to 2020 and RSL projections from 2005 to 2150 for processes known with medium confidence for SSP1-2.6 (blue), SSP2-4.5 (yellow), SSP3-7.0 (red), SSP5-8.5 (magenta) showing median and likely range (17th-83rd percentile) for tide gauges at Auckland, Tauranga (Moturiki), Wellington, Christchurch (Lyttleton), and Dunedin. Baseline reference period follows AR6 and is the mean of 1995-2014). QF = quality factor (see Supporting Information). B. Historical records from 1980 to 2020 and RSL projections from 2005 to 2040 for processes known with medium confidence for SSP1-2.6, SSP2-4.5, SSP3-7.0 SSP5-8.5 showing median and likely range (17th-83rd percentile) for tide gauges at Auckland and Wellington.

The inferred linear rate of RSL at the Tauranga (Moturiki) TG is 1.9 ± 0.2 mm y^{-1} (Hannah & Bell, 2012). The nearest cGNSS station is located ~ 13 km east and inland of the TG and records a vertical velocity of +0.01 ± 0.21 mm y^{-1} for the interseismic period 2003 to 2011 and -0.06 ± 0.07 mm y^{-1} for the interval from 2003 to 2022 (Fig. 7). Here we estimate an interseismic VLM rate of +1.22 ± 1 mm y^{-1} for the region within a ~0.6 km sampling radius around Site 1830 proximal to the TG. While this VLM estimate is slightly higher than the v_{GNSS} data for the same period, the estimates are consistent within error and show the region is slowly rising. Therefore, our sea level projections indicate that the region will experience a RSL rise between 0.20 and 1.90 m by 2150 for the likely range of all scenarios, values that are lower than the global mean (Fig. 6).

Reconciling long-term TG data with short-term VLM estimates in Wellington is more challenging than for other regions of New Zealand due to the local influence of tectonic events including large plate boundary ruptures and slow slip earthquakes (SSE) along the Hikurangi subduction zone (K. Clark et al., 2019; Pizer et al., 2021; Wallace & Beavan, 2010). TG data from Queens Wharf in Wellington indicate an average rise in RSL of 2.18 ± 0.17 mm y^{-1} between 1900 and 2015 (Denys et al., 2020). Denys et al., 2020 calculated an average vertical velocity at the Wellington (Queens Wharf) TG of -0.62 mm y^{-1} over the past century, significantly lower than the absolute vertical velocity of -2.84 ± 0.18 mm y^{-1} they measured for the interval from 2000 to 2015 at the cGNSS located on the national museum ~500m from the TG. The difference in their observed short-term vs calculated long-term average VLM rate is due to adjustments made for Glacial Isostatic Adjustment (v_{GIA}), Solid Earth Deformation (v_{SED}), and estimates of local uplift due to historical regional earthquake events and SSE's ($v_{\mathrm{LOCAL}} + v_{\mathrm{EQ}}$). Absolute vertical velocities at the Wellington tide gauge cGNSS calculated using ITRF14 are -2.41 ± 0.25 mm y^{-1} for the period from 2003 to 2011 and -2.94 ± 0.27 mm y^{-1} for the period from 2000 to November 2016, which includes the Christchurch earthquakes (Fig. 7) but excludes the effect of the Mw 6.3 Kaikoura earthquake (Hamling et al., 2017). Significant uplift during the Kaikoura event decreases the multi-decadal vertical velocity rate at the Wellington TG cGNSS to -1.66 ± 0.64 mm y^{-1} (Fig. 7). Data collected at the Wellington TG cGNSS following the Kaikoura event and associated afterslip and triggered SSE's (Wallace et al., 2018) show that absolute vertical velocity from 2018 to 2022 is +0.00 ± 0.2 mm y^{-1}.

Hamling et al. (2022) used ITRF14 calibrated cGNSS velocities and InSAR data to estimate an interseismic VLM rate of -3.09 ± 0.11 mm y^{-1} within a ~0.7 km sampling radius around the Wellington TG, which is slightly higher than the TG v_{GNSS} data for the same period. This rate is also approximately double the Kaikoura earthquake-adjusted rate for the period from and while subsidence is still significant over this longer time interval, our RSL projections across the Wellington region represent maximum estimates. VLM measurements at the Christchurch (Lyttleton) TG cGNSS further emphasise the effect of the earthquakes. Average cGNSS velocity at the Lyttelton TG from 2003 to 2011 is -0.92 ± 0.20 mm y^{-1} and +5.7 ± 1.8 mm y^{-1} for the period from 1999 to 2022 due to significant uplift (~10 cm) during the 22 February 2011, Mw 6.3 Christchurch earthquake (Fig. 7). In contrast to uplift at the Wellington TG, the Mw 7.8 Kaikoura earthquake caused co-seismic subsidence (~2 cm) at Lyttleton (Fig. 7). These data illustrate the challenge associated with estimating VLM for RSL projections along highly dynamic coastlines like those that characterise New Zealand (see also King et al., 2020). The potential for time-variability of vertical deformation rates in New Zealand due to coseismic (and post-seismic) deformation will be considered in a future study. Regardless, we propose that cGNSS and InSAR data offer a more accurate and robust assessment of regional VLM for local RSL projections over the near-term (to 2100), than do longer term VLMs extracted from TG records, and should be used for coastal planning and decisions over decadal time scales.

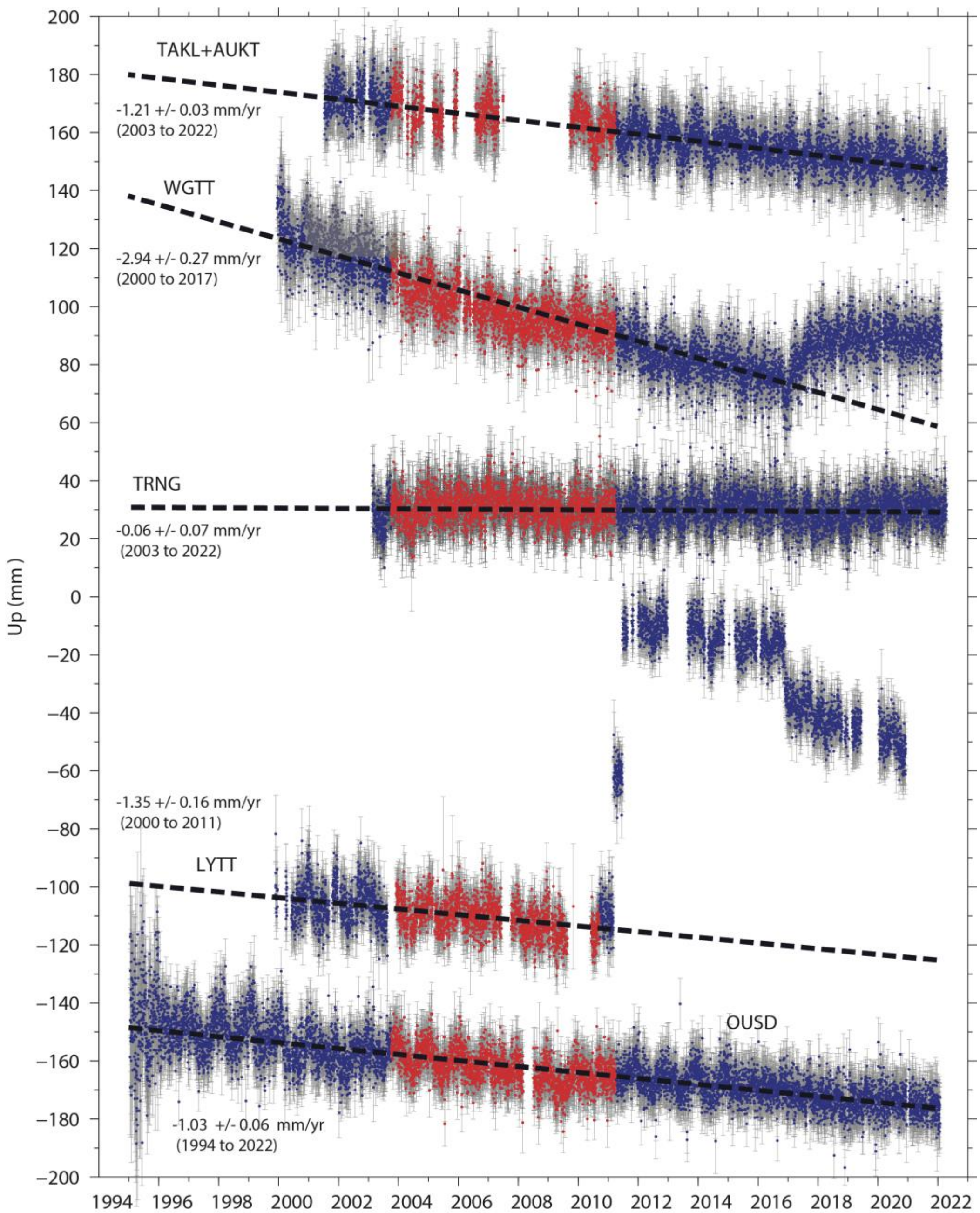


Figure 7. Time series and interseismic rates of VLM for cGNSS stations located near five New Zealand tide gauges (TAKL + AUKT – Auckland TG, WGTT – Wellington TG, TRNG – closest to Moturiki, LYTT – Christchurch/Lyttleton TG, OUSD – Dunedin TG). Red = interseismic InSAR period 2003-2011. Black dashed line = interseismic trend.

4.3 An example of regional-scale variation in RSL projections.

High resolution spatial coverage offered by our InSAR and GNSS analysis reveals that vertical land movement can vary significantly across short distances in many coastal regions. These short wavelength variations can be attributed to a range of processes including local tectonics, postseismic relaxation, sediment compaction, and anthropogenic factors such as groundwater extraction. The effects of the interplay between these processes are clearly illustrated along the Hawkes Bay coastline between Cape Kidnappers and the region around Napier (Fig. 8). Here rates of VLM vary by ~5 mm across 22 km along the coast from Te Awanga (-0.2 mm y^{-1}) to Ahuriri (-4.73 mm y^{-1}). This spatial pattern is nearly the inverse of the uplift and subsidence that occurred in the 1931 Mw7.4 Hawke's Bay earthquake where uplift of ~1.5 m occurred at Ahuriri and subsidence of ~0.5 m occured near Clive (Hull, 1990). The correspondence of these vertical deformation patterns could imply the coastline is still responding to the sudden coseismic changes of 1931 through postseismic relaxation, however given the magnitude of the 1931 earthqauke and the depth to mantle, other processes such as groundwater removal and compact seem more likely. Compounding this pattern may be ongoing compaction of the Holocene fluvial and estuarine sediments that infill the former Ahuriri Lagoon, and the pre-1931 lagoon and swamp areas that underlie much of the suburban areas of modern Napier. Ongoing groundwater extraction from aquifers underlying the Heretaunga Plains could also be amplifying the subsidence. The near stable VLM rates near Cape Kidnappers may be due to a less-compressible substrate (fluvial gravel-dominated rather than the silt and peat layers that underlie Ahuriri Lagoon), distance from areas of more intense groundwater extraction, and localised uplift on on reverse faults that lie just offshore Cape Kidnappers block (Barnes et al., 2010).

The pattern of differential vertical deformation across the Cape Kidnappers to Ahuriri transect also mirrors longer term tectonic signals. Ahuriri Lagoon has a geological record of Holocene subsidence with up to 7 earthquakes in the past 7300 years creating 8-10 m of net subsidence (Hayward et al., 2015; Hayward et al., 2016). Uplift in the 1931 earthquake was an anomaly within the longer term context. In contrast the Clive to Waimarama coast, including Cape Kidnappers, has a Holocene history of earthquakes that have caused uplift (Hull, 1987) and ~125ka Pleistocene marine terraces lie at up to 200 m elevation.

These variations in VLM have a significant effect on sea level projections along the relatively short distance across the Hawkes Bay coast. For example, the likely range (17th to 83rd percentile) of RSL at Te Awanga (Site 2242, Fig. 8) for SSP2-2.6 by 2150 is 0.39 m to 1.13 m, while at Ahuriri (Site 2263, Fig. 8) the likely range under the same emissions scenario is 1.05 to 1.76 m. This is a 100% increase or doubling of the median value (0.72 m to1.38 m) due to VLM along. This variability highlights that use of a single set of relative sea level projections for coastal planning in New Zealand is not appropriate, even at a regional scale. These data also suggest that New Zealand's TG records cannot accurately capture regional variations in relative sea level.

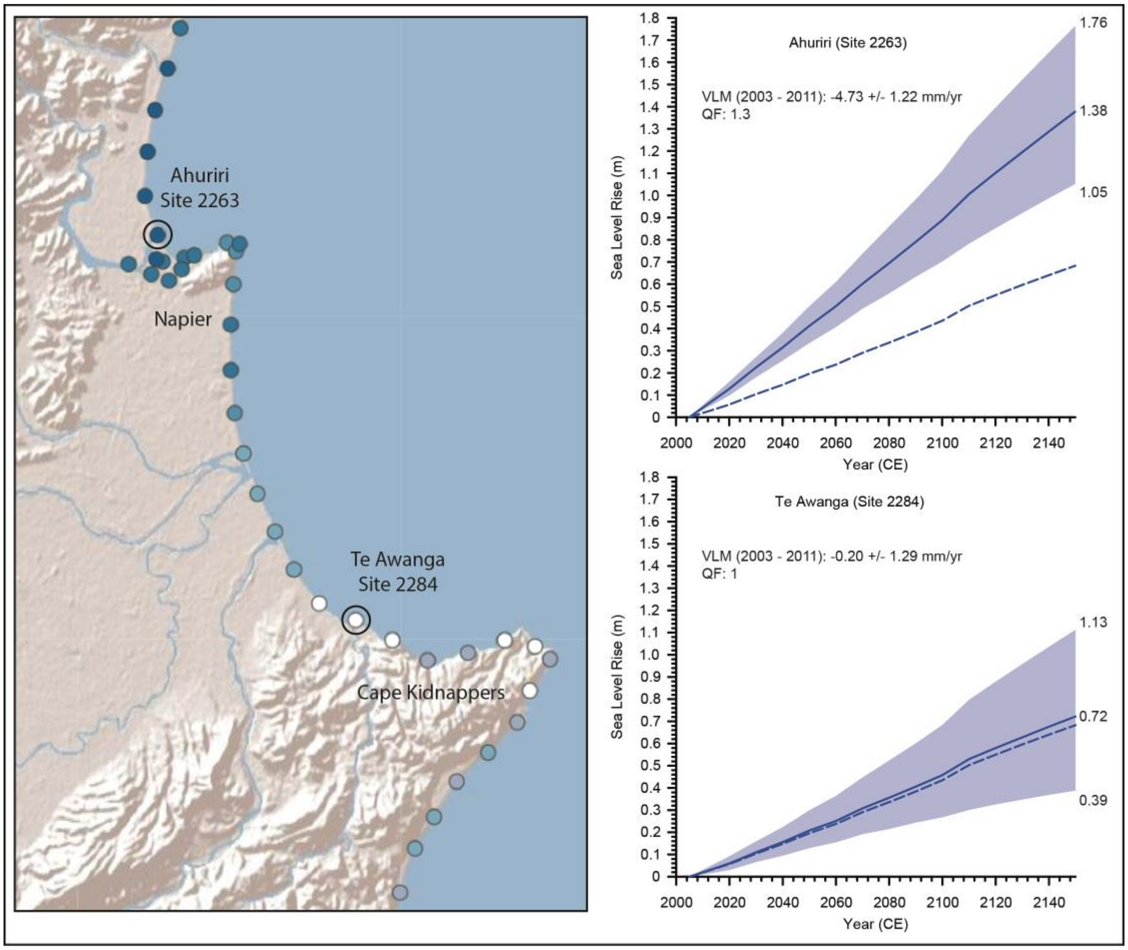


Figure 8. RSL projections (median 13th-87th percentile; medium confidence) to 2150 for (A) Napier Airport - Ahuriri and (B) Haumoana - Te Awanga showing the dramatic variability in VLM influence on the Hawkes Bay coastline for SSP1-2.6. Baseline reference period follows AR6 and is the mean of 1995-2014. QF = quality factor (see Supporting Information).

4.4 Low confidence RSL projections & long-term committment to sea-level rise.

In order to explore the potential influence of low confidence processes, which may lead to rapid, non-linear and self-sustaining collapse of large sectors of the Antarctic ice sheet grounded on bedrock below sea-level, we have plotted *low confidence* (likely 17th-83rd percentile) projections for emission pathways SSP1-2.6 and SSP5-8.5 to 2300 for our highest subsidence and highest uplift sites (Fig. 9). These low confidence processes are currently only incorporated into a single ice sheet model as discussed in sections 2.2 and 3.2, but when this model is incorporated into probabilistic sea-level projections, they provide a plausible upper bound for extreme sea-level rise, which cannot be ruled out.

At the highest subsidence site in the southern Wairarapa coast at Oroi Stream (Figs. 1A, 9; the upper bound (83rd percentile) of RSL rise by 2300 for SSP1-2.6 and SSP5-8.5 is 5.52 m and 17.61 m, respectively. At the highest uplift site on eastern Bay of Plenty coastline near Ohinepanea (Figs. 1A, 9) the upper bound (83rd percentile) of RSL by 2300 for SSP1-2.6 and SSP5-8.5, is 1.81 m and 14.45 m, respectively. Whereas VLMs significantly amplify or ameliorate RSL rise for the SSP1-2.6 emissions scenario, VLMs are overwhelmed by Antarctic ice sheet loss for higher emissions scenarios by 2300. This is especially the case for SSP5-8.5. We also note that extrapolation of VLMs out to 2300, which are based on interseismic rates, for some parts of the New Zealand coastline will begin to overlap with an increased likelihood of a sesimic event that may reverse the sign and dramaticaaly increase the instantaneous rate of VLM.

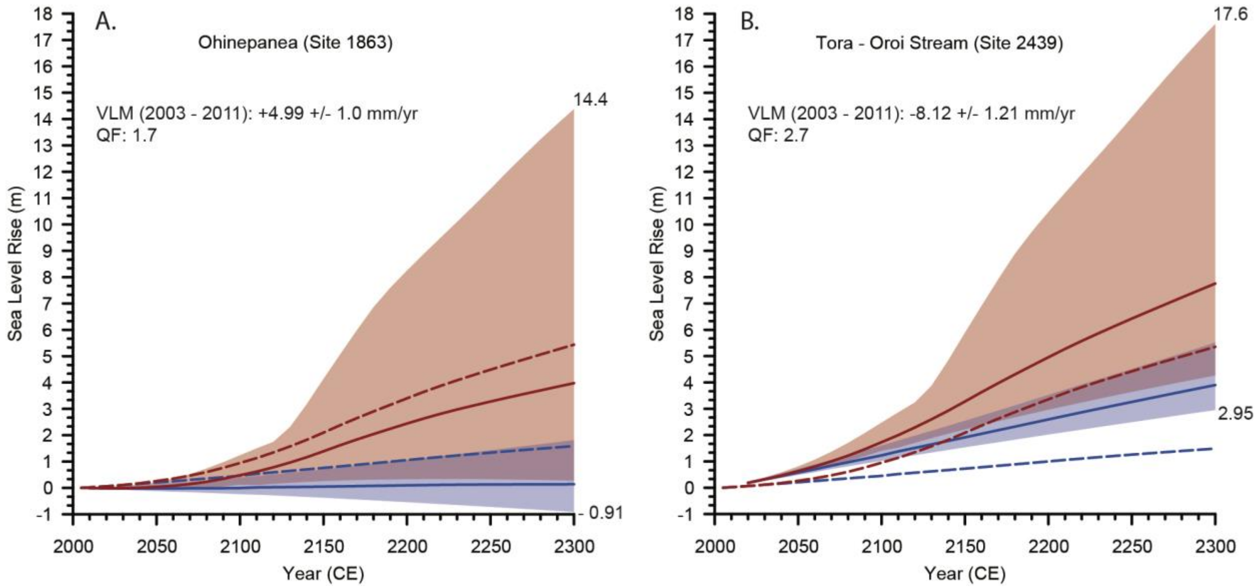


Figure 10. RSL projections (median 17th-83rd percentile; *low confidence*) to 2150 for (A) Tora - Orio Stream, Wairarapa coast and (B) Ohinepanea - Pikowai, Bay of Plenty Coast, showing the influence of VLM for SSP1-2.6 and SSP5-8.5. Baseline reference period follows AR6 and is the mean of 1995-2014. QF = quality factor (see Supporting Information). Dashed lines = no VLM included in projection.

Our results reflect the influence of a tipping point affecting the Antarctic ice sheet, that may be avoided by stabilisation of global warming in line with the Paris Climate Agreement (SSP1-2.6) (DeConto et al., 2021; Golledge et al., 2015). This point appears to be crossed when the majority of Antarctica's stabilising apron of ice shelves is lost allowing unstable and irreversible processes such as MICI and MISI to dominate ongoing ice-mass loss. The potential of this threshold creates deep uncertainty for GMSL estimates beyond 2100 and the commitment to inter-generational sea-level rise.

5. Implications of subsidence for coastal risk assessments and planning

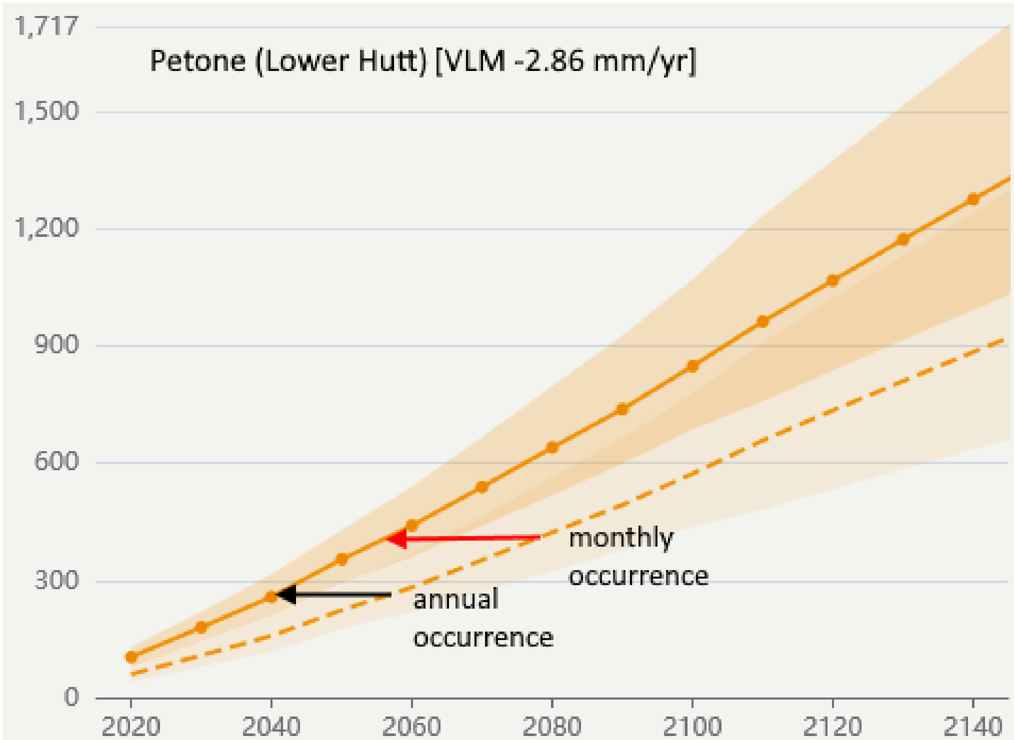
For regions where land subsidence is occurring at rates >2mm yr^{-1} (large parts of New Zealand's coastline), VLM makes a significant contribution to RSL projections for all scenarios out to 2150, bringing forward planning decisions. Beyond 2150 the VLMs become increasingly uncertain, and for higher emissions scenarios, the land ice contribution to global sea-level starts to dominate. Here we discuss the planning implications of our RSL projections, where timing of threshold exceedance can be brought forward by decades in subsiding regions.

5.1 Case study 1. Implications for decision-making and planning for more frequent coastal flooding

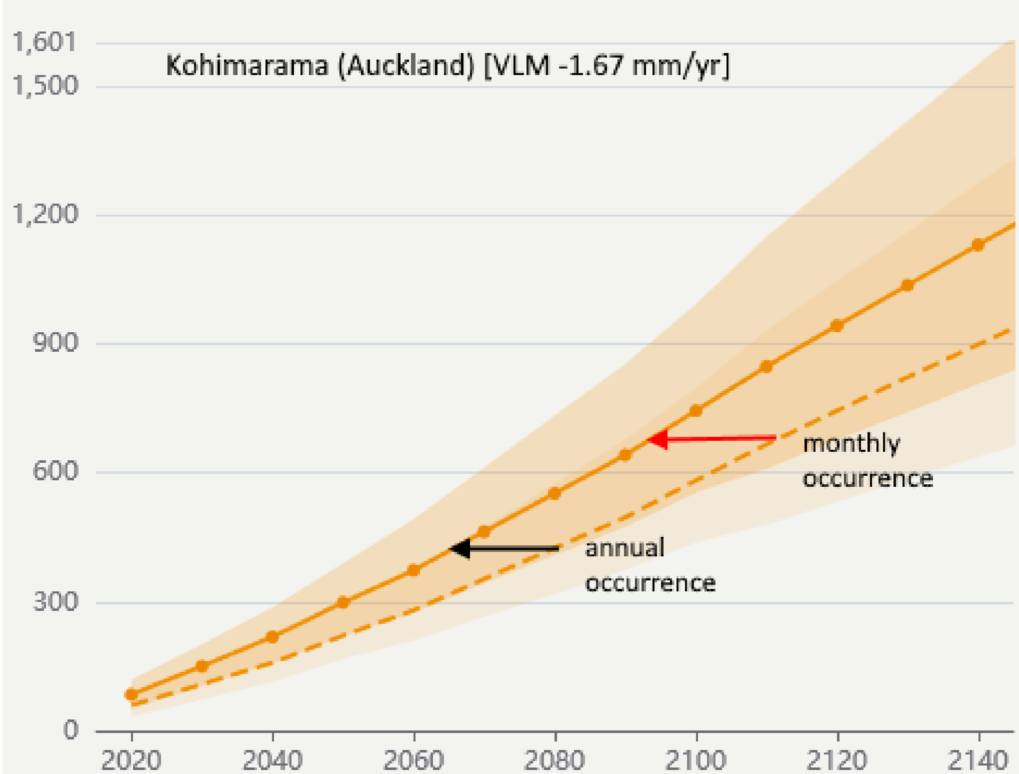
The rise in mean sea level of ~0.2 m since 1900 around New Zealand has driven an increase in nuisance, chronic and extreme coastal flooding. There is very high confidence that projected sea-level rise will cause even more frequent coastal flooding in New Zealand before mid-century (Lawrence et al., 2022), which leads to higher cumulative risks over time (Paulik et al., 2020). Improved decision-relevant information can be communicated by outlining how future changes in the frequency of rare coastal flood levels or a specific flood event of the recent past will transpire from the ongoing rise in RSL, e.g., 1% annual exceedance probability (AEP) or a centennial event on average (Rasmussen et al., 2022; Stephens et al., 2018). Tabulated changes in occurrence of an equivalent magnitude 1% AEP event for the recent past have been produced for increments of RSL for the four main New Zealand ports (Parliamentary Commissioner for the Environment, 2015). The analysis shows that previously rare events will occur on an annual basis (on average) with only modest increases in RSL (0.30–0.45 m). This shift in frequency will occur earlier in areas that have small tide ranges as New Zealand coastal flooding is strongly influenced by tidal range (vs. storm-surge dominated) (Stephens et al., 2018).

Figure 11 shows the impact that VLM has on planning, design and decision-making timelines under SSP2–4.5 RSL projections near three of New Zealand's main ports. These results clearly show that subsidence rates shift adaptation planning timeframes forward. Petone (Lower Hutt) (Fig. 11; top panel) will experience the historical 1% AEP coastal flood occurring every year when RSL rise reaches 0.27 m. A relatively high rate of subsidence rate of –2.86 mm y^{-1} at the Petone means this flood frequency change to annually will occur 17 years earlier than it would without subsidence. A change to a higher frequency of once a month, happens at this site when sea level rises by 0.42 m, which occurs 22 years earlier.. Sites in Kohimarama-Auckland (Fig. 11; mid-panel) and New Brighton-Christchurch (Fig. 11; bottom panel) have lower subsidence rates than Petone, which means the onset of historic rare coastal floods becoming annual and monthly events occur later than in Petone, but sooner than will occur without considering VLM. At New Brighton, with a modest subsidence rate of -0.77 mm.y^{-1}, the change to an annual occurrence (on average) of a past 1% AEP flood is brought forward by only 5 years (9 years to reach a monthly occurrence threshold). However, we note that GNSS measurements at New Brighton show post-earthquake subsidence of ~8 mm y^{-1} for the period 2014-2022 and it is uncertain when or if this suburb will return to its pre-seismic subsidence rate. The New Brighton example highlights the challenge associated with projecting sea level along highly dynamic coastal margins at plate boundaries. Applying an interseismic VLM at New Brighton likely underestimates relative sea-level rise in the near term and may misidentify the time at which flood frequency thresholds will be crossed.

Importantly, subsidence driven forward shifts in the date at which flood-frequency thresholds are reached are more pronounced for SSP1–2.6 (not shown). Under this lower emissions scenario, the emergence of the annual flood occurrences is brought forward 25, 23 and 9 years respectively for the three urban locations.



Petone (Lower Hutt) [VLM -2.86 mm/yr]
1,717
1,500
1,200
900
600
300
0
2020
2040
2060
2080
2100
2120
2140
monthly occurrence
annual occurrence



Kohimarama (Auckland) [VLM -1.67 mm/yr]
1,601
1,500
1,200
900
600
300
0
2020
2040
2060
2080
2100
2120
2140
monthly occurrence
annual occurrence

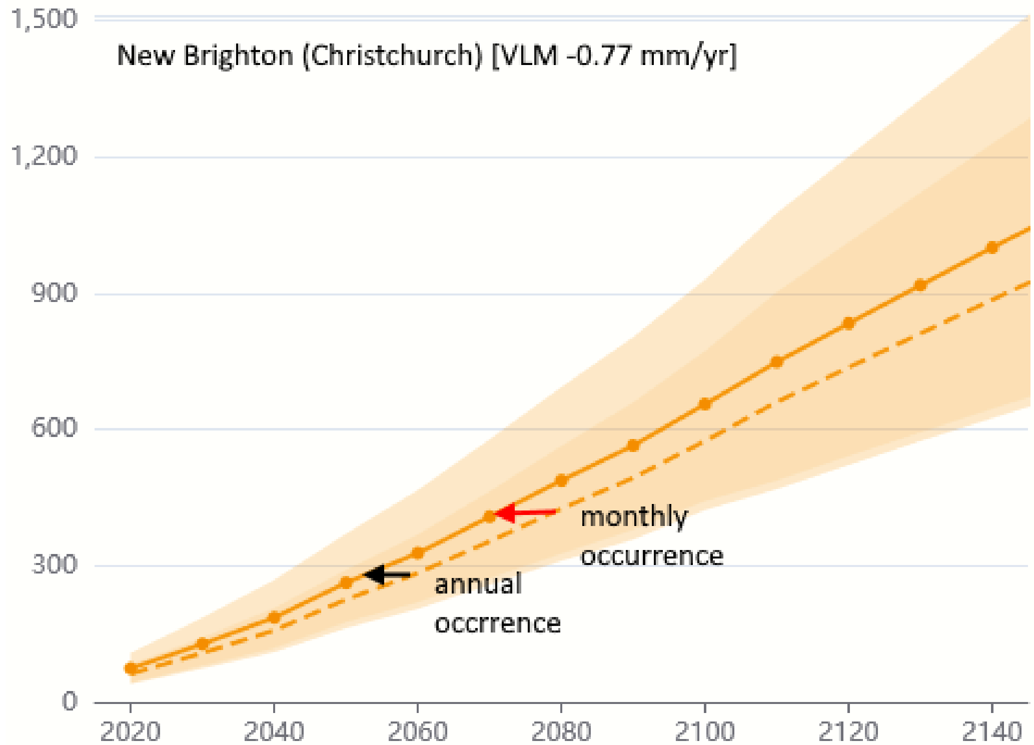


Figure 11: Ocurrences of extreme coastal flooding levels will increase from what used to be a rare 1% AEP event of the recent past, to become more regularly exceeded. Two such flooding thresholds (when annual and monthly occurences occur on average locally) are shown in relation to sea-level rise projections for SSP2–4.5 (median and 17th to 83rd percentile range), both with VLM included (heavy line with markers) and without (dashed line). Sites represent 3 major urban areas in New Zealand where subsidence is present. Inclusion of local subsidence rates brings flood-frequency thresholds forward.

National guidance for coastal adaptation in New Zealand (Lawrence et al., 2018) is framed around a dynamic adaptive pathways planning (DAPP) process that embodies the deepening uncertainty, including when RSL projections encompasse uncertainties in the long-term trends in VLM rates. DAPP is a process through which a series of alternative pathways comprising combinations or sequences of adapation options and planning actions are co-developed with communities (Haasnoot et al., 2021; Lawrence et al., 2018). To guide ongoing implementation of an adaptive strategy derived using DAPP, monitoring indicators of change in risk is essential. Indicators can be tied to early signals (warnings) to inform and enable a switch to the next action on the pathway or to an alternative pathway in a timely manner, before reaching a pre-agreed adaptation threshold, such as intolerable risk or frequency of hazard events (Stephens et al., 2018). Clearly local VLM adjusted RSL projections can shift planning timeframes forward (or backwards) by triggering decision-points in a DAPP strategy earlier (or later). Furthermore, carefully designed monitoring programmes (including ongoing GNSS and InSAR analysis) can be used to assess changes in VLM and update DAPP strategies as time progresses.

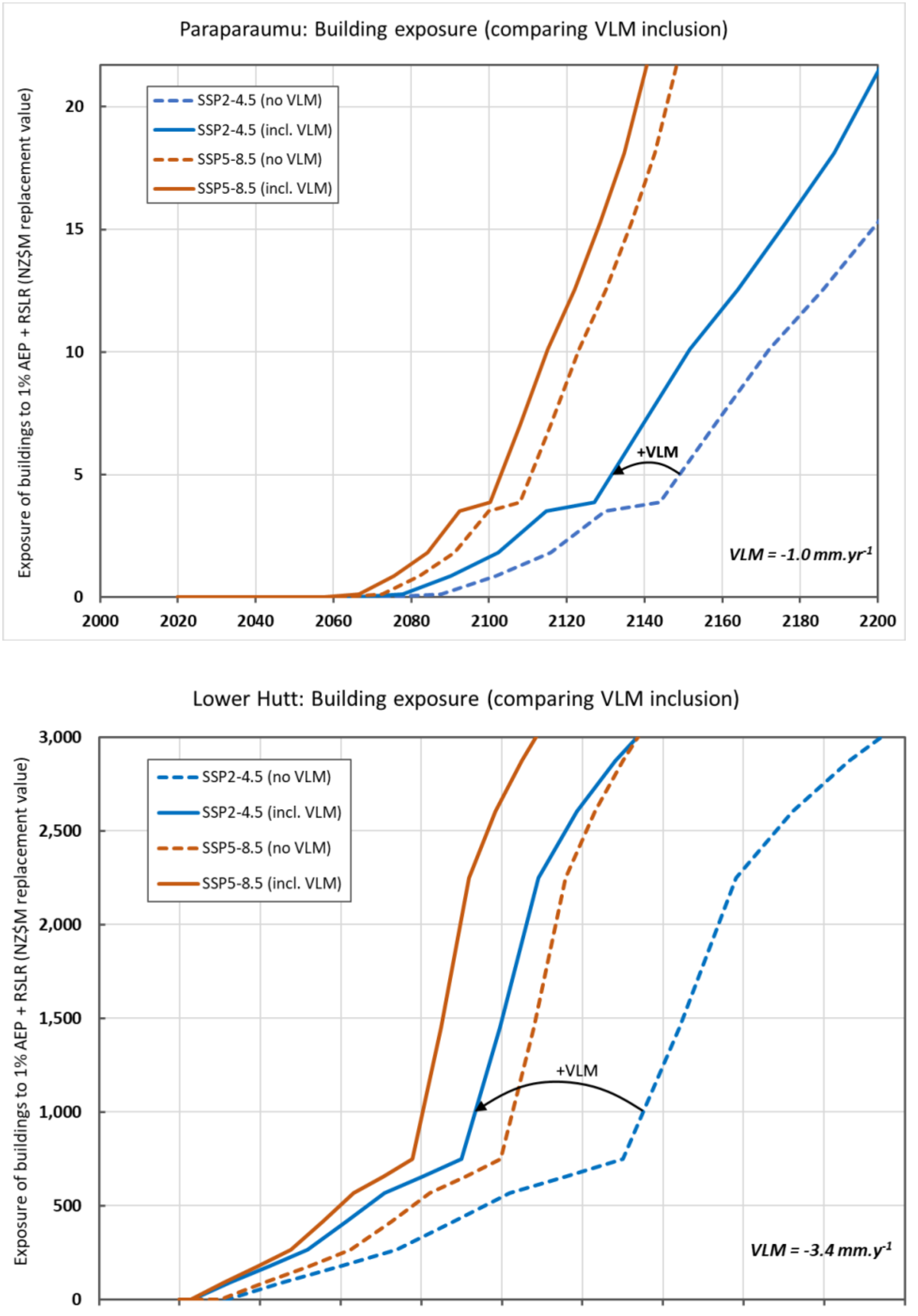


Figure 12: Building replacement value (2021 NZ$M) exposed to 1% AEP coastal flooding and median LSL projections for SSP2-4.5 and SSP5-8.5, with the red lines incoporating average VLM rates of -1.0 mm.y^{-1} (top panel; Paraparaumu) and -3.4 mm.y^{-1} (bottom panel; Lower Hutt).

Case study 2: Implications for risk, damage and loss

To further illustrate the risk, damage and loss effect for RSL projections with different subsidence rates, a static coastal inundation model (only including overland flow with inclusion of levees) was applied in the Wellington region to assess and compare building exposure to present 1% AEP coastal flooding (excluding waves) plus 0.1 m increments of RSL. Here, exposure is expressed as building replacement value (2021 NZD $), calculated on building floor area, storeys and a construction cost index (Paulik et al., 2020). The urban areas of Paraparaumu (~28,000 pop.) and Lower Hutt (~104,000 pop.) were compared using area-averaged VLM subsidence rates of -1.0 and -3.4 mm.y^{-1} respectively. The VLM effect on flood exposure for the two urban areas are shown in Fig. 12, and compare SSP2-4.5 and SSP5-8.5 median projections with and without the VLM subsidence component. Paraparaumu is developed on a cuspate foreland and shows a modest flood exposure increase until 2100 when dune systems are breached by storm-tide flooding. Lower Hutt, built in the late 19th century on a river deltaic system (Kool et al., 2020), exhibits a sharp increase in overland flood exposure (Fig. 12; bottom panel) once RSL exceeds paleo-foredunes from 2080 for the SSP5-8.5 projection.

Local subsidence can significantly shorten planning timeframes for adaptation actions before coastal water level change thresholds are reached. As shown in Fig. 12, land subsidence also hastens flood-risk exposure of built-environments, bringing foward adaptation thresholds. Lower Hutt's high subsidence rate means the SSP2-4.5 RSL projection with VLM, overtakes building exposure for the higher-emissions SSP5-8.5 RSL projection if VLM was not considered (bottom panel; Fig. 12). This highlights the critical role of RSL in informing adaptation planning, compared with only using regional or down-scaled GMSL projections. Conversely, for the Paraparaumu urban area, there is no cross-over of pairs of RSL projections for the two scenarios (with and without VLM) because subsidence is considerably lower than Lower Hutt (-1 mm y^{-1}).

In relation to Lower Hutt, further compound groundwater and hydraulic head effects on stormwater/drainage networks in conjunction with RSL can occur even earlier than by only considering overland flow. Kool et al. (2020) determined a substantially lower adpatation threshold of a 0.3 m RSL rise for stormwater/drainage and wastewater networks in the landward suburbs of Lower Hutt, where the land is low-lying behind the paleo-dune features. Therefore some of the exposure related to building replacement value in Lower Hutt (Fig. 12; bottom panel), would emerge sooner for this lower 0.3 m RSL adaptation threshold because of the limits to the present gravity-based networks. This lower 0.3 m RSL threshold would be reached at ~2043 including VLM for the SSP2-4.5 RSL projection, but two decades later if VLM was not considered.

These examples highlight the need to determine local VLM rates that can inform adaptation guidance for decision makers and infrastructure providers that is cognizant of spatial VLM variability.

5. Concluding remarks

In this study we have used high-resolution vertical velocity data generated for the period 2003-2011 (Hamling et al., 2022) to generate probabilistic RSL projections every 2 km along the coastline of New Zealand. Spatial coverage that was previously limited to our tide gauges (Kopp et al., 2014) has been extended to 7435 sites. We have used the IPCC AR6 approach (Fox-Kemper et al., 2021; Garner et al., 2021) and present an ensemble of probability distributions of RSL for *medium confidence* processes for Shared Socioeconomic Pathways (SSP) scenarios to 2150 and *low confidence* processes in SSPs to 2300. These new, local “NZSeaRise” projections and underpinning data can be accessed through a web-based GIS-visualisation tool (www.searise.nz/map-2).

Our approach and methodology reveal new insights into the complex role of VLM in projecting future sea level change and impacts and can be applied to any region of the world where the coastline is affected by active tectonic processes. Downward VLM > 2 mm y^{-1} makes a significant contribution to RSL projections for all climate scenarios out to the end of this century bringing forward adaptation planning decision thresholds by decades. In these regions, the influence of VLM on RSL may continue to be significant over the next 300 years but becomes overwhelmed by the accelerating contribution of land ice mass loss. The opposite occurs in regions where land is uplifting, which will experience a slower relative rise in sea-level.

Whereas VLM can vary through time, rates are relatively constant over decadal timescales between large earthquakes. Contemporary subsidence is also prevalent across low lying sedimentary basins around the New Zealand coastline. Here we use the inter-seismic and/or sedimentary basin VLM trend measured from InSAR and GNSS data to produce relative sea level projections at high spatial resolution. However, users of these projections should also consider local seismic hazard risk and known local subsidence hotspots (e.g., historic land reclamation) when planning for coastal adaptation. On timescales longer than the seismic cycle (~100 years), significant sections of New Zealand's coastline are either stable or rising due to the aggregate effect of vertical motion during earthquakes. However, it is important to highlight that 40% of New Zealand's coastline, including the lower North Island and upper South Island, is subsiding over time frames most relevant for planning and decision-making in the near-term (generally before 2050 but out to 100 years).

Uncertainties in VLM rate used in the NZSeaRise projections range from a minimum ± 0.02 mm y^{-1} to maximum ± 5.07 mm y^{-1} and are due to changes in measurement quality at each site. Here we assume that extrapolation of the inter-seismic VLM rate is valid (in lieu of an earthquake) and incorporate VLM measurement uncertainty as part of the full range of uncertainty in relative sea level projections. These additional uncertainties associated with local VLM projections, provides another reason for coastal planners and practitioners to adopt a flexible approach to adaptation (e.g., DAPP). This approach encourages monitoring of VLM alongside other factors that may change risk and allows a shift in adaptation response if VLM changes and becomes a more (or less) significant contributor to future RSL. This new ability to identify the variability that can occur in rates of VLM and hence RSL projections over short stretches of a coastline is very decision relevant for prioritising local adaptation.

Finally, we acknowledge that further work is needed to develop an understanding of the influence of earthquake-cycle related deformation on forecasts of VLM within tectonically active regions around the world. This work should use probabilistic approaches including seismic hazard models and forecasts. There is a need to better assess and quantify uncertainties due to the range of processes that cause short-term temporal variations in VLM at high spatial resolution. This information is critical to inform coastal planning as communities attempt to adapt to unavoidable sea-level rise. This important work will be the topic of a future study.

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Open Research

The Antarctic Research Centre at Te Herenga Waka: Victoria University of Wellington (ARC), the Institute of Geological and Nuclear Sciences Limited (GNS Science), and the National Institute of Water & Atmospheric Limited (NIWA) have provided data on vertical land movements. The VLM data (Envisat) was collected across the period 2003 to 2011. Sea level projections were made using the FACTs methodology and code published by Garner et al. (2021) and Fox-Kemper et al. (2021) and available

The data, including rates of vertical land movement, errors, quality factors and the the sea-level projections, are available for download from https://searise.takiwa.co/map/6245144372b819001837b900/embed.

 This uses the Takiwā Data Analytics Platform, Takiwā Data Analytics Platform is a SaaS tool that enables users to visualise and present data in different formats and views and to download the data.

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