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Late Holocene Sea-Level Changes and Vertical Land Movements in New Zealand

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ABSTRACT

Coasts in tectonically active regions face varying threat levels as land subsides or uplifts relative to rising sea levels. We review the processes influencing relative sea-level change in New Zealand, and the geological context behind ongoing land movements, focussing on major population centres. Whilst Holocene sea levels have been reconstructed using a variety of techniques, recent work uses salt-marsh microfossil assemblages to reconstruct relative sea-level changes over the past few centuries. For the twentieth century, these proxy-based studies often show enhanced rates of sea-level rise relative to tide-gauge observations. The effects of tectonic subsidence must be considered, alongside vertical and dating uncertainties in the sea-level reconstructions. Global Positioning Systems (GPS) observations for the past few decades show that vertical land movement (VLM) may be influencing rates of relative sea-level rise. However, the short period of GPS observations, during which trends and rates have varied at some localities, raises questions over the longer-term contribution of VLM to sea-level change over the past few centuries and for future projections. We argue that high-resolution palaeo-sea-level reconstructions from salt-marsh sedimentary sequences can help to answer these questions regarding the interplay between sea-level change and VLM at key locations.

KEYWORDS: Sea level, Holocene, New Zealand, palaeoenvironment, climate change, sea-level rise, palaeoclimate, vertical land movement, tectonics, palaeoseismicity

Introduction

The tectonic complexity of New Zealand introduces a great deal of uncertainty in the projection of future local sea-level changes. New Zealand's land-use planning policies typically work on a timeframe of 100 years or so (Department of Conservation 2010; Bell et al. 2017; Ministry for the Environment 2017), with the Ministry for Environment currently recommending infrastructure guidelines that plan for a minimum

1 m of sea-level rise by 2120. During this timeframe, however, the rate of relative sea-level change will vary considerably from region to region due to New Zealand's complex tectonics.

For example, in the capital city Wellington, continuous global positioning system (cGPS) records reveal that the land is currently undergoing tectonic subsidence at a rate of 3 mm/yr, although periodic uplift, approximately every five years during slow slip events (SSEs), reduced this to a net rate of 2.2 mm/yr between 2000 and 2015 (Denys et al. 2017). Assuming the interseismic subsidence and periodic SSE uplift pattern continues, this region is expected to experience enhanced sea-level rise in the future relative to regions of tectonic stability, and at present shows considerably faster rates than other parts of the country (Cole 2010).

Whilst it is apparent from the Wellington example that vertical land movement (VLM) needs to be factored into local to regional scale relative sea-level projections in New Zealand, questions arise from the short period of instrumental observations. The longest continuous cGPS records only span around twenty years and the longevity of trends observed in the cGPS record is unknown. In many cases (particularly in the North Island), the longer term (tens to hundreds of kyr) VLM trends determined from geological and geomorphological observations are the reverse of the observed cGPS trend (Beavan and Litchfield 2012; Stephenson et al. 2017). Also, cGPS data are presented relative to a reference station, which in New Zealand has traditionally been Auckland, owing to its assumed vertical stability (e.g. Beavan and Litchfield 2012; Houlié and Stern 2017). Nevertheless, some studies have used the International

Reference Frames ITRF2000 (Tenzer and Gladkikh 2014) and ITRF2008 (Tenzer and Fadil 2016; Denys et al. 2020), allowing for the identification of VLM in any Auckland cGPS records, and the rest of the country, relative to the Earth's geoid. A limited number of studies contextualise VLM in a longer-term (Holocene) timescale (e.g. Hayward et al. 2012; 2015a; 2015b; 2016), but notwithstanding the oft-cited work by Gibb (1986), knowledge of Holocene relative sea-level changes in New Zealand is scarce and fragmented (Clement et al. 2016).

Here we review the present knowledge of Holocene relative sea-level change in New Zealand to provide geological context and to test the longevity of current instrumentally observed VLM patterns (Figure 1) with the aim to help better understand how parts of New Zealand are likely to be affected by future sea-level rise. Common methods of Holocene sea-level reconstruction are summarised in Figure 2. We focus especially on the late Holocene (past ~2 kyr) because it provides temporal continuity with the instrumental era. Also, Gibb (1986) suggested that sea level (i.e. the 'regional eustatic' signal unrelated to VLM) was approximately stable in New Zealand during the late Holocene until the last ~100 years. First, we consider the tectonic and climatic controls on relative sea-level change in New Zealand, followed by evaluation of previous studies that have generated relative sea-level curves in New Zealand, with emphasis on those which have used foraminiferal assemblages as sea-level proxies to create high-resolution centennial-scale records.

Owing to its multiple possible meanings, Gregory et al. (2019) decried the use of the term 'eustatic' or 'global eustasy' to refer to global sea-level changes and influences. Several of the papers discussed in this review generate 'regional eustatic curves' (defined sensu Gibb (2012) as a time-dependent approximately uniform change in sea level around New Zealand). This definition is flawed, because 'eustatic' sea-level change is not uniform around New Zealand due to oceanographic and gravimetric processes. Here, we use the term 'sea-surface height' for the changes in water height relative to the Earth's ellipsoid instead. For all other wordage, this paper primarily uses the sea-level terminology of Gregory et al. (2019), with relative sea level being defined as the change in local mean sea level relative to the solid surface (i.e. seafloor or land), where mean sea level is determined relative to the international reference frame. Spatial variability is observed in both long-term (Holocene) relative sea-level changes (Clement et al. 2016) as well as in recent sea-level changes during the satellite altimetry era (see Ackerley et al. 2013) that shows up to 2.9 mm/yr of sea-level rise around the coasts of Auckland and Northland, decreasing southwards to 2.1 mm/yr around the coast of the southern South Island since 1993 (AVISO 2019) (Figure 3).

Controls on relative sea-level change in New Zealand

Tectonic controls

Regional tectonics dominate the relative sea-level signature across much of New Zealand, and trends of uplift and subsidence can vary significantly depending on the timescale of analysis. For example, while cGPS records show that much of the east, south, and west coasts of the North Island are aseismically subsiding at a mean rate of ∼1.5 mm/yr (Beavan and Litchfield 2012), uplifted marine and fluvial terraces show that these same regions have undergone substantial net uplift over the past 125 kyr (e.g. Grapes 1991; Beavan and Litchfield 2012; Ninis 2018) in response to upper plate and/or subduction earthquakes (Berryman 1993a; 1993b; Berryman et al. 2012; Clark et al. 2015). Over the longer time scale (the past ~125 kyr), approximately 45% of the New Zealand coast has been undergoing uplift (with uplift being gradual and aseismic in northwest North Island, northwest South Island, and Bay of Plenty), 15% has been undergoing subsidence, associated with the plate boundary zone, and the remaining 40% has been either stable or lacks sufficient data to determine its stability (Beavan and Litchfield 2012).

It is firmly established that the North Island's tectonic deformation is the result of subduction of the Pacific Plate beneath the Australian Plate at the Hikurangi Margin over the past 20–25 Myr (Rait et al. 1991). Both the degree of coupling and the obliquity of convergence between the plates increase southwards along the North Island (Litchfield et al. 2007; Wallace and Beavan 2010) (Figure 1B), with the regions most strongly coupled undergoing interseismic subsidence in excess of −3 mm/yr (Houlié and Stern 2017), and in some cases by as much as −10 mm/yr (Tenzer and Gladkikh 2014). Further north (in the central and eastern North Island), the weakly coupled parts of the margin are undergoing 1–3 mm/yr of uplift (Houlié and Stern 2017). Finite element modelling by Litchfield et al. (2007) suggests that 1 mm/yr of this uplift is the result of the subduction of the relatively thick and buoyant crust comprising the Cretaceous Hikurangi Plateau Large Igneous Province. Uplift in excess of 1 mm/yr in the northern and central parts of the margin was explained by their model to be caused by seamount subduction and sediment underplating. This mechanism explains the lack of faulting linked with uplift of the North Island axial ranges (Houlié and Stern 2017).

In the South of the North Island (the Southern Hikurangi Margin), where coupling-induced interseismic subsidence is gradually lowering the land (Figure 1B) and enhancing relative sea-level rise, cGPS data reveal the presence of slow-slip events (SSEs): intervals of gradual aseismic slip around the subduction interface, causing mm-scale uplift in the overlying crust. Since 2003, SSEs have been documented four times in the south of the Hikurangi margin (Wallace and Beavan 2010; Wallace et al. 2017; Wallace 2020), with durations between 200 and 480 days and moment magnitudes equivalent to Mw 6.6 (2003) – 7.2 (2004–5) (Wallace and Beavan 2010). As mentioned in the introduction, cGPS data from two sites, situated 30 km apart, show that these events have diminished the impact of subsidence on the expected sea-level trend of Wellington by 0.8 mm/yr between 2000 and 2015 (Denys et al. 2017, 2020).

In the northern Hikurangi Margin, around Gisborne and Hawke's Bay, SSEs occur far more rapidly on the shallow portion of the subduction interface (10–15 km), with a recurrence interval of approximately two years. They are also of much shorter durations than in the south, typically lasting for approximately two weeks (Wallace and Beavan 2010). The initiation of these events has been linked to seamount subduction (Barker et al. 2018; Schwartz et al. 2018). In the southern Hikurangi margin, SSEs occur deeper (25–60 km) than those in the northern margin, but both occur in regions of frictional stability, in either the transition zone between velocity-strengthening and velocity weakening-behaviour on the plate interface, or in regions of high fluid pressure (Wallace and Beavan

2010). The processes causing SSEs are not entirely clear, but it is now known that they can be triggered by earthquakes from the far-field, with SSEs in both the northern and southern Hikurangi Margin having been dynamically triggered by passing waves from the 2016 Mw 7.8 Kaikōura earthquake in the northern South Island (Wallace et al. 2017, 2018; Bartlow et al. 2018; Wallace 2020). Uplift in Wellington during this event has accommodated much of the past decade's subsidence at the Wellington cGPS sites (see GeoNet 2019a). Whether this uplift should be treated as the amplification of the SSE by post-seismic deformation, or the uplift is dominated by the postseismic signal (as modelled by Denys et al. 2019), is currently a matter of debate and ongoing research.

There is currently no geological evidence to evaluate the longer-term patterns and recurrence times of SSEs in New Zealand, though these will become clearer with time as cGPS records lengthen. However, in Wellington at least, it would seem reasonable to assume that large SSEs and similar aseismic uplift events have occurred multiple times during the last century, if we assume a constant rate of coupling-induced inter-SSE subsidence (currently 3 mm/yr). If this were not the case, then relative sea-level rise in Wellington since the 1943 relocation of the Wellington tide gauge would be expected to be ~ 3.3 mm/yr: comprising ~1.1 mm/yr mean rise in sea-surface height around New Zealand for the twentieth century (Tenzer and Gladkikh 2014) plus 2.2 mm/yr net ground subsidence (Denys et al. 2017). However, the observed rate over the past century is 2.18 ± 0.17 mm/yr (Denys et al. 2020), and even less since 1943; considerably lower than would be expected if the rates of change observed in the pre-2015 cGPS record were representative of the entire past century (and less than the magnitude of relative sea-level rise that should be derived from subsidence alone, if the cGPS trend were representative of the long-term VLM rate). Whether this discrepancy between expected and actual rates of relative sea-level rise in Wellington results from large (and/or frequent) SSEs or fluctuating inter-SSE subsidence rates is not currently clear. The fact that calculations by Tenzer and Gladkikh (2014) for New Zealand's changes in sea-surface height questionably assume no regional variability may also be a source of discrepancy, as this assumption is not supported by satellite data (Figure 3).

One area of note on Figure 1A, where cGPS data show abnormally fast rates of uplift (9.8 mm/yr relative to ITRF2008 (Tenzer and Fadil 2016)) is the central Bay of Plenty near Matatā. As discussed by Beavan and Litchfield (2012), this uplift is predominantly the result of a series of earthquake swarms initiating around 2005. Prior to this, the heights and ages of nearby raised beaches suggest that uplift over the past 5 kyr has generally been very slow (0 to ~0.6 mm/yr), albeit with several instances of abrupt uplift and subsidence (Begg and Mouslopoulou 2010). Modelling by Hamling et al. (2016) suggests that the modern earthquake swarms are the result of the inflation of a large magma chamber at a depth of ~9.5 km, associated with rifting in the Taupo Volcanic Zone (TVZ). Lamb et al. (2017) gave an alternate explanation for the uplift, attributing it to melting-induced episodic changes in vertical flow forces associated with mantle upwelling in the TVZ rift axis. In any case, the abnormally fast rates of uplift near Matatā appear to be a localised and temporary phenomena related to volcano-tectonic rifting processes.

In the South Island, continental collision, transpression around the Alpine Fault, and crustal thickening cause a general signature of uplift in the cGPS record, with uplift being greatest proximal to the Alpine Fault (6–8 mm/yr), and decreasing to 1–2 mm/yr towards the coastal regions (Houlié and Stern 2017). Most of the coastline to the northeast and southwest of the Southern Alps is undergoing subsidence, typically on the order of 1.4–1.5 mm/yr in the northwest South Island (Tenzer and Fadil 2016) and <1 mm/yr in the southeast South Island (Tenzer and Fadil 2016), although much of this subsidence is within the margin of error and may not be a genuine signature (Stern 2019 pers. comm.). The central western South Island may be tectonically stable (Beavan and Litchfield 2012), but limited data exist to provide any confidence in this. Tenzer and Gladkikh (2014) note that VLM velocity rates are, on average, notably much faster on Australian Plate (where stations have a mean VLM velocity of −1.4 mm/yr) than on the Pacific Plate (mean VLM velocity 0.5 mm/yr). However, it should be noted that the comparative characterisation of vertical plate motion on the Pacific Plate is possibly less reliable than on the Australian Plate, due to fewer and widely dispersed Pacific Plate (and South Island) stations (Figure 2), and that VLM is negligible in several Australian Plate localities (Figure 1A) (furthermore, it may be difficult to confidently say which plate sites located along the plate boundary zone around the Alpine Fault belong to). The Dunedin region is of particular note regarding VLM on the Pacific Plate. Here, subsidence between −0.66 and −1.89 mm/yr is observed (Denys et al. 2020), yet only 1.35 ± 0.15 mm/yr relative sea-level rise is recorded from the city's tide gauge since 1899 (Denys et al. 2020).

This is the lowest rate of relative sea-level rise observed in New Zealand, and indicates, by extension of the GPS trends across the past century, approximately 0 mm/yr sea-surface height change across some parts of the harbour over the past century (Denys et al. 2020). Noting that this is unrealistic, Denys et al. (2020) proposed that the low-rate of long-term sea-level rise is the result of frequent uplift events associated with earthquakes in Fiordland.

Climatic controls

During the Common Era, the main climatic processes contributing to sea-level change have been ice melt and thermal expansion accompanied by ocean circulation. Prior to the industrial revolution, global climate in the Common Era underwent an irregular, long-term cooling trend (-1.1 to -0.3^{o}C/kyr), with globally asynchronous intervals of heightened cooling or warming (Ahmed et al. 2013; McGregor et al. 2015; Neukom et al. 2019). Global mean sea level fluctuated by up ca. 0.1 m on multi-decadal to centennial timescales (Kopp et al. 2016). The cooling trend terminated around ~AD 1800 with sustained global temperature rise accompanying increased anthropogenic greenhouse gas emissions (McGregor et al. 2015). These climate patterns are also apparent in New Zealand, where archaeological and palynological evidence suggests that the first Polynesian settlers (~AD 1250) encountered a warmer climate than did the first European settlers (~AD 1800) (Anderson 2014; Newnham et al. 2018), although a tree-ring record from Westland suggests that a gradual warming trend may have initiated around AD 1610 (Cook et al. 2002).

From the middle 1800s, melting of ice sheets and glaciers worldwide and thermal expansion have been the main contributers to sustained global mean sea-level rise (Church et al. 2013), with an additional contribution from the melting of glaciers (Leclercq et al. 2014). Over a 40-year period centred on ca. AD 1925, proxy and measured sea-level datasets from around the world show a significant positive inflexion, hypothesised to be in association with ice-mass loss in the Arctic region (Gehrels and Woodworth 2013). Initially only a minor component of sea-level rise (Wigley and Raper 1987), observations from bathythermographs and Argo floats now suggest that thermal expansion has increased its contribution to global sea-level rise from 0.6 mm/yr (1971–2010) to 0.8 mm/yr (1993–2010) (Church et al. 2013). Tide-gauge records suggest a global mean sea-level rise of 1.1–1.2 mm/yr from 1901–90 (Hay et al. 2015; Dangendorf et al. 2017), accelerating significantly to 3.3 ± 0.4 mm/yr during the satellite altimetry era (Cazenave and Remy 2011), and still accelerating at a mean rate of 0.084 ± 0.025 mm/yr^2 (Nerem et al. 2018).

These observed sea-level changes for the past century are not globally uniform, however, owing to a number of climate-related variables, including oceanic and gravimetric responses to ice melt. Satellite data show that much of the Tropical and Subtropical Pacific has experienced particularly high rates of rise since at least 1993 due to the influence of the Interdecadal Pacific Oscillation (IPO), El-Niño Southern Oscillation (ENSO), and wind forcings (Mimura and Horikawa 2013). These factors also influence New Zealand (Figure 3), resulting in a range of sea-level projections (all higher than the global average) over the coming century (Ackerley et al. 2013) (Figure 1A). Between 1993–2019, the coastlines around parts of Northland and Auckland experienced 4.6–4.8 mm/yr sea-surface rise, generally declining further south, with 4–4.3 mm/yr sea-surface rise off the coast of much of the South Island, and 3.8 mm/yr off the coast of Fiordland. Major exceptions to this trend can be observed around the Greater Wellington region, with 4.8–5.2 mm/yr, and around the northern South Taranaki Bight and the Tasman Bay, where sea-surface rise as low as 1–2 mm/yr is measured (Figure 3). The general southwards decrease in this absolute (geocentric) sea-level rise can possibly be attributed to the equatorward increase in temperature and thermal expansion, as well as the influence of Antarctica (where melting ice decreases the gravitational pull of the ice sheet, leading to redistribution of water mass in the far-field (i.e. closer to the equator), rather than at proximal high latitudes, as discussed in Tamisiea et al. (2003)).

The IPO is a 20–30-year cycle defined by positive and negative phases of sea-surface temperature (SST) anomalies. Positive phases involve cooler than normal SSTs in the West Pacific and warmer SSTs in part of the East Pacific. Negative phases involve warming in the West Pacific and cooling in part of the East Pacific. Because of this West Pacific warming, negative IPO phases associated with higher sea surfaces in New Zealand can be identified in New Zealand's tide-gauge record from 1947–1975, and 1998-present, with an intervening positive phase 1976–1997 (Bell and Hannah 2012). Across a cycle, the IPO can affect New Zealand's sea surface by ±5 cm (Dawe 2008).

Superimposed on the IPO, the ENSO is a recurring climatic pattern in the Central and East Pacific that occurs over an irregular 2–5 year cycle. The ENSO is characterised by 'El Niño' phases and 'La Niña' phases when SSTs, in the central and eastern tropical Pacific are anomalously warmer and cooler, respectively. This cycle can affect New Zealand sea surfaces by ±6 mm, with rises during La Niña and falls during El Niño (Hannah and Bell 2012). New Zealand tree-ring records indicate that the strength of the ENSO increased significantly during the twentieth century relative to the preceding five centuries, suggesting that ENSO activity, at least proximal to New Zealand, increases with global warmth (Fowler et al. 2012).

Longer-term Common Era periods that may have affected sea level in the Pacific include the Medieval Warm Period (MWP) and Little Ice Age (LIA). The spatial variation in the timing and amplitude of temperature change in these events leads to a great deal of uncertainty regarding whether or not they are even expressed in the Pacific, and how they could have impacted regional sea level, with significant debate around the global or regional nature of the MWP (Hughes and Diaz 1994; Broecker 2001; Nunn 2007a; Ahmed et al. 2013; Chen et al. 2018) being largely unresolved. Neukom et al. (2019) noted that several climate reconstructions across the Common Era do not fit the standard MWP/LIA narratives, and using data from 257 palaeoclimate proxies plotted on a global grid, found that <50% of the globe shows consistent timings of cold or warm intervals in the pre-industrial Common Era. Neukom et al. (2019) showed that regionally specific mechanisms controlled multi-decadal climatic variability prior to the industrial era, and that neither the MWP nor LIA can be treated as globally consistent events.

Such regional variability in late Holocene climate is apparent in the Pacific region. Nunn (2007a) attributed Pacific archaeological and palynological evidence for warming ~AD 750–1250 and cooling ~AD 1350–1800 to the MWP and LIA, respectively. These timings have been contested, however, with coral palaeothermometry indicating a relatively warm West Pacific during Nunn's postulated LIA (Cobb 2002), and some glacial advances have been identified during the postulated MWP (Schaefer et al. 2009). Nevertheless, Nunn (2007a) speculatively linked the Pacific MWP to sea levels ~1 m above the modern in several sites, such as Lord Howe Island in the Tasman Sea, as well as at Bering Island in the Bering Sea, and Kunashir Island (North of Japan). These +1 m horizons are far from globally ubiquitous, however, and there is an overall scarcity of global high-resolution sea-level data for this time period (Kemp et al. 2011). Indeed, several studies have called Nunn's conclusions on this matter into question (e.g. Gehrels 2001; Allen 2006; Fitzpatrick 2010; Clark and Reepmeyer 2012). A cooling interval is present in New Zealand tree-ring records from AD ~1240–1310 (Cook et al. 2002), coinciding with Nunn's (2007a) AD 1300 cooling event. However, whether or not such a cooling event was Pacific-wide, or if the 0.7–0.8 m sea-surface fall postulated by Nunn (2007b) (from evidence from Pacific Islands) occurred in New Zealand, is far from clear.

Longer-term climate-related processes that can affect relative sea-level change typically relate to the displacement of the lithospheric mantle due to the loading and unloading of ice onto the land during major glacial-interglacial cycles, in what is referred to as glacial-isostatic adjustment (GIA) (e.g. Benn and Evans 2010; Whitehouse 2018). Although this is typically regarded as a localised process due to greater degrees of VLM occurring in proximity to major ice sheets and glaciers as they melt (or build), the Earth's viscoelastic response to ice-mass changes is now understood to be manifested globally (Riva et al. 2017). As a result of far-field continental ice-sheet displacements alone, much of the Northern Hemisphere is generally undergoing uplift, while much of the Southern Hemisphere is undergoing subsidence. An area of crust spanning from the southern Indian Ocean, across the entirety of Australia and New Zealand, and extending eastwards into the central south Pacific has undergone −0.6 to −0.8 mm/yr of vertical deformation during 2003–14 (Riva et al. 2017). Riva et al. (2017) note that the rates of far-field vertical deformation vary globally (and, usually, accelerate) with the increasing acceleration of ice melt, even during the twentieth and twenty-first centuries.

As the effects of longer-term GIA have not yet been quantified for New Zealand, most palaeo-sea-level and VLM studies apply the global model of Peltier (2004). This model suggests that much of New Zealand should be undergoing ±0.1 mm/yr VLM due to GIA, but fails to accurately account for any of New Zealand's local ice-mass changes (Cole 2010; Fadil et al. 2013). It may be beneficial for future studies to use the more recent ICE-6G GIA model (Argus et al. 2014; Peltier et al. 2015, further improved by Peltier et al. 2018). Work to quantify the effects of GIA more accurately in New Zealand may prove invaluable to future sea-level studies. For example, Riva et al's. (2017) model of the influence of twentieth to twenty-first century ice wastage on VLM was applied to

New Zealand's tide gauges by Denys et al. (2020), who showed that it had driven ~30 mm (or 0.25 mm/yr) subsidence around the South Island, and ~36 mm (or 0.30 mm/yr) subsidence in the North Island (with uplift in the Southern Alps accounting for the reduced rate in the South Island).

GIA also affects global mean sea level indirectly, as the collapse of glacial forebulges in high-latitude once-glaciated regions prompts the migration of water into those regions (referred to as 'ocean syphoning') (Mitrovica and Milne 2002). The loading of additional seawater onto continental shelves can also trigger upwarping of the adjacent land ('continental levering'; Mitrovica and Milne (2002)). The process of crustal loading due to the distribution of ocean water is referred to as hydro-isostasy (Benn and Evans 2010) and its effects on New Zealand sea level are also currently under investigation, though this process appears to have been driving subsidence in the Northland Peninsula, on the order of 1–12 metres across the Holocene, with the magnitude of subsidence increasing northwards (Clement et al. 2016).

Orbital Controls

Another mechanism that affects the sea surface in the Pacific on a centennial time-scale is Earth's rotation. A relationship between the Earth's rotation and sea level has long been understood, primarily with regard to the influence of glacioisostatic rebound and water mass distribution on the Earth's oblateness, and the resultant effect on the rotational state of the planet's orbit (e.g. Peltier 1988; Nakada and Okuno 2003; Peltier and Luthcke 2009; Mitrovica et al. 2015). This relationship is not in one direction however, as the position of the Earth's rotational axis affects the position of its 'rotational bulge', which also affects the Earth's oblateness, and from there the distribution of water on its surface (Mitrovica et al. 2005). It is now also understood that, on a local scale, the direction by which water from major rivers flows into the ocean is controlled by the Earth's rotation, leading to elevated water levels to the left of Southern Hemisphere rivers, though the long-term centennial effects of such processes are not yet clear (Piecuch et al. 2018)).

Holocene sea-level reconstructions

Most studies of Holocene relative sea-level change in New Zealand have focussed on regions of presumed tectonic stability in order to understand the regional signature of sea-level rise and use these as a benchmark for work involved in calculating palaeo-VLM. Estimates of long-term site stability have been based on the position of the last interglacial shoreline, which was approximately 5 m above modern sea surface height in New Zealand (Pillans 1990). Gibb (1986) generated a widely-cited regional 'eustatic' curve for New Zealand based on 82 radiocarbon-dated sea-level indicators (mostly intertidal molluscs) from presumed tectonically stable sites at Blueskin Bay, Weiti River Estuary and Kumenga, as well as sites of known instability such as Pauatahanui, Christchurch, and Firth of Thames. Gibb (1986) isolated tectonic movements from the presumed unstable localities using data from the presumed stable sites to remove anomalous data, and generated the curve displayed in Figure 4A. Gibb's 1986 New Zealand record shows a relative sea-level rise from -33.5 ± 2 m at 10 ka BP, to approximately the present mean sea level at 6.5 ± 0.1 ka BP. This rise was interrupted by stillstands during 9.2–8.4 ka BP and 7.5–7.3 ka BP (at -24 ± 2.9 and -9 ± 2.8 m relative to modern sea level, respectively). The 6.5 ka plateauing of sea level reported by Gibb is approximately coincident with the 7 ka final deglaciation of the Laurentide Ice Sheet, and a change in global sea-level behaviour from a dominant glacioeustatic control to a dominant glacioisostatic control (Dlabola et al. 2015). Gibb (1986) also noted decimetre-scale fluctuations in sea level during the past 6.5 ka, identifying a regression minimum of −0.4 m at 4.5 ka BP, and a transgression maximum of 0.5 m at 3.5 ka BP.

The Gibb (1986) record has recently come under reconsideration owing to the low precision of the palaeo-depth indicators and the fact that the radiocarbon dating was not calibrated conventionally, so cannot be converted into true sidereal years (Clement et al. 2016). Kennedy (2008) argued that the absence of a mid-Holocene highstand (observed in other Southwest Pacific relative sea-level reconstructions such as Nunn (1990) and Baker et al. (2001)) in the Gibb (1986) record may have been due to the low-resolution of the data, while Clement et al. (2016) suspected the highstand was assumed to represent uplift and removed from the curve. Doubts were further cast on aspects of the Gibb curve by Dlabola et al. (2015), who generated a relative sea-level curve for Fiordland over the last 18 kyr. This Fiordland record, reconstructed using the heights of overtopped isolation basin sills, as well as diatom assemblages from sediment cores taken from two fjords, contains a significant increase in the rate of sea-level rise beginning ~9.7 ka BP at a time when Gibb (1986) postulated a stillstand. This record also indicated a slower initial rate of sea-level rise from 11.4–9.7 ka BP than the Gibb record. However, Dlabola et al. (2015) acknowledge that the differences may be due to VLM. What is clear from this discussion is that key assumptions regarding tectonic stability that underpinned Gibb's seminal New Zealand sea-level record need to be revisited in light of subsequent studies of sea-level changes and vertical land movements.

Hayward et al. (2010, 2015a, 2016) used preliminary New Zealand Holocene relative sea-level data from an unpublished conference abstract, supplemented by data from Hicks and Nichol (2007), Dougherty and Dickson (2012), Hayward (2012), and Hayward et al. (2007, 2012), to infer VLM in several coastal sites across New Zealand. As with Gibb's (1986) record, this sea-level reconstruction assumed uniform sea-surface height across all stable coasts of New Zealand, and that all changes thereof were similarly uniform in magnitude during the middle and late Holocene. This assumption of regional coherence in timing and amplitude of sea-surface changes is problematic, for reasons already discussed. Sea-surface change over hundreds of kilometres is seldom uniform (see Lewis et al. 2013; Clement et al. 2016), as is now evident from the modern satellite data (Figure 3).

Clement et al. (2016) addressed the problem of regional variations in relative sea-level history by integrating a broad selection of mostly published pre-existing local sea-level proxy data to generate a series of relative sea-level curves for different parts of New Zealand. They also deployed more advanced radiocarbon techniques than were available to Gibb (1986), applied GIA corrections using the ICE-5G ice model and VM2 radial viscosity profile of Peltier (2004), and incorporated feedbacks between GIA and Earth's rotation (Mitrovica et al. 2005) with consideration for time-dependent migration of the shoreline (Mitrovica and Milne 2003). In their study, a highstand in the northernmost North Island was identified from 8.1–7.3 ka BP (0.6–1.4 kyr prior to Gibb (1986) in agreement with Australian records (e.g. Horton et al. 2007; Lewis et al. 2013)), reaching ~2.65 m above present mean sea level, before falling to present values between 7.8 and 6.4 ka. Importantly, this highstand was not temporally uniform across New Zealand, but occurred later further south (as did the first occurrence of present meal sea level). For example, in the South Island, the relative sea level high stand reached ~2 m above modern sea level from 7.0–6.4 ka BP (Figure 4B-D).

These regional variations have yet to be fully explained, but Clement et al. (2016) offered several suggestions, including a decrease in the gravitational attraction of the shrinking Antarctic Ice sheet, possibly combined with post-glacial meltwater loading and hydro-isostatic levering. However, as the authors acknowledge, this hypothesis is not supported by Australian Holocene relative sea-level reconstructions (e.g. Horton et al. 2007; Lewis et al. 2013), nor the GIA model predictions. Furthermore, the manner in which GIA was quantified and accounted for by Clement et al. (2016) calls aspects of the study into question, as the ice model (Peltier 2004) used in this study has been argued by Cole (2010) and Fadil et al. (2013) to be unsuitable for use in New Zealand, due to its failure to incorporate isostatic shifts arising from New Zealand ice-mass changes (as discussed earlier). It may also be questioned how well the model encapsulates the lithospheric heterogeneities present at the Pacific-Australian plate boundary, as such issues are not addressed by Peltier (2004) in his discussion of the model. This particular concern is underpinned by the extreme sensitivity of South Island glaciers to climatic shifts (Vargo et al. 2017) and their well-documented patterns of significant growth and deglaciation during the Holocene (e.g. Schaefer et al. 2009). The possibility, posed by Mathews (1967), that Holocene glacial mass changes in New Zealand have been sufficient to produce significant GIA requires further investigation, as does the presumed millennial-scale and short-term vertical stability of much of New Zealand's coastline, variations in which may contribute to the regional differences observed in Clement et al.'s (2016) reconstruction.

Late Holocene Centennial-Scale Records

Several studies have used benthic foraminiferal assemblages from salt-marsh sediments to reconstruct Holocene relative sea-level changes in New Zealand in presumed tectonically stable settings (e.g. Figueira 2012; Gehrels et al. 2008; Grenfell et al. 2012), or to constrain past vertical land movement in unstable regions (e.g. Hayward et al. 2004, 2007, 2015a, 2015b, 2016; Clark et al. 2015). Salt-marsh foraminifera are highly useful in sea-level reconstructions as they occupy far narrower vertical ranges in the intertidal zone than the bivalves used in previous low-resolution studies (e.g. Gibb 1986; 2012). This allows sea level to be estimated to within ±5 cm precision in some cases (Southall et al. 2006).

A key study of this type was conducted at Pounawea, southern South Island (Figure 1; Gehrels et al. 2008). The site was considered to be tectonically stable based on the +4 m height of the Last Interglacial shoreline, as well as local stratigraphic work by Hayward et al. (2007), which indicated no VLM over the past 1 kyr. The Pounawea sea-level reconstruction shows a gradual (0.3 ± 0.3 mm/yr) relative sea-level rise from AD 1500–1900, followed by a dramatic increase to 2.8 ± 0.5 mm/yr in the twentieth century (Figure 5), much higher than the observed twentieth-century New Zealand mean, estimated as between 1.46 mm/yr (Fadil et al. 2013) and 1.6 mm/yr (Hannah 2004). The high rate of relative sea-level rise at Pounawea was attributed to a possible regional high in thermal expansion (Gehrels et al. 2008) although this is not reflected in tide gauge records for the region. As shown in Figure 5, the sea-level rise at Pounawea is notably faster than the sea-level change observed from the nearest tide-gauge records at Lyttelton, Bluff, and Dunedin (with trends of 2.0, 1.8, and 1.3 mm/yr, respectively (Hannah and Bell 2012)). However as shown in Figure 5, the spread of the data at

Dunedin is far greater than in the other South Island tide gauges, suggesting another regional influence may apply at that location. Denys et al. (2020) argue that the overall lower observed rate of sea level rise at Dunedin may reflect the influence of uplift from earthquake events in Fiordland.

Fadil et al. (2013) argued that the high rate of relative sea-level rise recorded at Pounawea was due to sediment compaction, which they argued was poorly constrained in New Zealand. However, Brain et al. (2012) applied geotechnical modelling experiments to samples from salt marshes in a variety of depositional settings, and showed that well-consolidated, sub-0.5 m thick salt-marsh sediment sequences such as those in New Zealand are likely to have only negligible compaction (on the order of millimetres). It seems therefore that relative sea-level rise in the southern South Island is noticeably faster than the regional change in sea-surface height for the majority of New Zealand (even as observed in the modern satellite record, Figure 3, which shows a post-1993 sea-level rise of 4.0 mm/yr around Pounawea), and typical of the rest of the South Island. Several possible explanations for these higher rates at Pounawea emerge from the range of tectonic and climatic controls on New Zealand sea level discussed earlier in this review. Of these, a possible explanation is localised aseismic tectonic subsidence in locations where this has not previously been observed in the geological record. Another possibility is that the relatively small modern training set developed at the site has constrained the accuracy of the sea-level reconstruction.

At Puhinui Inlet, Auckland (which was assumed to be tectonically stable, Figure 1), a similar study was conducted by Grenfell et al. (2012), with two sea-level reconstructions (from cores ‘Puh3’ and ‘Puh5’) giving estimates of 2.8 ± 0.5 and 3.3 ± 0.7 mm/yr since 1890. Although these rates are consistent with those at Pounawea (Gehrels et al. 2008), they are inconsistent with the Auckland tide-gauge record, which gives 1.41 mm/yr of rise for this same interval (Cole 2010). This is problematic, as Denys et al. (2017) find no evidence of a tectonic influence on the sea-level record for Auckland. One possible explanation relates to the fact that Puhinui Inlet lies on the west (Tasman Sea) coast of Auckland, whilst the Auckland tide gauge is situated on the east (Pacific) coast. The difference could be explained by enhanced thermal expansion on the Tasman Sea side associated with the region’s ocean circulation pattern. However, if that were the case, it is not evident in the satellite altimetry record, which shows a 4.6–4.8 mm/yr rise in sea-surface height adjacent to both Auckland’s Pacific and Tasman coastlines since 1993 (Figure 3).

Alternatively, it is possible that the Puhinui cores were taken from too low in the salt marsh to enable accurate sea-level reconstructions. This is supported by the low (<20%) abundance of the high-marsh (Southall et al. 2006) foraminifer Trochamminita salsa in the upper part of the cores. As discussed by Hayward et al. (2016), and Scott and Medioli (1978), palaeoelevation estimate precision increases significantly (by magnitudes of tens of cm) higher up the marsh, due to the smaller elevation ranges of foraminifera in the high-marsh environment, as well as the tendency for sedimentation rates to more closely reflect sea level (Gehrels and Kemp In press). Uncertainties with the Grenfell et al. (2012) transfer function may also contribute to the discrepancy, as some of the residual errors are poorly modelled (+12 and −20 cm), and a negative trend is observable in the residual errors with respect to increasing height, suggesting a possible overprediction in height for lower elevations, and an underprediction for higher elevations. As at Pounawea, the predictive power of the transfer function is further limited by the small number of surface samples that were taken from Puhinui Inlet and a significant gap between 275 and 325 cm in the vertical range. These are common limitations and elsewhere it has been shown that the predictive power of sea-level reconstructions can be enhanced by developing regional microfossil training sets that incorporate data from other salt marshes (e.g. Horton and Edwards 2005; Watcham et al. 2013; Hocking et al. 2017).

However, VLM provides another possible explanation for the high rate of sea-level rise reconstructed for Auckland, despite previous work and assumptions to the contrary. A 2003–2007 Envisat time series across Auckland reveals three distinct regions of subsidence within the city (all ~4 mm/yr), with scattered regions of uplift (maximum of 4 mm/yr) (Samsonov et al. 2010). This land movement was linked to fluctuations in groundwater recharge and depletion, due to a lack of correlation with known faults or volcanic centres (Samsonov et al. 2010), an interpretation supported by subsequent genetic algorithm inversion modelling (Latimer et al. 2010), though not entirely confirmed. Altamimi et al. (2016) incorporated Auckland's cGPS sites into their international terrestrial reference frame (ITRF2014) for global geodetic data, and found the city to be subsiding by 0.8 mm/yr. Subsidence in Auckland of 0.83 mm/yr relative to the previous ITRF (ITRF2008) was calculated by Tenzer and Fadil (2016), and ongoing work suggests that the true subsidence rate is as high as 1.2 mm/yr (Hreinsdóttir 2019, pers. comm). Whether this subsidence is a long-term process (it may relate to a viscoelastic response to ice wastage (Riva et al. 2017) and/or to tectonics), it is of concern because studies of New Zealand cGPS signatures such as Beavan and Litchfield (2012) and Houlié and Stern (2017) assume complete stability in Auckland, and give all cGPS data relative to this site, meaning that sites of equivalent subsidence might not be acknowledged in the current literature. Furthermore, the observed spatial variability in this land movement (Latimer et al. 2010; Samsonov et al. 2010) could provide an explanation for why the proxy sea-level record at Puhinui differs so significantly from the Auckland tide-gauge record. Further salt-marsh records may be needed in the Auckland region, including from higher in the Puhinui salt-marsh sequence, to assess whether or not the Grenfell et al. (2012) record truly reflects an enhanced relative sea-level rise due to land subsidence. If the enhanced subsidence is a genuine signal, it would be ideal to extend the record beyond 1890, in order to assess whether this VLM is due to anthropogenic disturbance of groundwater (as interpreted by Samsonov et al. 2010) , or has a longer-term, tectonic origin. Tenuous evidence for long-term subsidence can be interpreted from Thorne Bay, northern Auckland, where a wave-cut platform linked with the Last Interglacial is located 3 m above sealevel (Ballance and Williams 1992), a time when sea level in the region was estimated to be ~7 m above present (Beavan and Litchfield 2012), although such subsidence in this locality would be orders of magnitude less than is indicated by Samsonov et al. (2010)'s data. This difference could result from the extreme spatial variability in the latter study's observed VLM changes.

Figueira (2012) generated sea-level reconstructions from salt marshes at Waikawa Harbour, southeast Southland, and Whanganui Inlet, northwest Nelson (Figure 1). These records are by far the longest salt marsh sea-level reconstructions to date from New Zealand, extending across most of the past millennium. The record from Waikawa Harbour displays sea-level rise of approximately 2.6 mm/yr between AD ~700 and ~1150, reaching approximately 80 cm above present mean sea-level before abruptly declining to lower-than-present values by AD ~1250, reaching −40 cm by 1700. A subsequent abrupt rising trend commencing around 1900 is coincident with the onset of anthropogenic enhancement. The magnitude of Waikawa reconstructed sea-level rise between AD ~700 and ~1150 is comparable with speculative estimates from other Pacific sites for the MWP (Nunn 2007a), but the rate of rise far exceeds what would be expected from this locality (assuming tectonic stability), while the termination of the rise and abrupt fall (the 'AD 1300 Event') occurs at least a century earlier than elsewhere (Nunn 2007a). This high sea-level interval has very wide error bars, in part because the assemblages used to make this calculation are rich in the benthic foraminifer Miliammina fusca, which has a large vertical range at the site, and the peak appears to be highly model-dependant. Indeed, the high abundance of M. fusca during this older interval could indicate that the marsh had colonised a pre-existing mudflat (see Hayward et al. 1999). Immature, flat-colonising marshes typically have sedimentation rates in excess of the rate of sea-level rise, creating regressive sequences that are difficult to interpret in terms of sea-level changes (Gehrels and Kemp In press).

Therefore, it is entirely possible that the 'MWP' sea-level peak presented by Figueira (2012) from Waikawa Harbour is simply an artefact of both the uncertainty introduced by the assemblage and the problems encountered when trying to reconstruct sea level using flat-colonising marsh sediments. A mean rate of sea-level rise of 3.5 ± 0.5 mm/yr is indicated in the Waikawa Harbour record for the past 120 years, notably greater than any of the South Island tide gauges. Statistically, far greater confidence is placed on the reconstruction in this part of the record due to its foraminiferal makeup. The Figueira (2012) record from Whanganui Inlet shows a mean rate of modern sea-level rise of 0.6 mm/yr from 1840–1910, and 3.6 ± 0.6 mm/yr post-1910, also notably faster than the South Island tide gauges.

In summary, detailed sea-level reconstructions for the past few centuries from different regions (Auckland, northern South Island, eastern Otago, Southland) all show rates of sea-level rise that are higher than expected from the nearest tide-gauge records. Clearly, errors and uncertainties in the reconstruction methodology cannot be ruled out at the sites, but other factors should be considered as well. If we accept from the work by Brain et al. (2012) that these sites should experience negligible sediment compaction, it is possible that slow subsidence has enhanced modern anthropogenic rates of sea-level rise at some of these sites. In the case of Figueira's (2012) sites, while slow subsidence of approximately identical rate at both the northern and southern South Island may seem too coincidental to be realistic, subsidence is entirely consistent with the vertical cGPS records from Golden Bay and Mahakipawa Hill, in the Northernmost South Island near Whanganui Inlet (GeoNet 2019b, 2019c), while subsidence of ~1.5 mm/yr in the northwest South Island, proximal to Whanganui Inlet, was observed by Tenzer and Fadil (2016), who integrated the local cGPS data into the ITRF2008 global reference frame. Intervals of subsidence and uplift of approximately equal magnitude are also documented in the cGPS record from Bluff (the closest cGPS record to both Waikawa Harbour and the Pounawea site of Gehrels et al. 2008) (GeoNet 2019d). However, we point out that the vertical responses to Fiordland earthquakes may differ between Bluff and the Waikawa and Pounawea salt marshes, due both to increasing distance from the source, and because the salt-marsh sites lie atop different tectonostratigraphic terranes with different basement geology to Bluff Harbour (detailed in King 2000).

Conclusions

Vertical land movement (VLM) needs to be considered as a factor in all New Zealand relative sea-level reconstructions, particularly at the multi-centennial scale where slow tectonic motion may be less obvious than in longer records. Even at presumed stable locations, VLM could explain enhanced or dampened rates of sea-level rise observed at the centennial scale. VLM could also help explain some of the contentious or variable observations from Holocene sea-level reconstructions in New Zealand and throughout the Pacific. The consequences of VLM-enhanced relative sea-level rise could be significant for large cities, most of which are situated on the coast. Of particular concern are Wellington, where the long-term effects of coupling-induced subsidence and SSEs are unknown, and Auckland, where satellite altimetry (Latimer et al. 2010; Samsonov et al. 2010) and high rates of sea-level rise in the Puhinui salt-marsh record (Grenfell et al. 2012) invite new questions regarding the city's tectonic stability. Dunedin, Napier and Christchurch are other cities where vulnerability to VLM-enhanced sea-level rise should be considered. Of particular note, Dunedin's cGPS record indicates variable subsidence rates up to 1.89 ± 0.56 mm/yr (Denys et al. 2020), whilst in South Dunedin, around 11,500 people live on lowlands reclaimed from coastal marshes and dunes, that could prove extremely vulnerable to future sea-level rise (Morris 2008). Centennial salt marsh sea-level records from these regions are currently either lacking or have wide uncertainties, and it is recommended that they are implemented in future work to contextualise trends in modern VLM, as they bridge a gap in scale between high-precision short-term instrumental records and long-term geological reconstructions.

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Data Sharing Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Figure 1. Maps displaying a) the trends of VLM in New Zealand as given by GeoNet's cGPS sites, relative to ITRF2008 (Tenzer and Fadil 2016), and the mean absolute sea-surface height change rise predicted by IPCC's AR4 AOGCMs under emissions scenario A1B (which assumes a balanced emphasis on all energy sources), for the interval 2080-2099, relative to the mean sea-surface height over the interval 1980-1999 (Ackerley et al. 2013). b) The 15-year mean degree of coupling between the Australian and subducting Pacific Plates (after Wallace and Beavan (2010)), note that subsidence is highest where coupling is greatest. All locations named in the paper are labelled for context. TVZ = Taupo Volcanic Zone (shaded region), SA = Souhern Alps (shaded region) BoP = Bay of Plenty, HB = Hawke's Bay, STB = South Taranaki Bight, TB = Tasman Bay.

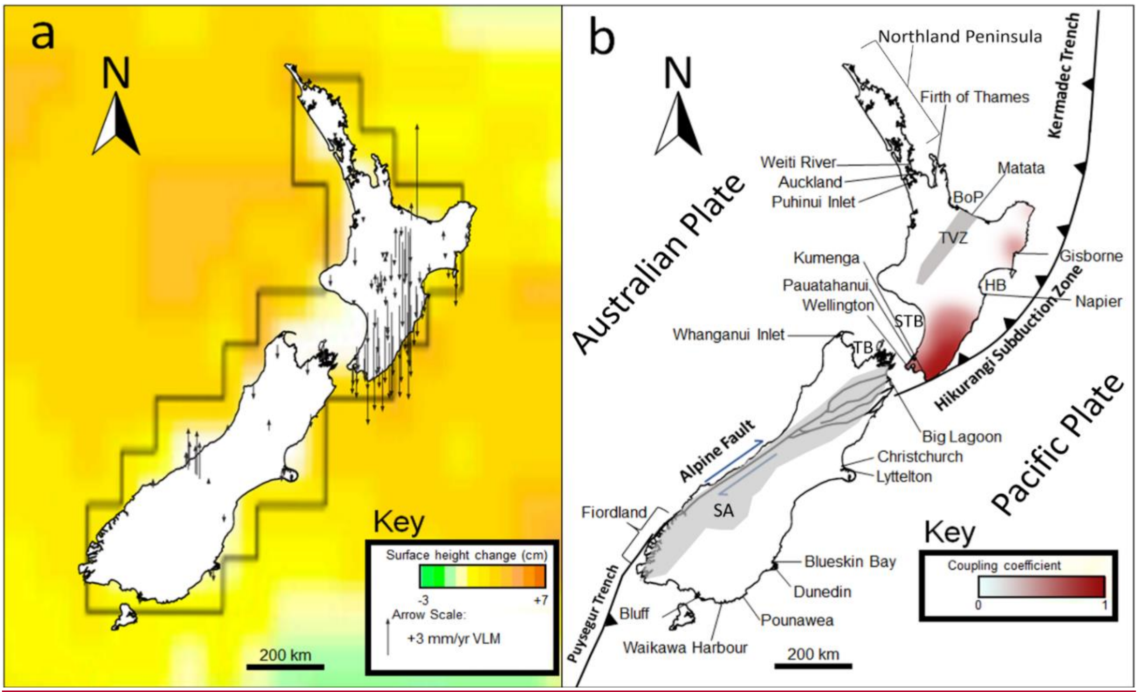


Figure 2. A summary of the methods of generating sea-level records in New Zealand, their temporal resolution and the time intervals for which they can be used. Tide-gauge data exists in New Zealand since at least 1900 (Hannah and Bell 2012). *The ten-day resolution listed for satellite altimetry is the resolution given by Ablain et al. (2019). ˣThe resolution given for salt-marsh micropalaeontology is dependent upon sedimentation rates, accuracy of dating techniques, and the differing speed of response

to environmental change by different microfossil groups.

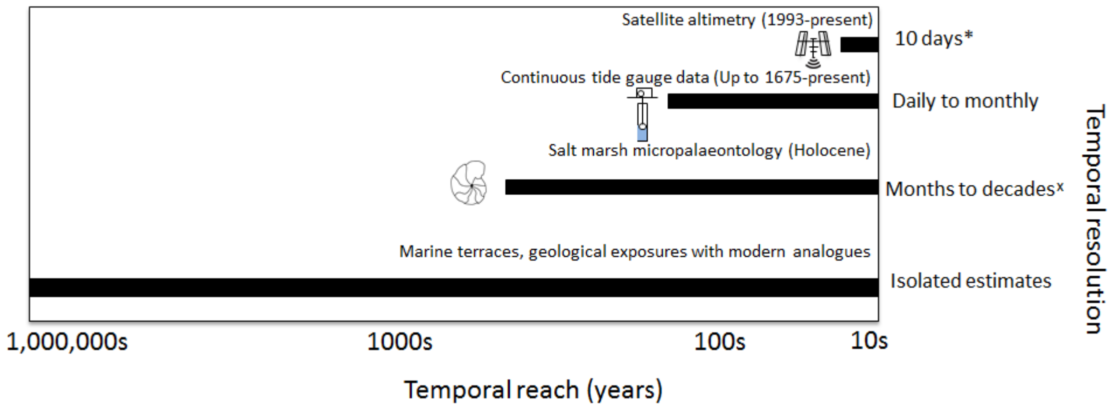


Figure 3 Map displaying the mean change in sea-surface height, relative to the Earth's geoid, around New Zealand September 1992 and May 2019. Data is averaged between all Topex/Poseidon and Jason 1 and 2 satellites during this interval, accessed via AVISO (2019).

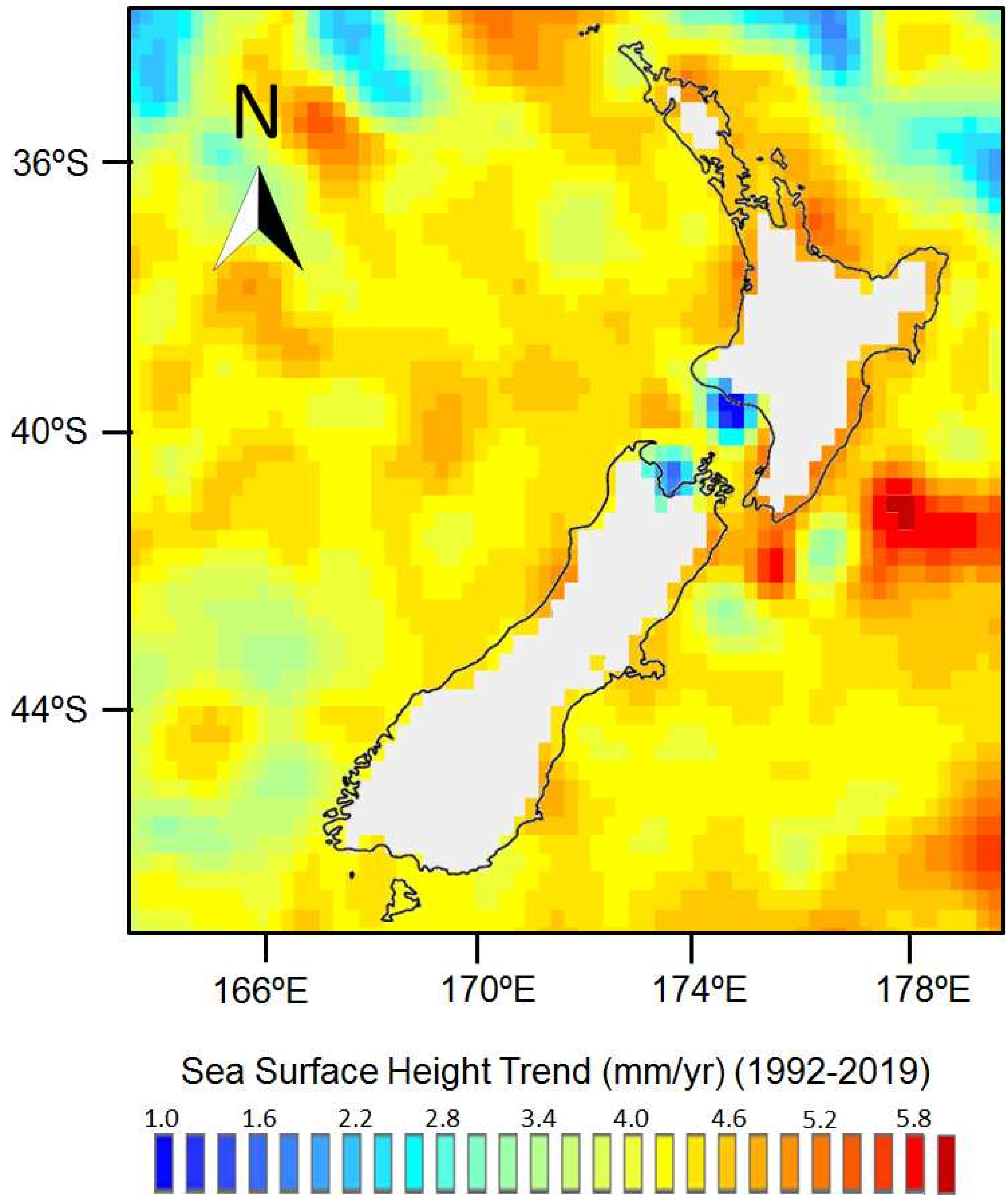


Figure 4. Holocene relative sea-level curves for New Zealand, as determined by Gibb (1986) (a), and three of the regional curves by Clement et al. (2016) (b-d). The locations and types of proxies used are detailed in the respective studies. As discussed in the text, the regional curves display an increasingly later onset of the first attainment of present mean sea-level (shaded) southward. The curves displayed on b-d reflect GIA-modelled predictions of relative sea-level, as discussed in the text of Clement et al. (2016). Modified after Gibb (1986) and Clement et al. (2016).

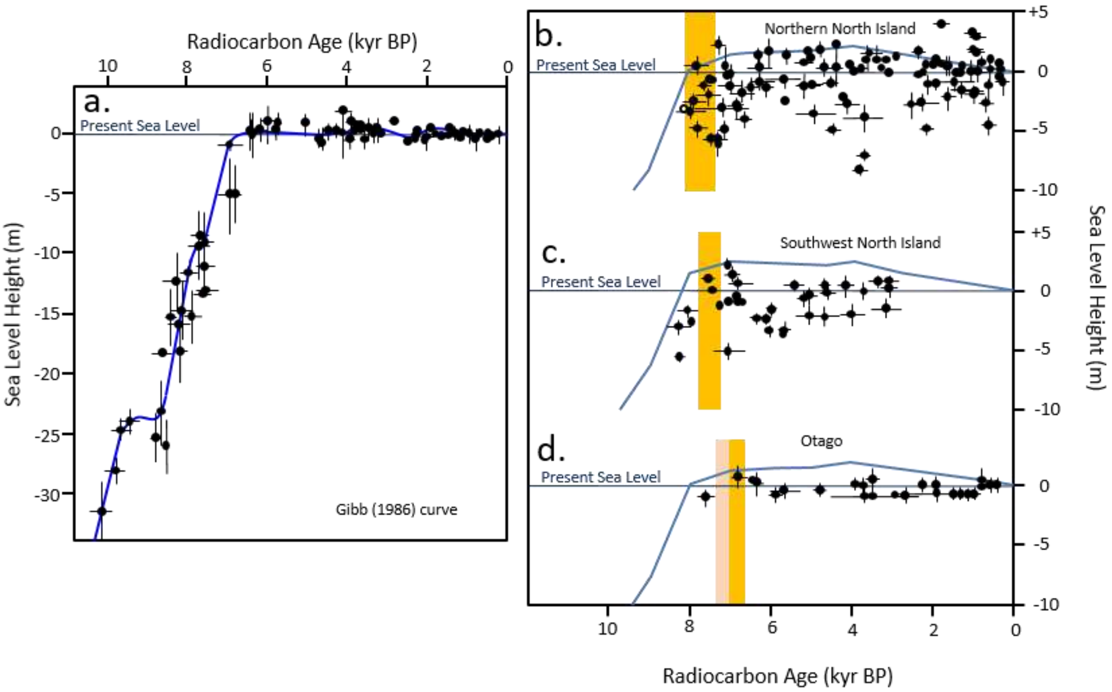
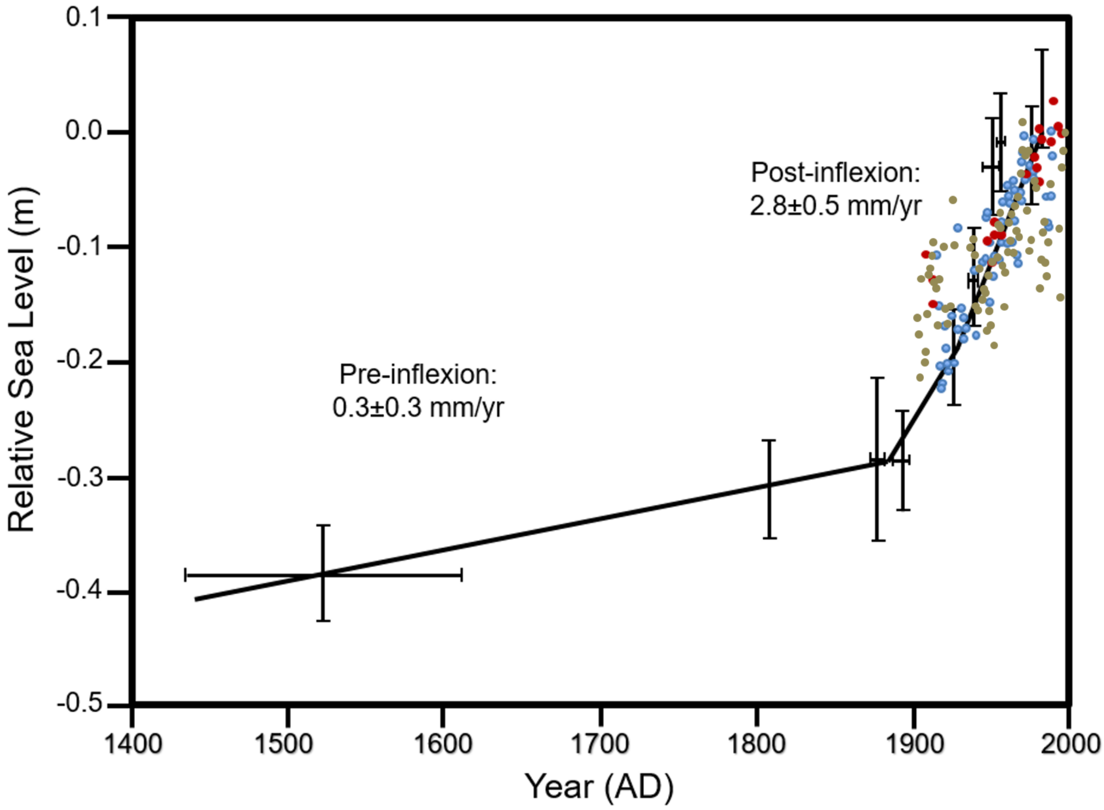


Figure 5. The relative sea-level curve derived from the Pounawea salt marsh by Gehrels et al. (2008), plotted with the annual sea-level data recorded at the Lyttelton (blue dots), Bluff (red dots), and Dunedin (green dots) tide gauges. Modified after Gehrels et al. (2008), with additional data from the Permanent Service for Mean Sea Level (Holgate et al., 2013).


Relative Sea Level (m)
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
1400
1500
1600
1700
1800
1900
2000
Year (AD)
Pre-inflexion:
0.3±0.3 mm/yr
Post-inflexion:
2.8±0.5 mm/yr