Te tai pari o Aotearoa – Future sea level rise around New Zealand's dynamic coastline

Richard Levy, Tim Naish, Rob Bell, Nick Golledge, Lara Clarke, Greg Garner, Ian Hamling, Zoe Heine, Sigrun Hreinsdottir, Judy Lawrence, Dan Lowry, Rebecca Priestley and Lauren Vargo

Meltwater flows off the Nansen Ice Shelf, Western Ross Sea, Antarctica (Photo: Won Sang Lee, Korea Polar Research Institute).

Introduction

Our planet is warming as greenhouse gas concentrations in Earth's atmosphere continue to increase. The warmer temperatures are causing sea level to rise as warming oceans expand and water from melting glaciers, ice caps and ice sheets flows into the sea. These rising seas will impact the things we value including private and public infrastructure and our coastal environment, much of which defines us as a nation. At risk will be dunes, coastal wetlands, estuaries, beaches, shellfish, fish nursery habitats like seagrass, groundwater and artesian water quality, and coastal habitats that provide storm surge protection and act as rich carbon sinks.

However, projecting just how much and how fast sea level will rise is difficult and this makes it challenging for us to plan into the future. This difficulty is mostly because we don't know enough about Antarctica's ice sheets nor how global emissions will track this century. Understanding Antarctica's likely contribution to future global sea level rise (SLR), and projecting sea level change around Aotearoa, is a major focus of the NZ SeaRise Programme (www.searise.nz/about) – a multi-million-dollar Endeavour Research Programme supported by our Ministry of Business, Innovation, and Employment (MBIE).

Uncertainty in Antarctic ice sheet response is not the only challenge. There is also public ambiguity and confusion regarding some aspects of climate change, SLR, and the widening uncertainty in future projections. As part of a public engagement workstream of the NZ SeaRise Programme, we surveyed 1000 New Zealanders to find out what they understood about SLR. Our survey showed that most people were correct in understanding that SLR in Aotearoa New Zealand could reach 1 m by 2100, or up to 2 m under a worst-case scenario. But it also showed that some people significantly overestimated how high sea level could reach, checking the survey boxes for 5 m, 8 m, 12 m, or even '15 m or more' of SLR. Thankfully, these higher amounts of SLR by 2100 are not physically possible, but a 1 m rise will still cause a lot of issues.

It's important that people have access to the right information – if they underestimate SLR there is a risk that our communities won't take the measures that are needed to adapt. But the same thing can happen if people overestimate SLR – research shows that overestimating the risk can lead to feelings of helplessness and a lack of willingness to act.

Our goal is to provide the public with the best location-specific information about current and future SLR – so that people can plan for the SLR that cannot be avoided, prepare for a range of uncertain future SLR, and act to avoid the higher SLR scenarios through deep carbon emission reductions.

In this chapter we outline the current state of knowledge regarding global and local SLR. We emphasise that New Zealanders should follow the New Zealand Coastal Hazard Guidance (Ministry for the Environment, 2017). Projections in the guidance are based on previous global assessments (Kopp et al., 2014) and indicate that sea level could rise by as much as 1.2 m by 2100 under high emissions scenarios. However, these projections do not include local influences such as vertical land movement due to tectonics, land compaction, or sediment accumulation.

The NZ SeaRise Programme is updating our national projections to incorporate state-of-the-art information regarding future response of Earth's large ice sheets and local non-climatic influences. These local projections will be used to help make local decisions to inform adaptation.

Sea level rise since 1900

Global mean sea level has risen approximately 18 cm since 1900 (Frederikse et al., 2020). For Aotearoa New Zealand, the observed local SLR averaged across our four main ports (Auckland/Tāmaki Makaurau, Wellington/Te Whanganui-a-Tara, Lyttleton/Ōhinehou, and Dunedin/Ōtepoti) is 21 ± 0.6 cm from 1900-2018 (MfE/StatsNZ, 2019). Whereas 20 cm may not seem like a lot, this historical rise in sea level has increased the frequency of coastal flooding events around the world (Lin et al., 2016) (see Figure 1) and future SLR will amplify this impact (Paulik et al., 2020).

Approximately two-thirds of the historical rise in sea level is due to an increase in ocean water mass as fresh water from melting ice sheets and glaciers enters the sea. The remaining third is due to expansion of the ocean as it warms. While the average rate of SLR through this time interval is 1.56 ± 0.33 mm yr^{-1} (Frederikse et al., 2020), measurements from satellites indicate SLR has accelerated over the past 25 years (Nerem et al., 2018) and that the current rate of rise is approximately 3 ± 0.4 mm yr^{-1}. Similarly, from the gauge records at our four main ports, the rate of rise in mean sea level has doubled since 1960 (MfE/Stats NZ, 2019). 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 (Hock et al., 2019; Rignot et al., 2019; Velicogna et al., 2014).

The most recent Intergovernmental Panel on Climate Change (IPCC) projections show global mean sea level will 'likely' (17%-83%)* rise between 29 cm and 1.1 m above a late 20th century baseline by 2100, depending on the greenhouse gas emissions pathway we follow (Oppenheimer et al., 2019). Whereas these projections primarily rely on outputs from process-based models, it is important to note that sea level will rise approximately 65 cm by 2100 if we simply extrapolate the observed rate of current acceleration (Nerem et al., 2018). We also emphasise that sea level will continue to rise well beyond 2100 for several centuries – albeit at a rate of rise tied intricately to how global emissions track. Evidence shows we must act now to reduce our greenhouse gas emissions and mitigate future warming and associated impacts.

* In the calibrated language of IPCC, 'likely' means a one-third probability that SLR by 2100 may lie outside the 'likely' range.

Sea level rise is not uniform

Unlike a uniform increase in water height that occurs as water is added to a bathtub, SLR varies across geographic location and over time – SLR at any specific location can depart markedly from the global average. So, while global mean sea level (GMSL) projections help us understand the total magnitude of change, they do not offer estimates that are always relevant at a local scale.

Local Sea Level (LSL) is the sea level experienced at a specific point on a coastline and has obvious relevance when it comes to planning and adapting to inevitable change. LSL is influenced by a range of complex climate change related processes including: ice sheet melt, oceanographic processes (including changing currents and thermal expansion), glacier and ice cap melt, and changes in land water storage (including both natural and human controlled mechanisms). Non-climatic geodynamic processes also influence LSL and include instantaneous changes in Earth's gravity field and rotation, and vertical land movement due to tectonics, sediment compaction, and glacial isostatic adjustment (or GIA, which is an ongoing response to previous episodes of ice sheet growth and retreat) (see Figure 2). Vertical land movement is particularly important in New Zealand as our nation sits across the active boundary between the Pacific and Australian plates. NZ SeaRise is integrating the latest understanding regarding these processes at global, regional, and local levels to generate Local Sea Level projections around the entire New Zealand coastline.

Ice sheet melt

Most of the fresh water on our planet's surface is locked up in the ice sheets on Greenland and Antarctica. The Greenland Ice Sheet contains enough ice to raise sea level by 7.4 m (Morlighem et al., 2017) while the Antarctic Ice Sheet holds enough frozen water to raise sea level by 58 m (Fretwell et al., 2013). The Greenland Ice Sheet is currently losing mass at approximately twice the pace of the Antarctic Ice Sheet and has already contributed approximately 5.2 cm of SLR since 1900 (Frederikse et al., 2020). However,

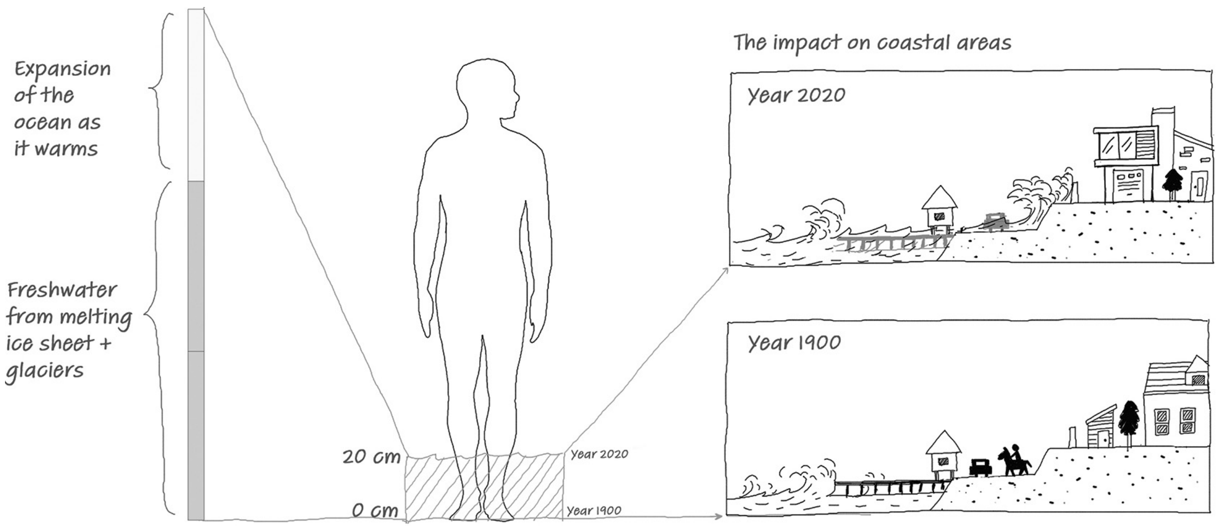

Figure 1: Sea level has risen by approximately 20 cm since 1900 causing an increase in the frequency of coastal flooding around the world. Future sea level rise will exacerbate this trend towards increased incidents and impacts or coastal flooding (Graphic: Katy Kelly, GNS Science).

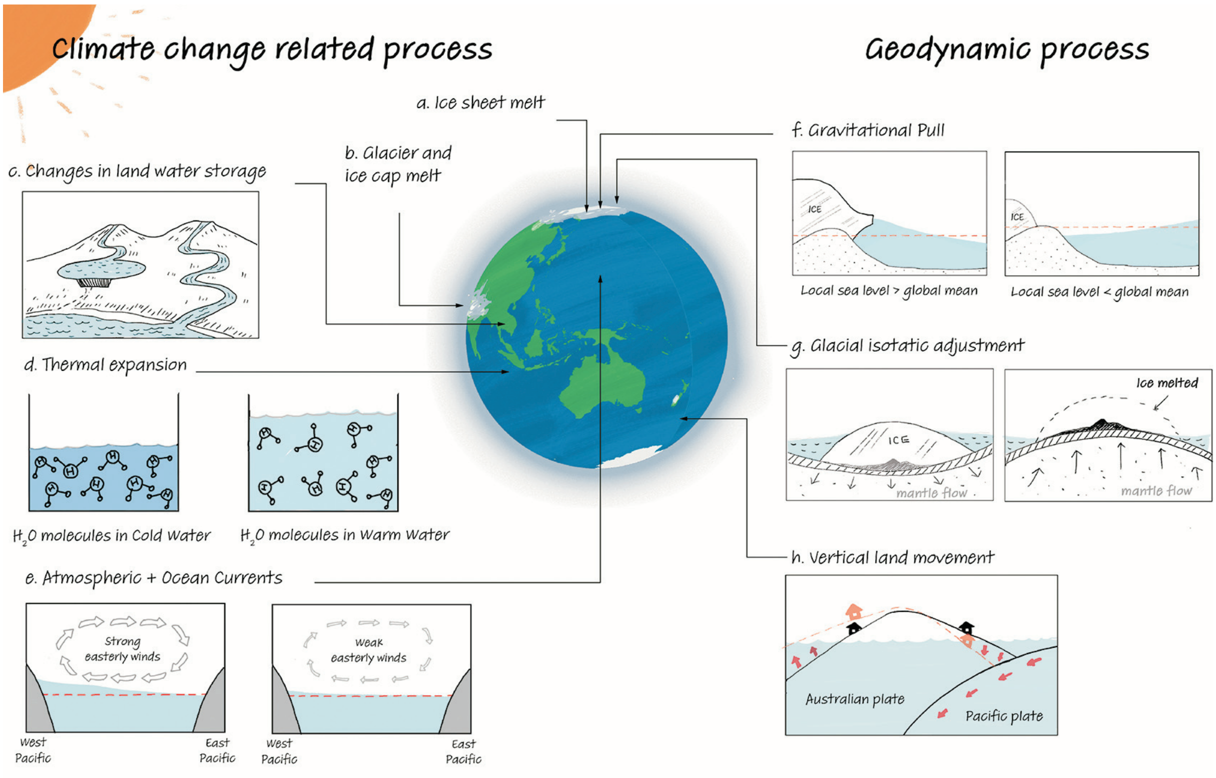

Figure 2: Processes that influence mean and local sea level. Each process is discussed in this chapter (Graphic: Katy Kelly, GNS Science).

large regions of the Antarctic Ice Sheet sit on ground below sea level and are vulnerable to ocean warming.

Whether Earth's ice sheets grow or shrink is determined by the balance between ice mass gain and mass loss (see Figures 3a and 3b). Ice sheets typically gain mass when snow falls and accumulates across inland regions and lose mass as ice and snow melts at their margins. Whereas the Antarctic Ice Sheet is currently gaining mass in some regions, the overall mass balance is negative (Rignot et al., 2019). The West Antarctic Ice Sheet is losing significant mass in areas where the ice is connected to the ocean.

Ice flow in many of these regions is accelerating as buttressing ice shelves, that provide resistive stress to the flow of the ice sheet towards the ocean, melt and thin due to warm ocean water flowing up and across Antarctica's continental shelves. When the ice shelves thin the grounded ice behind them flows faster, causing more thinning, which in turn allows previously grounded ice to float, forcing the grounding zone to retreat inland (see Figures 3a and 3b). This process speeds up, and may be unstoppable, in areas where the bedrock surface beneath the ice sheet slopes inwards toward the centre of the ice sheet (retrograde slope), as it does under much of the West Antarctic Ice Sheet. This process of Marine Ice Sheet Instability can lead to runaway retreat as the ice flux across the grounding zone increases and surface mass accumulation feeding the ice shelf margin remains stable or decreases. Science suggests we may reach a tipping point if global mean temperatures warm by 2°C, at which point positive feedbacks and dynamic processes such as Marine Ice Sheet Instability produce rates of SLR at least an order of magnitude greater than those observed now (Pattyn, 2018) and cause ice loss for centuries to come (Golledge et al., 2015).

Despite our ever-improving understanding of ice sheet dynamics, difficulties associated with modelling polar ice sheet response to climate change remains the largest source of uncertainty in sea level projections. One of the primary objectives of the NZ SeaRise Programme and the related Antarctic Ice Dynamics Project in the Antarctic Science Platform (http://antarcticscienceplatform.org.nz), is to generate new constraints on ice sheet behaviour from historical records. These constraints are used to test and improve ice flow models that are commonly used to predict how the Greenland and Antarctic ice sheets change as air and ocean temperatures increase. So far, these models have differed significantly in their projections of future ice sheet contributions to the global sea level. To help address this issue, the recent Ice Sheet Model Intercomparison Project 6 (ISMIP6) sought to understand these differences and improve model performance by using the most up-to-date atmospheric and oceanic influences from state-of-the-art climate models. This international effort, which brought together ice, ocean and atmosphere scientists, has generated new estimates of how much Earth's melting ice sheets could contribute to global sea level change by 2100. If greenhouse gas emissions continue apace, the Greenland and Antarctic ice sheets could together contribute more than 44 cm of global SLR – and that's beyond the amount that has already been set in motion by Earth's warming climate (Goelzer et al., 2020; Seroussi et al., 2020).

ISMIP6 investigated two different greenhouse gas emissions scenarios to predict SLR between 2015 and 2100: one with carbon emissions increasing rapidly, and another with lower emissions. In the high emissions scenario, the models show that melting of the Greenland Ice Sheet leads to an additional global SLR of about 9 cm by 2100. In the lower emissions scenario, the ice loss would raise global sea level by about 3 cm. This rise in sea level is on top of the anticipated future increase due to Greenland Ice Sheet melt that will occur because of warming that has already occurred since pre-industrial times. Previous studies have estimated that 'locked

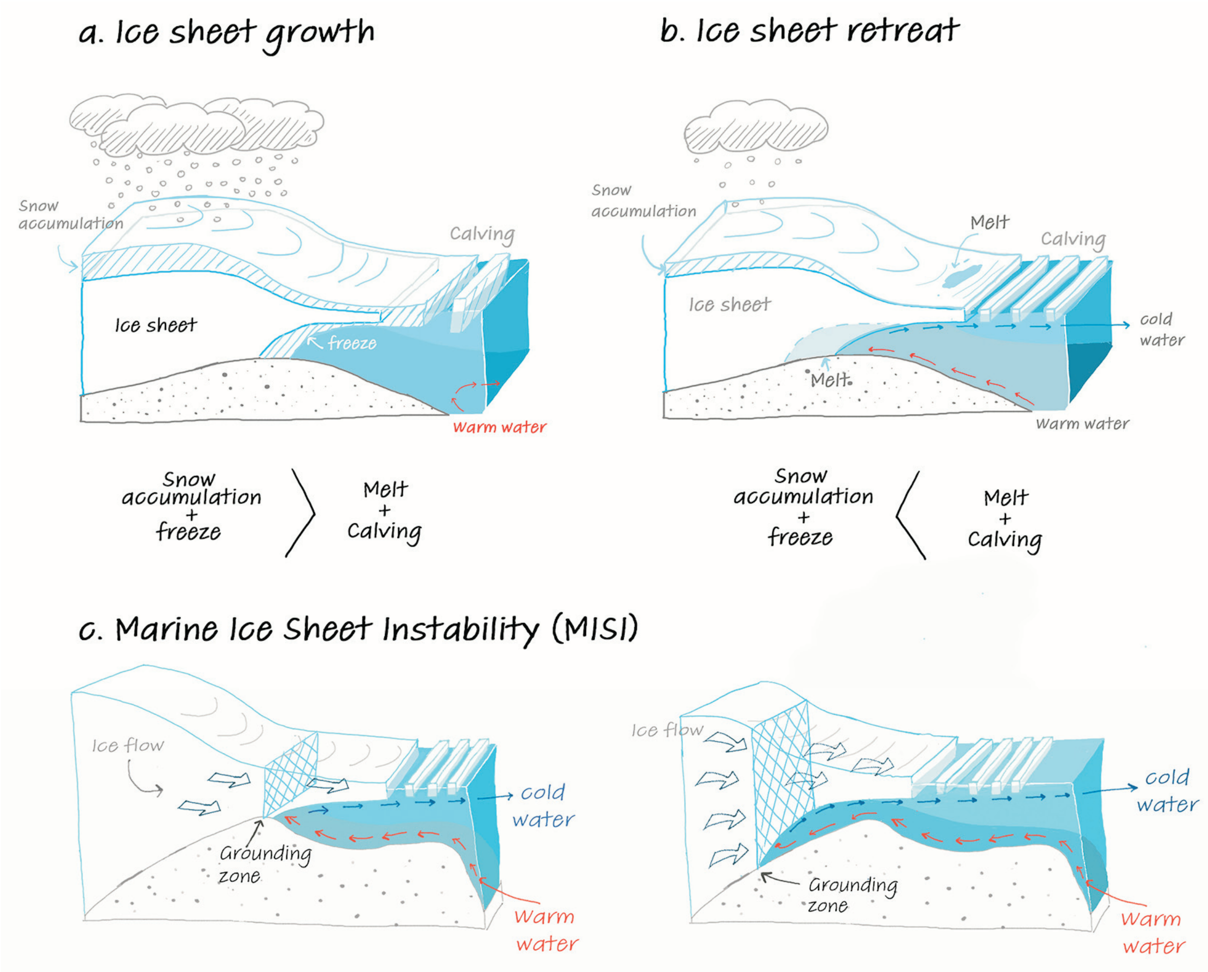

Figure 3: Processes that influence ice sheet advance (a) and retreat (b) (mass balance); (c) Marine Ice Sheet Instability can contribute to ice sheet collapse even when climatic warming slows or stops causing an unstoppable commitment to future sea level rise (Graphic: Katy Kelly, GNS Science).

in' contribution to global SLR by 2100 to be about 6 mm for the Greenland Ice Sheet. The models also indicate that the ice mass loss is largely from melting on the surface of the ice sheet.

In contrast to Greenland, ice loss from the Antarctic Ice Sheet is more difficult to predict. In West Antarctica, warm ocean currents erode the bottom of large floating ice shelves, causing loss; while the vast East Antarctic ice sheet may gain mass, as warmer temperatures cause increased snowfall. This results in a greater range of future possibilities, from ice sheet growth that decreases sea level by 7.8 cm to ice sheet melt that increases sea level by 30 cm by 2100. Ice sheet projections show the greatest loss in West Antarctica, where melting ice may cause up to 18 cm of SLR by 2100 under the warmest conditions. The main cause of the differences between the Antarctic Ice Sheet model projections is the melting underneath the floating ice shelves that surround Antarctica (see Figures 3 and 4). Many of the models underestimate modern melt rates at the base of ice shelves. Better understanding of ocean circulation underneath the ice shelves is therefore critical for improving these ice flow models. But for now, we need to live with, and adopt adaptive approaches to work with, the uncertainty.

Oceanographic processes

Increasing temperatures generally cause materials to become less dense and therefore increase the material's volume per unit of mass. When this process of thermal expansion occurs in the world's oceans, sea level increases even when the water mass remains constant. The world's oceans have absorbed 93% of the increase in heat in the climate system, and approximately one-third of the observed increase in sea level since 1900 is due to thermal expansion of the ocean (Frederikse et al., 2020).

Regional sea level is affected by variations in atmospheric and oceanic circulation. Wind stress is the main driver of changes in regional ocean height and these changes are connected to climate modes including El Niño/Southern Oscillation (2 to 4 year cycles), Pacific Decadal Oscillation (20 to 30 year cycles), and the Southern Annular Mode ('see-saw' of air mass between mid and southern latitudes). Differential heating and freshening of layers in the ocean also influence variations in global sea surface height. Together, these factors can cause regional sea level trends as much as four times the rate of global mean sea level (GMSL). Perhaps nowhere is this effect more apparent than the Western Tropical Pacific, where satellite altimetry indicates sea level is rising at a rate over 1 cm yr^{-1} (Zhang and Church, 2012) (the current trend in GMSL is approximately 3 mm yr^{-1}) (see Figure 5).

Glacier and ice cap melt

Glaciers (outside of Antarctica and Greenland) have been the largest contributor to SLR over most of the twentieth century (Frederikse et al., 2020) and are expected to continue

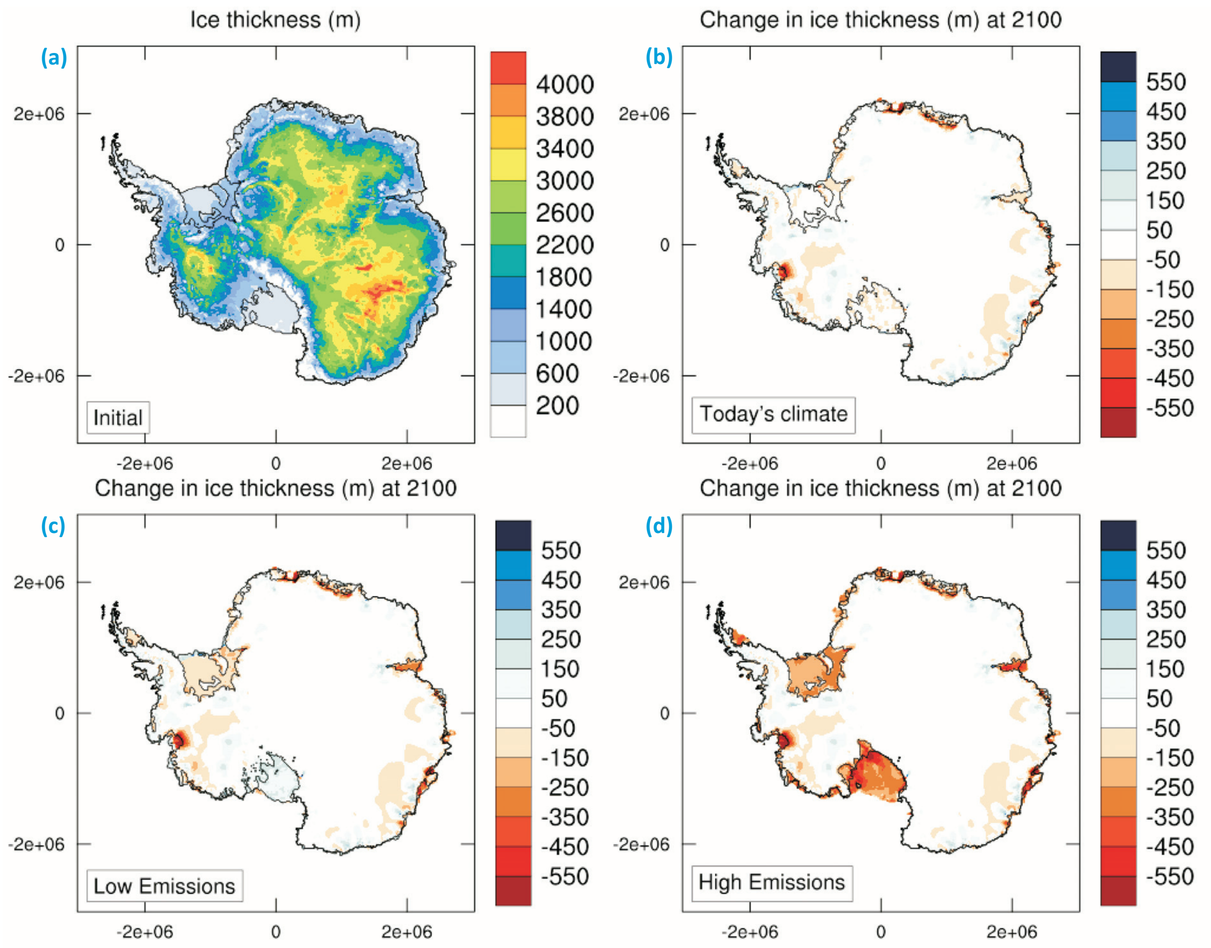

Figure 4: Example of model outputs from the Parallel Ice Sheet Model highlighting the influence of basal melt on ice thickness under different future climate scenarios including (b) a continuation of today's climate, (c) a low emissions future, and (d) a high emissions future.

to melt and contribute to sea level throughout this century. Glaciers store approximately 1% of global ice volume, enough to raise sea level by 32 ± 8 cm if they were to completely melt. Overall, glaciers will likely lose around 18 ± 7% of their ice mass in a low emission scenario (Representative Concentration Pathway, RCP 2.6), or around 36 ± 11% in a high emissions scenario (RCP 8.5), contributing between 9.4 ± 2.5 and 20 ± 4.4 cm to SLR by 2100 (Hock et al., 2019; Marzeion et al., 2020).

New Zealand glacier ice volume was approximately 73 km^3 in 1978, or enough to raise sea level by 0.2 mm if completely melted (Farinotti et al., 2019). Monitoring of New Zealand glaciers since the late 1970s shows that ice has been melting

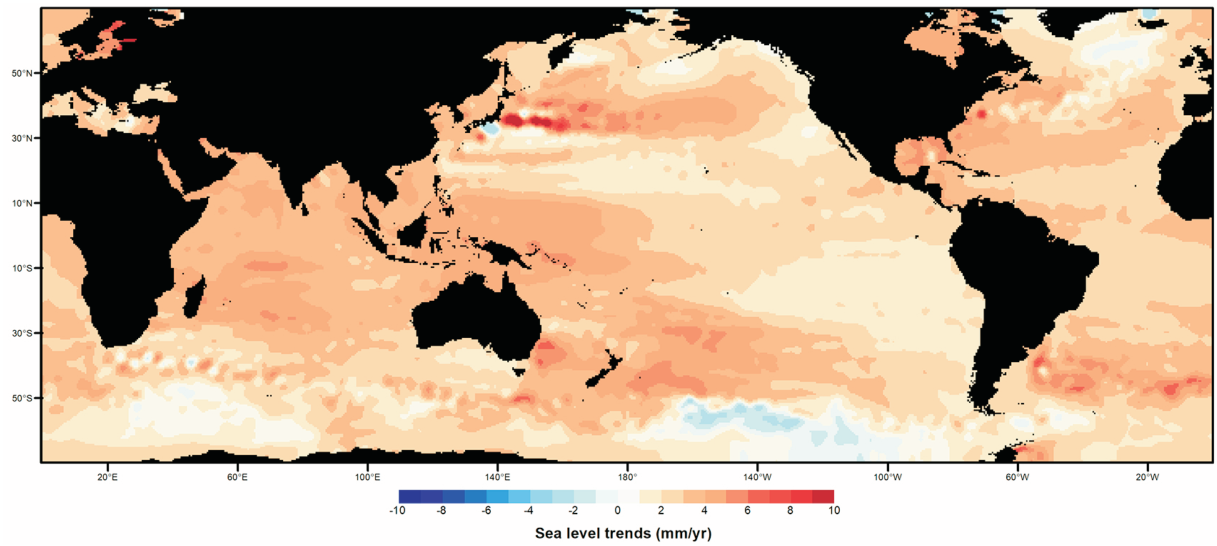

Figure 5: Estimates of local sea level trends for the period from 1993 to 2020 based on measurements from satellite radar altimeters (TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3). Altimetry data are provided by the NOAA Laboratory for Satellite Altimetry.

and retreating, contributing to SLR and influencing water resources and tourism access. Digital elevation models generated from aerial images of New Zealand glaciers (Vargo et al., 2017) show that Brewster Glacier lost approximately 14.4 million m^3 of ice over three years from March 2016 through to March 2019. From 2009 to 2018, Franz Josef Glacier/Kā Roimata o Hine Hukatere retreated 1.4 km, and Fox Glacier/Te Moeka o Tuawe retreated 0.9 km (Purdie et al., 2014; World Glacier Monitoring Service, 2020). A subset of fourteen New Zealand glaciers decreased in area by 21% from 1978 through to 2016 (Baumann et al., 2020). Modelling future changes in New Zealand glaciers shows that these trends in glacier mass loss will continue over this next century (Marzeion et al., 2020).

Terrestrial water storage

Human activity has had a dramatic effect on Earth's surface with significant impact on water exchange between land, atmosphere, and ocean (Wada et al., 2017). For example, natural patterns of river flow have been altered as part of irrigation and flood protection schemes. Construction of reservoirs and artificial lakes to store water for power generation, drinking water supply, and irrigation has reduced the outflow of water to the sea (see Figure 2). In contrast, river runoff has increased due to groundwater extraction, wetland destruction and subsequent storage losses, deforestation, and hardening of surfaces in urban catchments. These activities affect the amount of water flowing from the land to the sea and have had a negative contribution to global mean sea level over the past 120 years (Frederikse et al., 2020). This negative contribution is primarily caused by the construction of reservoirs and dams that began in the 1950s and peaked in the 1970s. These activities produced a cumulative decrease in global sea level of 2.5 to 3 cm.

Future change in terrestrial water storage is closely tied to estimated changes in global population. However current projections suggest changes in terrestrial water storage will contribute a likely range between -1 and 9 cm to sea level between 2081 and 2100 (Oppenheimer et al., 2019).

Gravitational pull and Earth's rotation

The massive ice sheets in Antarctica and Greenland exert a gravitational pull on the ocean around them, causing sea level to be higher next to the ice sheets (see Figures 2 and 6). So, when ice in Greenland melts, sea level drops next to the ice sheet and rises at locations far away from Greenland – including in Aotearoa. The opposite occurs when Antarctica's ice sheets melt because the decreasing ice mass exerts less pull on the nearby ocean and sea level near the ice sheet margin falls. Each ice sheet produces a distinct sea level fingerprint of change (Mitrovica et al., 2009).

Redistribution of mass around the planet due to changes in ice sheet volume and the location of ocean water also affects Earth's rotation, which has a 'feedback' influence on Local Sea Level. For example, a full collapse of the West Antarctic Ice Sheet displaces the south rotation pole towards West Antarctica driving a sea level increase in North America and the Indian Ocean that is greater than the global mean (Mitrovica et al., 2009).

Vertical land movement

Vertical land movement (VLM) has a direct impact on local sea level along the world's coastlines. The shape of Earth's land surface is slowly changing in response to the retreat and final disappearance of massive ice sheets that covered large areas of our planet during the last ice age, 20,000 years ago. In the parts of the world that carried the weight of huge ice sheets – much of the Northern Hemisphere, Antarctica's continental shelves, and New Zealand's South Island – the land is now slowly rising. This process is called glacial isostatic adjustment (GIA). Other areas of land are subsiding as the Earth's mantle flows away from these regions and toward the areas of glacial rebound. These

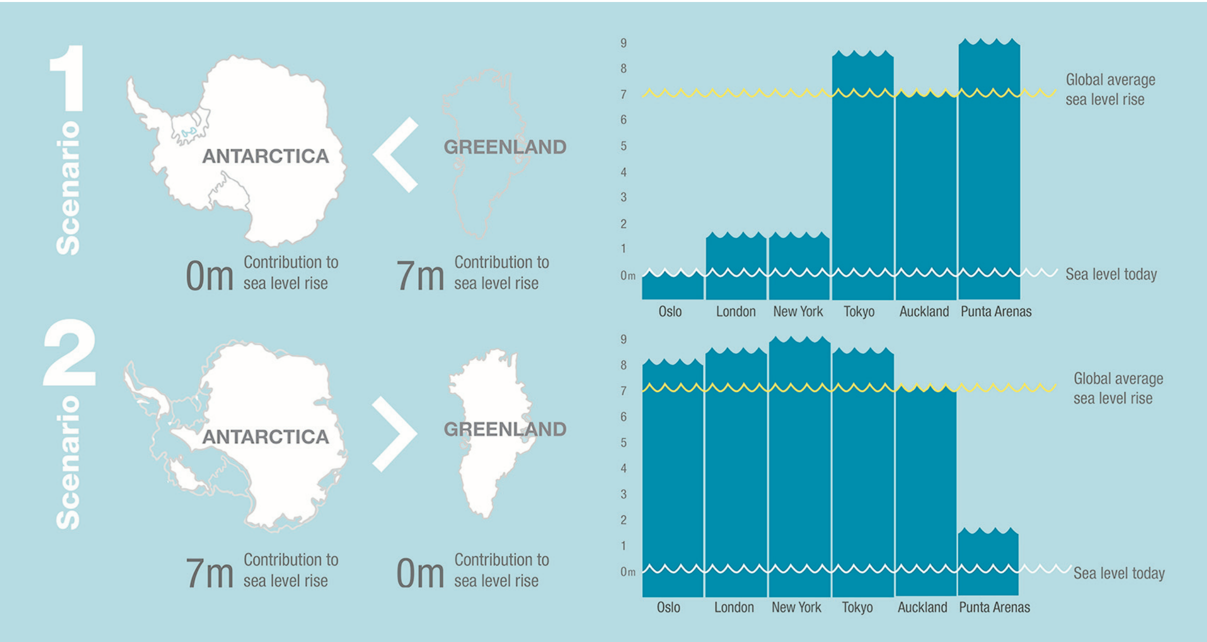

Figure 6: Schematic illustrating the effect of gravitational pull on sea level. Under scenario 1, if the entire Greenland ice sheet were to melt, global mean sea level would increase by approximately 7 m. In Oslo, close to the ice sheet, sea level would not change. In London and New York, it would rise by 1 to 2 m. In Southern Hemisphere cities like Punta Arenas, sea level will rise by 9 m. In scenario 2, if Antarctica's ice sheets melt, the opposite pattern in sea level rise would occur.

changes in the shape of Earth's crust cause local sea level to fall in some regions and rise in others.

The vertical position of our coastlines is also changing due to the movement of tectonic plates. New Zealanders understand the impact of plate movement better than most people in the world. We live on a plate boundary and our coastline is always changing. Scientists can measure the amount of vertical land movement using global positioning satellite technology and radar systems mounted on Earth observing satellites such as Envisat and Sentinel. These instruments show us that parts of our coast are going up at a rate of 1 cm every year and others are sinking by as much as 5 mm per year.

Areas of land that are going up reduce the effect of global SLR and can even cause a local fall in sea level – at least in the short term. But local SLR will be higher in areas that continue to subside. Subsidence often happens in low lying areas, or deep-seated sedimentary basins or deltas, that are usually filled with soft sediment. These sediments compact over time causing the land to sink. This sinking can be accelerated when we pump water out of the basin to use the land for farming and industry or to build houses and airports. These low-lying subsiding regions are the most susceptible to SLR. The Waikato Coast, Hauraki Plains, mid to lower eastern North Island, Marlborough, Nelson, Wellington, and Dunedin are regions where SLR will be faster than the global and regional means due to land subsidence.

Measuring vertical movement along New Zealand's entire approximately 15,000 km-long coastline through traditional approaches, such as with tide gauges, is near impossible. To help overcome this problem we have combined spaceborne geodetic observations from interferometric Synthetic Aperture Radar (InSAR) and Global Navigation Satellite Systems (GNSS) to increase both the spatial extent and density of VLM estimates around the entire New Zealand coastline (see Figure 7).

New Zealand's permanent GNSS network (https://www.geonet.org.nz/data/types/geodetic) provides precise surface location data that can be used to accurately determine both vertical and lateral movement at sites along our coast, including our tide gauges (Denys et al., 2020). However, the network is generally too sparse to provide continuous estimates of the VLM across many regions of interest including coastal deltas and sedimentary basins, where our urban areas are often located. However, by integrating GNSS with InSAR observations, which provides data at approximately 100 m spatial resolution, we can generate an almost continuous coastal estimate of the VLM (see Figure 7). InSAR utilises radar satellites which illuminate the ground's surface as they orbit the Earth. When received by the satellite, the reflected radar signals give a measurement of the distance between the ground and the satellite. By collecting data acquired on successive passes of the satellite instrument, we can examine the interference patterns produced by the electromagnetic waves (interferograms) to identify millimetre scale surface displacements over thousands of square kilometres. Unlike optical satellites, which rely on the sun to illuminate the Earth's surface and whose view can be obscured by clouds, radar systems are able to see through clouds, and with their own radiation source, acquire images at any time of day or night.

To generate a first VLM map of New Zealand's coast (see Figure 7), we have used historical InSAR images acquired by the European Space Agency's Envisat satellite between 2003 and 2011. One advantage of using this time interval is that we can minimise the influence of some of the larger earthquakes which have struck New Zealand in recent years, starting in Dusky Sound in 2009. Using all the available images, we have generated more than 1000 individual

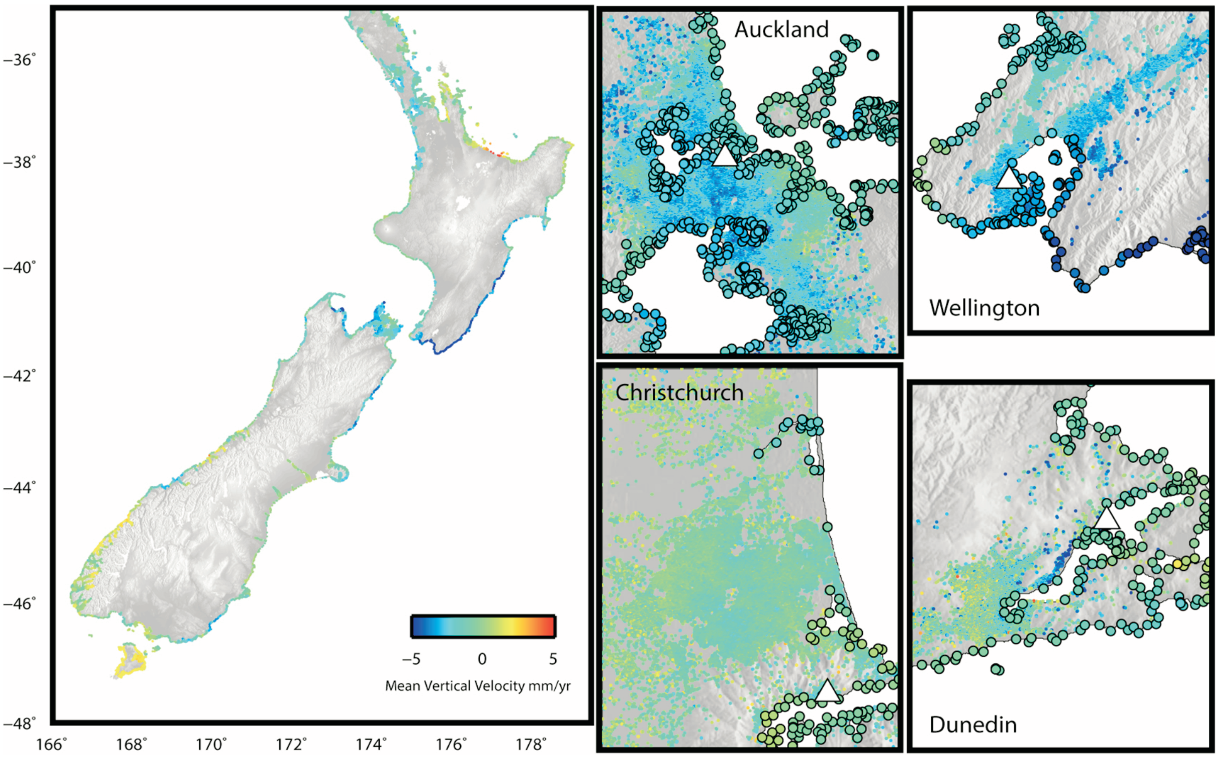

Figure 7: Vertical land motion map for New Zealand with insets for our four major coastal cities (-ve values = subsidence, +ve values = uplift). Circles indicate location and mean vertical velocity of coastal data areas used for sea level projections. White triangles indicate tide gauge locations.

interferograms which are used to estimate the best fitting vertical displacement rate over the approximately eight-year observation period. GNSS data are used to help correct the InSAR observations and put them in a consistent reference frame. In a final step, for any given point along the coast we average all the VLM estimates, from both InSAR and GNSS, within a 5 km radius.

Our preliminary results provide the first almost continuous estimate of the VLM around the entire New Zealand coastline (see Figure 7). The estimated rates show some interesting variations in VLM in different areas of the country. Along the east coast of the North Island, there is evidence of extensive subsidence of up to approximately 5 mm yr^{-1} with a general increase in magnitude from north to south. This variation can be largely attributed to the ongoing subduction of the Pacific Plate beneath the North Island. Across the Bay of Plenty, there is an approximately 30 km-long region of uplift which, over the observation period, reached approximately 10 mm yr^{-1}. This has been attributed to a deep magmatic intrusion associated with the 2005-2009 Matata earthquake swarm (Hamling et al., 2016). Since the end of the swarm in 2009, GNSS data show a drop in the uplift rates highlighting the transient nature of some of the VLM observations. The top of the South Island north of Kaikōura shows subsidence of a 2-3 mm yr^{-1}, but this area was dramatically uplifted during the 2016 earthquake. With the additional complexity of events such as the Matata earthquake swarm and Kaikōura earthquake, estimating the evolution of the coastal VLM will pose an ongoing challenge.

Probabilistic projections for Aotearoa New Zealand

We have generated Local Sea Level (LSL) projections for New Zealand, which are an aggregate sum of individual sources that contribute to sea level change (outlined in previous text). The workflow for these projections is primarily based on a probabilistic methodology for a given RCP and extreme sea level tail distribution, that has been used in local to national scale sea level change assessment in the United States (Kopp et al., 2014). This workflow has been modified to include high-resolution VLM data for New Zealand. The methodology for each contributor is briefly summarised in Box 1.

In this chapter we show new LSL change projections that were produced using the described methods (Box 1) for the tide gauge at Port Chalmers (DunedinTG: -45.814313938, 170.629403272) and an area of reclaimed land along the harbourside boundary of Dunedin City (DunedinHS: -45.89101, 170.508) (see Figure 8). Separate probabilistic

Box 1: How we generate sea level projections

Projections of ice-sheet contributions to global mean sea level change are generated from calibrated time-dependent log-normal distributions fit to the projected rates of equivalent sea level change from the IPCC Special Report on the Ocean and Cryosphere Change (SROCC) (Oppenheimer et al., 2019) and published expert elicitation rates. The SROCC projections inform the median and 'likely' range (16.7th-83.3rd percentiles) of the distribution while the expert elicitation informs the shape of the tails. A rate is sampled at each time step from the fitted distribution and used to project linearly to the next time step where the process is repeated. Samples from these fitted distributions are correlated in time to ensure a single projected time series is self-consistent. The resulting projections of ice sheet melt contributions to the global mean sea level is then localised using a sea level fingerprint that accounts for the uneven distribution of mass across the world's oceans.

Projections of glacier and ice cap contributions to global mean sea level change are generated by fitting a multi-variate t-distribution to ice mass change with a mean and covariance derived from an ensemble of output from process-based models for 17 different source regions. Global contributions are then localised using the sea level fingerprint method like the ice sheets.

Global sea level change due to thermal expansion of ocean water and the local sea level change due to regional steric and dynamic effects are projected using a t-distribution calibrated to the mean and covariance of a multi-model ensemble of Climate Model Intercomparison 5 (CMIP5) models. Each model is represented in this ensemble with a single model realisation (i.e. one model, one vote). A linear correction is applied to the output from each model in the CMIP5 ensemble due to model drift. Furthermore, the standard deviation of the fitted t-distributions is scaled by a factor of 1.7 to be consistent with the AR5 judgement that the 5th-95th percentiles of the CMIP5 model ensemble represent the likely range for global mean thermal expansion.

Global mean sea level change due to terrestrial water storage is estimated by the relationship between changes in reservoir impoundment, ground water depletion, and global population. Reservoir impoundment is estimated with a sigmoidal function response to global population as a function of time. A conservative 2-sigma error in the resulting impoundment of ± 50% is applied. Ground water depletion is represented by a linear response to global population as a function of time. The slope of the linear relationship is sampled from a normal distribution with a mean and standard deviation estimated from model-based studies. An additional 2-sigma error of ± 50% can account for the reported errors in the model-based studies. Global population projections from the Shared Socioeconomic Pathways (SSPs) are used to drive these terrestrial water storage models to year 2100 at which point population rates provided by the United Nations for low, middle, and high scenarios are used to extend the SSP population projections to year 2150.

Rates of vertical land movement were derived from InSAR and Global Positioning System (GPS) measurements with high-spatial resolution obtained from a campaign spanning years 2003-2011. These observed rates and the reported associated errors are used as the moments of a normal distribution from which a rate is sampled and used to project forward in time.

projections for three greenhouse-gas emissions scenarios (Representative Concentration Pathway (RCP) 2.6, RCP 4.5, and RCP 8.5) were generated for the years 2020-2150 in ten-year increments. Projections were generated both with and without vertical land movement to highlight the effect that our dynamic coastline can have on SLR. Rates of vertical land movement at the tide gauge location were determined from the GNSS station (DunedinTG-GPS: -1.25 ± 0.10 mm yr^{-1}) and InSAR data averaged across a 5 km area (DunedinTG-InSAR: -0.75 ± 0.14 mm yr^{-1}) and from InSAR at the harbourside location (DunedinHS: -2.40 ± 1.40 mm yr^{-1}). All projections here report changes in sea level above a zero-baseline set at 2005.

Impacts, risk, and adaptation

Vulnerability of our coastal environment to SLR is already apparent. Exposure assessments show that, after one metre of SLR, around 125,600 buildings, at a replacement value of NZ$38 billion, along with 178,000 residents, could be exposed to future extreme storm-tide events (Paulik et al., 2020). A national-scale assessment of local government assets determined that over NZ$5 billion of public council assets (reserves, buildings, utility networks, roads) are also exposed to a one metre rise in sea level, without considering the impact of extreme storm-tide events (Local Government New Zealand, 2019). These risk exposure assessments point to the challenge ahead for infrastructure in the low-lying coastal areas of Aotearoa New Zealand. Our natural coastal and estuarine environments will also be affected as sea level rises. They will change and migrate inland, but only if they have space to do so – otherwise rising sea levels will diminish these intertidal areas (see 'Estuaries and lowland brackish habitats', p55).

New Zealand's national coastal policy (Department of Conservation, 2010) requires that coastal hazard risk assessments consider the impact of SLR for at least 100 years into the future. Global mean sea level will likely rise between 12 and 26 cm relative to a baseline from 1986 to 2005 by 2050 (Oppenheimer et al., 2019), but sea level projections beyond this time become subject to wider and deeper uncertainty. This is due largely to ambiguity surrounding the rate at which global greenhouse gas emissions can be reduced and whether runaway polar ice-sheet instabilities occur once a tipping point is reached. Despite this uncertainty, practitioners are required to consider best available information on the cumulative and likely effects of climate change when planning for coastal activities, uses, and development. Furthermore, the effect of SLR on communities and our natural environmental systems will differ depending on location. To ensure just and equitable adaptation to SLR, up-to-date and credible information and evidence should be made available to tangata whenua, communities, central and local government, the judiciary and elected representatives. This evidence can then be used to develop adaptation plans. Our national coastal guidance (Ministry for the Environment, 2017) recommends a dynamic adaptive pathways approach to accommodate the range of uncertainty.

Clearly there is a need to present SLR information so it can be used by communities as they work to establish adaptation plans. To this end, researchers within the NZ SeaRise

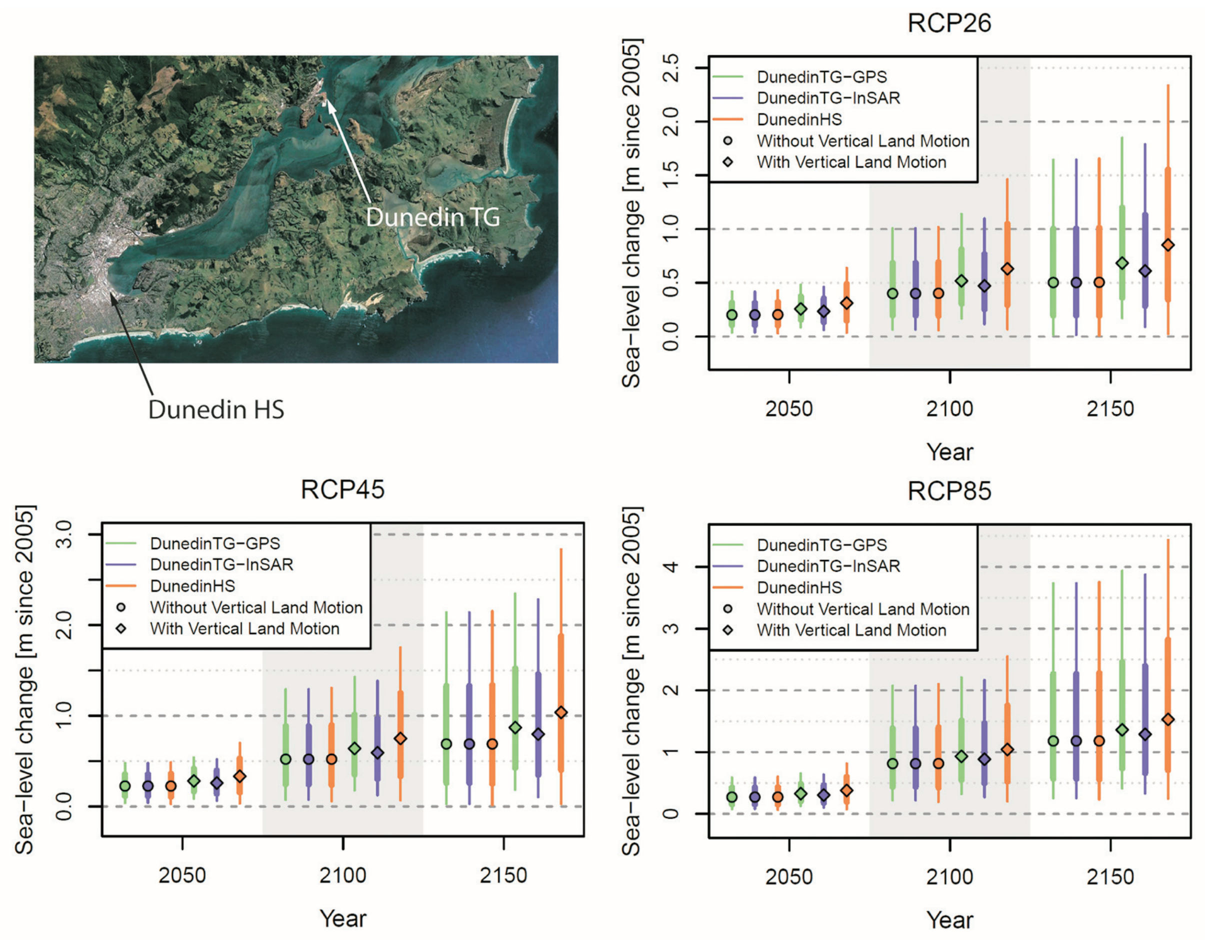

Figure 8: Preliminary Local Sea Level projections for two locations in the Dunedin region under RCP 2.6, 4.5, and 8.5 with and without vertical land movement. Plot bars/symbols – Thin = 5-95th, Thick = 16.7-83.3rd, Circle/Triangle = 50th (percentiles).

Programme and the Resilience to Nature's Challenges (RNC) National Science Challenge (https://resiliencechallenge.nz) are developing a sea level rise toolkit designed for a range of users. This toolkit will likely include an online portal with local SLR projections, vertical land movement data, links to relevant peer reviewed climate change information, and guidance for policy and planning. The toolkit will provide access to scientific evidence that will help agencies, business, and communities to understand the SLR hazard and will inform risk and vulnerability assessments. Access to this underpinning information will assist the discussion and development of planning, funding, design and engineering responses for application at national and local levels. The NZ SeaRise team will begin more active engagement in 2021, alongside the Science Challenges, to design this toolkit which is expected to be available at the end of the NZ SeaRise Programme in late 2022.

References

Baumann, S, et al. (2020). Updated inventory of glacier ice in New Zealand based on 2016 satellite imagery. *Journal of Glaciology* 1-14.

Denys, PH, et al. (2020). Sea level rise in New Zealand: The effect of vertical land motion on century-long tide gauge records in a tectonically active region. *Journal of Geophysical Research: Solid Earth* 125(1), e2019JB018055. doi:10.1029/2019jb018055

Department of Conservation (2010). *New Zealand Coastal Policy Statement 2010*. Wellington, New Zealand: Department of Conservation.

Farinotti, D, et al. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. *Nature Geoscience* 12(3), 168-173. doi:10.1038/s41561-019-0300-3

Frederikse, T, et al. (2020). The causes of sea-level rise since 1900. *Nature* 584(7821), 393-397. doi:10.1038/s41586-020-2591-3

Fretwell, P, et al. (2013). Bedmap2: Improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere* 7(1), 375-393. doi:10.5194/tc-7-375-2013

Goelzer, H, et al. (2020). The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6. *The Cryosphere Discuss., 2020*, 1-43. doi:10.5194/tc-2019-319

Golledge, NR, et al. (2015). The multi-millennial Antarctic commitment to future sea-level rise. *Nature* 526(7573), 421-425. doi:10.1038/nature15706 (www.nature.com/nature/journal/v526/n7573/abs/nature15706.html#supplementary-information)

Hamling, IJ, et al. (2016). Off-axis magmatism along a subaerial back-arc rift: Observations from the Taupo Volcanic Zone, New Zealand. *Science Advances* 2(6), e1600288.

Hock, R, et al. (2019). GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology* 65(251), 453-467. doi:10.1017/jog.2019.22

Kopp, RE, et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2(8), 383-406. doi:10.1002/2014EF000239

Lin, N, et al. (2016). Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *Proceedings of the National Academy of Sciences* 113(43), 12071-12075. doi:10.1073/pnas.1604386113

Local Government New Zealand (2019). *Vulnerable: the quantum of local government infrastructure exposed to sea level rise*. Retrieved from www.lgnz.co.nz/our-work/publications/vulnerable-the-quantum-of-local-government-infrastructure-exposed-to-sea-level-rise/

Marzeion, B, et al. (2020). Partitioning the uncertainty of ensemble projections of global glacier mass change. *Earth's Future* 8(7), e2019EF001470. doi:10.1029/2019ef001470

Ministry for the Environment (2017). *Coastal hazards and climate change: Guidance for local government*. Retrieved from www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government

Mitrovica, JX, et al. (2009). The sea-level fingerprint of West Antarctic collapse. *Science* 323(5915), 753. doi:10.1126/science.1166510

Morlighem, M, et al. (2017). BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. *Geophysical Research Letters* 44(21), 11,051-011,061. doi:10.1002/2017gl074954

Nerem, RS, et al. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.1717312115

Oppenheimer, M, et al. (2019). Sea level rise and implications for low-lying islands, coasts and communities. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

Pattyn, F, (2018). The paradigm shift in Antarctic ice sheet modelling. *Nature Communications* 9(1), 2728. doi:10.1038/s41467-018-05003-z

Paulik, R, et al. (2020). National-scale built-environment exposure to 100-year extreme sea levels and sea-level rise. *Sustainability* 12(1513).

Purdie, H, et al. (2014). Franz Josef and Fox Glaciers, New Zealand: historic length records. *Global and Planetary Change* 121, 41-52.

Rignot, E, et al. (2019). Four decades of Antarctic ice sheet mass balance from 1979–2017. 201812883. doi:10.1073/pnas.181288 3116 %J Proceedings of the National Academy of Sciences.

Seroussi, H, et al. (2020). ISMIP6 Antarctica: A multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere* 14(9), 3033-3070. doi:10.5194/tc-14-3033-2020

Vargo, LJ, et al. (2017). Using structure from motion photogrammetry to measure past glacier changes from historic aerial photographs. *Journal of Glaciology* 63(242), 1105-1118.

Wada, Y, et al. (2017). Recent changes in land water storage and its contribution to sea level variations. *Surveys in Geophysics* 38(1), 131-152. doi:10.1007/s10712-016-9399-6

World Glacier Monitoring Service (2020). *Fluctuations of glaciers database* (Publication no. DOI:10.5904/wgms-fog-2020-08). From World Glacier Monitoring Service http://dx.doi.org/10.5904/wgms-fog-2020-08

Zhang, X, and Church, JA (2012). Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters* 39(21). doi:10.1029/2012gl053240