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Sea Level Change in the Auckland Region

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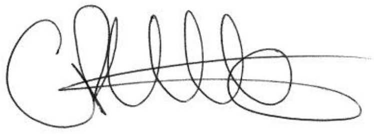

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Sea Level Change in the Auckland Region

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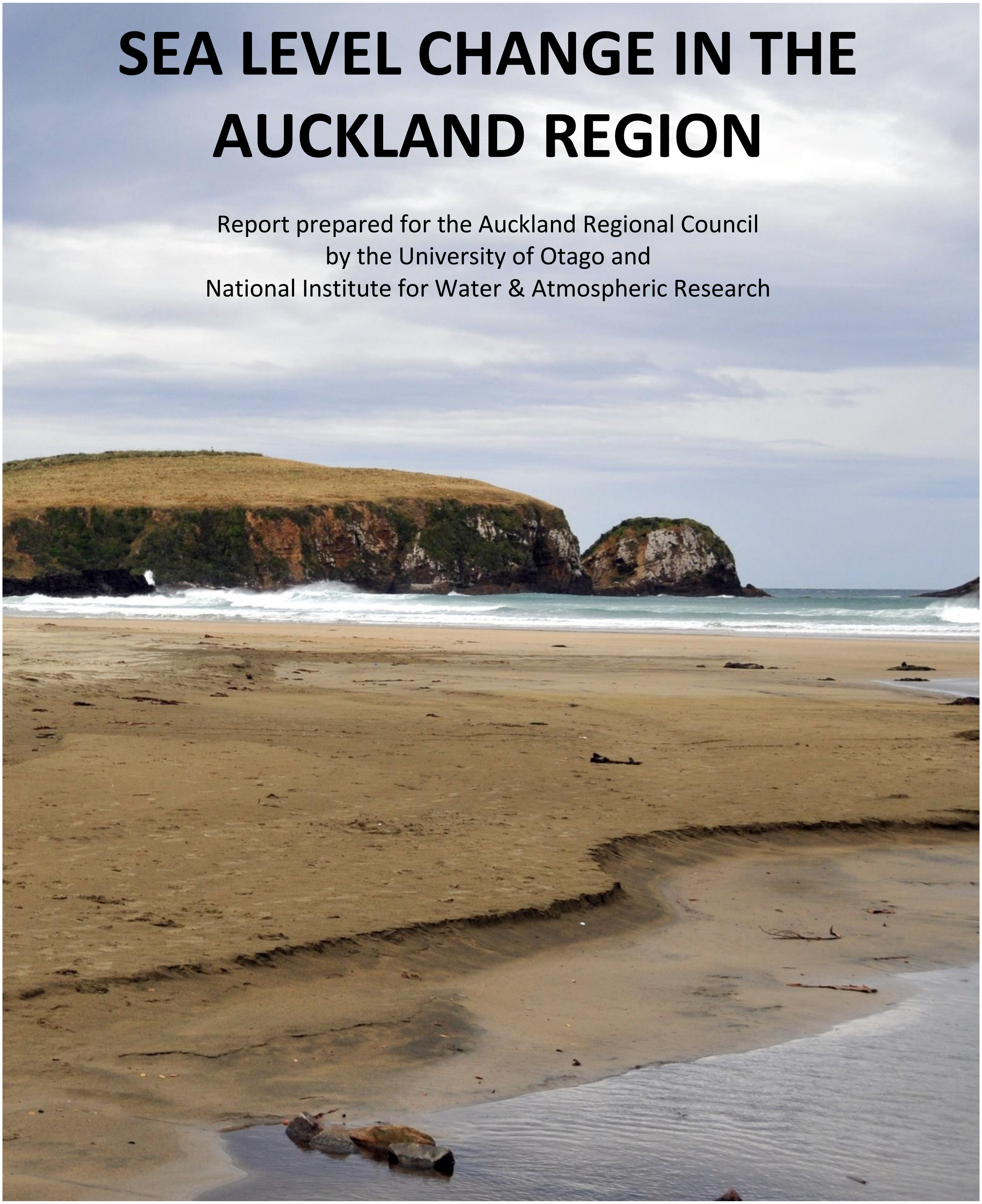
SEA LEVEL CHANGE IN THE AUCKLAND REGION

Report prepared for the Auckland Regional Council
by the University of Otago and
National Institute for Water & Atmospheric Research



Preface

This report was commissioned by the Auckland Regional Council through the University of Otago. In preparing the report, the University of Otago collaborated with the National Institute of Water and Atmospheric Research.

While the University of Otago was the lead agency in the project (with Professor John Hannah acting as the Principal Investigator), the report incorporates a substantial input from Dr Rob Bell (NIWA). The second chapter was contributed by Ryan Paulik of the Auckland Regional Council.

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NEW ZEALAND

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Table of Contents

Executive Summary

The Auckland Regional Council has sought an assessment of past, present and future sea level change in the Auckland Region.

The assessment of past changes in sea level has an important role in informing likely future change. Geological evidence suggests that at specific periods in the past, New Zealand sea levels have risen by rates well in excess of 15 mm/yr. Current evidence suggests that during the mid-Holocene climatic optimum (5,500 to 3,000 years before present), when global temperatures are thought to have been 2^{o}C or more higher than at present, New Zealand sea levels stood 0.5 m – 1.0 m above present day levels. The range of different climate change scenarios produced by the Intergovernmental Panel on Climate Change (IPCC) in 2007, predict a possible rapid return to these temperatures and sea levels by 2100 AD. Sea levels during the mid-Holocene climatic optimum can thus be expected to provide a likely upper bound for sea level rise over this century, provided the ice sheet response doesn't reach a tipping point due to the rapidity of the future change in global temperatures. Temperature rise during the mid-Holocene is thought to have been at a slower rate than is anticipated over the next century.

It is now well established that after a considerable period of stability, global sea levels began to rise towards the end of the 19^{th} Century. A relatively small, but reliable global set of tide gauges (of which Auckland is one), indicate that over the past 100 – 150 yrs there has been a global average sea level rise of 1.7 ± 0.3 mm/yr. These error bars represent a 95% confidence interval. In calculating this figure the relative sea level trends at each of the tide gauges used have been corrected for global isostatic adjustment (GIA). The corresponding GIA corrected sea level rise at Auckland, between 1901 and 2010, is 1.8 mm/yr. When GPS data on vertical land movement is used, the current estimate for absolute sea level rise at Auckland is 1.4 mm/yr. This latter figure, however, has an estimated standard deviation of approximately ± 0.5 mm/yr due to reference frame and processing uncertainties.

New analyses show no evidence of a recent acceleration in sea level rise at Auckland – a finding that is consistent with analyses from other long term sea level records, both in New Zealand and in Australia. Apart from Wellington where subduction of approximately 1 mm/yr appears to be occurring, 10 years of continuous GPS data reveal no evidence of significant vertical motion due to tectonic effects at any of New Zealand's long-term tide gauges sites.

Since 1993, satellite altimetry data have been collected and used to monitor sea level changes over the global oceans. These data indicate a sea level rise of 3.2 ± 0.4 mm/yr from 1993 – 2010. The sum of the climate related contributions during this same period has been assessed as 2.85 ± 0.35 mm/yr. While some have concluded that this marks the beginning of acceleration in the rate of sea level rise, the brief time period for data collection (16 years) plus residual uncertainties in the satellite reference frames used indicate the need for considerable caution before such a conclusion should be reached.

In looking to the future, this report notes the consistency between the rate of GIA corrected sea level rise at Auckland and the best long-term global average estimates of sea level rise. This suggests that long-term sea level rise predictions developed by the international community, including IPCC, should form a starting point for a reliable estimate of the sea level rise that can be expected in the Auckland region. Although it is now well recognised that globally sea level rise has significant spatial variations and thus a single global-average figure may not be appropriate for regional predictions, recent analysis by NIWA of global ocean-climate models used for the IPCC 2007 Fourth Assessment indicates that the projected sea level rise by the 2090s for the wider New Zealand area is not too dissimilar from global-average projections, but could be up to 0.05 m higher.

Strong parallels between the UK data and the New Zealand data, both in terms of currents rates of sea level rise and the clear lack of any acceleration, suggest that the most recent 2009 UK Climate Impacts Programme Study[1] might provide a useful guide for Auckland Regional Council policy makers. They note that for a tectonically stable earth, the most probable sea level rise by 2095 would be in the range of 12–76 cm. These limits deal with both low and high emission pollution scenarios and represent 5th percentile to 95th percentile limits. These limits are generally consistent with the existing Ministry for the Environment (NZ) 2008 planning guidelines for coastal hazards and climate change. The clear, and ongoing lack of any evidence for acceleration in sea level rise from coastal tide gauges, suggests that the upper bound in these figures would provide a very reasonable margin of comfort. In total, we find that there is little reason to depart from existing MfE planning guidelines, which do include the accommodation of higher sea level rises for planning or design of high risk activities or projects and where future adaptation options are limited.

To cover the variability in month-to-month MSL response (including seasonal, inter-annual and inter-decadal cycles), an additional allowance in planning and design should take into account a range from -0.17 m to +0.25 m. The latter needs to be added to extreme value analyses of storm-tide levels, along with sea-level rise (past and future projections) to cover climate-induced variability in monthly MSL.

Apart from the long-term trend, the three main components contributing to long-term variability in MSL are:

- Seasonal (annual) cycle, from the heating and cooling effects on Hauraki Gulf waters, with an average range of 0.09 m (–0.05 to +0.04 m)
- Interannual cycle due to the 2–4 year ENSO, with an overall range of 0.24 m (-0.1 to +0.14 m) with higher monthly MSL during La Niña episodes
- Inter-decadal cycles from the20-30 year Interdecadal Pacific Oscillation, with an overall range of 0.1 m (–0.05 to +0.05 m), with the higher MSL occurring during the “negative” phase (which we are currently in).

[1] http://ukclimateprojections.defra.gov.uk

1. Introduction

The Auckland tide gauge has one of the longest, and certainly the most complete sea level records of any tide gauge in New Zealand. Furthermore, its record is one of the few reliable long-term records (i.e., greater than 100 year), available in the Southern Hemisphere. The importance of this record is increased both by the tectonic setting of the gauge (in that it is somewhat distant from an active plate boundary), and also by the completeness of the data set.

The gauge is part of an international Global Sea Level Observing System (GLOSS) network of sea-level gauges (site #127)[2] coordinated by UNESCO's Intergovernmental Oceanographic Commission (IOC). Therefore, from both a national and an international point of view, it is considered to be an important site for monitoring and assessing global sea level change.

Sea level data itself is an important element in the assessment of regional coastal hazards, being subject to variations from a wide variety of causes, including, but not limited to, movement of the moon with respect to the earth, and the earth with respect to the sun (both of which cause tidal variations), storm surge, the seasonal cycle (Bell & Goring, 1998), climate variability including inter-annual and inter-decadal oscillations (Goring & Bell, 1999), climate change and vertical land movement.

The objectives for this study were as follows:

- To identify millennial scale sea level effects that may have influenced the current elevation of mean sea level in the Auckland region.
- To determine historical annual mean sea level trends from the Ports of Auckland tide gauge.
- To determine how monthly mean sea level trends from the Ports of Auckland tide gauge vary in response to inter-annual and inter-decadal climate variability.
- To determine how historical sea level change in the Auckland region compares with historical global sea level change and future sea level rise projections issued by the Intergovernmental Panel on Climate Change (IPCC) in their latest 4th Assessment Report[3] in 2007.

In preparing this study, the term "eustatic sea level change" is used to indicate the change in volume of water in the global oceans. Such changes can arise from the thermal expansion of the oceans and by the addition or removal of water by, for example, the melting of glaciers. "Absolute sea level change" is the change in sea level relative to the centre of mass of the earth. This reflects the combined influence of eustatic sea level change plus any vertical uplift or subsidence to the ocean basins that may arise from tectonic motion. Glacial Isostatic Adjustment (GIA) is a component part of the total tectonic motion. The term "relative sea level change" is used to indicate the change in sea level relative to the fixed coastline as determined from stable local benchmarks.

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[2] https://www.bodc.ac.uk/data/information_and_inventories/gloss_handbook/stations/country-asc
[3] http://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/wg1-ar4.html

2. A Geological Perspective on Millennial Scale Sea Level Changes in the Auckland Region

Kennedy (2008) provides a helpful review of the studies undertaken to assess past sea level changes that have occurred in New Zealand - particularly those that occurred in the Holocene period. An understanding to how sea level has responded to climate change in the past can help greatly with the assessment of future impacts of climate change.

2.1 Late Quaternary Sea level Change

It is generally considered that relative sea level change during the Quaternary period (i.e., over the last 1.68 million years [1.68 ma]) was influenced by the interaction of several processes operating over varying spatial and temporal timescales. The most important control on sea level elevation during this period was the construction and wasting of continental ice sheets by cyclic glacial-interglacial periods that arose from the earth's orbital variations. These cycles are considered to have caused global sea level fluctuations greater than 100 m over periods of ~100,000 years. This process was superimposed on local and regional processes such as land movement (e.g. tectonics and ice loading), oceanic currents, and shorter-term climate variability that combine to determine sea level elevation on a coastline.

The general pattern of eustatic sea level change during the past 1 ma is largely inferred from the last glacial-interglacial cycle dated between 20-128 ka before present (BP) – see dotted lines in Figure 1. Based on this cycle a uniform theory is extrapolated backwards to 1 ma on the assumption that a similar global pattern of eustatic sea level rise and fall has occurred over ~100 ka cycles in response to variations in the earth's tilt, this in turn controlling global ice volumes (Pillans et al., 1998). This theory is reliant on marine oxygen isotope (^{18}O) data from deep-sea sediment cores which demonstrate a similar timing and amplitude of isotopic changes to represent eustatic sea level changes for the past seven glacial cycles. Since a 0.1‰ change in ^{18}O is broadly equivalent to a 10 m change in eustatic sea level the magnitude of eustatic sea level fluctuations can be indirectly inferred from the isotopic record of deep-sea cores, along with allowances for local isotopic variations in response to water temperatures and salinity (Shackleton and Opdyke, 1973; Chappell and Shackleton, 1986; Shackleton, 1987). The timing of eustatic sea level

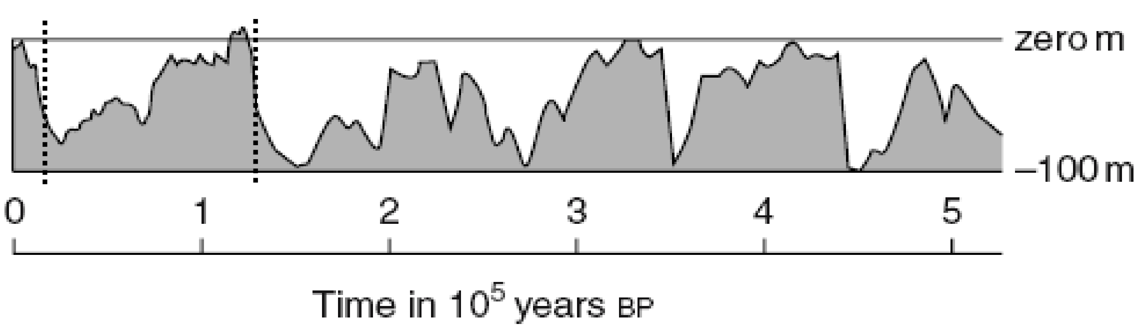

Figure 1: Schematic representation of general eustatic sea level fluctuation trends since ~500 ka with present on left side. Dotted lines mark the last glacial cycle ~20–128 ka. (Morner, *2008)*.

changes is constrained by calculating sedimentation rates within deep-sea sediment cores that are later calibrated through dating of organic material or known magnetic polarity changes. Further support on timing and amplitude of sea level changes is provided from coastal sites where past sea level datums (e.g. coral reefs, marine terraces) are preserved.

The limitations involved in dating the timing of eustatic or relative sea level changes beyond 100 ka BP means the most detailed records of relative sea level changes on coastlines are derived since the last interglacial maximum at ~120 ka BP. One of the most detailed eustatic sea level records for this period comes from the Huon Peninsula, Papua New Guinea (Figure 2). In the absence of a local record, this site is close enough to New Zealand to provide an indication of glacio-eustatic sea level changes in the region during the last glacial-interglacial cycle. For the last 140 ka, there is a fairly good comparison between

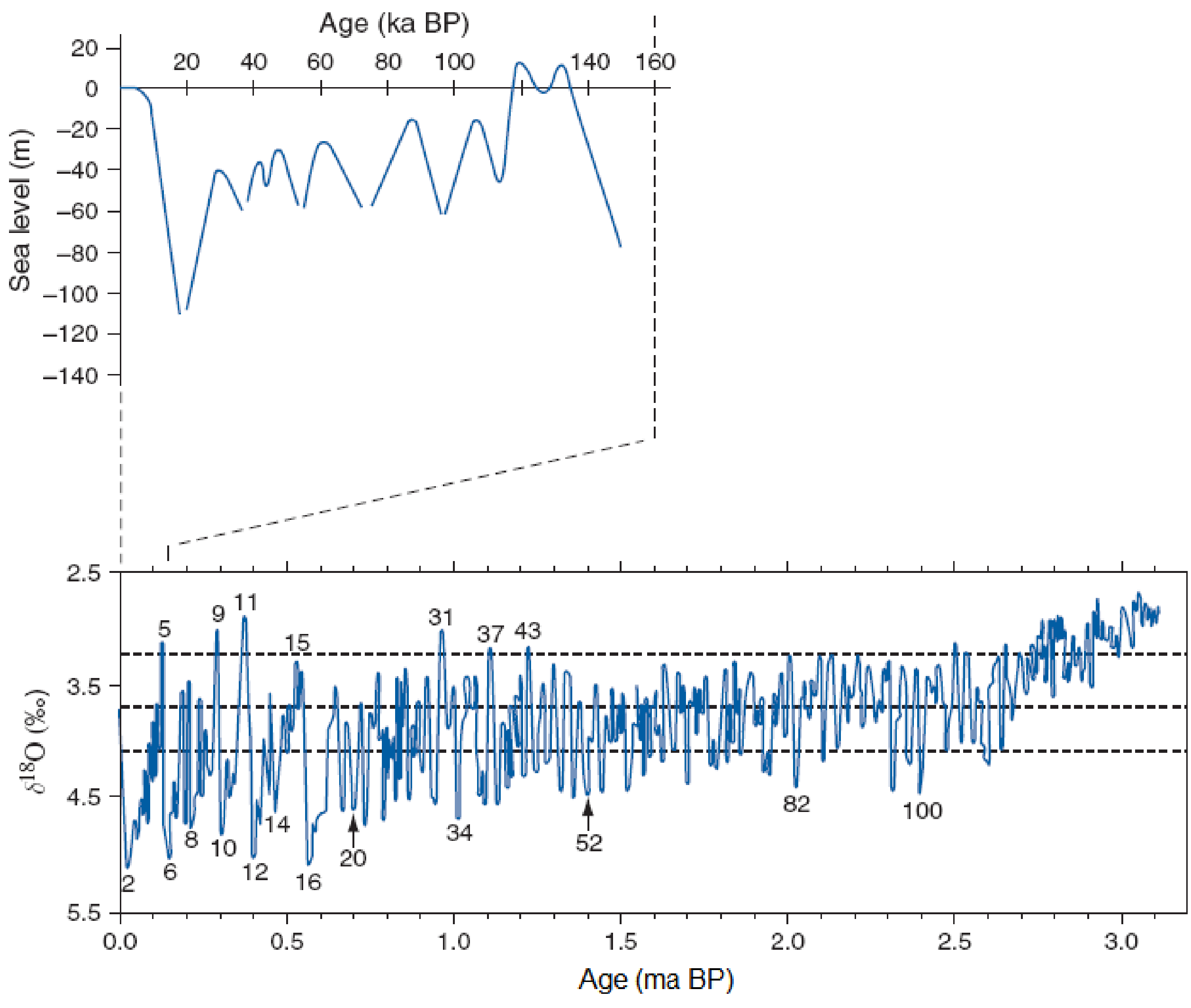

Figure 2: Glacio-eustatic sea-level curve from Huon Peninsula, Papua New Guinea for the last glacial-interglacial cycle. The curve demonstrates the general trend between changing sea level elevation and orbitally controlled global ice volume, along with supporting evidence from marine oxygen isotope concentrations. (Murray-Wallace, *2007)*.

marine oxygen isotope (^{18}O) variations and actual dates of coral reef levels on the Huon Peninsula (Chappell et al., 1996). Notwithstanding local effects on sea level elevation (e.g. tectonic uplift), the record demonstrates changing global sea level elevations in response to global ice volume fluctuations

At the last interglacial maximum (~120 ka BP) evidence from coastal sites worldwide indicates global sea levels were at least 2 m above present levels though higher estimates of 2 and 9 m are cited from Indian and Pacific Ocean islands (Veeh, 1966). Evidence from Lord Howe Island, Tasman Sea, estimates that sea level was 4-5 m higher than present at the last interglacial maximum (Woodroffe et al., 1995). The relative elevations of relict Pleistocene and Holocene coastal dunes along the Kaipara Harbour and Awihtu Peninusla coastlines, suggest sea level in the Auckland region may have attained these heights at this time (Smith et al., 2010; Schofield, 1975). Marine oxygen isotope (^{18}O) records suggest sea level fell by as much as 20 m within a few thousand years following the last interglacial maximum (Figure 2). Global sea levels continued to fall gradually to the last glacial maximum at ~22-20 ka BP, though was interrupted with significant temporal rises of 5-10 m at approximately 105 ka BP and 15-20 m at 82 ka BP (Shackleton, 1987; Chappell et al. 1996). At the last glacial maximum, global sea levels had lowered to an elevation of approximately -125 ± 5 m below present levels (Lambeck et al. 2002; Chappell et al. 1996).

Following the last glacial maximum eustatic sea level rose rapidly in response to decreasing global ice volumes. There is a broad agreement at a number of coastal sites worldwide that post-glacial eustatic sea level rose from –125 ± 5 m below present levels at ~22-20 ka BP to near present levels between 7 to 6 ka BP (Figure 3). This graph includes data from nearby Australian sites.

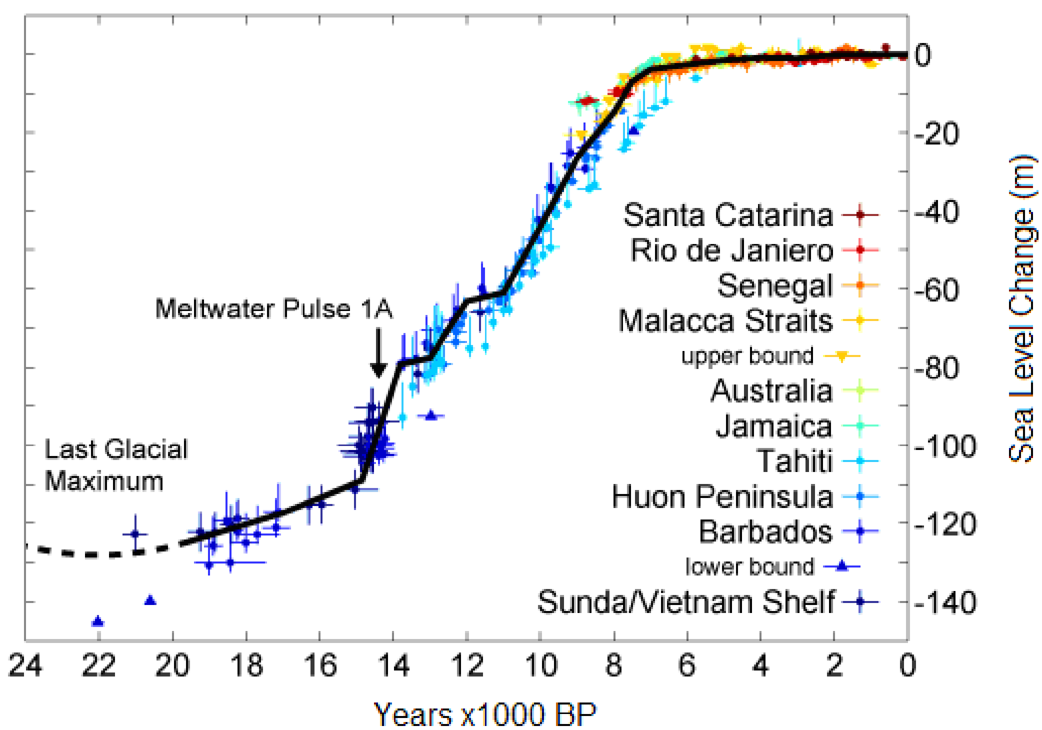

Figure 3: The general eustatic sea level trend since the last glacial maximum (Fleming et al., *1998*; Milne et al., *2005*).

The global average sea level rise rate over this period of ~8–9 mm/yr was punctuated by more rapid periods of sea level rise including ~24 m in 1000 years (24 mm/yr) around 14 ka BP. This is known as Meltwater Pulse 1A, a period when continental ice volumes melted at an average rate of approximately 14,000 km^3/yr (Fairbanks, 1989). Sea level rise rates declined following Meltwater Pulse 1A to ~5.6 mm/yr for approximately 2000 to 3000 years but were followed by another rapid temporal rise at 11.3 ka BP (tentatively known as Meltwater Pulse 1B), where sea level rose by a further 28 m in approximately 1,500 years (~19 mm/year). Rates of sea level rise then lowered slightly in many parts of the world until reaching stillstand during the Holocene at 7 to 6 ka BP. The timing of Holocene stillstands varies globally (e.g. at approximately 2 ka BP in southern England) though has generally been cited at approximately 6.5 ka BP for the southwest Pacific/Tasman Sea regions, including the Auckland region (Gibb, 1986; Chappell, 1987; Sloss et al. 2007).

Relative sea levels have continued to fluctuate along world coastlines following Holocene stillstands. Since this time local and regional processes involving land movement (e.g. tectonics and isostatic rebound), oceanic currents and climate variability (e.g. Mid-Holocene Climatic Optimum) have had an important influence on relative sea level elevation thereby preventing the identification of a generalised global sea level trend. Due to these processes, Morner (1996) suggested that since post-glacial eustatic sea level rise terminated at stillstands around 6–7 ka BP, local (relative) sea level changes represent the processes associated with the redistribution of oceanic water masses across the globe. If true, this would reflect a recent change in processes driving relative sea level from a global (glacio-eustatic) control dominated by the melting of continental ice, to local or regional controls dominated by land movement, oceanic currents and climate variability, along with a more minor eustatic influence.

2.2 Holocene Sea level Change in the Auckland Region

Holocene sea level change in the Auckland region broadly follows post-glacio-eustatic sea level trends observed globally. The New Zealand sea level curve developed by Gibb (1986) demonstrates the general pattern of post-glacial sea level rise during the Holocene (Figure 4). Eustatic sea-level rose rapidly from -33.5 ± 2.5 m below present sea-level at 10 ka BP with "temporary" still-stands occurring at -24.0 ± 2.9 m from 9.2 to 8.4 ka BP, and -9.0 ± 2.8 m from 7.5 to 7.3 ka BP. Post-glacial eustatic sea level rise culminates on the New Zealand coastline close to the present sea-level at 6.5 ± 0.1 ka BP. Since this time, eustatic sea level oscillations of up to 1 m above present sea level occurred from 5.5 to 3 ka BP along the New Zealand coast including sites in or close to the Auckland region (Gibb, 1986; Woodroffe et al. 1983; Hicks and Nichol, 2007). This period of higher sea levels has also been observed on coastlines in the Tasman Sea (Woodroffe et al. 1995) and Queensland (Lambeck et al., 2010), and it is commonly argued to have been instigated by the mid-Holocene climatic optimum, a period of warmer global temperatures (Chappell, 1987). It is of particular relevance to note that global average surface warming through to 2100 AD is expected to rapidly (within a 100 years) return the global climate to conditions akin to this mid-Holocene optimum.

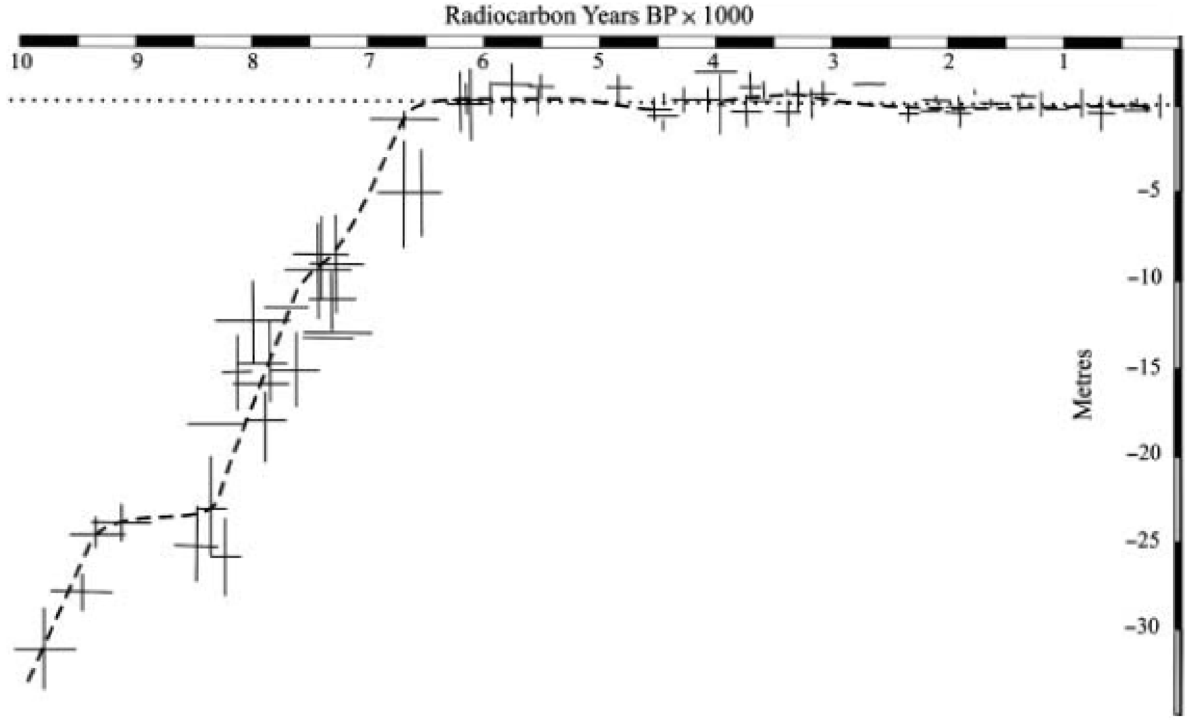

Figure 4: The Holocene eustatic sea level curve for New Zealand produced by Gibb (1986). *Source:* Kennedy, *2008*.

The most detailed Holocene sea level records in or near the Auckland region are derived from the east coast at Weiti River estuary and Firth of Thames at Kaiaua and Miranda (Figure 5). The Weiti River estuary enters the Hauraki Gulf 4 km north of Orewa, an area assumed to be tectonically stable since the last interglacial maximum. The site's stability suggests an accurate record of eustatic sea level change is provided for the region during the Holocene. Gibb (1986) surveyed and radiocarbon dated the elevation of carbonate material in chenier ridges (sand-shell deposits sitting above mud) within the estuary. The results showed post-glacial sea level reached an elevation close to present at 6.94 ± 0.08 ka BP followed by oscillations of higher sea levels of ~0.8 m between 5.5 to 4.9 ka BP, 0.3 to 0.5 m between 3.9 to 3 ka BP and 0.4 m at 1.4 ka BP. A significant sea level fall of ~0.9 m is observed between 4.9 and 3.9 ka BP and since 3.5 ka BP a gradual trend of lowering sea level to its lowest recent elevation in the 1800s prior to the instrumented modern record which shows a linear rise (see Section 4).

Kaiaua and Miranda are locations on the Firth of Thames east coast where sea level trends are useful for identifying Holocene sea level changes in the Auckland region. Since the culmination of post-glacial sea level rise at 6.5 ka BP relative sea level at Kaiaua has oscillated by up to ~0.8 m with the most notable rise between 2.2 and 1.8 ka BP (Figure 5B). A maximum sea level elevation of 0.5 ± 0.2 m above the present level is noted at 3.4 ka BP which is supported by a similar elevation of 0.5 ± 0.7 m (adjusted for tectonic uplift) at 3.6 ka BP observed from stranded intertidal shells 6 km south at Miranda (Woodroffe et al., 1983). Similarly, a higher sea level of this magnitude is observed at the Weiti River estuary at 3.5 ka BP. Since this time, relative sea level at Kaiaua and Miranda broadly display a similar trend to the

Weiti River where relative sea level has lowered to its lowest recent elevation in the late 1800s. However, the relatively low resolution of Auckland's sea level records makes it difficult to detect the onset of the late Holocene sea level rise in the region as has been observed in southern New Zealand since 1500 AD (Grehals et al., 2008). Despite this, similar Holocene sea level trends have been observed in the Tasman Sea (Woodroffe et al. 1995) and Australia's east coast (Sloss et al. 2007; Chappell, 1987 Howarth et al. 2002) which suggests Holocene relative sea level curves from the Auckland region manifest the influence of global and local environmental processes which control sea level elevation.

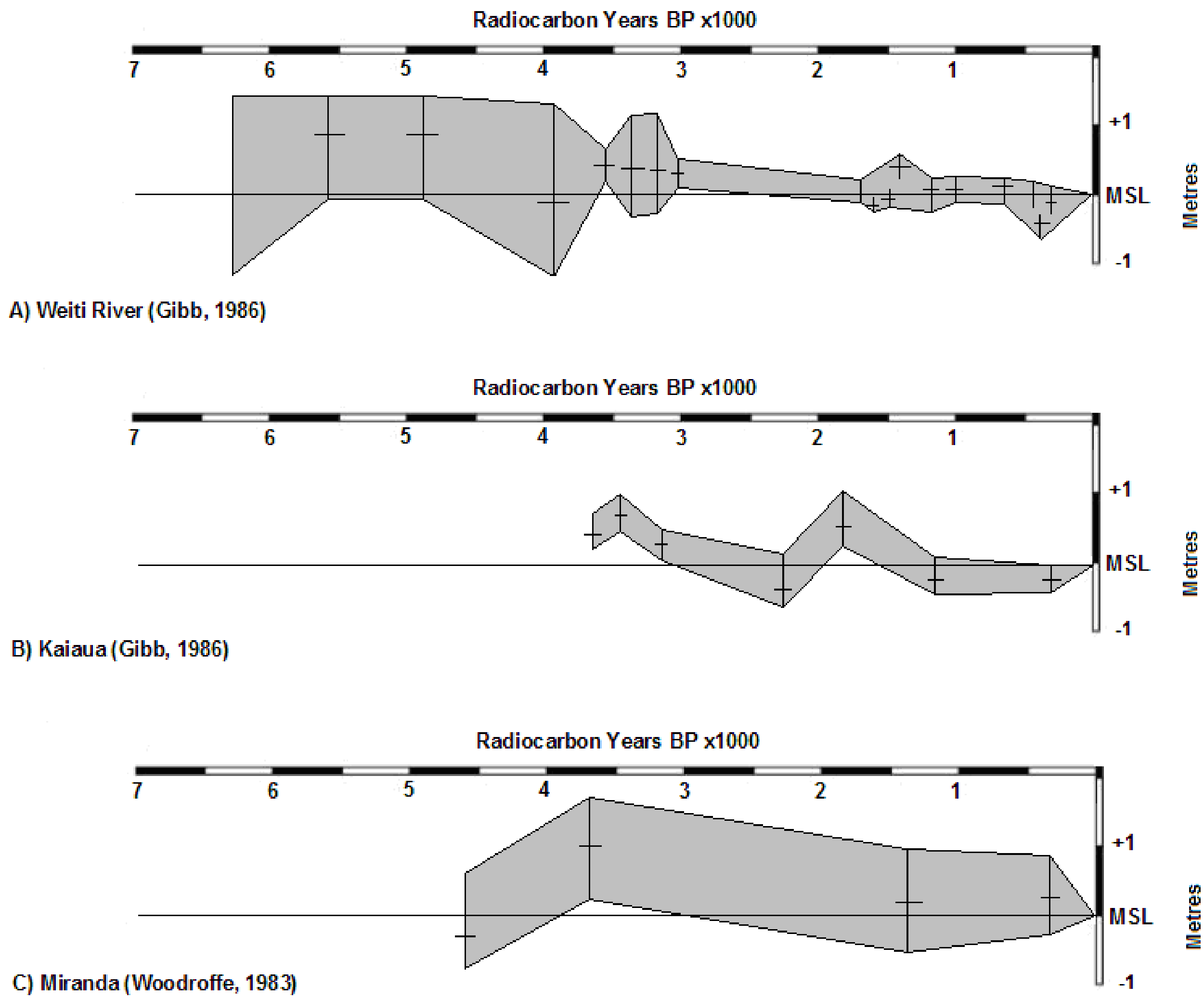

Figure 5: Relative sea level curves for (A) Weiti River estuary, (B) Kaiaua and (C) Miranda. Note: the data is uncorrected for tectonic influences although tectonic stability is assumed for the Weiti River estuary since the last interglacial maximum. *Source:* Gibb, *1986;* Woodroffe et al., *1983.*

3. Auckland Tide Gauge History

Before any reliable assessment of sea level change can be undertaken, it is essential that the quality of the sea level record be verified. This in turn requires an assessment of the reliability of the tide gauge(s) that may have been used in order to collect the data. The reliability of a tide gauge, however, depends upon four primary factors. Firstly, the maintenance history of the gauge - including the care taken to regularly ensure that the records are referenced correctly with respect to time and with respect to the gauge zero. Secondly, the consistency with which a tide gauge datum has been maintained. Thirdly, the stability of the local wharf structures to which the tide poles and gauges are attached and, finally, the stability of the land to which the wharf structures are attached.

The quality of the sea level record collected in the Port of Auckland basin (Waitemata Harbour) since 1899 has been discussed previously (Hannah, 1990; 2009). The important points may be summarised as follows.

1. Prior to 2000, the Auckland sea level data is considered to be of a high quality with the gauge showing all the evidence of being well maintained since 1904. It has an almost continuous data history as well as historical levelings that verify the vertical stability of the site. It should be noted, however, that a datum shift of 0.5 ft (0.152 m) was applied to the gauge at the start of 1973, and thus 0.152 m has been added to all Mean Sea Level (MSL) data collected after that time to maintain continuity of datum in the sea level trend analysis reported here.

2. In March 2000, a new gauge (a Vegapuls63 radar unit) and a new tide pole were installed next to the Pilot Hut at Captain Cook Wharf. The previous tide pole (at Queens Wharf) was removed although the old gauge (also at Queens Wharf) continued to operate until it was decommissioned in August 2007 and relocated. A new tide pole was installed in 2007 (Bruce Wallen, PoA, private communication). No field data has been able to be found to confirm continuity of datum during the shift of the tide gauge. However, in 2003 a gauge calibration undertaken by the RNZN revealed that the gauge was reading 0.0347 m too low. An adjustment of +0.035 m has thus been applied by Land Information New Zealand (LINZ) to all the data collected from 00:00 hr on 1 January 2001 (when the new gauge formally commenced operation) to 13:10 hr on 8 May 2003, when a gauge re-adjustment was made. No other data adjustments have been made.

3. In the last 7 years there appears to be a lack of data that provide an unambiguous link of the tide gauge zero back to a verifiably stable tide gauge bench mark. Checks on the TG BM (a metal bar beside the transducer unit) and on BM DD1N between 2000 and 2007 show the wharf structure itself to be stable. However, it is not known if the TG zero has remained at the same level throughout this time.

In summary, the Auckland gauge has produced adequate sea level information from 1899 – 1903, an excellent record from 1904 – 2000, and a less reliable record from 2000 – 2009. Given the regional, national and international importance of this gauge, it is of real importance that procedures be established to ensure that the present uncertainties are not continued into the future.

4. Historical Annual Mean Sea Levels

A number of analyses of the Auckland MSL data have been completed with the first being undertaken in 1990, the second in 2004, the third in 2008 and the most recent as part of this study. The methodology used in every case was the same and is as outlined in Hannah (1990).

The data used in these analyses are plotted below and are given in Appendix 1.

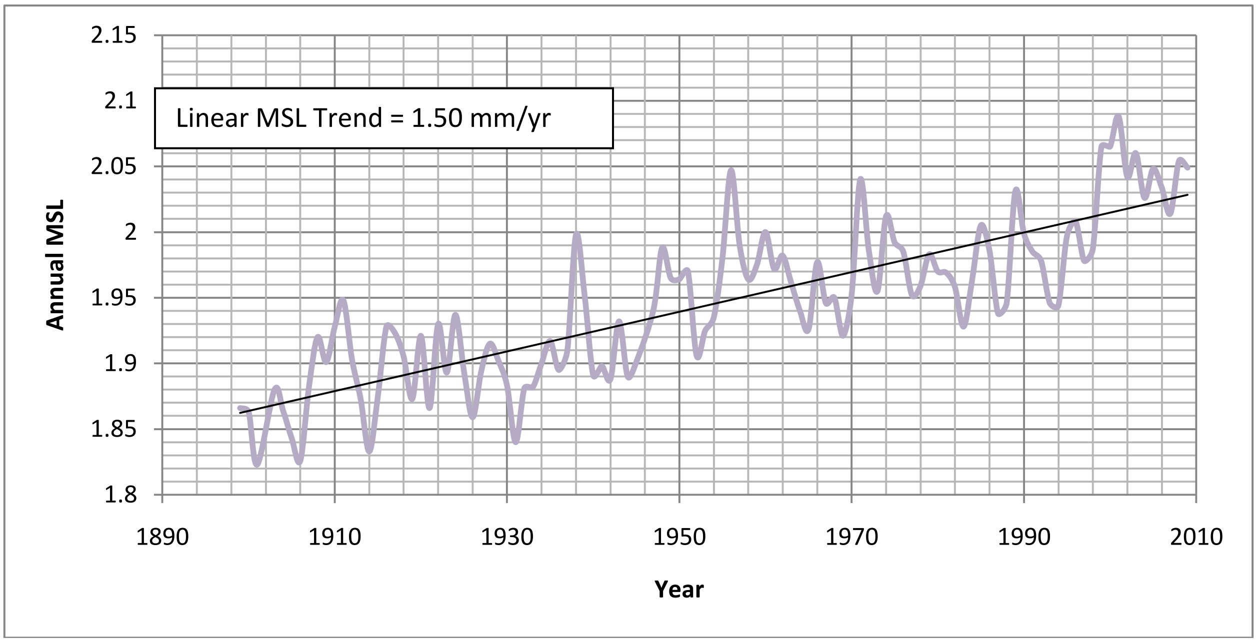

Figure 6: Linear trend in Auckland annual MSL data (to pre-1973 Port of Auckland Chart Datum)

The results of these analyses are listed in Table 1 below.

Table 1: Summary of Auckland MSL linear trends

Year of Analysis	**Data Used** Inclusive years	**Liner Trend** (mm/yr)	**Standard Deviation** (mm/yr)
1990	1899 - 1988	1.34	0.11
2004	1899 - 1999	1.30	0.09
2008	1899 - 2007	1.48	0.09
2010	1899 - 2009	1.50	0.09

These linear trends are relative to stable local benchmarks on the fixed shoreline and are uncorrected for regional vertical land motion. However, it is of interest to note the increase in the trend that occurs when data from the first decade of the 21st Century is added. It is surmised that this reflects the influence of the inter-decadal oscillation that switched modes around 1998-2000. A very recent analysis of the Auckland tide gauge data (Watson, 2010) reveals no evidence of acceleration. This result, which has been confirmed by Cole (personal communication), will be discussed in greater detail in Section 6.

Before comparing the Auckland sea level trend with the trends as determined at other New Zealand tide gauges with long data records, it is important to consider, and if possible eliminate, any local or regional tectonic effects that might exist. The New Zealand wide GIA corrections, computed using Peltier's ICE-5G v.1.2b (M2) model, are shown in Figure 7. The specific corrections calculated for each of the tide gauges referenced in this report are shown in Table 2.

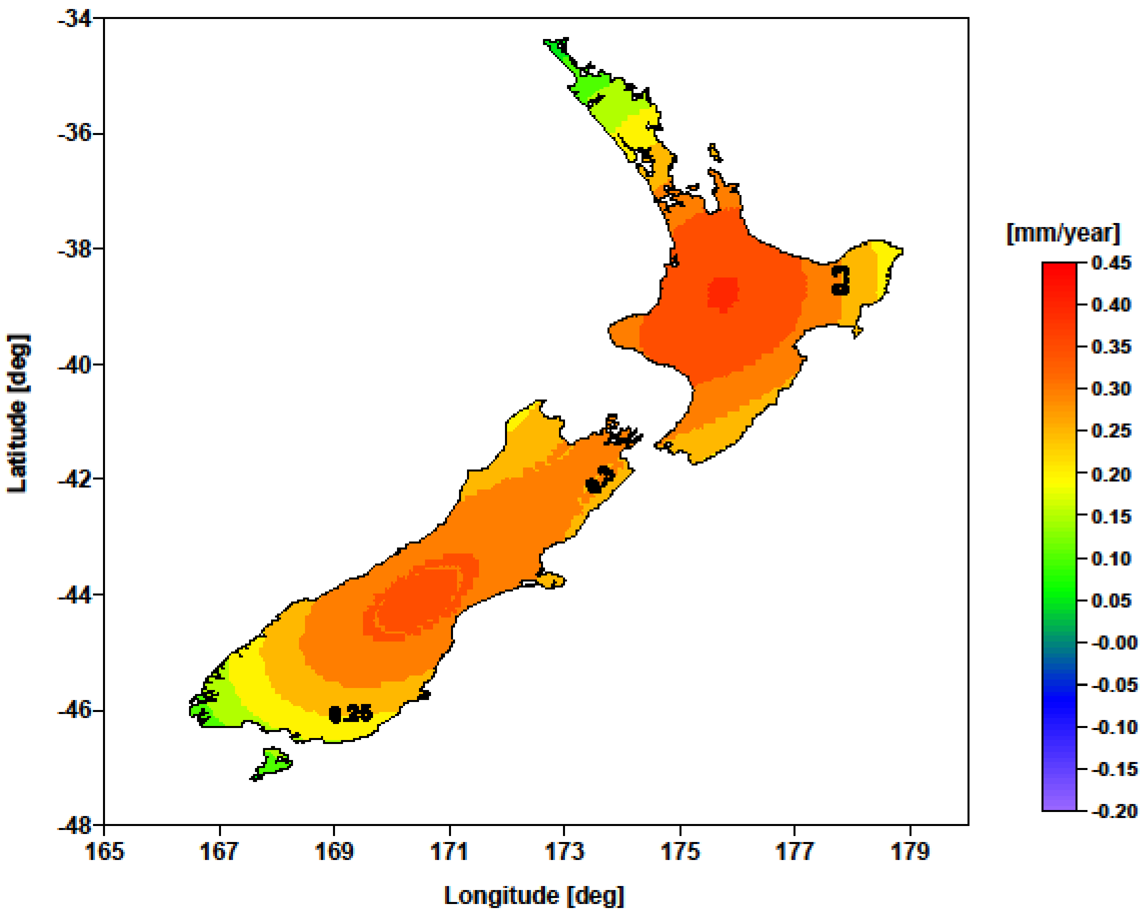

Figure 7: GIA corrections for New Zealand (Peltier, 2004).

While the GIA corrections are of interest, the more important issue relates to the overall vertical movement of the land. Such movement would be expected to be the sum of the GIA plus any other regional tectonic effects that might be present.

The University of Otago and GNS Science have been collecting continuous GPS (cGPS) data for almost 10 years, with a GPS receiver co-located with each of the Auckland, Wellington, Lyttelton and Dunedin tide gauges. This data has recently been analysed (Denys et al., 2010), the results of which are also summarised in Table 2.

Table 2: Sea level trends in New Zealand

Port	Relative sea level change (linear trend) ***a***	GIA Correction ***b***	GIA corrected sea level trend ***a + b***	Local Tectonic Motion from cCPS data ***c***	Absolute sea level trend ***a + c***
Auckland	+1.50 (0.09)	+0.30	1.80	-0.1	+1.4
Taranaki	+1.24 (0.32)	+0.33	1.57		
Wellington	+2.00 (0.17)	+0.30	2.30	-1.4	+0.6
Lyttelton	+1.90 (0.10)	+0.29	2.19	-0.2	+1.7
Dunedin	+1.28 (0.09)	+0.25	1.53	-0.2	+1.1
Mean	***1.6 mm/yr***		***1.9 mm/yr***		***1.4 mm/yr***

Note: All units are in mm/yr with standard deviations in brackets.

The following comments are relevant to Table 2.

Firstly, with the exception of Auckland where annual MSL data through to the end of 2009 have been used, the relative sea level trends reflect a data series ending in December 2007, i.e., they reflect the trends as computed in 2008.

Secondly, it is important to understand that the cGPS results, at least when calculated to sub-millimetre level, are both reference frame and processing dependent. In other words, the data processing strategy adopted, the software used and the reference frame adopted will influence the outcome. The cGPS data presented here have been calculated in the ITRF 2005 reference frame and reflect the University of Otago processing strategy. Preliminary results obtained from the University of Newcastle (UK) software with the same data, show total tectonic motion as being -0.4, -1.5, -1.1, and 0.0 mm/yr for Auckland, Wellington, Lyttelton and Dunedin respectively.

Thirdly, given the wide distribution of sites and their various tectonic locations (i.e., Dunedin and Lyttelton on the Pacific Plate, Auckland on the Australian Plate and Wellington in the transitional zone between plates, the consistency of result at all sites (except for Wellington) is encouraging. Here the cGPS derived motion is large enough to indicate a genuine tectonic motion – i.e., a subduction of approximately 1 mm/yr. For this reason Wellington has not been used in calculating the mean absolute sea level trend. If the Wellington result is excluded, the GIA corrected result for the other four gauges gives an average linear sea level rise of 1.8 mm/yr, if it is included this figure rises to 1.9 mm/yr. Either way the overall figure fits very well with best GIA corrected global estimates of linear sea level changes over the 20th century of 1.7 ± 0.3 mm/yr (Church & White, 2006). Clearly there is a very high level of consistency between the average sea level trend as computed in New Zealand versus best global average estimates.

5. Historical Monthly Mean Sea Levels

Monthly MSLs are able to be determined from November 1903, the time from which original tide charts were available when the data were digitised by the Department of Survey and Land Information in 1988. Prior to 1903 tide charts were not available, with the sea level data only being recorded in the form of Annual Mean Tide Levels which values were found in historical documentation.

These monthly mean sea-level data are plotted in Figure 8a, in terms of present Port of Auckland Chart Datum (CD) and in Figure 8b relative to Auckland Vertical Datum 1946 (AVD-46). The present average MSL over the 19-year period 1991–2009 is 1.86 m CD (Land Information NZ, 2010), which is shown in Figure 8a.

Most planning and engineering design in the Auckland region are based on levels relative to AVD-46, so the monthly mean sea levels are also provided in this datum (Figure 8b). This zero datum was set in 1946 based on sea levels measured by this gauge for the period 1909 to 1923, which matches the mean for this early part of the record shown in Figure 8b. However, the present-day mean sea level no longer aligns with AVD-46 due to the rise in sea level in the interim. The equivalent mean sea level for the recent 19-year period 1991 to 2009 is +0.12 m AVD-46 (or 1.86 CD).

For subsequent analysis, the linear trend in MSL was removed from the time series of monthly MSLs as shown in Figure 9. For the 107-year record, the monthly-MSL anomaly varied between –0.17 m and +0.25 m. The former occurred during August 1994 during a El Niño episode and the highest monthly anomaly occurred during May 1956. This high value was re-checked in the hourly dataset and while it is difficult to check the operation of the gauge, there were two storm surge sequences that month along with a monthly-mean barometric pressure that was 3 hPa lower than normal. Also this month coincided with the peak of a La Niña episode (see later).

Overall, for month-to-month variability (including seasonal, interannual and inter-decadal cycles), an allowance in planning and design should take into account this range from –0.17 m to +0.25 m relative to the average MSL (excluding the sea-level rise trend).

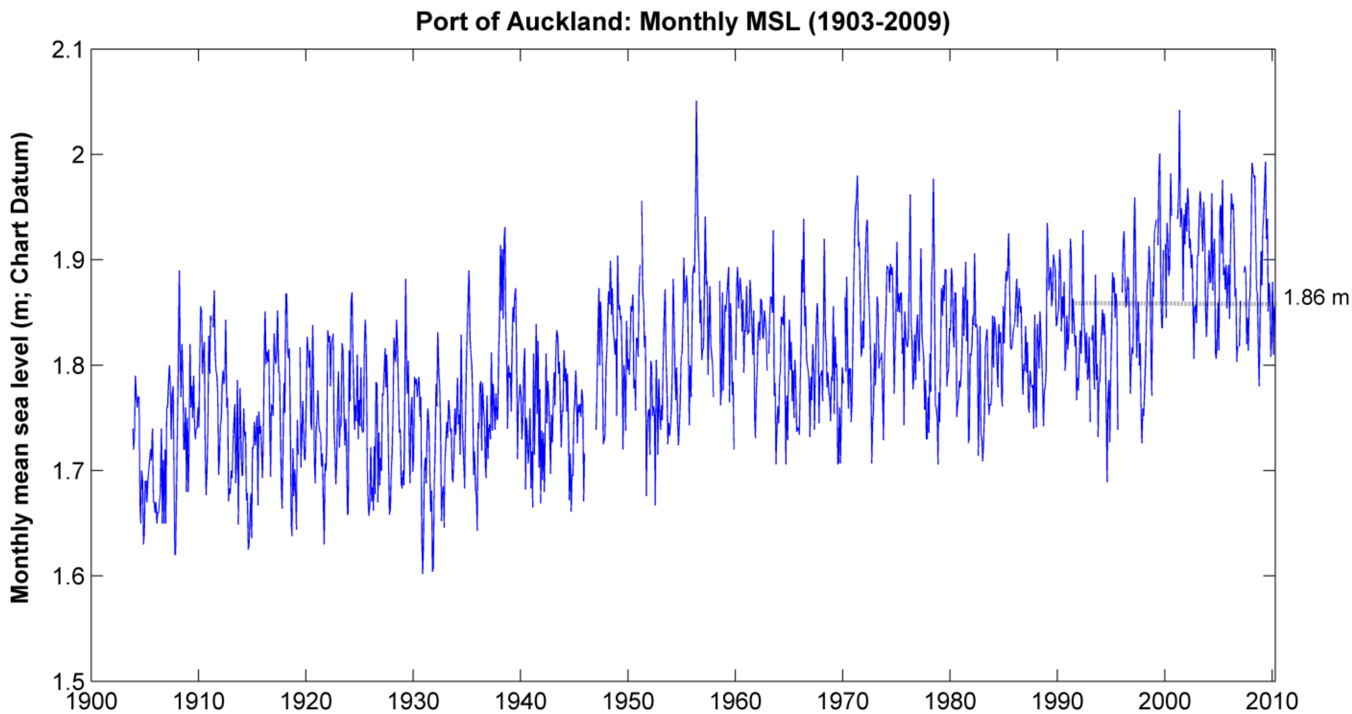

Figure 8a: Monthly mean sea level relative to present Chart Datum. The 1.86 m line is the present average MSL over the 19-year period 1991–2009.

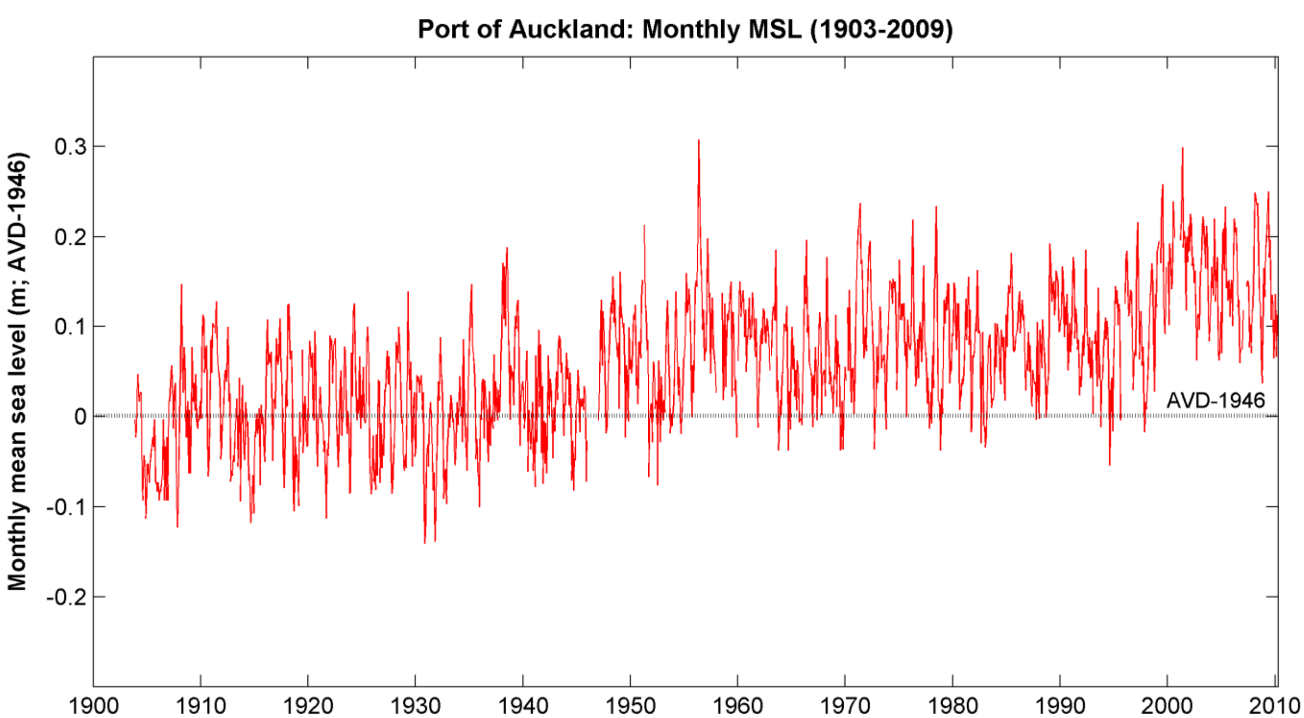

Figure 8b: Monthly mean sea level relative to the regional survey datum AVD-1946.

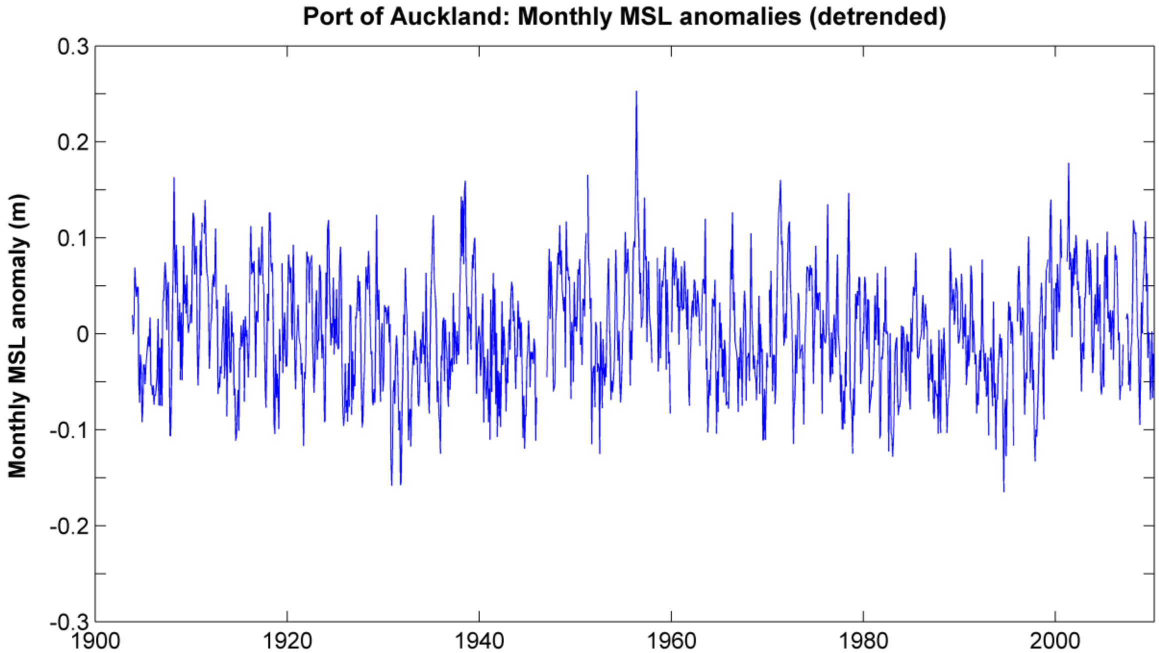

Figure 9: Monthly MSL anomalies relative to the linear trend line, removing the rise in sea level.

5.1 MSL response to climate variability

This overall variability in monthly MSL was unpacked into components due to the:

- Seasonal (annual) cycle, from the heating and cooling effects on Hauraki Gulf waters
- Interannual cycle due to ENSO
- Inter-decadal cycles from the IPO

The average seasonal cycle was extracted from the monthly MSL anomaly time series by averaging all the monthly MSL values for a specific month (rather than fitting a smooth sine curve). In addition, the 107-year record was split in half from 1903–1956 and 1957–2009 and respective average annual cycles calculated. The results are shown in Figure 10. The overall average seasonal cycle peaks in March to May at 0.035 m above the average sea level, and drops to –0.043 m during October.

This seasonal cycle is largely due to thermal heating in summer (seawater expansion) and cooling in winter (contraction) as the annual astronomical tide is quite small. However, the response in sea level lags the seasonal change in seawater temperature (measured at Leigh Marine Reserve) by 1–2 months, similar to earlier work by Bell & Goring (1998). In the latter 50+ years, the cycle has shifted slightly to peak earlier (in March) and fall slightly more in October, with an average range of 0.09 m (–0.05 to +0.04 m). This accounts for only about 15–20% of the variability in the month-to-month changes in sea level (Figure 9).

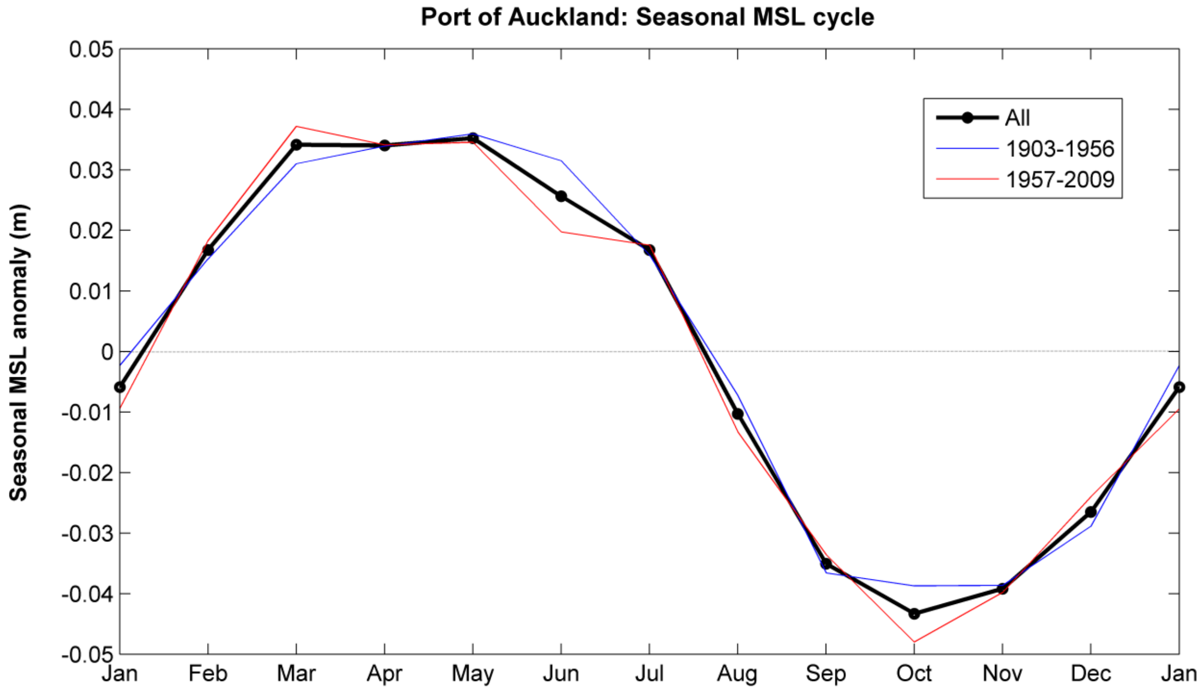

Figure 10: Average annual (seasonal) cycle for the entire record (heavy black line) and the lighter lines show the results for the two halves 1903–1956 (blue) and 1957–2009 (red).

The analyses to extract the effects of the longer climate cycles (ENSO and IPO) were performed using a wavelet band-pass filter to isolate the relevant periods in the sea-level and relevant climate indices.

Climate indices for the interannual El Niño–Southern Oscillation (ENSO) cycle (represented by the Southern Oscillation Index or SOI) and the Inter-decadal Pacific Oscillation (represented by the PDO index) were extracted from 1900 up to September 2010 (Figures 11 & 12) to assist with the determination of longer-term climate variability on Auckland sea levels. The NIWA-derived SOI is based on Troup's method using the Tahiti minus Darwin barometric pressure difference (hPa) for each month, subtracting the mean Tahiti – Darwin difference over a base period 1941–80 and dividing by the standard deviation for the same base period. Positive values indicate La Niña episodes (blue in Figure 11) and negative for El Niño episodes (red in Figure 11). These episodes typically last 2-4 years before switching to opposite phase. It generally varies between +3 to +4 (strong La Niña event) and –3 to –4 (strong El Niño event).

The longer 20-30 year Inter-decadal Pacific Oscillation (IPO) is a longer ENSO-like background climate cycle that affects the entire Pacific and appears to change relatively quickly to the opposite phase. It is detected as warm or cool surface waters in the Pacific Ocean, particularly north of 20° N. During a "warm", or "positive", phase, the west Pacific becomes cool and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. Updated standardized values for the PDO index[4] (Figure 12) are derived from the leading principal component of monthly sea-surface temperature (SST) anomalies in the North Pacific Ocean, poleward of 20N. The monthly mean global average SST

[4] http://jisao.washington.edu/pdo/PDO.latest

anomalies are removed to separate this pattern of variability from any "global warming" signal that may be present in the data.

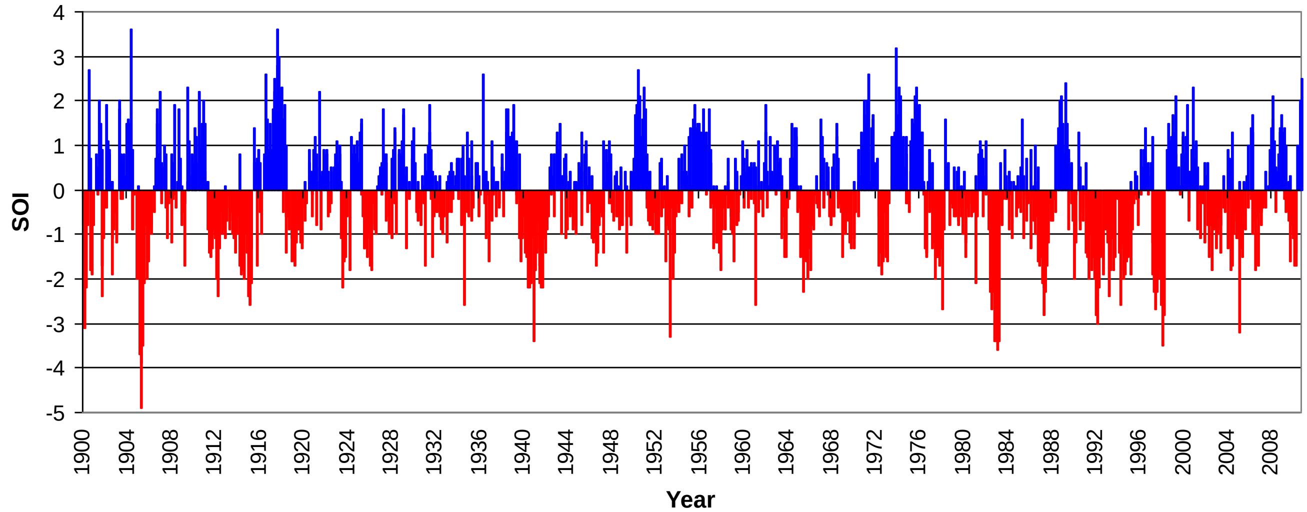

Figure 11: Southern Oscillation Index (SOI) distinguishing La Niña (blue) from El Niño (red) episodes

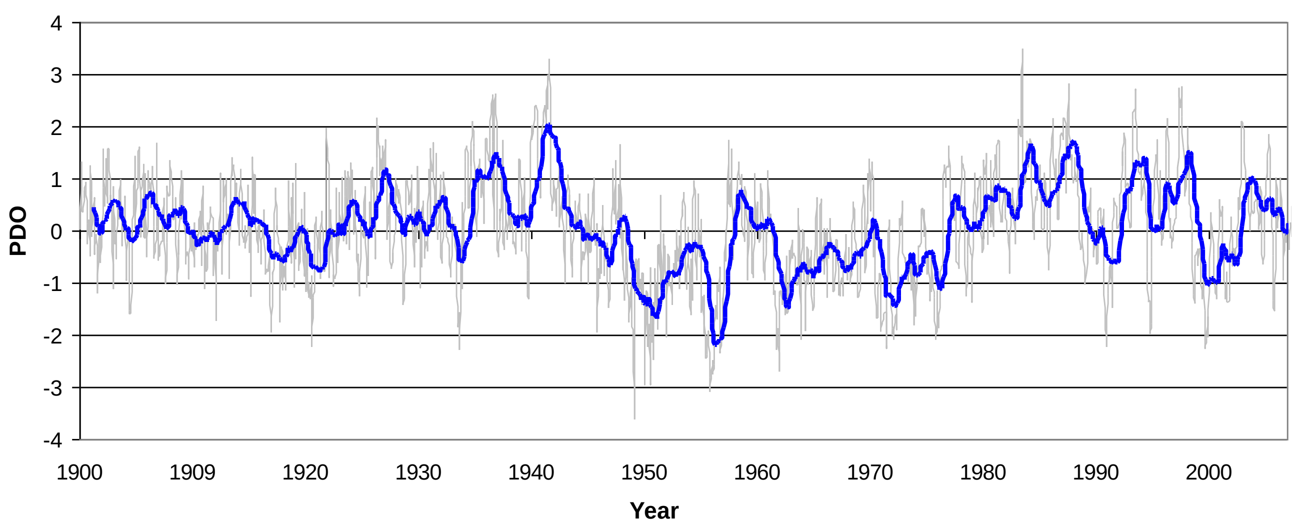

Figure 12: Pacific Decadal Oscillation Index (PDO): warm phase (positive), cold phase (negative). The heavy blue line is a moving average over 16 months of the underlying monthly index (grey).

The low-pass filtered component of the monthly MSL anomaly for periods longer than 1 year is shown in Figure 13 plotted alongside the SOI (also band-pass filtered). A more recent period is shown in Figure 14.

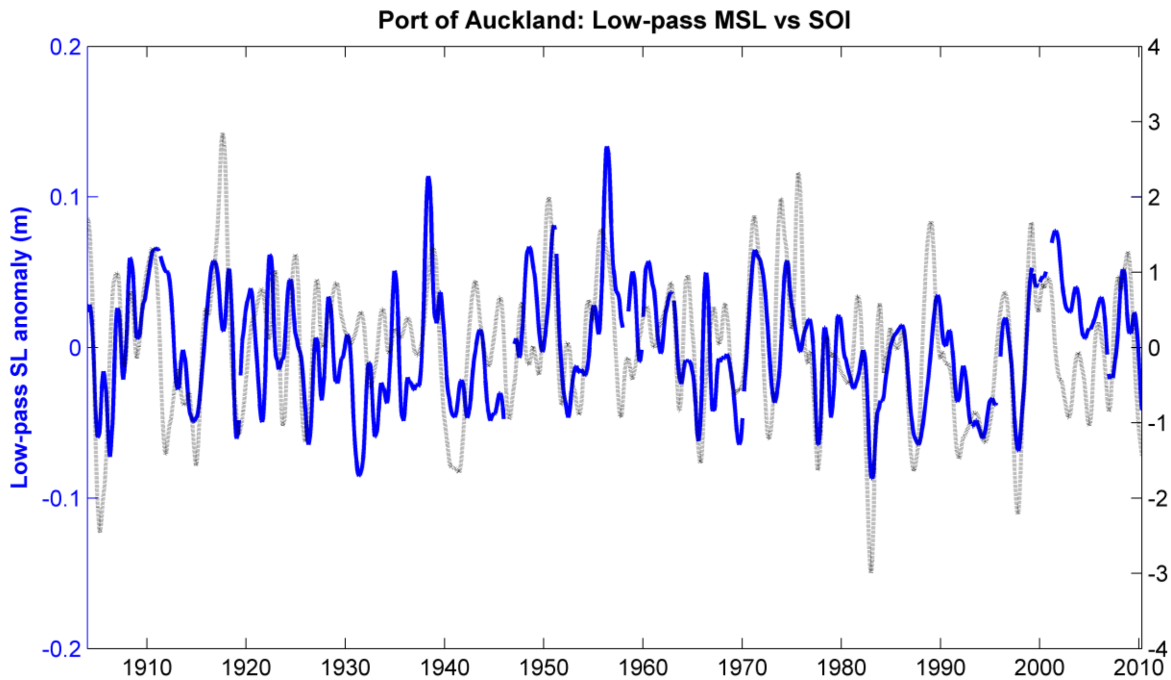

Figure 13: Low-passed filtered MSL anomaly (blue) versus the Southern Oscillation Index (grey).

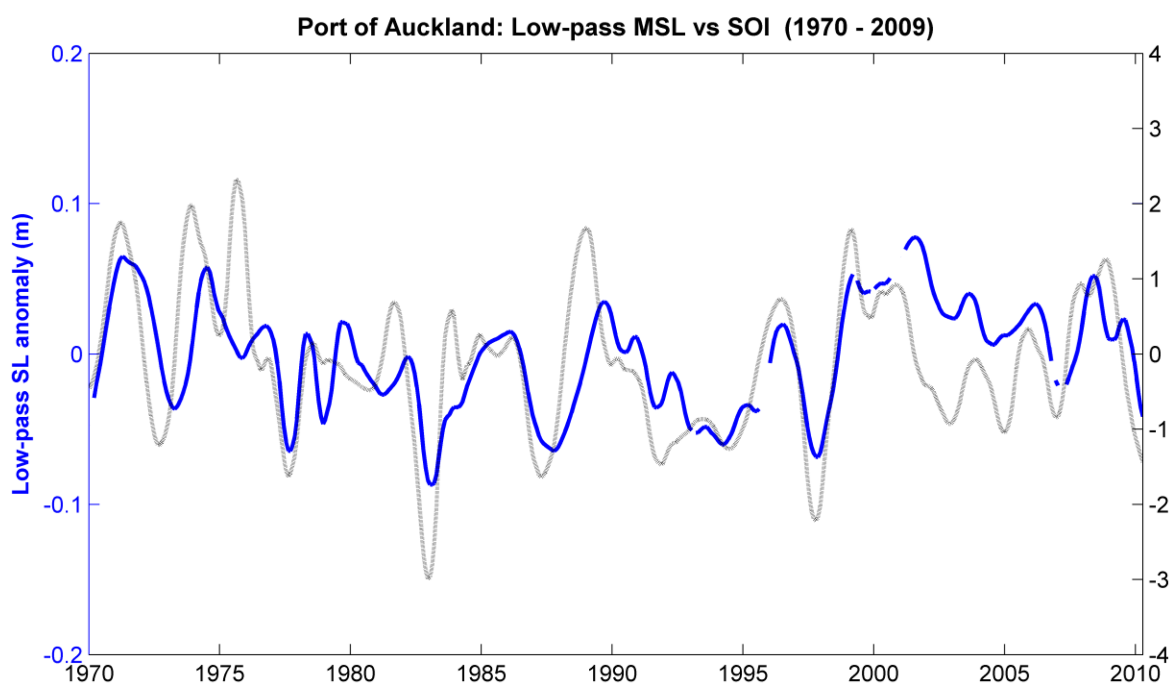

Figure 14: Low-passed filtered MSL anomaly (blue) versus the SOI for the recent period (1970–2009).

Figures 13 and 14 clearly show that there is a strong relationship between MSL and the SOI at interannual timescales. During El Niño episodes (negative SOI), MSL is depressed below the average sea level down by nearly -0.1 m. Recent examples have been the strong El Niño events of 1982/83 and 1997/98 and a smaller recent event (2009/2010) as shown more clearly in Figure 14. Conversely, La Niña episodes (positive SOI) lead to higher than average MSL in the Hauraki Gulf, by up to +0.14 m. Recent examples are the La Niña events of 1970/71, 1973/74, 1988/89 and 1998/99. Over the 107-year record, the highest interannual MSL events over 0.1 m (Figure 13) were during La Niña events in 1938/39 (+0.11 m) and 1955/56 (+0.14 m).

The interannual response of the Port of Auckland MSL to ENSO can be attributed to two main factors on order of importance:

- coastal and ocean sea temperatures are warmer during La Niña (and hence more thermal expansion of the water column) and colder than normal during El Niño (with more contraction than normal of the water column)
- predominant wind direction— during La Niña winds tend to be onshore north-easterlies (and hence a higher than normal set-up in MSL) while during El Niño, winds tend to blow in an offshore direction from the west to south-west, causing more set-down in sea level relative to the average condition;

Considering the magnitude of the interannual MSL (ignoring the sign), the slightly higher magnitudes achieved during some La Niña episodes (compared to El Niño) is due to the higher likelihood of extra-tropical storms (from the north Tasman Sea) and ex-tropical cyclones causing higher sea level set-ups during some months of a La Niña episode. The response of the Port of Auckland MSL to ENSO cycles has been assessed more rigorously by Goring & Bell (1999) but for a shorter record.

Turning now to the 20-30 year Inter-decadal Pacific Oscillation, the response of MSL to this long-term climate regime is shown in Figure 15, comparing low-passed MSL at greater than 8-year timescales with the PDO index (similarly low-pass filtered). This low-pass filtering effectively eliminates the shorter ENSO response. During a "warm"[5] phase of the IPO (positive PDO), the MSL at inter-decadal timescales is slightly lower than the average (minus the sea-level rise trend) and conversely, slightly higher during the "cool" phase of the IPO (negative PDO). The range in Auckland MSL at inter-decadal time scales is approximately ±0.05 m, which is similar to the range for the average seasonal (annual) cycle discussed earlier.

Since 1900, the approximate IPO positive phases have occurred between 1921–1944 and recently between 1977 and 2000, when sea level was slightly depressed. It also shows up as a reduced rate of rise in sea level during these periods (Figure 6) and also Figure 11 of MfE (2001). We are currently in a "negative" phase of the IPO (since approximately 2000), with previous "negative" phases in 1945–1976 and 18?? to 1920.

The interdecadal effect on MSL accounts for only about 15–20% of the variability in the month-to-month changes in sea level (Figure 9), with a similar magnitude to the seasonal (annual) cycle.

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[5] "Warm" relates to the eastern Pacific, but it is generally cooler around NZ and vice versa (used the term "positive" and "negative" phase to avoid confusion).

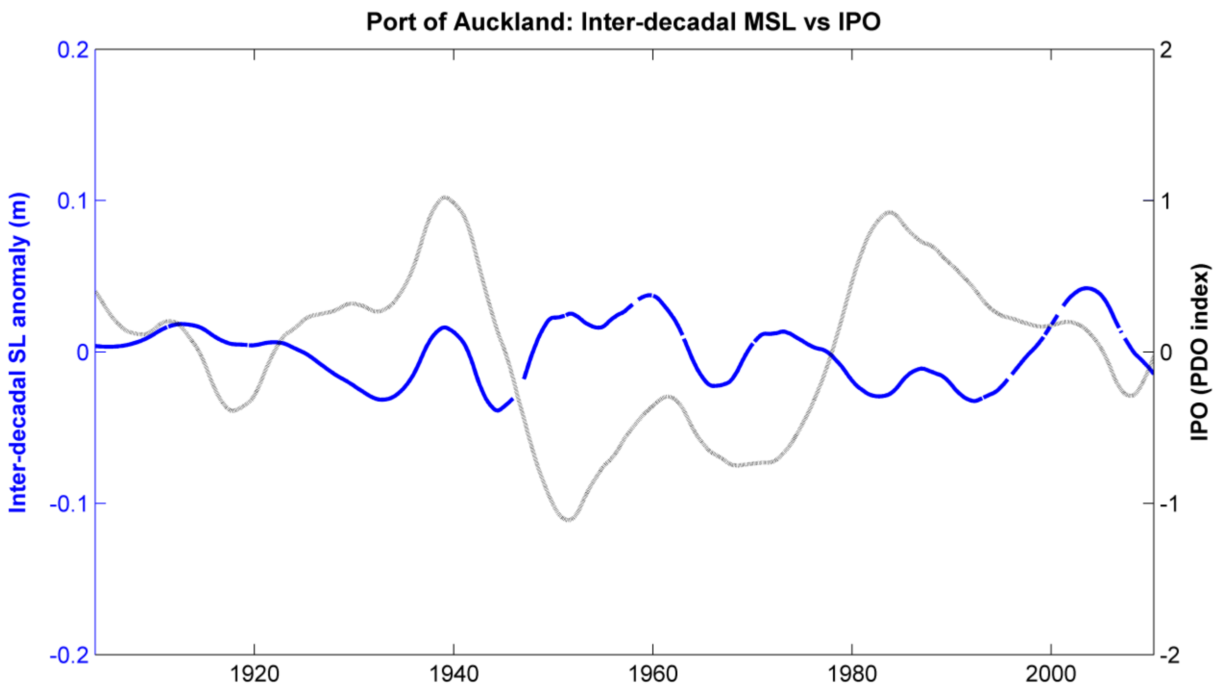

Figure 15: Low-passed filtered MSL anomaly (blue) versus the PDO Index (grey).

5.2 Summary of monthly MSL variability

To cover the variability in month-to-month MSL response (including seasonal, interannual and inter-decadal cycles), an allowance in planning and design should take into account a range from –0.17 m to +0.25 m relative to the average MSL (excluding the sea-level rise trend). The latter needs to be added to extreme value analyses of storm-tide levels, along with sea-level rise (past and future projections) to cover climate-induced variability in monthly MSL.

The three main components contributing to long-term variability (besides the trend) in MSL are:

- Seasonal (annual) cycle, from the heating and cooling effects on Hauraki Gulf waters, with an average range of 0.09 m (–0.05 to +0.04 m)
- Interannual cycle due to the 2–4 year ENSO, with an overall range of 0.24 m (-0.1 to +0.14 m) with higher monthly MSL during La Niña episodes
- Inter-decadal cycles from the 20-30 year Interdecadal Pacific Oscillation, with an overall range of 0.1 m (–0.05 to +0.05 m), with the higher MSL occurring during the “negative” phase (which we are currently in).

While the values may be slightly different, the west coast of the Auckland region also experiences similar (not opposite) responses in MSL to these three climate cycles as they generally affect ocean waters in a wider SW Pacific context.

6. Modern Sea-Level Change: New Zealand in the Global Context

20th century global estimates for sea level change are derived from a modest number of high-quality tide gauge records located on stable land regions that have had their records adjusted for the vertical land movements associated with glacio-isostatic motion. Bindoff et al. (2007) note, firstly, that the two significant drivers for this change are considered to be thermal expansion and the net exchange of water mass between the oceans and land-based sources (e.g., glaciers, ice sheets, water reservoirs and extracting groundwater) and, secondly, that this rate of rise is non-uniform around the world, with the spatial variability being mostly due to non-uniform changes in temperature and salinity in the global oceans. Further spatial non-uniformities arise from changes in ocean surface wind patterns (e.g., Han et al., 2010), and from changes in gravitational attraction on the ocean waters due to the re-distribution of ice mass from the polar ice sheets to melt water spread throughout the oceans (e.g., Bamber et al., 2009; Mitrovica et al., 2009).

In order to place these 20th century estimates into context, it is important to note that there is good evidence from a variety of different sources to suggest that there was little, if any, change in long term sea levels from the first century AD until the 19th Century (Church and White, 2006; Geherels et al., 2008). Bindoff et al. (2007), in the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report in 2007, note that the instrumental record indicates the current episode of sea level rise began in the late 19th century – a finding that is consistent with Geherels et al. (2006) observations made from saltmarsh cores collected in Pounawea (Otago). The global tide gauge records show a rise in sea levels beginning towards the end of the 19th century. Since then there has been a global average sea level rise over the 20th century (up to 2004) of 1.7 ± 0.3 mm/yr (Church & White, 2006). The error bars here are at a 95% confidence interval. It is particularly relevant to note that the tide gauge data show no evidence of a recent acceleration in sea level rise. Indeed, the emerging picture is one of an acceleration in sea level rise in the early part of the 20th century, followed, if anything, by a deceleration in the latter part of the century (Watson, 2010; Woodworth et al, 2009; Cole, private communication). This pattern is influenced by the response of MSL to interannual and inter-decadal climate variability as discussed in Section 5.

Whereas these tide gauge data provide coastal (or island) data only, high quality satellite altimeter observations made since 1993 (i.e., TOPEX/Poseidon, Jason-1 and -2) complement the sparse tide gauge network by providing global oceanic coverage from 66º N to 66º S. Altimeter observations reveal a global mean sea level rise of 3.1 ± 0.7 mm/yr since 1993 (Bindoff et al, 2007) – a number recently updated by CSIRO to 3.2 ± 0.4 mm/yr using the altimeter record through to March 2010[6]. The apparent inconsistency between these figures and the much longer 1.7 mm/yr trend obtained from the tide gauge records could be due to a number of factors including, the relatively short time frame of the altimetry record (and thus its sensitivity to more recent climate episodes), the much improved spatial coverage of satellite altimetry measurements (and thus a better overall global estimate), or possibly small biases in

[6] http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html

either the altimetry measurements themselves or the satellite reference frames. With regard to this latter point, similar reference frame uncertainties that afflict rates of vertical uplift as derived from cGPS positioning, can also be expected to afflict other satellite measurement systems.

In past IPCC Assessments, there have been substantial uncertainties in estimating the components that contribute to the observed rise in sea level, with a significant shortfall relative to the observed rise. But these uncertainties have improved substantially with the input of satellite information, particularly the inclusion of estimates of ice-sheet mass changes from the GRACE satellite mission, which have virtually closed the shortfall in the sea-level budget for the recent 5-year period 2003–2007 (Cazenave & Llovel, 2010). Over the recent satellite altimetry period (1993–2009), there has been a reduction in the thermal expansion contribution (overall around 33% of the observed sea-level rise) offset by an increasing ice-mass contribution from ice sheets, ice caps and glaciers which is around 50% of the observed rise (Cazenave and Llovel, 2010; Cazenave, unpublished data). The remainder is due to net land-water contributions, land-use changes, a small but significant increase in warming of deep ocean layers (Bindoff et al., 2007) and measurement uncertainties. This closure in the shortfall of the sea-level budget supports the view that global sea levels are rising at a faster rate than is indicated by coastal tide gauges (although perhaps not quite as fast as is indicated by the altimetry data).

The trends from the global tide-gauge network and recent satellite altimetry (red line) are combined in Figure 16, with the confidence limits (shaded areas) reducing with time as accuracy improves with the inclusion of longer sea-level tide gauge datasets.

In the past it has been recognised that there is danger in seeking to resolve accurately long-term sea level changes from data sets of less than 50–60 years in length. Douglas (1991, 1992), for example, concluded that large variations in the estimates of sea level rise could be explained in nearly all cases by the selection criteria used by a particular investigator – short records being one of the most important. He, and other investigators (e.g., Holgate and Woodworth, 2004) acknowledge the importance of eliminating the periodic effects from such signals as inter-decadal variability. Fortunately for the Auckland region (east coast), a reliable tide-gauge record of over 110 years is available and covers five phases of the 20-30 year Interdecadal Pacific Oscillation (see Section 5).

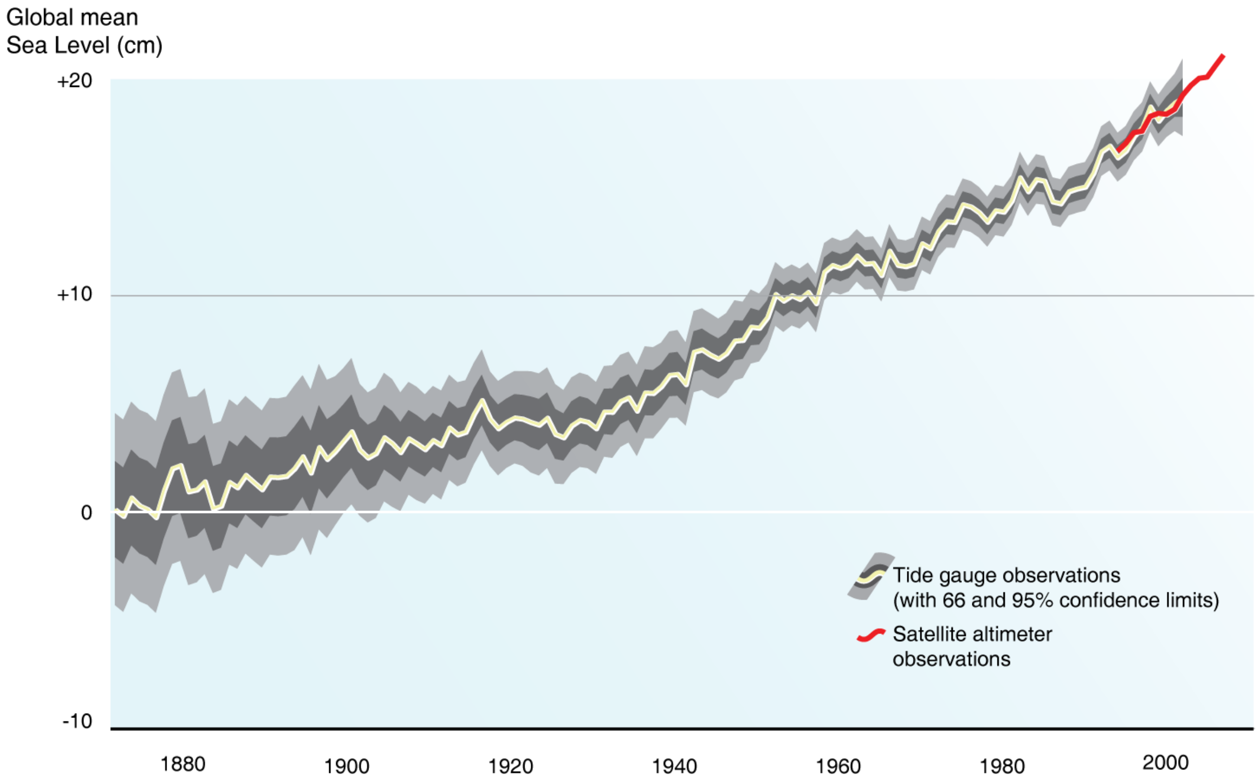

Figure 16: Observed global mean sea level from 1870 to 2006 from coastal and island sea-level gauges and latterly the satellite altimeter series from 1993. [Reprinted from *UNEP/GRID-Arendal* http://maps.grida.no/go/graphic/trends-in-sea-level-1870-2006 with data source Church & White (2006)

When the New Zealand data (see Section 4) is placed in the global context, we observe that the GIA corrected relative sea level rise observed in New Zealand is completely consistent with the best global-averaged absolute sea-level rise of 1.7 ± 0.3 mm/yr. The absolute sea level rises observed in New Zealand, while slightly lower than this figure, have uncertainties in calculation at the 0.5 mm/yr level – primarily due to reference frame instabilities and variations in processing strategies. In addition, the slight deceleration in sea level rise perhaps present in the latter part of the 20th century is consistent with results obtained both in the UK (Woodworth, 2009) and from the Freemantle tide gauge (Watson, 2010). In the Auckland record, this reduction in the rate of rise can be attributable in part to the positive phase of the Interdecadal Pacific Oscillation from 1977 to 2000 (see Figure 8a) and the associated predominance of El Niño events, which are accompanied by lower than normal sea level as discussed in Section 5. However, when the global altimetry data is incorporated into the picture we conclude as follows:

1. The consistency between the rate of GIA corrected sea level rise found in New Zealand and the best long-term global average estimates of sea level rise suggest that long-term sea level rise predictions developed by the international community, including IPCC, should form a starting point for a reliable estimate of the sea level rise that can be expected in the oceans around New Zealand.

2. Such long-term predictions, however, can be expected to have regional variations. A recent analysis by NIWA of global ocean-climate models used for the IPCC 2007 Fourth Assessment indicates that the projected sea level rise by the 2090s for the wider New Zealand area would not be dissimilar from global-average projections, but could be up to 0.05 m higher (Ackerley et al., in prep).

3. At this stage, and with the exception of Wellington where significant subduction appears to be taking place, the New Zealand landmass shows no evidence of ongoing vertical tectonic motion – at least to a level of ± 0.5 mm/yr. If such vertical motion is occurring, present results suggest that with the exception of Wellington it is not at the primary tide gauges.

4. There are close parallels between the rates of relative sea level rise as determined in the United Kingdom (taking into account the wide spatial variation in relative sea level rise due to GIA) and those found in New Zealand (Woodworth et al., 2009; Hannah, 2004). The same signs of acceleration about 1930, followed by a possible deceleration later in the century can also be found. For the first time, regional sea level rise projections were adopted for the UK – these were expected to vary from global mean sea level rise projections particularly because of the spatial variability in land movement in the UK ranging from glacial rebound in parts of Scotland and subsidence in southern England. In terms of regional planning and engineering design, it is the relative sea-level rise for that region that is important. The following Table has been extracted from this comprehensive report.

Table 3: UK **absolute** time mean sea level change (cm) over the 21st century, including ice melt, under three different scenarios, with 5th to 95th percentile confidence intervals. The changes are given for the period 1980–1999 to 2090–2099.

	5th percentile	**Central estimate**	**95th percentile**
High emissions	15.4	45.6	75.8
Medium emissions	13.1	36.9	60.7
Low emissions	11.6	29.8	48.0

It must be noted that the above figures reflect sea level rise relative to a tectonically stable earth. More specifically, we note that when any land movement is excluded, the most probable sea level rise by 2095 would be in the range of approximately 12–76 cm. The top end of this range is consistent with existing Ministry for the Environment (NZ) planning guidelines for coastal hazards and climate change (MfE, 2008) whilst the lower bound is considerably lower than existing guidelines. The UK guidelines also introduced a high-end, but physically plausible, H^{++} scenario of 0.93 m to 1.9 m by 2100 to be used to investigate contingency planning and limits of adapation.

We conclude by noting that a low probability but upper limit to any near term sea level rise expectations (i.e., in the next 90 years) must be informed from the historical evidence arising from the last interglacial period. Best evidence suggests that in the mid-Holocene climatic optimum when global temperatures were warmer than at present, eustatic sea levels around New Zealand (including sites in the Auckland region) were between 0.5 m – 1.0 m higher than at present.

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Appendix 1 – Auckland Annual MSLs (Adjusted to pre-1973 PoA Chart Datum)

1899	1.866
1900	1.863
1901	1.823
1903	1.880
1904	1.864
1905	1.843
1906	1.826
1907	1.882
1908	1.920
1909	1.901
1910	1.928
1911	1.948
1912	1.903
1913	1.873
1914	1.833
1915	1.875
1916	1.928
1917	1.923
1918	1.905
1919	1.873
1920	1.921
1921	1.866
1922	1.930
1923	1.893
1924	1.937
1925	1.894
1926	1.859
1927	1.894
1928	1.915
1929	1.902
1930	1.883
1931	1.840
1932	1.881
1933	1.882
1934	1.900
1935	1.917
1936	1.895
1937	1.910
1938	1.998
1939	1.952
1940	1.891
1941	1.898
1942	1.888
1943	1.932
1944	1.890
1945	1.901
1947	1.941
1948	1.988
1949	1.965
1950	1.964
1951	1.970
1952	1.906
1953	1.925
1954	1.935
1955	1.980
1956	2.047
1957	1.990
1958	1.964
1959	1.975
1960	2.000
1961	1.972
1962	1.982
1963	1.961
1964	1.940
1965	1.926
1966	1.977
1967	1.946
1968	1.950
1969	1.921
1970	1.952
1971	2.040
1972	1.986
1973	1.955
1974	2.012
1975	1.992
1976	1.985
1977	1.952
1978	1.959
1979	1.983
1980	1.970
1981	1.969
1982	1.958
1983	1.926
1984	1.964
1985	2.005
1986	1.986
1987	1.938
1988	1.946
1989	2.031
1990	1.999
1991	1.985
1992	1.978
1993	1.946
1994	1.944
1995	1.997
1996	2.008
1997	1.978
1998	1.987
1999	2.065
2000	2.065
2001	2.088
2002	2.042
2003	2.060
2004	2.026
2005	2.048
2006	2.034
2007	2.014
2008	2.054
2009	2.049