Auckland: A Case Study in the Regional Assessment of Long-Term Sea Level Change

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Key words: Climate change, sea level change,

SUMMARY

Climate change has a variety of important environmental impacts, one of which is reflected in changing sea levels. Increasingly, for coastal management activities planners, engineers and surveyors need a reliable assessment of the sea level changes that can be expected over the next 100 years. While the Intergovernmental Panel on Climate Change (IPCC) has produced such assessments, they give a global picture only – a picture that may not be applicable in a regional context.

This paper documents recent work undertaken in New Zealand to assess the likely sea level change out to 2100 AD at the country's largest city, Auckland. It draws together geological data from the Holocene period, sea level data from the last 110 years, continuous GPS (cGPS) collected over the last 10 years, and future climate change projections in order to build a long-term hazard profile for sea level rise in Auckland. This hazard analysis includes an assessment of the seasonal, decadal, and inter-decadal variability in Auckland sea levels. It is perhaps the most comprehensive sea level change assessment undertaken in New Zealand to date and acts as a model for similar analyses elsewhere. It concludes that existing national planning guidelines used in New Zealand for coastal hazards and climate change which, paraphrased, state, "*plan for a 0.5 m sea level rise and assess sensitivity of activity to at least a 0.80 m rise by the 2090s*" are appropriate for Auckland. The paper also concludes that a low probability but upper limit to any near term sea level rise expectations (i.e., in the next 90 years) should be informed by the historical sea levels prevalent at the last the mid-Holocene climatic optimum when global temperatures were warmer than at present. At that time eustatic sea levels around New Zealand were between 0.5 m – 1.0 m higher than at present.

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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) 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 University of Otago was asked by the Auckland Regional Council to assess future coastal hazard by, firstly, identifying millennial scale processes that may have influenced the elevation of mean sea level in the Auckland region, secondly, examining historical monthly mean sea level trends so as to determine inter-annual and inter-decadal variability and, thirdly, assessing any long-term trends in the sea level data. This information was then aggregated and combined with long term climate change predictions so as to build a risk profile for the Auckland region. This paper summarises the information presented in the project report.

2. MILLENIAL SCALE SEA LEVEL CHANGES IN THE AUCKLAND REGION

An understanding of past sea level rise episodes and their driving forces can be very helpful in setting a framework for likely future rise.

Best evidence suggests that post-glacial eustatic sea level rise culminated on the New Zealand coastline close to the present sea-level approximately 6,500 years ago. Since then, eustatic sea level oscillations of up to 1 m above present sea levels are thought to have occurred from 5,500 to 3,000 years ago at 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 other coastlines in the Tasman Sea (Woodroffe et al. 1995), Queensland (Lambeck et al., 2010) and southeast Australia (Sloss et al. 2007). It is commonly argued that the sea level oscillation was instigated by the mid-Holocene climatic optimum, a period when global temperatures are thought to have been at least 1 to 2ºC (and perhaps as much as 6ºC in some regions) higher than at present (Chappell, 1987). A composite Holocene eustatic sea level curve for New Zealand is shown in Figure 1.

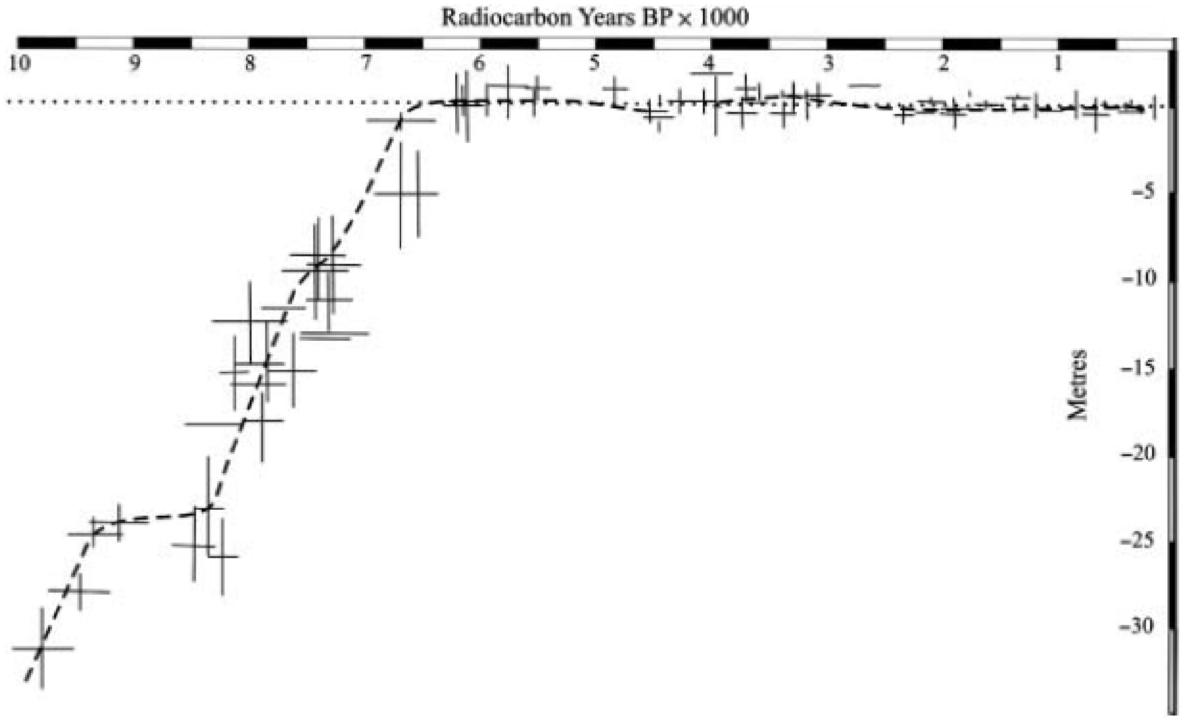

Figure 1. The Holocene eustatic sea level curve for New Zealand produced by Gibb (1986). *Source:* Kennedy, *2008*.

Two of the most detailed Holocene sea level records in or near the Auckland region are derived from east coast sites in the Firth of Thames, at Kaiaua and Miranda (see Figure 2). At these sites Gibb (1986) surveyed and radiocarbon dated the elevation of carbonate material in chenier ridges (sand-shell deposits sitting above mud). The results showed that 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. 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, at 3.5 ka BP a higher sea level of this magnitude is observed at the tectonically stable Weiti River estuary located 90km north of Miranda. This elevation is, however, lower than at 5.5ka when sea levels in the Weiti River estuary were observed to be approximately 0.8 m above present (Gibb, 1986). The similarity of these Holocene sea level trends with those observed in the Tasman Sea (Woodroffe et al. 1995) and Australia's east coast (Sloss et al. 2007; Chappell, 1987 Howarth et al. 2002) suggests that Holocene relative sea level curves from the Auckland region manifest the influence of global and local environmental processes which controlled sea level elevation during this period.

Figure 2. Auckland Region (*Source:* Google Earth)

It is important to note that global average surface warming through to 2100 AD is expected to rapidly return the global climate to conditions akin to the mid-Holocene optimum, a period when eustatic sea level in the Auckland region reached an elevation up to 0.8 m above late 19th Century levels.

3. THE POST 1899 AUCKLAND MEAN SEA LEVEL DATA

The post 1899 sea level data used in this study are described in Hannah (1990, 2004 and 2008). To these data files the additional data for 2008 and 2009 were added. All hourly data were processed into monthly and annual MSLs using the University of Hawaii's SPLR2 software (c.f., Caldwell, 2000). It is these monthly and annual means that were used in the analyses to be described in the coming sections. It is important to note that a correction of 0.5 ft (0.152 m) has been made to all post 1973 data (when the tide gauge zero was altered), to ensure that all data refer to the same datum. Further details regarding the tide gauges used and the data collected can be found in Hannah et al (2010)

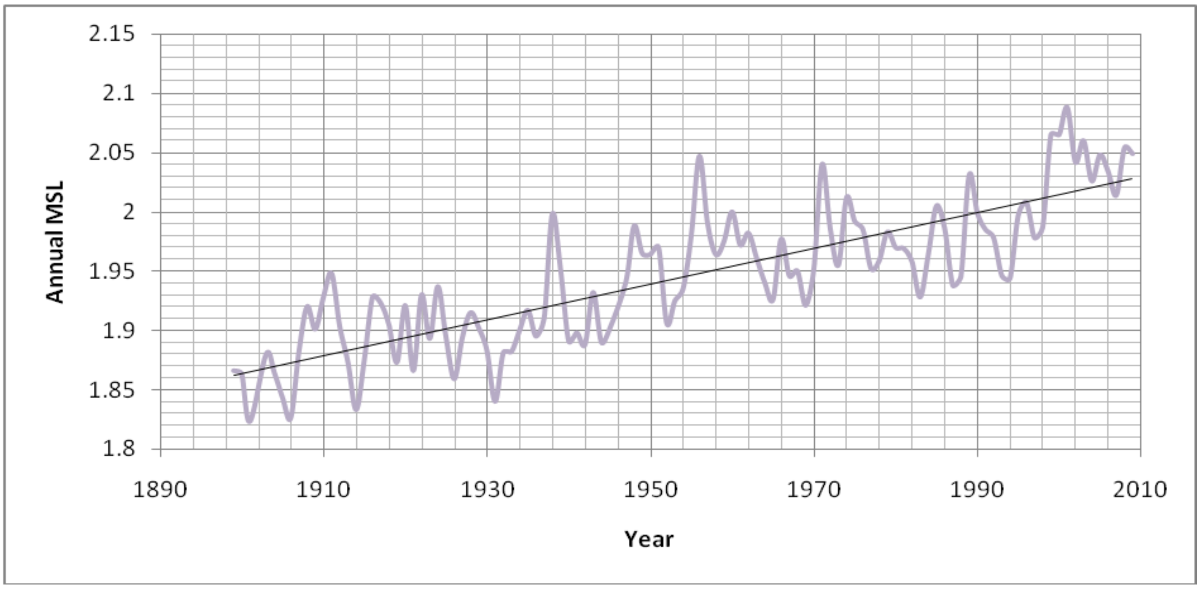

Figure 3. Linear trend in Auckland annual MSL data (to pre-1973 Port of Auckland Chart Datum)

The Auckland Annual MSL data are shown in Figure 3. The calculated linear trend relative to stable local benchmarks on the fixed shoreline and uncorrected for any regional vertical land motion is 1.5 ± 0.09 mm/yr. The most recent analysis of the Auckland data (Watson, 2010, Cole, 2010) reveals no acceleration in the rate of sea level rise. Indeed, their analyses suggest a slight positive acceleration in the early-mid 20th Century followed by a slight negative acceleration in recent years.

Before comparing the Auckland sea level trend with the trends as determined at other global sites with long data records, it is important to consider, and if possible eliminate any local or regional tectonic effects that might exist. In order to achieve this, Peltier's ICE-5G v.1.2b (M2) model was used to calculate an estimate for the Global Isostatic Adjustment (GIA) at the Auckland tide gauge site. A correction of +0.30 mm/yr was calculated thus giving a GIA corrected sea level trend of 1.8 mm/yr.

In addition, the 10 years of almost continuous cGPS data have also been able to be used to compute an estimate of regional tectonic motion. These data provide a computed correction of -0.1 mm/yr thus giving an absolute sea level trend of 1.4 mm/yr at Auckland. However, reference frame uncertainties and possible variations in processing strategies suggest an uncertainty of perhaps 0.5 mm/yr in this computed estimate of regional tectonic motion.

4. THE ASSESSMENT OF ANNUAL, DECADAL AND INTER-DECADAL VARIABILITY IN SEA LEVEL

In order to assess sea level variability with periods of up to 30 years the monthly MSL data were used to undertake three different sets of analyses. Previous studies (e.g., Hannah, 1990) had determined that the magnitude of the 8.85 yr and 18.61 yr lunar tides at Auckland were very small (12 mm or less). Because of their small magnitude relative to the size of the annual, decadal and inter-decadal variability, they were ignored in this study.

For the purposes of these analyses, the linear trend described in Sec. 3 was removed from the time series of monthly MSLs thus producing a de-trended data set (see Figure 4). This data set was then unpacked into components due to the:

- Seasonal (annual) cycle, from the heating and cooling effects on Hauraki Gulf waters.
- Interannual cycle due to ENSO (El Niño–Southern Oscillation).
- Inter-decadal cycles from the IPO (Inter-decadal Pacific Oscillation).

The average seasonal cycle was extracted from the monthly MSL anomaly time series by averaging all the monthly MSL values for a specific month over the entire data record. The results are shown in Figure 5. 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. This accounts for only about 15–20% of the variability in the month-to-month changes in sea level shown in (Figure 5).

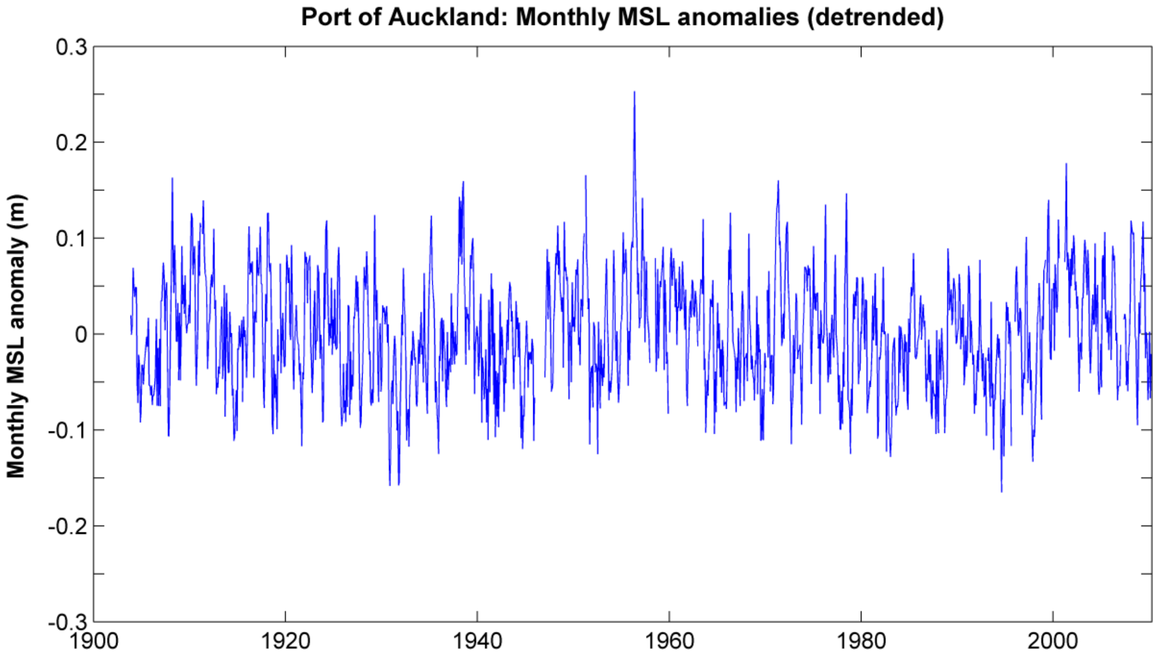

Figure 4: Monthly MSL anomalies relative to the linear trend line, removing the rise in sea level

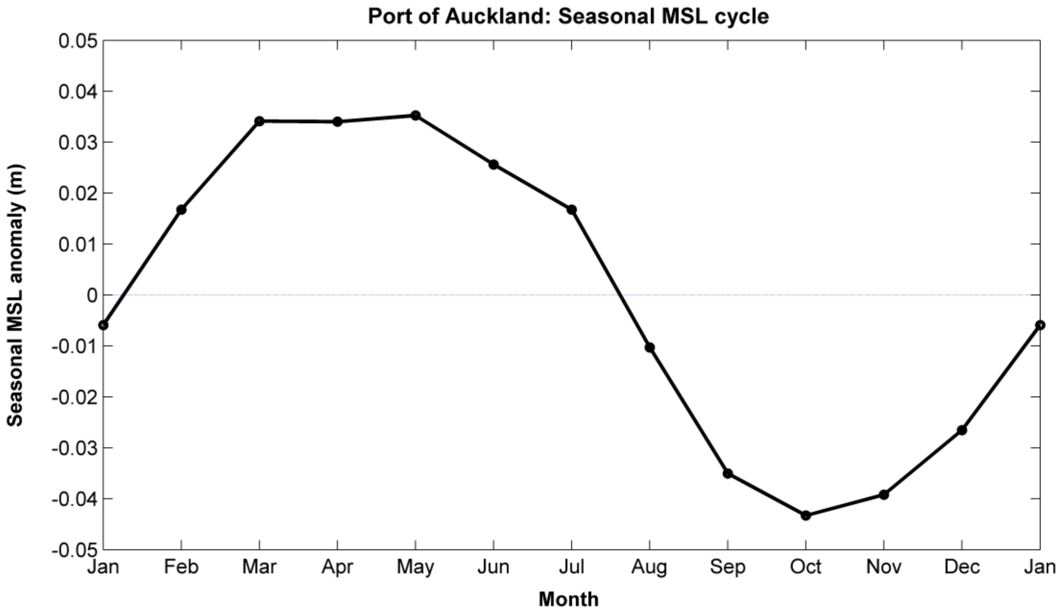

Figure 5: Average annual (seasonal) cycle for the entire record 1903–2009.

The analyses to extract the effects of the longer climate cycles (El Niño–Southern Oscillation, and the Inter-decadal Pacific Oscillation) were performed using a wavelet band-pass filter to isolate the relevant periods in the sea-level and relevant climate indices. A detailed outline of how these analyses proceeded is given in Hannah et al. (2010).

The ENSO cycle (represented by the Southern Oscillation Index or SOI) and the Inter-decadal Pacific Oscillation (represented by the PDO index) between 1900 and September 2010 were extracted from existing climate databases. La Niña and El Niño episodes typically last 1-3 years before switching to the opposite phase.

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.

It was found that there is a strong relationship between MSL and the SOI at inter-annual timescales. During El Niño episodes, MSL is depressed below the average sea level down by nearly -0.1 m. Conversely, La Niña episodes lead to higher than average MSL in the Hauraki Gulf, by up to +0.14 m. Over the 107-year record, the highest interannual MSL events over 0.1 m were during La Niña events in 1938/39 (+0.11 m) and 1955/56 (+0.14 m). This inter-annual response can be attributed both to changes in coastal and ocean sea temperatures and changes to coastal water level set-up from shifts in predominant winds.

For the longer Inter-decadal Pacific Oscillation, it was found that the response of MSL to this long-term climate regime was approximately ±0.05 m – i.e., in a range very similar to 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 rise was slightly depressed. As with the seasonal (annual) cycle, this inter-decadal effect on MSL accounts for only about 15–20% of the variability in the month-to-month changes in sea level (Figure 4).

5. AN ASSESSMENT OF FUTURE SEA LEVEL CHANGE

5.1 The global picture

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 of the global oceans 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).

There is good evidence 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), note that the tide gauge record indicates the current episode of sea level rise began in the late 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 New Zealand and United Kingdom tide gauge data show no evidence of a recent acceleration in sea level rise. Indeed, the emerging picture in these regions is one of 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).

Whereas 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 66°N to 66°S. Altimeter observations reveal a global mean sea level rise of 3.1 ± 0.7 mm/yr since 1993 (Bindoff et al, 2007). The apparent inconsistency between this figure and the much smaller 1.7 mm/yr trend obtained from the tide gauge records seems 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), and possible small biases in either the altimetry measurements themselves or the satellite reference frames.

In past science 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). The satellite altimetry period (1993–2009), has seen 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 sea-level budget suggests that global sea levels are rising at a faster rate than is indicated by coastal tide gauges (although perhaps not quite as fast as indicated by the altimetry data).

The trends from the global tide-gauge network and recent satellite altimetry (red line) are combined in Figure 6, with the confidence limits (shaded areas) reducing with time as accuracy improves with the inclusion of longer sea-level tide gauge datasets.

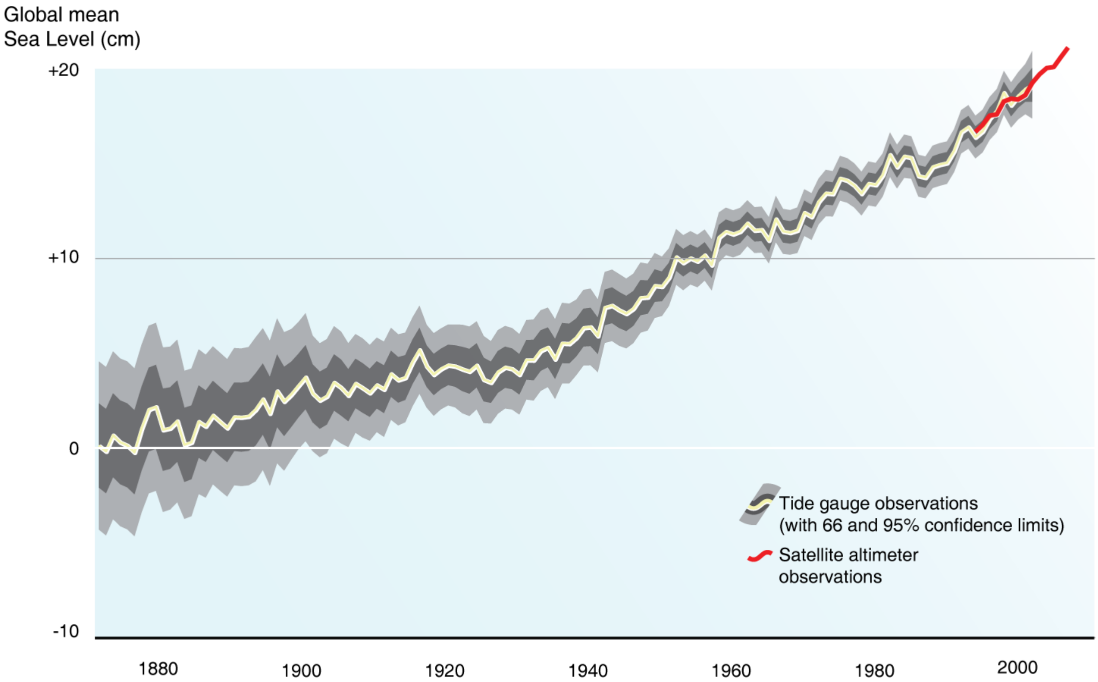

Figure 6: Observed global mean sea level from 1870 to 2006 from coastal and island sea-level gauges and latterly the satellite altimeter series from 1993. [Reprinted from *UNEP/GRID-Arendal* http://maps.grida.no/go/graphic/trends-in-sea-level-1870-2006 with data source Church & White (2006)

5.2 Auckland in the Global Context

When the Auckland data (see Section 3) 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 in the Auckland data 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 and the associated predominance of El Niño events, which are accompanied by lower than normal sea level as discussed in Section 4. 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 Auckland 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 (unpublished data) 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.

3. At this stage Auckland shows no evidence of ongoing vertical tectonic motion – at least to a level of ± 0.5 mm/yr.

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 1: 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 the 2090s 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.

We conclude by noting that a low probability but likely 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 current interglacial period. Best evidence suggests that during the mid-Holocene climatic optimum when global temperatures were warmer than at present, eustatic sea levels around the Auckland region were between 0.5 m - 0.8 m higher than at present.

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).

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.

CONCLUSIONS

This study not only presents a first attempt at sea level regional hazard assessment in New Zealand but it draws together data from a range of historical and present day data records in a manner not previously undertaken. The study, while producing a comprehensive result, could be improved by further investigation into Holocene climates (and their associated sea level changes), as well as by improved regional ocean-climate prediction models, which NIWA is currently evaluating. Further improvements, both in the processing of cGPS data and in reference frame stability will also be of assistance. It is anticipated that these will all be areas for fruitful ongoing research.

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BIOGRAPHICAL NOTES

John Hannah BSc, DipSci, MSc, PhD, MNZIS, RPSurv, completed his first two degrees at the University of Otago, New Zealand. Two years later, in 1974, he became a Registered Surveyor. In 1976 he began study at The Ohio State University, completing an MSc and a PhD, both in Geodetic Science. From 1982 until 1988 he was Geodetic Scientist, and then subsequently, Chief Geodesist/Chief Research Officer with the Department of Lands and

Survey, New Zealand. After a 17 month appointment to the Chair in Mapping, Charting and Geodesy at the US Naval Postgraduate School, California, he returned to New Zealand as Director of Geodesy and subsequently, Director of Photogrammetry for the Dept. of Survey and Land Information. In 1993 he joined the School of Surveying, as Professor and Head of Department, becoming its Dean in 2001. He relinquished this administrative role at the end of 2004 in favour of more teaching and research. His publications reflect his research interests in sea level change and surveying education. He is a Registered Professional Surveyor and is a former President of the NZ Institute of Surveyors.

Rob Bell, is a Principal Scientist (Coasts and Natural Hazards) with the National Institute of Water and Atmospheric Research (NIWA), Hamilton. He has completed a BE(Hons) (Civil Engineering) and PhD (Civil Engineering–Canterbury) and is a Chartered Professional Engineer (CPEng) in environmental engineering. Rob has been involved for 30 years in research and consultancies involving coastal engineering, natural hazards, climate change and marine water quality. His applied research covers natural physical hazards, such as tsunami, storms, floods, waves, coastal erosion, maritime hazards and sea-level variability and change. Rob was a co-author of New Zealand's 2008 guidance manual to local government on planning for coastal climate change and coastal hazards and was an invited participant in the IPCC Working Group I Workshop on Sea-level Rise and Ice Sheet Instabilities in Kuala Lumpur in June 2010.

Ryan Paulik, is the Principal Specialist (Hazards), with the Auckland Council, New Zealand. He has completed a BSc. (Hons) (Physical Geography) and an MSc (Coastal Geomorphology). Ryan is involved in the research and development of land use policy to manage natural hazards in the Auckland region, New Zealand. This includes natural hazards influenced by sea level change such as, beach erosion, coastal cliff erosion, coastal and riverine flooding and tsunami. He also has an active involvement rock coast geomorphology research which has included identifying the role of Holocene sea level elevations on shore platform development.

CONTACTS

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