Sea-level variability and trends: Wellington Region

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Executive summary

Greater Wellington Regional Council (GWRC) contracted NIWA to provide a synthesis of historic sea-level variability and trends in the Wellington region and how these relate to sea level in national and global contexts. NIWA sub-contracted Professor John Hannah (Vision NZ Ltd.; formerly University of Otago) to provide a robust analysis of sea-level trends from annual mean sea level values, adjusted for vertical datum changes and vertical land movement.

The Wellington region is situated astride a complex network of faults associated with the convergence of the Australian and Pacific crustal plates some 20–40 km beneath the surface. As such, the region has a more complicated spatial and temporal pattern of long-term relative sea-level rise than other stable parts of New Zealand. Over the past decade or so, Wellington City has been subject to recent slow-slip events that have produced an average subsidence of 1.7 mm/year since 2000. Subsidence from GPS records over the past 6 years shows it varies across the Wellington region from subsidence of around 1 mm/yr on the Kapiti coast up to between 2 to 3 mm/yr along the Wairarapa coast. A parallel study to this Report has shown there has been long-term tectonic uplift west of the Ohariu Fault and relative long-term stability east of the Fault over the Holocene (Gibb, 2012).

The historic analysis of the Wellington Harbour sea-level record for sea-level variability covers the period 1944 to 2011, for which monthly mean sea levels are available, while the long-term sea-level trend is based on available annual means from the late 1800's to 2011.

In the analysis period 1945 to 2011, month-to-month variability in mean sea level ranged from -0.16 to +0.20 m after the linear trend in sea-level rise was removed. Higher than normal sea level occur during La Niña episodes and the negative phase of the 20–30 year climate cycle called the Inter-decadal Pacific Oscillation (IPO). Conversely, monthly sea levels are lower than normal during El Niño episodes and the positive phase of the IPO.

Currently, the mean sea level in Wellington Harbour is 0.20 m above Wellington Vertical Datum-1953 (WVD-53), and like the range in monthly variability, needs to be taken into account when assessing present-day coastal hazard risks. For future hazard risk assessments, incorporating an appropriate sea-level rise needs to be relative to a zero baseline sea level, usually taken as the average across the years 1980–99, centred on 1990. The mean sea level for this average at Wellington is 0.14 m above WVD-53.

Wellington Harbour has experienced an average rise in relative sea level of 2.03 ±0.15 mm/year or 0.2 m in the last 100 years, which is relative to the inner-city landmass. The rate has increased substantially since the last assessments by Hannah (1990, 2004) obtained an average rises of 1.73 mm/yr up to 1988 and 1.78 mm/yr up to 2001. However, most of this apparent acceleration is due to slow-slip events from tectonic processes under Wellington city since around 1997 that has produced a land subsidence of 1.7 mm/yr in the last 10 years and an upwards shift in mean sea level in 1998-2000 when the Pacific-wide IPO switched to the negative phase.

Sea-level monitoring in Wellington Harbour since 1990 shows that relative sea level is currently tracking towards a 0.8 m rise by the 2090s or ~1 m by 2115 (covering a period of at least 100 years from the present, as required by the NZ Coastal Policy Statement or NZCPS). Similar sea-level rise values are also being used in planning instruments by most Australian states and in the United Kingdom and align with the guidance provided by the Ministry for the Environment in 2008 (although planning timeframes from this guidance need to be extended out to at least 100 years to integrate with the new NZCPS).

Suggested sea-level guidance for the Wellington Region is based around distinguishing explicitly between existing coastal developments versus new or greenfields development. For existing development, the current best-estimate is a 1 metre sea-level rise to accommodate by 2115, allowing for a bounded flexibility either way, covering a range of 0.7 m to 1.4 m by 2115 depending on the potential consequences (=risk) for the activity or objective and the ability or scope for future adaptation. However, for new or greenfields developments, taking the lead from the NZCPS where future risk avoidance is required and taking into account that sea levels will continue to rise for several centuries, it is suggested that in most cases e.g., new subdivisions or new infrastructure such as roads, that a sea-level rise of at least 1.5 metres (relative to the 1990 baseline) be used, depending on the future risks and potential for future adaptation. If the risk or consequences of sea-level rise on a new activity in a largely undeveloped area can be demonstrated to be limited in time, small in magnitude or an isolated asset (rather than a subdivision) can be readily relocated or retro-fitted, then a lower sea-level rise of no less than 1.0 m could be cautiously applied.

An additional offset may need to be added to these future sea-level rise values for areas of Wellington City or other areas of the region affected by slow tectonic subsidence, if this tectonic process persists.

For vulnerability (“what if”) studies to underpin on-going strategic planning processes, sea-level rises of 0.5, 1.0, 1.5 and 2 m, irrespective of the timeframe, would cover the range of plausible estimates of potential sea-level rise for the Wellington region for the foreseeable future.

It is recommended that on-going monitoring of both relative sea level at Wellington Harbour, and vertical land movement at continuous GPS sites around the city and region, are updated every 5 years with a more rigorous assessment undertaken every 10 years. These regular assessments will be crucial to map the trajectory being taken by relative sea-level rise in Wellington City in particular and how it is likely to track over the following 100 years, as on-going feedback into adaptation objectives. A further long-term sea-level gauge elsewhere in the Wellington region (west or east coasts) should also be considered to complement the continuous GPS network in the GeoNet system and provide a back-up to the Wellington Harbour gauge.

1 Introduction

Greater Wellington Regional Council (GWRC) contracted NIWA to provide a synthesis of historic sea-level variability and trends in the Wellington region and how these relate to sea level in national and global contexts. NIWA sub-contracted Professor John Hannah (Vision NZ Ltd.; formerly University of Otago) to provide a robust analysis of sea-level trends from annual mean sea level values adjusted for vertical datum changes.

The agreed project scope (NIWA Proposal: 22 September 2011) including the following elements:

1. Data processing and quality assurance on monthly and annual mean sea level (MSL) data measured at the Port of Wellington since 1901. Note: much of the historic data processing for annual MSL had been previously completed, but more processing was required on recent monthly MSL data to the end of 2011. Short gauge records for Porirua Harbour and Riversdale (Wairarapa) were also to be analysed for annual sea-level cycles to compare with Wellington Harbour.

2. Analysis of historic sea-level variability and trends for Wellington to the end of 2011. Variability in the mean level of the sea will include seasonal, inter-annual (El Niño/La Niña) and longer decadal cycles, as these longer-period cycles moderate or exacerbate sea-level rise trends at periods of decades or more. They also contribute a background sea level to storm-tide events. Trends from continuous GPS (cGPS) data from the Wellington Harbour gauge will be updated and assessed in the light of known vertical movement of the wharf structure the gauge sits on.

3. Synthesis of projections for relative sea-level rise relevant to the Wellington region based on the historic trends and a review of recent research findings on global sea-level rise since the IPCC 4th Assessment Report published in 2007. Extrapolations to the wider Wellington Region will be attempted, but largely based on Wellington sea-level gauge data. This step will also require input on Holocene sea-level rise from an external contractor to Council.

4. Guidance on credible sea-level rise values to use within specific planning timeframes, considering planning requirements for existing versus greenfields developments and a set of sea-level trajectories for vulnerability studies to support long-term strategic planning and asset management.

5. Report to council on the methodology, findings and recommended guidance for projected sea-level rise in the Wellington region.

This report covers all the above aspects.

Wellington gauge

Wellington Harbour, along with three other ports (Auckland, Lyttelton, Dunedin), has one of the longest sea level records in New Zealand. A tide gauge is known to have operated in the Wellington Harbour in the very late 1800's producing sea level records dating back to 1891 – at least eight years prior to any other existing New Zealand sea level record. Despite annual MSLs not being available for the years 1894–1900 and 1902, the record still comprises a valuable 113 gauge years in the form of either annual MSLs or from December 1944, as monthly MSLs.

The Wellington gauge also sits in an active tectonic setting so has been affected by varying changes in vertical movement of the local landmass. Sea-level gauge records are a direct measure of the relative sea-level change that needs to be locally adapted to, as sea level rises. It is also important to account for the vertical land movements associated with the gauge site in order to quantify the absolute sea-level rise, and therefore make a regional connection with global sea-level projections, which are expressed in terms of absolute sea-level rise.

Sea-level spectrum

Sea level itself is an important element in the assessment of regional coastal hazards, being subject to variations over a wide range of time scales from a variety of causes, including, but not limited to:

- regular tidal fluctuations (determined by the relative movement of the Moon and Earth with respect to the Sun)
- storm surge (barometric pressure and winds)
- the seasonal (annual) cycle
- climate variability including interannual and inter-decadal oscillations
- climate-change trends (past and future)
- vertical land movement (tectonic and ice-age crustal readjustment)
- tsunami (where the impact is partially governed by the sea level at the time).

Objectives

The objectives for this study were as follows:

- To determine how monthly mean sea level from the Wellington Harbour tide gauge varies in response to seasonal, interannual and inter-decadal climate variability.
- Quantify the historic trend in annual mean sea level from the Wellington Harbour tide gauge, and whether any recent acceleration in the rate of rise can be observed.
- Determine how historical sea-level change in Wellington Harbour compares with historical global sea-level change and the connection to future global projections of sea level rise e.g., Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report[1] released in 2007 and more recent publications.
- Provide guidance on regional sea-level rise values that could be used for land-use planning for either existing or new (greenfields) development or alternatively for “what-if” coastal vulnerability assessments.

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[1] http://www.ipcc-wg1.unibe.ch/publications/wg1-ar4/wg1-ar4.html

2 Terminology

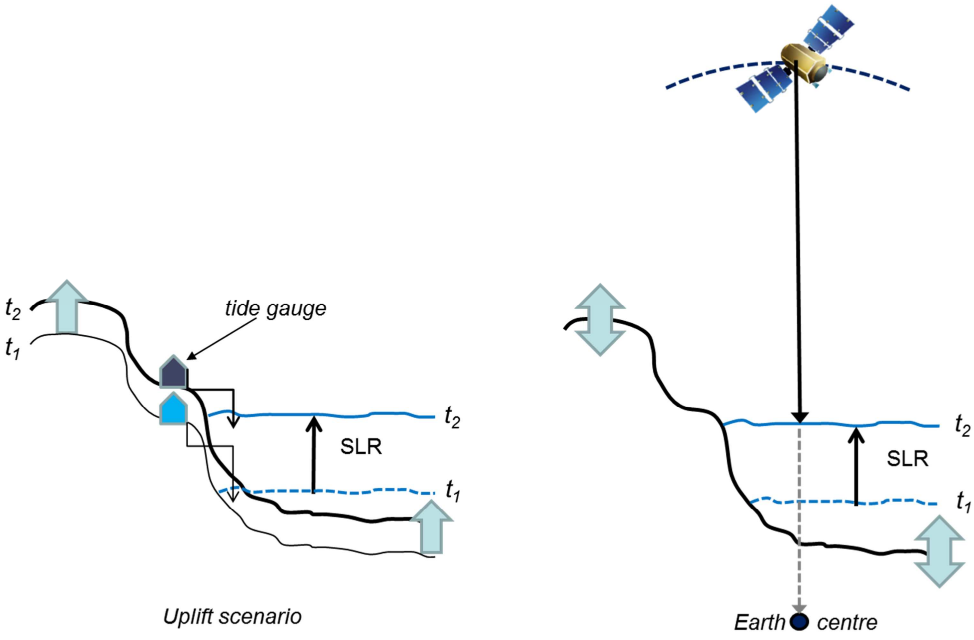
Sea level reference frames
At any specified location, long-term sea level trends are defined as being either **relative** or **absolute**.

The term "*relative sea-level change*" is used to indicate the change in sea level relative to the "fixed" coastline as determined at a local tide-gauge site (Figure 2-1), but adjusted, firstly, for any datum shifts that may have occurred to the zero of the gauge, secondly, for any instability in the local wharf structures to which the tide poles and gauges are attached and, finally, for any localised vertical movement of the land to which the wharf structures are attached. In this context, the word "site" may cover a spatial distance of perhaps 1 km, depending upon where the gauge has been moved during its recording history. It is relative sea level that needs to be adapted to at the local or regional level. If the local landmass is subsiding, then the relative sea-level rise will be significantly higher than absolute sea-level rise, and vice versa if the local landmass is being uplifted by tectonic processes or Glacial Isostatic Adjustment (see below) (Figure 2-1).

"*Absolute sea-level change*" is the change in sea level relative to the centre of mass of the earth (Figure 2-1). This reflects the combined influence of eustatic sea level change (from changes in ocean volumes) plus any vertical uplift or subsidence to the ocean basins that may arise from tectonic motion. It is absolute sea level that is measured by satellite altimetry such as TOPEX/Poseidon and Jason 1, 2 and is also the sea level referred to by global average sea-level rise projections by, for example, the Intergovernmental Panel on Climate Change (IPCC, 2007).

Glacial Isostatic Adjustment (GIA), is also a component of the total crustal motion. GIA is the on-going readjustment of the Earth's crust to the retreat of extensive ice loading following the last major Ice Age. Across New Zealand, the GIA is estimated to be a small rebound of around 0.2–0.4 mm/yr (Hannah & Bell, 2012), so is a relatively small portion of relative sea-level rise. To date the GIA correction has typically been estimated using geophysical models such as that produced by Peltier (2004), as shown in Figure 7-2. These models, while useful for providing a macro-scale understanding of the GIA influence, are much more limited when used at a regional level.

However, over the last decade dedicated GPS data collection and processing strategies have been implemented to correct tide gauges records, thus allowing the estimation of a GPS-corrected set of 'absolute' or geocentric sea-level trends. Unfortunately, the estimates arising from this technically challenging task are subject to uncertainties, both with respect to the stability of the reference frame used and with respect to variations in the processing strategies used. In reality these "geocentric" trends are actually relative to the chosen reference frame such as ITRF2000 or ITRF2005 [Wöppleman et al. 2009; Collilieux and Wöppelmann (2011)]. Although rarely discussed, this is equally true for the satellite altimetry data mentioned earlier. There is disagreement in excess of 1 mm/yr between the velocity of the Earth's centre of mass in these two frames [Argus, 2007], thus implying that the "absolute" vertical rates estimated in the global studies may be subject to errors of this magnitude, at least in certain regions of the Earth. Variations in processing strategy add a further uncertainty of perhaps 0.5 mm/yr (Denys et al. 2012).



Relative sea-level rise

Absolute sea-level rise

Figure 2-1: Schematic showing difference between relative and absolute sea-level rise.

Sea level variability

Generally referred to in this report as variations in the mean level of the sea at timescales ranging from monthly up to a few decades. Variability in mean sea level is important to understand and quantify to ensure it is properly accounted for in storm-tide and wave set-up extreme coastal water levels, besides the main factors – tides, storm surges and wave heights. It will also interact with long-term trends in sea-level rise, masking the trend for some periods of years to decades if mean sea levels are lower than normal, and exacerbating short-term trends if sea levels are higher than normal.

Variability arises from storminess or persistent anticyclonic weather (at the monthly scale), the influence of seasonal climate processes, interannual variations due to the El Niño–Southern Oscillation or ENSO (periods of 2–4 years) and inter-decadal variability due to long-period variability in ENSO and a Pacific-wide climate oscillation over a 20–30 year period, referred to as the Inter-decadal Pacific Oscillation (IPO).

Sea level trend

Sea-level trend is generally referred to in this report as the long-term linear trend in annual MSL over the entire record. Trends from any sea-level gauge record will be in terms of a relative sea-level rise. Note: long-term trends should not be applied to records any less than 50–60 years to isolate most of the effects of interannual and inter-decadal climate variability (Douglas, 1997).

3 Tectonic and Holocene context: Wellington region

3.1 Tectonic setting

The main cause of tectonic deformation of the Wellington region is the convergence of the Australian and Pacific crustal plates some 20–40 km beneath the Wairarapa coast through to Pukerua/Porirua on the west coast. Within the region, most of the strike-slip component of plate motion is taken up by faults of the North Island Dextral Fault Belt (Gibb, 2012). The three primary faults in the Wellington, Porirua and Kapiti Coast areas are, from east to west, the Wellington Fault (through Wellington City and up the Hutt Valley), Ohariu Fault (through Porirua Harbour) and the Pukerua Fault (off Titahi Bay and through Pukerua Bay). These three faults are shown in Figure 3-1. All three faults are dextral strike-slip faults with the up-thrown side to the west and the downthrown side to the east (Gibb, 2012).

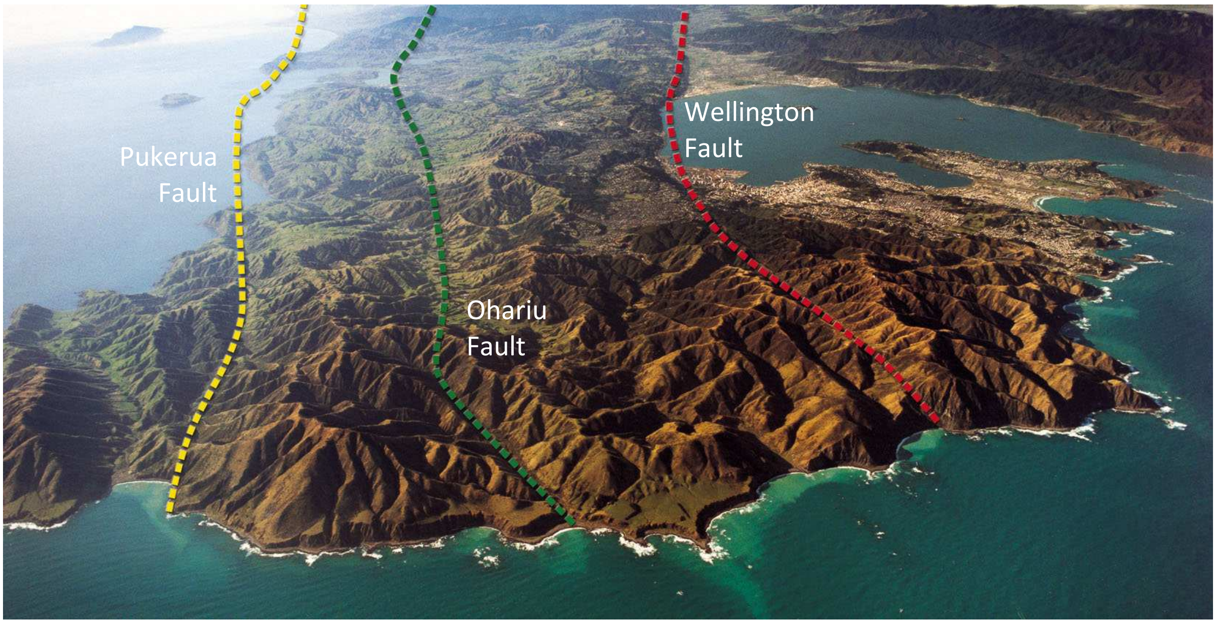


Figure 3-1: Main tectonic fault lines in the Wellington, Porirua and Kapiti areas looking north-east. [Source: GNS Science].

The fourth main fault is the Wairarapa Fault, that intersects with the south-east Wellington coast at Turakirae Head and on up north through the Rimutaka Range. The Wairarapa Fault last ruptured during the M_w 8.2 earthquake of 23 January 1855. The main subduction zone offshore from the Wairarapa coast is the Hikurangi Subduction Margin.

These faults have all been all associated with varying vertical movements from past rupture events (Berryman & Hull, 2003; Gibb, 2012; McSaveney et al. 2006), that have produced sudden changes in relative sea-level rise, which will continue to occur episodically over geological timescales.

3.2 Holocene sea-level change

An understanding of how sea level has responded to climate change in the past can help greatly with the assessment of future impacts of climate change. 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 extending back to 10,000 years before present (BP). Most recently, Gibb (2012) in a report to Greater Wellington, undertook a study to determine the local Holocene sea level curve for the Porirua area using dated material collected from sediment cores and palaeo-shoreline markers.

Holocene sea level change in the Wellington region broadly follows last post-glacial eustatic sea-level trends observed globally, but interspersed with instantaneous vertical changes to relative sea level from tectonic movement. The New Zealand Holocene sea-level curve developed by Gibb (1986) demonstrates the general pattern of post-glacial sea-level rise in New Zealand during the Holocene (Figure 3-2).

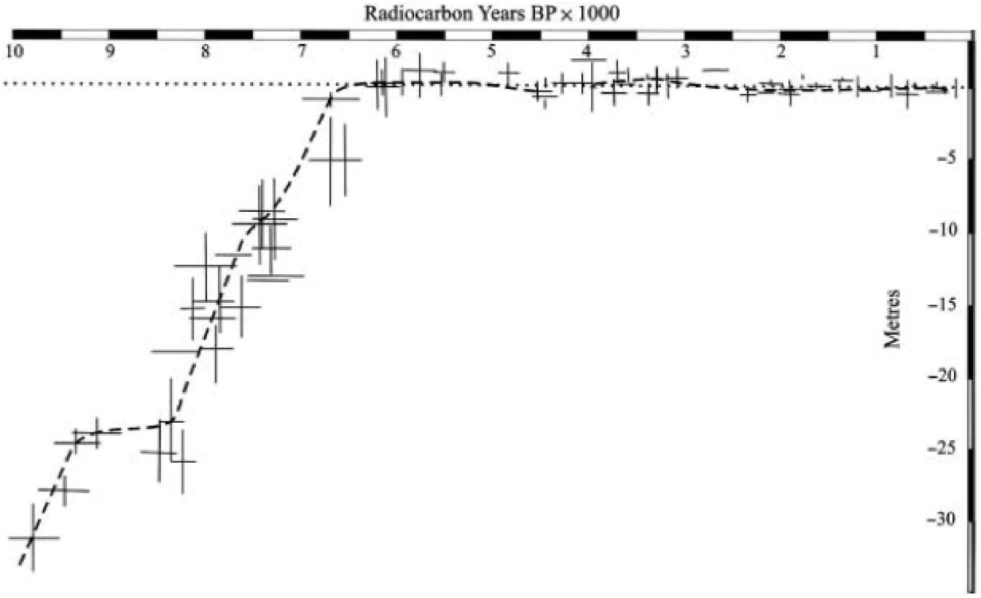


Figure 3-2: The Holocene eustatic sea-level curve for New Zealand produced by Gibb (1986). Source: Kennedy (2008).

In the New Zealand region, the Postglacial Marine Transgression of rising sea levels (since the Last Glacial Maximum) culminated at the present sea level about 7550-7300 years ago (Gibb, 1986; Gibb, 2012). Recent research has shown that sea level was around 0.5 to 1 m higher than present during the mid-Holocene optimum period from 7550 to 2000 BP (Gibb, 2012; Kennedy, 2008). Over the last 2000 years BP, there has been little change in sea level other than a slight rise of 0.3 mm/yr determined by Gehrels et al. (2008) for an Otago coast site from AD1450 to the late 1800s.

Locally, in the Porirua Basin, Gibb (2012) determined from various palaeo sea-level indicators and sediment cores that local relative sea-level changes indicate tectonic uplift west of the Ohariu Fault decreasing from 0.5 m per 1000 years (0.5 mm/yr) to about 0.2 m per 1000 years (0.2 mm/yr) further west. Over the past 7500 years BP, sea-level fluctuations have been of the order of a few decimetres with a probable mid-Holocene highstand of 0.5–1.0 m above present sea level from 7500 to 2000 years BP, during which time both arms of Porirua Harbour have shallowed from both terrestrial and marine sedimentation at about 1 mm/yr (Gibb, 2012).

Turakirae Head (on the south-east Wellington coast) possesses one of the world's finest sequences of Holocene raised marine terraces, formed by coseismic uplift from four simultaneous ruptures of the Wairarapa Fault in the past 9000 years (McSaveney et al. 2006). The last raised terrace is understood to have been uplifted beyond the reach of all but overwash from storm waves in the M_w 8.2 earthquake of 23 January 1855, with spatially-varying uplift from 2–6 m. Overall, the coastal uplift at the anticline crest adjacent to Turakirae Head area has averaged 3.32 ± 0.17 mm/yr in the last 9000 years (McSaveney et al. 2006).

4 Wellington Harbour tide gauge

Within New Zealand, the Wellington sea level record is unique. A tide gauge is known to have operated in the Wellington Harbour in the very late 1800's producing sea level records dating back to 1891 – at least eight years prior to any other existing New Zealand sea level record. These very old data, in the form of monthly mean tide levels, are held by the Greater Wellington Regional Council (GWRC).

Old correspondence files held by the former Department of Lands & Survey (now Land Information New Zealand [LINZ]) indicate the existence of a continuously operating tide gauge in the port area from 1901 onwards.

The gauge is known to have been moved in late 1944. While all hard copy tide gauge records collected after this move have been digitised and used in the analyses discussed in this report, those collected prior to the move were discarded some decades ago. With the exception of the GWRC data, all pre-1944 tide gauge records used in these analyses have thus had to be derived from LINZ files or reports. Unfortunately, these files only record annual sea level means, not monthly means. For this reason, the long-term sea level trend analyses undertaken here use annual Mean Sea Levels (MSLs) only.

Where tidal records do exist, MSLs are created by using hourly sea level data to form a daily mean. These daily means are then used to create monthly means that are in turn averaged so as to form a yearly mean. This process is outlined in Caldwell (1998).

The quality of the sea level record collected in the Port of Wellington since 1891 has been discussed previously (Hannah, 1990; 2009). The important points may be summarised as follows.

1. All pre-1945 sea levels have been derived either from Annual Reports published by the Department of Lands & Survey or from archived LINZ file data. In searching these records, annual MSLs were able to be found for 15 of the pre-1945 years (1901, 1909, 1915, 1919, 1921–24, 1927, 1930, 1933, 1936–37, 1939, and 1942). Of these years, the 14 MSLs from 1909–1942 were used to define the Wellington Vertical Datum-1953 (WVD-53). As was consistent with practice at that time, these MSLs were most likely derived by averaging the hourly point sea level data.

2. Mean Tide Levels or MTL (calculated by using daily high and low waters only) were available for most of the other years prior to 1945. Due to the non-symmetrical nature of tidal data, a small correction was made to these MTLs in order to derive an equivalent MSL.

3. The only years between 1891 and 1944 for which no data exists (either MTLs and MSLs) are 1894–1900, and 1902.

4. Relocation of the tide gauge to a new location in 1944 appears to correspond with an unrecorded shift in the tide zero. Because no documentation has been able to be found relating to this relocation, an additional parameter that allows for a datum shift of an unknown size, has been carried in all Wellington sea-level trend analyses. This datum shift is estimated as being between 15 mm and 26 mm, depend upon the data processing strategy used.

5. Since 1944, excellent records exist, both of hourly sea level data and of the various levelling checks made to confirm tide gauge stability. There are only eight years where a monthly MSL is missing and only in two of these years (1990 and 1995) is the accuracy of the annual MSL value significantly compromised.
6. Since 1945, regular levelling has linked the tide gauge zero to stable benchmarks on or near the waterfront. Since May 2001 this work has been repeated every two to three years. These repeat levelling's, when combined with previous levelling's undertaken in 1970/71 and 1980, appear to indicate a slow subsidence in the wharf structures of 0.2 mm/yr between 1970 and 2001 (Beavan, 2001). This subsidence, which is consistent with a possible trend seen in earlier data, has led to all annual MSL data from 1946 onwards being adjusted by this subsidence rate. While it is possible that this subsidence may have continued through to 2005, an apparent reversal between 2005 and 2008 resulted in the 2008 levels being little different from those observed in 2001. On this basis, an adjustment for a wharf subsidence of 0.2 mm/yr has been applied to all MSL data from 1946–2001. The wharf structures have been treated as stable since 2001.
7. File notes from the former New Zealand Department of Lands and Survey indicate that the tide gauge zero was shifted down by 1.0 feet (0.305 m) on 1 May, 1973. This shift was clearly evident in the data. All MSL data since that date has been adjusted accordingly, so that all annual MSL values are relative to the pre-1973 tide-gauge zero.

The Wellington Harbour gauge is situated on Queen's Wharf and is owned and operated by GWRC. The relativity between the various datums for the Wellington gauge is shown in Figure 4-1. The main tide mark levels relative to Wellington Vertical Datum-1953 (WVD-53) are shown in Figure 4-2, based on tide predictions over a 100-year period of tides. The levels are solely derived from astronomical tides relative to the present-day MSL (averaged from 2006 to 2011) and don't include any sea-level variability or trends in MSL.

Monthly sea-level data from two other short-term gauges on the Wairarapa Coast (NIWA gauge at Riversdale from July 1997 to June 2003) and Kapiti Coast (Porirua Marina gauge from 2009 to 2011) were used to compare the local annual cycle in sea level with that at Wellington Harbour. However, these records are too short to compare the response to longer interannual and inter-decadal climate cycles.

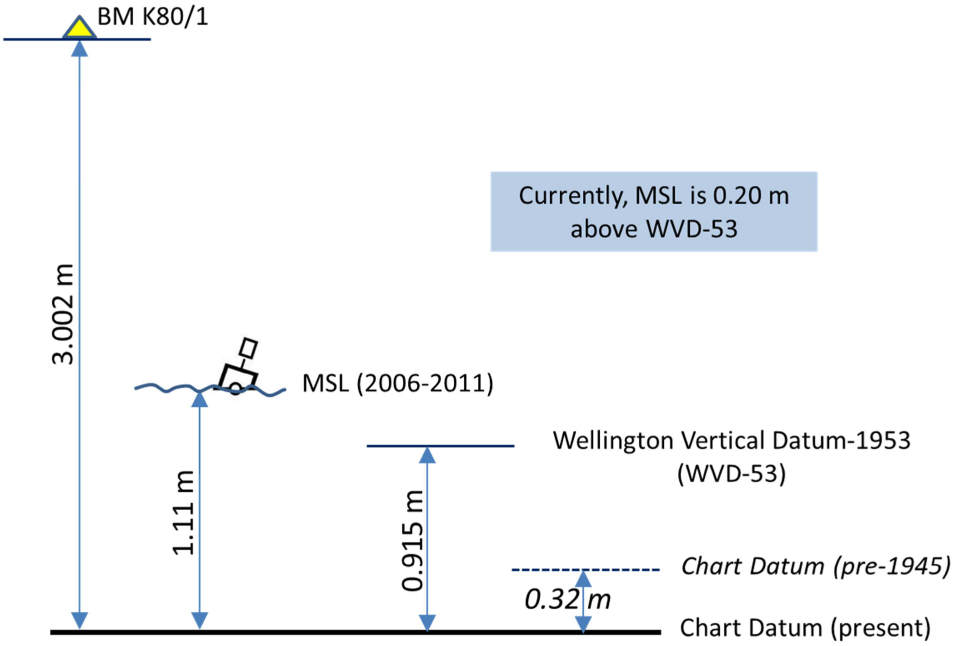


Figure 4-1: Relativity between various Wellington datums, the fundamental benchmark and the current MSL (2006–2011).

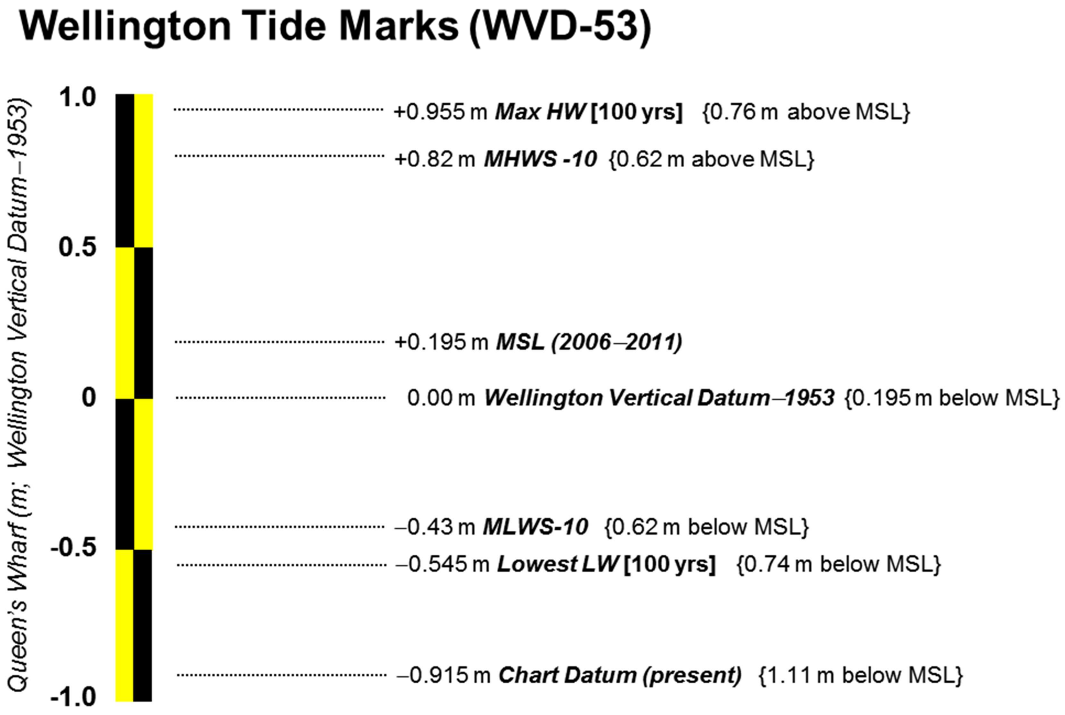


Figure 4-2: Present-day tide marks at Wellington relative to WVD-53. Note: MHWS-10 is the level exceeded by 10% of all high tides; MLWS-10, low tide mark at which 10% of all low tides descend below, and MSL is the present mean level of the sea for period 2006-2011.

5 Sea-level variability

5.1 Variability in monthly MSL

Monthly MSLs are able to be determined for Wellington Harbour from December 1944, the time from which hourly tide levels are available (Section 4). The analysis includes monthly MSL up to January 2012.

These monthly mean sea-level data are plotted in Figure 5-1 in terms of present Wellington Chart Datum (CD). The present average MSL over the recent 6-year period 2006–2011 is 1.11 m CD or an average 1.08 m CD over the last 19 year nodal-tide period from 1992 to 2010 ((Land Information NZ, 2010).

As discussed in Section 8, most sea-level rise projections (e.g., IPCC assessment reports) are anchored to a baseline comprising an average of annual MSL across the period 1980 to 1999, with a mid-year centred on 1990. The average MSL for this baseline period centred on 1990 was 1.054 m above CD (0.749 m above pre-1973 CD).

Most land-based planning and engineering design in the Wellington region are based on levels relative to the local vertical datum Wellington Vertical Datum–1953 (WVD-53), so the monthly mean sea levels are also provided in this datum (Figure 5-2). This zero “MSL datum” was set in 1953 based on sea levels measured by the Wellington Harbour gauge from 14 years of data measured between 1909 to 1946 (Hannah & Bell, 2012). However, the present-day mean sea level no longer aligns with WVD-53 due to the rise in sea level and changes in vertical landmass movements in the intervening decades. The equivalent mean sea level for the recent 6-year period 2006 to 2011 is +0.20 m WVD-53 (Figure 5-2) and is a substantial enough offset that needs to be built into engineering design, hazard risk assessments and land-use planning. For the baseline period 1980–1999, the average MSL was +0.14 m WVD-53 centred on 1990. Note: referring to WVD-53 as a “MSL datum” is now a misnomer.

A(i): Offset for present-day MSL above WVD-53 datum = 0.20 m

A(ii): Offset for 1980–1999 average MSL above WVD-53 = 0.14 m

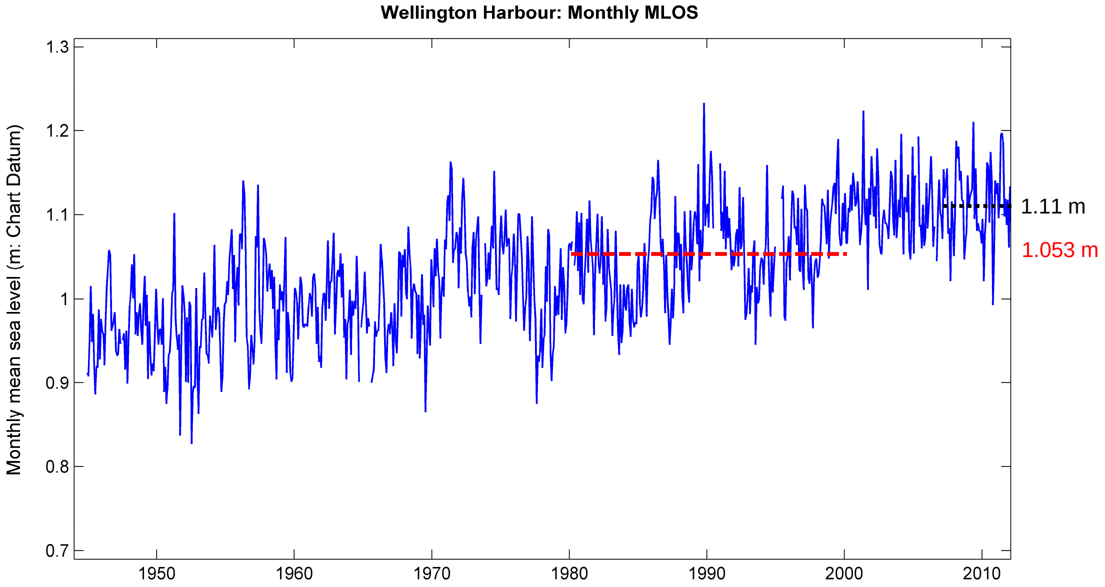


Figure 5-1: Monthly mean sea level for Wellington since 1944 relative to present Chart Datum. The dotted line at 1.11 m marks the present average MSL over the 6-year period 2006–2011 and red dashed line the average MSL for the baseline period 1980–1999, which is the zero line for projections.

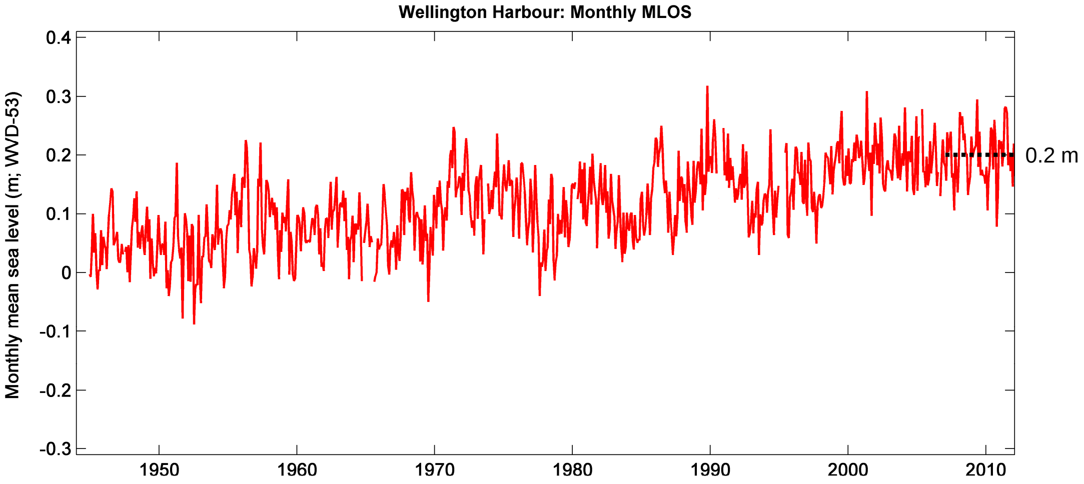


Figure 5-2: Monthly mean sea level for Wellington since 1944 relative to present Wellington Vertical Datum-1953. The dotted line at 0.20 m marks the average MSL over the past 6 years (2006-2011).

For subsequent analyses, the linear trend in the monthly MSL record was removed from the time series of monthly MSLs. The distribution of monthly anomalies (departures) from the average sea-level trend is approximately Gaussian as shown in Figure 5-3, both for all measured MSL values and with the average annual cycle removed (see next sub-section). For the 67-year record, the monthly-MSL anomaly varied between –0.16 m and +0.17 m about the average linear trend. The lowest set-down in monthly MSL occurred during August 1977 coinciding with a strong El Niño episode and higher than normal barometric pressure (1019.1 hPa compared with a long-term mean for August months of 1012.9 hPa) and more southerlies. Conversely, the highest monthly anomaly during October 1989 coincided with the strong La Niña episode of 1988/89 and lower than normal barometric pressure (1005.8 hPa compared with the long-term mean of 1012.9 hPa) and more northerlies. This highest +0.17 m monthly MSL value becomes +0.20 m above the average sea-level trend when the average annual cycle is removed – arising from that peak MSL occurring in October (1989) when the annual sea-level cycle was at a seasonal minimum.

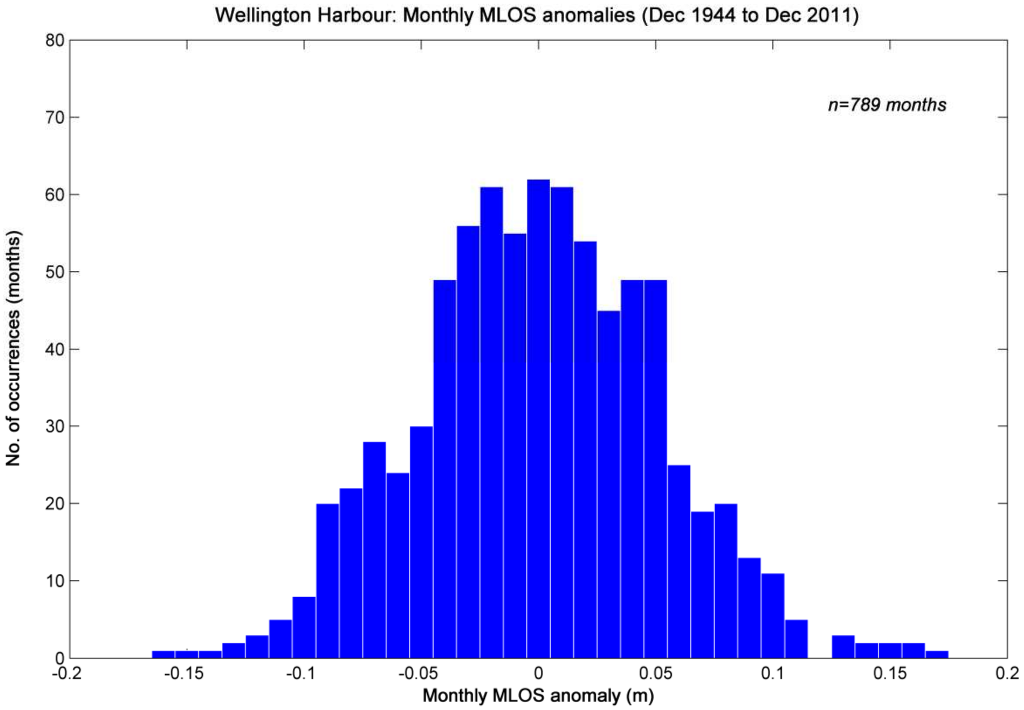
Overall, for month-to-month variability (including seasonal, interannual and inter-decadal cycles), an allowance in planning and design should take into account this range from –0.16 m to +0.20 m relative to the average MSL.

B. Monthly variability about the average MSL ranges between

-0.16 m to +0.20 m due to climate cycles and persistence of weather patterns

So combining A(i) and B in boxes above, an offset of up to 0.4 m above WVD-53 should be included as a background sea level for any analysis of present-day coastal inundation hazards and risk. Alternatively, explicitly incorporate the occurrence distribution for monthly variability in Figure 5-3 into Monte Carlo probability approaches, plus the 0.2 m offset of the present average MSL above WVD-53.

Any hazard analysis for future risk needs to include sea-level rise relative to the benchmark period 1980–1999 centred on 1990, so the offset from WVD-53 in A(ii) i.e., +0.14 m, needs to be the starting point for adding in sea-level rise magnitudes (rather than the present 0.2 m which already includes some SLR). Future risk assessments also need to include the monthly variability of up to +0.2 m (see B above), which may alter with climate change but at this stage it is unknown how variability in monthly MSL will be affected.



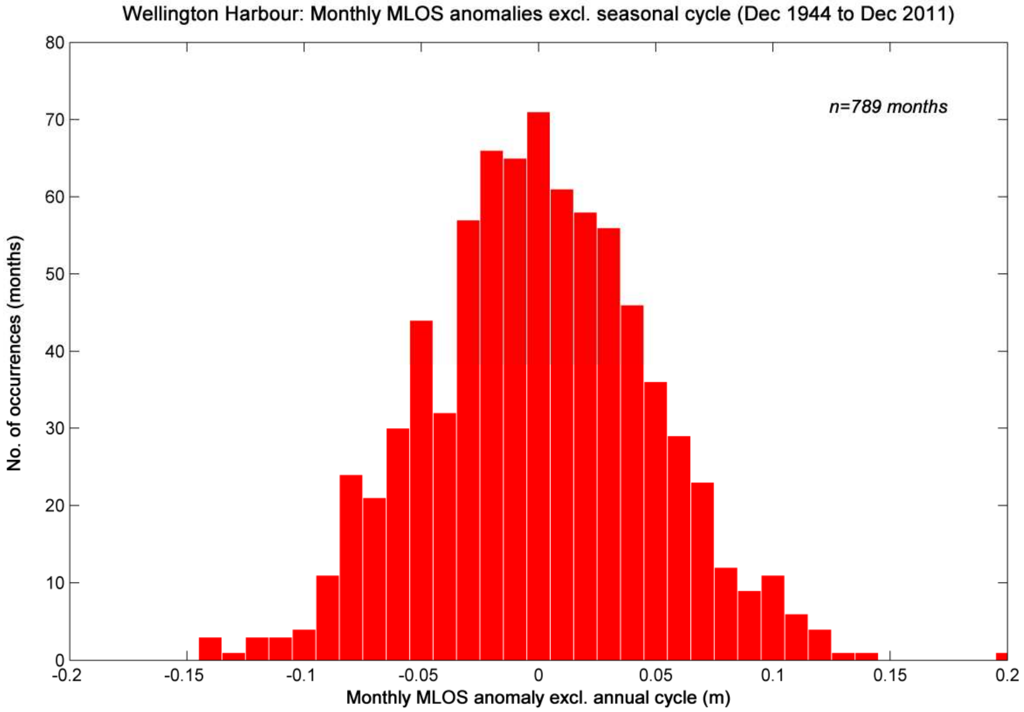


Figure 5-3: Distribution of monthly MSL anomalies for Wellington Harbour about the linear trend in sea level. (TOP) For measured MSL; (BOTTOM) with average annual cycle removed.

5.2 Climate cycles contributing to MSL variability

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

- Inter-month variability from storminess or anticyclonic persistence.
- Seasonal (annual) cycle, from the heating and cooling effects on coastal and shelf waters.
- Interannual cycle from the 2–4 year El Niño-Southern Oscillation (ENSO).
- Inter-decadal cycles from the Inter-decadal Pacific Oscillation or IPO, which in the South Pacific is mainly driven by inter-decadal variability in ENSO.

The various components of the 67-year record of monthly MSL at Wellington Harbour were extracted by a wavelet technique and are shown in Figure 5-4 for each of average periods 3, 6, 12, 24, 48, 96 months and the longer-period residual component.

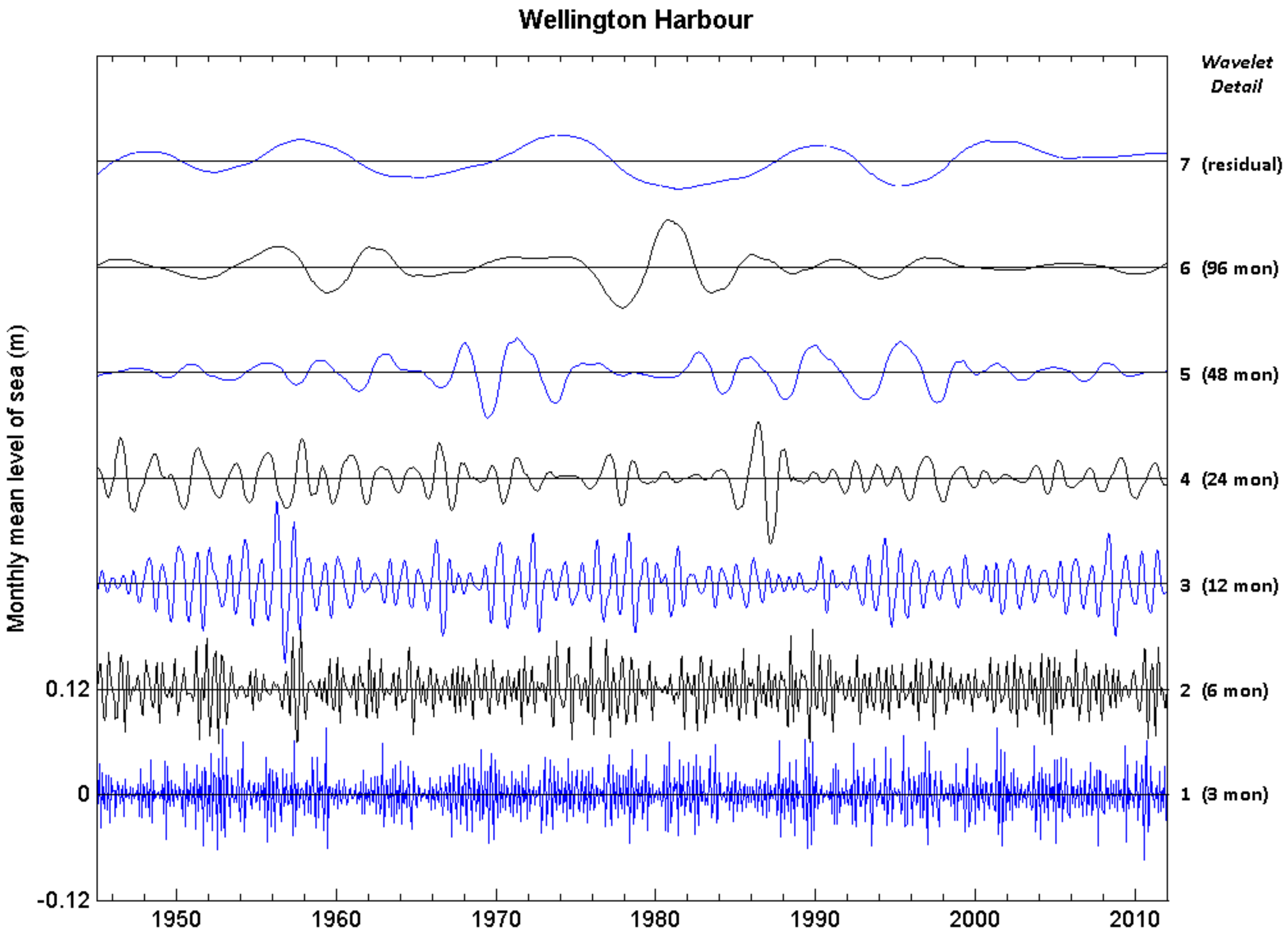


Figure 5-4: Wavelet details for components of monthly MSL at Wellington at different periods in months annotated. Each component is plotted by a 0.12 m offset.

Variability at inter-month (3-month) and semi-annual (6-month) timescales ranges between ±0.06 m. The amplitude of the annual cycle varies substantially from as low as ±0.02 m up to ±0.10 m. The average annual cycle is discussed below. ENSO covers the variability at 24, 48 and 96 months (2-8 years) and inter-decadal climate cycle influences the residual component shown at the top of Figure 5-4. Some of the variability at these longer periods (>24 months) will also include slow-slip tectonic events (SSEs).

5.2.1 Annual MSL cycle

The average seasonal cycle was extracted from the monthly MSL anomaly time series for Wellington Harbour by averaging all the monthly MSL values for a specific month (rather than fitting a smooth annual sine curve). In addition, the record was split into successive phases of the longer-period IPO, followed by calculating the respective average annual cycles. Average annual cycles were also extracted from short sea-level records from Riversdale (Wairarapa) and Porirua Harbour marina (Kapiti coast) and compared to the annual cycle at Wellington for the relevant concurrent periods.

The overall average annual cycle and monthly range are shown in Figure 5-5. The overall average seasonal cycle peaks in May at 0.035 m above the average sea level, and drops quickly over winter to –0.035 m during September. But as mentioned previously, the variability for any given month can be substantial. The high upper range value for October is the 1989 event mentioned in Section 5-1.

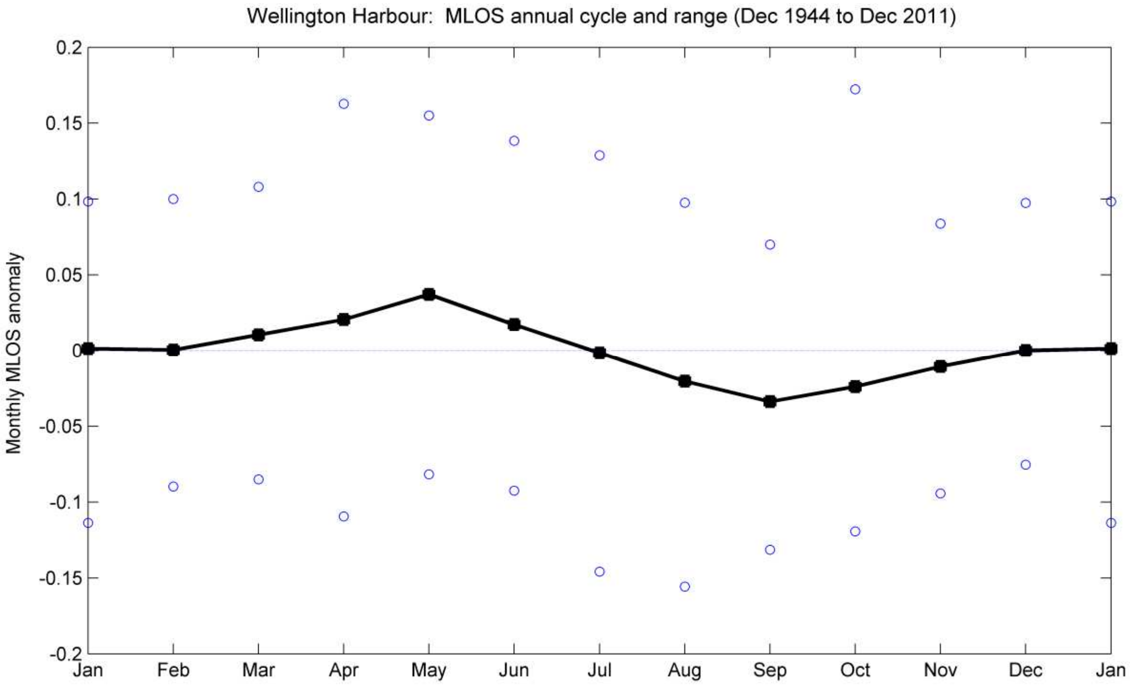


Figure 5-5: Overall average annual cycle in MSL at Wellington with the upper and lower ranges for each month.

This seasonal cycle is largely due to thermal heating of the upper ocean layer 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 by around 2 months, similar to earlier work by Bell & Goring (1998).

The comparisons of the short-term annual cycle at Riversdale and Porirua Harbour marina with Wellington are shown in Figure 5-6. While there is more inter-month variability, the comparison shows that the Wairarapa coast responds more to oceanographic/climate processes typical of New Zealand's east coast, with a seasonal peak around March, whereas Wellington and Porirua Harbour are more influenced by processes on the west coast derived from the D'Urville Current.

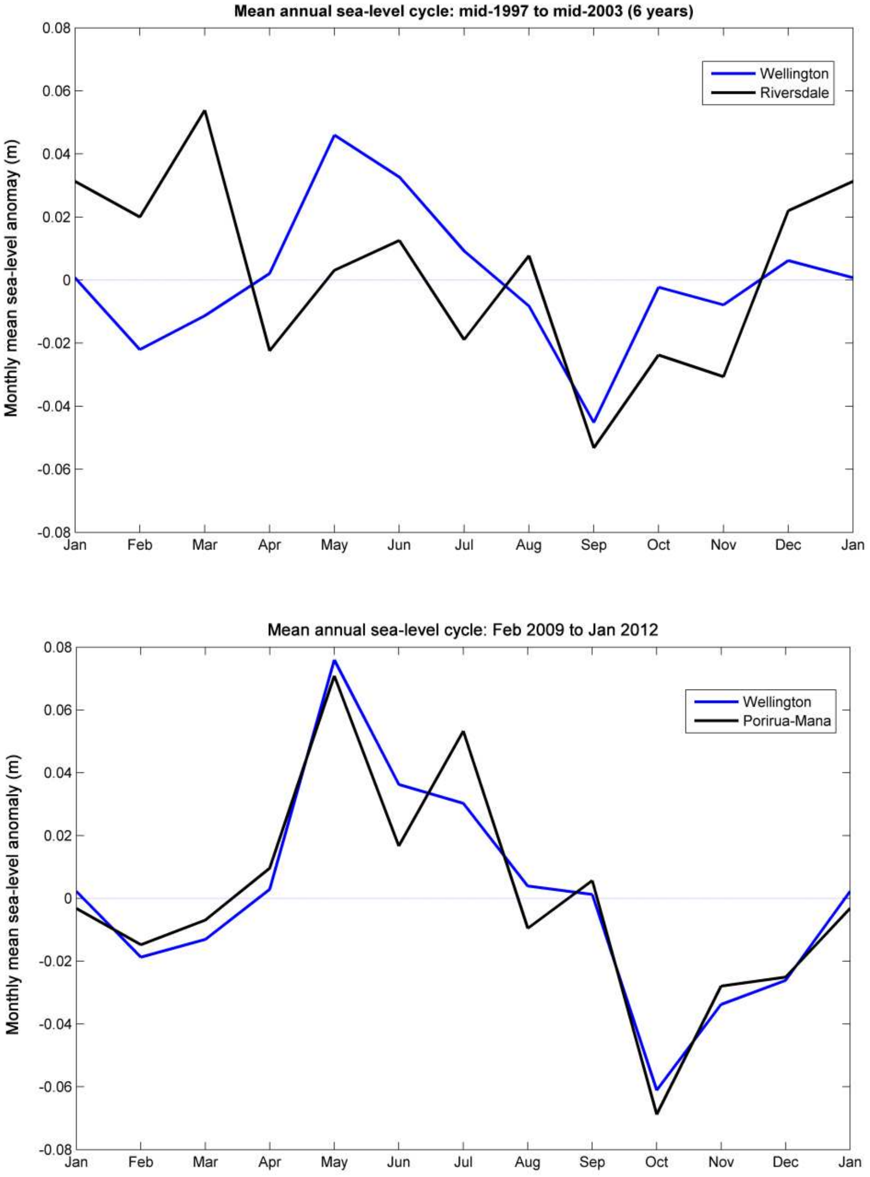


Figure 5-6: Comparison of the average annual MSL cycle at Riversdale and Porirua Harbour with Wellington over short periods.

The 67-year Wellington MSL record coincides with three cycles of the IPO covering the periods 1947-1975 (negative phase), 1976-1997 (positive) and 1998 onwards (negative phase). The average annual MSL cycles for these IPO episodes is shown in Figure 5-7. The annual cycle pattern is similar in terms of amplitude and the peak/trough but generally sea levels are higher during the negative phase of the IPO (which is explained in the next sub-section).

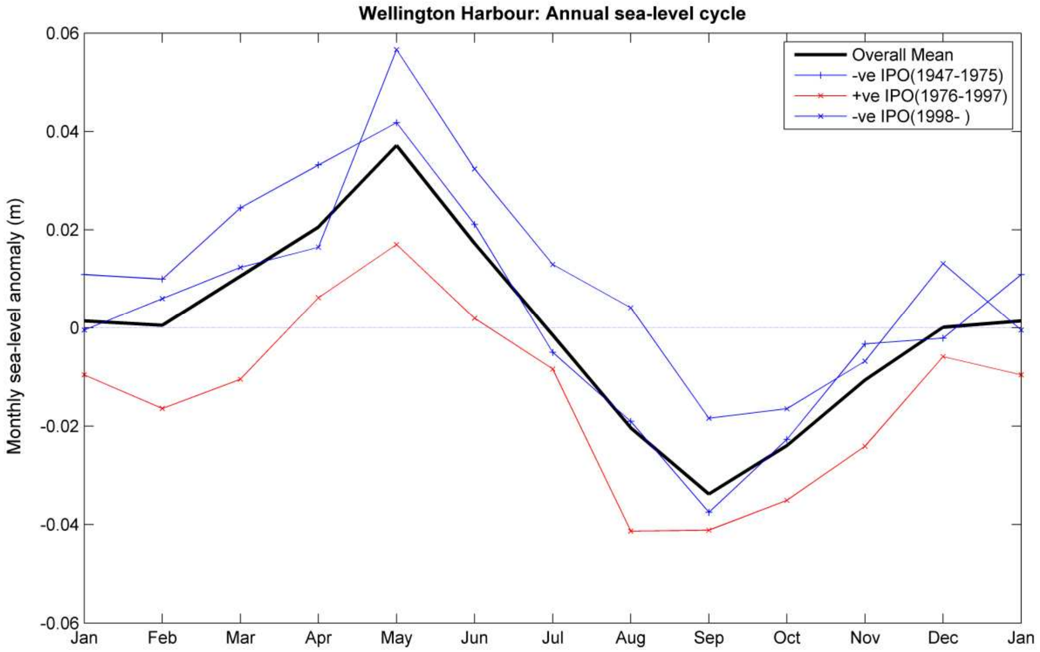


Figure 5-7: Overall average annual cycle in monthly MSL compared with cycle for successive IPO episodes 1947–1975, 1976–1997 and 1998 onwards).

5.2.2 MSL variability due to ENSO and IPO

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 and the longer 20-30 year Inter-decadal Pacific Oscillation were extracted from 1944 up to the present (Figure 5-8).

ENSO is represented by the Southern Oscillation Index or SOI, which 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 top panel of Figure 5-8) and negative for El Niño episodes (red). These episodes alternate in cycles that typically last 2-4 years alternately switching between phases. It generally varies between +3 to +4 (strong La Niña event) and –3 to –4 (strong El Niño event), with significant ENSO events defined as having SOI magnitudes of 1 or more.

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. In the South Pacific, the IPO is mainly driven by inter-decadal variations in ENSO (Messié & Chavez, 2011), whereas the North Pacific exhibits a more distinct IPO pattern called the Pacific Decadal Oscillation or PDO. The signature of IPO is detected as persistent warmer or cooler surface waters alternating on each side of the Pacific Ocean over timescales of 20-30 years. During a "warm", or "positive", phase, the west Pacific becomes cooler than normal and part of the eastern ocean warms; during a "cool" or "negative" phase, the opposite pattern occurs. A Mode 1 sea-surface temperature pattern in the Pacific, with cycles shorter than 8 years (ENSO band) filtered out (M1-8 in bottom panel of Figure 5-8), was developed by Messié & Chavez (2011). The M1-8 index is used in this study for determining the response of MSL to IPO, being more applicable to the South Pacific than the more well-known PDO index (Messié & Chavez, 2011). Updated standardized values for the PDO index[2] (also in bottom panel of Figure 5-8 shown as thin bars) are derived from the leading principal component of monthly sea-surface temperature (SST) anomalies in the North Pacific Ocean, poleward of 20°N. The monthly mean global average SST anomalies are removed to separate this pattern of variability from any "global warming" signal that may be present in the data.

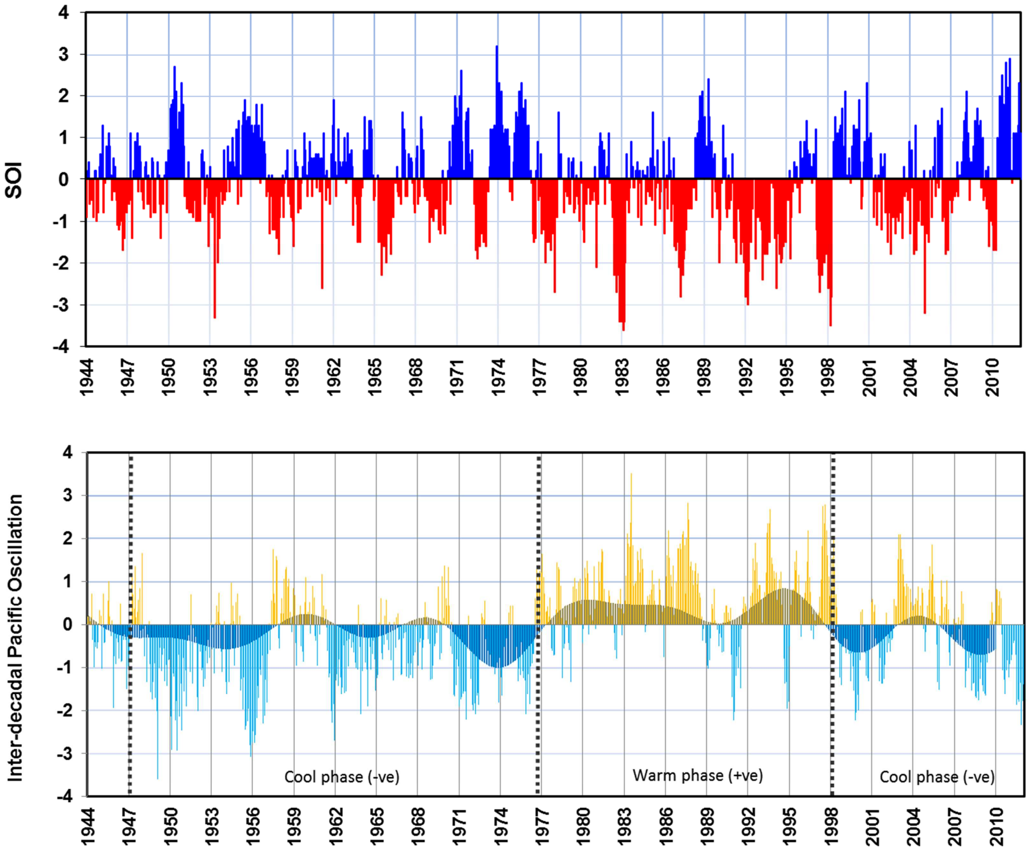


Figure 5-8: Climate cycle indices from 1944 to 2011. (TOP) Southern Oscillation Index (SOI); (BOTTOM) Inter-decadal Pacific Oscillation represented by the PDO index (monthly thin bars) and the smoother M1-8 index (up to 2010). The cool (-ve) and warm (+ve) phases of the IPO are marked.

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

The interannual components of monthly MSL at Wellington were assembled by combining wavelet details 4, 5 & 6 (see Figure 5-4) covering periods from 2–8 years. This reconstructed interannual MSL series is plotted in Figure 5-9 and compared with the SOI (also wavelet filtered to include the same timescales). The recent period from 1970 onwards is shown in the bottom panel to more clearly show the relationship between MSL and SOI.

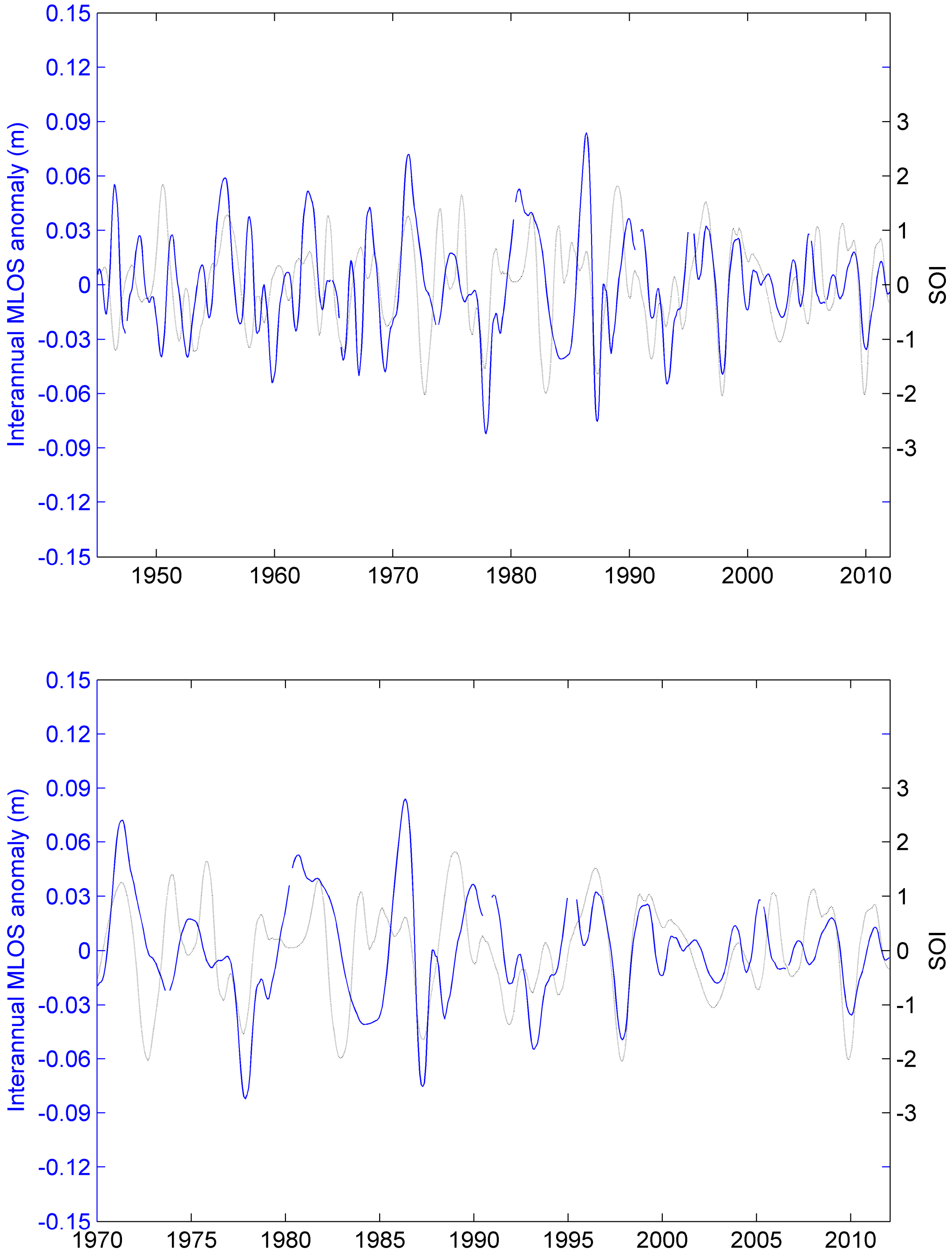

Figure 5-9: Filtered MSL anomaly for Wellington covering the 2–8 year ENSO band. (TOP) the entire record from 1944; (BOTTOM) since 1970; MSL (heavier blue line) and SOI (lighter grey line).

Figure 5-9 clearly shows that there is a strong relationship between MSL and the SOI at interannual timescales of 2–8 years. During El Niño episodes (negative SOI), MSL is generally depressed below the average sea level, down to nearly -0.09 m for intense El Niño's. Recent examples have been the strong El Niño events of 1977/78, 1987 and 1997/98 and a smaller recent event (2009/2010) as shown more clearly in the bottom panel of Figure 5-9. Conversely, La Niña episodes (positive SOI) lead to higher than average MSL in Wellington, by up to +0.09 m. Recent examples are the La Niña events of 1971/72, 1988/89, 1996 and 1998/99. The highest peak was during 1986 was associated with a moderate, but persistent La Niña.

The interannual response of higher than normal MSL at Wellington to ENSO can be attributed to warmer coastal and ocean sea temperatures in New Zealand during La Niña episodes causing more thermal expansion of the water column along with a general set-up in western Pacific sea levels from warmer seawater and strengthening easterly trade winds. The opposite occurs during El Niño episodes with colder than normal water around New Zealand and generally around the western Pacific (Goring & Bell, 1999). Besides the influence of ENSO, the response in MSL at Wellington over 2–8 year timescales may also have been influenced by interannual variability from slow-slip tectonic events (SSEs), although cGPS measurements are only available from 2000 (Section 6).

Turning now to the 20-30 year Inter-decadal Pacific Oscillation (IPO), a MSL series comprising 8-year and longer timescales was re-constructed combining wavelet detail 6 and the residual MSL at the top of Figure 5-4. The response of this inter-decadal MSL variability to this long-term IPO climate regime is shown in Figure 5-10, compared with the IPO index M1-8 (from Figure 5-8).

During a "warm"[3] phase of the IPO (positive index value), the MSL at inter-decadal timescales is slightly lower than the average MSL (minus any sea-level rise trend) and conversely, slightly higher during the "cool" phase of the IPO (negative index value). The lower panel of Figure 5-10 shows the IPO index inverted showing the closer in-phase relationship with IPO which generally applies in the western Pacific. The range in Wellington MSL at inter-decadal time scales is approximately ±0.05 m, which is the same range measured at the Port of Auckland. It is also in a similar range to the average seasonal (annual) cycle of ±0.035 m at Wellington discussed earlier.

Since 1944, IPO positive phases have occurred between 1977 and 1998, when sea level was slightly depressed in New Zealand. It also shows up as a reduced rate of rise in sea level during these periods (Figure 5-1). We are currently in a "negative" phase of the IPO (since approximately 1998), with a previous "negative" phases in 1947–1977, both associated with higher rate of rise in MSL (Figure 5-1).

In summary, ENSO accounts for variations up to approximately ±0.09 m, with higher than normal sea levels during La Niña episodes and the longer 20-30 year IPO cycle accounts for sea-level variations of approximately ±0.05 m. These ranges in variability are similar across New Zealand, as shown by Hannah & Bell (2012), as they are driven by Pacific-wide cycles

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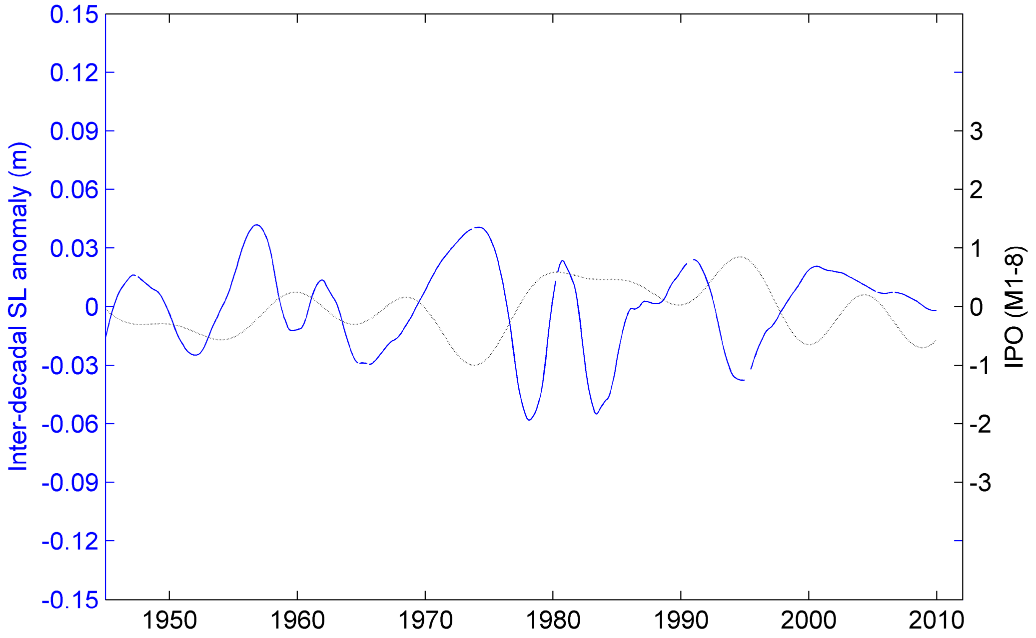
[3] "Warm" relates to the eastern Pacific, but it is generally cooler around NZ and vice versa (so have used the term "positive" and "negative" phase to avoid confusion).

in climate-ocean processes. Consequently, this long-period variability measured at Wellington will also apply to the Wairarapa and Kapiti coasts.



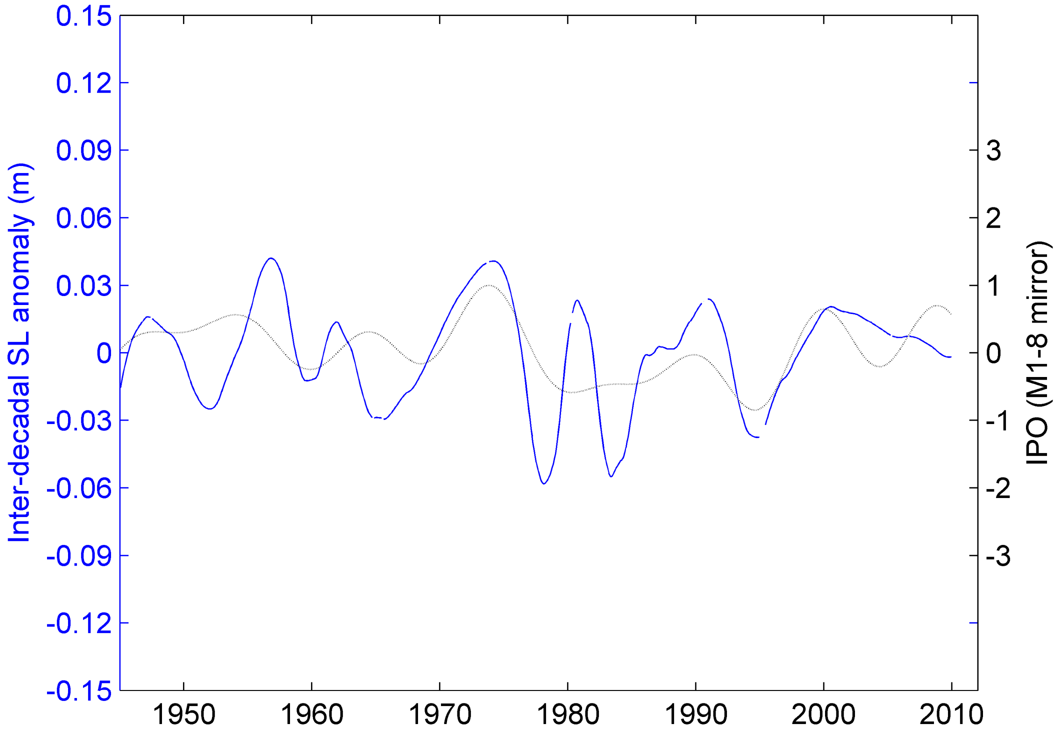


Figure 5-10: Inter-decadal variability in MSL at Wellington compared with the IPO index M1-8 from 1944 to 2010. (TOP) M1-8 index; (BOTTOM) inverse M1-8 index. MSL is blue line.

6 GPS measurements and processing

Continuous GPS (cGPS) data has been collected in the Wellington region since the year 2000. Due to the lack of sky visibility at the tide gauge location a GPS receiver was not mounted at the tide gauge site itself, but rather was installed on top of Te Papa, some 500 m away. This building was constructed in the 1990s on piles driven into weak sediments that were compacted by the repeated dropping of heavy weights. Due to the impractical nature of leveling inside the building up several flights of stairs (so providing a vertical tie between the tide gauge and the GPS receiver), the stability of the tide gauge has been monitored by using a short-baseline 24-hour GPS survey between the Te Papa receiver (WGTT) and a benchmark on the wharf some 50 m from the tide gauge. The tie is completed by leveling the final 50 m. This process has typically been repeated every six months since the time of GPS receiver installation.

When combined, the precise leveling and the GPS leveling show a subsidence of -0.9 ± 0.1 mm/yr of WGTT relative to the Tide Gauge (see Figure 6-1). Due to the overall stability of the tide gauge since 2001, it is concluded that the cause is due to Te Papa settling on its foundations.

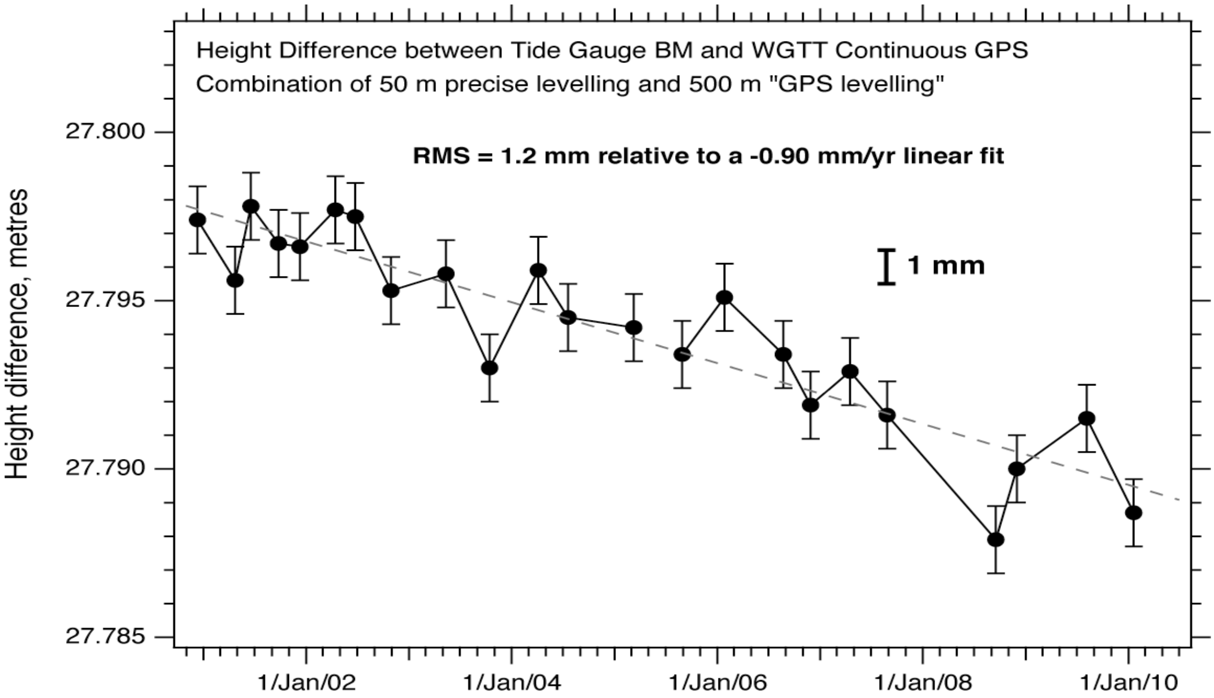


Figure 6-1: Height difference between WGTT (on Te Papa) and the Wellington Tide Gauge. (P. Denys, pers. comm.)

In order to give greater insight into the regional tectonics of Wellington, an additional cGPS receiver was installed in 2000 on a stable site at the Wellington Airport [WGTN (REF_{GPS})].

All GPS data collected at both sites have been processed by GNS Science and by the School of Surveying at the University of Otago. While different processing strategies were used, the resulting trends are consistent to the 0.5 mm/yr level. The results, taken from Denys et al. (2012) are shown in Table 6-1 below.

Table 6-1: Estimated vertical trends at Wellington from cGPS data (2000-2010) with associated standard deviations.

Location	Otago University (mm/yr)	GNS Science (mm/yr)	Mean (mm/yr)
WGTN (REF_{GPS}) Wellington Airport	-1.48 ±0.29	-1.97 ±0.29	-1.72 ±0.21
WGTT on Te Papa	-2.78 ±0.27	-2.87 ±0.26	-2.82 ±0.19
Difference	-1.30 ±0.40	-0.90 ±0.39	-1.10 ±0.28

Two things become clear from the results. Firstly, both solutions show that over the last decade Te Papa has been subsiding relative to WGTN (REF_{GPS}) at a rate of about 1.0 mm/yr. This result is independent of, but entirely consistent with the data shown in Figure 6-1. Secondly, and perhaps more importantly it appears that the WGTN (REF_{GPS}) site has been subsiding at a rate of approximately 1.7 mm/yr. Given the expectation that the Airport site is stable, the question arises as to whether or not this effect is real. For example, could it be a function of some processing or reference frame inconsistency? To answer this question, the 10-year time series for the WGTN (REF_{GPS}) site is compared with similar reference sites at Auckland [uAUCK], Lyttelton [uMQZG] (prior to the earthquakes), and Dunedin [uOUSD]. These data are shown in Figure 6-2.

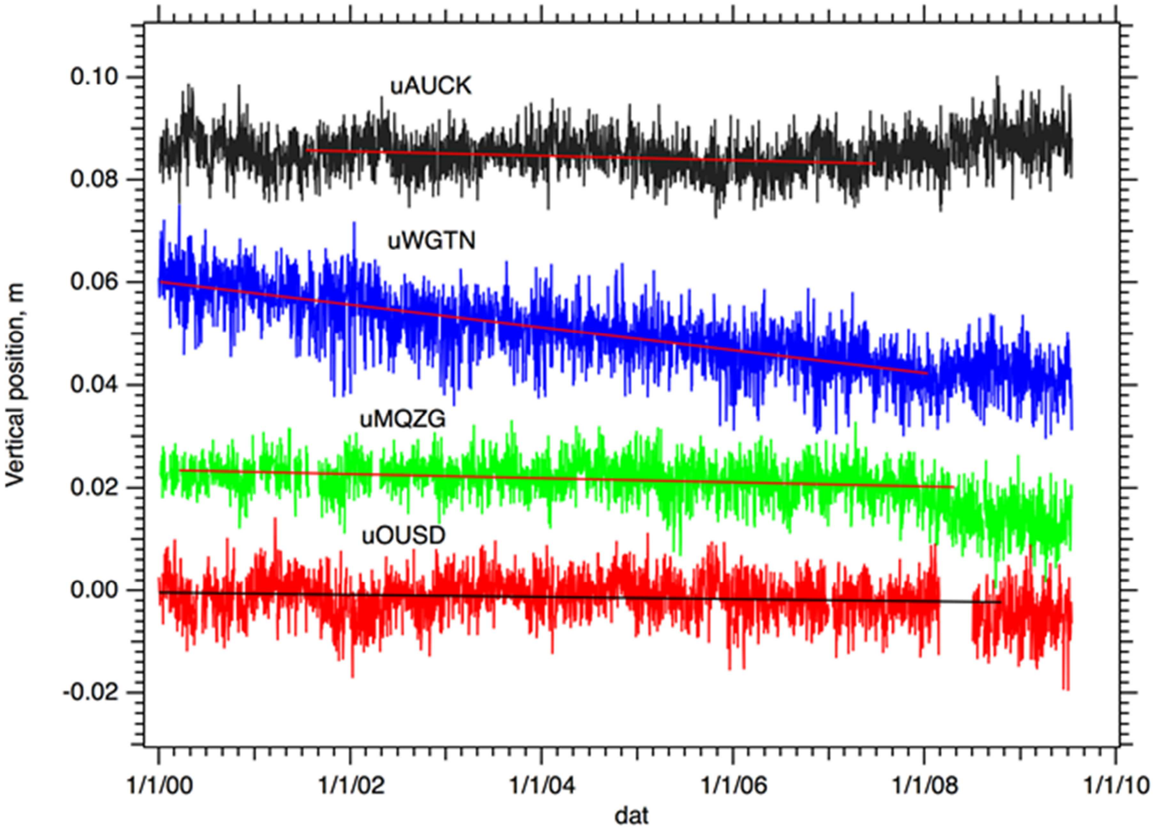


Figure 6-2: University of Otago solutions for all New Zealand REFGPS sites with linear regression fits on an arbitrary vertical axis. (Taken from Denys et al. (2012)).

This comparison provides strong evidence that the subsidence is real, most likely being a reflection of a regional tectonic signal. Secondly, data from additional GPS receivers in the Wellington region, that are part of the GeoNet system[4], have been processed. These cGPS data, covering the last six years, show a regional tectonic subsidence of between 2 mm/yr and 3 mm/yr that extends up the Wairarapa coast as far as Napier. A similar subsidence, but of a lesser magnitude is found up the western Kapiti coast up to Foxton Beach and beyond (Fadil et al. 2012). The detailed explanation for this signal, and the length of time that it has been present, are subject to some conjecture. However, Denys et al. (2012) are of the view that it is the outcome of two related tectonic events. One is the coupling between the Pacific and Australian plates on the subduction interface that underlies Wellington (Wallace et al. 2004), and the other the outcome of slow slip events (SSEs) that have twice been observed in the region since 1997 (Wallace and Beavan, 2010). The coupling causes the Wellington region to be dragged westward relative to the interior of the Australian plate, causing uplift or subsidence of the region depending on the exact distribution of the coupling between the plates. Superimposed upon these longer-term forces are the SSEs on the deeper part of the subduction interface, west of Wellington (Wallace and Beavan, 2010).

The fact that the cGPS trend estimates are derived from data collected between 2000–2009 i.e., between the two SSEs is likely to result in regional ground motion that is quite different from the overall average for the 1891–2011 period of the tide gauge record. Unfortunately, ground motion prior to 1997 (if any) cannot be determined due to the lack of measurement records of the necessary accuracy.

Denys et al. (2012) conclude that because of the non-linearity in the vertical ground motion history at Wellington, and because no independent measurement data is available prior to 1997, the Wellington tide gauge record should not be used as a reliable indicator of absolute mean sea level change.

However, and at least from the viewpoint of climate-change adaptation, it is the measured relative sea-level rise that needs to be adapted to, even if there have been, and may continue to be, temporal variations in rates due to tectonic processes. Consequently, monitoring of SLR in Wellington, via the tide gauge and associated cGPS stations, will be of critical importance locally for on-going tracking of relative SLR for Wellington. This would need to include regular reviews on how it compares with the absolute SLR at other New Zealand gauges and the global-average rate, in order to downscale global SLR projections to the Wellington region.

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[4] www.geonet.org.nz

7 Sea-level trend analysis

A number of analyses of the Wellington MSL data have been completed with the first being undertaken in 1990 (Hannah, 1990), the second in 2004 (Hannah, 2004), 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, following adjustments outlined in Section 4, are plotted below in Figure 7-1 in terms of the pre-1945 datum and are listed in Appendix A. The linear sea level trend of 2.03 mm/yr, as calculated with data collected from 1891 to the end of 2011 has been superimposed on the time series of annual MSL in Figure 7-1.

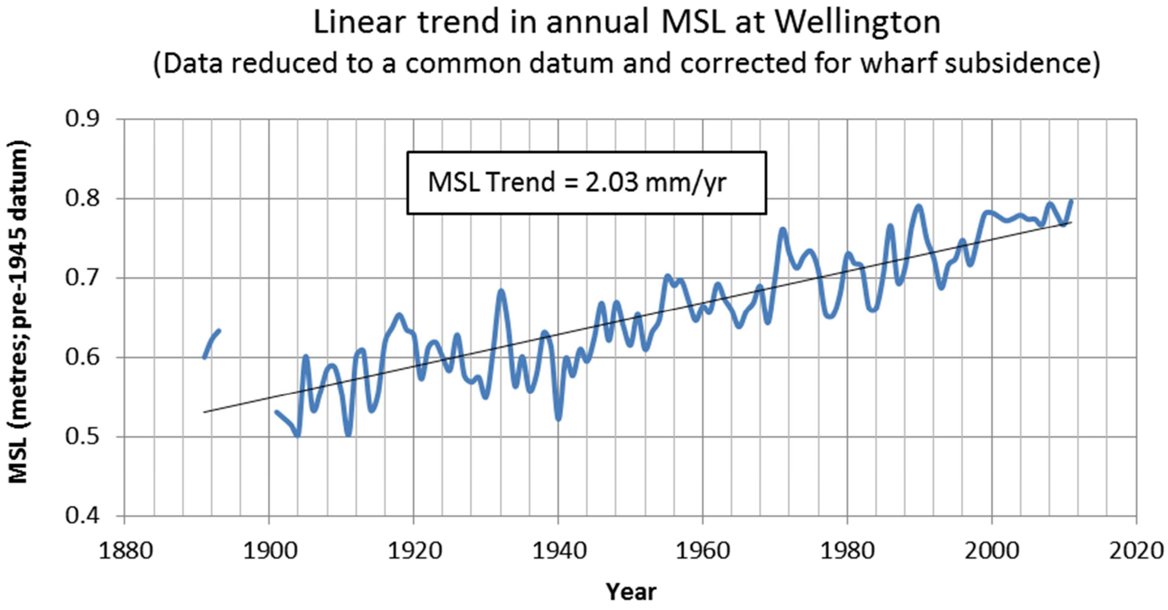

Figure 7-1: Linear trend in annual MSL at Wellington since 1890. Datum: in terms of pre-1945 datum. Add 0.321 m to obtain levels to present Chart Datum.

In considering the plot above, it is clear that the data from 1891-1893 (before the gap in the series) are well above the linear trend. However, it must be remembered that there is no record as to the quality of these data or what tide gauge was used for their collection. These three data points are considered to be the weakest in the entire time series and have been down-weighted accordingly in the trend solution, but left in for completeness.

The results of the three analyses are listed in Table 7-1 below.

Table 7-1: Summary of Wellington annual MSL linear trends for different record lengths.

Year of Analysis	Data used (inclusive years)	Linear trend (mm/yr)	Standard deviation (mm/yr)
1990	1901 - 1988	1.73	0.27
2004	1891 - 2001	1.78	0.21
2011	1891 - 2011	2.03	0.15

These linear trends are relative to stable local benchmarks on the fixed shoreline, but are unadjusted for regional vertical land motion, such as has been detected at WGTN (REF_{GPS}) described in Section 6.

It is of interest to note the increase in the overall trend that occurs when data from the first decade of this century is added. Of the ~0.3 mm/yr increase in the overall rate, when annual MSL data since 1988 up to 2011 is included (Table 7-1), some of this increase is due to climate variability and some arises from the subsidence in Wellington from recent SSEs, as discussed in the previous Section. An increase in the overall sea-level trend of ~0.16 mm/yr occurred at the more stable Auckland gauge site over the same time period. This reflects the influence of the Inter-decadal Pacific Oscillation (IPO) that switched modes around 1998-2000 (see Section 5.2.2), which exhibited a very similar response around New Zealand (Hannah & Bell, 2012). Consequently, the recent increase in the long-term rate of relative sea-level rise in Wellington is a combination of climate variability, compounded by the recent regional tectonic subsidence in Wellington already mentioned.

Before drawing all these data together, it is relevant to include an estimate of the Glacial Isostatic Adjustment (GIA). Figure 7-2 shows the magnitude of the GIA effect across New Zealand as calculated using Peltier's ICE-5G v.1.2b (M2) model. The specific correction for the Wellington region is given in Table 7-2.

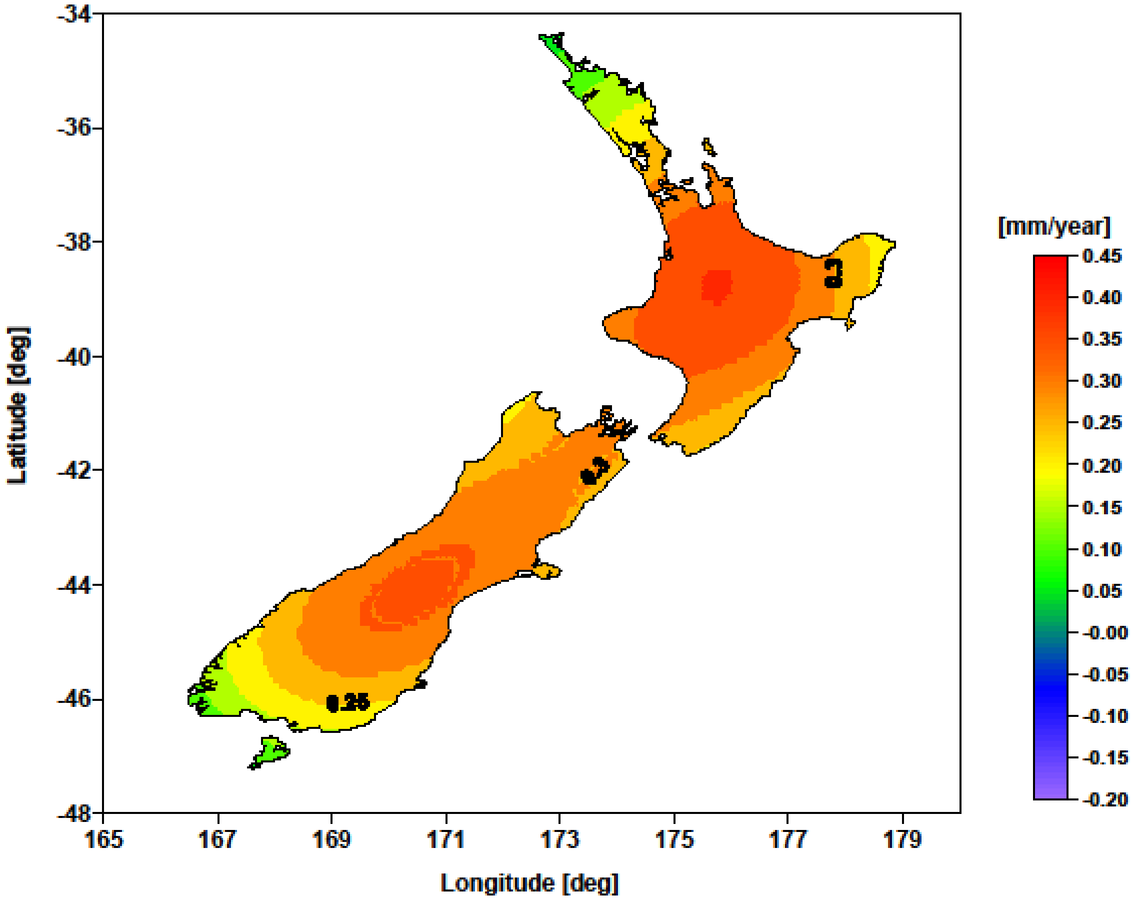

Figure 7-2: GIA corrections for New Zealand (from Peltier, 2004).

Table 7-2: Current estimates of the relative and absolute sea-level trends at Wellington (mm/yr). Standard deviations in brackets.

Port	Relative sea level change (linear trend) *a*	GIA correction *b*	Local tectonic motion from cCPS data *c*	Tectonic motion With GIA component removed *b + c*	Absolute sea level trend *a + c*
Wellington	+2.03 (0.15)	+0.30	-1.7 (0.21)	-1.4	+0.33 (0.26)

In drawing these various elements together, a number of comments should be made.

Firstly, the relative sea level trend is well determined and is consistent with the relative trends as determined at nine other New Zealand sites (Hannah and Bell, 2012). However, it must be remembered that the relative trend in Wellington has been determined from 113 years of data and thus the regional tectonic motion that is thought to have occurred over the last 10-15 years will not have greatly influenced the solution. Excluding Wellington, the average relative MSL trend across all New Zealand sites is 1.7 mm/yr – a rate that increases to approximately 2.0 mm/yr once GIA corrections have been applied. This New Zealand average rate fits very well with best global GIA corrected global estimates of linear sea level changes over the 20th century of 1.7 ± 0.3 mm/yr (Church & White, 2006; Bindoff et al. 2007; Church & White, 2011). There is thus excellent consistency between the average sea-level trend as computed in New Zealand and global average rate to present day. This similarity means global-average projections for future sea-level rise can be applied more or less directly to New Zealand regions, taking into account local anomalies, such as tectonic or basin subsidence effects.

Secondly, the formal estimated accuracy of the local tectonic motion as determined from the cGPS data is probably optimistic, being more a reflection of the repeatability of the height solutions rather than their accuracy. Denys et al (2012) consider that a standard error of ± 0.5 mm/yr is probably more realistic. Nevertheless, the Wellington region has clearly been subsiding between 1–3 mm/yr for at least the last decade and most probably since the first (1997) slow seismic event. How long this might continue, or even if it will continue, is unknown.

Thirdly, if the current (regional) tectonic motion continues at its present rate, then the combination of a 1.7 mm/yr relative sea level rise (such is occurring on average around the New Zealand coast) plus regional subsidence in the Wellington region that varies between 1–3 mm/yr, would suggest a near-future relative sea level rise could range from 3–5 mm/yr over short periods, depending on the magnitude and persistence of SSEs. This excludes any near-future acceleration in absolute sea-level rise in New Zealand waters.

Finally, and most relevantly, no statistically-significant acceleration in relative sea-level rise can be detected in the wider New Zealand record (Cole, 2011). Accelerations extracted from sea-level records depend on what timescales and starting points are considered, which may or may not include natural variability. This aspect is discussed in more detail in Section 8.5.2.

1. The historic rate of relative SLR for Wellington Harbour from the late 1800’s up to present is 2.03 ±0.15 mm/yr

2. Regional subsidence, from slow-slip events, has increased the relative sea-level trend in the wider Wellington City area since ~1997. This trend varies across the Wellington region from subsidence of around 1 mm/yr on the Kapiti coast up to between 2 to 3 mm/yr along the Wairarapa coast, but it is not clear for how long this will persist

3. No statistically-significant acceleration in SLR can be detected in the wider New Zealand sea-level record, taking into account variability due to climate cycles

8 Background to guidance on sea-level projections

This section provides a summary of projections for future sea-level rise, both from New Zealand (MfE, 2008) and overseas guidance. An appraisal compares how relative sea-level rise in Wellington and global-average sea-level rise have been tracking since 1990 in relation to the projections for the same short period.

8.1 Wellington context

8.1.1 Geographical context

The Wellington region straddles a diverse coastal environment, from the more sheltered Kapiti Coast in the west (Tasman Sea), to the exposed Wellington south coast (Cook Strait) and along the high energy Wairarapa coast in the east. The only long-term sea-level record for the region is derived from Wellington Harbour gauge, where the relative sea-level rise is affected to some degree by local tectonic movement (Section 6). More information is now available on vertical land movement at various cGPS sites around the Wellington region, although records only cover the present decade.

8.1.2 Historic relative sea-level rise

Wellington has experienced an average rise in sea level of 2.03 ±0.15 mm/yr, as calculated using data collected from 1891 to the end of 2011, which is relative to the regional landmass movement (Section 7). The New Zealand average relative sea-level rise for a similar period is 1.7 mm/yr (Hannah & Bell, 2012), which is similar to the average trend of 1.78 mm/yr at Wellington up to 2001 (Table 7-1). Allowing for a small on-going GIA rebound of ~0.3 mm/yr in the landmass elevation, due to past glacial loading of the crust, means the absolute rise in sea level around New Zealand has averaged ~2.0 mm/yr, which is within the range for the global average sea-level rise of 1.7 ±0.3 mm/yr (Church & White, 2006; Bindoff et al. 2007; Church & White, 2011).

This result implies that future projections of global-average sea-level rise can be more or less applied directly to obtain reasonable projections of sea-level change in New Zealand, until such time that local sea-level monitoring of relative sea-level rise shows otherwise. The latter caveat is pertinent to the Wellington region, given the evidence of recent periods of vertical subsidence from slowly-varying tectonic processes, and may require an additional tectonic contribution to projected relative SLR estimates for the Wellington region.

8.2 Relevance of the MfE coastal guidance manual

The effect of climate change and sea level rise on coastal areas of New Zealand is discussed in detail in the MfE guidance manual *Coastal Hazards and Climate Change* (MfE, 2008). It should be the primary basis for any coastal adaptation planning and vulnerability assessments taking into account on-going peer-reviewed publications and IPCC reviews.

This coastal hazards guidance manual identifies that a significant proportion of New Zealand’s coastal edges have been settled by urban development, particularly cities and coastal beach settlements. Some of this development has been located in areas currently vulnerable to coastal hazards (such as coastal erosion or inundation by storm-tides and wave overtopping, drainage problems, saltwater intrusion into landward areas and estuaries).

Climate change effects, while gradual, will increasingly exacerbate existing coastal hazards and begin to affect previously untouched areas.

Locally managing the effects of coastal hazards along with the progressive influence of climate change, through monitoring, reviewing and appropriate implementation of adaptation plans, are fundamental to maintaining or developing sustainable and resilient communities.

The coastal hazards guidance manual specifically:

- provides information on the key effects of climate change on coastal hazards in the New Zealand context
- provides a risk assessment framework for incorporating coastal hazard and climate change considerations into decision-making processes (policy, planning, consenting)
- promotes the development of long-term adaptive capacity for managing coastal hazard risk through adoption of adaptive management[5] and no-regrets[2] or low-regrets[2] response options.

8.2.1 Risk-based approach

The use in the MfE guidance manual of a risk assessment framework is the fundamental basis for selecting which sea-level rise to accommodate for any locality, project or objective. Let's look at two extreme examples. An activity where the future consequence of being inundated is low e.g., new or upgraded boat ramp or toilet block may only be required to accommodate a modest sea-level rise. However, a new subdivision or strategic bridge crossing, where the future consequences of inundation are very high, may need to accommodate a substantially higher sea level rise, depending on the anticipated permanency and investment associated with the activity.

A risk-based approach contrasts with a coastal planning approach where a single sea-level rise value over a particular time-frame is adopted for land-use activities e.g., a 0.8 m sea-level rise by 2100 in the Queensland Coastal Plan (Dept. of Environmental & Resource Management, 2011). This one-size fits all approach does provide regional consistency and is much easier to communicate, but has no flexibility to consider the scale of future consequences as illustrated in the previous paragraph. Objective 5 of the NZCPS also signals that different approaches should be applied to green-fields and existing developments, implying different sea-level rise values and timeframes are considered in each situation to avoid or mitigate risk respectively.

8.2.2 Sea-level rise guidance

At its 2008 publication date, the MfE guidance manual was based mainly on the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) which was released in 2007 (Bindoff et al. 2007; Meehl et al. 2007; IPCC, 2007). However, the MfE guidance also encapsulated additional peer-reviewed scientific studies on sea-level rise that appeared after the 2007 IPCC report was published. These follow-on studies indicated sea levels may rise higher than the upper levels presented by IPCC (notwithstanding that IPCC

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[5] see Glossary

were not prepared to provide a best estimate or an upper bound, because the understanding of some effects was too limited, particularly the future response of polar ice-sheets).

In terms of climate-change impacts, the 2008 MfE guidance manual advocates planning for:

- A range of sea levels by the 2090s (2090-2099) based on a risk assessment process to circumvent uncertainties in the timing of future sea-level rise. The full rendition of the 2008 MfE sea-level rise guidance is shown in Box 1 below with an updated commentary on its usage.
- Climate change impacts on tides, storm surges, waves, swell and sediment supply; both the magnitude of the effect and changes to the frequency of occurrence.
- The present mean high water spring (MHWS) level will be exceeded more frequently in the future and increasingly so.

BOX 1: Sea-level rise guidance within a risk-assessment framework

The 2008 MfE guidance manual *Coastal hazards and climate change* recommends for planning and decision timeframes out to the 2090's (2090-2099):

1. a base value sea-level rise of 0.5 m relative to the 1980–1999 average should be used, along with
2. an assessment of potential consequences from a range of possible higher sea-level rises (particularly where impacts are likely to have high consequence or where additional future adaptation options are limited). At the very least, all assessments should consider the consequences of a mean sea-level rise of at least 0.8 m relative to the 1980–1999 average. Guidance is provided in Table 2.2* (*of the guidance manual*) to assist this assessment.

**Note: Frequently, citations of 2008 MfE guidance manual indicate that it is limited to an upper sea-level rise of 0.8 m and therefore is increasingly outdated. However, Table 2.2 of that guidance covers a range of sea-level rise projections by the 2090s or 2100 with upper bounds from 0.8 m from IPCC (2007) up to 1.0–1.4 m (based on three empirical studies from 2007 and 2008 described in the Table 2.2), to which values from more recent studies outlined in RSNZ (2010) could also be considered within the risk-based assessment that underpins the guidance.*

3. For longer planning and decision timeframes where, as a result of the particular decision, future adaptation options will be limited, an allowance for sea-level rise of 10 mm per year beyond 2100 is recommended (in addition to the above recommendation).

8.2.3 Commentary on the 2008 MfE sea-level guidance:

Risk assessments, that underpin the guidance, should be based on a broad consideration of the potential consequences (direct impacts, loss of assets and amenity) from different sea-level rise magnitudes on a specific decision, objective or issue. The particular sea-level rise adopted in each case should be based on the acceptability of the potential consequences and likelihood of that sea-level rise (=risk) and the potential future adaptation or protection costs that may be incurred at that sea-level rise.

Each risk assessment should also take into account the land-use and physical shore-type context (e.g., gravel, sandy or cliffed coasts). In particular, improving the resilience of existing development should be treated differently from new developments ("green-fields"). For the latter, risk avoidance and a precautionary approach are paramount in the NZCPS, along with the need to recognise that sea levels will continue to rise for possibly several centuries (rather than some arbitrary 100-year "design life" or planning timeframe). So in undertaking a risk assessment and appraising future adaptation for greenfield developments, sea-level rises well over 0.8 m should be considered. The MfE guidance, as it stands, is for assessing a range of sea levels, starting any appraisal with a 0.5 m rise (by 2090s) and the "at least 0.8 m" was inserted as a minimum higher sea-level rise to consider, but not to be limited to that value.

Hence the risk assessment process, as recommended in the MfE guidance manual, is generally an enduring approach, although it will need updating periodically in terms of timeframes. The 2010 NZCPS requires assessments of hazards for "at least 100 years" (see Section 9.1). So already (in 2012) the range of sea-level rises that should be considered needs to take into account an extension of the sea-level tie-points in the MfE guidance. Based on a planning time frame out to 2115, the equivalent tie-points for sea-level rise (relative to the 1980–1999 average) would be (Table 8-1) for an assessment **starting at a base value of 0.7 m** (equivalent to 0.5 m rise by 2090s) and **considering a range of possible higher values including at least a 1.0 m rise** (was a 0.8 m rise by 2090s). Both these 2115 values have been rounded to the nearest decimetre, taking into account the present guidance is for the 2090s decade with mid-point at 2095. These values are also found in Section 2 of *Pathways to Change* (Britton et al. 2011).

Table 8-1: Equivalent sea-level rise tie-points from the MfE guidance manual (MfE, 2008) to at least be considered, extended out to 2115.

Tie-point in risk assessment	SLR (m) to consider
Start risk assessment at:	0.7 m
At least also consider at least:	≥1.0 m

8.3 Planning values used internationally

A survey of sea-level rise values being used for planning purposes in Australia, the UK and The Netherlands was undertaken. This review extends and updates the results presented in the Royal Society of New Zealand's emerging paper on sea-level rise (RSNZ, 2010) and provides some context as to how other jurisdictions are incorporating sea-level rise into coastal planning. Sea-level values embedded in plans and policies are identified separately from those values used in broader-scale "what-if" or vulnerability scoping scenarios.

8.3.1 Australia

National scoping study and 2011 review

At a national level, the Australian Government has developed a series of sea-level rise maps[6] to help communicate the risks of sea-level rise up to 2100 from climate change.

The three scenarios developed by CSIRO for Department of Climate Change (2009) for sea-level rise between 2030-2100 (relative to 1990) were:

- The *low scenario* (B1): considers sea-level rise in the context of a global agreement which brings about dramatic reductions in global emissions and represents the upper end of the range for sea-level rise by 2100 which is likely to be unavoidable.
- The *medium scenario* (A1FI): Represents the upper end of IPCC 4th Assessment Report (IPCC, 2007) projections and is in line with recent global emissions and observations of global average sea-level rise.
- The *high-end scenario*: considers the possible high end risk identified in the AR4 and more specifically in post IPCC AR4 research. This scenario factors in recent publications up to 2009 that explore the impacts of recent warming trends on ice sheet dynamics beyond those already included in the IPCC projections.

The benchmark values for these three scenarios are listed in Table 8-2 along with an extrapolation of the curve fit to 2115 by NIWA to align with the timeframe being considered in this report.

Table 8-2: Three sea-level scenarios developed by CSIRO for Dept. of Climate Change (2009) for assessing national risk to coastal communities relative to 1990 sea levels. Sea-level rises by 2115 (italics) have been extrapolated by NIWA from curves fitted to the 1990 (0 m), 2030, 2070 and 2100 values in the Table.

Year	Scenario 1: B1	Scenario 2: A1FI	Scenario 3: High-end
2030	0.13	0.15	0.2
2070	0.33	0.47	0.7
2100	0.50	0.82	1.1
2115	*0.6*	*1.05*	*1.35*

The sea-level rise values (Table 8-2) used in the 2009 national study for Australia were chosen as being appropriate for a first-pass nationwide risk assessment to illustrate diagrammatically on maps, the potential effects of such a rise superimposed on the highest astronomical tide. It was not intended for use by local councils and states in their land use planning processes.

Recently, the federal government Climate Commission Secretariat released a review of climate change science, risks and responses (Dept. of Climate Change & Energy Efficiency, 2011) entitled *The Critical Decade*. Their key messages on sea-level rise were:

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[6] http://www.ozcoasts.org.au/climate/sd_visual.jsp

- A plausible estimate of the amount of sea-level rise by 2100 compared to 2000 is 0.5 to 1.0 m. [*Note 1*: relative to the more commonly-used 1990 baseline, the additional sea-level rise is only about another 0.03 m on these values; *Note 2*: the equivalent range by 2115 would be around 0.6 m to 1.25 m].
- Very recent sea-level rise projections, such as those using semi-empirical methods, of 1.5 to 2.0 m (see Section 8.4) seem high in the light of recent questions surrounding estimates of the current rate of mass loss from polar ice sheets.
- Much more has been learned about the dynamics of large polar ice sheets in the last decade but critical uncertainties remain, including the rate at which mass is currently being lost, the constraints on dynamic loss of ice and the relative importance of natural variability, longer-term trends.
- The impacts of rising sea-level will mostly be experienced through “high sea-level events” when a combination of sea-level rise, a high tide and a storm surge or excessive run-off trigger an inundation event.

Australian state coastal plans and policies

Australian state governments have or are reviewing and changing their state policy and plans to account for rising sea levels and other climate change impacts. States have adopted sea-level rise policies, which have benchmark sea-level rise values as listed in Table 8-3.

In prescribing a 2100 benchmark SLR, Australian states that have finalised their plans or policies have for the present settled on SLR values of 0.8 to 1.0 m by (2100) that straddle CSIRO Scenarios 2 and 3 in Table 8-2. Extended out to 2115, this is equivalent to a sea-level rise between 1.0 to 1.25 m (interpolating the last row of Table 8-2).

The reliance on a single benchmark sea-level rise value adopted by most States in Australia does provide regional consistency and is much easier to communicate. However, there is little flexibility to consider the scale of future consequences or risk, nor distinguish between differing requirements for existing development compared with greenfield developments.

Most state government agencies have also indicated in their policy documents that they are not intending to update these benchmark values further until the IPCC 5th Assessment Report is published in late 2013.

Table 8-3: Sea-level rise benchmark values used in various Australian state plans and policies. [*Source*: adapted and updated from http://www.ozcoasts.org.au/climate/supporting.jsp].

State	2050 (on 1990 levels)	2100 (on 1990 levels)	Plan/Policy Reference
QLD	–	0.8 m	State Planning Policy for Coastal Protection, Queensland Coastal Plan (Dept. of Environmental & Resource Management, 2011)
NSW	0.4 m*	0.9 m*	NSW Sea Level Rise Policy Statement (Dept. of Environment, Climate Change and Water, 2009), and the NSW Coastal Planning Guideline: Adapting to SLR (Dept. of Planning, NSW, 2010)
VIC	–	≥0.8 m	Victorian Coastal Strategy (Victorian Coastal Council, 2008)
TAS	–	TBD	State Coast Policy 1996, with review in progress of draft State Coastal Policy released 2008 (Dept. of Premier & Cabinet, 2009). The Tasmanian Government has commenced work on a Climate Change Project to facilitate the development of adaptation strategies for Tasmania
SA	0.3 m	1.0 m	Coast Protection Board Policy Document (Coast Protection Board, 2002)
WA	–	0.9 m (by 2110)	State Coastal Planning Policy 2003 (West Australian Planning Commission, 2006) and sea-level rise position statement (Bicknell, 2010)
NT	–	TBD	Northern Territory Climate Change Policy–2009. Developing a climate-change Adaptation Action Plan by 2011.

* Includes an allowance for an extra 0.1 m for regional NSW differences relative to the global average SLR

8.3.2 UK guidance

In the United Kingdom, the Department for Environment, Food and Rural Affairs (DEFRA) have published national projections of climate change (Jenkins et al. 2009) to support decision makers in adapting to climate change. Part of the Briefing Report contains projections for sea-level rise.

SLR projections were updated in a number of ways, primarily through using results from the most recent IPCC Fourth Assessment Report. Jenkins et al. (2009) give projections of UK coastal absolute sea level rise (not including land movement) for three emission scenarios out to 2095 that range from approximately 0.12–0.76 m (relative to 1990). The upper end of this range (rounded to 0.8 m) is the same as one of the 2090s benchmark values in the MfE guidance manual (MfE, 2008), which extrapolated to 2115 would be a SLR of 1.0 m (Table 8-1).

One significant component of future SLR is from the melting of large ice sheets. Due to a lack of current scientific understanding of some aspects of ice sheet behaviour, Jenkins et al. (2009) also provided a low-probability High-plus-plus (High++) scenario for sea level rise of between 0.93 m and 1.9 m by 2100 around the UK in addition to their main scenarios described above. The IPCC Fourth Assessment Report (IPCC, 2007) provides some illustrative possibilities of how this lack of understanding of ice sheet dynamics might affect sea level projections, and the bottom of the H++ scenario range (0.93 m) was set by Jenkins et al. (2009) from the maximum global mean sea level rise value given by the IPCC Fourth Assessment Report. The top of the H++ scenario range (1.9 m) was derived by Jenkins et al. (2009) from indirect observations of sea-level rise in the last interglacial period, at which time the climate bore some similarities to the present day, and from estimates of maximum glacial flow rate. The upper part of the range of sea level increase is thought to be very unlikely to be realised by 2100, but Jenkins et al. (2009) provided the scenario as some "*users may wish to investigate contingency planning and the limits of adaptation*".

In terms of local council plans in the UK, the Thames Estuary flood risk management plan was the first to utilise the scenarios produced by Jenkins et al. (2009). The adaptive management approach taken, with timing of various stages based on a sea-level rise trajectory out to 0.9 m by 2100, is outlined as a case study in Box 6.6 in *Pathways to Change* (Britton et al. 2011).

8.3.3 Netherlands

The Delta Commission in their report *Working together with water: A living land builds for its future* (Deltacommissie, 2008) provided sea-level rise projections for planning out to 2100 of 0.55 m to 1.2 m, assuming an atmospheric temperature increase of 6℃. The recommended planning value was 1.1 m by 2100 (RSNZ, 2010).

However, sea level will continue to rise for several centuries. Research conducted for the Delta Committee for longer-term planning shows that by 2200 we can expect a global maximum sea level rise of around 1.5 to 3 m (see Figure 8-1), depending on the method used (Deltacommissie, 2008). Figure 8-1 also shows the long-range estimates by the German Advisory Council on Global Change (2006) which suggest very approximate sea-level rise of 2.5 to 5 m by 2300.

While these long-range estimates will continue to change, Figure 8-1 has been included mainly to illustrate that sea-level rise will continue for at least the next few centuries, which is easy to forget when using a limited planning timeframe. This on-going trend needs to be factored into values of sea-level rise adopted for new greenfield developments or new high-risk infrastructure. This is addressed more specifically at the end of this Section.

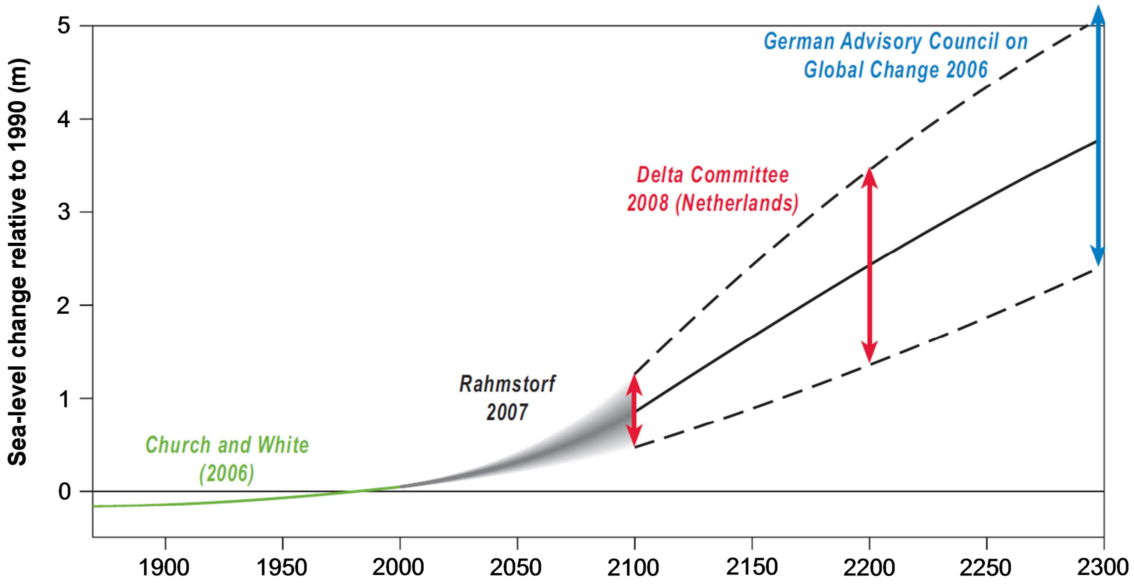

Figure 8-1: Recent indicative projections of global sea-level rise up to 2300 (relative to 1990) adapted from Dept. of Climate Change (2009) and Copenhagen Diagnosis (2009). Initial line for 1900s is trend for global-average observed data (after Church and White, 2006); Grey shaded area, Rahmstorf (2007), based on IPCC 3rd Assessment Report temperatures; Red bar, after Deltacommissie (2008); Blue bar after German Advisory Council on Global Change (2006).

8.4 Recent estimates of sea-level rise (post IPCC, 2007)

A review of recent peer-reviewed papers (up to mid-2010) on sea-level rise was presented by a Royal Society of NZ Emerging Issues paper (RSNZ, 2010). A brief updated summary follows.

Since the 2006 cut-off point for science publications to be considered within the IPCC Fourth Assessment Report process, further scientific papers have been published containing projections on global sea-level rise. These papers add to the array of information on potential future sea-level rise over this century and include:

- Consideration that sea levels are tracking close to the upper end (e.g., A1FI emission scenario) of the AR4 projections (Rahmstorf et al. 2007; Copenhagen Diagnosis, 2009)– currently global average sea level (section 8.5.1) is tracking along the projection trajectory that would lead to a 0.8 m rise by the 2090s (Figure 8-6).
- Confirmation that the loss of mass from Greenland and Antarctic ice sheets may be occurring more rapidly than from surface melting alone (e.g., Rignot et al. 2008, 2011; Shepherd & Wingham, 2007; Bamber et al. 2009).
- Revision of some earlier estimates of the recent contribution from polar ice sheets. Wu et al. (2010) and summarised by Bromwich & Nicolas (2010) show that present-day ice sheet mass losses previously calculated from GRACE satellite measurements (e.g., Figure 2 of RSNZ, 2010) have been overestimated by a factor of two (due to a revised estimate of vertical land

movement from past glaciation) although there remain uncertainties due to the sparse network of coastal GPS measurements.

The increasing contribution of present-day sea-level rise due to ice-sheet losses has led to a number of more recent estimates of sea-level rise over the 21st century (Rahmstorf, 2007; Horton et al. 2008; Pfeffer et al. (2008); Vermeer and Rahmstorf, 2009; Grinsted et al. 2010; Jevrejeva et al. 2010).

The overall ranges of these more recent sea-level rise estimates by 2100 or in some cases the 2090s (2090-2099) are summarised in comparison to the projections from the IPCC Fourth Assessment Report (IPCC, 2007) in Figure 8-2, including available confidence limits.

Aside from the IPCC AR4 (IPCC, 2007) and Pfeffer et al. (2008), the other projections are based on semi-empirical methods that calibrate sea-level rise to atmospheric temperature for past and present climate reconstructions, then attempt to project these relationships with temperature forwards using IPCC projections for temperature from the IPCC Third Assessment Report (TAR), as undertaken by Rahmstorf (2007), or for the other studies, the Fourth Assessment Report (AR4). However, there is still considerable debate over the robustness of these semi-empirical methodologies adopted in making these projections (Holgate et al. 2007; IPCC, 2010; Price et al. 2011). A recent workshop of Working Group I of the IPCC in Kuala Lumpur (IPCC, 2010), attended by the author, also debated the ability of semi-empirical approaches to estimate future sea-level rise, particularly the coefficients that define the considerable time lag between a temperature change and sea-level rise reaching a new “equilibrium”. In summarising, they concluded that a major limitation of these approaches is the inability to calibrate them on a climate-system behaviour expected later this century, and therefore “the physical basis for the large estimates from these semi-empirical models is therefore currently lacking’’ (p. 2, IPCC, 2010).

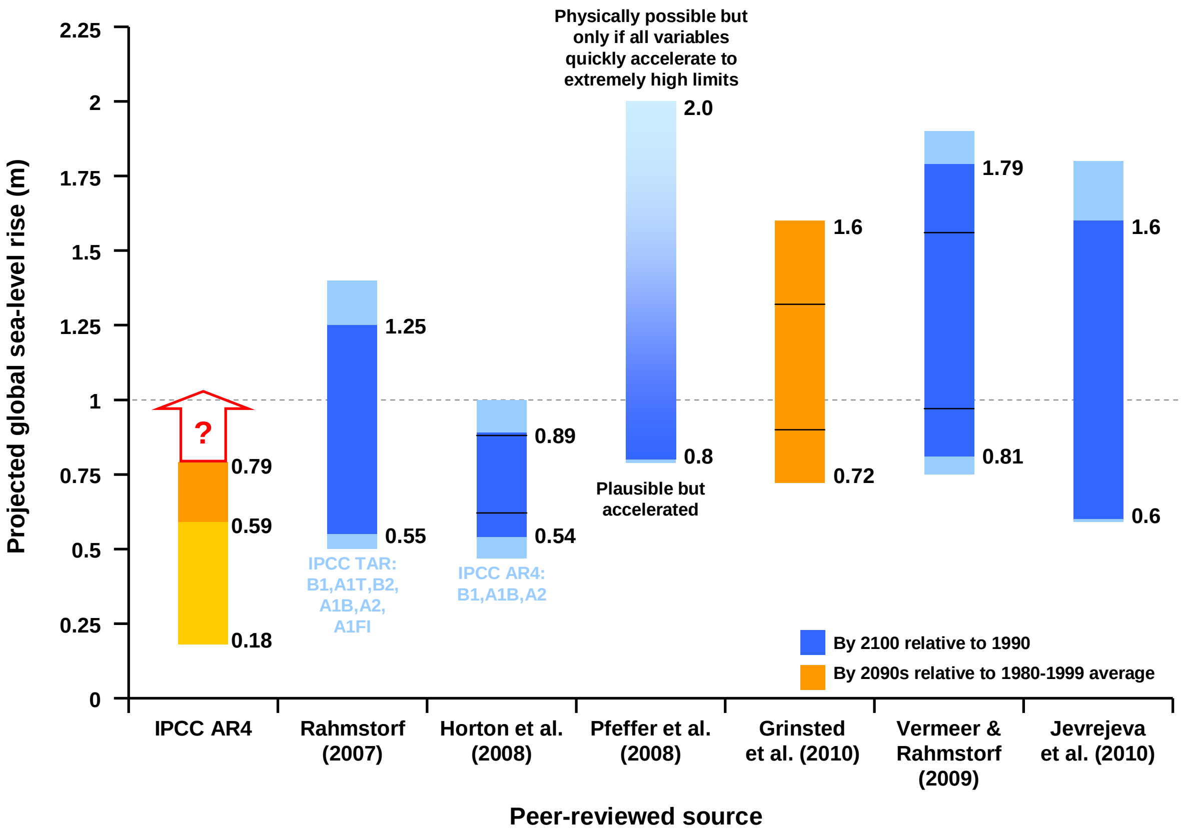

Figure 8-2: Comparison of sea-level rise projections from recent peer-reviewed papers and the IPCC Fourth Assessment Report (AR4). Projections out to the 2090s are orange and those out to 2100 are blue. Light blue shading indicates confidence limits. The AR4 (IPCC, 2007) projections include a caveat for inclusion of a limited ice-sheet component, but IPCC were not prepared to provide any upper limit (hence ? mark). Citations can be found in References section.

Pfeffer et al. (2008) took a different tack, looking at the possibly largest constraints on ice sheet mass loss. They concluded that the glaciological conditions required for a sea-level rise of 2 metres by 2100 are very unlikely to occur (i.e., physically possible but only if all variables quickly accelerate to extremely high limits) and that a more plausible, but still accelerating ice sheet contributions, lead to a sea-level rise by 2100 of about 0.8 m. Price et al. (2011), using a 3-dimensional dynamic ice flow model for Greenland that accounts for periodic variability, determined that the dynamic mass flow contribution from Greenland Ice Sheet would be up to 0.045 m by 2100 (half the upper bound estimate by Pfeffer et al. 2008), and also including the time-varying change in ice-sheet surface mass balance, up to 0.085 m by 2100. Rignot et al. (2011) summarised recent accelerations in ice sheet loss over the last 18 years and concluded that if present trends in ice sheet accelerations persist, polar ice sheets could become the dominant contributor to sea-level rise this century.

In summary, projected sea level rise values in the scientific literature range over wide range from approximately 0.2 m to 1.8 m by 2100. Projections are based on a variety of methods such as physically-based climate-ocean numerical models, assessments of lower and upper physical constraints on ice-sheet loss or semi-empirical models that relate past changes in atmospheric temperature to lagged changes in sea-level rise and project these relationships forward in time. The merits of the latter approach, which produce the high upper-end sea-level rises (Figure 8-2), remains a topic of on-going debate. Credible estimates of sea-level rise by 2100 are more likely to be in the range 0.5 to 1.0 m, but rises above 1 m cannot be ruled out.

8.5 Update on monitoring of global and Wellington sea levels

8.5.1 How is sea-level rise tracking?

Satellite altimeters (based on radar) have been used to monitor the mean level of the sea since 1993 over most of the globe (0–66° N & S). Figure 8-3 shows the latest trend in the global average sea level for the “satellite period” (1993 to present). The satellite altimeter data has shown an increase in global mean sea level (GMSL) of around 3.1 mm/year over that period up to January 2012. In the slightly shorter period 1993 to 2009, the GMSL from altimetry had the same trend (3.2 ± 0.4 mm/year) compared to in-situ tide gauge data of 2.8 ± 0.8 mm/year (Church & White, 2011). These rates are around 65–90% higher than the longer-term global average rise of 1.7 ± 0.2 mm/year from 1900 to 2009 (Church & White, 2011). Whether or not this represents a further increase or acceleration in the rate of sea level rise is not yet certain, as the satellite record is relatively short and also coincided with a regime shift around 1999-2000 of the 20–30 year Inter-decadal Pacific Oscillation (IPO) cycle (Section 5). The full ~19-year lunar nodal tide has also not yet been fully resolved from the satellite record, with recent estimates indicating that it is a significant non-climate contributor to the trend in the recent satellite record (Baart et al. 2012a; Cherniawsky et al. 2012). The nodal tide contribution will soon be fully realisable directly from the satellite data now a 19-year record exists, with the global-average contribution of the nodal tide likely to explain around 0.4 mm/yr of the 3.1 mm/yr trend to present (Cherniawsky et al. 2012).

Normally, for tide gauge data, at least 50–60 years of data is required to fully resolve these longer decadal cycles (Douglas, 1997). Although Church & White (2011) resolved a small rise in the rate of sea-level rise up to 2009 from 1.7 mm ± 0.2 mm/year (starting from 1900) up to 1.9 mm ± 0.4 mm/year (starting from 1961), to date no statistically-significant acceleration has been detected in the rate of rise over recent decades e.g., The Netherlands (Baart et al. 2012a) and New Zealand (Cole, 2011). See the next section for a fuller synthesis on detection of any acceleration in sea-level trends.

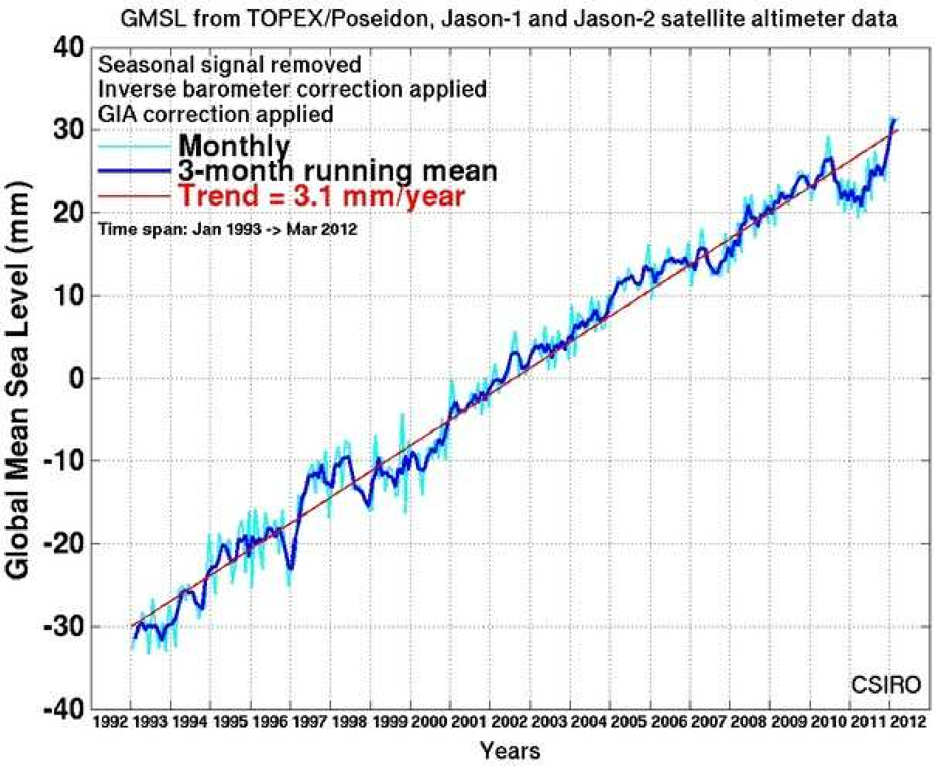

Figure 8-3: Global average mean sea-level trend since 1993 to March 2012 as measured by satellite altimeters [Source: CSIRO, Australia]. Based on data from TOPEX/Poseidon (launched August, 1992), Jason-1 (launched December, 2001) and Jason-2 (launched June, 2008). The annual seasonal cycle has been removed and a Glacial Isostatic Adjustment (GIA) applied to remove on-going variations in the Earth's crustal movement.

The rise in global mean sea level is in some ways an artefact of averaging over the entire globe, but regionally, the mean sea level can and will exhibit substantial spatial differences. For instance the western Pacific Ocean has shown a higher rate of rise over the “satellite period” since 1993, while in the north-eastern Pacific (Bromirski et al. 2011), sea level has either been static or shown a slight fall (light blue/green areas), as shown in Figure 8-4. The New Zealand region, for this period, mirrors or exceeds the global-average rate of 3.1 mm/yr for the satellite period. For instance, the short-term rate from the Wellington Harbour gauge that straddles the 1993 to 2011 satellite altimetry era is around 4.3 mm/yr—temporarily double the long-term rate. Again, the influence of climate variability on short-term rates of the rise in sea level regionally is another important reason to continue monitoring sea levels in Wellington to monitor variations between the global average and the regional rate of rise.

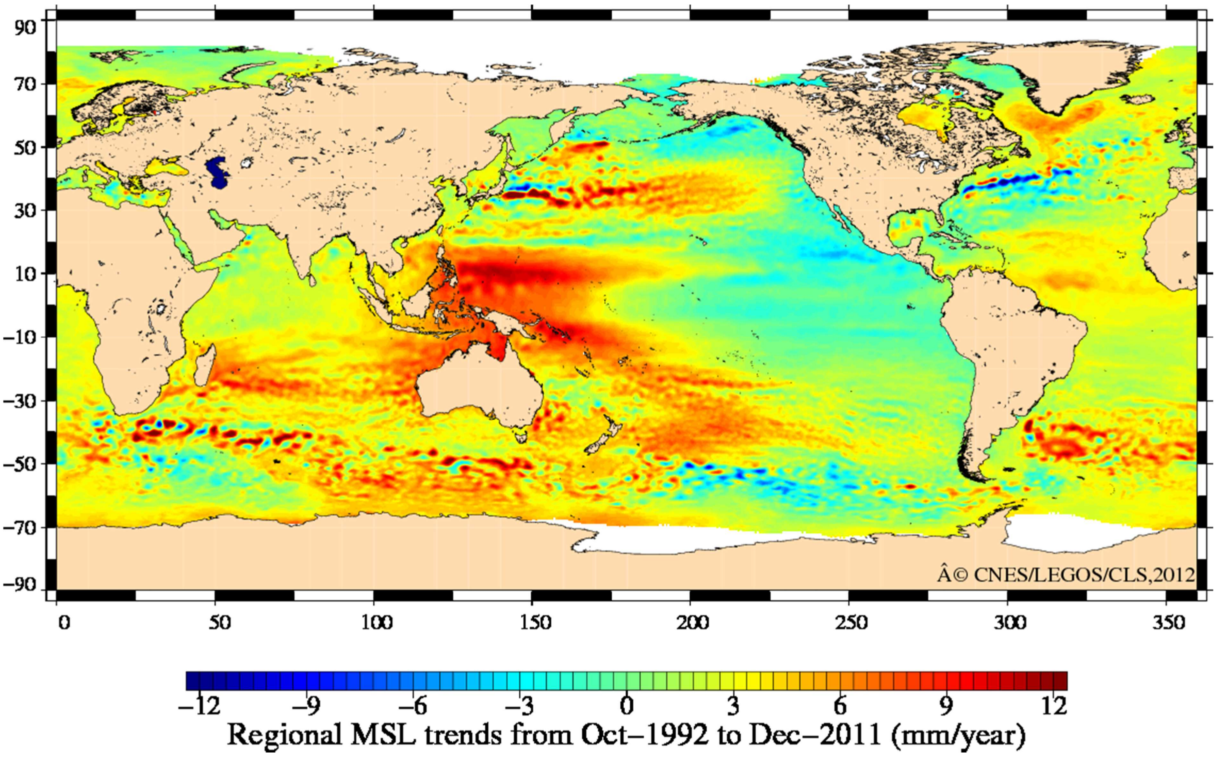

Figure 8-4: Global distribution of the rates of absolute sea-level rise between October 1992 to December 2011 as measured from satellite altimeter data – with no GIA applied. Source: http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/index.html.

These latest monitoring results indicate that the global-averaged rate of sea-level rise during the satellite era (1993 to present) has been holding at a more-or-less steady linear rise, albeit slightly higher than average rates for last century (Figure 8-3). The temporal variability is partly related to El Niño and La Niña episodes (global-average sea level rises during El Niño and falls during La Niña e.g., the 2010/11 event) and associated changes in the hydrological cycle. The spatial variability of the modern sea-level trend in the Pacific shown in Figure 8-4 is similar to the horse-shoe pattern of higher sea levels (and sea-surface temperature) around both hemispheres of the western Pacific, which is the same characteristic pattern of the Pacific-wide negative (cool) phase of the IPO which changed regimes around the turn of the century. Therefore the faster rate of rise over the satellite era partly reflects a change in atmospheric circulation patterns including a possible shift to the average ENSO state in recent decades (Power and Smith, 2007) along with the associated shift in the Pacific to the negative phase of the IPO in 1999-2000 (Hannah and Bell, 2012). In addition, the same uncertainties that affect GPS reference frames (see Section 2) also affect the satellite altimetry data.

Even extrapolating the higher “satellite-period” trend of a constant 3.1 mm/year for another 40 years would mean a sea-level rise of only ~0.2 m by 2050, relative to 1990 (lower curve of Figure 8-5). Therefore, it is clear that a substantial acceleration is now required, possibly through an ice-sheet tipping-point response, to achieve any projected rise of more than 1.2 m by 2115. The lack of such a signal in present day tide gauge data suggests that a measure of caution be taken before higher-end sea level rise scenarios be adopted in statutory plans.

At present (Figure 8-5), relative sea level change in Wellington Harbour (averaged over the 6-year period 2006–2011) is tracking along the trajectory that would lead to a sea-level rise of ~1.0 m by 2115 (which is equivalent to 0.8 m by the 2090s), although the averaging period is very short and a range of future lower or higher outcomes are possible. However, as stated, part of the recent rise in sea level at Wellington (and all around New Zealand) was due to the jump in sea level in 1999-2000, when the IPO switched regimes, and annual sea levels have since been slightly lower (Figure 8-5). Reaching the highest projections discussed in the previous section (Figure 8-2) and the higher scenarios in Figure 8-5, will require a substantial acceleration to occur soon, that is one or two orders of magnitude above the small acceleration observed in long-term global sea-level trends between 1900 and 2009 (Church & White, 2011).

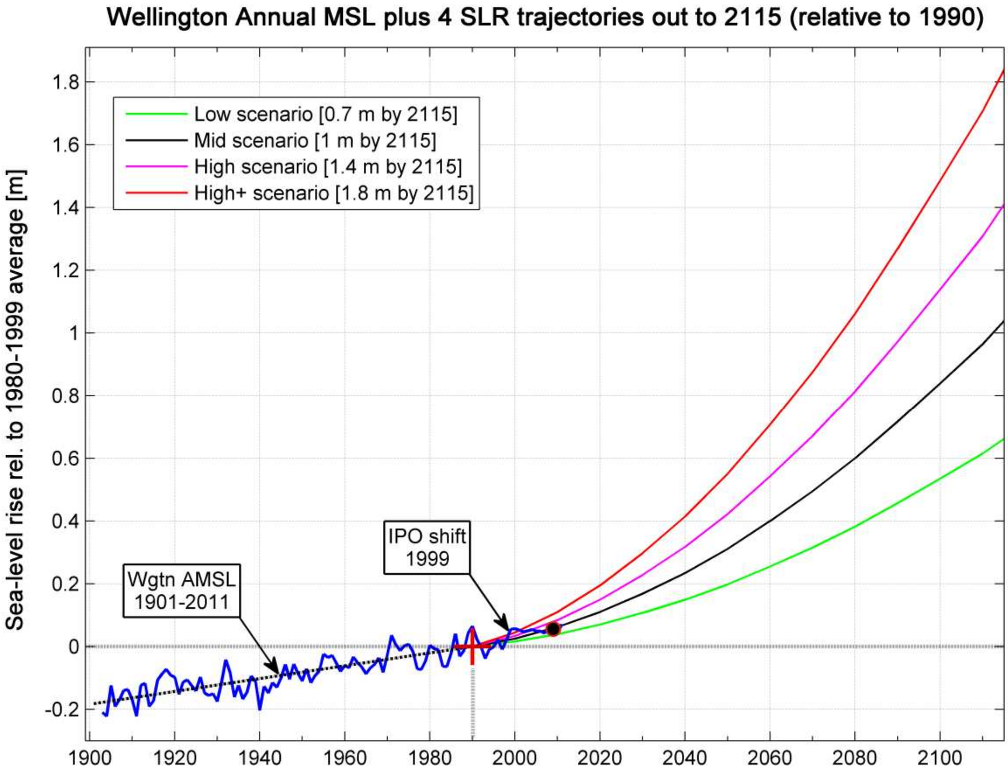

Figure 8-5: Comparison of past annual mean sea levels (AMSL) at Wellington with four credible sea-level rise scenarios relative to 1990 (red cross). Sea-level rise scenarios for comparison are benchmarked to reaching 0.7, 1, 1.4, and 1.8 m by 2115 (or 0.54, 0.85, 1.15, 1.5 m by 2100), the blue line is the annual mean sea level relative to 1990 (from 1901 to 2011), and the black dot is the 6-year average sea level for 2006–2011, centred at start of 2009.

The track being taken by recent sea-level rise in Wellington (and similarly in the other main ports of New Zealand) is also consistent to the trajectory being taken by the global-average SLR, as shown in Figure 8-6. It shows that global-average SLR from both combined tide gauge records and the satellite-altimetry record are tracking close to the upper end of the range of SLR projections published by IPCC (2007), including the ice-sheet caveat of an additional 0.1-0.2 m. The upper line for the projections in Figure 8-6 stretches out to reach 0.8 m by 2100 (Church et al. 2011). As previously mentioned, the averaging timeframe is relatively short and somewhat influenced by climate variability to be able to make robust estimates of potential magnitudes by the end of the century. However, what can be clearly stated is the absolute global sea-level rise from the global tide-gauge dataset and satellite altimetry are currently both tracking above the mid-range estimates of IPCC(2007).

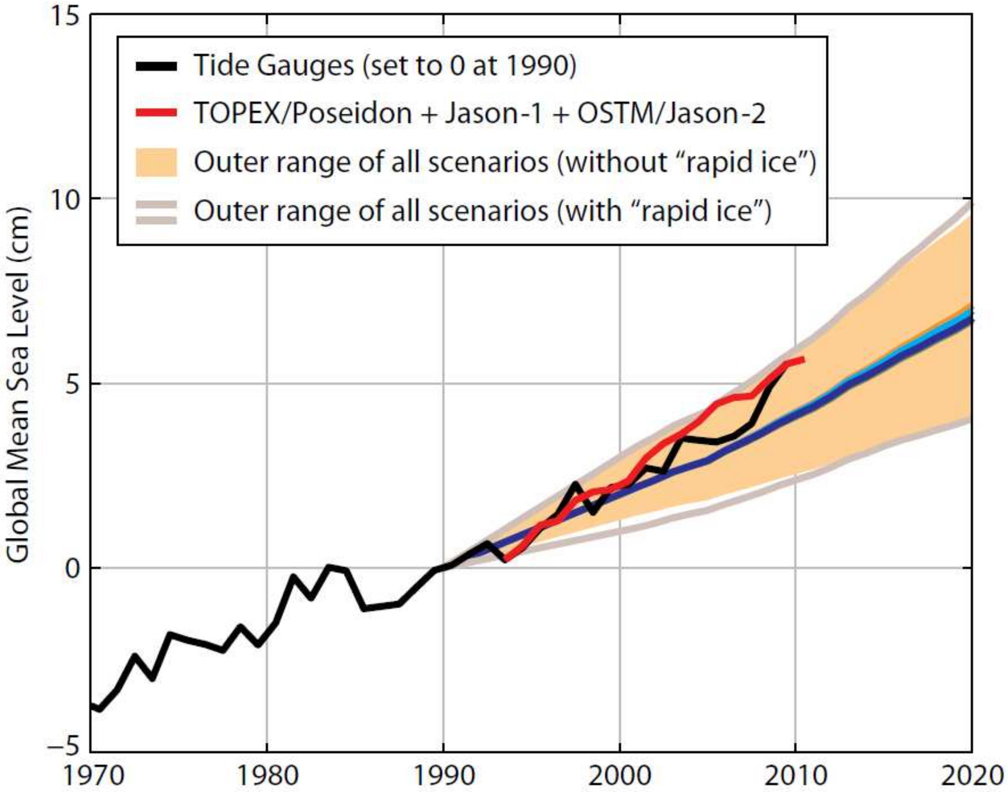

Figure 8-6: Global-averaged projections of sea level rise to 2020 (IPCC, 2007), with respect to 1990, and how recent sea level has been tracking (Church et al. 2011). The shaded region/outer light lines show the full range of projections, not including/including any more-rapid ice component. The observations of global-averaged sea level based on tide-gauge data (black) are set to zero at the start of the projections in 1990, and the satellite altimeter data (red) are set equal to the tide-gauge data at the start of the record in 1993.

8.5.2 Any acceleration in sea-level trends?

Acceleration in sea-level rise and its detection is a critical and much-debated topic, as it has major implications for bounding the magnitude of sea-level rise reached by the end of this century. Detection of accelerating trends in sea level is very dependent on the timescale being considered and the starting point of any analysis and the methodology used (e.g., see Rahmstorf & Vermeer, 2011; Baart et al. 2012b).

Based on a few long tide-gauge records from Europe and New York and proxy records from salt marshes, sea levels accelerated during the mid to late 1800s through to the early 1900s, from very slow rates of rise in the preceding centuries, to average global rates in the 20th century of around 1.7–1.8 mm/yr – an increase in rate of around 2–6 times (Mitchum et al. 2010; Woodworth et al. 2011). One of the proxy marsh studies was undertaken in Otago by Gehrels et al. (2008) who found sea level accelerated from a slow rise (0.3 ± 0.3 mm/yr) between AD 1500 to end of the 1800s, increasing during the 20th century to 2.8 ± 0.5 mm/yr (the latter since adjusted to ~2.0 mm/yr using the correct local vertical datum). There is general agreement from these and other studies that the most rapid changes in the rate of sea-level rise in the modern historical era occurred during the latter half of the 1800s.

For the modern instrumented era post-1880, Church & White (2011) obtained a small, but statistically-significant global-average acceleration of sea level over the entire period between 1880 and 2009 of 0.009 ± 0.003 mm/year^2, by fitting a quadratic to the sea-level time series starting at 1880 (Figure 8-7). Other studies have focused more on accelerations at shorter multi-decade timescales in the 20th century. Most long-term sea-level datasets (which make up the global-average trend) originate from either Europe or North America, with both the sets displaying evidence for a positive acceleration, or 'inflexion', around 1920–1930 and a negative one around 1960 (Woodworth et al. 2009). These inflexions are the main contributors to reported accelerations since the late 19th century (e.g., Church & White, 2006, 2011) and to short-term decelerations during the mid- to late 20th century (e.g., Holgate, 2007). A similar outcome was obtained by Cole (2011) using the New Zealand sea-level records. Commencing any analysis of accelerations during either of these inflexions can profoundly alter the outcome. However, these characteristic features are not always found in records from other parts of the world, although their presence in Australian and the Auckland records was confirmed by Woodworth et al. (2009).

The critical and hotly-debated issue for the present is whether the rate of change in sea levels over the past several decades is increasing or remaining at a linear rate of rise, as it has implications for the magnitude of future sea-level projections.

Merrifield et al. (2009) extracted global-average accelerations of 0.09 mm/yr^2 since the late 1970s increasing to 0.12 mm/yr^2 since1990, but cautioned that these accelerations are not significantly different from zero, given the short analysis periods. Most of this apparent acceleration is accounted for by changes in the tropical and southern oceans (Merrifield et al. 2009). However, this latter period, which largely covers the satellite altimetry era (1993 onwards), has also coincided with a regime shift in the Inter-decadal Pacific Oscillation in 1998-2000, which increased short-term rates of sea-level change in New Zealand (Hannah & Bell, 2012). In the Tropical Pacific, Meyssignac et al. (2012) showed that sea-level trend fluctuations are still dominated by the internal natural variability of the ocean-atmosphere coupled system. While their analysis could not rule out any influence of anthropogenic forcing, they concluded that the latter effects on regional sea-level patterns are still hardly detectable.

In the past year, several papers and discussion papers (e.g., Houston & Dean, 2010; Rahmstorf & Vermeer, 2011; Watson, 2011) have hotly debated the issue of whether there has been an acceleration or deceleration in sea-level rise over recent decades along with the merits or otherwise of the methods used, including start and end points of the analysis. A synthesis of the technical issues in the debate was provided by Baart et al. (2012b), focusing on the need for on-going constructive discussions on best-practice methods for determining trends and accelerations and interpretation of model forecasts, whether they be physically based or empirical.

At least two studies have been undertaken in the Australasian region (Watson, 2011; Cole; 2011) where a search has been made for any evidence of an acceleration in relative sea level rise. Both studies, using different methodologies, have concluded that no statistically-significant acceleration is able to be detected at this time, even though the overall trends at the four main ports in New Zealand have crept up with the addition of data from the recent decade 2000-2011 (Hannah & Bell, 2012). Cole (2011) found a marginally significant acceleration in the Wellington data but noted that this was quite inconsistent with the remainder of the New Zealand data and concluded that if indeed real, it was most likely a function of tectonic effects rather than an absolute sea-level signal. Indeed, presently at a global level there is no clear body of evidence from recent tide-gauge and satellite data that any significant acceleration has occurred in the rate of sea level rise (Figure 8-3). As an additional element in the debate, Holgate (2007) and Church & White (2011) found that some long-term tide gauges and a global sea-level reconstruction respectively, reveal similar short-term rates of sea-level rise during the 20th century, as the present rates of ~3 mm/yr, so it is hard to be sure the present short-term rates are exceptional.

Taken together, the overall sense in the sea-level science community is that there has been a possible but unconfirmed small acceleration in recent decades that is not statistically significant due to the “noise” in the sea-level record from natural variability (e.g., Marshall, 2012). However, if recent rates of rise, exhibited by the satellite altimetry record averaging 3.1 mm/yr, continue for the next decade or so, further acceleration in the long-term rates could soon begin to emerge as being statistically significant. A further indication of pending changes in the rate of sea-level rise comes from Rignot et al. (2011), who summarised recent accelerations in polar ice sheet loss over the last 18 years. They concluded that if present trends in ice sheet accelerations continue they could contribute around 0.56 m of sea-level rise by 2100 and become the dominant contributor to sea-level rise this century. While this sea-level rise value may not be used as a projection, given the considerable uncertainty in future acceleration of ice-sheet mass loss, it provides one indication of the potential contribution of polar ice sheets to sea level this century if the present acceleration in the ice-loss trend continues.

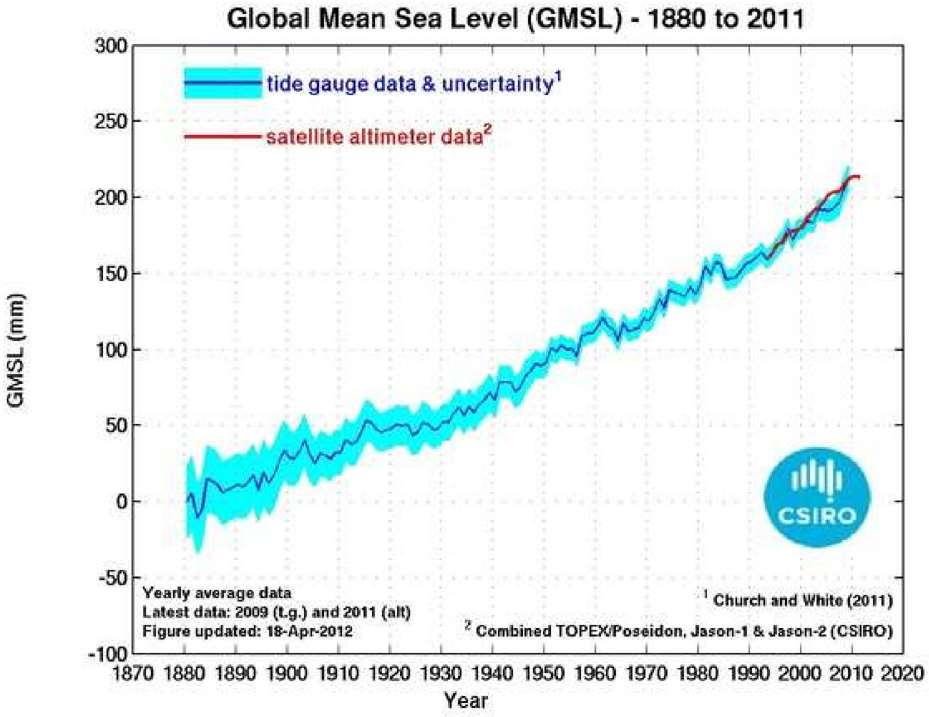

Figure 8-7: Combination of historical tide-gauge data and satellite-altimeter data to estimate global-averaged sea-level change from 1880 to 2009–2011. Source: CSIRO: http://www.cmar.csiro.au/sealevel/ .

8.5.3 Synthesis for Wellington

In summary, taking a more precautionary approach to upper-range estimates, these latest monitoring results globally and at Wellington indicate that planning benchmark sea-level rises of 0.8 m or perhaps up to 1.0 m by the 2090s are credible upper-range estimates to work with for planning coastal adaptation in Wellington. This range aligns with values adopted within planning instruments by various planning agencies in Australia, UK, Netherlands (Section 8.3) and including the MfE (2008) guidance (Section 8.2). The equivalent band of sea-level rises potentially reached later on by 2115 would be 1.0 m, or perhaps up to 1.3 m, relative to 1990 sea levels, which are between Scenarios 2 and 3 developed by CSIRO (Table 8-2). However, using these estimates, particularly for existing coastal development that is being managed adaptively in stages, needs to be strongly coupled with regular monitoring updates (similar to Figure 8-5) and reviews of timing of staged or incremental adaptation plans (which could result in slowing down or speeding up of such plans depending how sea level changes).

Based on historical rates of sea-level rise in Wellington (Section 7), a slightly lower range of 0.5 to 1.0 m by 2100 is also a credible range, supported by similar sea levels reached during the mid-Holocene climatic optimum when temperatures were warmer by 2℃ or more than at present (Section 3). The same range of 0.5 to 1.0 m sea level rise by 2100 was synthesized as being credible by the recent Australian Climate Commission synthesis (Department of Climate Change & Energy Efficiency, 2011), in the light of the latest downward revision of estimates for the recent loss of ice-sheet mass (Wu et al. 2010; Bromwich & Nicolas, 2010). However, it is now generally accepted that ice sheet mass loss will accelerate this century (e.g., Rignot et al. 2011). Consequently, there is now a reasonable chance that the lower estimate of 0.5 m will be exceeded by 2100**.** These figures take no account of any changes that may occur due to regional tectonic effects due either to SSEs or earthquakes.

To work around this uncertainty in the upper-range of sea-level projections, an adaptive management approach is recommended, where practicable, for areas of existing development. Timing of incremental staging of adaptation options should start with credible rates of sea-level rise more likely to be attained in the planning timeframe and periodically adjusting adaptation plans according to future monitoring of Wellington sea level and reviews, including assessment of on-going tectonic effects such as slow-slip events. For greenfield developments, higher plausible sea levels towards the top end of current projections should be adopted, given the permanency of such developments and factoring in that sea level will continue to rise for at least a few centuries (Figure 8-1). The NZCPS also requires new or redevelopment to avoid increasing the risks of coastal hazards, along with adopting a precautionary approach.

1. Relative SLR at Wellington is presently tracking towards a SLR of 0.8 m by 2090s or ~1.0 m by 2115 and is similar to tracking of the global-mean (relative to 1980–99 sea levels), although based on a short sea-level average at Wellington from 2006–2011

2. This SLR is the likely best estimate at present for the Wellington region. There is a reasonable chance that a lower estimate of 0.5 m by 2090s (0.7 m by 2115) will be exceeded, or a plausible upper-range estimate of 1.0 m by the 2090s (1.3 m by 2115) could be reached.

3. Similar SLR values (0.8 to 1.0 m by 2100 or 2110) have been adopted for planning purposes by Australian States and in the UK

4. There is presently no clear body of evidence that there has been any recent statistically-significant acceleration in global sea-level rise, despite the recent satellite record averaging around 3 mm/yr since 1993

5. A possible additional component of relative sea-level may be required for future projections in the Wellington region if tectonic subsidence continues

6. Risk/vulnerability assessments should take into account that a SLR above 1 m by 2090s (or >1.3 m by 2115) cannot be ruled out, particularly if polar ice-sheet loss continues to accelerate

9 Synthesis: Planning for sea-level rise in Wellington

9.1 Policy and land-use planning context

Under Part II matters of the RMA [s. 7(i)], resource-management decision makers shall have particular regard to the effects of climate change. Both regional and territorial authorities have as one of their functions, the control of any actual or potential effects of the use, development or protection of land, including for the purpose of avoidance or mitigation of natural hazards [s. 30 & 31].

The 2010 NZ Coastal Policy Statement (NZCPS) requires consideration of climate change effects in Policies 3 (precautionary approach), 24, 25, 27 (hazards and coastal development) covering at least a 100-year planning horizon. Given that the NZCPS specifies a minimum timeframe to be considered (at least 100 years), a nominal planning horizon out to 2115 has been adopted for this report (see previous Section).

Adaptation to climate change, particularly sea-level rise and associated effects on coastal hazards, will require substantially different approaches depending on whether the coastal margin comprises existing urban development or is largely undeveloped land (other than for agricultural uses), that is earmarked for future development (e.g., green-fields). These different approaches are recognised in Objective 5 of the NZCPS.

Existing coastal development including infrastructure will require incremental or staged plans to adapt to rising sea levels to keep hazard risk to tolerable levels until a point eventually when managed retreat becomes the only sustainable option for buildings or infrastructure. This situation pertains to most of the urbanised or developed coastal fringes of the Wellington Region. In contrast, risk avoidance is promoted by the NZCPS (Objective 5 and Policy 25) for green-field developments such as new subdivisions, backed up by a need to take a precautionary approach to cover uncertainties in the effects of climate change (Policy 3).

Where a reclamation is considered a suitable use of the coastal marine area, its form and design should have particular regard to the potential effects on the site of climate change, including sea-level rise, over no less than 100 years (Policy 10).

9.2 Principles for sea-level rise guidance

Rather than adopt a single sea-level rise value for planning purposes, as undertaken by some Australian states (Section 8.3.1), it is recommended that a more flexible risk-based approach is taken that aligns with the overall thrust of the MfE guidance manual (MfE, 2008). Such an approach can also embrace a differentiation between existing and greenfield developments and maintaining a partially flexible risk-based approach for assets and buildings. One such approach is to set a default sea-level rise to be accommodated within the planning timeframe (2115 in this case) but where it can be demonstrated that the future consequences (=risk) are low, limited or can be circumvented in the future (e.g., easily relocatable) for certain asset categories, then a slightly lower sea-level rise may be accommodated. The approach used in the MfE guidance manual (MfE, 2008) is to consider the consequences of a range of SLR values and determine an appropriate SLR that might be accommodated that is commensurate with the future risk and adaptation costs, including how residual risks might be managed.

9.2.1 Existing *vs.* greenfield development

As discussed in Section 9.1 in relation to the 2010 NZCPS, a different set of guidance should be developed for existing legacy development compared with greenfield development. In relation to greenfield developments and associated new infrastructure:

- It is now well established that sea levels will continue rising for several centuries, even if the magnitude is uncertain (Figure 8-1).
- Major new development (e.g., roads or subdivisions) tends to be permanent (as distinct from a nominal design or planning life) and difficult to withdraw from or extinguish existing use rights when threaten by coastal hazards in the future.
- There is a mandate in the 2010 NZCPS for risk avoidance (Objective 5 and Policy 25) for greenfield developments such as new subdivisions, backed up by a need to take a precautionary approach to cover uncertainties in the effects of climate change (Policy 3).

Consequently, for greenfield developments, the opportunity should be taken for future generations to build in substantial resilience to sea level rise and associated coastal hazard impacts through siting lots and minimum ground, building platform and infrastructure levels to avoid foreseeable inundation and coastal erosion. Therefore a higher magnitude of sea-level rise for an extended timeframe (not just the minimum 100 years) should be considered. Depending on the future risks and potential for future adaptation, sea-level rises above 1.5 m, irrespective of the likely timeframe in which they will be attained, should be considered for new greenfield developments.

Conversely, adaptation of existing development and infrastructure requires an adaptive management approach that is integrated across different timeframes and spatial scales such as: a) <u>individual</u> buildings or assets requiring to be upgraded or re-developed; b) long-term strategic adaptation plan for the <u>entire suburb or community</u>. Setting sea-level rise values too high, particularly for individual properties or short-term fixes for infrastructure, can result in unintended mal-adaptation. This can lead to local distortions such as run-off and drainage issues for neighbouring properties (if minimum ground or road levels are set too high in relation to accommodating sea-level rise and coastal hazards), compromised landscape values (from elevated buildings in relation to minimum floor levels) and discontinuities in elevation of utility services across low-lying sections of communities.

Therefore, guidance on which sea-level rise value to adopt for existing development needs to integrate short-term requirements for upgrading buildings and assets within the confines of a long-term adaptation plan for the wider coastal community or suburb. Such integration can then flow through to appropriate planning and building requirements e.g., minimum ground levels, minimum floor levels, style of foundation, relocatability of assets, sustainable coastal hazard protection measures, and limits on existing use rights to facilitate eventual managed retreat.

9.2.2 Risk-based flexibility

While it is recognised that a single sea-level rise value is easier to understand and communicate, nevertheless some flexibility should be retained to allow a risk-based approach to be used where appropriate. For planning purposes, particularly for existing development, one suggestion is to provide a best estimate SLR from current monitoring (as provided in Section 8) to guide adaptation planning, particularly timing of incremental staging of adaptation options and update staging timeframes through regular SLR monitoring and planning/policy reviews. But also provide a range of plausible sea-level rise values, where:

a) the risk or consequences of sea-level rise on an activity can be demonstrated to be limited in time, small in magnitude or the asset can be readily relocated, then a slightly lower sea-level rise value could be applied (e.g., toilet blocks, council assets on esplanade strips (playgrounds, boat ramps, etc.), small utility buildings), or

b) applying higher sea-level rise values where future consequences are high, future adaptation options are limited, or future-proofing is needed for foundations or ground improvements of major infrastructure, such as roads that can be raised in stages.

9.2.3 Vulnerability assessments

Guidance on use of SLR values needs to also distinguish between uses in formal planning instruments and engineering quality standards (which require more rigour and should be somewhat conservative, but able to be updated regularly) and those used for vulnerability ("what if") assessments to underpin long-term strategic planning for coastal areas. Vulnerability assessments often include a range of SLR values spanning the entire plausible range, such as the range of projections in Figure 8-2 .

9.3 Sea-level guidance for the Wellington region

9.3.1 Plans and Policies

The following guidance in Box 2 on benchmark sea-level rise values are suggestions to consider in formulating objectives, policies and rules for regional and district planning instruments.

BOX 2: Suggested planning guidance on sea-level rise for Wellington region.

Planning horizon: Out to 2115 for existing development (except for interim adaptation measures to buy time for longer-term solutions)

Zero baseline sea level: Based on 1980-99 average (centred on 1990) from Wellington Harbour gauge of +0.14 m Wellington Vertical Datum–1953 (as outlined in section 5.1)

Sea-level rise guidance:
a) For existing communities and developed areas plan for a sea-level rise of at least 1.0 m by 2115 (*Note 1*). If the risk or consequences of sea-level rise on an activity can be demonstrated to be limited in time, small in magnitude or the asset can be readily relocated, then a sea-level rise equivalent to 0.7 m by 2115 (*Note 1*) could be applied. Potential examples could include small utility buildings (e.g., garage, shed) and council assets on reserve or esplanade strips (e.g., toilet blocks, playgrounds, boat ramps etc.). If the risk or consequences of sea-level rise on an activity or objective are high and/or future adaptation options are limited, then higher SLR values of 1 to 1.4 m or more should be considered. For areas of the Wellington region affected by on-going tectonic subsidence, ,an additional component may need to be added to these SLR values i.

Any activity (whether new or an upgrade) in a potentially-impacted existing coastal area should also be integrated into a strategic long-term adaptation plan for the relevant coastal suburb or community. Such a plan needs to be developed in conjunction with the local community and supported by vulnerability assessments for both coastal hazard exposure and socio-economic sustainability (see Section 9.3.2).

b) For new greenfield developments or new infrastructure projects, depending on the future risks and potential for future adaptation, sea-level rises of at least 1.5 m, irrespective of the likely timeframe (minimum of 100 years) in which they will be attained, should be considered for new greenfield developments, in conjunction with a full assessment of coastal hazard exposure (Policies 24 & 25, NZCPS). If the risk or consequences of sea-level rise on a new activity in any largely undeveloped area can be demonstrated to be small and limited in time, or an isolated asset (rather than a subdivision) can be readily relocated or retro-fitted, then a lower sea-level rise of no less than 1.0 m, as above for (a), could be cautiously applied.

New developments that could eventually be exposed to the impacts arising from mean sea levels of up to 2 m or more, should also incorporate an element of precaution and future-proofing in building requirements such as minimum floors levels, style of foundation (e.g., piles rather than poured concrete slab) and ease of retrofitting or removal to provide low-regrets adaptation options to future generations (including the co-benefits of a reduction in risk from impacts of tsunami inundation).

Coastal-hazard guidance:
Adaptation to climate change in coastal areas is not simply focused on changes in mean sea-level. Assessment of risk to coastal inundation or coastal erosion needs to incorporate the above sea-level rise values into a coastal-hazard assessment that includes appropriate storm-tide and wave extreme levels.

Note 1: From Table 8-1, the value of 0.8 m by the 2090s translates to ~1.0 m by 2115 and the rise of 0.5 m by 2090s translates to ~0.7 m by 2115.

9.3.2 Possible sea-level futures for vulnerability assessments

It is recommended that an adaptive management approach is undertaken where feasible, not only for updating sea-level rise guidance (Box 2), but also for strategic adaptation planning, particularly for existing vulnerable coastal suburbs or settlements. This can be undertaken once critical adaptation tipping points (thresholds) of sea-level rise have been assessed for each community in relation to the built environment and associated coastal protection measures (e.g., Kwadijk et al. 2010; Neumann et al. 2010; Reisinger et al. (in press), and *Pathways to Change* - Britton et al. 2011). The timing of when the stages for adaptation are implemented can be based on the same sea-level rise trajectory being used for the sea-level guidance for existing development (see cross-marked line in Figure 8-5) and updated to a revised trajectory with revised timing of stages as necessary from on-going monitoring updates of how MSL is tracking and changes needed to adaptation plans.

Box 3 outlines guidance on monitoring and reviewing how sea-level rise is tracking and a suggested range of possible sea-level futures (irrespective of timeframes when these rises may be achieved) for the purposes of undertaking strategic adaptation planning for coastal communities or suburbs supported by socio-economic vulnerability studies, asset planning, assessing the sustainability of coastal protection measures etc., to complement the SLR guidance within plans and policies (Section 9.3.1).

9.4 Recommendations

Besides the suggested separate sets sea-level rise values for planning and vulnerability ("what if") assessments, it is strongly recommended that a formal monitoring programme is put in place to track on-going relative sea-level rise in the Wellington region and assess the implications against adaptation objectives.

The monitoring should include regular monitoring updates every 5 years (e.g., similar to Figure 8-5) with more rigorous assessments every 10 years, to maintain a watch on how changing sea levels are tracking and how they may do so over the following 100 years, to better inform adaptive planning and management strategies. The assessments should include both absolute sea-level rise (at the New Zealand scale relative to the global-average trend used for projections) and local variations in relative sea levels, such as tectonic uplift or subsidence from continuous GPS records.

To complement the extensive continuous GPS network throughout the region (via the GeoNet system), it is recommended that a further sea-level gauge is maintained in the region (outside Wellington Harbour) for the purposes of monitoring long-term sea-level variability and change. The present Wellington gauge is affected at times by local tectonic movement, so a gauge elsewhere in the region should also be considered as a back-up for deriving regional relative sea-level rise e.g., Kapiti or Wairarapa coasts or Kapiti Island, given there are few coastal areas not affected to some degree by tectonic processes.

BOX 3: Plausible sea-level futures for assessing coastal vulnerability in Wellington region

Assessment horizon: Not tied to any specific timeframe ("time neutral")

Zero baseline sea level: Based on 1980-99 average (centred on 1990) from Wellington Harbour gauge of +0.14 m Wellington Vertical Datum–1953 (as outlined in section 4.1).

Plausible sea-level rise magnitudes for "what-if" assessments:
To underpin vulnerability assessments or development of strategic adaptation plans for existing coastal communities as well as monitoring the progression of sea-level rise for the Wellington region, the following four (4) sea-level rise scenarios, irrespective of timeframe, could be considered as a broad suite of plausible magnitudes of sea-level rise to work with:

Low scenario: 0.5 m **Medium scenario**: 1.0 m
High scenario: 1.5 m
High^{++} scenario: 2.0 m

Monitor & review:
A key component of any adaptive management approach to coastal adaptation is selecting a credible sea-level rise trajectory on which to base the timing for implementation of successive stages. Then over time, through monitoring sea levels in the Wellington region (*Note 2*) and monitoring progress with implementation of plans, policies and adaptation plans, undertake periodic reviews of the requirements and make any adjustments to timing of stages until the next review. If SLR has accelerated, then the next stage of the relevant adaptation plan will need to be advanced in council's long-term adaptation plans for a particular location, or vice versa, delay the implementation if sea-level rise is slower than anticipated. As shown in Figure 8-5 current sea level at Wellington is tracking at present along the 2nd-lowest trajectory (0.8 m by 2090s), taking into account that the rise due to the 1998-2000 shift in the IPO is primarily due to climate variability. Therefore in the interim, it would be reasonable to base implementation of successive adaptation stages (which are pegged to specific sea-level height thresholds or tipping points) to this sea-level trajectory that would reach ~1 m by 2115. For example, if Stage 1 of an adaptation plan needs to be implemented when mean sea level reaches 0.5 m (above the 1990 baseline), then from the 2nd lowest curve in Figure 8-5, this would indicate possible implementation around 2070.

On-going monitoring of sea level can be compared with various trajectories in a plot similar to Figure 8-5 , changing the trajectory used for timing implementation of stages as necessary.

Note 2: Relative sea-level rise should continue to be monitored and regularly assessed at Wellington Harbour and also long-term at a second site in the Region e.g., Porirua Marina, Kapiti Island to distinguish any on-going effects of local subsidence in the City from other parts of the region. This monitoring needs to be integrated more with cGPS records to determine any spatial variability in relative sea-level rise.

10 Acknowledgements

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Thanks to Iain Dawe (GWRC) for supplying updated Wellington Harbour and Porirua Marina data for 2011.

11 Glossary of abbreviations and terms

Absolute SLR	Sea-level rise measured relative to the Earth’s geocentre, usually by satellite altimeters, or adjusting for regional vertical motion measured by continuous GPS. Past and projected global-average sea-level rise are provided as absolute values.
Adaptive management	A structured, iterative process of optimal decision making in the face of uncertainty, with an aim to reducing uncertainty over time via system monitoring. In this way, decision making simultaneously maximizes one or more resource objectives and, either passively or actively, accrues information needed to improve future management [Source: Wikipedia].
cGPS	Continuous GPS. Units can be permanent at a site or deployed for a short time at regular intervals.
CD	Chart Datum at Wellington Harbour – used to set tide levels at Wellington for maritime use.
ENSO	El Niño–Southern Oscillation. The 2–4 year Pacific-wide climate cycle that gives rise to alternating La Niña and El Niño episodes.
GIA	Glacial Isostatic Adjustment. The vertical rate of rebound or subsidence of the Earth’s crust in a region following the retreat of ice loading following the last Ice Age.
GMSL	Global Mean Sea Level (as measured by satellite altimeters)
IPCC	Intergovernmental Panel on Climate Change (a UN agency tasked with regularly reviewing the impacts of global climate change).
IPO	Inter-decadal Pacific Oscillation, which affects the Pacific geo-region at cycle of 20–30 years, often accompanied by rapid regime shifts from positive to the negative phase. We are currently in a negative phase of IPO, which enhances La Niña episodes at expense of El Niño. In the Southern Hemisphere, IPO arises mainly from inter-decadal variability in ENSO but is connected to a distinct Pacific Decadal Oscillation (PDO) that affects mainly the Northern Pacific.

Low-regrets adaptation	Low-regret adaptation options are those where moderate levels of investment increase the capacity to cope with future climate risks. Typically, these involve over-specifying components in new builds or refurbishment projects. For instance, installing larger diameter drains at the time of construction or refurbishment is likely to be a relatively low-cost option compared to having to increase specification at a later date due to increases in rainfall intensity. [Source: The World Bank]
MHWS	Mean High Water Spring mark
MHWS-10	Pragmatic MHWS, defined as the level exceeded by 10% of all high tides
MfE	Ministry for the Environment
MTL	Mean Tide Level (calculated by using daily high and low waters only)
No-regrets adaptation	Adaptation options (or measures) that can be justified under all plausible future climate scenarios and even discounting anthropogenic climate change [Source: The World Bank]
NZCPS	New Zealand Coastal Policy Statement 2010 http://www.doc.govt.nz/conservation/marine-and-coastal/coastal-management/nz-coastal-policy-statement/
Relative SLR	Sea-level rise relative to the land-mass from which it is measured e.g., by a tide gauge, after adjusting for datum shifts and local wharf subsidence
SLR	Sea-level rise
SSE	Slow slip event due to slow tectonic processes
WVD-53	Wellington Vertical Datum-1953, the local vertical survey datum for the Wellington region.

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Appendix A Annual MSL values for Wellington Harbour

Annual MSL (m) for Wellington Harbour, adjusted to the pre-1945 chart datum (Figure 4-1). Note: to obtain levels relative to the present Chart Datum, add 0.32 m to these values.

1891	0.600
1892	0.622
1893	0.633
1894	–
1895	–
1896	–
1897	–
1898	–
1899	–
1900	–
1901	0.531
1903	0.515
1904	0.503
1905	0.601
1906	0.534
1907	0.555
1908	0.585
1909	0.588
1910	0.555
1911	0.503
1912	0.601
1913	0.608
1914	0.534
1915	0.552
1916	0.619
1917	0.637
1918	0.653
1919	0.634
1920	0.628
1921	0.573
1922	0.612
1923	0.619
1924	0.600
1925	0.584
1926	0.628
1927	0.577
1928	0.569
1929	0.575
1930	0.550
1931	0.610
1932	0.683
1933	0.642
1934	0.564
1935	0.601
1936	0.558
1937	0.579
1938	0.631
1939	0.613
1940	0.522
1941	0.598
1942	0.577
1943	0.610
1944	0.595
1945	0.625
1946	0.668
1947	0.621
1948	0.669
1949	0.639
1950	0.615
1951	0.654
1952	0.610
1953	0.632
1954	0.647
1955	0.701
1956	0.690
1957	0.697
1958	0.672
1959	0.646
1960	0.664
1961	0.657
1962	0.692
1963	0.673
1964	0.659
1965	0.638
1966	0.657
1967	0.668
1968	0.689
1969	0.643
1970	0.699
1971	0.761
1972	0.730
1973	0.712
1974	0.727
1975	0.733
1976	0.709
1977	0.654
1978	0.652
1979	0.679
1980	0.729
1981	0.718
1982	0.714
1983	0.662
1984	0.661
1985	0.704
1986	0.766
1987	0.694
1988	0.712
1989	0.768
1990	0.790
1991	0.749
1992	0.724
1993	0.687
1994	0.716
1995	0.724
1996	0.747
1997	0.716
1998	0.746
1999	0.780
2000	0.782
2001	0.777
2002	0.772
2003	0.775
2004	0.779
2005	0.774
2006	0.774
2007	0.767
2008	0.793
2009	0.780
2010	0.767
2011	0.796