Sea-level change and storm surges in the context of climate change

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This paper reviews the latest research in New Zealand surrounding the issues of sea-level rise and extreme sea levels in the context of global warming and variability in the Pacific-wide El Niño–Southern Oscillation (ENSO). Past records of climate, sea level (excluding tides) and sea and air temperatures have shown that they are continuously fluctuating over various long-term timescales of years, decades and centuries. This has made it very difficult to determine whether the anthropogenic effects such as increased levels of "greenhouse" gases are having an accelerating effect on global sea levels or an increased incidence of extreme storms. Over the past century, global sea level has risen by 10–25 cm, and is in line with the rise in relative sea level at New Zealand's main ports of +1.7 mm yr $^{-1}$. What has become very clear is the need to better understand interannual (year-to-year) and decadal variability in sea-level, as these larger signals of the order of 5–15 cm in annual-mean sea level have a significant "flow-on" effect on the long-term trend in sea level. The paper describes sea level variability in northern New Zealand—both long- and short-term—involved in assessing the regional trends in sea level. The paper also discusses the relative contributions of tides, barometric pressure and wind set-up in causing extreme sea levels during storm surges. Some recent research also looked at a related question—Is there any sign of increased storminess, and hence storm surge, in northern New Zealand due to climate change? The paper concludes that, while no one can be completely sure how sea-level and the degree of storminess will respond in the near future, what is clear is that interannual and decadal variability in sea level is inextricably linked with Pacific-wide ENSO response and longer inter-decadal shifts in the Pacific climate regime, such as the latest shift in 1976.

Keywords: *sea-level rise — storm surge — climate change — El Niño–Southern Oscillation — tides*

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1. Introduction

Knowledge of rising and extreme sea levels is very important for engineers and planners, because coastal developments, such as ports, marinas, subdivisions and coastal protection works, are invariably controversial. A number of regional councils and territorial local authorities now have procedures within coastal or land zoning plans which explicitly require sea-level rise to be taken into account when designing structures or have been incorporated into building floor levels for new coastal subdivisions. Therefore, questions about the effect of long-term rise in sea level and the likelihood of extreme sea levels always arise during the course of any coastal development project. Rising sea level and shifts in the frequency or intensity of storms have important socio-economic and environmental implications for the long-term stability of New Zealand's long 11 000 km coastline, particularly populated areas adjacent to the coastal margin. Even more at risk are some of our Pacific Island neighbours. Scientists studying climate change are also concerned with global sea-level rise as a means of calibrating ocean-climate models to improve prediction of the effects of global warming.

Various comprehensive analyses of worldwide sea-level records have demonstrated that over the past century eustatic (or global) sea level has been rising at a rate of +1.8 mm yr $^{-1}$ with a range of uncertainty of 1–2.5 mm yr $^{-1}$ (1)(2)(3). Further, there has been no compelling evidence of any acceleration in sea-level rise since the 1850s (4), when major harbours in Europe first began to install tide gauges (5). However, placed in a wider historical context of the past two millennia, it appears that the 0.1–0.25 m rise in sea level last century represents a comparatively recent acceleration, interpreted as the restoration of sea level following the drop caused by the Little Ice Age from AD 1500 to 1850 (1)(2)(6).

An analysis by Hannah (7) of sea-level trends from 1900 to 1988 from tide-gauge data at New Zealand's four main ports (Auckland, Wellington, Lyttelton, Dunedin) produced similar rates to the global trend with an average

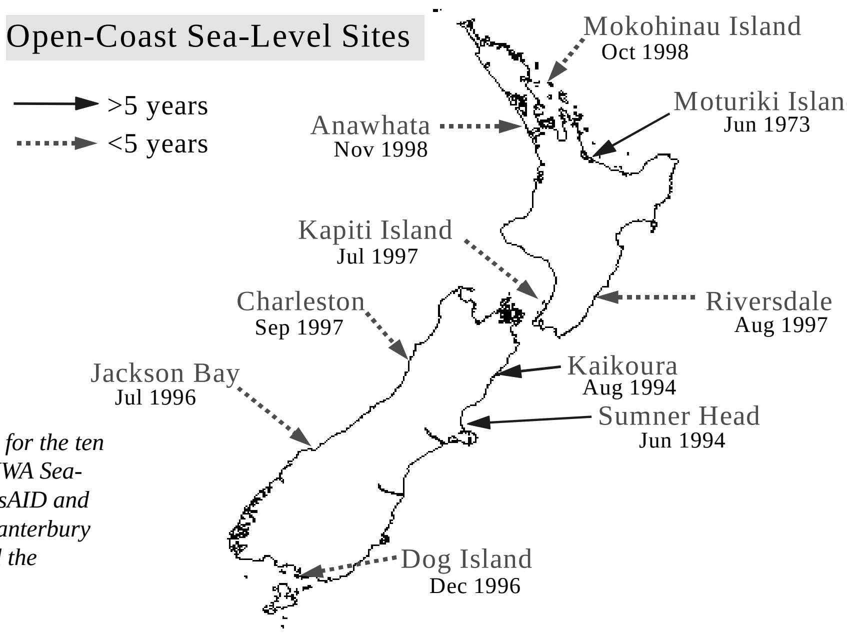

FIGURE 1: Locations and start dates for the ten open-coast gauges constituting the NIWA Sea-level Network (in association with AusAID and National Tidal Facility (Australia), Canterbury and Auckland Regional Councils, and the University of Canterbury).

rise of +1.7 mm yr^{-1} (range=1.3–2.3 mm yr^{-1}) and no apparent acceleration.

It became clear from these analyses of worldwide datasets in the late 1980s and early 1990s that, to proceed any further, considerable effort was needed to improve our understanding of interannual (year-to-year) and decadal variability in sea level that masks the underlying trend in sea level (4). Interannual and decadal fluctuations in annual-mean sea level are of the order 50–150 mm, and therefore are problematic in finding a reliable estimate of a much smaller trend that is of the order 20 mm per decade in relatively short tide-gauge records. These fluctuations are caused by slowly varying changes in wind patterns, sea temperature and oceanic circulation at seasonal to decadal timescales. Recent analyses of sea-level data from northern New Zealand have highlighted the important role that El Niño–Southern Oscillation (ENSO) plays in causing interannual fluctuations and the “flow-on” effect it has on sea-level rise [(8)–(10)]. However making progress on understanding low-frequency variability in sea level around New Zealand has been greatly hampered by patchy records from the more-sheltered main ports and a lack of long-term sea-level gauges on the open coast (11). The only long term open-coast recorder is located at Moturiki Island (near Mt Maunganui), which has produced good quality data since mid-1973 (i.e. a 26-year record).

From an international perspective, extreme sea levels in New Zealand are not a major hazard compared with equatorial regions such as the Bay of Bengal and the Gulf of Mexico. Nonetheless, storm surges can and do cause coastal flooding (e.g. Thames) and exacerbate coastal erosion around New Zealand. Storm surges, where the sea level is elevated well above the expected tide level, are produced from combined responses to: low atmospheric pressure; wind stress; and continental-trapped waves that have propagated along the coast from an adjacent region. At the shoreline where the impact is realised, additional contributions to the elevated sea level (storm surge) arise from wave set-up within the surf zone and wave run-up at the shoreline. Tsunami, although not considered here, are a specialised case of extreme sea levels created locally or remotely by earthquakes that cause a rupture of the seafloor or trigger a submarine landslide or from submarine or subaerial volcanoes (12).

This paper reviews the state of play on sea-level rise and extreme sea levels caused by storm surges. Case studies are drawn from analyses by Hannah (7) of the long Port of Auckland record (1899-1988) and recent studies [(8)–(11),(13)–(15)] of the comparatively shorter records from Moturiki Island (Fig. 1), Port of Tauranga, Port of Taranaki and a new NIWA recorder at Anawhata (Fig. 1).

2. Sea-level variability and trends

2.1 Interannual (year-to-year) fluctuations

A critical aspect of understanding trends in sea level is a knowledge of the cause and effect of interannual and decadal fluctuations or “cycles” in sea level records. Most of the research to date on interannual fluctuations in mean sea level (MSL) around New Zealand has been carried out on the 26-year record from Moturiki Island (Fig. 1). The key finding has been the important role of ENSO in causing interannual fluctuations in sea level. The strength of an ENSO episode (El Niño or La Niña) is represented by an index called the Southern Oscillation Index (SOI), which is based on the standard deviation of the normalised pressure difference between Darwin and Tahiti. SOI usually varies between –4 and +4, with negative values during El Niño events and positive values during La Niña events. Because these quasi-periodic fluctuations vary in both the magnitude and the timescale for each full cycle, a specialised analysis using a wavelet transform was necessary rather than the more traditional Fourier spectral analysis (9)(10). The wavelet method used to present the results (Fig. 2) only highlights signals of specific timescales (in months) for particular portions of the record that are significant at the 95% confidence level.

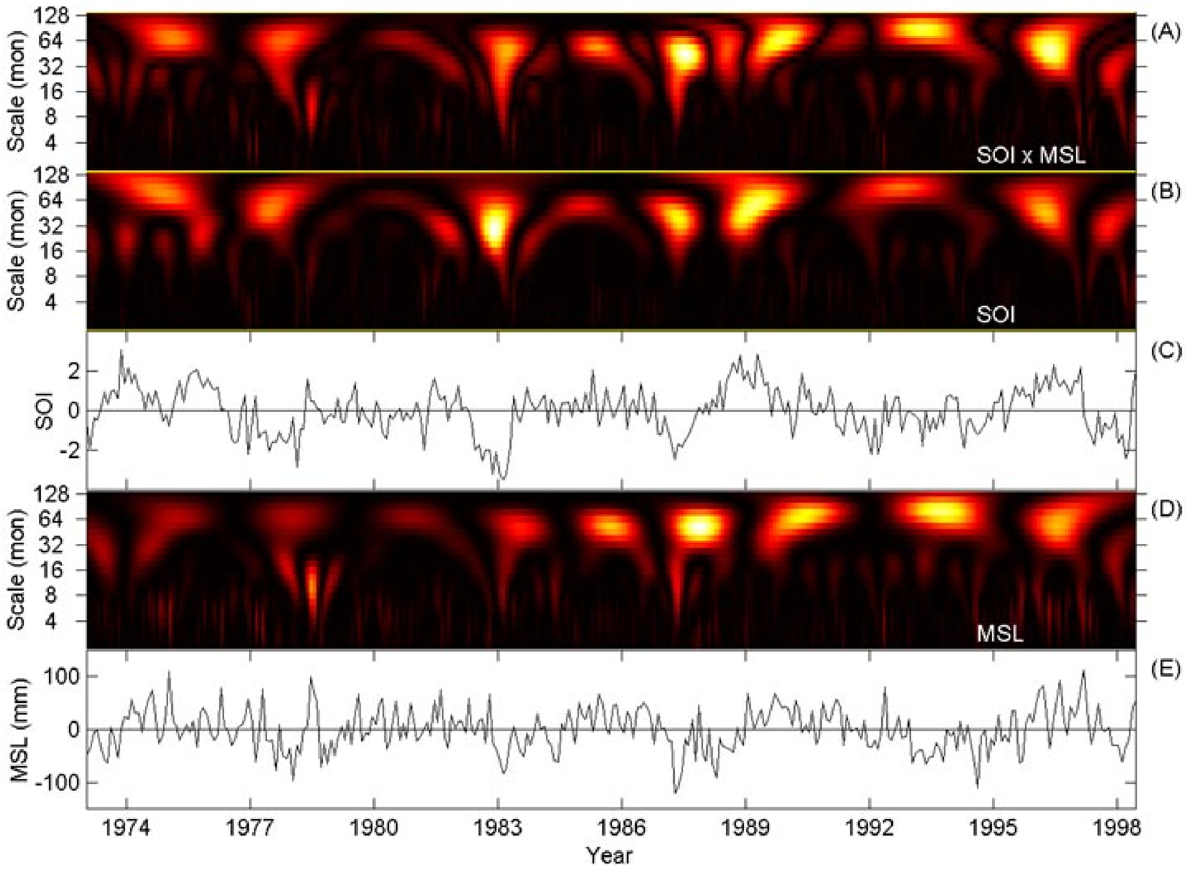

FIGURE 2: Comparison of monthly MSL from Moturiki with SOI: (A) wavelet cross-power between MSL and SOI, (B) SOI wavelet power (C) SOI time series, (D) MSL wavelet power, and (E) MSL time series. [Bright areas within the wavelet power spectrum highlight the timescales (in months) and the times during the record when the signal was significant at the 95% level.]

The monthly-mean values of MSL at Moturiki were computed from measurements at 15-minute intervals, from which the tides and the mean annual cycle were removed. The results of the wavelet analysis of the detrended Moturiki sea-level record and its relationship with the Southern Oscillation Index (SOI) are summarised in five plots in Fig. 2. The lowest two plots (D,E) are the times series of MSL for Moturiki and the corresponding wavelet power contour map highlighting timescales that are significant. The next two (B,C) are the time series of SOI and the corresponding wavelet power contour map. The top plot (A) shows the cross-product of the wavelet coefficients for both MSL and SOI. It shows bright patches where MSL and SOI are significantly correlated, but dark patches where they are not.

Most of the variability in SOI occurred at timescales between 16 and 64 months (~1½ to 5 years). These timescales coincide with the range of cycle times for the ENSO system that dominates oceanic and climatic responses in the Pacific. Sea level (MSL) on the other hand varies at somewhat longer timescales, mostly between 32 and 128 months (~2½ to 10 years).

Over the 25-year period (1973–98), interannual variability in monthly sea level at Moturiki (Fig. 2E) occurred within a total range of ±115 mm, which is markedly larger than the amplitude of ±37 mm for the mean annual cycle (8). The longer 50-year Port of Auckland record from 1947–97 exhibited an even larger range of variability of ±150 mm. These results highlight the extent of interannual and decadal variability in monthly sea level in northern New Zealand (up to a range of 0.3 m) and therefore the heightened potential for coastal erosion if higher than average monthly sea levels coincide with storm events and high tides. In particular for the northern coast, this is more likely to happen during La Niña episodes as described below.

A casual comparison of MSL (Fig. 2E) and SOI (Fig. 2C) reveals that during strong ENSO events, La Niña episodes (positive SOI) were accompanied by a rise in MSL and El Niño (negative SOI) by a fall in MSL, often lagged by a few months (13). This pattern of positive SOI being accompanied by a rise in MSL and vice versa a fall in MSL for negative SOI, is evident across the entire time series for both the Port of Auckland and Moturiki (10)(13). However, there are some changes in the intensity of this co-relationship (as represented by the brightness in Fig. 2A) for different decades. In particular, since the large 1982/83 El Niño event, there has been a continuing and consistent relationship between MSL and SOI. The striking feature of the last two decades has been the persistence of El Niño events, which has had a “flow-on” effect on the trend in sea-level rise (discussed in the next section). The entire 100-year Port of Auckland dataset also revealed earlier periods every few decades where the

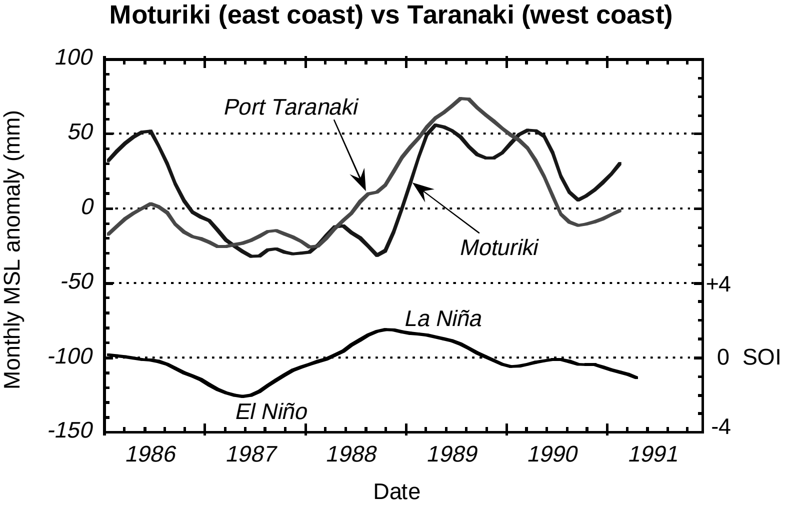

FIGURE 3: Comparison of monthly MSL from Moturiki (east coast) and the Port of Taranaki (west coast) for the 5-year period 1986–1990 showing depressed MSL during the 1986/87 El Niño and elevated MSL during the 1988/89 La Niña (with MSL lagging by around 6-8 months).

cross-correlation of MSL with SOI was significant, e.g. 1910s, early 1940s, early 1950s, and around 1970 (10).

A comparison of six years of sea-level data from Port Taranaki (west coast of the North Island) with Moturiki (Fig. 3) has shown that a similar ENSO response in monthly sea level occurs along both the west and east coasts of the upper North Island. This implies that interannual fluctuations in sea level, as a result of the effects of El Niño–Southern Oscillation on sea temperatures, winds and oceanic currents, occur over a wide region around New Zealand. The extent of this effect in the South Island awaits the collection of longer open-coast sea level records but early results from Canterbury recorders at Sumner and Kaikoura (see Fig. 1 for locations) indicate a similar interannual response of sea level to ENSO.

2.2 Inter-decadal fluctuations and sea-level rise

The annual MSL for the Port of Auckland since 1899 is shown in Fig. 4, and is largely based on data from Hannah (7). Fig. 4 also contains the time series of annual-mean SOI. The trend in relative sea level over the almost 100 year record is a linear rise of 1.3 mm yr^{-1}, which falls within the 1–2.5 mm yr^{-1} range for the global sea-level rise this century.

The two striking features of the long-term sea-level record in Fig. 4 are the large inter-decadal oscillations between 1930 and 1970 and the apparent levelling off in sea level rise since the late 1970s (shown by the bolder line type). The large inter-decadal fluctuations, with ranges of 100–150 mm, coincided with a period of 40 years up until the mid 1970s when the rise in sea level appeared to accelerate. For example, up until 1976 the linear rise in sea level was 1.7 mm yr^{-1}. During this period, wavelet analysis (10) showed significant correlation between MSL and SOI for those periods of the record when the largest oscillations occurred, e.g. early 1940s, 1950s and early 1970s (Fig. 4). Most likely there were other contributing climatic and oceanic factors, besides a heightened ENSO response, which also contributed to this behaviour.

More intriguing is the slower sea-level rise during the past 2 decades since 1976 during a period that also exhibited a consistent and highly significant relationship between MSL and SOI. This enhanced relationship explains the apparent easing in sea-level rise, stemming from the unusual preponderance of El Niño episodes (negative SOI) over La Niña episodes since the late 1970s, emphasised by the bolder linetype for SOI in Fig. 4. This extended period of El Niño episodes, including the most persistent event this century (1990–95), has contributed to a lower than expected rise in relative sea level, because around New Zealand, monthly/annual sea level is depressed lower than normal during El Niño episodes.

The impacts of ENSO on sea level are most pronounced within about 1000 km of the Equator. This occurs because the major changes in sea-surface temperature, the depth to the thermocline, and circulation strength occur mostly along the Equator. However recent work by northern hemisphere oceanographers and climatologists has uncovered a complex inter-decadal oscillation in the climate regime of the mid-latitudes of the North Pacific (16)(17), usually referred to us the Inter-decadal Pacific Oscillation (IPO). It seems that penta-decadal (50 year) cycles and bi-decadal (20 year) cycles apparently synchronise or phase-lock with one another, providing climatic regimes that last 20–30 years with associated rapid transitions (17). Data from the Southern Hemisphere are sparse, but recent TOPEX/Poseidon satellite observations of temperature and sea-surface height anomalies in the Pacific Ocean, and variability in New Zealand climate variables (18) and coastal sea levels (10), suggest that the mid-latitudes in the Southern Hemisphere may also show a strong response to the IPO. The last climatic regime shift or phase change in the IPO occurred in the mid 1970s coinciding with the start of persistent and enhanced El Niño episodes. The IPO seems to accentuate or curtail the effect of El Niño and La Niña events depending on its phase. Prior to the mid 1970s, the previous switch in the Inter-decadal Pacific Oscillation to a "cool" phase occurred in 1947–48, followed by a period of relatively rapid rise in sea level at Auckland (Fig. 4).

The resulting almost static trend in MSL at Auckland and Moturiki over the last 25 years (1973–98), as a result of the unusually persistent ENSO behaviour, completely

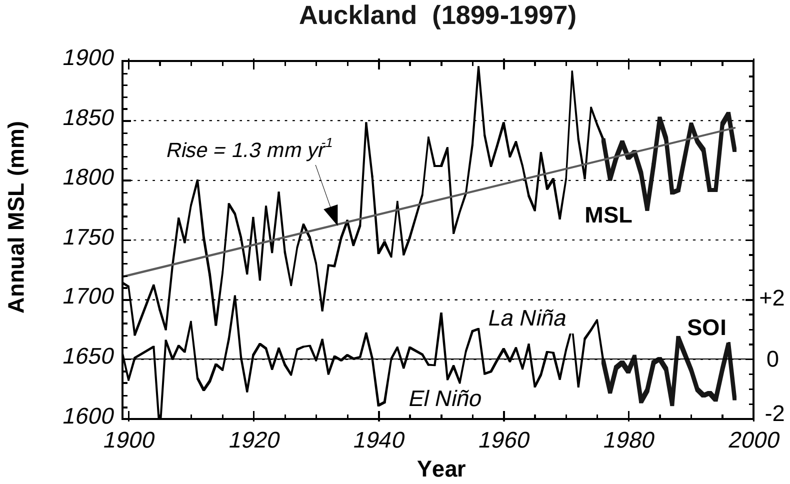

FIGURE 4: Annual MSL for Port of Auckland and annual SOI, showing linear trend in sea-level rise. Bolder linetype emphasises the recent period since 1976 of unusually persistent El Niño events.

masks the ongoing global rise in sea level. The next few years should see another climate regime shift to another "cool" phase (17), which would cause regional sea levels to rise more rapidly, similar to the 1950s. This confounding behaviour of interdecadal variability in sea level and its complex link with ENSO effects (including sea-surface temperature) highlights the problem in attempting to isolate any rise in sea level, due to climate change, over even medium-term periods of 20–30 years. It also clearly demonstrates the need to better understand very low frequency variability in sea levels around New Zealand, and their response to climatic variability, in order to place regional sea-level trends into a global context.

2.3 Sea-level projections

Questions that come to mind are: What is causing the linear rise in global sea level over the past century?; and, What are the projections for sea-level rise?

These are some of the questions being addressed by the Intergovernmental Panel on Climate Change (IPCC), established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). The IPCC is charged with assessing the most up to date scientific, technical and socio-economic research in climate change, including sea-level rise. The IPCC produced major assessment reports in 1990 and 1995, and their Third Assessment Report is scheduled for completion in March 2001. The forthcoming IPCC Third Assessment Report is unlikely to suggest any further reductions in projections for sea-level rise[1]. The 1995 Report contains model projections for increases in global sea level for various "greenhouse" gas (e.g. CO_2) emission scenarios and climate factors (2).

With respect to the past century, the 10–25 cm rise in global mean sea level has been due largely to a concurrent increase in global temperature since the end of the Little Ice Age, forced mainly by changes in solar input and a small warming effect due to ozone depletion in the stratosphere (6). The possible climate-related factors contributing to this rise include thermal expansion of the ocean and melting of glaciers, small ice caps and to a lesser extent, the large Greenland and Antarctic ice sheets (2). By thickening the Earth's atmosphere and trapping heat at the surface, "greenhouse" gases have helped melt large tracts of ice caps and alpine glaciers, especially in the Himalayan Mountains where glaciers are retreating by 30 m per year (19). Changes in surface water and groundwater storage may also have affected sea level, e.g. reduction in wetlands and groundwater extraction.

How might sea level change in the future? Projected sea-level rises for three different greenhouse gas emission scenarios in combination with climate factors that cover the mid-range and upper and lower limits are listed in Table 1A. For the mid-range emissions scenario IS92a and moderate change in climate factors, the "best estimate" is that global sea level will rise by 20 cm by the year 2050 and 49 cm by the year 2100 (with the range of uncertainties listed in Table 1B). The lowest projections (IS92c) are similar to sea-level rise continuing at present rates measured around New Zealand last century (7). These values are of the same order of magnitude as the variability in the mean level of the sea at seasonal to inter-decadal timescales.

The 1995 IPCC estimates are lower than those presented in the earlier 1990 IPCC report, due primarily to lower estimates of global *temperature* change which drive the projections of sea-level rise. The 1995 "best estimate" projections amount to an accelerating rate of rise in sea level relative to 1995 levels (Table 1B). At this stage, sea-level records from coastal and port gauges (e.g. Fig. 4) show no evidence yet of a statistically significant acceleration in sea-level rise (1)(4).

Explicitly or implicitly, one must convert a scenario into a probability estimate before one can decide whether the risk warrants a particular action. A thorough analysis of the risk was undertaken by the US Environmental Protection Agency, using computer models employed for previous IPCC assessments as well as subjective assessments of twenty climate and glaciology scientists about the values for the various model coefficients (26). The procedure isolates the ongoing <u>regional</u> trend in sea-level rise from a normalised projection of <u>global</u> rise (due to the

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[1] From the IPCC Data Distribution Centre web site: http://ipcc-ddc.cru.uea.ac.uk/

TABLE 1A: Revised 1995 IPCC projections in sea-level rise for the years 2050 and 2100 for three different greenhouse gas emission scenarios (IS92x) and climate factors (2), compared with an ongoing average linear rise from last century.

Scenario	Climate factors	2050	2100
Linear NZ trend continues (+1.7 mm yr^{-1})	Climate trend over the 1900s continues	9 cm	17 cm
IS92e/high	High ice melt +4.5°C climate sensitivity	39 cm	94 cm
IS92a/**mid**	Moderate ice melt +2.5°C sensitivity	20 cm	49 cm
IS92c/low	Low ice melt +1.5°C climate sensitivity	7 cm	13 cm

TABLE 1B: Revised 1995 IPCC projections in sea-level rise throughout the next 100 years based on the "Best Estimate" scenario IS92a.

Year	Sea-level rise cm	Mean rate of rise mm yr^{-1}	Range of uncertainty
2030	10	2.5 [1990–2030]	(5–21 cm)
2050	20	5 [2030–2050]	(8–38 cm)
2070	31	5.5 [2050–2070]	(11–55 cm)
2100	49	6 [2070–2100]	(20–86 cm)

TABLE 2: Projected sea-level rise (SLR) for New Zealand for two probabilities of exceedance based on the approach of assessing the risk associated with regional sea-level rise (26).

Year	**50% chance that SLR will reach**	**10% chance that SLR will reach**
2025	11 cm	18 cm
2050	20 cm	33 cm
2070	31 cm	50 cm
2100	45 cm	74 cm

greenhouse effect). The latter estimates the extent to which future sea-level rise may exceed that which would have occurred if current trends simply continued. Table 2 gives the projected regional sea-level rise for New Zealand during the present century associated with two probabilities (50% chance and a smaller 10% chance) based on the current regional trend of +1.7 mm yr^{-1} combined with the projected contribution from the greenhouse effect.

Finally, the IPCC recognise that changes in future sea level will exhibit regional variations and will not occur uniformly around the globe (2). This poses the question as to the usefulness of a single value of a mean global rise in sea level (20). Some of the difficulties with such an approach are:

- the heavy bias in the number and longevity of sea-level gauge records in the northern hemisphere compared with the desolate southern hemisphere;
- wide global variations in the post-glacial rebound of the Earth's crust following the last Ice Age *c*.7000 years ago, e.g. relative sea level is falling in parts of Scandinavia;
- for any particular region or island, the critical socio-economic impact is the relative sea-level rise (relative to the landmass) rather than a global mean sea-level rise. However the global mean does serve a useful function as an index of overall global climate change;
- the possibility that warming and ice melt may be different between the two hemispheres.

Factors which will, and have already, affected the relative sea-level rise around New Zealand are regionally coherent changes in sea surface topography resulting from interannual and decadal fluctuations in atmospheric pressure, wind patterns, oceanic currents and sea temperatures together with small vertical shifts in the land mass. Research is currently in progress to tie-in high quality sea-level gauges around the world (including New Zealand– see Fig. 1) with satellite monitoring of the ocean surface through missions such as TOPEX/Poseidon and JASON (21), and GPS satellite positioning of the absolute vertical movements of sea-level gauges (Prof. J. Hannah, Univ. of Otago, pers. comm.). These approaches will permit the separation of vertical land movements from changes on ocean height thus providing a more accurate determination of absolute sea-level rise, better spatial information on interannual and inter-decadal fluctuations and a quicker evaluation of any impending acceleration in rising sea levels.

3. Extreme sea levels

The most common natural hazard for coastal areas worldwide is inundation associated with storm surges. They may be defined as a temporary rise of mean sea level along a coast, over a few hours or days, due to the effects of low atmospheric pressure and sea-level gradients set-up by strong winds. Trends in extreme sea levels, such as produced by storm surges and accompanying waves, are of concern globally as well as in New Zealand because of the flood damage potential and coastal erosion in low-lying coastal areas.

3.1 Storm surges in New Zealand

Comparatively little is known in New Zealand about the recurrence intervals of extreme sea levels generated by storm surges, waves or tsunami because of the paucity of good quality sea-level data of any length. To a certain extent this reflects the smaller storm surge heights that are generated in the New Zealand region compared with surges of up to 3–9 m that can occur in equatorial regions (e.g. Bay of Bengal and Gulf of Mexico) and high latitudes (e.g. North Sea, Japan). However coastal flooding in the Thames region from two closely spaced storm surges in July 1995 and January 1997 was a wake-up call. The 0.6 m storm surge on 14 July 1995 coincided with one of the highest tides that year and caused $3–4M worth of damage in the Thames area.

Storm surges are superimposed on all other waves or sea-level fluctuations acting on the coast at the time. Most notable are coincidental high tides, which can vary up to 2–2.4 m above mean sea level in parts of New Zealand, but seasonal cycles and ENSO fluctuations can also provide an increased elevation in prevailing sea level by up to 0.1–0.2 m. Therefore tides play a very crucial role in increasing the hazard when the tide wave crest (High Water) coincides with the storm surge peak. Tides can now be forecast or hindcast with high accuracy anywhere within New Zealand's EEZ (22). We concentrate in this paper on storm surges because little is known about them and further, they are stochastic in nature unlike predictable tides. Case studies of storm surges in the last three decades are briefly discussed to illustrate the combination of factors that contribute to extreme sea levels at the coast.

During the recent storm of 17 April 1999 (Fig. 5), elevated sea levels exacerbated flooding in Dargaville. Fig. 5 shows the situation measured at the Anawhata sea-level gauge (Fig. 1).

New Moon occurred on 16 April and the lunar perigee[2] on the 17 April, producing a combined perigean-spring tide of 1615 mm above mean sea level (MSL) at 10:15 on 17 April. The tide was a reasonably high, but not unusual, perigean-spring tide. Barometric pressure had a nadir of 988.9 hPa at 06:00 on 17 April. The corresponding inverted barometer (IB) set-up component of the storm surge was a maximum of 250 mm above MSL around 4 hours prior to high water (Fig. 5). Storm surge in Fig. 5 has been calculated by subtracting the forecast tide (dashed line) from the measured sea level record. This event was extremely sharp-peaked over one tidal cycle with a maximum storm surge set-up of nearly 0.5 m. Therefore approximately half the storm surge height can be explained by the inverted barometer effect of the low pressure system and the other half by wind set-up and other factors.

Another storm that was reasonably well recorded was extra-tropical cyclone *Bola* between 6–9 March 1988. This low-pressure system, with a nadir of ~980 hPa, moved due South from Fiji and hovered off North Cape for 4 days. The resulting storm surge, after removing the tides, is shown in Fig. 6 for Marsden Point on the north-east coast. Peak SE winds of up to 25 m/s combined with a peak inverted barometer set-up of 270 mm caused a peak storm surge of 0.63 m at Marsden Point around midnight on the 7 March. Other sea-level gauges operating at the time recorded lower storm surge extremes: Opua, Bay of Islands (+0.50 m); Auckland (+0.40 m); Moturiki (+0.23 m) and Gisborne (+0.20 m), reflecting the temporary stationarity of the storm off North Cape. Fortuitously the *Bola* storm surge coincided with a period of mean tides.

Unfortunately few good sea-level records are available for Cyclone *Giselle* on 9–10 April 1968 (the so-called "Wahine" storm). At the Port of Tauranga, the maximum recorded storm surge was at least 0.88 m (15), which is markedly higher than the next largest storm surge of 0.57 m recorded during the three decades (1960–97). Barometric pressure had a nadir of 963 hPa recorded on a ship with sustained winds of 26 m/s gusting to 40 m/s (15). The minimum central pressure at this low level would generate an inverted barometer set-up of 0.5 m, which is

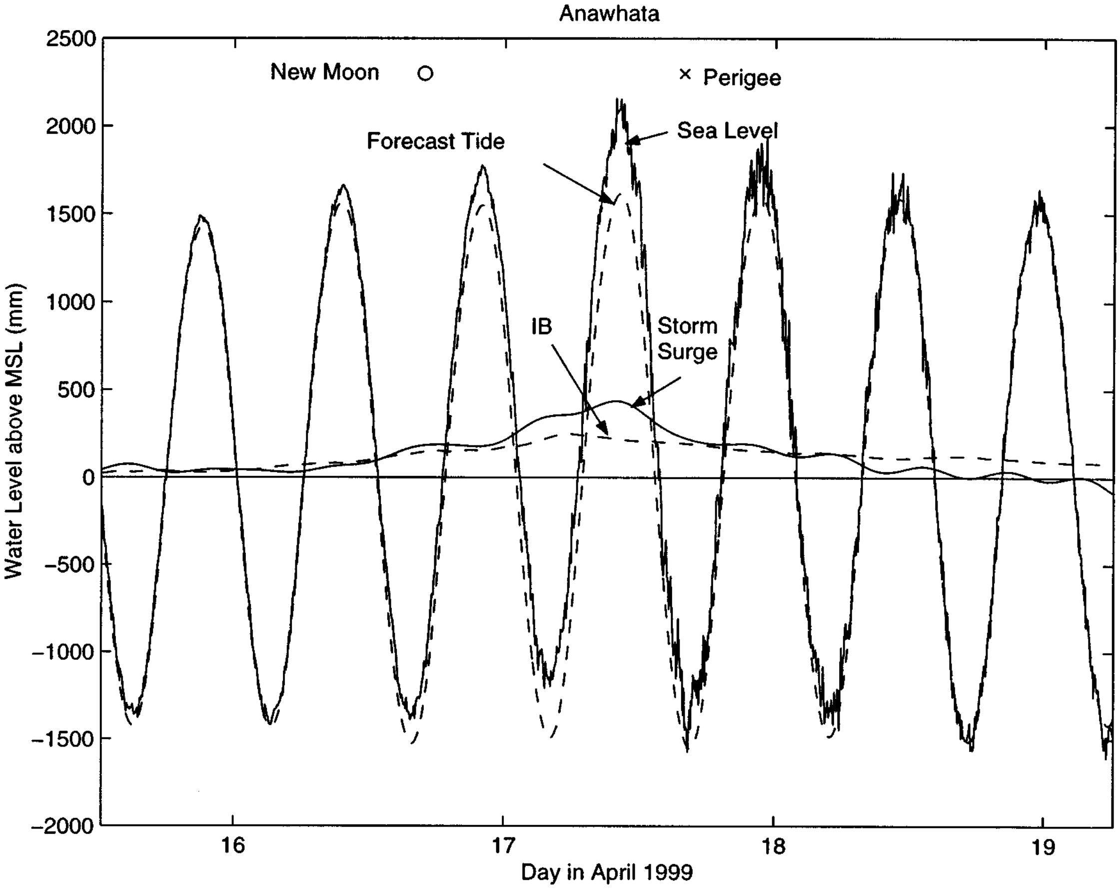

FIGURE 5: Storm surge event of 17 April 1999 measured at Anawhata, near Piha (NIWA Sea-level Network).

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[2] Perigean tides occur every month (27.5 days) in conjunction with the position of the Moon in its <u>elliptical</u> orbit around Earth. When the Moon is closest to Earth, it is in its perigee and larger than normal perigean tides occur.

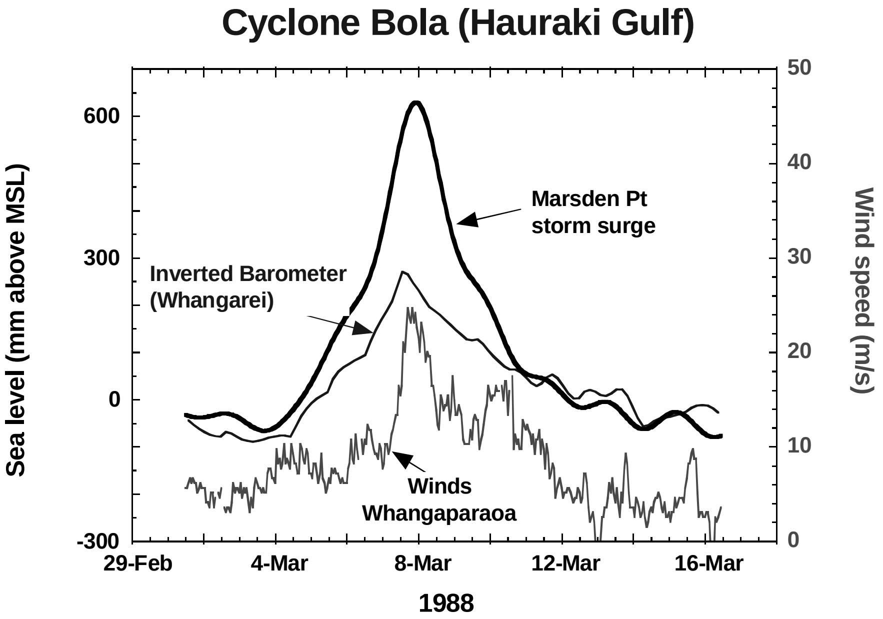

FIGURE 6: Storm surge event at Marsden Point generated by extra-tropical cyclone Bola in March 1988. The inverted barometer component of the set-up is calculated from barometric pressure measured at Whangarei Airport and wind speeds were only available from Whangaparaoa Peninsula.

probably as extreme as the inverted barometer set-up would reach around the North and South Islands.

Based on the limited sea-level data currently available, open-coast storm surge heights for New Zealand appear to have an upper limit of ~1 m (23)(24). For northern New Zealand, extreme storm surge heights are around double the inverted-barometer effect. The maximum upper limit in surge height would appear to be applicable for the coastline around mainland New Zealand, with spatial variations in the actual inverse barometer response being compensated for by changes in the effectiveness of set-up due to wind stress (25).

Good quality information on tidal constituents is now available for a number of open-coast sites (including those in Fig. 1), which will enable tidal height–frequency distributions, such as the one for Moturiki (Fig. 7) to be determined more accurately. Therefore as storm surge–frequency distributions are improved over time with the acquisition of more sea-level data, and combined with tidal-height distributions via joint probability methods, better distributions of extreme sea level return periods will be forthcoming in the future.

3.2 Climatic effects on storm surges

Leaving aside any change in storm climatology (e.g. greater storm intensities, more frequent cyclones) induced by climate change, rising sea level will lead to a decrease in the recurrence interval (or return period) of a storm surge of a given height above datum, because the surge is superposed on an increasingly higher base level (1).

Concerning the effect of climate variability on the frequency and intensity of storm surges, the jury is still out due to the paucity of long-term open-coast records of sea level. However some trends have emerged in a study of tide-gauge records in the Port of Tauranga (15) over the period of nearly three decades (1960–1997). The magnitude and frequency of storm surges varied considerably during the three decades, with a marked shift occurring around 1976, when the Inter-decadal Pacific Oscillation changed phases. The period since 1976 corresponded to a reduction in the frequency and magnitude of storm surges, compared with the previous period 1960–75. The ENSO phase also affected the number of days exceeding a storm surge threshold of 0.1 m per year, with La Niña events being associated with more storm surge days (15). Conversely during the intense 1982/83 El Niño event, the number of storm surges recorded at the nearby Moturiki gauge was half the "normal" number of around ten events per year >0.15 m as a result of the persistent offshore winds from the SW–W. Further analyses of sea-level records around other parts of New Zealand is proceeding as longer sea-level records become available.

4. Conclusions

An analysis of sea-level data for northern New Zealand from an open-coast gauge at Moturiki and the nation's longest port record at Auckland has highlighted the non-stationary behaviour of sea level at interannual and decadal timescales. Interannual contributions explain around 25% of the total variance in monthly sea level (excluding tides) and mainly arise from ENSO effects. To what extent low-frequency variability in coastal and oceanic currents (e.g. East Auckland Current) contribute to interannual variability in sea level is not clear due to lack of long-term oceanographic data.

The linear rise in secular sea level last century at the Port of Auckland of 1.3 mm yr^{-1}, falls within the 1–2.5 mm yr^{-1} range for the global sea-level rise that century. However there has been an almost static trend in sea level since the mid-1970s caused by a "flow-on" effect from the unusually lengthy period of predominantly El Niño episodes which have kept sea levels lower than normal. This regional response has masked any ongoing global rise in sea level caused by thermal expansion of seawater and ice melt. It is likely within the next few years that the

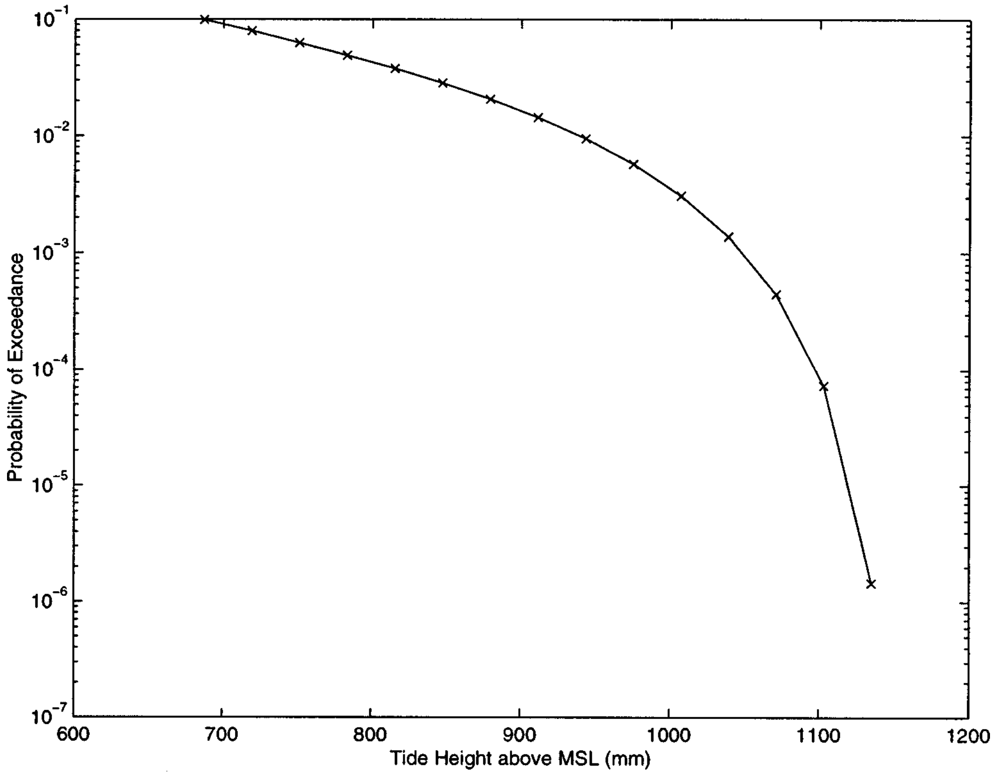

FIGURE 7: Cumulative exceedance probability for the higher and extreme tide heights from a 100-year forecast of tidal heights at hourly intervals for Moturiki (Bay of Plenty). The overall range in tide heights for 100 years is -1176 to +1147 mm, relative to the mean level of the sea (MSL). To place the extreme tides in context, Mean High Water Spring is 830 mm above MSL (or 880 mm above Moturiki Datum–1953).

Inter-decadal Pacific Oscillation switches to a "cool" phase (relative to the Eastern Pacific), which is likely to enhance La Niña episodes, and therefore raise regional sea level.

Consequently inter-decadal variability is an important consideration in assessing the long-term rise and any acceleration in regional sea level around the New Zealand coast. There is a fundamental need to better understand the causes of very low frequency variability in sea level in various regions of the Pacific. To this end, the recent completion of extensive networks of open-coast sea-level gauges set up by the National Tidal Facility in Australia and Pacific Islands and by NIWA in New Zealand (Fig. 1) should provide the necessary high-quality sea-level data to further investigate interannual and decadal variability in sea level. It will also considerably improve our poor understanding of storm surges and their frequency distributions, in particular the effects of inverted barometer, wind set-up and ENSO climate variability. Research is also underway to model the physics of low-pressure systems to gain a better understanding of how various storm characteristics, such as storm speed, minimum central pressure and winds combine to cause a response in coastal sea levels around New Zealand.

Estimates of the projected global rise in sea level by the 1995 IPCC report (2) indicate a "best estimate" rise of 20 cm by 2050 (range of uncertainty 7–39 cm) and 49 cm by 2100 (range of uncertainty 20–86 cm). We await with interest the third IPCC reportdue to be released in March 2001, for any revision of these estimates, although indications are that projections for sea-level rise will remain similar to those issued in 1995.

Ongoing research on tides, storm surges and tsunami and a stronger commitment by national and regional government agencies to long-term monitoring of sea level will markedly improve future predictions of extreme sea levels and determine which coastal areas are potentially vulnerable to the ongoing rise in relative sea level. This will pave the way for much more informed forecasting methods for storm surges in critical areas and long-term forecasts of regional sea-level rise around New Zealand.

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