A New Approach to Determining the Long-Term Trend in Relative Sea Levels

John HANNAH and Rob Bell (New Zealand)

Key words: Sea level change, tide gauges, height datum

SUMMARY

This paper uses historical MSL height datum information and shows how it can be combined with a new MSL height datum determination to provide an estimate of long-term relative sea level change.

ABSTRACT

New Zealand is a tectonically active country that straddles the Australian and Pacific plates, having over 15,000 km of coastline stretching in latitude from 34° to 47°S. Assessing long-term changes in relative sea-level at a regional level is important to future development decisions. In the past, and as recommended by *Douglas* (1991,1992), relative sea level changes have typically only been determined at sites with at least 50 – 60 years of almost continuous sea level data. In New Zealand, this has been done at the four main ports of Auckland, Wellington, Lyttelton, and Dunedin. This paper describes a new approach to improve the spatial coverage of reliable estimates of sea level rise at a regional level. Here, data from other regional tide gauges, typically with broken discontinuous records, and previously used only to define local height datums were used. The process involved a comparison of an old historical Mean Sea Level (MSL) datum with a newly defined MSL datum. A simple linear trend was fitted between the two datum points and then the trend assessed for possible bias due to inter-annual and inter-decadal sea level variability. This process, not previously used for trend determination, has enabled new sea level trend estimates to be derived at a further six tide gauge sites around New Zealand. The average relative sea level rise from these gauges is 1.7 ± 0.1 mm.y-1, a result that is entirely consistent with the analyses of the four long-term, primary tide gauge records. Most importantly, the process offers a relatively simple solution for improving the spatial determination of relative sea level trends in data sparse areas of the world.

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1. INTRODUCTION

Sea level change, as measured at tide gauges, is an important signal not only in climate related studies, such as those of that have featured in all recent Intergovernmental Panel for Climate Change (IPCC) scientific assessments (e.g., *IPCC*, 2001; *IPCC*, 2007), but also in some tectonic studies (e.g., *Bouin and Wöppelman* 2009; *Wöppelman et al*. 2009). Over the last two decades a great deal of work has been undertaken with the aim of reconstructing or extending various time series of sea level data from which estimates of long-term sea level change can be derived. Some studies have extended the length of previous data sets (e.g., *Raicich* 2007; *Testut et al*. 2010), while others have compiled new, but highly fragmented data sets (e.g., *Hunter et al*. 2003; *Woodworth et al*. 2010). In addition, some have used comparisons with nearby gauges to help verify or improve the quality of the analyses undertaken (e.g., *Raicich* 2007; *Woodworth et al*. 2010). The greater the number of reliable data sets, the better the assessment of relative sea level change at a regional level.

Since 1990, the assessment of relative sea level trends in New Zealand has been derived from the sea level records collected at the four long-term tide gauge sites of Auckland, Wellington, Lyttelton and Dunedin - records that go back to the start of the 20th century. These trends, originally reported by *Hannah* [1990] and subsequently updated by *Hannah et al*., [2010], show an average relative sea level rise of 1.7 mm/yr along the east coast of New Zealand.

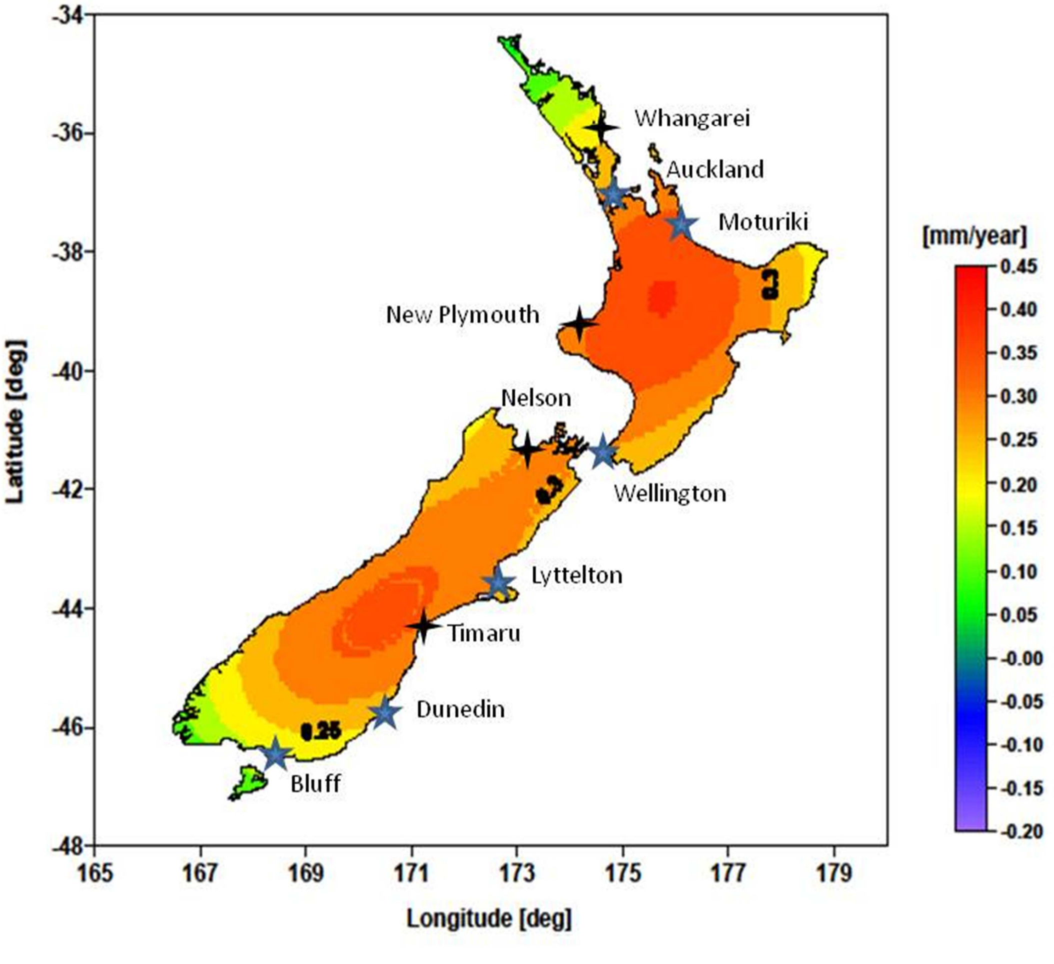
Recently, in a desire to assess future coastal hazards at a regional level, the authors of this paper undertook an investigation to see if historical sea level data from other tide gauge sites could provide additional spatial coverage of sea-level trends around New Zealand. In this case, however, old geodetic records were combined with sea level data collected over the last decade to provide such estimates. In principle, the process involved a comparison of an old, historical Mean Sea Level (MSL) datum with a newly defined MSL datum. A simple linear trend was fitted between the two data points and error estimates determined by a simple error propagation process. The results were then assessed for possible bias due to inter-annual and inter-decadal signals in the sea level data and compared with results obtained from the lon-term tide gauge records mentioned above.

This technique, not previously used for trend determination, has enabled new relative sea level trend estimates to be derived at a further six tide gauge sites (Whangarei, Moturiki, New Plymouth, Nelson, Timaru, and Bluff). The average relative sea level rise as calculated from all six new data points is 1.7 ± 0.1 mm/yr - a result that is completely consistent with the analyses of the primary tide gauge records. Most importantly, the process offers a solution to improving the spatial determination of relative sea level trends in coastal areas.

2. HISTORICAL SETTING

From an historical perspective, surveyors have typically considered MSL, if averaged over a complete lunar cycle of 18.6 yr, to be a stable reference surface. While this was true during the earliest colonial times in New Zealand, in 1908 the then Surveyor General recognised the possibility of problems with this approach due to observed tectonic instabilities. In order to provide both some form of monitoring for such instabilities, as well as a zero reference datum for the design of structures on the coastal margin, he requested that the Department of Lands and Survey, which was responsible for the national survey network, give emphasis to recording information on the tide gauges that were in operation. They were to note the type of gauge, its position, the quality of its record and, most importantly, the link between the gauge zero and any permanent bench mark (*Lands & Survey Department*, 1908).

Figure 1. Tide gauge locations (5-point stars are primary gauges and the 4-point stars are secondary gauges) overlaid on a background of GIA corrections [*Peltier*, 2004] for New Zealand



It was as a result of this directive that primary tide gauges were established in the ports at Auckland, Wellington, Lyttelton, Dunedin and Bluff. Over the next three decades, gauges were also established at the secondary ports/locations of Tararu, Napier, New Plymouth, Gisborne, Nelson, Picton, Westport, Greymouth and Timaru. Still later, additional primary datums were established at One Tree Point [near Whangarei]) and also at Moturiki Island (Bay of Plenty). The sea level data collected at each of these tide gauges (typically at hourly intervals), were used to define a local MSL height that was in turn used to define a local height datum. By the early 1960s New Zealand thus had seven primary height datums and nine secondary datums, all of which were used for local surveying and mapping purposes. In each case the length of the MSL data record used to define the datum varied, but was typically between one and eight years. Figure 1 shows the location of all the gauges that were subsequently found useful to this study. For reference purposes, it also shows the Glacial Isostatic Adjustment (GIA) corrections for New Zealand based upon *Peltier* [2004].

3. THE DATA

In the late 1980s, a formal programme for converting hourly sea level data from hard copy form (typically on rolls of paper) into digital form was undertaken in New Zealand. This was only done at the ports of Auckland, Wellington, Lyttelton and Dunedin where there was a long (typically >70 yr), reasonably complete, tidal record. These data were then used to determine the long-term relative sea level trends *Hannah* (1990). The average trend was found to be 1.7 ± 0.2 mm/yr. At that time it was recognised that these sea-level changes had invalidated all the historical MSL height datums described earlier [*Hannah*, 1989].

As part of a project to better inform the planning community of likely regional trends in relative sea level and also to provide data better suited to modern needs, it was decided to update as many of these local MSL datums as possible.

As a first step in the process, each of the tide gauges with shorter records was assessed to determine:

1. If there was documentation on how the original MSL was obtained.
2. If the tide gauge zero had been stable since the establishment of the original MSL, or if there was sufficient documentation to allow any movements to be determined.
3. If there were data (typically levelling), confirming the stability of the tide gauge site.
4. If there were at least nine years of modern records for the site (i.e., one half a lunar cycle) that would allow a new (modern) determination of MSL. A one-half lunar cycle was selected because the majority of the gauges with shorter records only had good-quality sea level data spanning the last decade.

The assessment was undertaken by examining old file records from the New Zealand Department of Lands and Survey that dated back to the early 1900s. It was very fortunate that despite major upheaval in government administration since 1986, detailed correspondence records could still be located. Indeed, the original Dept. of Lands & Survey had been restructured out of existence or morphed into new organisations on at least two occasions.

A summary of all primary and secondary gauges in New Zealand is shown in Table 1. Excluding the gauges with long-term data records, those additional gauges that were generally found to have met the above criteria were the Ports of Bluff, Whangarei, New Plymouth, Nelson, and Timaru, as well as Moturiki Island (Tauranga). While the Port of Whangarei gauge is not listed in Table 1, it was found that the One Tree Point gauge only collected data from 1960-1963, but had not operated since. However, a second gauge (17 km away) had been established in the Harbour Basin at Whangarei in 1962 (with an associated MSL determination), and had operated consistently over much of the last decade. The data from this latter gauge was found to meet our criteria.

Table 1. Historical primary and secondary MSL height datums in New Zealand together with the tide gauge (TG) data used to define them. The tide gauges not previously used for sea level rise determination, but meeting the screening criteria, are in bold type. The year attached to a datum name is when the datum was formally established.

Datum Name	Location	Definition
Primary Datums		
Auckland (1946)	Port of Auckland	MSL from 7 years of TG data collected in 1909,17-19,21-23
Wellington (1953)	Port of Wellington	MSL from 14 years of TG data collected between 1909-1946
Lyttelton (1937)	Port of Lyttelton	MSL from 9 years of TG data collected in 1917,18,23-27,30,33
Dunedin (1958)	Port of Dunedin	MSL from 9 years of TG data collected in 1918,23-27,29,35,37
Bluff (1955)	Port of Bluff	MSL from 8 years of TG data collected between 1918-1934
One Tree Point (1964)	Whangarei region	MSL from TG data collected between 1960-1963
Moturiki (1953)	Moturiki Is., Tauranga	MSL from TG data collected between 7/2/49 and 15/12/52
Secondary Datums		
Tararu (1952)	Tararu, Thames	MSL from TG data collected between 1922-1923
Napier (1962)	Port of Napier	No record of derivation
New Plymouth (1970)	Port of New Plymouth	MSL from TG data collected between 1918 - 1921
Gisborne (1926)	Port of Gisborne	MSL from TG data collected throughout 1926
Nelson (1955)	Port of Nelson	MSL from TG data collected between 12/6/1939-12/10/1942
Picton	Port of Picton	MSL from TG data collected from 1942-1943
Westport	Port of Westport	MSL from TG data collected from 1918-1922
Greymouth	Port of Greymouth	MSL from TG data collected from 1939-1943
Timaru	Port of Timaru	MSL from TG data collected from 1935-1937

4. THE NEW ANALYSIS

During the early 1990s, many port authorities became fully commercial entities with the consequence that regular tidal data collection suffered. However, these problems had largely been overcome by 1999 by which time new digital tide recorders had also been installed. The tidal data collected since then has typically been of a high and consistent quality. Given this consistency and quality, where possible it was decided to use the 10 years of data from 1999 – 2008 inclusive (approximately one half the 18.6 year lunar cycle), in order to define a new MSL datum for the port. Wherever possible a reference epoch of 1 January 2004 was selected for the new datums calculated as part of this study.

Table 2. Sea level trends and their standard deviations as inferred from MSL Datum changes.

Port or location	**MSL Datum defined from original data** (Reference epoch and definition - see also Table 1)	**MSL Datum defined from new data** (Typically with a reference epoch of 1 Jan. 2004)	**Inferred linear sea level rise** (mm/yr)	**Linear sea level rise** [*Hannah et al.***,** 2010] (mm/yr)
Auckland	(1916) 5.72 feet above the 1973 gauge zero	1.896 m above the 1973 gauge zero	1.7 ± 0.14	1.5 ± 0.1
Wellington	(1927) 1.96 feet above the post-1973 gauge zero	0.802 m above the post - 1973 gauge zero	2.2 [(a)] ± 0.13	2.0 ± 0.2
Lyttelton	(1925) 3.07 feet above the 1918 gauge zero	1.091 m above the 1918 gauge zero	2.0 ± 0.15	1.9 ± 0.1
Dunedin	(1927) 3.26 feet above the 1980 gauge zero	1.094 m above the gauge 1980 zero	1.3 ± 0.15	1.3 ± 0.1
Whangarei	(1962) 5.71 feet above the tide gauge zero	1.832 m above the tide gauge zero [(b)]	2.2 ± 0.6	
Moturiki	(1951) 4.88 feet above the tide gauge zero	1.588 m above the tide gauge zero	1.9 ± 0.2	
New Plymouth	(1920) 5.92 feet above the zero of the Newton King Wharf gauge (1973 position)	1.932 m above the zero of the Newton King Wharf gauge (1973 position)	1.5 ± 0.2	
Nelson	(1941) 7.35 feet above the tide gauge zero	2.323 m above the tide gauge zero	1.3 ± 0.25	
Timaru	(1936) 4.41 feet above the tide gauge zero	1.4475 m above the tide gauge zero [(c)]	1.7[(d)] ± 0.25	
Bluff	(1926) 5.27 feet above the tide gauge zero	1.743 m above the tide gauge zero	1.8 ±0.15	

[a] The inferred sea level rise at Wellington has been reduced to account both for a datum change of approximately 0.02 m in 1944, when a new tide gauge was installed, and for wharf subsidence since that time (estimated to be 0.15 mm/yr).

[b] The data record for the new MSL datum at Whangarei only covered the period 9/1999 to 1/2007. The reference epoch for the new MSL datum is thus May 2003.

[c, d] The data record for the new MSL datum at Timaru covered the period 2002 to 2008 inclusive. The reference epoch for the new MSL datum is thus 1 January 2005. The inferred sea level rise has been corrected for a datum change of 0.015 m when the gauge was metricated in 1976.

Once the new MSL datum had been computed, the inferred sea level trend was calculated merely by fitting a straight line between this new reference MSL epoch and the old data reference epoch formed by the previous MSL datum (converting from feet units). The reference epoch for the original MSL determination is taken to be the mid-point over the years that original sea-level data used in the definition was collected. For comparison purposes the same trend determination was also done at the four long-term primary tide gauges where a much more complete MSL trend analysis had been undertaken [c.f., *Hannah*, 1990; *Hannah et al*., 2010]. The results are shown in Table 2.

5. DISCUSSION

Before embarking upon a discussion of the results, it must be recognised that the above analysis has a number of potential weaknesses. In the first instance, it is constrained both by the length of data records used in the two datum definitions and by the intervening time period. It is also potentially biased by a number of periodic signals present in the annual MSL data. These include the lunar nodal tide, variability in annual cycles, the 2-4 year El Niño – Southern Oscillation (ENSO) cycle, and the 20-30 year Interdecadal Pacific Oscillation (IPO) as described by *Bell and Goring* [1998]; *Douglas*, [2001]; and *Goring and Bell* [1999].

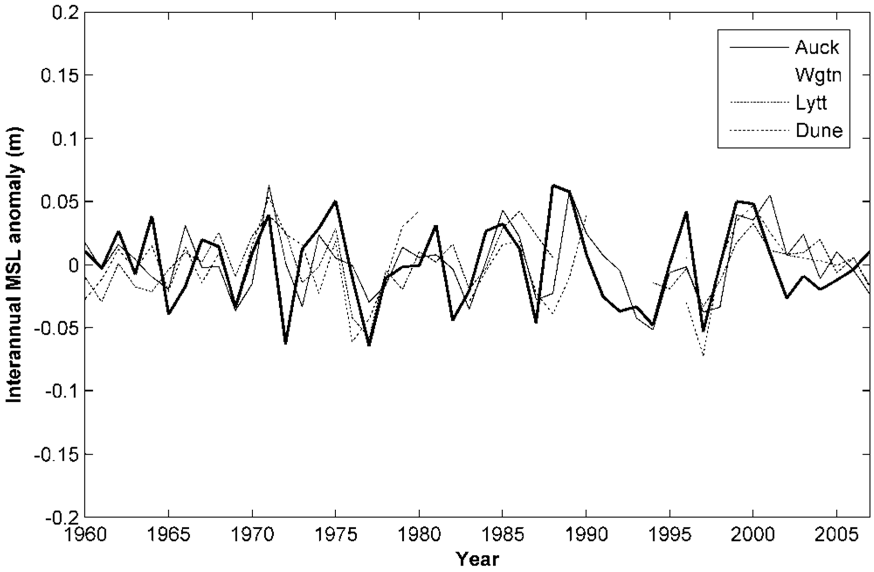
It has previously been established by *Hannah* [1990] that the lunar nodal tide (18.6 yr period) has an average amplitude around New Zealand of 6 mm and is, in general, small and ill defined. This effect was considered no further.

Bell and Goring [1998] have shown that the annual cycle (as represented by monthly MSLs) for Moturiki Island can vary within ± 8 mm average annual amplitude over a decade but is generally symmetric about the annual mean with little annual bias. Similar results, using unpublished data, have been obtained for other tide gauge sites. Annual MSLs in the various datum definitions are therefore expected to be relatively immune from seasonal biases.

Goring and Bell [1999], together with *Hannah, et al*., [2011], show that for Auckland the ENSO effect influences annual MSLs within the range -0.10 m to +0.14 m. Similar response patterns to ENSO were also isolated by a band-passed wavelet filter (1-8 year band) for the other primary tide gauge records, albeit for the shorter common period 1960-2007 (see Figure 2). Possible bias due to ENSO in each of the historic MSL datums (Table 1) was thus a possibility, being complicated by the fact that each datum was based on different TG record lengths – the bias being dependent on the record length relative to the average 4-5 year ENSO cycle (Figure 2). Fortuitously, the TG record lengths for the relevant gauges mostly spanned three to eight years (Table 1), a circumstance that is expected to remove much of this bias. For the modern MSL datum period (1999 to 2008), the Southern Oscillation Index exhibited a near-zero average SOI of –0.01 (a neutral state), a circumstance that should essentially eliminate bias due to ENSO variability.

The IPO introduces a smaller long-term cycle, measured at ±0.05 m at Auckland, which tends to be manifested as a rapid rise in annual sea level when transitioning from a positive to a negative IPO phase (as defined by the Pacific Decadal Oscillation at: http://jisao.washington.edu/pdo/PDO.latest), followed by a gradual decrease before repeating. The other three primary gauges also exhibited similar amplitudes to Auckland in sea-level variability for the longer IPO cycle. In this case, each MSL datum period is far shorter than the 20-30 year IPO phase, so a small bias will also be present from sampling incomplete IPO cycles – a bias that can only be overcome by access to long-term records such as at the four primary ports.

Figure 2: Interannual (1-8 year) band-pass signal from the four primary tide gauges (Auckland, Wellington, Lyttelton, Dunedin) from 1960 to 2007 in comparison to the annual-average Southern Oscillation Index (Troup Index) scaled by 1/20 [heavy line]. Peaks in SOI relate to La Niña episodes.



The results given in Table 2 show that the inferred sea level rise at the ports with the four long-term sea level records (Auckland, Wellington, Lyttelton and Dunedin) as computed from the old and new MSL datum definitions are consistent with the best estimates able to be derived from a formal analysis of the total annual data series. This consistency corresponds with the expected errors and biases in the method and provides a measure of confidence in the results obtained at the other ports where no continuous sea level record is available.

The accuracy of the inferred linear sea level rise estimates shown in Table 2 is a function of the elapsed time since the respective datum definitions, (the longer the time the better) and the number of years of data used in both the original definition and the new definition and how it synchronizes with the dominant longer-term ENSO and IPO cycles. In this case, these accuracy estimates were derived as follows. Firstly, the least squares analyses undertaken to derive the sea level trends at the four long-term tide gauge records were used c.f., *Hannah* [1990]. These indicated that once the annual MSL data was de-trended, a standard deviation of 0.025 m could be assigned to a single year of data. Thus, assuming each year of data was independently derived, a standard deviation for a MSL derived from 10 years of de-trended data would be in the order of 0.008 mm. An approximate standard deviation could thus be derived for each MSL datum point. By propagating errors into the trend model, an estimate of the standard deviation of the trend was able to be calculated. While it is recognised that these estimates are indicative only, their validity is supported by their consistency with the more rigourous estimates as computed at the four primary ports.

We now consider each of the new results in turn. The inferred trend at the Port of Whangarei is by far the weakest, due both to the shortness of the original datum definition (one year of data) and the relatively short time between definitions (42 years). In 1962, the ENSO cycle (as represented by the South Oscillation Index) was generally weakly positive, indicating very mild La Niña conditions and a slightly elevated MSL for that year. Conversely, the IPO (as represented by the Pacific Decadal Oscillation Index) was mildly negative, thus generating a slightly depressed MSL for that year. Given that the two effects work in opposite directions, the inferred sea level rise estimate should be largely unbiased.

Annual MSL at Moturiki is highly correlated with MSL at Auckland, as they lie on the same north-east facing coast of the North Island (Figure 1). The period 1949 – 1952 was a period starting initially with a positive La Niña event (higher sea level) and ending with a El Niño (lower sea level), whereas the IPO response was on an upward trend. Again (fortuitously) the combined influence is expected to be essentially neutral.

Unfortunately, there is no long-term tide gauge data on the West Coast of New Zealand that would allow an assessment of the possible impact of ENSO and IPO events on New Plymouth. However, the inferred trend at New Plymouth has been derived from an original datum definition that used four years of MSL data and is calculated over an intervening time period of 84 years. The estimate should thus be reasonably robust. Interestingly, this is the only estimate of sea level rise that could be derived for the entire West coast of New Zealand. The geographic position of the Nelson tide gauge (Figure 1) is more oceanographically connected to the West Coast, so is in a similar state to the New Plymouth site. An almost complete ENSO cycle straddled the 1939–1942 record used to define the Nelson datum, so again the bias is probably small. The strength of the original datum definition and the elapsed time (63 yr) to the new definition suggest a robust sea level trend estimate.

The determination of the relative sea level trend at Timaru is based upon a 68 year time lapse with good data points at each end. The original record from 1935 to 1937 coincided with a fairly weak (neutral) SOI. Perhaps fortuitously, the inferred trend is exactly as would have been derived from a spatial interpolation based upon the long term gauge records at Lyttelton and Dunedin.

Finally, the similarity of the Bluff Datum definitions (both old and new) to those of the four major ports provides a high level of confidence with the generated result.

A more detailed analysis of these effects and their likely impacts on the individual tide gauge datums is given in Hannah and Bell (2012)

When taken together these six new estimates of relative sea level rise provide a weighted mean estimate of 1.7 ± 0.1 mm/yr, a result that is completely consistent with the mean rise computed at the four primary sites with long term tide gauge records. In the absence of some countervailing effect, they provide the best evidence yet to suggest that there is very little differential regional tectonic motion or subsidence between sites over the last 80 years.

6. CONCLUSIONS

While clearly with some limitations, old MSL datum records can have value in helping to assess regional sea level change, provided the tide gauges are still in operation, sufficient documentation exists to resolve issues such as datum definition and long-term datum stability, and provided sufficient data exists to allow an assessment of the likely impact of longer term oceanographic influences and climate cycles on the datum derivation. It is also beneficial if the method can be cross-checked with long-term gauge data. While such assessments are unlikely to have the strength and rigour that comes from the analysis of a long-term continuous record, they nevertheless can highlight any major regional variations in relative sea level rise that might exist due to, for example, local tectonic motion or ground water withdrawal. They thus have value to the scientific community and planners and engineers who seek additional data that might assist with long-term coastal development, coastal hazard assessments and engineering design that need to accommodate ongoing sea-level rise.

It is important to note that this project would have been impossible to complete had the former Department of Lands and Survey file records covering the last century not been available. This observation should offer some comfort to those who seek to preserve both raw observational data and metadata for the use of future generations!

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BIOGRAPHICAL NOTES

John Hannah BSc, DipSci, MSc, PhD, MNZIS, RPSurv, completed his first two degrees at the University of Otago, New Zealand. Two years later, in 1974, he became a Registered Surveyor. In 1976 he began study at The Ohio State University, completing an MSc and a PhD, both in Geodetic Science. From 1982 until 1988 he was Geodetic Scientist, and then subsequently, Chief Geodesist/Chief Research Officer with the Department of Lands and Survey, New Zealand. After a 17 month appointment to the Chair in Mapping, Charting and Geodesy at the US Naval Postgraduate School, California, he returned to New Zealand as Director of Geodesy and subsequently, Director of Photogrammetry for the Dept. of Survey and Land Information. In 1993 he joined the School of Surveying, as Professor and Head of Department, becoming its Dean in 2001. He relinquished this administrative role at the end of 2004 in favour of more teaching and research. His publications reflect his research interests in sea level change and surveying education. He is a Registered Professional Surveyor and is a former President of the NZ Institute of Surveyors.

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

CONTACTS

Professor John Hannah
School of Surveying
University of Otago
PO Box 56 Dunedin New Zealand
Ph. +64 3 479 9010
Fax +64 3 479 7586
Email: john.hannah@otago.ac.nz