Regional sea level trends in New Zealand

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[1] In terms of sea level data sets able to be used for long-term sea level trend analysis, the Southern Hemisphere is a data sparse region of the world. New Zealand lies in this region, presently having four (major port) data sets used for such trend analysis. This paper describes the process followed to compute new sea level trends at another six ports, each with very discontinuous tide gauge records. In each case the tide gauge has previously only been used for precisely defining an historical local Mean Sea Level (MSL) datum. The process used involved a comparison of the old MSL datum with a newly defined datum obtained from sea level data covering the last decade. A simple linear trend was fitted between the two data points. Efforts were then made to assess possible bias in the results due to oceanographic factors such as the El Niño–Southern Oscillation (ENSO) cycle, and the Interdecadal Pacific Oscillation (IPO). This was done by taking the longer time series from the four major ports and assessing the spatially coherent variability in annual sea level using the dominant principal component from an empirical orthogonal function (EOF) analysis. The average relative sea level rise calculated from these six newly derived trends was 1.7 ± 0.1 mm yr^{-1}, a result that is completely consistent with the analysis of the long-term gauge records. Most importantly, it offers a relatively simple method of improving our knowledge of relative sea level trends in data sparse regions of the world.

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1. Introduction

[2] For the last 2 decades the assessment of relative sea level trends in New Zealand has been solely derived from the sea level records obtained from the four main port tide gauges of Auckland, Wellington, Lyttelton and Dunedin, where the only long-term (>70 year) data sets exist (Figure 1). These records go back to the start of the 20th century. These trends, which were originally reported by *Hannah* [1990], revised by *Hannah* [2004] and subsequently updated by *Hannah et al.* [2010], show an average relative sea level rise of 1.7 ± 0.1 mm yr^{-1} for all four ports, all of which are located on the east coast of New Zealand. These four gauges now also have continuous GPS records that span the better part of a decade.

[3] Recently, in a desire to assess future coastal hazards including relative sea level rise at a regional level, an investigation was undertaken to determine whether historical data from other tide gauge sites could provide additional spatial coverage of relative sea level trends around New Zealand. This paper describes the data rescue and mining process that was undertaken and outlines the results derived. Because of the broken nature of the tide gauge records at the additional locations, they would normally not be used for long-term sea level change analyses. However, each of these gauges had historically been used as the basis for defining a local mean sea level (MSL) survey datum. The process used here involved a comparison of an old, historical MSL datum with a newly defined MSL datum covering most of the past decade. A simple linear trend was fitted between the two data points. Error estimates were then determined through a formal error propagation process. Efforts were then made to assess the likelihood of bias in the derived sea level trends due to oceanographic factors such as El Niño–Southern Oscillation (ENSO) and the Inter-decadal Pacific Oscillation (IPO). This was done by considering the spatially coherent variability in annual sea level, using the dominant principal component from an empirical orthogonal function (EOF) analysis. This analysis, using the longer time series from the four main ports, captured the inter-annual and decadal sea level response seen around the New Zealand coastline.

[4] The data-mining technique for establishing sea level trends, not previously used for such determinations, has enabled new relative sea level trend estimates to be derived for a further six tide gauge sites in New Zealand at Whangarei, Moturiki, New Plymouth, Nelson, Timaru, and Bluff (Figure 1). The average relative sea level rise calculated from these six newly derived trends is 1.7 ± 0.1 mm yr^{-1}, a result that is completely consistent with the far more rigorous and conventional analyses previously undertaken for the four main ports using long-term tide gauge records. Most importantly, the process offers a relatively simple solution

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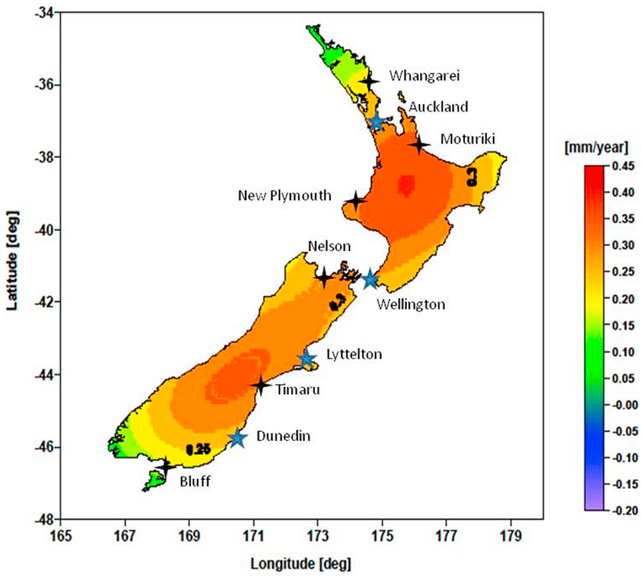

Figure 1. Tide gauge locations (five point stars are the four main ports where long-term (>70 year) data sets exist and the four point black stars mark the additional six sites where local datums exist) overlaid on a background of GIA corrections [*Peltier*, 2004] for New Zealand.

(provided historic records are discoverable) to improving the spatial determination of relative sea level trends both in data sparse regions of the world, and in active tectonic regions.

2. Historical Setting

[5] Historically, the surveyors involved in the early development of New Zealand considered MSL, if averaged over a complete lunar nodal cycle of 18.6 years, to be a stable reference surface. However, in 1908 the then Surveyor General of New Zealand recognized the possibility of the occurrence of regional tectonic motion. In order to provide some form of monitoring for such motion, as well as a zero reference datum for heighting purposes, he requested that the New Zealand 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 benchmark (New Zealand Lands and Survey Department, Circular 847, departmental report, 1908).

[6] As a result of this directive, primary tide gauges were established in the ports at Auckland, Wellington, Lyttelton, Dunedin, and Bluff (Figure 1). Over the subsequent 3 decades, gauges were also established at the secondary ports/locations of Tararu, Napier, Gisborne, Picton, Westport, Greymouth, Nelson, New Plymouth, and Timaru (only the relevant latter three ports are shown in Figure 1). In still later years additional primary vertical datums were established at One Tree Point (near Whangarei) and also at Moturiki Island in the Bay of Plenty (Figure 1). 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 regional height datum. By the early 1960s, New Zealand thus had seven primary height datums and nine secondary datums. In each case the length of the MSL data record used to define the datum varied, but was typically between 1 and 8 years, and the years sampled varied between locations. Figure 1 shows the location of those primary and the secondary gauges that were subsequently found useful to this study, relative to the location of the previously analyzed four main ports. For reference purposes, it also shows an estimate of glacial isostatic adjustment (GIA) corrections for New Zealand based upon *Peltier* [2004].

3. The Data

[7] The original sea level trend analyses undertaken in New Zealand, as reported by *Hannah* [1990, 2004], only used data from the four main port gauges at Auckland, Wellington, Lyttelton, and Dunedin (Figure 2) where there were long data records (typically 70–100 years). The average trend in relative sea level rise was found to be 1.6 ± 0.2 mm yr^{-1} (up to 1988) and 1.7 ± 0.1 mm yr^{-1} (up to 2000), respectively. At the time it was recognized that these sea level changes were likely to have invalidated all historical MSL height datums [*Hannah*, 1989]. Because of the need of the New Zealand planning community for better regional assessments of coastal hazards (including relative sea level rise), it was decided to update as many of these local MSL datums as possible, including those for which only shorter records could be found. In undertaking this process, it was not only found that reliable estimates of sea level rise could be obtained, but also that it presented an opportunity to significantly increase our knowledge of the spatial distribution of sea level change in a data sparse region of the world.

[8] As a first step in the process, each of the six tide gauges (Figure 1) with shorter records was assessed to determine (1) if there was good 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

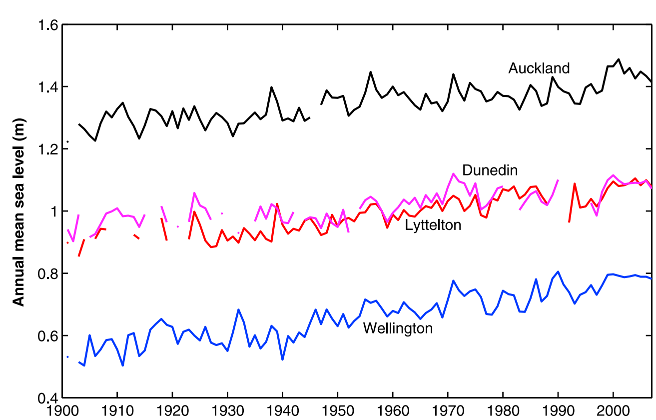

Figure 2. Annual mean sea level time series to 2008 from the four primary tide gauges (Auckland, Wellington, Lyttelton, Dunedin) before detrending. Sea level is relative to a particular port datum, with an arbitrary 0.6 m offset subtracted from Auckland to reduce the plot size.

Table 1. Historical Primary and Secondary MSL Height Datums in New Zealand Together With the Tide Gauge Data Used to Define Them[a]

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 and 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 and 1934
One Tree Point (1964)	Whangarei region	MSL from 4 years of TG data collected between 1960 and 1963
Moturiki (1953)	Moturiki Island, Tauranga	MSL from 4 years of TG data from 7 February 1949 to 15 December 1952
Secondary Datums		
Tararu (1952)	Tararu, Thames	MSL from TG data collected between 1922 and 1923
Napier (1962)	Port of Napier	No record of derivation
New Plymouth (1970)	Port of New Plymouth	MSL from 4 years of 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 3.5 years of TG data from 12 June 1939 to 12 October 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 3 years of TG data collected from 1935–1937

[a]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. TG, tide gauge.

levelling), confirming the stability of the tide gauge site; and (4) if there were at least 9 years of modern records for the site (i.e., one half of a lunar nodal cycle) that would allow a new (modern) determination of MSL. A one-half lunar cycle was selected because the majority of the gauges with fragmented records only had good-quality sea level data spanning the last decade.

[9] The assessment was undertaken by systematically examining old file records from the New Zealand Department of Lands and Survey that dated back to the early 1900s. It was fortunate that despite major upheaval in government administration since 1986, detailed correspondence records could still be located.

[10] A summary of all primary and secondary gauges in New Zealand is shown in Table 1. Excluding the four main port 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), operated by the National Institute of Water and Atmospheric Research. While the Port of Whangarei gauge is not listed in Table 1, it was found that the nearby gauge at One Tree Point only collected data from 1960 to 1963 to determine the MSL datum, 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.

[11] The original time series of annual mean sea level for each of the four main ports (Figure 2), used in the successive determinations of sea level trend by *Hannah* [1990, 2004] and *Hannah et al.* [2010], were subsequently detrended and then subjected to EOF analysis to isolate the dominant pattern of sea level variability along New Zealand's east coast.

4. The New Analyses

[12] The original intention in updating these MSL datums had been one of using 18–19 years of recent data (one complete lunar nodal cycle) symmetrically positioned around a new reference epoch of 1 January 2000. However, the last decade in the 20th century was one of corporatization for many port authorities, with the consequence that tidal data collection suffered at some ports. These problems had largely been overcome by 1999, by which time new digital recorders had also been installed. The tidal data collected since then has typically been of a high and consistent quality. Consequently, and where possible, it was decided to use 10 years of data from 1999–2008 inclusive (approximately one half of the 18.6 year lunar cycle), where possible giving a reference epoch of 1 January 2004 for the new datums calculated for this present study.

[13] Once the new MSL datum had been computed, the inferred sea level trend was calculated from a linear fit 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 midpoint over the years that original sea level data used in the definition was collected. For comparison purposes and to verify the approach, 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 [cf., *Hannah*, 1990, 2004; *Hannah et al.*, 2010]. The results are shown in Table 2.

[14] Such an approach, fitting a linear trend to two end-members, can be biased by sea level variability present during the periods used for the end-member averages. In New Zealand waters, ENSO can induce up to ± 0.06 m variations in annual mean sea level (Figure 3), with higher than normal sea levels during La Niña episodes and vice versa during El Niño. The longer-period IPO induces much smaller variations in sea level [*Goring and Bell*, 1999], but generally a step jump in sea level accompanies a shift from a positive (warm-phase) IPO episode to a negative (cool-phase) episode, as occurred recently in 1998–2000 (see Figure 2).

[15] A qualitative assessment of the influence of long-period variability at interannual scales (e.g., ENSO) and inter-decadal scales (e.g., IPO) was based on an EOF

Table 2. Sea Level Trends and Their Standard Deviations as Inferred From MSL Datum Changes[a]

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 January 2004)	Inferred Linear Sea Level Rise (mm yr^{-1})	Linear Sea Level Rise [*Hannah et al.*, 2010] (mm yr^{-1})
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 ± 0.13[b]	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[c]	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[d]	1.7 ± 0.25[e]	
Bluff	(1926) 5.27 feet above the tide gauge zero	1.743 m above the tide gauge zero	1.8 ± 0.15	

[a]For each of the stations shown, an inferred absolute rate of sea level rise can be derived by applying the GIA corrections of *Peltier* [2004] shown graphically in Figure 1.

[b]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^{-1}).

[c]The data record for the new MSL datum at Whangarei only covered the period September 1999 to January 2007. The reference epoch for the new MSL datum is thus May 2003.

[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.

[e]The inferred sea level rise has been corrected for a datum change of 0.015 m when the gauge was metricated in 1976.

analysis [e.g., *Björnsson and Venegas*, 1997], of the long-term detrended time series from the four main ports (original time series shown in Figure 2). EOF is a mathematical analysis that finds the spatial patterns (modes) of variability, their temporal cyclical pattern, and a measure of the explained variance within the data for each mode. Prior to the EOF analysis, the annual sea level time series were detrended and gaps temporarily interpolated. From the EOF analysis, two modes were significant, (based on scaling typical errors between neighboring eigenvalues developed by *North et al.* [1982]), with Mode 1 explaining 54% of the variance and Mode 2, 20% of the variance. For the purposes of assessing bias from sea level variability in the historic MSL datum period for each of the six gauges, only Mode 1 is used, which describes a spatially consistent response in sea level to ENSO, decadal variability in ENSO and IPO combined. The reconstructed sea level time series for the four main ports, based only on Mode 1 principal component, is shown in the background of Figure 4. This reconstruction was used to assess that the bias in the initial MSL datum end-member is mostly minor. The sea level reconstruction is quite similar to the EOF principal component of sea level anomaly extracted for the entire South Pacific (14.5°S–59.5°S) by *Sasaki et al.* [2008], which confirms the EOF approach taken here. *Sasaki et al.* [2008] demonstrate the dominant mode is largely explained by wind-driven long Rossby waves propagating westward across the South Pacific, driven by atmospheric fluctuations associated with decadal variability in ENSO and IPO.

5. Discussion

[16] Before embarking upon a discussion of the results, it must be recognized that the analysis of fitting a trend to two known end-members has a number of potential weaknesses. In the first instance, it is constrained both by the length of the data records used in the two datum definitions at each end and by the intervening time period. While it would have been preferable to have longer and more complete data sets, these were simply not available at any other gauge sites in New Zealand other than the four main ports. This will apply to other countries where deployments at tide gauge sites have been sporadic. The derived trends are also open to bias due to a number of periodic signals present in the annual MSL data. These include the 18.6 year lunar nodal tide, variability in annual cycles, the 2–4 year ENSO cycle, and the 20–30 year IPO as described by *Bell and Goring* [1998], *Douglas* [2001], and *Goring and Bell* [1999].

[17] It has previously been established by *Hannah* [1990] that the lunar nodal tide (18.6 year period) has an average amplitude around New Zealand of 6 mm and is, in general, small and ill defined. The 8.85 year cycle of lunar perigee,

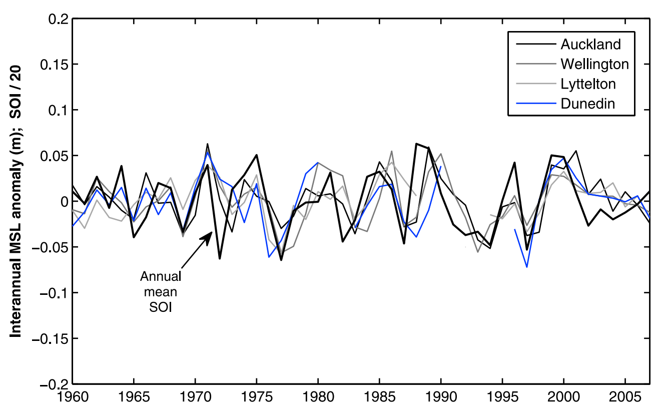

Figure 3. Interannual (1–8 year) wavelet band-pass signal from the four main port tide gauges (Auckland, Wellington, Lyttelton, Dunedin) from 1960 to 2007 compared with the annual-average Southern Oscillation Index (Troup Index) scaled by 1/20 (bold line). Peaks in SOI relate to La Niña episodes.

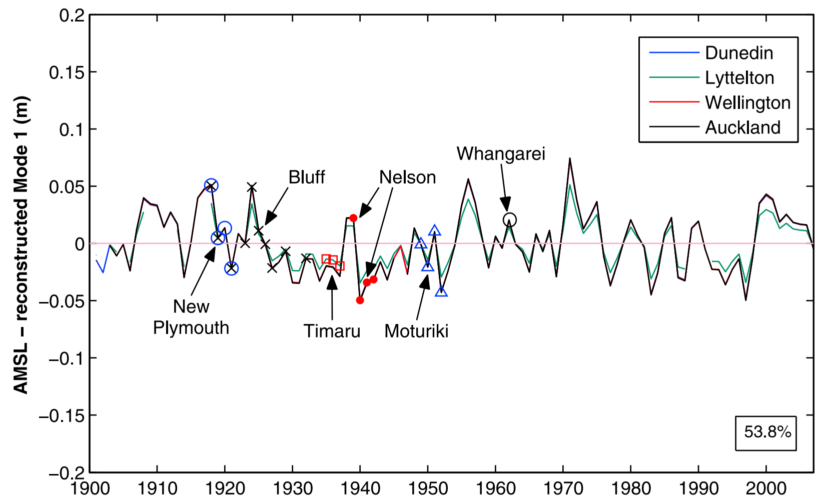

Figure 4. Reconstructed sea level principal component for the four main ports based on EOF Mode 1. The individual years used in determining the historic MSL datum for each of the six additional gauge sites are marked by symbols on the reconstructed sea level series for the primary port nearest to the secondary gauge (Table 3).

on the other hand, while better defined was still found to have an amplitude that rarely exceeded 12 mm. While little can be done about its effect on the original MSL datum definitions, it is still well within the assessed standard deviation for any single year of MSL data (see later discussion). Given that all the new datum definitions for the six gauge sites use 8–10 years of MSL data, the effects of the lunar perigee cycle on the new datum definitions should essentially be eliminated.

[18] *Bell and Goring* [1998] have shown that the annual cycle (as represented by monthly MSLs) for Moturiki Island can vary within ±8 mm of the 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.

[19] *Goring and Bell* [1999], together with *Hannah et al.* [2011], show that for Auckland the ENSO effect influences monthly MSL within the range −0.10 m to +0.14. Similar response patterns to ENSO were also isolated by a band-passed wavelet filter (1–8 year band) for all four primary tide gauge records from 1960 to 2007, with a reduced variability of −0.05 m to +0.06 m when based on annual MSL (see Figure 3). 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 historic MSL datum was based on different record lengths, the bias being dependent on the record length relative to the typical 2–5 year ENSO cycle (Figure 3). Fortuitously, the tide-gauge record lengths for the relevant gauges mostly spanned 3–8 years (Tables 1 and 3), a circumstance that is expected to remove much of this bias.

[20] For the modern MSL datum period (1999–2008), the Southern Oscillation Index (Troup Index) exhibited a near-zero average of −0.01, a situation that should minimize any bias due to ENSO variability.

[21] 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 (e.g., 1998–2000 in Figure 2) when transitioning from a positive to a negative IPO phase (as defined by the Pacific Decadal Oscillation, 2010, http://www.jisao.washington.edu/pdo/), followed by a gradual decrease or stability in average MSL before repeating the cycle. The EOF Mode 1 principal component reconstruction (Figure 4) shows a spatially coherent response of annual MSL at all four main ports, comprising a combination of interannual and decadal variability. In this case, each MSL datum period is considerably shorter than the 20–30 year IPO phase, or the decadal variability (Figure 4), so a small bias will also be present from sampling incomplete IPO and decadal cycles, as shown by the Mode 1 reconstruction sea level anomalies in Table 3: a bias that can only be overcome by access to long-term records such as at the four primary ports.

[22] The results given in Table 2 show that the inferred sea level rise at the for main ports with 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 [*Hannah et al.*, 2010]. 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.

Table 3. Average Reconstructed Mode 1 Long-Period Sea Level Anomaly (From the Nearest Main Port) Over the Period Used to Derive the Historic MSL

Port or Location	MSL Datum Averaging Period	Nearest Main Port	Average Reconstructed Mode 1 Sea Level Anomaly (m)
Whangarei	1962	Auckland	0.020
Moturiki	1949–1952	Auckland	−0.014
New Plymouth	1918–1921	Wellington	0.012
Nelson	1939–1942	Wellington	−0.023
Timaru	1935–1937	Lyttelton	−0.015
Bluff	1918–1934[a]	Dunedin	0.005

[a]MSL datum based on 8 years during this period.

[23] 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, decadal, and IPO cycles. In this case, these accuracy estimates were derived as follows. First, the least squares analyses undertaken to derive the sea level trends at the four long-term tide gauge records were used; cf., *Hannah* [1990]. These indicated that once the annual MSL data was detrended, 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 detrended 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 recognized that these estimates are indicative only, their validity is supported by their consistency with the more rigorous estimates as computed at the four primary ports.

[24] 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 (1 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 mild La Niña conditions and a slightly elevated MSL for that year. This is also present in the Mode 1 reconstruction (Figure 4), where the sea level anomaly is +0.02 m (Table 3). This implies that the inferred sea level rise trend could be slightly underestimated on the basis of long-period sea level variability.

[25] Annual MSL at Moturiki is highly correlated with MSL at Auckland, as they lie on the same northeast facing coast of the North Island (Figure 1) where the oceanography and sea-temperature patterns are coherent [*Bell and Goring*, 1998]. The historic MSL datum period 1949–1952 was a period starting initially with a moderate La Niña event (higher sea level) and ending with an El Niño (lower sea level), with the average Mode 1 reconstruction anomaly slightly negative (−0.014) over the period (Table 3, Figure 4). The combined influence of sea level variability is expected to only contribute a small bias, slightly overestimating the trend by $\sim$0.2 mm yr^{-1}, which is also more consistent with the trend from the nearest regional gauge at Auckland (Table 2), albeit over a substantially longer record.

[26] Unfortunately, there is no long-term tide gauge data on the entire 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 4 years of MSL data (1918–1921) and is calculated over an intervening time period of 84 years. The Mode 1 sea level anomaly at the nearest Wellington gauge (although more on the east coast) indicates sea level was slightly higher for that period (Table 3, Figure 4), so the inferred trend is likely to be reasonably robust, if not conservative. Interestingly, this is the only estimate of sea level rise that could be derived for the entire west coast of New Zealand, bordering the Tasman Sea. The geographic position of the Nelson tide gauge (Figure 1) is more closely connected to the ocean processes on New Zealand's west coast, so has a similar context to the New Plymouth site. An almost complete ENSO cycle straddled the 1939–1942 record used to define the Nelson datum, although with a small net negative Mode 1 sea level anomaly based on the nearest Wellington gauge on the east coast (Table 3, Figure 4), so the bias is probably small. The strength of the original datum definition and the elapsed time (63 years) to the new definition suggest a reasonable sea level trend estimate.

[27] The determination of the relative sea level trend at Timaru is based upon a 68 year time lapse with good-quality data records at each end. The original record from 1935 to 1937 coincided with a fairly weak (neutral) SOI, although with a slight negative average Mode 1 sea level anomaly (−0.015 m) based on the nearest Lyttelton gauge (Table 3, Figure 4). 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.

[28] Finally, the similarity of the Bluff datum definitions (both historic and modern) to those of the four major ports provides a high level of confidence with the generated result. Further, the longer period of 1918–1934, over which 8 years of data were used for the historic MSL datum, had a negligible average Mode 1 sea level anomaly (Table 3, Figure 4), based on the nearest main port at Dunedin.

[29] When taken as a whole, the sea level trends show a high level of coherence, particularly when given New Zealand's position on a very active plate boundary. In the absence of some countervailing effect, they provide the best evidence yet to suggest that over the last 80 years any relative, vertical, differential tectonic motion on the east coast of New Zealand, has been small. (Update: Outside this analysis period, the recent Christchurch earthquakes of 2010–2011 have caused an uplift of the Lyttelton tide gauge of about 0.10 m (P. Denys, University of Otago, personal communication, 2011).) This observation of small relative vertical motion corresponds with the results from continuous GPS (cGPS) data collected at the Ports of Auckland, Lyttelton (prior to the recent earthquakes), and Dunedin over the last 10 years [*Hannah et al.*, 2010]. These data show no evidence of any differential tectonic motion at these sites. However, the situation at Wellington (cGPS data since 2000) and Nelson (cGPS data since 2003) is not so clear. The analyses of these cGPS data indicate the presence of small but ongoing subduction events (P. Denys, University of Otago, personal communication, 2011), further complicated by the likely presence of slow seismic events [e.g., *Wallace and Beavan,* 2010]. These cGPS data are currently the subject of more extended and ongoing analyses.

[30] At a detailed level, it is tempting to seek explanations for the lower estimates of inferred sea level rise at Dunedin and perhaps to a lesser extent, at New Plymouth. From a practical point of view, the reconstruction of the long-term tide gauge record at Dunedin has always been considered difficult, particularly in regard to maintenance of the tide gauge datum. This issue was raised in *Hannah* [2004], where it was noted that in terms of overall quality and continuity of data, the Dunedin gauge is the poorest of the four long-term gauges in New Zealand. While not reflected in the formal error estimates, there is considerably less confidence in this result than at the other gauges.

[31] As regards the result from New Plymouth, we note that it is the only station geographically located on the west coast of New Zealand. Unfortunately, there is no local cGPS receiver producing data that might allow an assessment of any recent tectonic motion. Being a west coast site it is oceanographically different from the other sites, perhaps with the exception of Nelson, but recent sea level measurements show the ENSO signal in sea level at New Plymouth is highly coherent with the pattern at Moturiki on the east coast. The EOF analysis of *Sasaki et al.* [2008] also confirms that decadal variability in sea level in the Tasman Sea to the west of New Zealand is similar to the east coast.

[32] The six new estimates of the relative sea level rise provide a weighted mean estimate of 1.7 ± 0.1 mm yr^{-1}, a result that is completely consistent with the results as calculated from the four long-term gauge records. Even if Nelson is excluded, the average estimate remains unchanged. In addition and in a global context, this average trend in relative sea level rise is also consistent with the results of *Church and White* [2011], who find a global average linear trend in secular sea level rise of 1.7 ± 0.2 mm yr^{-1} from 1900–2009 and 1.9 ± 0.4 mm yr^{-1} since 1961. Importantly, *Church and White* [2011] specifically note the paucity of Southern Hemisphere gauges, finding less than ten with pre-1940 records, a number that had increased to about 50 sites by 1960.

[33] At a regional (Australasian) level, there are only three other long-term gauge records, the two most reliable of which are found at Freemantle (Indian Ocean) and Fort Denison–Sydney (Tasman Sea). The linear trend of relative sea level rise at Freemantle is 1.5 mm yr^{-1} and at Sydney 0.9 mm yr^{-1} (P. Watson, New South Wales Department of Environment Climate Change and Water, personal communication, 2011). The disparity between the trend at Fort Denison and those at Auckland and Freemantle is of ongoing research interest that would be aided by the installation of cGPS monitoring equipment at the Sydney site.

6. Conclusions

[34] While clearly with some limitations, old MSL datum records can have value in helping to assess and constrain regional sea level change, provided the tide gauges are currently 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 interannual and decadal sea level variability 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 rigor 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, mining, or groundwater withdrawal. They thus have value to the scientific community, planners and engineers who seek additional data that might assist with decision-making on coastal development, coastal hazard assessments, and engineering design that needs to accommodate ongoing relative sea level rise. They also have value in adding to the wider global picture of sea level rise, particularly in the South Pacific where there have historically been few reliable >50 year gauge records with data predating 1950.

[35] It is important to note that this project would have been impossible to complete had the former New Zealand 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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