Sea Level Rise and Continuous GPS in New Zealand – Summary

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Introduction

Global sea level change can be estimated by averaging the mean sea level (MSL) change as determined from a globally distributed set of long-term tide gauge (TG) records. Because tide gauges actually measure Relative Sea Level change (RSL), i.e., the difference between the change in sea level and the change in the vertical position of the adjacent land, one source of bias in these MSL estimates is regional vertical crustal motion, due, for example, to tectonic activity, gas/oil/water extraction or glacial isostatic adjustment.

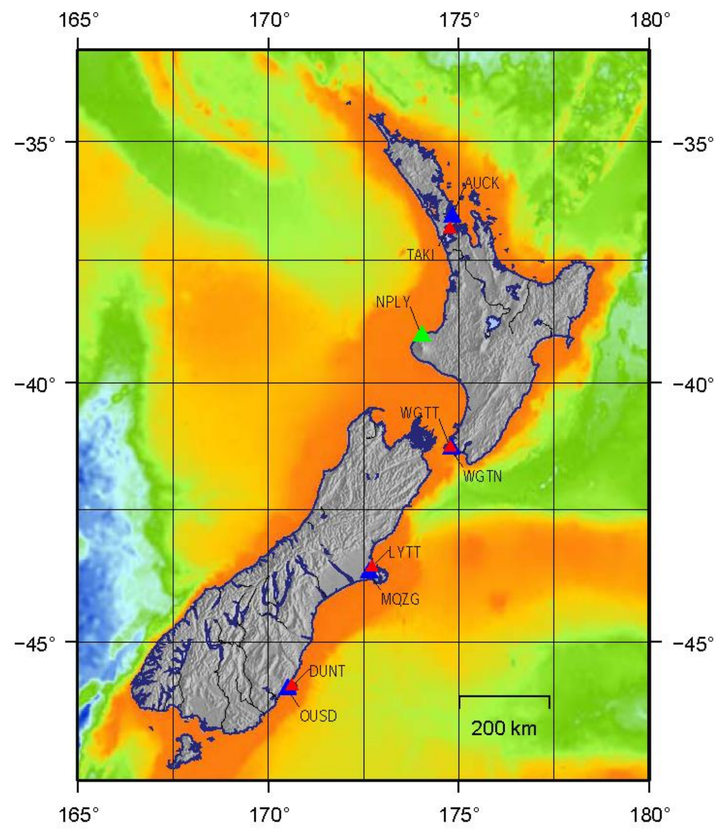

Figure 1: Location of New Zealand's cGPS at tide gauge sites (red triangles), each of which has a nearby reference cGPS site (blue triangles). The green triangle labelled NPLY is the cGPS site closest to the New Plymouth tide gauge, but this gauge does not have a cGPS at the tide gauge site. In the bathymetry image, the orange colour indicates continental crust while green through blue shows progressively deeper oceanic crust.

This study provides an updated estimate of the long-term RSL change at four tide gauges in New Zealand (*Figure 1*) using data through to 2013 are provided - an additional 13 years compared to the previous study. Using a long-term series of TG data, an estimate of RSL change at a fifth New Zealand tide gauge (New Plymouth) is also included.

The rate of vertical crustal motion at four sites (Auckland, Wellington, Lyttelton and Dunedin) using up to 15 years of continuous (cGPS) data has also been determined. However, earthquake events and slow slip events (SSE) have had a major impact on the vertical component at three sites (Wellington, Lyttelton and Dunedin).

Tide Gauge Record

The procedures outlined by *Hannah* [1990] were used in the analysis of the tide gauge records reported here. While the mathematical model can be used to estimate any unknown datum offsets, this feature was only used at Wellington where a new TG was installed in a new location in 1944 (but with an unknown vertical offset). This is described in greater detail in *Hannah* [1990]. The model not only calculates the linear trend of the TG record, but additional terms are included to account for annual variations in MSL due to pressure and temperature variations as well as the influence of the two long term lunar tides (8.85 and 18.6 years).

A critical step in deriving the RSL rates has been the assessment of the reliability of the tide gauge records. This issue has previously been discussed in *Hannah* [1990; 2010]. As part of this project, however, a complete reassessment of all the datum information related to each of the existing long-term TG records was undertaken. In addition, a first complete assessment of the New Plymouth gauge was undertaken.

The Auckland data from 2001-2013 were sourced from Land Information New Zealand who applied a + 0.0347 m datum correction for the period 1 January 2001 – 8 May 2003 prior to delivery of the data. On 1 January 2001 a new gauge commenced operation but in May 2003 its zero level was found to be incorrectly set. We follow Land Information New Zealand in assuming that this correction is applicable for the entire 2.35-yr period. The reconstruction of the data from New Plymouth from 1956 – 1973 was a particularly difficult task with a number of datum shifts (typically of one, two or three feet) being encountered. There were also periods of time when this gauge did not function satisfactorily. At Lyttelton the reassessment of the gauge history resulted in three small corrections being made to the tide pole zero from 1956 – the present day. These corrections differ from those applied in previous analyses. In addition, the tide pole zero was changed by –0.293 m in 2001. The Christchurch earthquake sequences have added a further complication. The data for 2010-2012 have been sourced from Land Information NZ who, prior to supplying the TG files, had corrected them for the uplift associated with the various Christchurch earthquakes sequences (G. Rowe, personal communication). Finally, at Dunedin, and with the advantage of new levelling, a previous assumption that the entire tide gauge data should be corrected for wharf subsidence since 1964 was found to be incorrect.

Tide Gauge Trends

The results from the new and historical analyses of RSL change at Auckland, Wellington, Lyttelton and Dunedin are given in Table 1. These data, together with the most recent trends, are shown in Figure 2.

Auckland

Since 1990, the trend at Auckland has increased by 0.21 (± 0.14) mm/yr, a time interval that covers several El Niño – Southern Oscillation (ENSO) cycles and perhaps one Interdecadal Pacific Oscillation (IPO) cycle (Hannah and Bell, 2012). Given that the influence of these periodic phenomena would be expected to have been averaged out over the intervening 23 years, the increase in trend, while not yet statistically significant, is nevertheless of interest.

Table 1: Relative sea level trends with their associated standard deviations

	Hannah (1990) (mm/yr)	Hannah (2004) (mm/yr)	This paper (mm/yr)
Auckland	1.34 ± 0.11	1.30 ± 0.09	1.55 ± 0.08
New Plymouth			1.31 ± 0.28
Wellington	1.73 ± 0.27	1.78 ± 0.21	2.14 ± 0.16
Lyttelton	2.26 ± 0.14	2.08 ± 0.11	1.98 ± 0.09
Dunedin	1.36 ± 0.15	0.94 ± 0.12	1.36 ± 0.08

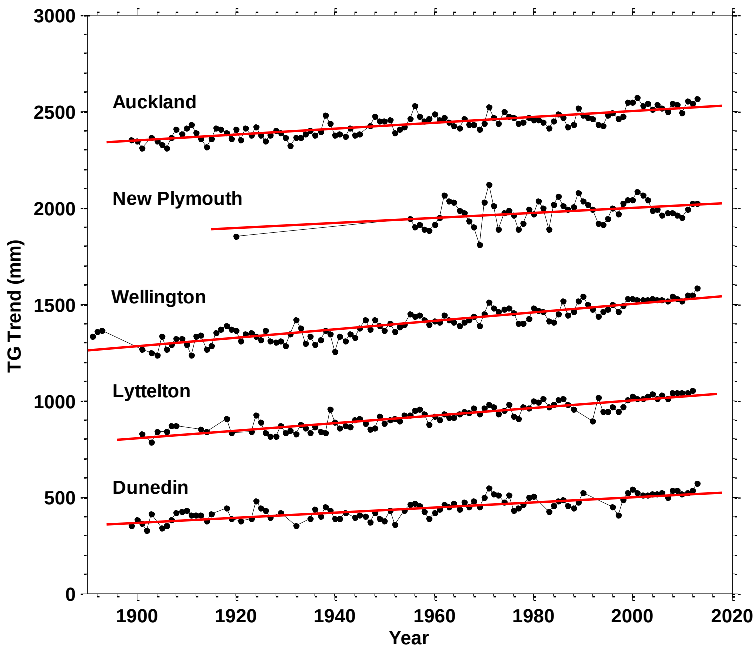

Figure 2: RSL trends with an arbitrary vertical offset applied to each sea level

New Plymouth

The sea level trend at the New Plymouth tide gauge has not previously been determined from a long-term series of data. The record, particularly between 1955 and 1976, is influenced significantly by datum shifts of one type or another. A great deal of effort was spent in attempting to resolve these issues with the information available. The RSL trend is strongly influenced by the mean value for RSL for the period 1918-1921. This single value, which was found in old correspondence files, is known to have been derived from the original tide charts. Unfortunately, these charts were discarded decades ago, making verification impossible. The RSL trend, while lower than at other ports, has a standard deviation that reflects both the shorter span of data and its inherent uncertainties.

Wellington

Much of the pre-1944 Wellington data is not based upon annual MSLs, but rather upon annual mean tide levels [*Hannah*, 1990]. As a consequence, most of the pre-1944 data has been given larger standard deviations (thereby down-weighting it) in the trend solution. As the time series of high quality data extends, so the standard deviation of the resulting trend diminishes. As with Auckland, the IPO and ENSO cycles are known to be present in the data but once again should have little influence on the calculated change in trend (0.41 ± 0.31) mm/yr since 1990.

Lyttelton

In previous analyses, the linear trend derived from RSL data at the Lyttelton gauge has been higher than the New Zealand average. It has been hypothesised in the past that the primary reason for this has been the lack of data prior to 1924 [*Hannah*, 1990]. While this is still likely, the revised assessment of the datum history has had by far the greatest influence in reducing the previous trend value. Due to as yet unresolved problems with the 2013 TG data, the analysis here extends only to the end of 2012.

Dunedin

The linear RSL trend in Dunedin has shown the greatest change since the 2004 analysis. This is due to new evidence that points to the stability of the wharf pile to which the gauge is attached. In the 1990 analysis the wharf pile was assumed to be stable, but in the 2004 analysis the pile was assumed to be sinking along with nearby local benchmarks. However, new levelling collected over the last decade has confirmed both the stability of the wharf pile and the instability of the nearby local benchmarks. The trend thus reverts back to a similar figure as derived in the 1990 analysis when the gauge was assumed stable.

Table 2: Estimated vertical rates from cGPS. For each TG location, the last line is the trend derived directly from the differenced (or baseline) time series. The errors shown are standard deviations. The last two columns indicated the number of offsets and Slow Slip Events (SSE) in the time series.

		Span (years)	Trend (mm)	σ (mm)	Offsets	SSE
Auckland						
	AUCK	14.9	-0.14	±0.04	3	
	TAKL	6.0	-0.69	±0.07	-	
	AUKT	5.1	-0.80	±0.12	1	
	TAKL + AUKT	13.3	-0.74	±0.04	2	
New Plymouth						
	NPLY	11.7	-0.88	±0.04	1	
Wellington						
	WGTN	14.9	-3.61	±0.05	3	2
	WGTT	14.9	-3.25	±0.04	2	2
Lyttelton						
	MQZG	14.9	-1.25	±0.05	7	
	LYTT	14.7	-0.45	±0.03	4	
Dunedin						
	OUSD	14.9	-0.22	±0.04	2	
	DUNT	14.9	-0.77	±0.04	1	

Continuous GPS Trends

Each TG site has a continuous GPS (cGPS) site collocated with the long term TG recorder. The sites were established in 1999-2001 and have been running for approximately 15 years. The exception is

Auckland, where the TG site was moved to a new location that necessitated new cGPS site. The trend for both sites is shown as TAKL+AUKT in Table 2.

Table 2 tabulates the estimated trends at each site and the precision is given as standard deviations. The precision estimates are based on a white noise model that is acknowledged as being optimistic. Although not reported here, other models can be used that generally give precisions in the range ±0.2-±0.5 mm/yr.

Auckland

The tide gauge at Ports of Auckland was relocated in 2007. This has resulted in the relocation of the original cGPS, TAKL (July 2001 – July 2007), with a second site, AUKT (September 2009 – to date). The measured subsidence of the combined time series (TAKL + AUKT) is consistent with the two separate time series (Figure 3).

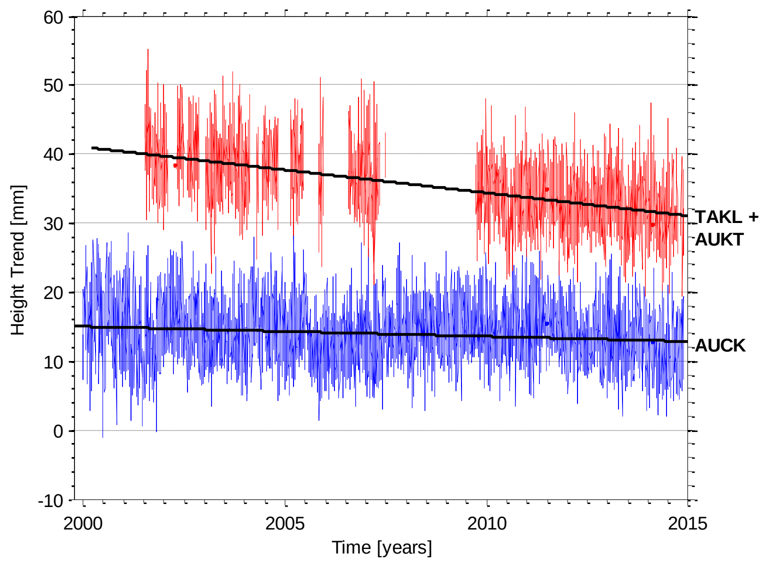

Figure 3: Height time series for AUCK and TAKL+AUKT (Auckland region). The TAKL + AUKT time series combines two cGPS sites collocated with the tide gauge.

New Plymouth

There is no cGPS located at the the TG site (Port Taranaki). The vertical trend (Table 2) for the New Plymouth cGPS site (NPLY) is included for completeness, but the site is some 15km from Port Taranaki and situated on the northern slopes of Mt Taranaki (elevation 400m).

Wellington

The Wellington region is undergoing tectonic plate subduction where the Pacific plate is subducting under the Australian plate. The effects of the subduction is wide spread along the East Coast of the North Island from north of Gisborne, the Kapiti Coast and the north of the South Island. The rate of subduction in Wellington is over -3 mm/yr.

Subduction zones are associated with Slow Slip Events (SSE), where elevated levels of seismicity results in crustal deformation that occurs over days to months. These events repeat at regular intervals. For example Gisborne every 18-24 months and the SSEs on the Kapiti Coast have repeated twice in the last 15 years.

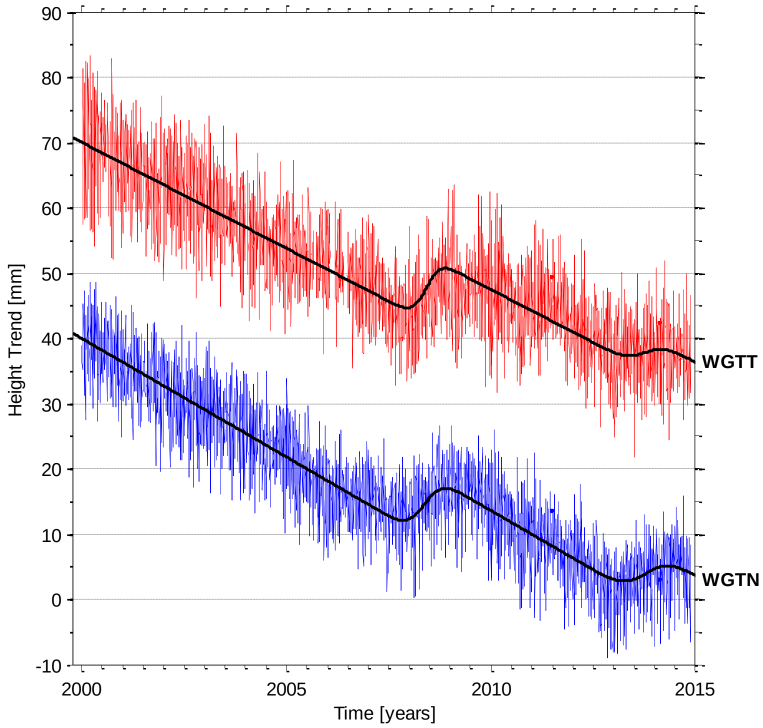

Figure 4: Height time series for WGTN and WGTT (Wellington region) showing the two Kapiti Coast SSE in 2008 and 2013

Figure 4 shows the two Wellington cGPS sites being subducted at rates greater than -3mm/yr but also being uplifted by the Kapiti Coast SSE in 2008 and 2013. The length of the SSE are 1 year and 1.3 years for the 2008 and 2013 events respectively, which has resulted in uplift of up to +10mm for each event.

Table 3: Rate of subsidence of the cGPS sites in the Wellington Region

Site	**Vertical Rate (mm/yr)**	**Trend over 15 years (mm)**	**SSE 2008 (mm)**	**SSE 2013 (mm)**	**Net Subsidence (mm)**
WGTT	-3.25	-48.8	+9.9	+5.1	-33.8
WGTN	-3.63	-54.5	+9.9	+8.2	-36.4

The effective rate of subsidence, taking into account the uplift caused by the SSE is therefore approximately -2.3 mm/yr (~-35mm over 15 years, Table 3). Although we have cGPS measurements for only 15 years, it can be assumed that the subduction combined with SSEs has been occurring for many years and presumably over the whole period of the TG measurements (>100 years). The rate of subduction combined with the regularity of the uplift caused by the SSEs will become clearer and better understood overtime as measurements continue.

Whether the net-subsidence rate is representative of the long term rate will only be verified in time. Since the TG RSL rate is similar to the other NZ RSL rates (and the global RSL rates), it can be hypothesised that, over time, the subduction and SSE uplift approximately cancel.

Lyttelton

The Christchurch earthquake events that occurred between September 2010 and December 2011 resulted in both regional subsidence and uplift. The two cGPS sites, MQZG and LYTT were uplifted by approximately +4 and +108 mm respectively. See Figure 5 and Table 4.

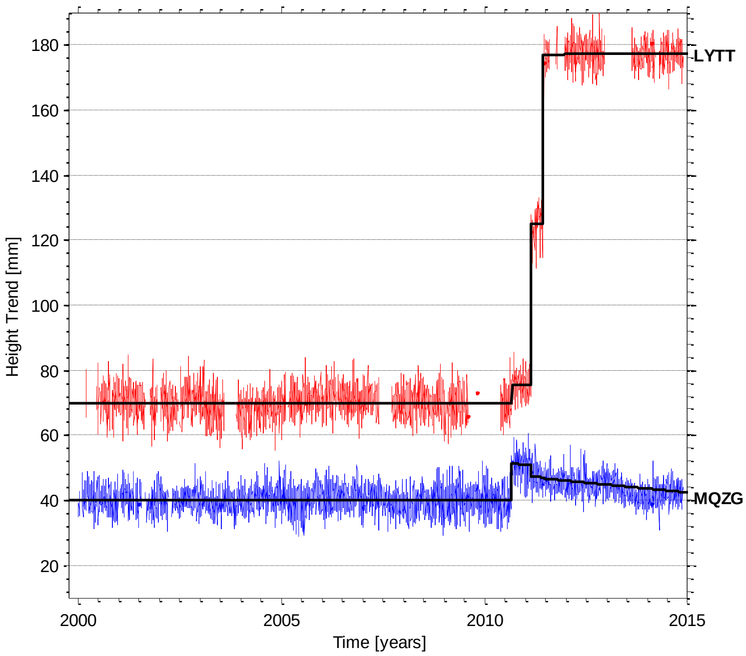

Figure 5: Height time series with offsets at MQZG and LYTT(Christchurch region). The offsets are caused by the Christchurch earthquake events in 2010 and 2011.

Table 4: Measured height offsets due to the Christchurch earthquake event between September 2010 and December 2011.

Site	Sep 2010 (mm)	Feb 2011 (mm)	Jun 2011 (mm)	Dec 2011 (mm)	Total (mm)
LYTT	5.5	49.6	51.8	0.6	107.5
MQZG	11.1	-4.0	-0.8	-2.5	3.8

Dunedin

The M_w 7.8 Dusky Sound earthquake in 2009 was a major earthquake that affected the whole region south of approximately Christchurch. The Dunedin (and Otago) region horizontal displacement was in the order of 20mm. There was also a small vertical offset approximately <5mm (Figure 6).

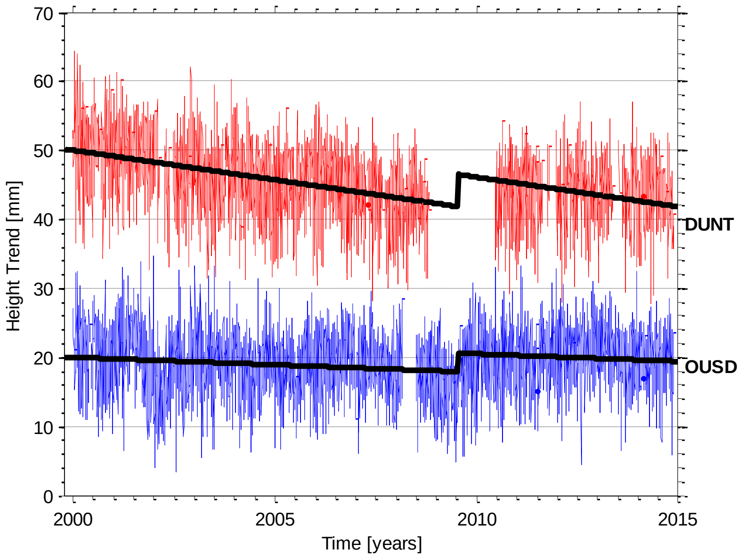

Figure 6: Height time series with offsets at OUSD and DUNT (Dunedin region). The offsets were caused by the Dusky Sound 2009 earthquake.

Summary

The updated analyses of the tide gauge data alone continue to support previously published information regarding RSLs in New Zealand.

Auckland has been unaffected by (vertical) tectonic activity and is currently the most stable tide gauge site in New Zealand. Wellington, Lyttelton and Dunedin have all been affected to various levels of tectonic plate motion over the last 15 years.

Wellington is in a region of plate subduction resulting in crustal subsidence that is periodically reduced SSEs that cause regional uplift. Lyttelton was significantly affected by coseismic uplift with a combined effect of ~110mm from the Christchurch 2010-11 earthquake events. Dunedin has been affected by the cosesmic uplift caused by Dusky Sound 2009.

This project has shown the significance of regional (vertical) tectonic signals and has demonstrated the importance of being able to measure accurately the generally unpredictable tectonic activity. It is anticipated that the cGPS (vertical) trend estimates will become more reliable as the time series of data lengthen.

References

Hannah, J. (1990), Analysis of mean sea level data from New Zealand for the period 1899-1988, *J. of Geophys. Res.,* 95(B8): 12399-12405.

Hannah, J. (2004), An updated analysis of long-term sea level change in New Zealand, *Geophys. Res. Letters*, 31(3): 3307-3307.

Hannah, J. (2010), The difficulties in using tide gauges to monitor long-term sea level change, in Proceedings, XXIV FIG International Congress, Sydney.

Hannah, J., and R. Bell (2012), Regional sea level trends in New Zealand, *J Geophys. Res.*, doi:10.1029/2011JC007591.