New Zealand’s Long Term Tide Gauge Record and the Effect of Seismically Induced Vertical Land Motion

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SUMMARY

New Zealand’s tide gauge record extends back over 100 years and is one of the oldest records in the Southern Hemisphere. The record therefore makes an important contribution to global sea level change studies. Tide gauge measurements record Relative Sea Level (RSL), which is the change between sea level and the land. Any local and/or regional vertical land motion (VLM) will affect the tide gauge and is therefore included in the tide gauge record. By measuring VLM at a tide gauge site we are able to determine true sea level changes. Typically VLM can be caused by gas/oil/water extraction, glacial isostatic adjustment or tectonic activity, which is thought to predominate throughout New Zealand.

In 2000, a combined Otago University and GNS Science project established continuous GPS (cGPS) at four of New Zealand’s long record tide gauges, namely Auckland, Wellington, Lyttelton and Dunedin, with the specific objective of measuring the VLM at each site. The rate of VLM at these four sites, as well as regional trends determined from nearby cGPS sites, has been determined using up to 20 years of cGPS data. However, the earthquake events in Christchurch and Fiordland as well as ongoing East Coast slow slip events (SSE) in the Wellington region have had a major impact on the vertical component. As a result, determining VLM has required the development of tools to model and correct for these transient effects.

In addition to the analysis of VLM at tide gauge sites, this project provides an updated estimate of the long-term RSL change at four tide gauges in New Zealand using data through to 2013 - an additional 13 years compared to the previous study. Data from a fifth New Zealand tide gauge (New Plymouth) has now been analysed and is also included.

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1. INTRODUCTION

Global sea level change can be estimated by averaging the change in mean sea level (MSL) as determined from a globally distributed set of long-term tide gauge (TG) records. Because tide gauges measure relative sea level change (RSL), i.e. the difference between the change in sea level and the vertical position of the adjacent land, one source of bias in MSL estimates is the combined effect of local and regional vertical land motion (VLM). Common causes of VLM include compaction, tectonic activity, gas/oil/water extraction or glacial isostatic adjustment.

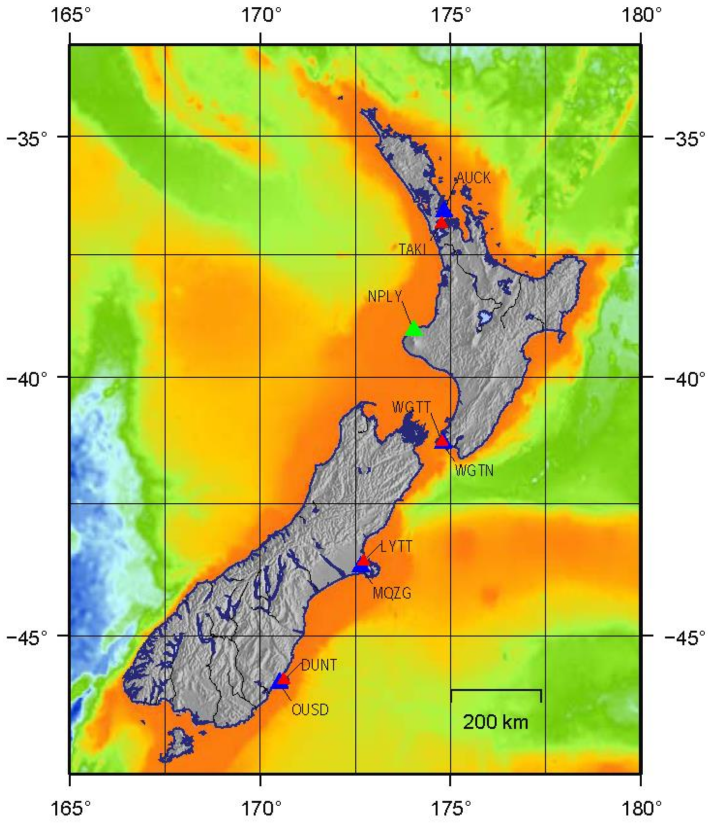

Figure 1: Location of New Zealand's cGPS at tide gauge sites (red triangles), each of which has a nearby reference cGPS site (blue triangles). The green triangle labelled NPLY is the cGPS site closest to the New Plymouth tide gauge, but this gauge does not have a cGPS at the tide gauge site. In the bathymetry 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 − 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 VLM 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 of these sites, namely Wellington, Lyttelton and Dunedin.

2. TIDE DAUGE 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 1944 (but with an unknown vertical offset). The model estimates the linear trend of the TG record and includes additional terms 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 (LINZ) 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 the advice of the tidal oficer at LINZ 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 to 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 LINZ 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.

3. 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.

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

3.1 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.

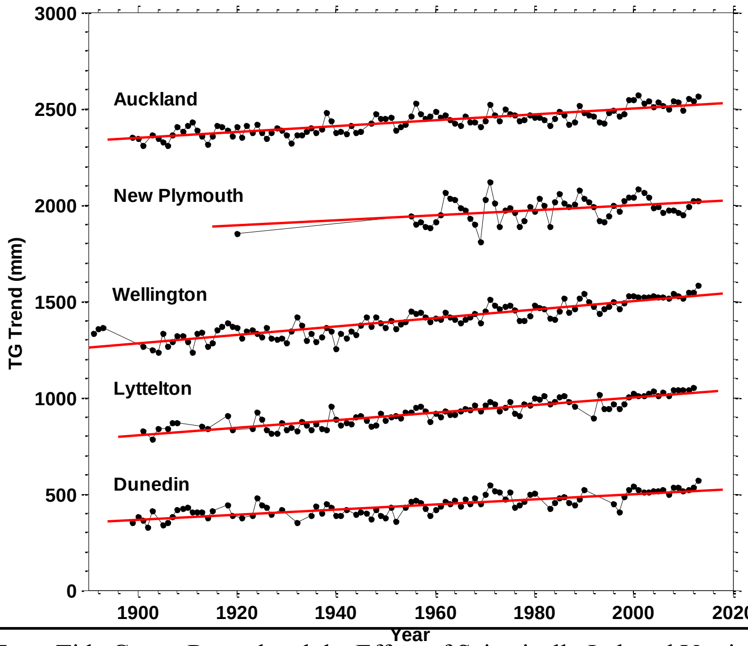

Figure 2: RSL trends with an arbitrary vertical offset applied to each sea level record.

3.2 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.

3.3 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.

3.4 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.

3.5 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.

4. CONTINUOUS GPS TRENDS

To measure VLM, a continuous GPS (cGPS) site was collocated at each TG site (except New Plymouth) in additon to a second cGPS site within 30km of the TG. The collocated cGPS were established in 1999-2001 and have been running for approximately 15 years.
The Bernese GNSS software V5.2 (Dach *et al.*, 2015) was used to process the GPS to determine daily positions in the ITRF2008 reference frame (see Denys *et al.* (2017) for a detailed description). Table 2 tabulates the estimated linear trends at each site and the precision is given as standard deviations. The uncertainity estimates are based on a white noise plus power law model estimated using the HECTOR software (Bos *et al*., 2013).

Additional parameters to account for sytematic height time series baises are also tabulated. These include offsets for equipment (antenna) changes and earthquake events and parameters for slow slip events and post seismic decay caused by large earthquake events. More detailed explanation of the mathematical models used is given in Denys and Pearson (2105, 2016).

4.1 Auckland

The tide gauge at the Ports of Auckland was relocated in 2007. This has resulted in the relocation of the original cGPS site, 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 (Table 2, Figure 3).

Table 2: Estimated vertical rates from cGPS. The errors shown are standard deviations based on a white noise plus power law model. The last four columns indicated the number of offsets, SSE and post-seismic decay events parameterised in each position time series.

		Span	**Trend**	**σ**	**Equipment**	**Earthquake**		
		(years)	**(mm/yr)**	**(mm/yr)**	**Offsets**	**Offsets**	**SSE**	**Log Decay**
Auckland								
	AUCK	19.9	-0.48	±0.12	3			
	TAKL	6.0	-0.63	±0.13				
	AUKT	5.1	-0.54	±0.19				
	TAKL + AUKT	14.1	-0.62	±0.05	1			
New Plymouth								
	NPLY	12.4	-0.99	±0.07	1			
Wellington								
	WGTN	19.2	-2.93	±0.06	2	2	3	
	WGTT	15.6	-3.09	±0.06		2	3	
Lyttelton								
	MQZG	15.6	-1.19	±0.14	3	5		1
	LYTT	15.4	-0.45	±0.03		5		1
Dunedin								
	OUSD	19.9	-1.17	±0.18	2	4		
	DUNT	15.9	**-0.73**	±0.29		4		

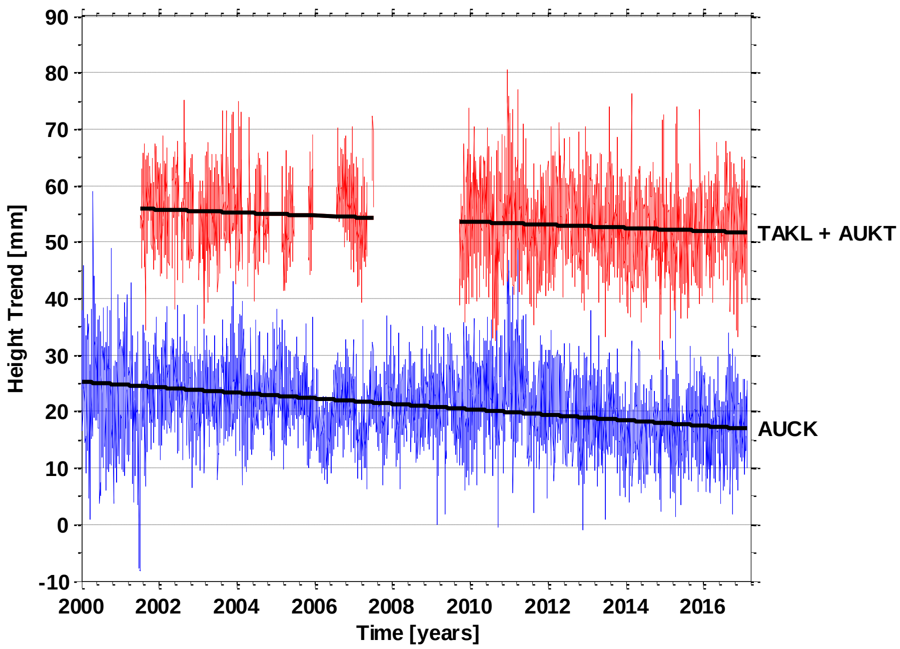

Figure 3: Height time series for AUCK and TAKL+AUKT (Auckland region). The TAKL + AUKT time series combines two cGPS sites collocated with the tide gauge.

4.2 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 located 15km from Port Taranaki on the northern slopes of Mt Taranaki at an elevation of 400m.

4.3 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 for over 500 km from north of Gisborne, along the Kapiti Coast to the northern South Island. The rate of subduction in the Wellington region is approximately -3 mm/yr (Table 3).

Subduction zones are associated with slow slip events (SSE), where elevated levels of seismicity results in crustal deformation that occurs periodically over days to months. These events repeat at regular intervals. For example, SSEs occour every 18-24 months at Gisborne and have repeated three times over the last 20 years on the Kapiti Coast.

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

Site	Vertical Rate (mm/yr)	15 years Subsidence (mm)	SSE 2008 (mm)	SSE 2013 (mm)	Net Subsidence (mm)
WGTT	-2.93	-43.9	+7.6	+3.1	-33.2
WGTN	-3.09	-46.3	+6.9	+6.8	-32.6

Figure 4 shows the two Wellington cGPS sites being subducted at rates close to -3 mm/yr, but also being uplifted by the Kapiti Coast SSE in 2008 and 2013 (a third SSE that finished in late 1999 is not shown). The length of the SSE are 1 year and 1.3 years for the 2008 and 2013 events respectively, which has resulted in a total uplift of +10 – +14 mm.

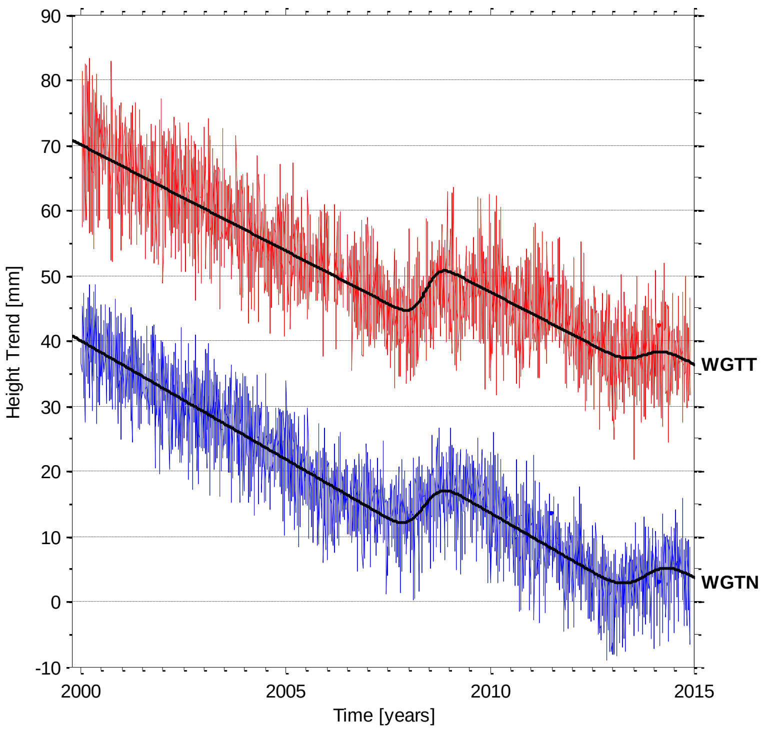

Figure 4: Height time series for WGTN and WGTT (Wellington region) showing the two Kapiti Coast SSE in 2008 and 2013

The effective or net rate of subsidence, taking into account the uplift caused by the SSE is therefore approximately -2.2 mm/yr (-33mm over 15 years, Table 3). Although we have cGPS measurements for nearly 20 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 over time.

Whether the net-subsidence rate is representative of the long term rate can only be verified with further measurements. 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 cancels approximately.

4.4 Lyttelton

The Christchurch earthquake events that occurred between September 2010 and December 2011 resulted in both regional subsidence and uplift. The coseismic uplift at the two cGPS sites, MQZG and LYTT, is approximately +4 mm and +108 mm respectively (Table 4 and Figure 5). In addtion, as the position time series lengthens, there is a small but significant post-seismic decay as a result of the Darfield (M_w 7.2) and February 2011 Christcurch (M_w 6.2) events.

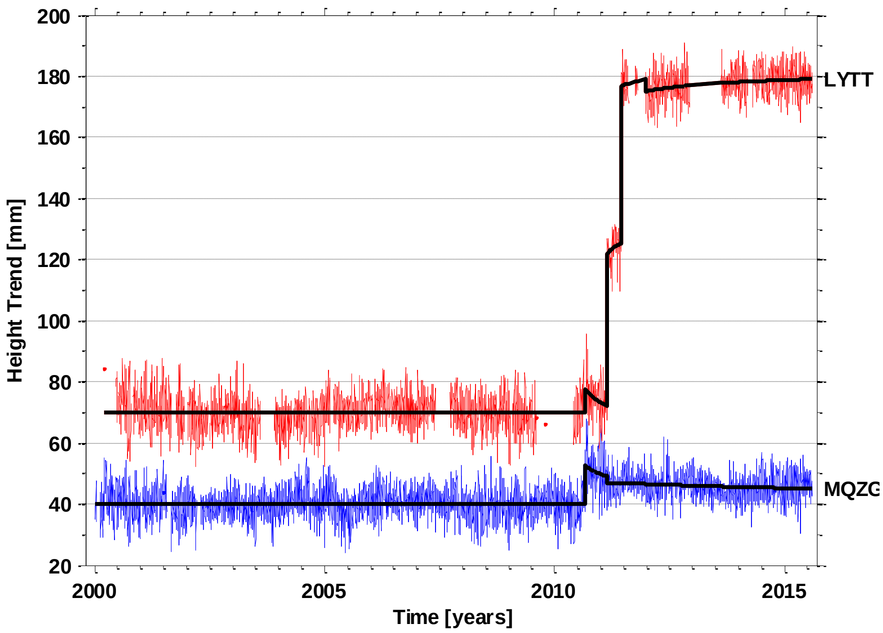

Figure 5: Height time series with offsets at MQZG and LYTT (Christchurch region). The offsets are caused by the Christchurch earthquake events in 2010 and 2011.

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

4.5 Dunedin

Since 2000, there have been four major earthquake events that have potentially resulted in VLM around Dunedin. These events include the 2003 Secretary Island (M_w 7.2), 2004 Macquarie Island (M_w 8.1), 2007 George Sound (M_w 6.7) and the 2009 Dusky Sound (M_w 7.8) earthquake that affected the whole region south of approximately Christchurch.

Table 5: Measured height offsets due to the Christchurch earthquake event between September 2010 and December 2011.

Site	SI 2003 (mm)	MI 2004 (mm)	GS 2007 (mm)	DS 2009 (mm)	Total (mm)
DUNT	-3.0	2.7	-1.0	+4.3	+3.0
OUSD	1.2	3.6	-1.0	+0.8	+4.6

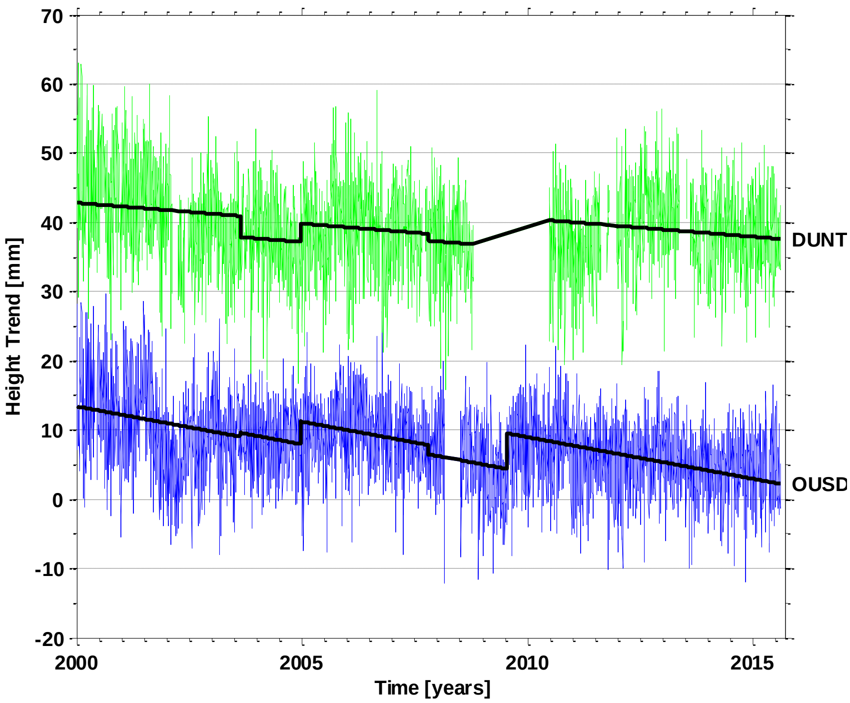

Figure 6: Height time series with offsets at OUSD and DUNT (Dunedin region). The offsets were caused by the Dusky Sound 2009 earthquake.

Although the offsets are small (Table 5), cumulatively they may contribute to VLM that results in net uplift (or subsidence) over time that is significant. The effect of the VLM is similar to that observed in the North Island East Coast subduction zone. The cumulative VLM will therefore affect the RSL measurements.

5. SUMMARY

The updated analyses of the tide gauge data alone continue to support previously published information regarding RSLs in New Zealand. However, collocated and near-by cGPS sites shows that VLM is significant at several New Zealand tide guage sites. Although the cGPS measurment record is relatively short (< 20 years), some VLM trends are apparent. Auckland is largely 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 land subsidence that is periodically reduced by SSEs that cause regional uplift. Lyttelton was significantly affected by coseismic uplift with a combined effect of ~110 mm from the Christchurch 2010-11 earthquake events. Ongoing post-seismic deformation continues to affect the lyttelton site. Dunedin has been affected by the cosesmic deformation caused by major regional earthquakes including Dusky Sound 2009. Although the effect of the VLM is small, it is likely to occour sufficently frequently to cummulatively offset at least some of the observed subsidence of the TG site.

This project has shown the significance of regional (VLM) 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.

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BIOGRAPHICAL NOTES

Paul Denys has been an academic staff member at the School of Surveying, Otago University since 1995.He teaches papers in Survey Methods and Survey Mathematics. His primary interest is GNSS positioning and geodetic data analysis with a focus on active deformation. New Zealand offers an excellent opportunity to study and understand the broad scale deformation of the Australian-Pacific plate boundary as well as focusing on specific problems: Central Otago and Cascade deformation, Southern Alps uplift and sea level rise. He has also been involved with the geodetic measurement analysis of many of the earthquake sequence that have occoured in recently in New Zealand and the maintenance of the geodetic infrastructure.

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