# Analysis of the Sea Level Change in New Zealand

R. Tenzer and V. Gladkikh

### Abstract

We analyse the sea level change in New Zealand using tide-gauge records available for over a century. The least-squares linear regression analysis is applied to estimate the linear and acceleration trends in (annual) mean sea level (MSL) data from tide gauges (TGs) in Auckland, Wellington, Lyttelton and Dunedin. The results reveal that the linear trends in relative sea level at these four TGs are between 1.2 mm/year (TG Dunedin) and 2.1 mm/year (TG Wellington). The relative sea level trend in New Zealand over the last century is estimated to be $1.7 \pm 0.1$ mm/year. The relative sea level trends are further corrected for the vertical land motions in order to assess the "absolute" sea level rise in New Zealand. The vertical land motions are investigated throughout New Zealand based on the analysis of GPS time series at 101 permanent sites. The GPS solutions are aligned to the ITRF2000 reference frame. The prevailing pattern of vertical motions in New Zealand is dominated by tectonic subsidence in the lower North Island, while the largest tectonic uplift is detected across the central Southern Alps in the South Island. The estimated rates of absolute sea level rise at the four TGs (co-located with GPS) are between 0.4 mm/year (TG Wellington) and 1.8 mm/year (TG Lyttelton). Based on these estimates, the absolute sea level in New Zealand raised over the last century at an average rate of $1.1 \pm 0.3$ mm/year.

### Keywords

GPS • Sea level rise • Tide-gauge records • Vertical land motion

## 1 Introduction

Because of the lack of long term (>60 years), reliable sea level records in the southern hemisphere and their relatively low spatial coverage, the sea level data from TGs in New Zealand represent an important information for studying the global sea level change (Hannah 2004). These data have been collected over a century at TGs located at the ports of Auckland, Wellington, Lyttelton and Dunedin. Hannah (1988) analysed the MSL trends in New Zealand from historical tidal data. A first analysis of the tide-gauge records was reported by Hannah (1990) with a limited, more detailed higher-frequency analysis of the Auckland data being reported by Goring and Bell (1999). A more recent, updated analysis of the long-term sea level trends in New Zealand can be found in Hannah (2004) and Hannah and Bell (2012).

In the aforementioned studies, the relative sea level trends were analyzed without taking into consideration tectonic and other vertical motions. This is due to the fact that until recently studies investigating vertical land motions over the entire New Zealand have not been completed. In contrary, horizontal motions have been studied extensively by Bourne et al. (1998), Beavan et al. (1999, 2002, 2007), Beavan and Haines (2001), Beavan and Blick (2005), and others. The existing studies of vertical motions have been

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focused primary on the Southern Alps due to their close proximity to the Pacific and Australian plate boundary (see e.g., Wellman 1979; Bull and Cooper 1986). More recently, Beavan et al. (2004, 2010) investigated the rate of relative vertical movement across the central Southern Alps. The first study of vertical motions over the whole New Zealand was completed by Tenzer et al. (2012). They used the regionally-filtered GPS time series at 101 sites situated throughout the country. The regional studies of horizontal and vertical crustal motions due to ocean-tide and atmospheric loadings can be found in Gladkikh and Tenzer (2011) and Tenzer et al. (2011). The crustal deformations in New Zealand caused by the pole motion were studied by Marinovich and Tenzer (2011).

In this study we use the annual MSL datasets at TGs in Auckland, Wellington, Lyttelton and Dunedin to estimate the relative sea level trends in New Zealand over the last century. The MSL data were prepared by Hannah (2009) according to the procedure described in detail by Hannah (1990). This procedure utilises the University of Hawaii's data processing strategy and it is described by Caldwell (1998). The analysis of MSL data is done in Sect. 2. There are several limiting aspects making the estimation of absolute sea level changes difficult. The major reasons are attributed to the realisation and definition of the global reference frame as well as to uncertainties in estimated values of the GPS vertical velocities. These aspects are discussed for instance by Blewitt (2004); see also Beavan (2005). Despite these deficiencies, we conduct the preliminary assessment of the absolute sea level rise in Zealand based on available MSL and GPS data at TGs (which are co-located with GPS sites). The tectonic setup and vertical land motions in New Zealand are first briefly reviewed in Sect. 3. The estimation of the actual sea level trends is then done in Sect. 4. Summary and concluding remarks are given in Sect. 5.

## 2    Relative Sea Level Trends

The least-squares linear regression analysis was applied to estimate the linear trends in relative sea level. We used the annual (i.e., seasonally-corrected) MSL data at TGs in Auckland (over the period between 1899–2008), Wellington (1891–2008), Lyttelton (1901–2008) and Dunedin (1899–2008). The annual MSL data and the corresponding sea level trends at these TGs are plotted in Fig. 1. The estimated linear trends and their ($1-\sigma$) uncertainties are summarised in Table 1.

The relative sea level changes are between 1.2 mm/year (TG Dunedin) and 2.1 mm/year (TG Wellington). The ($1-\sigma$) uncertainty of estimated linear trends is the same 0.1 mm/year at each TG. The average rate of sea level rise in New Zealand is $1.7 \pm 0.1$ mm/year. This figure is very similar to that given by Hannah (2004) and Hannah and Bell (2012). Hannah (2004) reported that relative sea levels in New Zealand have been rising at an average rate of 1.6 mm/year over the last century. Hannah and Bell (2012) acquired based on the analysis of MSL data taken from six TGs in New Zealand that the average relative sea level rise is $1.7 \pm 0.1$ mm/year.

## 3    Vertical Land Motions

The regionally-filtered GPS time series at 101 stations of the New Zealand's GeoNet permanent GPS network (28 GPS sites in the South Island and 73 GPS sites in the North Island) were used to estimate the rates of vertical land motions throughout New Zealand. The strategy used for processing GPS data including the outlier detection and regional filtering procedure are described in detail by Beavan (2005, 2009). He utilised the methodology of Williams et al. (2004) to model the spatially correlated noise signal in GPS data. The estimated rates of vertical motions in New Zealand are shown in Fig. 2. These vertical velocities are aligned to the ITRF2000 reference frame (note that GPS results defined in more recent ITRF solutions have not yet been publically released by the GNS Science).

Despite a low spatial coverage of permanent GPS stations in some parts of the country, general features of systematic vertical motions are clearly exhibited in Fig. 2. The upper region of the North Island is without the presence of significant vertical motions; the maximum rates there are below 1 mm/year. The subduction of the Australian tectonic plate beneath the Pacific plate results in large vertical motions in the lower North Island. The maximum rates of tectonic subsidence there reach ∼10 mm/year. Both, the localized uplift as well as subsidence detected along the Central Volcanic Zone (typically within ±5 mm/year), are more likely to be associated with active volcanic and geothermal processes in this part of the country. The vertical motions in the South Island are characterised by tectonic uplift along the Southern Alps, with the maximum rates up to ∼5 mm/year. This tectonic uplift is coupled by systematic subsidence detected on both sides of the Southern Alps. The maximum rates of subsidence of ∼2.5 mm/year are identified in the northwest region. The observed rates of subsidence along the east coast of the South Island are much smaller; typically less than 1 mm/year.

The detected tectonic uplift of the Southern Alps of ∼0.5 cm/year very closely agrees with the values given by Beavan et al. (2010). Wellman (1979) used geochronological data to compile a map of vertical tectonic motions for the whole South Island. From his results, the maximum uplift along the Southern Alps reaches 10 mm/year with the velocity rates of 1–7 mm/year along the Alpine Fault
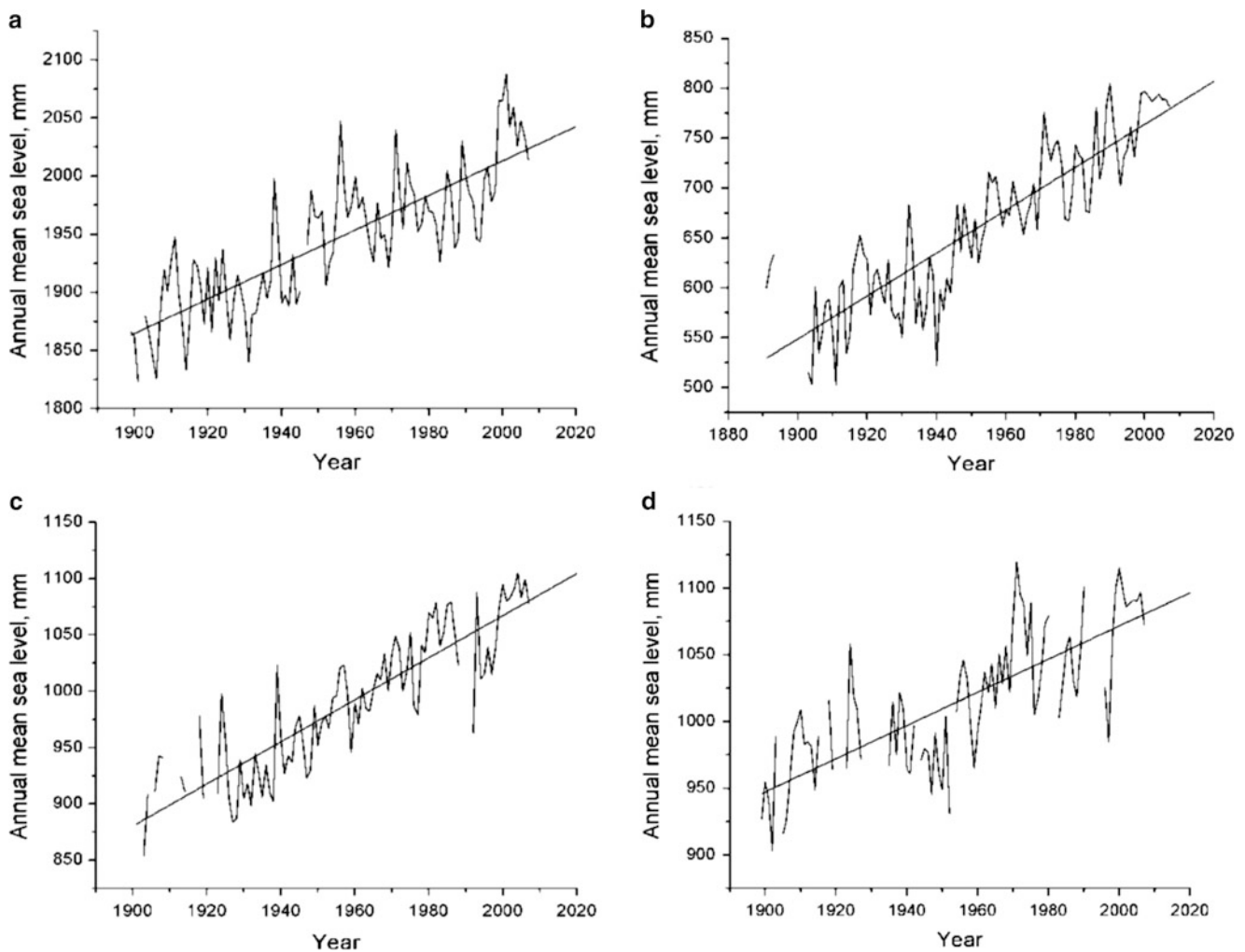
**Fig. 1** The linear trends in annual MSL data at TGs in: (**a**) Auckland, (**b**) Wellington, (**c**) Lyttelton and (**d**) Dunedin

**Table 1** The linear trends in MSL data and their ($1-\sigma$) uncertainties at four TGs in New Zealand

| TG | Relative sea level change (mm/year) |
|---|---|
| Dunedin | $1.2 \pm 0.1$ |
| Lyttelton | $1.9 \pm 0.1$ |
| Wellington | $2.1 \pm 0.1$ |
| Auckland | $1.5 \pm 0.1$ |

further decrease to less than 1 mm/year in the southeast and northwest parts of the South Island. The uplift rates estimated by Wellman (1979) throughout the Southern Alps agree with more recent estimates from the geochronological data by Tippett and Kamp (1993), but are larger than results obtained from GPS data analysis. Elsewhere in the South Island the vertical velocity rates at GPS sites are similar to the results from the geochronological data (Wellman 1979; Tippett and Kamp 1993).

The plate boundary between the Pacific and Australian tectonic plates in New Zealand does not have a single location. Instead, it is a broad zone of deformation covering much of the country as well as the offshore area of the Tasman Sea along the west coast of the South Island and the offshore area of the Pacific Ocean along the east coast of the North Island. Despite this broad band of deformation, the Alpine Fault in the South Island can be considered as the boundary between these two tectonic plates, while the position of the whole North Island can be attributed to the Australian tectonic plate (cf. Wallace et al. 2004, 2007). Statistics of the GPS vertical rates for this single-boundary tectonic configuration are summarized in Table 2. The average vertical velocity rates at GPS sites situated on the Pacific and Australian plates are 0.5 and −1.4 mm/year respectively.

## 4 Absolute Sea Level Trends

The estimated vertical motions at GPS sites which are co-located with TGs in Auckland (GPS site TAKL), Wellington (GPS site WGTT), Lyttelton (GPS site LYTT) and Dunedin (GPS site DUNT) were used to correct the
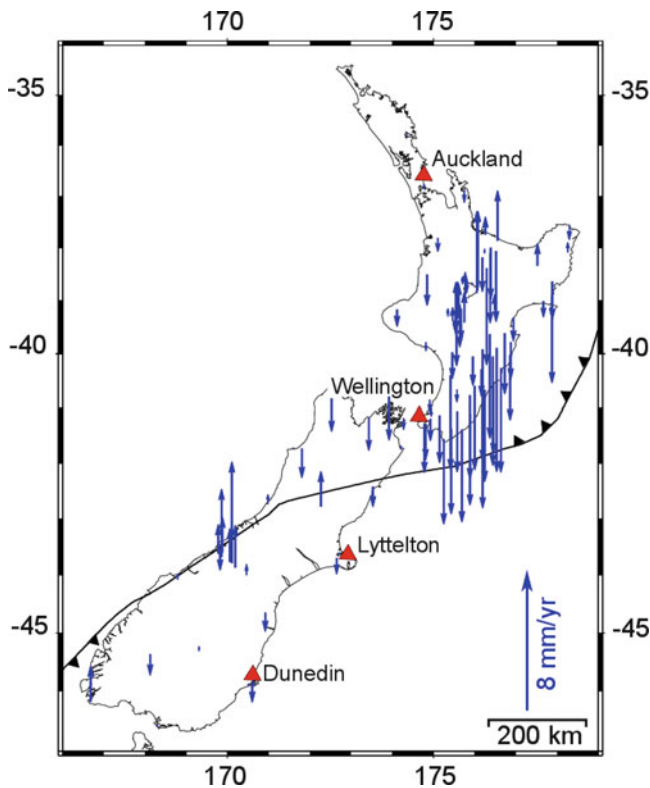
**Fig. 2** The estimated rates of vertical land motions at 101 GPS sites in New Zealand

**Table 2** Statistics of the GPS vertical velocity rates for the adopted single-boundary configuration of the Pacific and Australian tectonic plates in New Zealand

| Tectonic plate | Min (mm/year) | Max (mm/year) | Mean (mm/year) |
|---|---|---|---|
| Pacific | −1 | 5 | 0.5 |
| Australian | −10 | 5 | −1.4 |

**Table 3** The estimated trends in relative sea level (RSL), vertical land motion (VLM) and absolute sea level (ASL) with their (1−σ) uncertainties at four TGs in New Zealand

| TG | RSL (mm/year) | VLM (mm/year) | ASL (mm/year) |
|---|---|---|---|
| Dunedin | $1.2 \pm 0.1$ | $-0.4 \pm 0.4$ | $0.8 \pm 0.4$ |
| Lyttelton | $1.9 \pm 0.1$ | $-0.1 \pm 0.2$ | $1.8 \pm 0.2$ |
| Wellington | $2.1 \pm 0.1$ | $-1.7 \pm 0.3$ | $0.4 \pm 0.3$ |
| Auckland | $1.5 \pm 0.1$ | $-0.2 \pm 0.4$ | $1.3 \pm 0.4$ |

relative sea level trends. The computed actual sea level trends and their (1−σ) uncertainties at four TGs are given in Table 3. The absolute sea level rise in New Zealand (obtained based on averaging these estimates) is $1.1 \pm 0.3$ mm/year.

As seen from the results in Table 3, the sea level trends decreased considerably when corrected for the vertical land motion. The largest change between the relative and absolute sea level trends at TG in Wellington is due to the large rates

of subsidence detected in the lower North Island. Elsewhere, these differences are less pronounced. This is due to the fact that TGs in Auckland, Lyttelton and Dunedin are situated at relatively tectonically stable locations with the rates of subsidence 0.4 mm/year or less.

The errors in GPS vertical velocity rates represent the largest contribution to the uncertainties of estimated absolute sea level trends. These errors are about two to four times larger than the corresponding errors in estimated MSL trends. There are several reasons causing this inconsistency, among others the short GPS data availability (typically only over the last decade) compared to over a century long recording of sea level.

## 5    Summary and Concluding Remarks

The relative sea level in New Zealand raised over the last century at an average rate of $1.7 \pm 0.1$ mm/year. This figure was obtained based on the analysis of annual MSL data at four TGs in Auckland, Wellington, Lyttelton and Dunedin.

The locations of TGs in Auckland, Lyttelton and Dunedin are relatively stable; the detected rates of subsidence there are 4 mm/year or less. The sea level recorded at TG in Wellington is substantially affected by the presence of a significant subsidence at an estimated rate of 1.7 mm/year.

According to estimates of the relative sea level trends and the GPS vertical velocity rates at four TGs (co-located with GPS sites), the absolute sea level in New Zealand raised at a rate of $1.1 \pm 0.3$ mm/year over the last century. This value is significantly smaller than the average rate of relative sea level rise. This indicates that a special attention must be given to the analysis of vertical land motions when predicting the sea level rise in New Zealand.

We expect large uncertainties in the estimated absolute sea level trends especially due to errors in the estimated GPS vertical velocity rates. These errors are about two to four times larger than errors in the estimated MSL trends. The main reason is a relatively short period of GPS time series compared to over a century long recording of MSL data used for the analysis in this study.

Despite MSL data collected at TG in Wellington have shown the largest relative sea level rise (of 2.1 mm/year), the corresponding absolute sea level trend (of 0.4 mm/year) is much smaller. Since this region is relatively tectonically unstable and seismically active, this figure of absolute sea level rise might be unrealistic. Here, a careful inspection of MSL and GPS data is required. Moreover, altimetry data and other available geophysical evidence (such as the analysis of salt march coastal deposits) should be used to validate the results.

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