GEOPHYSICAL RESEARCH LETTERS, VOL. 31, L03307, doi:10.1029/2003GL019166, 2004

An updated analysis of long-term sea level change in New Zealand

J. Hannah

School of Surveying, University of Otago, Dunedin, New Zealand

Received 25 November 2003; accepted 15 January 2004; published 12 February 2004.

[1] The original analysis of long-term sea level change in New Zealand is updated with a new and extended analysis. In this new analysis the original hourly sea level data have been re-examined to remove obvious errors that were still present, new data covering the period 1989–2000 has been added, and the sea level record for Wellington extended by the inclusion of recently discovered data covering the years 1891–1893. These new results indicate that relative sea levels in New Zealand have been rising at an average rate of 1.6 mm/yr over the last 100 years - a figure that is not only within the error bounds of the original determination, but when corrected for glacial-isostatic effects has a high level of coherency with other regional and global sea level rise determinations. There continues to be no evidence of any acceleration in relative sea levels over the record period. *INDEX TERMS:* 4556 Oceanography: Physical: Sea level variations; 1223 Geodesy and Gravity: Ocean/Earth/atmosphere interactions (3339); 1635 Global Change: Oceans (4203); 1229 Geodesy and Gravity: Reference systems; 8150 Tectonophysics: Plate boundary—general (3040). **Citation:** Hannah, J. (2004), An updated analysis of long-term sea level change in New Zealand, *Geophys. Res. Lett.*, *31*, L03307, doi:10.1029/2003GL019166.

1. Introduction

[2] In the last two decades, interest in long-term changes in global sea levels has increased greatly due to the linkages between such changes and a variety of scientific and environmental outcomes. These linkages include (but are not limited to), the geophysical processes associated with glacial-isostatic adjustment [*Peltier*, 1999], the physical processes associated with climate change [*Gornitz*, 1995], the environmental issues associated with coastal erosion and inundation [*Douglas et al.*, 2001], and the legal issues associated with defining coastal jurisdictional boundaries [*Hannah*, 1999].

[3] There is a consensus view that on average global absolute sea levels have risen in the last 100 years by between 1 and 2 mm/yr, with a favoured value towards the mid to upper end of this range [*Peltier*, 2001; *Church et al.*, 2001]. There is also a convincing body of evidence indicating that this rise in sea level was not present over the previous 3000 years [*Douglas*, 1995; *Lambeck and Bard*, 2000]. Because of the lack of long term (>60 yr), reliable tide gauge records in the world and their relatively poor spatial distribution, the New Zealand sea level data forms an important part of the global data set [c.f., *Douglas*, 1997]. These data, which have been collected by tide gauges located at the ports of Auckland, Wellington, Lyttelton and Dunedin, all form time series in excess of 70 years in length.

[4] A first analysis of these data was reported in *Hannah* [1990] with a limited, more detailed higher frequency analysis of the Auckland data being reported in *Goring and Bell* [1999].

[5] The original analyses undertaken by *Hannah* [1990], largely relied upon data that had been captured in electronic form by the hand digitization of old tide charts. While quality assurance (QA) procedures were used in the digitization process, the hourly point data were never plotted, with the result that some obvious data errors escaped detection. One of the objectives of this research project was not only to eliminate these data errors as far as possible, but also to extend the time series of data used in the sea level trend analysis by a further 11 years. This paper then, gives the results of this updated analysis.

2. Data Verification

[6] The original, hourly, sea level data files as described in *Hannah* [1990] were made available by Land Information New Zealand. These were augmented by any additional data that had become available since that time. Table 1 summarizes this new data.

[7] Two points are worthy of note here. Firstly, the length of the Wellington gauge record has been further improved by the addition of data for the years 1891–1893. This data, found in the form of monthly mean tide levels, were discovered recently and corrected to approximate MSLs using the same conversion factor as was described in *Hannah* [1990]. Secondly, the tide gauge at Dunedin suffered severe neglect in the 1990s. This has only recently been rectified by the installation of a new gauge located some kilometers closer to the open ocean.

[8] In order to check the quality of the hourly point data, all annual sea level files were processed using the University of Hawaii's data processing package [*Caldwell*, 1998]. The raw data were first plotted and then compared against a predicted tide in order to detect data discrepancies. Obvious blunders that had occurred in the original digitising process and that had been overlooked in the original QA procedures were corrected. Data that evidenced an obvious datum inconsistency (generally evidenced by a sudden block shift in the tidal record) were eliminated from the record. Obvious timing errors that were evidenced in short periods of data were dealt with in two different ways. In the first instance, short spans of data (generally no more than a few days in length) were moved in time so as to coincide with the predicted tide.

[9] In the second instance, longer spans of data were generally left untouched since the effect of such a timing error on any derived monthly sea level mean would be

Table 1. Additional Sea Level Data Obtained Since the *Hannah* [1990] Analysis

Tide Gauge			
Auckland	Wellington	Lyttelton	Dunedin
1989–1999 inclusive	1891–1893 inclusive 1989–2001 inclusive	1989–2001 inclusive	1989, 1990, 1996, 1998

marginal at best. Data that was obviously incompatible with the surrounding record were removed from the record altogether.

[10] Apart from the improved QA procedures made possible by the University of Hawaii's processing package, it also served to give a much better indication of the quality of the data from each gauge than had been available at the time of the original analysis. This information was subsequently used when assigning standard deviations to the annual MSL values.

[11] Once the above procedures had been completed, the hourly point data were then processed into daily, monthly and annual means. The procedures used were generally as described in *Caldwell* [1998]. The significant exception to the use of these procedures related to the construction of monthly sea level means. In this analysis monthly sea level means were formed for any month in which at least one half of the data for that month was available. The University of Hawaii software, on the other hand, will only form a monthly mean if no more than seven days of data are missing.

[12] The new annual sea level means, once formed, were compared with those used in the original analysis. It was found that while they occasionally varied by as much as 5 mm, the vast majority were within 2 mm of the original values.

[13] With one exception, these new annual sea level means were then reduced to a common datum by eliminating both known datum shifts from the data and the effects of gauge subsidence [c.f., *Hannah*, 1988]. In this latter regard, all the gauges with their associated (stable) benchmarks have been subject to re-leveling over the last four years. While the Auckland and Lyttelton gauges have continued to exhibit vertical stability, the Wellington gauge has been shown to have a previously unknown subsidence of 0.2 mm/yr [c.f., *Beavan*, 2001], a subsidence that upon closer analysis appears to have been present since 1946. In addition, these levelings have confirmed an ongoing subsidence of 1 mm/yr at the Dunedin gauge.

[14] The one exception noted above relates to the Wellington gauge where a second datum shift parameter was used in the least squares analysis to cater for a suspected datum shift in 1944. A more detailed discussion of this matter is given in *Hannah* [1988].

3. Data Analysis and Results

[15] The data analysis proceeded using exactly the same mathematical models and least squares techniques as were employed in *Hannah* [1990] - a paper that should be referred to both for a detailed discussion on these models and the resulting analysis. On this occasion, however, the standard deviations applied to the annual means were derived on a more consistent and rigorous basis than had previously been the case.

[16] The Auckland data, which represents the longest, most consistent, high quality tidal record available in New Zealand, was used to test the appropriateness of the 0.02 m standard deviations for the annual sea level means that had been used previously to weight the annual means in the least squares adjustment process. By analyzing the a posteriori variance of unit weight resulting from a fully parameterized adjustment, it was concluded that a more appropriate standard deviation for an annual mean, formed from 12 months of good quality data from an historical 'float' type tide gauge, was 0.025 m. This in turn implied that a data record of one month in length should be given a standard deviation of 0.09 m. In general, therefore, each annual mean was given a standard deviation calculated from $0.09/\sqrt{n}$, where n = the number of months of data present. Some deviations from this general rule occurred, firstly, at Lyttelton and Dunedin when an annual mean was formed from only a few months of data (the data at both gauges was far noisier than that at Auckland) and, secondly, at Wellington for those years where mean tide levels only were available - c.f., *Hannah* [1990].

[17] With the data verified and an observational weighting scheme finalized, the sea level trend analysis proceeded in the same manner as was outlined in *Hannah* [1990]. Again a full mathematical model incorporating parameters for datum bias (C_D), linear sea level trend (C_L), a pressure parameter (C_P), a temperature parameter (C_T), and parameters for the 8.8 yr and 18.6 yr lunar tides (a_1, b_1, a_2, b_2) were used. Rather than repeat the arguments and explanations advanced there, only points of particular relevance and/or significant difference in this study will be reported here.

[18] For comparison purposes, both the original and recomputed RSL trends, with their associated standard deviations are shown in Table 2. The degrees of freedom in the most recent analysis are given as are estimates for present day glacial-isostatic adjustment [as per *Peltier*, 2001].

[19] As will be apparent from Table 2, the re-estimated trends at Auckland and Wellington showed no appreciable difference from those computed in 1990, although it must be remembered that all the Wellington data since 1946 has

Table 2. Linear Relative Sea Level Trends

	Auckland	Wellington	Lyttelton	Dunedin
1990 sea level trend (mm/yr)	1.34 (0.11)	1.73 (0.27)	2.26 (0.14)	1.36 (0.15)
New sea level trend (mm/yr)	1.30 (0.09)	1.78 (0.21)	2.08 (0.11)	0.94 (0.12)
Degrees of Freedom	91	94	81	72
Estimated GIA (mm/yr)	0.45	0.55	0.49	0.56

now been corrected for a gauge subsidence of 0.2 mm/yr - a correction that was not applied at the time of the 1990 analysis. The larger formal standard deviation for the trend from this gauge results from the uncertainties associated with the use of annual mean tide levels for the earlier years of this gauge record [c.f., *Hannah*, 1990].

[20] The smaller trend calculated for the Lyttelton gauge is most likely a function of the extended time series of data now available. In the original analysis, and relative to the other gauges, Lyttelton had a paucity of data available prior to 1924 - a time when sea levels appear to show a linear change that is less marked than in the subsequent five decades. Another, less marked rise in sea levels from the mid-1970s to 1997 has recently been detected at the Port of Auckland by *Bell et al.* [2000] and is seen as being as a consequence of interdecadal variability. The new result for Lyttelton may also be due to the influence of this variability, albeit at a more southward latitude than anticipated.

[21] The new result for the Dunedin gauge has been heavily influenced by the larger than anticipated subsidence in the wharf structure to which the gauge is attached. Of all the gauges, the location of the gauge at Dunedin, its maintenance, and the overall quality and continuity of its data is by far the poorest of the four used in this study. For these reasons we have some concern about the reliability of the Dunedin result.

[22] A simple mean of the results from the four gauges produces an RSL trend of 1.53 ± 0.25 mm/yr. If, because of the legitimate concerns about reliability, the relative weight of the Dunedin result is considered to be half that given to the other three results, the mean RSL trend becomes 1.61 ± 0.24 mm/yr - a result that is considered to best reflect the new RSL trend for New Zealand.

[23] Using the new data sets, two additional analyses were undertaken. Firstly, it was decided to see how well a simple (weighted least squares) linear regression model (i.e., datum bias parameter(s) plus linear trend), was able to fit the new data set. While the residuals from the adjustment were considerably larger, this being reflected in an a posteriori variance of unit weight that in every case failed the Chi (χ^2) test at a 95% confidence interval [c.f., *Hamilton*, 1964], the estimated parameters were almost exactly the same as those calculated by the more comprehensive and complete nine-parameter mathematical model described earlier. In other words, while a simple linear regression model (with the appropriate number of datum bias parameters), may not remove all systematic effects from the data, it does allow an accurate determination of any linear sea level trend.

[24] Secondly, and as in *Hannah* [1990], the data were also analysed by including an additional (tenth) parameter that was used to describe the acceleration in RSL, should any exist. As was the case previously, it was concluded that the additional term was either statistically insignificant, or that it led to no improved model fit to the data.

3.1. Linkages to Other Climate Change Phenomena

[25] As in the 1990 study, additional parameters were estimated for the response of annual mean sea level to changes in both annual mean atmospheric temperatures and annual mean atmospheric pressures. The new results and discussion, largely mirror the old.

[26] As was explained in *Hannah* [1990], while much of the data used in this study is in the form of hourly point heights, this is by no means uniformly so. Where such data is available, however, extended analyses may be undertaken. *Zhang et al.* [2000], for example, analyze the hourly tidal data from ten sites on the East Coast of the United States, in order to trace the historical record of extra-tropical storms. While they found a large interannual and interdecadal variability, they could find no discernable long-term trend in overall storminess.

[27] Similarly, but over a shorter time scale, *De Lange and Gibb* [2000] analyse 38 years of data (1960–1997) from the Port of Tauranga in New Zealand. They note that the magnitude and frequency of storm surge events varied over this time period, with a marked shift evident about 1976. The period 1976 to 1997 corresponded to a reduced storm surge frequency and magnitude as compared to the period 1960 to 1976. Perhaps more importantly, though, they suggest that the frequency of storm surge events varies in response to both the Inter-decal Pacific Oscillation (IPO) and the El Niño Southern Oscillation (ENSO). *Bell et al.* [2000] note this same variability and conclude that an understanding of these phenomena is an important element is assessing both the long-term trends in sea level, and detecting any possible future acceleration. Because of these seasonal and decadal effects, *Douglas* [1997] suggests that in the absence of eliminating extreme anomalies from the data record (a task that was not undertaken in this study), best long-term sea level trend results are determined from at least 70 years of records.

4. Conclusions

[28] An updated analysis of New Zealand's long term sea level records that both uses historical data that have been subject to improved quality control procedures and includes data from 1989–2001, leads to a new relative sea level rise figure for New Zealand of 1.6 mm/yr with a standard deviation of 0.2 mm/yr - a figure that is not significantly different from the original (1990) assessment of a rise of 1.7 mm/yr. While the new analysis does lead to a significantly lower estimate of sea level rise at one gauge (Dunedin), the overall low quality of the data from this gauge suggests that this particular result should be treated with some care - an issue that has lead to its down-weighting in final calculations. If these figures are corrected for present day glacial-isostatic effects (using *Peltier*'s [2001] estimates), then the average sea level rise becomes 2.1 mm/yr. No attempt has been made to apply corrections for other (vertical) tectonic motions because of the coarse nature of present day estimates derived from geological data. Continuous GPS monitoring is now being undertaken so as to provide new estimates of these motions.

[29] When viewed from a global perspective, the New Zealand sea level data has particular importance to the analysis of long-term sea level change, not only because of the paucity of reliable long-term sea level data from the Southern Hemisphere but also because of its mid-latitude location. The updated estimate of a 2.1 mm/yr rise in absolute sea levels since the start of the 20th Century is in close agreement with the various estimates of sea level rise reported elsewhere [e.g., *Douglas* 1997; *Peltier* 2001]. It is

also of interest to note the high level of coherency between these new results and those reported for the long-term tidal records on both the East and West Coasts of Australia i.e., for both Freemantle and Sydney - see *Salinger et al.* [1996]. This regional and global coherency of result in turn infers the possibility that there is little or no differential tectonic uplift occurring across the New Zealand section of the Australian/Pacific plate boundary.

[30] This new analysis supports at least two other conclusions. Firstly, it continues to indicate that in New Zealand, at least, there has been neither a significant change in the rate of sea level rise nor any detectable acceleration. Secondly, it reveals that a simple weighted linear regression model fitted to the annual sea level means will provide linear trends that closely match those derived from a much more comprehensive model that includes parameters describing the effects of changes in mean annual pressure and temperature on sea level as well as the periodic effects of the 8.8 and 18.6 yr lunar tides. While the observational residuals following such an analysis are much larger, the linear trend so derived is a robust trend estimate.

[31] From an experimental design point of view, the work associated with this new analysis reveals clearly the danger that exists in attempting to interpret long-term sea level trends in the absence of reliable spirit leveling to tide gauge sites. One of the gauges used in this study (Dunedin) is attached to a wharf structure that sits on reclaimed land. This gauge has been found to be subsiding at a rate of 1 mm/yr. A second gauge, Wellington, was also found to have a very small, but previously unsuspected, subsidence.

[32] As part of a wider research project, all four tide gauges mentioned in this paper (with the exception of Dunedin), have had continuously tracking GPS receivers co-located in their near vicinity. Their phase centers have been rigorously surveyed and linked to the tide gauge benchmarks. In the case of Dunedin a new gauge has been located much closer to the harbor entrance and it is here that the GPS receiver has been located. In the longer term it is planned to use the GPS receivers to determine the combined effects of local tectonic change and glacial-isostatic uplift, thus enabling the removal of these effects from the sea-level record. In the final analysis it is expected that this data will make a valuable contribution to a global assessment of eustatic sea level change.

[33] **Acknowledgments.** The work described in this paper has been undertaken as part of FoRST contract 98-GNS-16-6638. In addition, the author wishes to acknowledge the invaluable assistance of the Ports of Auckland, Wellington, Lyttelton and Dunedin in collecting the original sea level data, Land Information New Zealand for releasing the archived data files, and to the National Institute of Water and Atmospheric Research for providing annual temperature and pressure data. The author also acknowledges the work of his colleagues in the School of Surveying and the Institute of Geological and Nuclear Science who undertook the recent levelings onto the tide gauges that have been used in this analysis. Finally, the author gratefully acknowledges the support provided by the US Naval Postgraduate School while he was on study leave during which a substantial part of the analyses described in this paper were undertaken.

References

Beavan, R. J. (2001), Long-term stability of Wellington tide gauge, 1911–2001, incorporating May 2001 levelling survey to Wellington fundamental benchmark K80, *IGNS Science Report 2001/9*, 18 pp., Inst. of Geological and Nuclear Sciences Ltd., Lower Hutt, New Zealand.

Bell, R. G., D. G. Goring, and W. P. de Lange (2000), Sea-level change and storm surges in the context of climate change, *Trans.*, *27(1/Gen)*, 10 pp., Inst. of Professional Eng. N. Z.

Caldwell, P. (1998), Sea level data processing on IBM-PC compatible computers, Version 3.0, *JIMAR Contribution No. 98-319*, 72 pp., Univ. of Hawaii at Manoa, School of Ocean and Earth Science and Technology, Honolulu, Hawaii.

Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, N. T. Nhuan, D. Qin, and P. L. Woodworth (2001), Changes in sea level, in *Climate Change 2001, the Scientific Basis*, edited by Houghton et al., pp. 641–693, Cambridge Univ. Press.

De Lange, W. P., and J. G. Gibb (2000), Seasonal, interannual, and decadal variability of storm surges at Tauranga, New Zealand, *N. Z. J. of Marine and Freshwater Res.*, *34*, 419–434.

Douglas, B. C. (1995), Global sea level change: Determination and interpretation, *Rev. of Geophys.*, Suppl., 1425–1432.

Douglas, B. C. (1997), Global sea level rise: A redetermination, *Surveys in Geophysics*, *18*, 279–292.

Douglas, B. C., M. S. Kearney, and S. P. Leatherman (Eds.) (2001), *Sea Level Rise History and Consequences*, 232 pp., Academic, San Diego.

Goring, D. G., and R. G. Bell (1999), El Niño and decadal effects on sea-level variability in northern New Zealand: A wavelet analysis, *N. Z. J. of Marine and Freshwater Research*, *33*, 587–598.

Gornitz, V. (1995), Monitoring sea level changes, *Climatic Change*, *31*, 515–544.

Hamilton, W. C. (1964), *Statistics in Physical Science*, 230 pp., Ronald Press Company, New York.

Hannah, J. (1988), Analysis of mean sea level trends in New Zealand from historical tidal data, *Report No. 2*, 41 pp., Dept. of Survey and Land Information, Wellington, N. Z.

Hannah, J. (1990), Analysis of mean sea level data from New Zealand for the period 1899–1988, *J. Geophys. Res.*, *95*(B6), 12,399–12,405.

Hannah, J. (1999), Sea level rise: Impacts upon the surveying profession, *N. Z. Surveyor*, *288*, 3–7.

Lambeck, K., and E. Bard (2000), Sea-level change along the French Mediterranean coast since the time of the last glacial maximum, *E. Plan. Science Lett.*, *175*, 203–222.

Peltier, W. R. (1999), Global sea level rise and glacial isostatic adjustment, *Global and Plan. Change*, *20*, 93–123.

Peltier, W. R. (2001), Global glacial isostatic adjustment and modern instrumental records of relative sea level history, in *Sea Level Rise History and Consequences*, edited by B. C. Douglas et al., Academic Press, San Diego.

Salinger, J. M., R. Allan, N. Bindoff, J. Hannah, B. Lavery, Z. Lin, J. Lindesay, N. Nicholls, N. Plummer, and S. Torok (1996), in *Greenhouse, Coping with climate change*, edited by W. J. Bouma, G. I. Pearman, and M. R. Manning, pp. 101–126, CSIRO Publishing, Australia.

Zhang, K., B. C. Douglas, and S. P. Leatherman (2000), Twentieth-century storm activity along the U.S. East Coast, *J. Clim.*, *13*, 1748–1761.

J. Hannah, School of Surveying, University of Otago, P.O. Box 56, Dunedin, New Zealand. (john_hannah1@albers.otago.ac.nz)