Update to 2018 of the annual MSL series and trends around New Zealand

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Executive summary

This data report outlines the updated annual mean sea level (AMSL) series for the 2016 and 2017 years, and subsequently for 2018 in a second phase of work, for six long-term sea-level gauge sites around New Zealand and associated trends in sea-level rise. The purpose of the report is to update the suite of indicators that the Ministry for the Environment (MfE) and Stats NZ use to report on the state of New Zealand's environment under the Environmental Reporting Act 2015.

The last update on the coastal sea-level rise indicator was in mid-2017 for the sea-level record up to 2015 (Macara, 2017), which coincided with the analysis of sea-level rise (SLR) for the 2017 MfE Coastal Hazards and Climate Change guidance for local government.

The AMSL time series is a measure of the relative SLR at each location – measured relative to the adjacent landmass – so is influenced by both vertical land movement (uplift or subsidence) and absolute changes in ocean levels.

All series of annual MSL have been normalised to an average MSL over the two-decade baseline period 1986-2005 (inclusive) used by the Intergovernmental Panel on Climate Change (IPCC). Given the different local datums used for the gauges, this enables a more consistent basis for comparison to be made of the relative SLR across New Zealand. It is the same zero baseline MSL period used by the IPCC and the MfE Coastal Guidance (2017) to add future sea-level projections to.

AMSL was the highest on record for most sites in the last 5 years (2014–2018). The inter-year variability in AMSL results primarily from:

- climate cycles such as the 2-4 year El Niño–Southern Oscillation (ENSO) and the longer 20–30 year Interdecadal Pacific Oscillation (IPO) as well as annual variability in regional sea-surface height (from changes in the seasonal sea temperatures on the continental-shelf). Generally, AMSL is higher during La Niña events and when the IPO is in its negative phase (as shown by the lift in AMSL in 1999 - Figure 4-1).

- changes in vertical land movement, e.g. Wellington and Lyttelton (and to a lesser degree Port Taranaki) were subject to varying land movements associated with the Kaikōura/North Canterbury earthquake, and the ongoing land adjustments from inter-seismic activity.

Climate change is generating an increasing rate of rise in the mean sea level around New Zealand that underlies the climate variability, with trends updated by Emeritus Professor John Hannah of Vision NZ Ltd (Appendix A and B) to the end of the 2017 and 2018 years respectively.

Wellington continues to exhibit the highest relative SLR rate for all sites of 2.30 mm/yr since 1901 (2.79 mm/yr since 1961), in part due to the underlying inter-seismic subsidence in the Wellington region, for which GPS measurements have only been available over the last 10–15 years (MfE Guidance, 2017). Making an average adjustment for vertical land movement in Wellington reduces the long-term trend to ~2 mm/yr. The lowest rate occurs at New Plymouth (Port Taranaki), although there are caveats on the reliability of the datum (Appendix A).

The NZ average rate of relative SLR for the 4 main ports is 1.81 ±0.05 mm/yr encompassing the records back to ~1900, which is similar to the global average SLR. The NZ average rate of rise has doubled from 2.44 ±0.10 mm/yr over the recent period since 1961, compared with 1.22 ±0.12 mm/yr for the similar-length period prior to 1961.

1 Context and purpose

The purpose of the Services is to improve the suite of indicators that the Ministry for the Environment (MfE) and Stats NZ use to report on the state of New Zealand's environment under the Environmental Reporting Act 2015. Specifically, the MfE requested an update to the coastal sea-level rise indicator (CSLR indicator) for the upcoming "Our Marine Environment 2019" report.

The Coastal Sea-level Rise (CSLR) indicator represents annual mean sea levels (AMSL) relative to a baseline average mean sea level at six stations around New Zealand. From this data, linear trends and standard deviations are updated, demonstrating changes in sea level over time. The Ministry will publish the data resulting from this Report under a CC-BY licence in "Our Marine Environment 2019".

This update reports AMSL for 2016 and 2017 years, and included 2018 in the second phase of the work, relative to the average mean sea level over 1986–2005 (baseline), for six coastal locations; Auckland, Wellington, Lyttelton, Dunedin, New Plymouth, and Moturiki (Mount Maunganui). The methodology used by Vision NZ Ltd and NIWA to update the CSLR trends is consistent with that of Macara (2017).

2 Data processing

2.1 Climate data

Climate data, comprising monthly and annual average air temperature and barometric pressure (adjusted to mean sea level), from climate sites listed in Table 2-1, were used as input parameters for determining coastal sea-level rise (CSLR) trends, using the method outlined in previous journal papers (Hannah 1990, 2004; Hannah & Bell, 2012).

Table 2-1: List of climate station data from NIWA's CliDB archive used to construct a monthly and annual time series of air temperature and mean sea-level pressure data. Used to process the AMSL time series data for the update for 2016–2018 years (and in the case of Moturiki Island – Mount Maunganui, for the entire record from 1973). Abbreviations: T = air temperature; MSLP = mean sea level pressure; EWS = Environmental Weather Station; AWS = Automatic Weather Station.

Name	Agent No.	Latitude (deg N)	Longitude (deg E)	Height (m MSL)	Type	Observing Authority
Auckland Aero	1962	-37.0081	174.7887	7	T, MSLP	Airways New Zealand
Christchurch Aero	4843	-43.493	172.537	37	T, MSLP	Airways Corporation
Christchurch Gardens	4858	-43.531	172.619	7	T	Christchurch City Council
Dunedin, Musselburgh EWS	15752	-45.9013	170.5147	4	T, MSLP	NIWA
New Plymouth Aero	2282	-39.012	174.181	27	MSLP	Taranaki Weather Services
New Plymouth AWS	2283	-39.008	174.184	30	T, MSLP	Met Service
Tauranga Aero	1612	-37.6724	176.1964	0	T, MSLP	Sun Air Aviation
Tauranga Aero AWS	1615	-37.673	176.196	4	T, MSLP	Met Service
Rotorua Aero 2*	1768	-38.1107	176.3176	281	MSLP	Airways Corporation
Tauranga 4*	1611	-37.677	176.165	2	T	Tauranga City Council

* Latter two sites were used to fill the gap from March 1989 to May 1990 between the older Tauranga Aero record and the present Tauranga Aero AWS record. Note: 0.34°C was subtracted from the monthly

temperature from the "Tauranga 4" city site, derived from a comparison of parallel data for the rest of the period 1989-1990, which accounts for the urban heat effect and cooler sea breezes between sites.

2.2 Input sea-level data and processing to derive annual MSL (AMSL)

Hourly sea-level data from each gauge site has been quality-checked for errors and gaps by John Hannah (Vision NZ Ltd; Emeritus Professor, University of Otago) for five of the gauge records while NIWA has quality-checked the record (from 1974) for Moturiki Island that it operates near Mount Maunganui (previously operated by the Water & Soil Division, Ministry of Works & Development).

The raw data were first plotted and then compared against the predicted tide to better detect data discrepancies including timing issues. Obvious errors that had occurred in the original digitising process (for earlier pre-digital records) and that had been overlooked in the original QA procedures were corrected.

Obvious timing errors that were evidenced in short periods of data were dealt with in two different ways (Hannah, 2004). In the first instance, short spans of data (generally no more than a few days in length) were offset in time to coincide with the predicted tide. In the second instance, longer spans of data showing timing errors were generally left untouched since the effect of such a timing error on any derived monthly sea level mean would be marginal at most. Data that was obviously incompatible with the surrounding record were removed from the record altogether.

Quality-assurance of the datum levels, the stability of the datum (from benchmarks and GPS measurements) and shifts in datum undertaken by gauge operators, was undertaken by John Hannah (Appendix A and B), apart from Moturiki Island (where the datum is monitored by NIWA field staff). Data that evidenced an obvious datum inconsistency (generally evidenced by a sudden block shift in a portion of the tidal record) were eliminated from the record. There is also a caveat on the quality of the datum for the Port Taranaki gauge – see Appendix A.

After the quality checks, monthly MSL averages were calculated from the hourly data (if available) for that month. In this analysis monthly averages were only formed for any month in which at least one half of the data for that month was available – otherwise left as a blank. Annual MSL were calculated from the calculated Monthly MSL values (leaving aside blank values). For Moturiki, a whole-of-year average was calculated with negligible differences (sub mm) to the average of the monthly means.

Annual MSL values for each specific gauge record were then reduced to a consistent vertical datum throughout each of the time series by applying offsets of both known datum shifts in the data (e.g., a gauge datum re-established when a new gauge was installed or shifted) and the effects of gauge subsidence (e.g., subsidence of the pier the gauge may be attached to relative to hinterland benchmarks). Subsidence of the actual gauge support structure is distinct from local and regional vertical land movement (which remains embedded in the time series of relative SLR, relative to the adjacent landmass).

The 5-minute or 1-minute sea-level datasets were originally measured by various port companies (Ports of Auckland Ltd., Port Taranaki – New Plymouth, CentrePort–Wellington, Lyttelton Port Co. Ltd, Port Otago – Port Chalmers) or NIWA (in case of Moturiki). These port datasets are submitted regularly to Land Information NZ (LINZ) as the National Hydrographic Authority and checked before archiving – so the data is obtained through LINZ for each update. Although further quality assurance and datum adjustments were undertaken for this report – we still rely on the integrity of the data measured by the port companies and NIWA field staff.

To augment the shorter Port Taranaki and Moturiki Island digital records, archived historic single averaged MSL values were retrieved from the LINZ archive as follows (having been used to establish the respective local vertical datums early last century):

- New Plymouth – single MSL value averaged for the four years from 1918–1921 of 1.771 m (relative to 1966 Port Chart Datum), placed in year 1920.
- Moturiki Island – single MSL value averaged for the 4 years 1949–1952 of 1.487 m above Tide Gauge Zero (or 0.0 m Moturiki Vertical Datum-1953), placed in year 1951 (also used in Hannah & Bell, 2012).

3 Updates of coastal SLR trends

3.1 Individual gauge sites

Long-term trends were calculated on the annual MSL updated values to the end of 2017, then up to the end of 2018 in the second phase of analysis, by Emeritus Professor John Hannah of Vision NZ Ltd using the methods outlined in the Hannah (1990, 2004) and Hannah & Bell (2012) papers and recent reports (Hannah; 2016; Macara, 2017).

The analysis to fit trends to the AMSL series included the influence of annual average air temperature and barometric pressure anomalies from year-to-year using the climate data extracted from climate stations (e.g., Table 2-1). These adjustments are usually very small (usually < mm) and have been consistently applied to all six gauge records for the trends up to the end of 2018. The trends for each gauge station include all the available digital data and the archived historic single averaged MSL values over several years for New Plymouth and Moturiki (as described at the end of the previous section).

The details of the analysis and results are described in Appendix A (up to end of 2017) and Appendix B (up to the end of 2018 including revised Moturiki trends).

The key results on trends in coastal SLR (CSLR) at each gauge station are reproduced in Table 3-1 (up to end of 2017) and Table 3-2 (up to end of 2018).

Table 3-1: Long-term coastal sea-level rise (CSLR) trends for six long-term NZ gauge sites up to the end of 2017. Source: Appendix A. Units in mm/yr together with standard deviations in parentheses. Note: Moturiki trends up to 2017 (strikethroughs) were revised in second phase of analysis (see Table 3-2 for results and Appendix B for the background).

Port	Length of Data Set (Total No. of yrs)	MSL Linear Trend							
		Start of data set to 1960		1961 - 2015		1961 - 2017		Full data set to the end of 2015	Full data set to the end of 2017
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend		
Auckland	1899-2017 (117)	60	1.76 (0.20)	55	2.34 (0.26)	57	2.49 (0.24)	1.60 (0.08)	1.65 (0.08)
Wellington	1891-2017 (118)	61	0.72 (0.43)	55	2.67 (0.21)	57	2.74 (0.20)	2.23 (0.16)	2.28 (0.15)
Wellington^{TC}				55	2.21 (0.20)	57	2.22 (0.19)	1.97 (0.15)	1.98 (0.14)
Lyttelton	1901-2017 (105)	48	1.33 (0.25)	55	2.54 (0.23)	57	2.70 (0.22)	2.12 (0.09)	2.19 (0.09)
Dunedin	1899-2017 (100)	50	0.76 (0.19)	48	1.47 (0.24)	50	1.63(0.22)	1.42 (0.08)	1.47 (0.08)
New Plymouth	1920-2017 (64)							1.28 (0.27)	1.31 (0.25)
Moturiki	1951-2017 (45)			42	~~1.63 (0.37)~~	44	~~1.84 (0.34)~~	~~1.84 (0.34)~~	2.08 (0.24)

Table 3-2: Long-term coastal sea-level rise (CSLR) trends for six long-term NZ gauge sites up to the end of 2018. Units in mm/yr together with standard deviations in parentheses. Shading shows latest results up to 2018. See Appendix B for the background).

Port	Length of Data Set (Total No. of yrs)	MSL Linear Trend							
		1961 - 2015		1961 - 2017		1961 - 2018		Full data set to the end of 2017	Full data set to the end of 2018
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend		
Auckland	1899-2018 (118)	55	2.34 (0.26)	57	2.49 (0.24)	58	2.54 (0.23)	1.65 (0.08)	1.67 (0.08)
Wellington	1891-2018 (120)	55	2.67 (0.21)	57	2.74 (0.20)	58	2.79 (0.19)	2.28 (0.15)	2.30 (0.15)
Wellington^{TC}		55	2.21 (0.20)	57	2.22 (0.19)	58	2.23 (0.18)	1.98 (0.14)	1.97 (0.14)
Lyttelton	1901-2018 (106)	55	2.54 (0.23)	57	2.70 (0.22)	58	2.73 (0.21)	2.19 (0.09)	2.21 (0.09)
Dunedin	1899-2018 (101)	48	1.47(0.24)	50	1.63 (0.22)	51	1.64(0.21)	1.47 (0.08)	1.48 (0.08)
New Plymouth	1920-2018 (65)							1.31 (0.25)	1.33 (0.24)
Moturiki	1951-2018 (46)	42	2.19 (0.33)	44	2.36 (0.30)	45	2.38 (0.28)	2.08 (0.24)	2.12 (0.23)

Notes for both Tables:

a) Superscript ^{TC} indicates an adjusted trend incorporating a tectonic correction for the more recent average rate of vertical land movement of the area – currently there are only well-researched estimates available for the Wellington gauge.

b) Wellington^{TC} = Wellington corrected for a GPS derived average (secular) rate for tectonic slow-slip subsidence of 1.8 mm/yr (noting it varies over time). This correction has only been applied from 1998 onwards when continuous GPS measurements began.

c) Due to the possible influence of data inconsistencies at New Plymouth over the period 1960–1980, no separate 1961–2018 analysis is reported for this port.

d) For Moturiki, the data series used to calculate the 1961–2018 trend starts in 1974 not 1961.

AMSL was the highest on record for most sites in the 2016 year, while there was a slight increase in 2017 for the upper North Island and a slight decrease in other sites. The inter-year variability results primarily from:

- climate cycles such as the 2-4 year El Niño–Southern Oscillation (ENSO) and the longer 20–30 year Interdecadal Pacific Oscillation (IPO) as well as annual variability in regional sea-surface height (from changes in the seasonal sea temperatures on the continental-shelf)
- changes in vertical land movement e.g., Wellington and Lyttelton and to a lesser degree Port Taranaki, were subject to varying land movements associated with the Kaikoura/North Canterbury earthquake (14 November 2016) and the ongoing land adjustments from associated inter-seismic activity.

Climate change is generating an increasing rate of rise in the mean sea level around New Zealand that underlies the climate variability and vertical land movement, with trends updated (Appendix A) to the end of the 2017 year. Note: it is these relative SLR rates (including vertical land movement) that have to be adapted to at the local/regional scale, not the absolute rise in ocean levels.

Wellington continues to exhibit the highest relative SLR rate for all sites of 2.30 mm/yr since 1901 (2.79 mm/yr since 1961), in part due to the underlying inter-seismic subsidence in the Wellington region, for which GPS measurements have only been available over the last 10–15 years (MfE Guidance, 2017). The lowest rate occurs at New Plymouth (Port Taranaki), although there are caveats on the reliability of the datum (Appendix A).

3.2 NZ average (4 main ports)

Averaging the relative SLR rate across NZ provides a measure of the overall historic rate of rise to compare with the global mean SLR, by filtering out some of the inter-site variations in vertical land movement, which explains much of the differences in SLR trends for each gauge site listed in Table 3-2. See the coastal guidance MfE (2017) and Hannah & Bell (2012) for more details.

Method: NZ average relative SLR
For the NZ-wide average SLR to be robust, only the trends from the 4 main ports are used as they are long-running records and span a similar historic period from ~1900, whereas the other two sites have shorter and interrupted records. Initially, a simple (unweighted) average was used (e.g. Appendix B). However, the confidence in the derived trends for each site also varies, as expressed by the standard deviations (parentheses in Tables 3-1 and 3-2), which can be partially related to the quality (or absence) of information on datum shifts for the gauge. Therefore, a weighted average relative SLR for NZ was calculated below, using the inverse of the variance (standard deviation squared or SD^2) as weights (w_i) applied to the trends (x_i) from each of the 4 main port sites (Equation 3.1). $$\bar{x} = \sum_{i=1}^{4} w_i\, x_i \Big/ \sum_{i=1}^{4} w_i \quad \text{, where } w_i = \frac{1}{SD_i^2} \qquad (3.1)$$

This method puts higher weights on those trends with a higher confidence (i.e., lower standard deviation) than those trends with a higher standard deviation. The weighted standard deviation associated with this mean was calculated as:

$$\overline{SD} = \sqrt{1 / \sum_{i=1}^{4} w_i} \qquad (3.2)$$

The Wellington[TC] trends were not used in this weighted average as similar adjustments for measured vertical land movement have not yet been determined for the other gauge sites – but will be available in the next assessment based on current research within the NZSeaRise project hosted at Victoria University of Wellington.[1]

The NZ weighted-average rate of relative SLR for the four main port gauge sites is shown in Table 3-3, encompassing the full record back to ~1900 and also splitting the record into the period up to 1960 and the more recent record from 1961 to 2018. This split at 1960 is explained in the coastal guidance (MfE, 2017; Section 5.2.3) and by 2018, happens to coincide with a fairly even split in number of years or record for the four main ports (Table 3-2).

Table 3-3: NZ average relative SLR for the 4 main ports (using a weighted mean) for the full record and also split into before and after 1960. Derived using equations 3.1–3.2.

	Start – 2018 mm/yr (± SD)	**Start – 1960 mm/yr (± SD)**	**1961 –2018 mm/yr (± SD)**
Weighted average relative SLR (4 main ports)	1.81 ± 0.05	1.22 ± 0.12	2.44 ± 0.10

The average rate for the 4 main ports for the full record of 1.8 mm/yr is similar to the global mean SLR. Estimates of average sea-level rise from tide gauges globally have now converged on a value of 1.7 ±0.2 mm/yr for the period 1900 to 2010 as described in IPCC's 5th Assessment Report (Rhein et al., 2013).

The average SLR trend has doubled since 1960, from 1.22 mm/yr for the prior gauge records up to 1960, up to 2.44 mm/yr for the period 1960–2018. Recently, Dangendorf et al. (2019) found a persistent acceleration in global SLR since the 1960s and demonstrate that this is largely associated with sea-level changes in the Indian-Pacific Oceans and South Atlantic.

4 Updated AMSL time series for coastal SLR

All supplied series of AMSL (in accompanying Excel spreadsheet)[2] were normalised to an average MSL over the two-decade IPCC baseline period 1986-2005 (inclusive) by NIWA. The six normalised AMSL time series up to the end of 2018 are graphed in Figure 4-1.

[1] https://www.searise.nz/

[2] *AMSL_6 NZ gauge series to 2018_rel 1986-2005 baseline_ex NIWA_JH.xlsx*

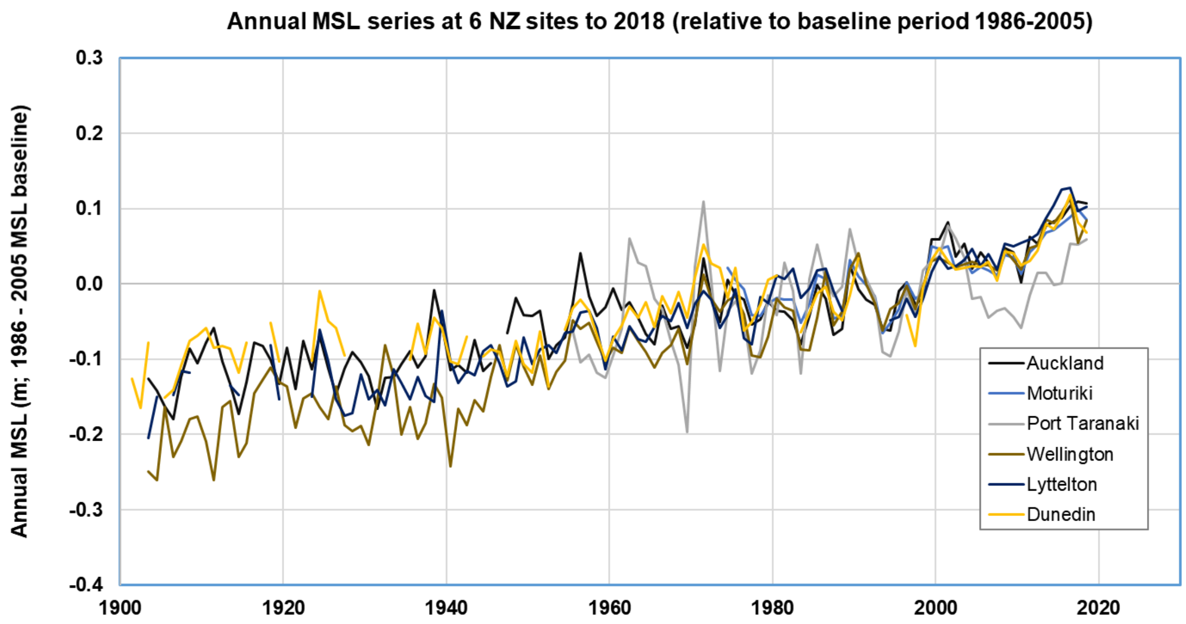

Figure 4-1: Updated AMSL series (to end of 2018) for six NZ gauge sites normalized to a 1986-2005 average baseline period. Source: supplied MS Excel datafile.

Given the different local datums used for the gauges, this normalization enables a more consistent basis for comparison to be made of the relative SLR across New Zealand The averaging period for the baseline is also long enough (20-years) to cover the range of tidal combinations (18.6 years) and some of the climate variability (e.g. the 2–4 year El Niño-Southern Oscillation or ENSO). Note: there is uncertainty with the gauge datum at New Plymouth (Appendix A), with future work needed to correlate the New Plymouth gauge data with the Wellington gauge to improve the quality of the results.

The 1986-2005 period (mid-point 1996) is the same zero baseline MSL period used by both IPCC and the MfE Coastal Guidance (2017) to which future sea-level projections are added to. Annual MSL values above zero in Figure 4-1 show the measured sea level increases above the SLR projections baseline. AMSL was the highest on record for most sites in the last 5 years (2014–2018).

The inter-year variability in AMSL results primarily from:

- climate cycles such as the 2-4 year El Niño–Southern Oscillation (ENSO) and the longer 20–30 year Interdecadal Pacific Oscillation (IPO) as well as annual variability in regional sea-surface height (from changes in the seasonal sea temperatures on the continental-shelf). Generally, AMSL is higher during La Niña events and when the IPO is in it's negative phase (as shown by the lift in AMSL in 1999).

- changes in vertical land movement, e.g. Wellington and Lyttelton (and to a lesser degree Port Taranaki) were subject to varying land movements associated with the Kaikōura/North Canterbury earthquake, and the ongoing land adjustments from inter-seismic activity.

5 Acknowledgements

Original 5-minute or 1-minute sea-level datasets were measured by various port companies (Ports of Auckland Ltd., Port Taranaki – New Plymouth, CentrePort–Wellington, Lyttelton Port Co. Ltd, Port Otago – Port Chalmers) or NIWA (in case of Moturiki).

Data for this updated report were sourced from Land Information NZ (LINZ) as the National Hydrographic Authority or from NIWA (in the case of Moturiki Island).

Helpful comments from MfE staff were appreciated, improving the text and the derivation of the NZ average SLR.

Gregor Macara (NIWA) was the Project Manager for this updated report.

6 Glossary of abbreviations and terms

AMSL	Annual mean sea level (averaged each year from hourly sea-level data to a consistent datum)
CD	Local Chart Datum (typically the level at which the lowest low tide seldom reaches)
CSLR	Coastal sea-level rise indicator (name of indicator reported by MfE/Stats NZ)
ENSO	El Niño-Southern Oscillation (2-4 year climate oscillation of the wider Pacific)
IPCC	Intergovernmental Panel on Climate Change (UN agency)
IPO	Interdecadal Pacific Oscillation (20–30 year climate oscillation of the wider Pacific – last IPO phase shift in AMSL was in 1999)
LINZ	Land Information NZ
MfE	Ministry for the Environment
MSL	Mean sea level (usually expressed over a period of several years, typically a full nodal tide epoch of 19-20 years)
SD	Standard deviation: a statistic that measures the deviations of a dataset relative to its mean or trend line and is calculated as the square root of the variance.
TC	Tectonic correction for average vertical land movement (applied only for Wellington)

7 References

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Appendix A Updated SLR trends to end of 2017

NZ WIDE SEA LEVEL TRENDS TO 31 DECEMBER 2017

Report to NIWA from Vision NZ Ltd (J Hannah)

1. INTRODUCTION

This report has been produced in response to a request from NIWA to update the sea level trends at Auckland, Lyttelton, Dunedin, and New Plymouth to the end of 2017. NIWA have also requested that the Moturiki data be processed using the same processing methodology. While the sea level trend at Wellington has been calculated and reported as part of a separate contract the results will also be shown here. The last trend analysis was undertaken for NIWA using data collected through to the end of 2015 (Hannah, 2016**).**

2. THE DATA

As with Hannah (2016) the raw hourly MSLs were provided to the author by the Tidal Officer at Land Information NZ. This hourly data has been processed into daily and monthly means using the University of Hawaii sea level processing software (Caldwell, 2014). These monthly means were then used to form the annual Mean Sea Levels (MSLs)

The sea level data sets for the years 2016, 2017 were largely complete. For documentation purposes outages are noted in Table A.1, below.

Table A.1: Data Availability 2016 - 2017

	Port				
	Auckland	Lyttelton	Dunedin	New Plymouth	Moturiki
Missing Data	6 days - April 2017 4 days – Dec.2017	7 days –May 2016 2 days – Nov 2016 2 days – Jan 2017 3 days – Feb 2017 2 days – March 2017 3 days – April 2017 1 day – May 2017 2 days – June 2017 1 day Sept 2017 2 days - Dec 2017	1 day – Oct 2016 2 days – Aug 2017	1 month April 2016 3 days – July 2016 4 days – Feb 2017 1 day – March 2017	100% complete in 2016 96% complete in 2017

These data outages are sufficiently few as to have a negligible effect on the sea level trend analyses.

The data for Moturiki were supplied by NIWA as annual means.

Prior to the analysis, the following corrections were applied to the sea level data.

Auckland. A datum correction of +0.5 ft (152 mm) was applied to the annual sea level means so as to create a datum consistent with earlier data.

Wellington. While Wellington has not been included in this project, for comparison purposes results from an earlier analysis from the WRC 19201 project will be noted. At Wellington a correction of -316 mm was applied to the annual sea level means to account for a datum correction of -1.0 feet (305 mm), plus accumulated wharf subsidence of 11 mm. Also, the daily raw data (as recorded by the tide gauge) has been corrected for the regional tectonic movement caused by the 2016 Kaikoura earthquake. Since 00.00 hours on 14 Nov. 2016, 27 mm has been deducted from the recorded data. The daily data files are thus already free of this datum inconsistency, as are the monthly and annual means

Lyttelton. The daily raw data (as recorded by the Lyttelton tide gauge) was corrected, in stages, between 4 Sept. 2010 and 7 Dec. 2012 to account for the regional tectonic movement caused by the various Christchurch earthquakes. On 8 Dec. 2012, the accumulated uplift of 111 mm was applied directly by the Port Company to the recorded data. At that time the adjustment (previously made by LINZ), was discontinued. However, the November 2016 Kaikoura earthquake produced another required adjustment of 30 mm. Since 00.00 hours on 14 Nov. 2016, 30 mm has been deducted by LINZ from the recorded data. The daily data files are thus already free of these datum inconsistencies, as are the monthly and annual means.

The resulting annual sea level means were then further corrected by -305 mm to compensate for the various datum corrections needed to ensure consistency with earlier data.

Dunedin. No corrections necessary.

New Plymouth. The tide gauge zero, as established for the 1966 Evershed & Vignoles (E & V) gauge, has been adopted as the datum reference point for the entire time series of data. On 1 January 1973, coinciding with metrication, the tide gauge zero was lowered 0.11 ft. Thus all data since that date has had 0.034 m subtracted. There is a high degree of uncertainty associated with the exact datum to which some monthly blocks of data in the 1960s and 1970 refer. While every attempt has been made to overcome these difficulties, additional work in correlating the New Plymouth gauge with the Wellington gauge could still be undertaken – potentially improving significantly the quality of the result. These uncertainties are typically associated with how the chart datum was set when a new tidal recording chart was placed on the old analogue recorder.

The daily raw data (as recorded by the tide gauge) has been corrected for the regional tectonic movement caused by the 2016 Kaikoura earthquake. Since 00.00 hours on 14 Nov. 2016, 12 mm has been deducted from the recorded data. The daily data files are thus already free of this datum inconsistency, as are the monthly and annual means.

Moturiki. These data were supplied by NIWA. Except for small outages, the data set is continuous from 1974. The only data point prior to 1974 is a single MSL value averaged for the year 1949 – 1952 with an approximate mid-point of January 1951. The data supplied by NIWA has been referenced to the TG zero. No other datum corrections have been made.

3. RESULTS

As was the case in Hannah (2016), the annual MSLs at Auckland, Lyttelton and Dunedin have been processed as two different data sets, i.e., the full data set, and then the data from 1961-2017. The processing of the data set from the start of the data record to 1960 has previously been reported in

Hannah (2016) and has not been repeated. However, for comparison purposes the results from that processing are shown in Table A.2.

Table A.2. Long-Term MSL Trends
(Units in mm/yr together with standard deviations)

Port	Length of Data Set (Total no. of yrs)	MSL Linear Trend							
		Start of data set to 1960		1961 - 2015		1961-2017		Full data set to the end of 2015	Full data set to the end of 2017
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend		
Auckland	1899-2017 (117)	60	1.76 (0.20)	55	2.34 (0.26)	57	2.49 (0.24)	1.60 (0.08)	1.65 (0.08)
Wellington	1891-2017 (118)	61	0.72 (0.43)	55	2.67 (0.21)	57	2.74 (0.20)	2.23 (0.16)	2.28 (0.15)
$Wellington^{TC}$				55	2.21 (0.20)	57	2.22 (0.19)	1.97 (0.15)	1.98 (0.14)
Lyttelton	1901-2017 (105)	48	1.33 (0.25)	55	2.54 (0.23)	57	2.70 (0.22)	2.12 (0.09)	2.19 (0.09)
Dunedin	1899-2017 (100)	50	0.76 (0.19)	48	1.47 (0.24)	50	1.63(0.22)	1.42 (0.08)	1.47 (0.08)
New Plymouth	1920-2017 (64)							1.28 (0.27)	1.31 (0.25)
Moturiki	1951-2017 (45)			42	1.63 (0.37)	44	1.84 (0.34)	1.84 (0.34)	2.08 (0.24)

Note:
1. $Wellington^{TC}$ = Wellington tectonically corrected
2. Due to the possible influence of data inconsistencies at New Plymouth over the period 1960-1975 (see earlier text), no 1961-2017 analysis is reported for this port.
3. At Moturiki, the data series used for the 1961-2017 trend starts from 1974 not 1961.

DISCUSSION

While not yet large enough to be statistically significant it is interesting to note that at every port and for all data sets the addition of the 2016 and 2017 data results in an increase in the calculated sea level trend when compared to the trends reported in Hannah (2016). When the full data sets at the four main ports are compared, this increase is remarkably consistent in size. This would indicate that the 2016 and 2017 MSLs are typically higher than prior years. Should this not be the product of the periodic features of the 2-4 year ENSO cycle or the longer period IPO cycle (i.e., should both cycles be at a neutral phase), then it would appear that some other influence is at work. It is possible that we may be seeing a very early indication of a further uptick in the rate of sea level rise. If the changes seen in 2016 and 2017 continue, it should take less than a decade of additional data for them to become statistically significant. In the modern tide gauge era this would be unprecedented. They highlight the importance of maintaining high quality tide gauge records at all sites into the future.

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Appendix B Updated SLR trends to end of 2018

NZ WIDE SEA LEVEL TRENDS TO 31 DECEMBER 2018

Report to NIWA from Vision NZ Ltd

1. INTRODUCTION

This report has been produced in response to a request from NIWA to update the sea level trends at Auckland, Wellington, Lyttelton, Dunedin, New Plymouth and Moturiki to the end of 2018. It essentially extends the work done in Hannah (2018). It also corrects a problem found in the Moturiki analyses done for the periods 1974-2015 and 1974-2017 (see later comments).

2. THE DATA

With the exception of Moturiki where NIWA provided monthly MSLs, raw hourly MSLs were provided to the author by the Tidal Officer at Land Information NZ. This hourly data has been processed into daily and monthly means using the University of Hawaii sea level processing software (Caldwell, 2014). These monthly means were then used to form the annual Mean Sea Levels (MSLs).

The sea level data sets for 2018 were largely complete. For documentation purposes outages are noted in Table 1, below.

Table 1: Data Availability 2018

	Port					
	Auckland	Wellington	Lyttelton	Dunedin	New Plymouth	Moturiki
Missing Data	3 days - July	100% complete	1 day – January 12 days- February 1 day –May 1 day – June 2 days – Nov. 2 days - December	12 days - January	1 day –Nov.	Daily data not supplied. All monthly MSLs were available.

These data outages are sufficiently short as to have a negligible effect on the sea level trend analyses.

Prior to the analysis, the same corrections were applied to the sea level data as documented in Hannah (2018).

3. RESULTS

Similarly to the methods reported in Hannah (2018), the annual MSLs at Auckland, Wellington, Lyttelton and Dunedin have been processed as two different data sets, i.e., the full data set, and then the data from 1961-2018. Updated results are shown in Table 2, below.

Table 2. Long-Term MSL Trends
(Units in mm/yr together with standard deviations)

Port	Length of Data Set (Total No. of yrs)	MSL Linear Trend							
		1961 -2015		1961 - 2017		1961-2018		Full data set to the end of 2017	Full data set to the end of 2018
		Yrs of data	Trend	Yrs of data	Trend	Yrs of data	Trend		
Auckland	1899-2018 (118)	55	2.34 (0.26)	57	2.49 (0.24)	58	2.54 (0.23)	1.65 (0.08)	1.67 (0.08)
Wellington	1891-2018 (120)	55	2.67 (0.21)	57	2.74 (0.20)	58	2.79 (0.19)	2.28 (0.15)	2.30 (0.15)
Wellington^{TC}		55	2.21 (0.20)	57	2.22 (0.19)	58	2.23 (0.18)	1.98 (0.14)	1.97 (0.14)
Lyttelton	1901-2018 (106)	55	2.54 (0.23)	57	2.70 (0.22)	58	2.73 (0.21)	2.19 (0.09)	2.21 (0.09)
Dunedin	1899-2018 (101)	48	1.47(0.24)	50	1.63 (0.22)	51	1.64(0.21)	1.47 (0.08)	1.48 (0.08)
New Plymouth	1920-2018 (65)							1.31 (0.25)	1.33 (0.24)
Moturiki	1951-2018 (46)	42	2.19 (0.33)	44	2.36 (0.30)	45	2.38 (0.28)	2.08 (0.24)	2.12 (0.23)

Note:
1. Wellington^{TC} = Wellington corrected for a GPS derived rate of tectonic subsidence of 1.8 mm/yr. This correction has been applied from 1998 onwards.
2. Due to the possible influence of data inconsistencies at New Plymouth over the period 1960-1980, no 1961-2018 analysis is reported for this port.
3. At Moturiki, the data series used to calculate the 1961-2018 trend starts in 1974 not 1961.

DISCUSSION

It is relevant to observe that at every port (and with the sole exception of Wellington^{TC}), the sea level trend as calculated from the start of the data set to the end of 2018 is slightly higher than the trend as calculated to the end of 2017. In addition, each dataset starting in 1961 and ending in 2015, 2017 and 2018 respectively, show similar patterns of upward movement. While the change at any individual port is not statistically significant, the similarity in trend confirms the comments made in Hannah (2018), namely that the 2016, 2017 and 2018 MSLs are above the average trend for the period. Should this not be the product of the periodic features of the 2-4 year ENSO cycle or the longer period IPO cycle (i.e., should both cycles be at a neutral phase), then it appears that some other influence is at work. In the three years since the end of 2015 (with the exception of the Wellington^{TC} results), the average trend since 1961 has risen from 2.24 (± 0.12) mm/yr to 2.42 (± 0.10) mm/yr. Should this rate of rise continue and not be associated with one or more of the periodic features mentioned earlier, it will be able to be identified as a new, statistically significant feature before 2025. Outside of explanations associated with tectonics or physical (periodic) oceanographic features, such a rate of change would be unprecedented in New Zealand in the modern tide gauge era.

The results at Moturiki from 1974-2015 and from 1974-2017 have been restated from those shown in Hannah (2018). In the earlier analysis, and because of the shortness of the data set, they were included as supplementary data and had not been subject to an independent check. However, during this analysis it was found that incorrect meteorological data had been used when assessing these particular trends. This problem has been corrected. As the Moturiki data set lengthens, these particular trend estimates become increasingly robust and thus of greater value.

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Caldwell, P., (2014). Hourly sea level data processing and quality control software (SLP64 User Manual). http:// *ilikai.soest.**hawaii**.edu/uhslc/jasl/slp64/SLP64_Manual.pdf.*

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