Journal of Geophysical Research: Solid earth

Supporting Information for

Sea level rise in New Zealand:
The implication of vertical land motion on tide gauge records

Paul H. Denys[1], R. John Beavan[2], John Hannah[1], Chris F. Pearson[1], Neville Palmer[2], Mike Denham[1], Sigrun Hreinsdottir[2].

[1] School of Surveying, University of Otago, PO Box 56, Dunedin, New Zealand.
[2] GNS Science, 1 Fairway Drive, PO Box 30368, Lower Hutt, New Zealand

Contents of this file

Text S1
Table S1 to S4

Additional Supporting Information (Files uploaded separately)

Captions for Datasets S1 to S5

Introduction

A detail description of the GPS data processing is given in Text S1 and the processing strategies and models used are tabulated in Table S1. For the time series modelling of each site Table S2 lists the station parameters estimated for each site including epoch times and the decay constants used. The estimated vertical rates using both a least squares estimate and the HECTOR software are tabulated in Table S3

The mean sea level data from the five tide gauge sites (Auckland, New Plymouth, Wellington, Lyttelton and Dunedin) are provided as comma delimited files (*.csv) as Datasets S1 to S5 respectively. These files are easily read by spreadsheet software e.g. Microsoft Excel. The file format is as follows:

Column	Data	Units
1	Date	year
2	Mean pressure	hPa
3	Mean temperature	°C
4	Mean sea level	metres
5	Standard deviation	metres

Text S1. GPS/GNSS Data Processing

The GPS data have been processed using the Bernese software package (v5.2) (Dach *et al*., 2015) using 24 hour daily position solutions. The Centre for Orbit Determination (CODE) precise satellite orbit and clock parameters together with the I08.ATX absolute GPS receiver and satellite antenna phase centre model (Schmid *et al.,* 2007) are used to generate daily position time series. The carrier phase ionosphere-free linear combination is used to correct the first order ionosphere. Higher-order ionospheric effects are not considered here, as Hernandez-Pajares et al. (2007) and Petrie *et al.* (2010) showed that these effects are less than 1 mm. Tropospheric effects are modelled using the Global Mapping Function, which maps the zenith troposphere delay to the elevation of each observation *(*Böhm *et al.,* 2007). A 10° elevation cut-off angle is used, a compromise to constrain tropospheric effects but minimize multipath errors. Non-tidal atmospheric loading displacements are modelled according to the Ray and Ponte (2003). The effects of ocean loading, are corrected using the FES2004 model (Lyard *et al*., 2006) from the Onsala Space Observatory (holt.oso.chalmers.se/loading). Ambiguity resolution involves a recursive strategy that includes code and phase-based widelane, QIF and direct L1/L2 fixed ambiguities, depending upon baseline length (Dach *et al*., 2015). The ITRF2008 reference frame is realised through the three parameter Helmert transformation of the daily coordinate positions. Global IGS sites include sites on the stable Pacific, Antarctic and Australian plates. Regional filtering of the resulting daily-coordinate time series was performed to attenuate common mode error (Wdowinski *et al.*, 1997) using a set of New Zealand stations that have close to linear behaviour over the 2000-2009 time period. During this filtering, data outliers were removed using the Median Absolute Deviation (MAD) robust estimator at the 4σ level with $\sigma = 1.4826 \times$ MAD.

Table S1. GPS data processing strategies and models used.

Model	Note	
Frame		ITRF2008 (COD Reproc 1)
Observables		Double Differenced Phase
Sessions		24 hr, Epoch Interval: 180s interval (Data Cleaning: 30 s)
Elevation Cut-off		7°
Antenna PCV		Absolute, I08.ATX
Ocean Loading Model	a	FES2004
Ionospheric Refraction		Ionosphere Free Linear Combination (1st Order effect only)
Tropospheric Refraction		Zenith Delay: Hourly, Troposphere Gradient: Daily Mapping Functions : Global Pressure Temperature Model (GMF)
Ambiguities		Fixed: strategy includes phase-based widelane, QIF, direct L1/L2 depending upon baseline length
Global Ionosphere Model		CODE
Daily Solutions	b	Helmert: 3 parameter

a. Calculated by Onsala Space Observatory
b. Daily solutions transformed onto a set of regional (Australia and Pacific) IGS stations.

Table S2. Station parameters associated with each cGPS site. The parameters include offsets (antenna, coseismic displacement Offsets), annual and semi-annual seasonal terms (Cyclic), logarithmic decay terms to model post-seismic relaxation (LogDecay) and the error function to used to model slow slip events (ErrorFn).

Site	Parameter	Date	Date	Seasonal Period (Year)	Decay Constant (Year)	Remarks
AUCK	Offset:	2001 10 28				Antenna
AUCK	Offset:	2005 11 4				Antenna
AUCK	Offset:	2011 3 1				Antenna
AUCK	Cyclic:			0.5		Semi-annual
AUCK	Cyclic:			1		Annual
AUKT	Cyclic:			0.5		Semi-annual
AUKT	Cyclic:			1		Annual
AVLN	ErrorFn:	2007 10 20	2008 9 28			Kapiti Coast 2007SSE
AVLN	ErrorFn:	2013 2 20	2014 5 26			Kapiti Coast 2013SSE
DUND	Offset:	2007 10 15				George Sound EQ
DUND	Offset:	2010 11 25				Antenna
DUND	LogDecay:	2009 7 15			0.019	Dusky 2009
DUND	Cyclic:			0.5		semi-annual
DUND	Cyclic:			1		annual
DUNT	Offset:	2003 8 23				Secretary Is EQ
DUNT	Offset:	2004 12 23				Macquarie Is EQ
DUNT	Offset:	2007 10 15				George Sound EQ
DUNT	Offset:	2009 7 15				Dusky Sound EQ 2009
DUNT	Cyclic:			0.5		Semi-annual
DUNT	Cyclic:			1		Annual
DUNT	LogDecay:	2009 7 15			0.019	Dusky Sound EQ 2009
LYTT	Offset:	2011 2 21				Christchurch EQ
LYTT	Offset:	2011 6 13				Godley Head EQ
LYTT	Offset:	2011 12 24				ChCh Boxing Day EQ
LYTT	Cyclic:			0.5		Semi-annual
LYTT	Cyclic:			1		Annual
LYTT	LogDecay:	2010 9 3			0.3	Darfield 2010
MQZG	Offset:	2001 9 3				Antenna
MQZG	Offset:	2005 3 1				Antenna
MQZG	Offset:	2009 7 15				Dusky Sound EQ 2009
MQZG	Offset:	2011 2 10				Antenna
MQZG	Offset:	2011 2 21				Christchurch EQ
MQZG	Offset:	2011 6 13				Godley Head EQ
MQZG	Offset:	2011 12 24				ChCh Boxing Day EQ
MQZG	Cyclic:			0.5		Semi-annual
MQZG	Cyclic:			1		Annual
MQZG	LogDecay:	2010 9 3			0.3	Darfield EQ 2010
NPLY	Offset:	2010 11 23				Antenna
NPLY	Cyclic:			0.5		Semi-annual
NPLY	Cyclic:			1		Annual
OUS2	Offset:	2003 8 23				Secretary Is EQ
OUS2	Offset:	2004 12 23				Macquarie Is EQ
OUS2	Offset:	2006 6 24				Antenna
OUS2	Offset:	2007 10 15				George Sound EQ
OUS2	Offset:	2011 6 23				Antenna
OUS2	Cyclic:			0.5		Semi-annual
OUS2	Cyclic:			1		Annual
OUS2	LogDecay:	2009 7 15			0.019	Dusky Sound EQ 2009
OUSD	Offset:	2003 8 23				Secretary Is EQ
OUSD	Offset:	2004 12 23				Macquarie Is EQ
OUSD	Offset:	2006 6 18				Antenna
OUSD	Offset:	2007 10 15				George Sound EQ

OUSD	Offset:	2011 07 26				Antenna
OUSD	Cyclic:			0.5		Semi-annual
OUSD	Cyclic:			1		Annual
OUSD	LogDecay:	2009 7 15			0.019	Dusky 2009
TAKL	Cyclic:			0.5		Semi-annual
TAKL	Cyclic:			1		Annual
WARK	Cyclic:			0.5		Semi-annual
WARK	Cyclic:			1		Annual
WGTN	Offset:	2005 3 22				Antenna
WGTN	Offset:	2010 11 15				Antenna
WGTN	Offset:	2013 7 21				Cook Strait [Seddon EQ1]
WGTN	Offset:	2013 8 16				Grassmere [Seddon EQ2]
WGTN	Cyclic:			0.5		Semi-annual
WGTN	Cyclic:			1		Annual
WGTN	ErrorFn:	1999 1 1	2000 7 1			Kapiti SSE1999
WGTN	ErrorFn:	2007 10 20	2008 9 28			Kapiti SSE2007
WGTN	ErrorFn:	2013 2 20	2014 5 26			Kapiti SSE2013
WGTT	Offset:	2013 7 21				Cook Strait [Seddon EQ1]
WGTT	Offset:	2013 8 16				Grassmere [Seddon EQ2]
WGTT	Cyclic:			0.5		Semi-annual
WGTT	Cyclic:			1		Annual
WGTT	ErrorFn:	1999 6 1	2000 7 1			Kapiti SSE1999
WGTT	ErrorFn:	2007 10 20	2008 9 28			Kapiti SSE2007
WGTT	ErrorFn:	2013 2 20	2014 5 26			Kapiti SSE2013

Table S3. GPS Site velocity estimates. Both vertical estimates based on the HECTOR software (Bos *et al.*, 2013) (see also Table 4, main text), and the least squares estimates are given for comparison purposes. As it is widely recognized that a white noise model results in unrealistically optimistic trends standard errors, we include both the least squares uncertainties estimates utilizing a white plus random walk noise model (see main text for explanation) while the HECTOR estimates use a white plus power law model. In general the uncertainty estimates from both stochastic models agree at the ±0.1 mm/yr level.

LSE	Least squares estimate using a white noise plus random walk stochastic model	
	Vel:	vertical velocity (mm/yr)
	Sigma:	one standard deviation precision (mm/yr)
HECTOR	Maximum likelihood estimate using a white noise plus power law stochastic model (HECTOR software)	
	Vel:	vertical velocity (mm/yr)
	Sigma:	one standard deviation precision (mm/yr)
Parameters	Additional parameter estimates for a position time series solution	
	Offset:	equipment offset due to equipment (e.g. antenna) changes
	EQ:	coseismic offset due to an earthquake event
	SSE:	displacement offset caused by slow slip events
	Log Decay:	displacement due to post-seismic decay, log decay function
Data	Data availability	
	Data span (years)	
Soln	Solution type; for a particular position time series, identifies the different data and associated estimated parameter(s) solution	
	A:	Combined TAKL and AUKT position time series
	B:	Pre Darfield earthquake event (3/9/2010) data only
	C:	Pre Dusky Sound earthquake event (15/7/2009) data only
	D:	No logarithmic term include, replaced by offset(s) only
	E:	No position data included between earthquake events 3/9/2010 to 24/12/2011, one offset parameter
	F:	Logarithmic term included.

Highlighted values have been used in the main text (Table 5).

		LSE		HECTOR		Site Parameters				Data	
Site	**Soln**	**Vel Hgt**	**Sigma [WN+RWN]**	**Vel Hgt**	**Sigma [WN+PL]**	**Offset**		**Event**		**Availability**	**Span**
						Antenna	**EQ**	**SSE**	**Log Decay**		
		mm/yr	mm/yr	mm/yr	mm/yr						years
Auckland											
AUCK		-0.37	0.11	-0.56	0.17	3				0.98	19.9
WARK		-0.63	0.20	-0.63	0.49					0.99	6.5
AUKT		-0.83	0.21	-0.71	0.31					0.99	5.9
TAKL		-0.53	0.22	-0.54	0.27					0.64	6.0
TAKL+AUKT	A	-0.62	0.13	-0.62	0.10	1				0.69	14.1
mean		**-0.54**	**0.15**	**-0.57**	**0.30**						
New Plymouth											
NPLY		-1.03	0.14	-1.16	0.28	1				0.98	12.4
Wellington											
WGTN		-2.74	0.11	-2.65	0.17	2	2	3		0.97	19.2
WGTT		-2.72	0.13	-2.84	0.18		2	3		0.94	15.6
AVLN		-3.12	0.17	-3.09	0.21			2		0.98	9.5
mean		**-2.86**	**0.14**	**-2.86**	**0.19**						
Lyttelton											
MQZG	B	-1.47	0.15	-1.07	0.31	2	1				
MQZG	D	-1.72	0.13	-1.33	0.28	3	5				
MQZG	E	-1.73	0.13	-1.34	0.29	2	2				
MQZG	F	-1.49	0.13	-1.10	0.27	3	5		1	0.96	15.6
mean		**-1.60**	**0.14**	**-1.21**	**0.29**						
LYTT	B	-0.43	0.15	-0.51	0.20		1				
LYTT	D	-0.42	0.13	-0.47	0.20		5				
LYTT	E	-0.42	0.13	-0.49	0.20		2				
LYTT	F	-0.43	0.13	-0.47	0.20		5		1	0.75	15.4
mean		**-0.43**	**0.18**	**-0.49**	**0.20**						
Dunedin											
OUSD	C	-1.47	0.13	-1.14	0.26	1	2				
OUSD	D	-1.42	0.11	-1.12	0.22	2	3			0.96	19.9
OUSD	F	-1.49	0.11	-1.29	0.22	2	3		1		
mean		**-1.46**	**0.12**	**-1.18**	**0.23**						
OUS2	C	-0.89	0.16	-0.56	0.51	1	2				
OUS2	D	-0.72	0.13	-0.70	0.41	2	3			0.88	15.7
OUS2	F	-0.93	0.13	-0.92	0.41	2	3		1		
mean		**-0.85**	**0.14**	**-0.73**	**0.45**						
DUND	C	-2.88	0.26	-3.22	1.06		1				
DUND	D	-1.57	0.16	-1.89	0.56	1	2			0.99	10.0
DUND	F	-2.37	0.16	-3.07	0.55	1	2		1		
mean		**-1.57**	**0.20**	**-2.72**	**0.76**						
DUNT	C	-0.62	0.17	-0.69	0.43		2				
DUNT	D	-0.59	0.13	-0.66	0.44		3			0.80	15.9
DUNT	F	-0.95	0.13	-0.95	0.42		3		1		
mean		**-0.72**	**0.14**	**-0.77**	**0.43**						

Table S4. Relative sea level (RSL) trends with their 1 sigma standard deviations. This is a repeat of Table 4 with the inclusion of the RSL trends from this analysis estimated using the approach outlined in Hannah (1990) (third column) as well as the rates estimated using HECTOR (column 4). This is to provide consistency with earlier analyses (Hannah 1990, 2004). For the current analysis, the rates estimated using the two approaches are almost identical (Auckland, Wellington, Dunedin < 0.04 mm/yr, New Plymouth 0.15 mm/yr and Lyttelton 0.09 mm/yr). The uncertainty estimates using HECTOR have nearly doubled (increased by factors of 1.1 to 1.9) due to the noise model accounting for correlated noise.

	Hannah (1990) (mm/yr)	**Hannah (2004) (mm/yr)**	**This paper (mm/yr)**	**This paper (mm/yr) HECTOR**
Auckland	1.34 ± 0.11	1.30 ± 0.09	1.55 ± 0.08	1.57 ± 0.15
New Plymouth			1.31 ± 0.28	1.46 ± 0.54
Wellington	1.73 ± 0.27	1.78 ± 0.21	2.14 ± 0.16	2.18 ± 0.17
Lyttelton	2.26 ± 0.14	2.08 ± 0.11	2.00 ± 0.09	1.91 ± 0.13
Dunedin	1.36 ± 0.15	0.94 ± 0.12	1.36 ± 0.08	1.35 ± 0.15

Data Set S1. Auckland mean sea level data 1899-2013. Comma delimited file with columns Year, Pressure (hPa), Temperature (°C), MSL height (m), standard deviation (m).

Data Set S2. New Plymouyh mean sea level data 1920-2013. Comma delimited file with columns Year, Pressure (hPa), Temperature (°C), MSL height (m), standard deviation (m).

Data Set S3. Wellington mean sea level data 1891-2013. Comma delimited file with columns Year, Pressure (hPa), Temperature (°C), MSL height (m), standard deviation (m).

Data Set S4. Lyttelton mean sea level data 1901-2012. Comma delimited file with columns Year, Pressure (hPa), Temperature (°C), MSL height (m), standard deviation (m).

Data Set S5. Dunedin mean sea level data 1901-2012. Comma delimited file with columns Year, Pressure (hPa), Temperature (°C), MSL height (m), standard deviation (m).