SUPPLEMENTARY INFORMATION

associated with the paper

Distribution of Present-Day Vertical Deformation Across the Southern Alps, New Zealand, from 10 Years of GPS Data

by

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This file contains a discussion of signals that may be present in our vertical rate data due to (1) glacial isostatic adjustment and (2) the elastic response to present-day ice loss.

It also contains three tables (Tables S1 – S3) consisting of information on the times of time-series offsets provided to the maximum-likelihood modeling of the GPS time series, and additional results from that modeling.

Vertical response to present-day and Holocene ice melting

The predicted vertical rate in the center of the Southern Alps network resulting from Holocene ice melting using the ICE-5G v1.2b VM2_L90 model (Peltier, 2004) is +0.34 mm/yr and the variation across the network is less than 0.03 mm/yr. Any ongoing viscous response to Holocene melting of New Zealand glaciers is likely to be small (because the load was relatively small in magnitude and of limited spatial extent) and smoothly varying across the network. Because we are concerned with relative vertical rates across the network we expect these signals to be less important for this study than the effects of present-day ice melting.

The terminus of the Tasman Glacier, the largest glacier in the Southern Alps, is only ~12 km from GPS site HORN, and a few km further from NETT. Other GPS sites in the network are significantly further from any large glaciers. Southern Alps glaciers have on average been losing ice over the past century (Chinn, 1988; Hochstein et al., 1995; Thomas, 2008; NIWA, 2008, 2009), and the mass loss on the Tasman Glacier has accelerated in recent decades since a lake formed at its terminus.

The Tasman Glacier is 26 km long, about 2 km wide near its terminus and had an estimated area of 99 km^2 in the 1980s (Ruddell, 1995). Hochstein estimated downwasting of 1.2 m/yr from 1972-1982, which corresponds to an equivalent water volume of up to 0.1 km^3/yr. Thomas (2008) estimated ice loss of 0.092 km^3/yr from 1965-2002 using ASTER satellite data, and 0.064 km^3/yr from 1977-2005 using annual snowline surveys. Purdie & Fitzharris (1999) estimated 0.14 km^3/yr equivalent water loss from the lower 10 km of the Tasman Glacier in the 1990s, of which 0.02 km^3/yr was from the lower 4 km. Ice loss has in general accelerated since the 1990s (NIWA, 2008, 2009) with an estimated ice loss of ~2 km^3/yr over 50 of the larger Southern Alps glaciers from 2005-2009. The ice loss from the Tasman Glacier over the 2001-2010 duration of our continuous GPS measurements is therefore likely to be significantly higher than the 0.14 km^3/yr estimated by Purdie & Fitzharris.

We estimate the vertical rate at HORN due to the reducing Tasman Glacier ice load using the Boussinesq solution for a point surface load on an elastic half space (e.g., Farrell, 1972). We adopt the equivalent water volume estimates of Purdie & Fitzharris (1999). Taking HORN to be 12 km from the glacier terminus we calculate the vertical displacement due to two point loads, one corresponding to a load of -0.02 km^3/yr of water at a distance of 14 km and the other corresponding to -0.12 km^3/yr of water at a distance of 19 km. The result is a vertical rate of +0.25 mm/yr at HORN. Based on the acceleration in ice loss from the Tasman and other glaciers (NIWA, 2008, 2009) since Purdie & Fitzharris's estimates in the 1990s, we suggest that the 2000-2010 rate could be a factor of 2 to 4 faster. This leads to the statement in the main text that the estimated vertical rate at HORN due to present-day ice melting is +0.3 to as much as +1 mm/yr.

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Table S1. Times and reasons for offset estimation

Site	Time, years from 2000.0	Offset[1] ± 1σ, mm	Equipment change at the site[2]
HOKI	2003 Sep 05	17.3±1.0	Antenna, radome, antenna mount, receiver
HOKI	2007 May 22	Not estimated	Receiver
QUAR	2000 Mar 09	2.1±1.5	Antenna mount
QUAR	2004 Oct 13	Not estimated	Receiver
KARA	2000 Mar 09	-2.9±2.0	Antenna mount
KARA	2004 Dec 04	4.2±3.0	Antenna
KARA	2007 Feb 01	Not estimated	Receiver
LEOC	2002 Jun 01	-1.0±1.9	Antenna (same type, different s/n)
WAKA[3]	2002 May 31	-4.4±1.9	Antenna mount
VEXA[3]	2009 Mar 13	17.7±1.3	Antenna, radome, antenna mount, receiver
CNCL	2000 Mar 09	3.2±1.6	Antenna mount
CNCL	2000 Aug 03	0.8±1.2	Antenna (same type, different s/n)
CNCL	2009 Mar 11	-9.5±1.0	Antenna cable[5]
PILK[3]	2009 Mar 12	17.0±1.9	Antenna, radome, antenna mount, receiver
MAKA	2001 Feb 01	1.3±2.3	Antenna (same type), antenna mount
MAKA[4]	2003 Feb 24	-3.1±4.4	Antenna mount
MAKA	2006 Mar 21	-1.9±2.1	Antenna (same type, different s/n)
NETT	2008 Mar 17	11.0±2.3	Antenna, radome, antenna mount, receiver
MQZG	2001 Sep 03	-10.2±1.2	Antenna, radome and receiver
MQZG	2005 Feb 28	22.8±1.2	Antenna, radome and receiver

[1]The value of the offset does not have any physical meaning as it depends on the GPS analysis strategy, in particular the antenna phase patterns used in the processing. The values are shown with their standard errors to indicate the precision with which the offsets are estimated.
[2]Offsets are not estimated when only the receiver is changed.
[3]Site was changed from semi-continuous to continuous at this time.
[4]Site was changed from continuous to semi-continuous at this time.
[5]This offset is clear in the time series, but the reason for the offset is not understood.

Table S2. Estimated seasonal terms and their standard errors

Site	Annual terms, mm				Semi-annual terms, mm			
	sin	Std err	cos	Std err	sin	Std err	cos	Std err
HOKI	0.5	0.2	-0.4	0.2				
QUAR	0.8	0.3	1.3	0.3				
KARA	0.5	0.5	-0.3	0.5				
LEOC	1.5	0.5	0.9	0.4				
WAKA	1.6	0.5	1.5	0.5				
VEXA	0.2	1.0	1.6	0.6				
CNCL	1.3	0.3	0.1	0.3				
PILK	8.0	0.6	3.3	0.6	0.0	0.4	1.8	0.5
MAKA	0.9	1.5	-0.5	0.9				
REDD	0.0	0.9	2.5	0.7				
MCKE	0.5	1.8	1.2	0.6				
NETT	10.3	0.6	0.2	0.6	1.6	0.5	1.7	0.5
HORN	2.0	0.6	-1.1	0.6				
BNET	0.9	0.4	-1.1	0.4				
MTCX	0.4	1.0	0.7	0.6				
MTJO	-0.8	0.2	-0.6	0.2				
MQZG	0.0	0.3	0.4	0.3				
OUSD	-0.4	0.2	-0.3	0.2				

Table S3. Estimated power-law and white noise amplitudes and their standard errors

Site	PL slope	Power-law noise		White noise, mm	
		amp	std err	amp	std err
HOKI	-0.71	6.38	0.30	1.85	0.12
QUAR	-0.83	8.72	0.38	2.42	0.11
KARA	-1.13	11.51	0.44	2.32	0.08
LEOC	-1.07	8.55	0.51	2.45	0.09
WAKA	-0.89	10.86	0.43	1.84	0.15
VEXA	-0.60	9.27	0.22	0.00	0.00
CNCL	-0.52	8.73	0.10	0.00	0.00
PILK	-0.85	13.14	0.56	1.96	0.25
MAKA	-1.34	9.52	1.05	3.19	0.11
REDD	-0.57	11.10	0.25	0.00	0.00
MCKE	-0.37	7.38	0.98	0.53	4.32
NETT	-0.58	16.16	0.25	0.00	0.00
HORN	-0.32	15.37	0.25	0.00	0.00
BNET	-0.34	9.49	0.81	0.32	8.32
MTCX	-0.33	6.26	0.21	0.00	0.00
MTJO	-0.74	5.53	0.31	2.28	0.09
MQZG	-0.76	8.29	0.39	2.42	0.13
OUSD	-0.50	6.83	0.08	0.00	0.00