Supplementary Information: Annual Variation of Coastal Uplift in Greenland as an Indicator of Variable and Accelerating Ice Mass Loss

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Atmospheric loading correction

Variable atmospheric pressure can cause cm-scale crustal deformation [*Magie*, 1963; *Darwin* 1882; *Petrov and Boy*, 2004] and has been detected in GPS time series [*Van Dam et al.*, 1994; *Dong et al.*, 2002]. Atmospheric contributions therefore need to be removed from the GPS time series in order to isolate the ice load effects. To correct for air pressure loading, we use pre-computed Atmospheric Loading Displacements (ALD) provided by the Atmospheric Pressure Loading Service (http://gemini.gsfc.nasa.gov/aplo/). This provides a global 3-D ALD model on a 2.5x2.5 degree grid for routine reduction of geodetic data. The procedure for computing ALD is described by *Petrov and Boy* [2004]. Briefly, ALD is calculated by convolving Farrell's elastic Green's functions [*Ferrell*, 1972] with modeled global pressure data (2.5x2.5 degree grid), obtained by subtracting the mean surface pressure field over a baseline period (1980 to 2002) from the NCEP Reanalysis pressure field [*Kalnay et al.*, 1996]. ALD can thus be considered a deviation from an average position. Accuracy of the ALD model is validated by comparing with VLBI observations, and the uncertainty of this model is considered to be better than 15%. However, there is no VLBI in Greenland so the model uncertainty in Greenland could be larger.

Figure S1 shows an example of GPS vertical displacement time series before and after ALD correction and time series of ALD. After the ALD correction, GPS vertical displacement (D_{cal}) caused by ice mass change is:

$$D_{cal} = D_{nal} - D_{alc} \quad (1)$$

where D is the displacement, subscript cal and nal represent values with corrected atmospheric loading and with non-corrected atmospheric loading, and D_{alc} is the atmospheric loading correction, the displacement caused by changes of surface air mass load. In the summer months (May to August) when air pressure decreases, D_{alc} may be as high as 13 mm (light blue zone in Figure 2). In winter months (November to January) when air pressure increases, D_{alc} is more negative (light yellow zone in Figure 2). Similar seasonal variations are observed in most time series used in this study.

Figure S2 shows a time series before and after atmospheric pressure loading correction and the respective best fit cubic spline models. The five parameters describing seasonal uplift derived from these models show slight differences (Table S1). Analysis of all time series shows that uplift values estimated from data corrected for atmospheric loading are higher compared to values estimated without correction.

Annual uplift (U) is the difference between annual highest displacement (D_h) and lowest displacement (D_l) estimated by the spline model:

$$U = D_h - D_l \quad (2)$$

The difference ΔU between annual uplifts estimated with and without atmospheric loading correction can be expressed as:

$$\Delta U = U_{cal} - U_{nal} = (D_{h\_cal} - D_{l\_cal}) - (D_{h\_nal} - D_{l\_nal}) \quad (3)$$

Substituting equation (1) into equation (3) yields:

$$\Delta U = [(D_{h\_nal} - D_{h\_alc}) - (D_{l\_nal} - D_{l\_alc})] - (D_{h\_nal} - D_{l\_nal}) = -D_{h\_alc} + D_{l\_alc} \quad (4)$$

Uplift start time is usually between May and July when D_{l_alc} is positive and uplift end time is usually between November to January when D_{h_alc} is negative (Figure S1), thus the value of ΔU is positive.

Except for Figure S2, all the data used in this paper are corrected for atmospheric loading as described above.

Local snow load effect

All GPS stations discussed in this report are installed on the rocky coastal margin of Greenland. These stations are sensitive not only to net surface mass balance and dynamic mass changes of the nearby ice sheet and glaciers, but also to local snow load changes. We assessed the impact of these local snow loading effects using the snow depth dataset provided by DMI. These data show that in general stations in southern Greenland tend to have high winter snow loads. We selected meteorological station WMO-ID 04272 (Table S2) in the southern Greenland coastal area as typical [*Carstensen and Jorgensen*, 2011]. Figure S3 shows the recorded snow depth from 1961 to 2003. The deepest snow depth recorded during that time is 100 cm in 1990. Assuming that 1 cm snow is equal to 1mm water (typical values for fresh snow) gives 100 mm water load. A simple elastic model for load-related subsidence dl at the surface of an infinite elastic medium is:

$$dl = \sigma \cdot l_0 / E \tag{5}$$

where σ is the normal stress due to snow load (100 mm water = 100 Pa), l_0 is the thickness of the crust (l_0=30 km), and E is the Young's modulus (E = 30 GPa). Calculated subsidence is less than one mm. Thus, we ignored the effect of local snow load.

Uncertainty calculation

Uncertainties for the various parameter estimates were determined with a Monte Carlo simulation, as follows. Random noise was added to the GPS daily solutions, scaled by the daily uncertainties. This creates a new time series, from which the five seasonal uplift variables were re-estimated using the spline technique. The process is repeated 10,000 times, producing 10,000 estimates for each parameter, for each GPS site. A histogram of these values in shown in Figure S4, for an example time series (SENU). The distribution is approximately Gaussian, and the range of values that contains 68% of the values is used to define the one sigma confidence level, also shown in Figure S4. The uncertainty analysis shows that the spline fit, which is sensitive to seasonal variations in the time series, is not sensitive to random daily position changes in the time series. As a results, the estimated uncertainties of the five seasonal parameters are small.

Reference:

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Table S1. Comparison of seasonal uplift patterns parameters estimated from fitting GPS vertical time series with and without atmospheric loading correction to a cubic spline model.

	2008		**2009**		**2010**	
	NO APLC	**APLC**	**NO APLC**	**APLC**	**NO APLC**	**APLC**
Start time (doy)	N/D	N/D	146	150	142	153
End time (doy)	320	315	323	321	327	332
Duration (days)	N/D	N/D	177	171	185	179
Uplift (mm)	N/D	N/D	9.2	11.5	16	19.3
Uplift rate (10^{-2} mm/day)	N/D	N/D	5.2	6.7	8.7	10.8

- NO ALC mean no atmospheric loading correction is applied; ALC means atmospheric loading correction is applied.
- Other symbols are the same as in Table 1

Table S2. List of meteorological stations

WMO-ID and station name	Latitude (deg N)	Longitude (deg E)	Elevation (m.a.s)	Near GPS site	Horizontal dist (km)	Elevation Diff (m)	Distance (km)
04205 Mitt.Qaanaaq*	77.48	-69.38	16	DKSG	231.4	579	231.4
				MARG	95.7	641	95.7
				THU3	105.5	20	105.5
04208 Kitsissorsuit	74.03	-57.82	40	KULL	63.4	54	63.4
04211 Mitt.Upernavik	72.78	-56.13	126	SRMP	58.8	218	58.8
04213 Mitt. Qaarsut	70.73	-52.70	88	QAAR	0.8	35	0.8
				RINK	138.4	1252	138.4
04221 Mitt.Iiulissat	69.23	-51.07	29	KAGA	49.5	120	49.5
04231 Kangerlussuaq*	67.02	-50.70	50	KELY	10.8	194	10.8
04272 Qaqortoq*	60.72	-46.05	32	SENU	71.6	634	71.6
				QAQ1	1.0	78	1.0
04351 Aputiteeq	67.78	-32.30	13	PLPK	123.1	56	123.1
04360 Tasiilaq*	65.60	-37.62	53	HEL2	93.1	374	93.1
				KULU	21.5	14	21.5
04361 Mitt.Kulusuk	65.58	-37.15	35	KSNB	158.6	1624	158.6
04373 Ikermit	64.78	-40.30	85	HJOR	157.3	680	157.3
				LYNS	39.6	89	39.6
				TREO	76.2	38	76.2
				TIMM	268.3	230	268.3

- WMO-ID and station information are provided by Technical Report 11-10 of Danish Meteorological Institute
- Horizontal dist: horizontal distance between GPS site and nearby MET station.
- Elevation diff: elevation difference between GPS site and nearby MET station.

Table S3. Five parameters of seasonal uplift patterns estimated from fitting GPS vertical data to a cubic spline model and parameters describing both atmospheric and oceanic condition at each GPS site.

Year	2008	2009	2010
DKSG			
Start time (doy)	136±12	233±7	197±5
End time (doy)	370±7	382±4	359±5
Duration (days)	234±12	149±7	162±6
Uplift (mm)	5.2±0.8	8.3±0.8	8.1±1.0
Uplit rate (*10^{-2}mm/day)	2.2±0.4	5.6±0.4	5.0±0.5
AMSAT (°C)	-9.2	-9.0	-6.8
CAPDD (days)	113	107	116
AMSSWT (°C)	0.5	0.3	0.5
HEL2			
Start time (doy)	144±5	154±5	174±2
End time (doy)	348±3	350±3	361±2
Duration (days)	204±5	196±5	187±3
Uplift (mm)	12.2±0.7	9.0±0.7	19.0±0.8
Uplit rate (*10^{-2}mm/day)	6.0±0.4	4.6±0.3	10.2±0.4
AMSAT (°C)	-0.5	-0.2	1.0
CAPDD (days)	180	183	188
AMSSWT (°C)	5.0	4.7	5.3
HJOR			
Start time (doy)	113±8	174±7	155±3
End time (doy)	336±3	344±3	346±2
Duration (days)	224±8	169±6	190±3
Uplift (mm)	12.5±0.7	7.0±0.6	18.3±0.7
Uplit rate (*10^{-2}mm/day)	5.6±0.4	4.2±0.3	9.6±0.4
AMSAT (°C)	-1.4	-1.0	0.5
CAPDD (days)	155	155	195
AMSSWT (°C)	5.4	5.1	5.8
KAGA			
Start time (doy)	149±8	186±4	158±3
End time (doy)	367±3	362±3	338±2
Duration (days)	218±8	177±4	180±3
Uplift (mm)	7.6±0.7	8.2±0.7	16.7±0.8
Uplit rate (*10^{-2}mm/day)	3.5±0.4	4.7±0.4	9.3±0.4
AMSAT (°C)	-3.7	-3.2	0.0
CAPDD (days)	148	144	182
AMSSWT (°C)	2.0	1.6	2.3
KELY			
Start time (doy)	153±28	205±74	108±36
End time (doy)	356±21	373±54	335±12
Duration (days)	203±29	169±75	228±35
Uplift (mm)	6.4±2.2	2.1±2.2	14.1±2.5
Uplift rate (mm/day)	3.2±0.4	1.2±0.5	6.2±0.6
AMSAT (°C)	-4.4	-4.7	-0.2
CAPDD (days)	163	148	196
AMSSWT (°C)	2.5	2.3	3.1
KSNB			
Start time (doy)	133±10	221±5	183±4
End time (doy)	370±5	366±3	375±4
Duration (days)	238±10	145±5	192±5
Uplift (mm)	9.6±0.8	7.6±0.6	12.0±0.8
Uplit rate (*10^{-2}mm/day)	4.1±0.4	5.2±0.4	6.3±0.4
AMSAT (°C)	-1.3	-0.6	0.5
CAPDD (days)	153	170	192
AMSSWT (°C)	5.0	4.8	5.4

KULL			
Start time (doy)	247±9	250±4	208±5
End time (doy)	393±5	399±5	355±4
Duration (days)	146±8	149±5	147±5
Uplift (mm)	6.0±0.7	8.5±0.7	6.5±0.8
Uplit rate (*10^{-2}mm/day)	4.1±0.4	5.7±0.4	4.4±0.4
AMSAT (°C)	-7.4	-7.0	-4.7
CAPDD (days)	108	108	138
AMSSWT (°C)	1.0	0.7	1.0
KULU			
Start time (doy)	318±179	110±36	108±24
End time (doy)	116±204	312±22	334±10
Duration (days)	-179±380	207±36	227±24
Uplift (mm)	5.1±5.1	2.9±1.7	11.9±2.0
Uplit rate (*10^{-2}mm/day)	0.0±1.0	1.4±0.3	5.2±0.4
AMSAT (°C)	-0.5	-0.2	1.0
CAPDD (days)	180	183	188
AMSSWT (°C)	5.3	4.9	5.7
LYNS			
Start time (doy)	77±10	193±11	172±3
End time (doy)	355±4	369±3	356±2
Duration (days)	278±11	176±11	185±3
Uplift (mm)	11.1±0.7	7.2±0.6	14.7±0.7
Uplit rate (*10^{-2}mm/day)	4.0±0.3	4.1±0.4	7.9±0.4
AMSAT (°C)	-1.4	-1.0	0.5
CAPDD (days)	155	155	195
AMSSWT (°C)	5.5	5.2	5.9
MARG			
Start time (doy)	121±8	259±4	210±6
End time (doy)	374±8	401±6	361±4
Duration (days)	254±11	142±5	151±6
Uplift (mm)	4.6±0.8	7.2±0.8	6.9±0.8
Uplit rate (*10^{-2}mm/day)	1.8±0.4	5.1±0.4	4.6±0.5
AMSAT (°C)	-9.2	-9.0	-6.8
CAPDD (days)	113	107	116
AMSSWT (°C)	0.3	0.1	0.2
PLPK			
Start time (doy)	85±9	186±17	172±4
End time (doy)	344±5	352±4	379±10
Duration (days)	258±10	165±16	207±10
Uplift (mm)	9.8±0.8	5.8±0.7	14.2±1.0
Uplit rate (*10^{-2}mm/day)	3.8±0.3	3.6±0.4	6.9±0.4
AMSAT (°C)	-3.3	-3.1	-2.6
CAPDD (days)	125	142	146
AMSSWT (°C)	5.0	4.8	5.4
QAQ1			
Start time (doy)	165+37	225+23	165+11
End time (doy)	350+19	384+13	370+8
Duration (days)	185+36	159+21	204+12
Uplift (mm)	3.6+1.6	5.1+1.5	12.4+1.7
Uplit rate (*10^{-2}mm/day)	1.9±0.4	3.2±0.4	6.1±0.4
AMSAT (°C)	0.5	1.4	4.6
CAPDD (days)	219	194	272
AMSSWT (°C)	4.6	4.3	4.9
RINK			
Start time (doy)	168±12	237±6	184±5
End time (doy)	376±6	380±3	357±4
Duration (days)	208±11	143±6	173±5
Uplift (mm)	6.9±0.8	7.3±0.7	10.0±0.8
Uplit rate (*10^{-2}mm/day)	3.3±0.4	5.1±0.4	5.6±0.4
AMSAT (°C)	-4.0	-3.8	-0.6
CAPDD (days)	135	129	184
AMSSWT (°C)	1.7	1.3	1.8

SENU			
Start time (doy)	N/D	151±3	152±2
End time (doy)	313±3	322±4	331±2
Duration (days)	N/D	170±4	179±2
Uplift (mm)	N/D	11.5±0.6	19.3±0.7
Uplit rate (*10^{-2}mm/day)	N/D	6.7±0.3	10.8±0.4
AMSAT (°C)	0.5	1.4	4.6
CAPDD (days)	219	194	270
AMSSWT (°C)	4.6	4.3	4.9
SRMP			
Start time (doy)	150±13	238±5	174±4
End time (doy)	373±5	376±3	350±3
Duration (days)	223±13	139±5	176±4
Uplift (mm)	6.9±0.8	7.7±0.7	11.6±0.8
Uplit rate (*10^{-2}mm/day)	3.1±0.4	5.6±0.4	6.6±0.4
AMSAT (°C)	-6.0	-5.5	-3.1
CAPDD (days)	118	114	150
AMSSWT (°C)	1.1	0.8	1.1
THU3			
Start time (doy)	76±277	218±37	211±16
End time (doy)	367±29	398±23	350±11
Duration (days)	333±257	184±36	139±16
Uplift (mm)	3.5±3.4	5.6±2.0	5.7±1.9
Uplit rate (*10^{-2}mm/day)	1.2±0.3	3.1±0.4	4.1±0.5
AMSAT (°C)	-9.2	-9.0	-6.8
CAPDD (days)	113	107	116
AMSSWT (°C)	0.3	0.1	0.2
TIMM			
Start time (doy)	151±7	196±9	181±3
End time (doy)	352±3	374±3	360±3
Duration (days)	200±7	177±8	179±3
Uplift (mm)	10.4±0.7	8.4±0.7	13.7±0.7
Uplit rate (*10^{-2}mm/day)	5.2±0.4	4.7±0.4	7.7±0.4
AMSAT (°C)	-1.4	-1.0	0.5
CAPDD (days)	155	155	195
AMSSWT (°C)	5.4	5.1	5.8
TREO			
Start time (doy)	122±6	176±6	162±4
End time (doy)	349±3	343±4	367±3
Duration (days)	227±6	167±6	205±4
Uplift (mm)	14.7±0.7	5.4±0.6	17.6±0.8
Uplit rate (*10^{-2}mm/day)	6.5±0.4	3.3±0.4	8.6±0.4
AMSAT (°C)	-1.4	-1.0	0.5
CAPDD (days)	155	155	195
AMSSWT (°C)	5.5	5.2	5.9

- Symbols are the same as in Table 1

Figure S1. GPS time series from site SENU before (pink) and after (black) atmospheric pressure loading correction. Green dots are vertical displacement due to atmospheric pressure loading. Light blue vertical bands mark approximate time period when atmospheric loading displacement is mainly positive. Light yellow vertical bands mark corresponding negative displacement.

Figure S2. Example GPS time series for site SENU, de-trended and fit with annual model shown in Figure 2. Pink and black dots represent daily vertical position estimates before and after atmospheric pressure loading correction respectively. Red and grey curves are respective best-fit cubic splines with smoothing parameter set to 0.91.

Figure S3. Snow depth recorded at a meteorological station (WMO-ID 04272, Table S2) in southern Greenland coastal area. Red star indicates location of the meteorological station.

Figure S4. Histogram showing statistical result for five seasonal uplift variables at GPS station SENU. Five variables are normally distributed.

Figure S5. Time series of GPS vertical component position. (a) Time series of long-term GPS records. (b) Time series of short-term GPS records. For comparison with other sites, time series between mid-2007 and early 2011 at sites KULU, QAQ1, KELY and KULU are also shown in (b). Vertical position is relative to arbitrary position. Pink curve shows constant acceleration model, including annual and semi-annual components. GPS stations are organized from south to north.

Figure S6. Time series of GPS vertical component position after removing long-term trend by low pass filter. (a) Time series of long-term GPS records. (b) Time series of short-term GPS records. In (b), we zoom in to the last 3 years of four long time series. Red curve is cubic spline best-fit model with 0.91 as smoothing parameter. Blue triangle is the maximum value per year, and green triangle is the minimum value per year.

Figure S7. Time series of surface air temperature at meteorological stations near 4 GPS site. Name of nearby GPS site and WMO-ID are on the right side of each plot.