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Abstract

The Arctic Monitoring and Assessment Program (AMAP 2017) report identifies the Arctic as the largest regional source of land ice to global sea-level rise in the 2003–2014 period. Yet, this contextualization ignores the longer perspective from *in situ* records of glacier mass balance. Here, using 17 ($>55^\circ\text{N}$ latitude) glacier and ice cap mass balance series in the 1971–2017 period, we develop a semi-empirical estimate of annual sea-level contribution from seven Arctic regions by scaling the *in situ* records to GRACE averages. We contend that our estimate represents the most accurate Arctic land ice mass balance assessment so far available before the 1992 start of satellite altimetry. We estimate the 1971–2017 eustatic sea-level contribution from land ice north of $\sim 55^\circ\text{N}$ to be 23.0 ± 12.3 mm sea-level equivalent (SLE). In all regions, the cumulative sea-level rise curves exhibit an acceleration, starting especially after 1988. Greenland is the source of 46% of the Arctic sea-level rise contribution (10.6 ± 7.3 mm), followed by Alaska (5.7 ± 2.2 mm), Arctic Canada (3.2 ± 0.7 mm) and the Russian High Arctic (1.5 ± 0.4 mm). Our annual results exhibit co-variability over a 43 year overlap (1971–2013) with the alternative dataset of Marzeion *et al* (2015 *Cryosphere* 9 2399–404) (M15). However, we find a $1.36\times$ lower sea-level contribution, in agreement with satellite gravimetry. The IPCC Fifth Assessment report identified constraining the pre-satellite era sea-level budget as a topic of low scientific understanding that we address and specify sea-level contributions coinciding with IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) ‘present day’ (2005–2015) and ‘recent past’ (1986–2005) reference periods. We assess an Arctic land ice loss of 8.3 mm SLE during the recent past and 12.4 mm SLE during the present day. The seven regional sea-level rise contribution time series of this study are available from AMAP.no.

1. Introduction

As climate change intensifies, the commitment of global land ice loss is increasing and is now almost entirely attributable to human activity (Marzeion *et al* 2014, 2018). An acceleration in global sea-level rise is now evident in satellite derived global sea-level data

(Nerem *et al* 2018). During 2004–2010, Arctic land ice (including sub-Arctic Iceland and sub-Arctic areas of Scandinavia and Alaska) was responsible for 35% of all global sea-level rise (Box and Sharp 2017).

While comprehensive and accurate when integrated regionally, the satellite gravimetry record is limited in continuous temporal coverage to 2003–2015.

Bamber *et al* (2018) expand a land ice sea level contribution assessment back to 1992 using satellite altimetry and regional-climate modeling. For the Arctic region as a whole, they integrate glaciers and ice caps and present five year mass change quantities. Here, we extend the Arctic global sea-level contribution 21 more years into the past by scaling the mass balance of 17 annually-resolved individual glacier mass balance records to seven regional mass balance estimates from satellite gravimetry. We include Alaska, Iceland and Scandinavia in our assessment even though some glaciers lie below the Arctic circle. We thus refer to the Arctic generally as the glaciated regions north of 55°N latitude (excluding the much smaller contributions from eastern Siberia). We thus construct a seven-region 47 year (1971–2017) annual mass balance time series from glacier and ice cap mass balance records north of 55°N that is constrained by satellite gravimetry. Our semi-empirical estimates of regional sea-level rise contribution are compared with independent estimates from Marzeion *et al* (2015) and with the satellite altimetry and gravimetry assessment of Gardner *et al* (2013).

2. Data

2.1. Glacier and ice cap climatic mass balance measurements

Annual surface mass balance from 61 glaciers and ice caps located between latitude 55° and 79° latitude are updated after Mernild *et al* (2013), using data from World Glacier Monitoring Service (WGMS 2017), Dyurgerov and Meier (2005), Cogley *et al* (1996), Thomson *et al* (2017) and through personal correspondence from principle investigators (see supplementary table 1, available online at stacks.iop.org/ERL/13/125012/mmedia). Each mass balance record represents the ‘specific’, i.e. per unit area, mass balance—accumulation minus runoff—area-integrated over each glacier’s area-altitude distribution. A 0.35 w.e. m uncertainty, suggested by Zemp *et al* (2013) and consistent with Beedle *et al* (2014) is assumed for the *in situ* glacier survey surface mass balance data.

Two thirds of the data series originate from the North Atlantic (Norway, Sweden, Iceland, Svalbard and Greenland). Scandinavia (here Norway and Sweden), with 43% (26 of 61) of the sampled glaciers, contains a very small (0.2%) fraction of the total Arctic land ice volume of $114,878 \pm 13,486 \text{ km}^3$ or $317 \pm 37 \text{ mm}$ eustatic sea-level equivalent (SLE) (Box and Sharp 2017). In comparison, Arctic Canada has just four continuous mass balance records since 1971. Yet, Arctic Canada contains 39% of the volume of all Arctic land ice (excluding Greenland). Alaska, with 18% of the Arctic ice volume, similarly of more significance to sea-level than Scandinavia, has four records maintained since 1971 (or before). The spatial

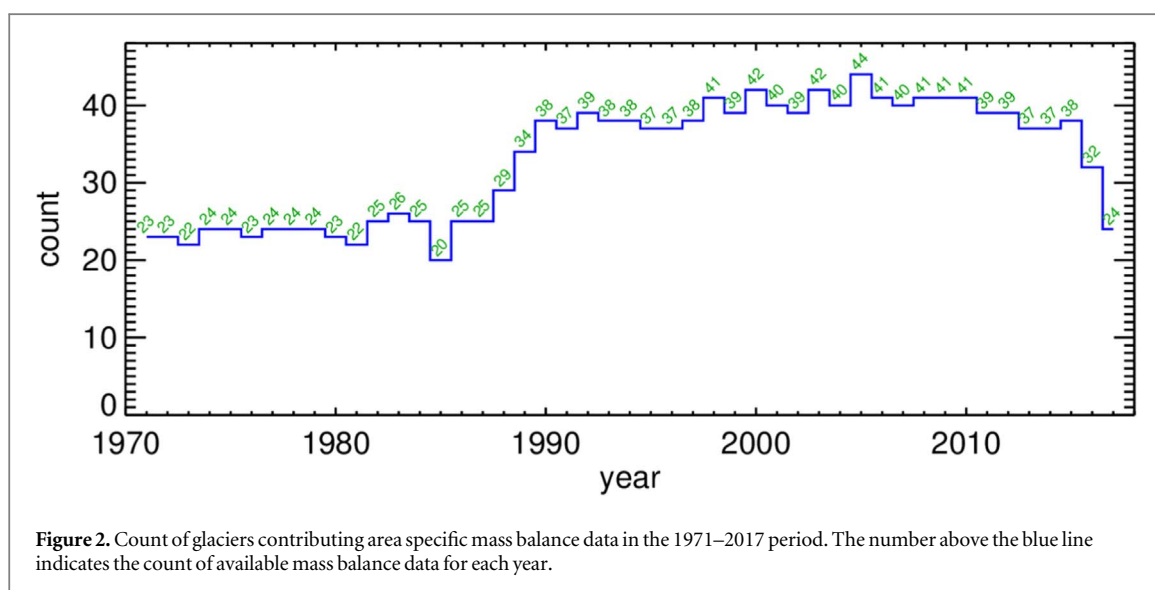
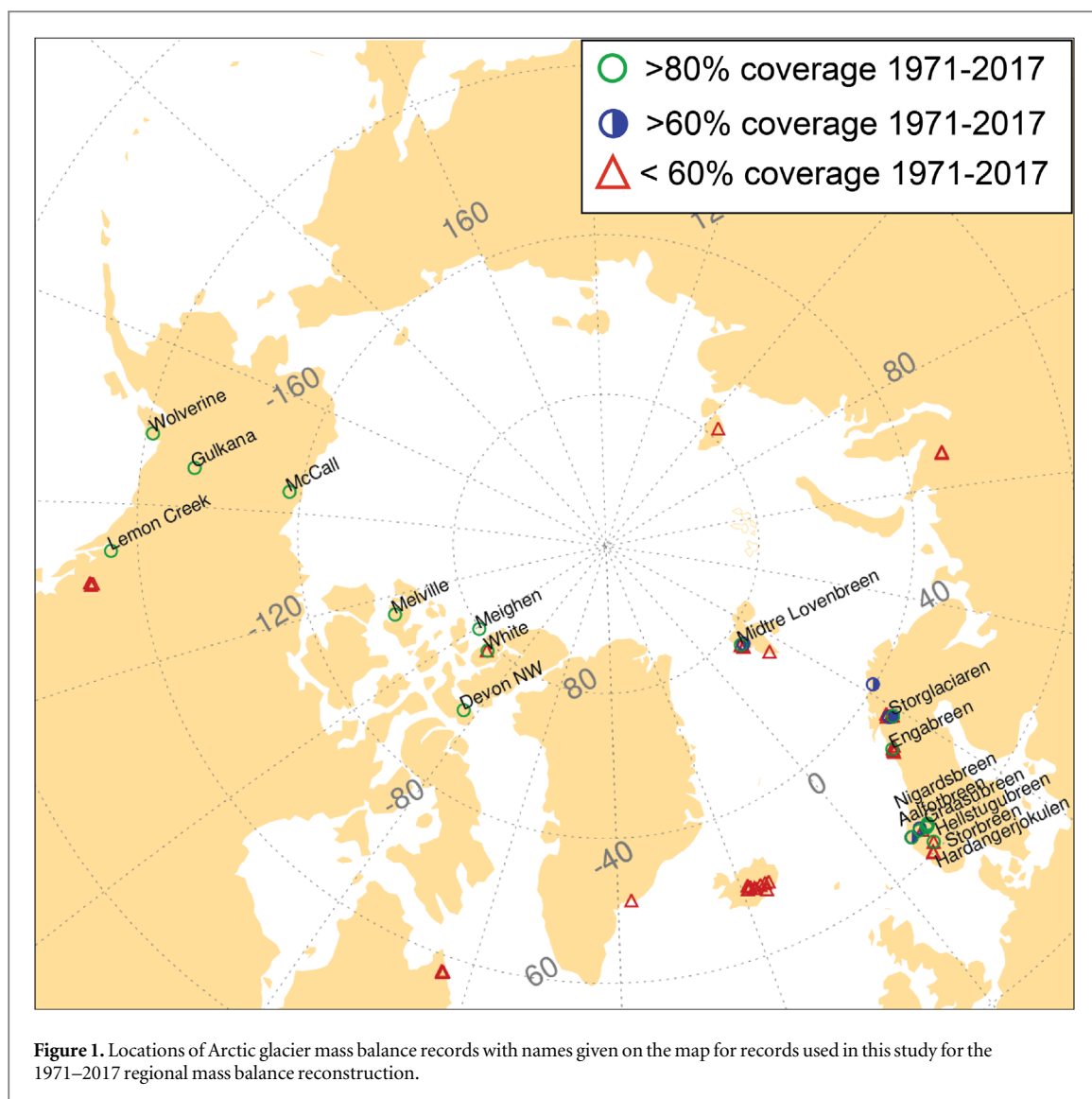
coverage of the mass balance records is particularly sparse over the Russian High Arctic ice caps, the Polar Urals and eastern Siberia (figure 1). While mass balance data prior to 1971 exist (e.g. Wolken *et al* 2017), they are more fragmentary in space and time. Starting in 1971 also gives sufficient coverage of the relatively low temperature period until the mid 1980 when Arctic warming increases substantially (Overland *et al* 2004).

There is a 50% increase in temporal coverage from the 1980s to the 1990s (figure 2) driven by the start of 10 Icelandic and one Greenland glacier record. The apparent drop in data availability after 2016 is an artifact of annual mass balance values that are not yet available to this study. While 33 glaciers (54% of 61) have at least 95% data availability in the 2003 to 2015 period coinciding with satellite gravimetry, over the entire 1971–2017 study period, 17 glaciers (28% of 61) have 80% data availability. We select 80% as the data availability requirement of this study. Thus, only the data from the selected 17 glaciers are used here in our regional mass balance reconstruction.

2.2. Regional land ice mass change from satellite gravimetry

Gravity Recovery and Climate Experiment (GRACE) satellite retrievals for regions other than Greenland are after Wouters *et al* (2008) (hereafter W08) are used to estimate regional land ice mass changes for the eight regions. The two Canadian regions are later combined. The glacial isostatic adjustment correction is after Caron *et al* (2018). As input, W08 use a ensemble combination of CSR RL05, GFZ RL05, JPL RL05 and ITSG-GRACE 2016 spherical harmonics, where each solution is given a weight according to its estimated monthly error. Mass balances are estimated by modeling mass anomalies in glaciated areas, converting this model to pseudo-GRACE observations and adjusting the anomalies until optimal agreement is reached with the actual observations in a least-square sense. See W08 and Gardner *et al* (2013) for more details. Results agree within uncertainties to the ‘mascon’ solutions of Jacob *et al* (2012). See Gardner *et al* (2013) supplementary material for a comparison.

Yearly W08 mass change for regions outside of Greenland is measured between successive Septembers. Spline interpolation is used to fill the missing September in 2013. Instrumental noise and high-frequency atmospheric and oceanic signals cause the mass change signal-to-noise ratio to decrease with the mass of a glacier region. To reduce this effect, a lowpass filter is applied to remove signals with periods less than three months, on the assumption that these signals mainly represent noise. The filtering is not applied to the Greenland time series, since signal-to-noise ratio is less of an issue there. W08 uncertainty values in table 1 are based on the calibrated



errors provided by the science team, and scaled to match the empirical derived uncertainties following Wahr *et al* (2006). The noisier 2002 and 2016

GRACE retrievals are excluded from this study that limits itself to mass changes from the 2003 to 2015 period (table 1). For Greenland, we use the

Table 1. Regional Arctic land ice mass balance 2003–2015 after Cazenave *et al* (2018)^a and Wouters *et al* (2008)^b.

Glaciated region	Mass balance 2003–2015, Gt yr ⁻¹	Uncertainty, Gt yr ⁻¹	Uncertainty, %	Fraction of total
Greenland ^a	−257	15	6%	61.1%
Alaska ^b	−70	17	24%	16.6%
Arctic Canada North ^b	−33	5	15%	7.8%
Arctic Canada South ^b	−29	6	21%	6.9%
Arctic Russia ^b	−14	5	36%	3.3%
Iceland ^b	−11	5	45%	2.6%
Svalbard ^b	−11	3	27%	2.6%
Scandinavia ^b	−1	5	500%	0.2%
Total	−421	61	14%	100.0%
Total mm eustatic sea-level	15.1	2.2		
Total mm/year eustatic sea level	1.16	0.17		

Cazenave *et al* (2018) ensemble GRACE values and error estimates (that include W08).

$$\Delta Ba'_{i,y} = (\Delta Ba_{i,y} - \overline{\Delta Ba_{i,2003-2015}}) / \sigma Ba_{i,2003-2015} \quad (1)$$

2.3. Greenland land ice mass balance 1971–2017

Annual Greenland land ice mass balance ($Ba_{\text{Greenland}}$) data (including peripheral glaciers) are compiled from Box and Colgan (2013) updated in Kjeldsen *et al* (2015). For reconstructed Greenland mass balance, Box and Colgan (2013) report a root mean squared difference (RMSD) of 69 Gt yr⁻¹ after calibration to Wahr *et al* (2006) GRACE data updated through 2011. Greenland mass balance is updated 2012–2016 after the Cazenave *et al* (2018) ensemble of multiple GRACE retrievals. We estimate 2017 $Ba_{\text{Greenland}}$ to be -59.5 ± 222.2 Gt yr⁻¹ using multiple regression of warm season (June through September) monthly average temperature and annual precipitation from NCEP/NCAR Re-analysis (Kalnay *et al* 1996). Explained variance is 43%. In the search to estimate $Ba_{\text{Greenland}}$ for 2017, we find that the highest predictive skill among regions examined in this study is Arctic Canada, but only at 22% explained variance. Thus, Arctic Canada mass balance is not considered a reliable predictor of $Ba_{\text{Greenland}}$.

3. Methods

3.1. Semi-empirical regional total mass balance assessment

Akin to Dowdeswell *et al* (1997) and Meier *et al* (2007), we aggregate *in situ* glacier mass balance time series to upscale to regional values. We enhance the approach by an absolute calibration to GRACE estimates and by representing a later time period (the 2000s onward) with more pronounced climate change impacts on glacier mass balance.

For each *in situ* mass balance record (i) having at least 80% of available data 1971–2017 (47 years), we calculate the 2003–2015 average ($\overline{\Delta Ba}$) and standard deviation (σ) and 1971–2017 anomalies ($\Delta Ba'$) relative to the W08 (years 2003–2015) baseline. Each record is divided by the standard deviation, i.e. standardized as:

The individual glacier $\Delta Ba'_i$ values are averaged over six regions (all but Greenland is) (table 1) and multiplied by the W08 regional GRACE mass balance averages (table 1). By this approach, we estimate mass balance totals for each region and year in the 1971–2017 interval in a way that is scaled to the GRACE mass balance retrievals. Lacking *in situ* mass balance record from Arctic Canada South, table 1 Arctic Canada North and South mass balance values are summed into a single regional value and thus the combined region is represented by four Arctic *in situ* mass balance records.

The mass balance contribution from tidewater glaciers is not directly treated by this method which relies on surface mass balance observations and their correspondence with GRACE mass change retrievals. For Arctic Canada during a period of low surface melting 1991–2005, half (52%) of its mass loss resulted from ice discharge (Millan *et al* 2017). During 2005–2014 when surface melting increased, the mass loss from ice discharge comprised just 10% of the total mass budget. Therefore, the reconstructed total mass balance here is minimally influenced by not directly accounting for ice discharge before the large increase in Arctic Canadian sea-level contribution in 2006. Similarly, Larsen *et al* (2015) find Alaskan ice loss (1994–2013) due to surface melting to be much greater than from its calving glaciers, including the large Columbia Glacier.

The McCall glacier data are not used in our scaling because they have two periods in the 1971–2017 period that lack annual data, with mass balance estimated from linear interpolation of multi-year geodetic mass balance (M Nolan, personal communication March, 2018). Because by far most of the Alaskan mass deficit is located in the southern coastal part of the region, the exclusion of the McCall glacier record (figure 1) increases the cumulative Alaska sea-level estimate by under 10%.

3.2. Data gap treatment

In the interest to include Iceland in this reconstruction, despite the WGMS-reported Icelandic surface mass balance records beginning in 1986, Iceland land ice mass balance is represented by a selection of six Norwegian mass balance series for which more than 30% explained variance is evident, that is, between Hofsjökull, Iceland and Austdalsbreen, Aalfotbreen, Nigardsbreen, Storbreen and Hardangerjokulen, Norway and between Tungnaárjökull, Iceland and Aalfotbreen, Norway. Searching the whole database of glacier mass balance series, it is only with Norwegian records that there is some predictive skill (explained variance above 30%) for Icelandic glaciers.

Given the lack of *in situ* mass balance series from the Russian High Arctic leads this study to use of the Svalbard composite, scaled to the satellite gravimetry of the Russian High Arctic. Uncertainty is higher for our Russian High Arctic reconstruction because presumably there is some difference in climate between the Russian High Arctic and Svalbard, for example differences in the variability of sea ice and atmospheric circulation. The uncertainty envelopes for Iceland and the Russian High Arctic are doubled in attempt to conservatively account for our approximation. The impact of the higher uncertainty for Iceland and Russian High Arctic for sea-level contribution is ultimately minimal since these regions represent under 7% of the total Arctic land ice contribution 1971 to 2017, presented later.

3.3. Sensitivity testing

The assumption that the 12 year (2003–2015) gravimetry observations represent the variability over the 1971–2017 period is tested by comparing the results of this study with the independent regional mass balance assessment of Marzeion *et al* (2015).

3.4. Uncertainty modeling

To account for an expected increased violation of temporal homogeneity of the statistical scaling of this study, mass balance uncertainty is estimated to increase linearly before 2003, reaching a value 50% larger than the 2003 value in 1971. The 2003–2015 uncertainty is set to that of GRACE results after Wouters *et al* (2008). The 2016–2017 Greenland mass balance uncertainty is set to $1.96\times$ the standard deviation of the multiple regression fit, representing the 95% uncertainty envelope of the fit.

3.5. Spatial inhomogeneity

A North Atlantic bias is evident when examining which individual glacier records best represent an all-Arctic-glaciers composite. Supplementary table S2 lists records with at least 20 years duration and how they correlate with an all-glacier composite series. Norwegian, Icelandic and Swedish individual records occupy the top 11 rankings. The ranking also shows

how the small number of non-North Atlantic records (four from Alaska or four from Arctic Canada) correlate poorly with the all-glacier composite. Devon, Arctic Canada has the top Canadian explained variance of 19%. McCall, Alaska (ultimately excluded from the regional scaling) has the top Alaskan explained variance of 15%. Alaskan and Canadian sources are of particular concern because they together comprise the majority of the 2003–2015 average satellite gravimetry derived 132 Gt yr^{-1} Arctic land ice loss, excluding Greenland. While the Scandinavian region hosts most (26 glaciers or 43%) of the mass balance records, it comprises just 0.8% of the non-Greenland (0.2% including Greenland) Arctic ice loss total.

Neglecting the North Atlantic bias would introduce destructive interference, for example between extreme Alaska mass loss in 2004 (figure 3(a)) while Canadian land ice gained mass (relative to the 2003–2015 baseline) (figure 3(b)) or how in 2015 the all glaciers composite suggests a year of mass gain despite substantial sea-level rise contributions from Alaska and Arctic Canadian.

To avoid destructive interference between regions, when scaling to the W08 regions (table 1), regional standardized composites (as in those for Canada and Alaska in figures 3(a) and (b)) are used. A major assumption and potential drawback is that the sampling is sufficiently robust to represent the 1971–2002 regional mass balance.

4. Results and discussion

4.1. Arctic regional land ice mass balance

Cumulative mass balance from each region (figure 4) indicates relative stability (or land ice growth) from 1971 until the mid-1980s. The Greenland ice mass gain until 1977 is attributable to increasing snowfall (Burgess *et al* 2010) associated with persistent atmospheric circulation (Bjørk *et al* 2017) and relatively low surface melt rates (Box 2013). The Greenland variability here is consistent with the Rignot *et al* (2008) reconstruction. Increased Greenland ice loss starting in 1998 is attributed to increasing surface melting (Box 2013) and through surface albedo feedback amplifying melt from a larger and increased duration of darker bare ice area (Tedesco *et al* 2011, 2013a, Box *et al* 2012). Increased rain fraction of total precipitation also amplifies Greenland ice mass loss (Doyle *et al* 2015). The bare ice albedo feedback that involves mineral and microbiological impurities (Stibal *et al* 2017, Ryan *et al* 2018) operates elsewhere in the Arctic than Greenland (Lutz *et al* 2016).

Alaska having a roughly constant ice loss rate starting in 1988 is consistent with Larsen *et al* (2015) who estimate an equivalent Alaskan ice loss rate ($75 \pm 11\text{ Gt yr}^{-1}$) while for 2003–2015 satellite gravimetry data after Wouters *et al* (2008) average

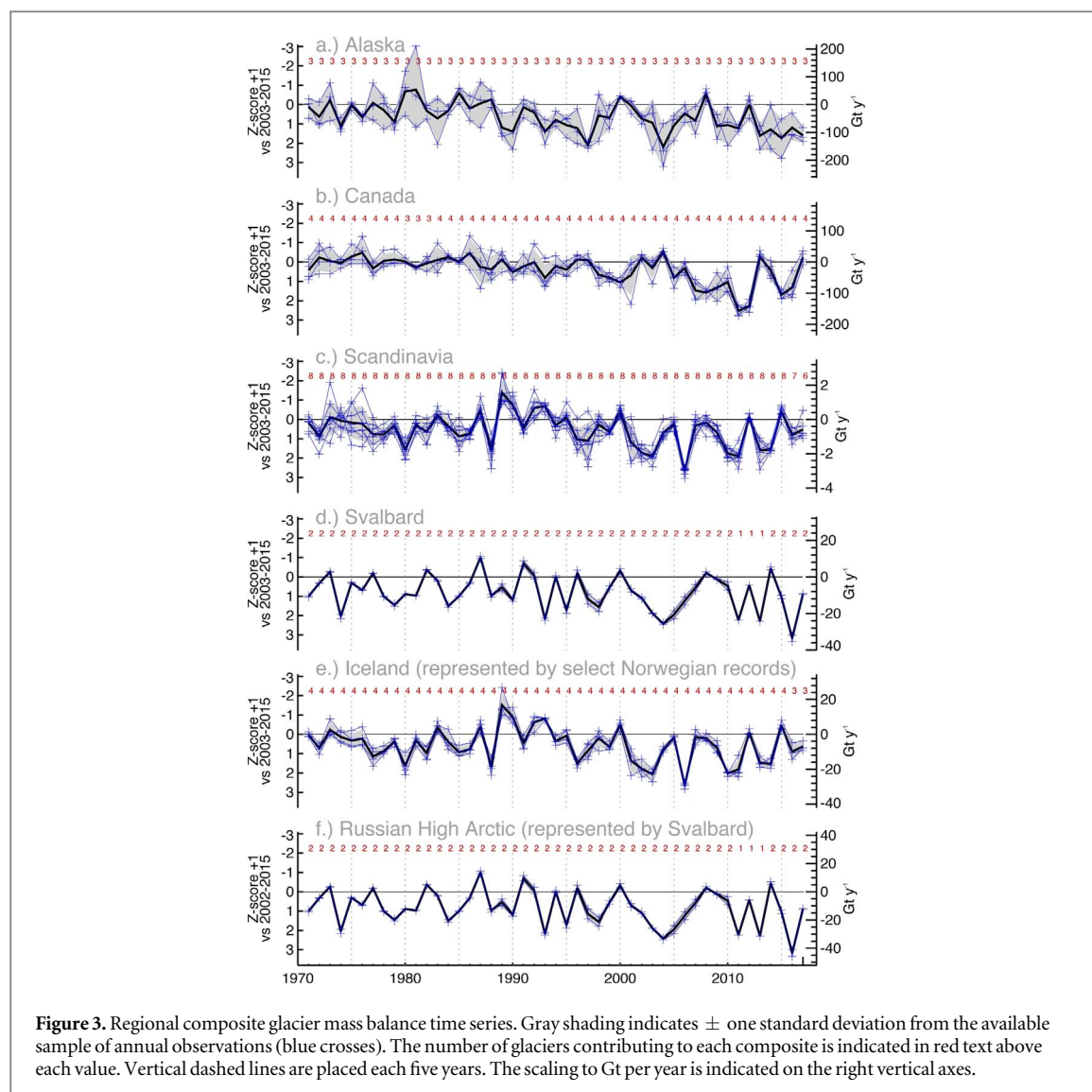


Figure 3. Regional composite glacier mass balance time series. Gray shading indicates $\pm$ one standard deviation from the available sample of annual observations (blue crosses). The number of glaciers contributing to each composite is indicated in red text above each value. Vertical dashed lines are placed each five years. The scaling to Gt per year is indicated on the right vertical axes.

$-70 \pm 17 \text{ Gt yr}^{-1}$ (table 1). Alaska land ice mass variability is less attributed to precipitation variability than surface melting (Larsen *et al* 2015).

Arctic Canada ice mass loss is characterized by an acceleration beginning in ~ 1986 , increasing sharply 2006–2012 (Sharp *et al* 2011) until 2013 which had positive mass balance (Sharp *et al* 2015) while Alaska had lower loss ice rates. The increase in Canadian Arctic land ice loss is mainly due to increased surface melting and from warmer summers (Gardner *et al* 2011) as precipitation rates have remained relatively stable (Gardner *et al* 2012). Atmospheric heat advection into Baffin Bay from a region of anomalously high sea surface temperatures in the northwestern Atlantic appears to have been responsible for the warming that contributed to the increase in ice loss from Arctic Canada (Sharp and Wolken 2011, Derksen *et al* 2012). Since *in situ* observations in the Canadian Arctic began in the early 1960s, the most negative balance years have occurred since 2005 (Wolken *et al* 2017). Documented increases in the post-2004 equilibrium line

altitude by $>250 \text{ m}$ relative to the pre-2005 levels (Burgess 2017, Thomson and Copland 2017) coincide with enhanced warming of ice cap surfaces above 1400 m a.s.l. (Mortimer *et al* 2016). Densification of ice cap firn areas due to warming has reduced or eliminated the refreezing storage capacity of the many ice caps in this region, thus increasing their sensitivity to future warming (Colgan *et al* 2008, Bezeau *et al* 2013, Noël *et al* 2018).

Arctic Canada and Greenland's reduced ice loss 2013–2017 is attributed to decreased surface melt from cold air temperature anomalies produced by persistent extremes in atmospheric circulation (Tedesco *et al* 2013b, 2014, Sharp *et al* 2015, Box and Sharp 2017). For example, 2013 was a positive mass balance year for Arctic Canada (Sharp *et al* 2015) while Svalbard, with an opposite pattern of persistent atmospheric circulation, had its strongest ice loss on record thus far (Lang *et al* 2015), superseded by 2016 mass loss. The 2012 pattern was the opposite, with extreme Greenland and Arctic Canada mass loss with

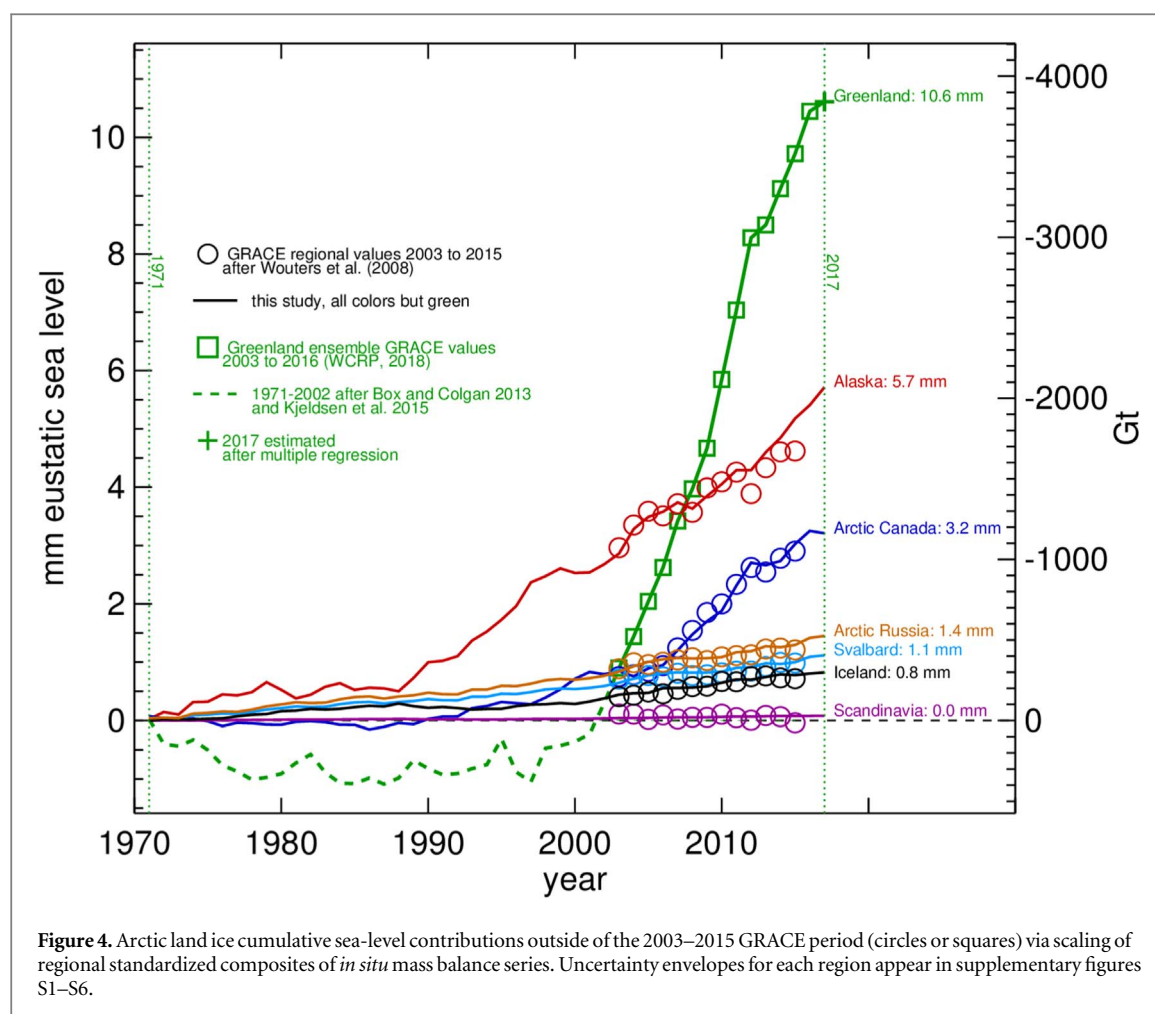


Table 2. Arctic Glacier and Greenland land ice sea-level contribution estimates.

Region	Sea-level contribution		IPCC SROCC recent past,		IPCC SROCC present day,	
	1971–2017, mm	Uncertainty, mm	1986–2005, mm	Uncertainty, mm	2005–2015, mm	Uncertainty, mm
Greenland	10.61	7.31	3.03	6.63	7.68	5.90
Alaska	5.71	2.16	2.93	1.32	1.69	0.82
Arctic	3.21	0.72	1.05	0.20	2.13	0.07
Canada						
Scandinavia	0.08	0.34	0.02	0.19	0.03	0.10
Svalbard	1.12	0.33	0.46	0.23	0.23	0.15
Iceland	0.82	0.70	0.22	0.40	0.31	0.23
Russian High	1.45	0.80	0.59	0.56	0.29	0.36
Arctic total	23.00	12.36	8.30	9.53	12.36	7.63

anomalously low Svalbard ice mass loss. The long term pattern of steady loss from Svalbard is simulated to have been persistent since 1980 (Østby *et al* 2017).

Relative to the 2003–2015 baseline, Scandinavia mass balance anomalies rates were positive for 8 years between 1987 and 1995 (except 1991 and 1994 which were nearly positive), attributable to persistent atmospheric circulation conditions associated with the North Atlantic Oscillation that increased snowfall rates (Nesje *et al* 2000). Svalbard mass balance has been relatively variable yet with increased ice loss rates

starting in 2003 (except 2008 and 2014). (See also Lang *et al* 2015.)

4.2. Arctic total sea-level contribution in the 1971–2017 period

The totaled all Arctic land ice sea-level rise contribution for 1992–2017 is estimated to be 21.8 ± 11.2 mm (table 2), equal to 31% (of 70 ± 10 mm) of the global sea-level rise after Nerem *et al* (2018). The all-Greenland land ice eustatic sea-level rise contribution for the 1971–2017 period (10.6 ± 7.3 mm) is

Table 3. Comparison with 1971–2013 annual values from this study and Marzeion *et al* (2015).

Region	Correlation	Confidence (1- <i>p</i>)	Average mass-balance M15 Gt yr ⁻¹	Average mass-balance this study Gt yr ⁻¹	Mass-balance ratio M15 ÷ this study	Mass-balance standard error ratio M15 ÷ this study
Alaska	0.672	>0.999	−30.3	−37.5	0.8	0.6
Arctic Canada	0.587	>0.999	−35.9	−22.4	1.6	0.9
Scandinavia	0.846	>0.999	−0.5	−0.6	0.8	1.6
Svalbard	0.678	>0.999	−24.2	−7.2	3.4	2.2
Iceland	0.505	0.999	−2.9	−6.3	0.5	0.5
Russian High Arctic	0.430	0.996	−19.9	−9.3	2.1	1.3
Total cumulative sea-level forcing 1971–2005			13.5	9.9		

Table 4. Comparison of regional mass balance values for the 2003–2009 period.

	Marzeion <i>et al</i> (2015) Gt yr ⁻¹	Gardner <i>et al</i> (2013) Gt yr ⁻¹	This study Gt yr ⁻¹	Ratio Marzeion <i>et al</i> (2015) ÷ Gardner <i>et al</i> (2013)	Ratio this study ÷ Gardner <i>et al</i> (2013)
Alaska	−48	−50	−57	1.0	1.1
Arctic Canada	−40	−60	−47	0.7	0.8
Iceland	−7	−10	−11	0.7	1.1
Svalbard	−43	−5	−8	8.6	1.6
Scandinavia	−1	−2	−1	0.5	0.6
Russian High Arctic	−25	−11	−11	2.3	1.0
average				2.3	1.0

46% of the total sea-level contribution (table 2). Greenland's contribution is $1.52\times$ that from Antarctica (7.6 ± 3.9 mm) in the 1992–2017 period (Shepherd *et al* 2018). During the IPCC SROCC recent past (1986–2005), the average stable Greenland mass balance has a substantial uncertainty relative to its near zero magnitude of mass change.

Alaska is the next largest sea-level contributor since 1971, $1.8\times$ larger than Arctic Canada (table 2). Even though the 2003–2015 Alaska rate is $1.1\times$ Arctic Canada (table 1), the larger 1971–2017 difference is attributable to Alaska beginning its sustained loss earlier than Arctic Canada.

Excluding Greenland, Dowdeswell *et al* (1997) found an Arctic sea-level contribution of 0.13 mm yr⁻¹ for a variable period roughly 1955 to 1995. Here, using a similar regional data set, we find the Arctic sea-level contribution to be $3.6\times$ larger (0.47 ± 0.19 mm yr⁻¹) for the 1971–2017 interval. Our findings are indicative of an accelerated sea-level contribution of Arctic Glaciers, that 20 years ago (Dowdeswell *et al* 1997) had not emerged from the noise. A driver of the acceleration is a substantial increase in Arctic warming occurring after the mid-1980s (Overland *et al* 2004). That warming signal is now unequivocal and attributed to anthropogenic climate change (Marzeion *et al* 2014, 2018).

4.3. Comparison with other studies

We compare our annual mass balance time series with the independent estimates from Marzeion *et al* (2015),

hereafter ‘M15’. M15 values are the result of a model driven by global gridded monthly precipitation and temperature observational data after New *et al* (2002) and Mitchel and Jones (2005). Here, Greenland is excluded because the Cazenave *et al* (2018) satellite gravimetry does not separate peripheral ice masses.

For the 43 year overlap (1971–2013), we find high confidence in correlations among the six compared regions, ranging from 0.430 ($1-p = 0.996$) for the Russian High Arctic to 0.846 ($1-p > 0.999$) for Scandinavia (table 3). Alaska and Scandinavia agree most in magnitude. The range of values in this study is larger for Alaska but smaller for Scandinavia. For Iceland, this study suggests twice the loss rate of M15, while M15 finds larger losses for Arctic Canada, Svalbard, and the Russian High Arctic. Totaled over the 43 years of overlap, M15 suggests a global sea-level contribution (13.5 mm) that is $1.36\times$ larger than this study (table 4) (figure S8). For Svalbard the M15 loss rate is $3.4\times$ this assessment. Given that mass balance from this study is tied to GRACE retrievals, we contend that our results are more accurate in magnitude.

A comparison with the satellite altimetry and gravimetry results from Gardner *et al* (2013) for the 2003–2009 period (the Svalbard result from Gardner *et al* 2013 is based on glaciological and local geodetic measurements) also suggests that the M15 mass balance is on average twice more negative than observed (table 4). Over the same period, our study is in agreement with Gardner *et al* (2013). Marzeion *et al* (2017) acknowledge that satellite-based mass balance estimates

Table 5. Multi-region averages for the comparison of Marzeion *et al* (2015) and this study four consecutive 10 year periods.

Period	Average correlation	Average multi-region mass balance ratio M15 $\div$ this study	Average multi-region standard error ratio
1971–1980	0.528	1.7	1.4
1981–1990	0.628	2.7	1.1
1991–2000	0.647	1.3	1.3
2001–2010	0.567	1.3	1.0

provide lower mass loss estimates than M15. The M15 overestimate appears tied to the delayed response of glacier geometry to climate forcing that may not be captured by the M15 glacier model (Marzeion *et al* 2017).

The high confidence in correlation between the independent M15 results and this study supports our extrapolation before year 2003. Nonetheless, to check for temporal homogeneity, examining four consecutive 10 year periods, we find an increase in the multi-regional average correlation and a decrease in the average mass balance bias ratio (table 5). However, the temporal change in agreement cannot confirm the validity of our temporal homogeneity assumption. The increase in correlation may be the result of an increase in time of the quality of the observational data driving M15. Further, if there is a decrease in the standard error ratio, that is, the width of the data distributions agreeing more in the last decade (2001–2010), it is unclear if this is the result of our method being more accurate later in our reconstruction. figure S8 illustrates an overall tendency for agreement. Overall, table 5 reinforces how M15 has a $\sim 30\%$ more negative mass balance than this study.

5. Conclusions

We compile annual standardized time series of individual glacier *in situ* surface mass balance measurements spanning up to 47 years, and develop seven regional (Alaska, Arctic Canada, Iceland, Scandinavia and the Russian High Arctic) mass balance estimates spanning the 1971–2017 period. Greenland is included in effort to completely represent the Arctic as a counterpart to e.g. Antarctica or non-polar land ice sea-level contributions. These semi-empirical regional estimates extend 32 years prior to the satellite gravimetry period or 19 years earlier than, e.g. Bamber *et al* (2018). We contend that the semi-empirical regional mass balance estimates presented here now represent the most observationally constrained and accurate estimates available prior to the 1992 start of satellite altimetry monitoring.

We show that the sea-level rise contribution from Arctic land ice is 31% of the global eustatic sea-level contribution since 1992, making it the largest regional land ice source of global sea-level rise. According to our semi-empirical reconstruction, Greenland alone represents roughly half (46%) of this Arctic land ice contribution to sea-level rise.

We address the IPCC Fifth Assessment identification of low scientific understanding in constraining the pre-satellite era sea-level rise budget and specify sea-level contributions coinciding with IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) ‘present day’ (2005–2015) and ‘recent past’ (1986–2005) reference periods. The rate of the total sea-level rise contribution of Arctic land ice has increased by $3\times$ between the 1986–2005 recent past and 2006–2015 present day periods adopted by IPCC SROCC. We assess an Arctic land ice loss of 8.3 mm SLE during the recent past and 12.4 mm SLE during the present day, equivalent respectively with net water fluxes of 5000 t s^{-1} rising between these two periods to $14\,000 \text{ t s}^{-1}$.

Our regional mass balance reconstruction correlates strongly with independent results from Marzeion *et al* (2015). However, this study finds $1.3\times$ lower mass loss overall, according to lower ice mass loss rates for Arctic Canada, Svalbard and the Russian High Arctic.

Alaska and Arctic Canada exhibited distinct regional variability, for example having opposite extremes in 2004 and 2011. These regional extremes are also evident in 2013 when Arctic Canada gained mass and Greenland had a relatively low mass loss year while Svalbard had its largest mass loss on record. These spatial extremes are all primarily attributable to persistent extremes in atmospheric circulation, highlighting not only the importance of assessing land ice changes at the regional scale, but also how the atmosphere is a dynamic driver of differing land ice changes over both space and time.

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