Terr. Atmos. Ocean. Sci., Vol. 24, No. 4, Part I, 657-670, August 2013 doi: 10.3319/TAO.2013.02.22.01(TibXS)

Current Ice Loss in Small Glacier Systems of the Arctic Islands (Iceland, Svalbard, and the Russian High Arctic) from Satellite Gravimetry

Koji Matsuo * and Kosuke Heki

Department of Natural History Sciences, Hokkaido University, Sapporo, Hokkaido, Japan

Received 9 April 2012, accepted 22 February 2013

ABSTRACT

Recent climate changes have brought about significant ice sheets and glacier melting in many parts of the world. Satellite gravimetry by the Gravity Recovery and Climate Experiment (GRACE) revealed that such ice melting also occurs in small glacier systems in the Arctic region, i.e., Iceland, Svalbard, and the Russian High Arctic. Using monthly gravity solutions from GRACE during 2004.02 - 2012.01, we obtained the average ice loss rates of 10.9 ± 2.1, 3.6 ± 2.9, and 6.9 ± 7.4 Gt yr^{-1}, for these three glacial systems, respectively. The total ice loss rate is 21.4 ± 12.4 Gt yr^{-1}, about twice as fast as the average rate over a ~40 years interval before the studied period. We found that the ice loss rates in Svalbard and Novaya Zemlya, in the Russian High Arctic, had significant temporal variability, showing decreasing trend before 2008 and increasing trend around the winter of 2009/2010, respectively. Due to such variability, the total ice loss rate becomes as high as 32.9 ± 19.2 Gt yr^{-1} during 2004.02 - 2008.01. Such variability in the rate might reflect the strong negative Arctic Oscillation (AO) in the northern hemisphere winter of 2009/2010.

Key word: Glacier, Gravity, GRACE, The Arctic Islands, Ice loss

Citation: Matsuo K. and K. Heki, 2013: Current ice loss in small glacier systems of the Arctic Islands (Iceland, Svalbard, and the Russian High Arctic) from satellite gravimetry. Terr. Atmos. Ocean. Sci., 24, 657-670, doi: 10.3319/TAO.2013.02.22.01(TibXS)

1. INTRODUCTION

Over 80 percent of the islands in the Arctic region (Arctic Islands) are covered with water ice (i.e., ice sheet, glacier, and ice cap), and form the largest store of water ice in the Northern Hemisphere (NH). The Arctic Islands consist of Greenland, the Canadian Arctic Archipelago, Iceland, Svalbard and the Russian High Arctic (Novaya Zemlya, Severnaya Zemlya, and Franz Josef Land). The total ice covered area in these islands is ~2000000 km^2, in which the Greenland ice sheet is the largest (~ 1750000 km^2). About a half of the glaciers and ice caps are located in the Canadian Arctic Archipelago (~150000 km^2). One quarter is found around the Greenland ice sheet (~76000 km^2), and the other quarter is located in Iceland, Svalbard, and the Russian High Arctic (~100000 km^2) (Dyurgerov and Meier 2005). The geographical location of these glacier systems is shown in Fig. 1.

In recent years, rapid polar ice sheets and mountain glacier melting due to global warming has been reported in various regions of the world. The satellite system Gravity Recovery and Climate Experiment (GRACE), launched in 2002, enables direct measurements of such mass losses. GRACE consists of two satellites. They are in the same polar circular orbit at an altitude of ~500 km. The changes in their along-track separation (~220 km) are measured precisely to recover time-variable Earth gravity fields. The gravity measured by GRACE is accurate to several μGal, and has spatial and temporal resolutions of ~300 km and ~1 month, respectively (Wahr et al. 1998).

Since its launch in 2002, GRACE observations have revealed ice loss in Antarctica and Greenland (e.g., Velicogna 2009; Sasgen et al. 2012), and of mountain glaciers in Alaska (e.g., Luthcke et al. 2008), Patagonia (e.g., Chen et al. 2007), the Asian High Mountain Ranges (Matsuo and Heki 2010), the Canadian Arctic Archipelago (Gardner et al. 2011), and so on. Recently, Jacob et al. (2012) estimated the ice loss rates of all of these glaciers and polar ice sheets using the GRACE data during 2003.1 - 2010.12 to be 536 ± 93 Gt yr^{-1}.

* *Corresponding author*
E-mail: kouji-matsuo@mail.sci.hokudai.ac.jp

Owing to the increasing time span covered by the GRACE data, we are able to discuss inter-annual variability of such ice losses (e.g., Chen et al. 2009; Matsuo and Heki 2010; Gardner et al. 2011). The increasing time span also enables us to investigate slight mass fluctuations of relatively small glacier systems that have been difficult to discuss because of low signal-to-noise ratio. In this paper, we investigate current ice loss and its temporal variability in the three small glacier systems of the Arctic Islands, i.e., Iceland, Svalbard, and the Russian High Arctic, using the GRACE data. To enable precise assessments of their quantities, spatial localizations and temporal variability, we employ the point-mass modeling approach by Baur and Sneeuw (2011), which is useful to discuss mass changes in small areas.

2. GRACE OBSERVATION

2.1 GRACE Data Processing

The GRACE inter-satellite ranging data are processed by several data analysis centers. Because the methods for data processing vary by each institute, we can see slight differences in the gravity data from these centers. To alleviate such a problem, we stacked the GRACE data provided by three centers, the University of Texas Center for Space Research (UTCSR), the Jet Propulsion Laboratory (JPL), USA, and the GeoForschungsZentrum Potsdam (GFZ), Germany. Here we used the Level-2 Release 05 GRACE data consisting of 94 monthly data sets from February 2004 to January 2012. The Earth's gravity field is modeled as a combination of spherical harmonics. A monthly GRACE data set includes a set of spherical harmonics coefficients (Stokes' coefficient) C_{nm} and S_{nm} with degree n and order m complete to 60. We used the degree-one components (C_{10}, C_{11}, and S_{11}), which reflect the geocenter motion, estimated by combining GRACE and ocean model (Swenson et al. 2008) because GRACE alone cannot measure them. In order to interpret gravity changes in terms of surface mass variations, we need to calculate equivalent water thickness (EWT) σ using the relationship (Wahr et al. 1998)

$$\Delta\sigma(\theta,\phi) = \frac{R\rho_{ave}}{3}\sum_{n=2}^{\infty}\sum_{m=0}^{n}\frac{2n+1}{1+k_n}(\Delta C_{nm}\cos m\phi + \Delta S_{nm}\sin m\phi)\, P_{nm}(\sin\theta) \tag{1}$$

where R is the equatorial radius, ρ_{ave} is the mean density of the Earth, and the load Love numbers k_n account for the Earth's elastic yielding effect under the mass load in question. Longitude and latitude are denoted by ϕ and θ, respectively. $P_{nm}(\sin\theta)$ is the n'th degree and m'th order fully-normalized Legendre function, and Δ indicates the deviation from the reference value. We assumed that the GRACE gravity changes reflect those of the surface load, and converted them into EWT. Chao (2005) showed that the inverse solution is unique in this case.

Because the GRACE data suffer from correlated errors and short-wavelength noise, spatial filtering is indispensable. Without spatial filtering, strong north-south stripes remain in the data due to correlated errors (Swenson and Wahr 2006). However, such north-south stripes diminish as the latitude becomes higher. This is because GRACE operates in the polar orbits and the spatial density of the GRACE measurements increase toward higher latitudes. Hence, GRACE achieves higher precision in the polar region including the Arctic Islands. In fact, we can recognize geophysical signatures there, such as Glacial Isostatic Adjustment (GIA) and mass loss in ice sheets and mountain glaciers, even in the GRACE data without any spatial filtering.

Here we apply only "weak" spatial filters, i.e., the anisotropic fan filter with averaging radius of 150 km to reduce short wavelength noises (Zhang et al. 2009) and the de-correlation filter using polynomials of degree 3 for coefficients with orders 14 or higher to reduce longitudinal stripes (Swenson and Wahr 2006). The choice for the de-correlation filter is important because glacial mass change signals could be weakened or moved away from the actual location depending on the combination of polynomial fitting or applied order of coefficients. Here we set up the optimal filter by trial-and-error based on visual inspection.

In addition, we should remove the effects of ongoing GIA in North America, Scandinavia and their vicinity from the GRACE data. Gravity signals associated with GIA would affect the gravity changes by ice loss, causing a biased estimate of the actual mass loss. We corrected for such contributions using the Peltier model (2004). The uncertainty of GIA correction will be discussed in section 4.1.

2.2 Ice Loss in Small Glacier Systems of the Arctic Islands from GRACE

Following the methods described in the previous section, we plotted the time-series of EWT at five points in small glacier systems of the Arctic Islands, i.e., Iceland (64°N, 16°W), Svalbard (78°N, 22°E), Novaya Zemlya (75°N, 59°E), Franz Josef Land (80°N, 60°E), and Severnaya Zemlya (79°N, 98°E), in Fig. 2c. The obtained time-series were modeled with linear, quadratic and seasonal changes by least-squares adjustment. The observed EWT time-series all showed negative trends (red line), suggesting that ice losses do occur there. Their EWT linear trends are -4.0 ± 0.3 cm yr^{-1} in Iceland, -1.4 ± 0.4 cm yr^{-1} in Svalbard, -2.3 ± 0.4 cm yr^{-1} in Novaya Zemlya, -0.8 ± 0.3 cm yr^{-1} in Franz Josef Land, and -0.8 ± 0.3 cm yr^{-1} in Severnaya Zemlya. The errors are one-sigma uncertainties of the linear terms.

It is notable that the EWT time-series in Svalbard, Novaya Zemlya and Franz Josef Land, show significant temporal variability. They decrease before 2008 and increase around 2009 - 2010. Then the linear trends before 2008 (green lines in Fig. 2c) are larger in these three regions, i.e., -2.4 ± 1.1 cm yr^{-1} in Svalbard, -4.3 ± 1.4 cm yr^{-1} in Novaya Zemlya, and -1.7 ± 0.9 cm yr^{-1} in Franz Josef Land. Those in Iceland and Severnaya Zemlya remain same within the uncertainty of the estimated trends (-3.6 ± 0.7 cm yr^{-1} for Iceland and +0.2 ± 0.9 cm yr^{-1} for Severnaya Zemlya). We map such linear trends in EWT during 2004.02 - 2012.01 and 2004.02 - 2008.01 in Figs. 2a and b, respectively. We can see stronger negative trends in the three glaciers, i.e., Svalbard, Novaya Zemlya and Franz Josef Land, for the period 2004.02 - 2008.01 in comparison with 2004.02 - 2012.01. Origin of such temporal variability will be discussed in the next chapter and section 4.2.

3. ESTIMATION OF ICE LOSS

3.1 Method for Estimation

Based on the linear trend maps obtained in the previous section, we estimated the total ice loss rates of the individual glacier systems of the Arctic Islands. Here we employed the point-mass modeling technique (Baur and Sneeuw 2011): a method suitable to derive mass changes at particular surface points from time-variable gravity fields from GRACE. The basic idea behind this method is to solve an inverse problem from the observed gravity changes to the actual mass variations using least-squares adjustment assuming that the mass variation occurs in these specific locations. The gravitational force acting on orbiting satellite from mass variation is determined using Newton's law of universal gravitation. So, the changes in distributed point-mass on the Earth's surface can be inverted from the Green function expressed in the Newton's equation and the gravity changes observed by GRACE. In this method, Tikhonov-regularized least-squares method is employed to stabilize the inverse problem (Tikhonov 1963; Koch 1999).

Here we assumed that mass changes occur only on ice covered areas (white dots in Fig. 1), and performed point-mass modeling using the linear trend maps of the EWT from GRACE. The optimum regularization parameters, expressed as λ in Eq. (10) of Baur and Sneeuw (2011), were inferred by grid-search to match the GRACE data best.

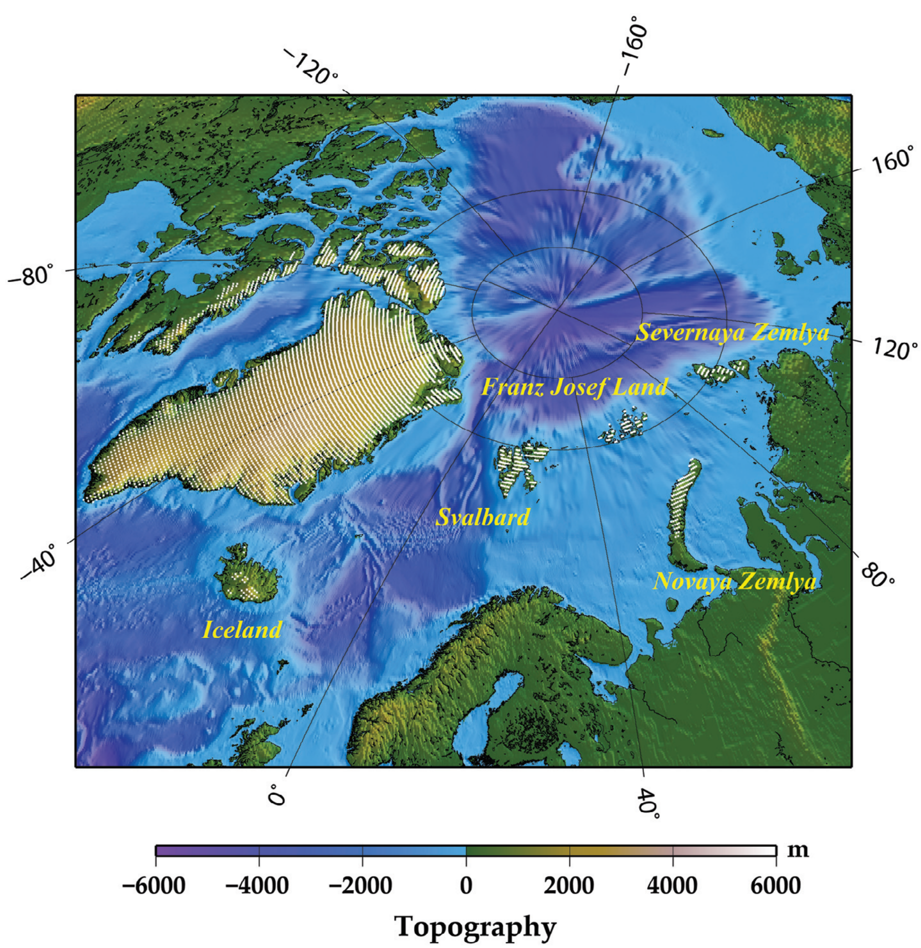

Fig. 1. Geographical locations of the small glacier systems in the Arctic Islands. White dots represent ice covered areas. The topographic and bathymetric data are from ETOPO1 global relief model (Amante and Eakins 2009).

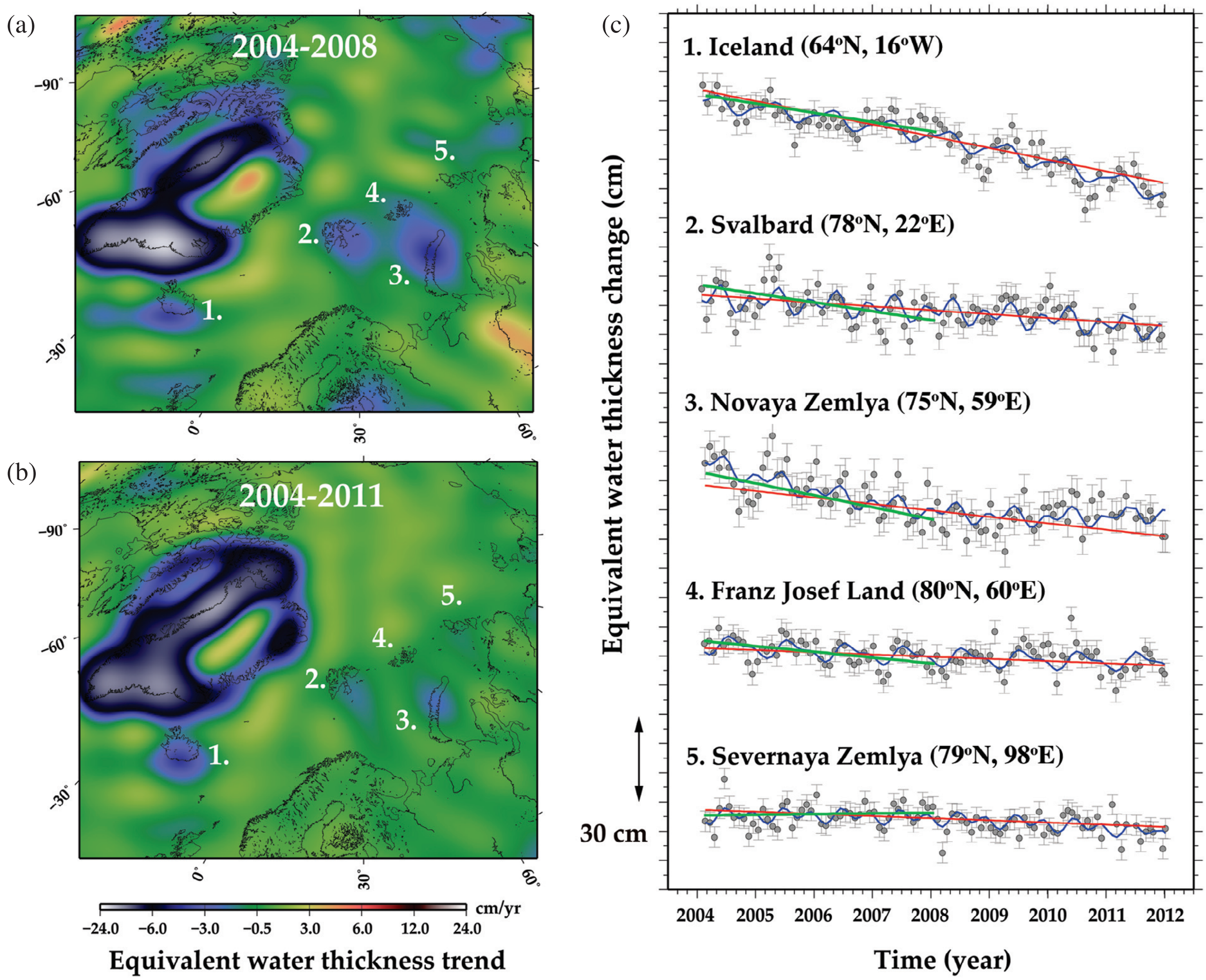

Fig. 2. (a) Map of the linear trends of the GRACE EWT in NH during 2004.02 - 2012.01. (b) That during 2004.02 - 2008.01. (c) Time-series of the GRACE EWT at points in 1. Iceland (64°N, 16°W), 2. Svalbard (78°N, 22°E), 3. Novaya Zemlya (75°N, 59°E), 4. Franz Joseph Land (80°N, 60°E), and 5. Severnaya Zemlya (79°N, 98°E). The smooth curves with blue color indicate best-fit models using the least-squares method assuming linear, quadratic and seasonal changes. The red and green lines show the linear components during 2004.02 - 2012.01 and 2004.02 - 2008.01. The errors are one-sigma uncertainties of the linear terms.

3.2 Iceland

Figure 3 shows the results for Iceland. The synthesized ice loss rates by point-mass modeling around Iceland suggest that ice loss mainly occurs in the southeastern glaciers, corresponding to the Vatnajokull Ice Cap, the largest glacial reservoir in Iceland. The majority of the glaciers in Iceland are located in the southeast where precipitation is high under the strong influence of the polar easterly. The total ice covered area in Iceland is ~10900 km^2, ~80 percent of which is within Vatnajökull (Dyurgerov and Meier 2005).

We integrated the synthesized ice loss rates at grid points in Iceland (Fig. 3b), and obtained the total ice loss rates as 10.9 ± 2.1 Gt yr^{-1} for the period 2004.02 - 2012.01 and 10.6 ± 3.4 Gt yr^{-1} for the period 2004.02 - 2008.01. The errors were estimated by combining one-sigma errors in the linear regression, uncertainties in the GIA models, and changes in the land hydrology. The detail of error estimation will be described in section 4.1. The residuals between the observed and the synthesized mass changes (Figs. 3d and h) are well below the estimated error level. It appears that the glaciers in Iceland are significantly and constantly melting during the studied period. Our estimates agree well with the previous estimates (Wouters et al. 2008; Jacob et al. 2012).

3.3 Svalbard

Figure 4 shows the results for Svalbard. There the ice covered area of ~21800 km^2 is located in its main island Spitsbergen, ~11300 km^2 in the northwestern island Nordaustlandet, ~2130 km^2 in the southern island Edgeøya, and ~1400 km^2 in other small islands. The total ice covered area is ~36600 km^2 (Dyurgerov and Meier 2005). These glaciers

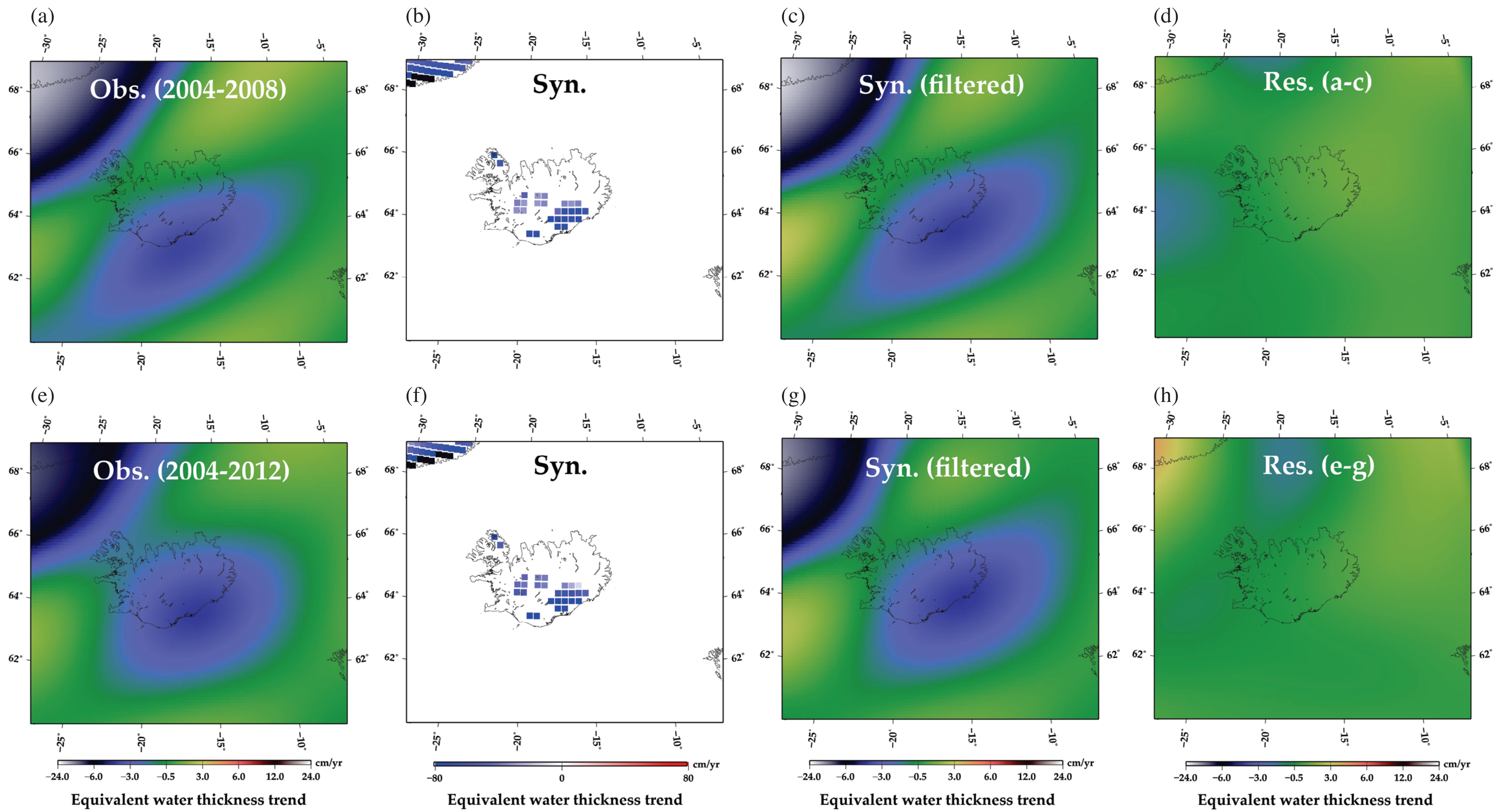

Fig. 3. Distributions of the EWT linear trends in Iceland. (a) - (d) are for the period 2004.02 - 2012.01 and (e) - (h) are for the period 2004.02 - 2012.01. (a) and (e) are the linear trend observed by GRACE, (b) and (f) are synthesized linear trend obtained using point-mass modeling, (c) and (g) are synthesized linear trend after applying the same filter as GRACE, and (d) and (h) are the residual between the observed (a) (e), and the synthesized (c) (g), respectively.

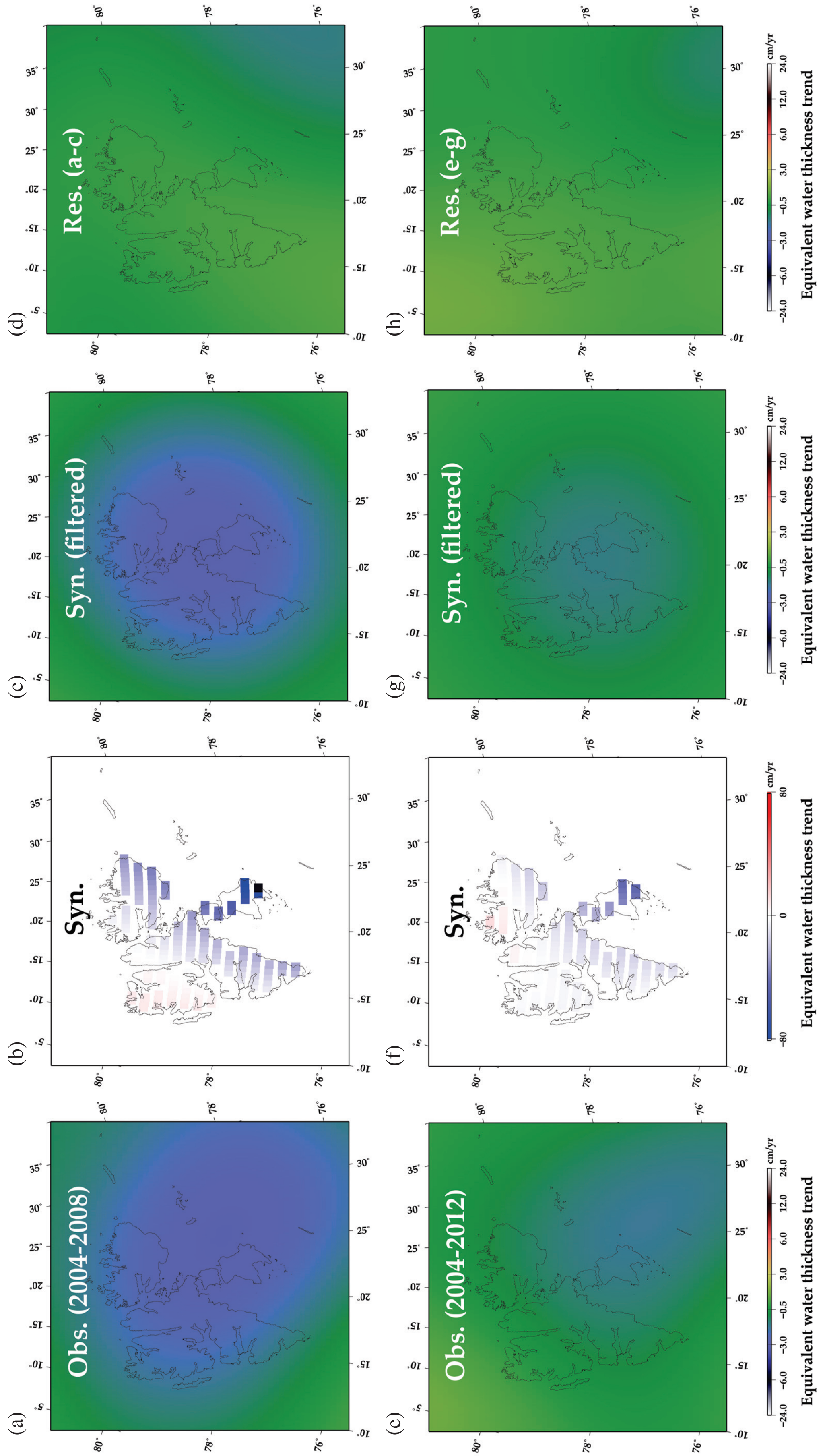

Fig. 4. Distributions of the EWT linear trend in Svalbard. See Fig. 3 for detail.

are fed by precipitation from the polar easterly and retain a bulk of water ice in southeastern Svalbard. The ice loss estimated using GRACE suggests that ice loss occurs mainly in the glaciers of Edgeoya and southeastern Spitsbergen. It is notable that the ice loss rate varies significantly in time. The obtained ice loss rate is 3.6 ± 2.9 Gt yr^{-1} for the period 2004.02 - 2012.01 and 6.9 ± 3.6 Gt yr^{-1} for the period 2004.02 - 2008.01.

Past GRACE studies in this region suggested the rate as 8.8 ± 3 Gt yr^{-1} (Wouters et al. 2008), 9.1 ± 1.1 Gt yr^{-1} (Mémin et al. 2011), and 3 ± 2 Gt yr^{-1} (Jacob et al. 2012). The latest estimate by Jacob et al. (2012) is considerably smaller than the two earlier estimates. This difference would reflect the inclusion of the GRACE data after 2009, i.e., Jacob et al. (2012) included the data up to 2010.12 while Wouters et al. (2008) and Mémin et al. (2011) used those up to 2008.01 and 2009.01, respectively. As described before, Svalbard shows significant mass increase around the 2009/2010 winter. We speculate that such mass increase is due to the strong negative phase of the Arctic Oscillation (AO) occurred in the 2009/2010 winter.

The unprecedentedly strong negative AO which occurred in that winter brought unusual coldness and heavy precipitation in various regions of the NH (e.g., Cohen et al. 2010; Seager et al. 2010). The AO is a seesaw like fluctuation in the sea-level pressure between polar and middle latitude regions of NH, and its index characterizes the dominant pattern of atmospheric circulation in NH (Thompson and Wallace 1998).

The GRACE observations suggested that the extreme negative AO in the 2009/2010 winter enhanced the precipitations in middle latitude regions of Eurasia, southeastern US, and southern Greenland (Matsuo and Heki 2012). The polarity of AO largely controls wintertime mass balance in Svalbard. Mass balance field studies showed a larger decrease during the period 1990 - 1996, when positive AO prevailed, than in the period 1997 - 2004 (Rasmussen and Kohler 2007). This tendency is consistent with the case in the 2009/2010 winter, a case opposite to 1990 - 1996. A detailed discussion on the relationship between the wintertime AO and mass balance in each glacier system will be described in the section 4.2.

3.4 Russian High Arctic

Figure 5 shows the results for the Russian High Arctic, where ice covers area of ~23600 km^2 in the Novaya Zemlya, ~13500 km^2 in the Franz Josef Land, and ~18300 km^2 in the Severnaya Zemlya. The total ice covered area amounts to ~55400 km^2 (Dyurgerov and Meier 2005). We jointly inverted mass changes in these three glacier systems to reduce the signal leakages from neighboring glacier systems. The synthesized result for the Novaya Zemlya suggests that the observed mass trend there can be well explained by the ice loss in the northern glaciers. The obtained ice loss rate there is 5.2 ± 3.9 Gt yr^{-1} for the period 2004.02 - 2012.01 and 11.2 ± 5.5 Gt yr^{-1} for the period 2004.02 - 2012.01, i.e., a significant difference exists between the periods. From the time-series of EWT shown in Fig. 2c, we can see the large positive EWT deviation in the 2009/2010 winter. This is coincident with the occurrence of the strongest negative AO during the studied period. Like in Svalbard, the mass balance there seems to have some relationship with AO.

The obtained ice loss rate in the Franz Josef Land is 0.8 ± 1.3 Gt yr^{-1} for the period 2004.02 - 2012.01 and 3.5 ± 1.9 Gt yr^{-1} for the period 2004.02 - 2008.01. This glacier system also shows gravity decrease (mass loss) with a time-variable rate. However, the rate is relatively small and it might be difficult to discriminate the fluctuation signature from the leakage of the mass changes in the Novaya Zemlya. Likewise, the noise in the GRACE data may also cause such a fluctuation. Further extended GRACE data would be necessary to investigate temporal variability of mass balance there.

The obtained ice loss rate in the Severnaya Zemlya is 0.9 ± 2.2 Gt yr^{-1} for the period 2004.02 - 2012.01 and 0.8 ± 1.3 Gt yr^{-1} for the period 2004.02 - 2008.01. The variability in trend is relatively small. Glaciers in the Severnaya Zemlya might be in a relatively stable state because this region is less influenced by low atmospheric pressure from the Barents Sea and has relatively small catchment and ablation of the glaciers (Koryakin 1986).

Finally, we obtained the total ice loss rate in the Russian High Arctic as 6.9 ± 7.4 Gt yr^{-1} for the period 2004.02 - 2012.01 and 15.4 ± 11.9 Gt yr^{-1} for the period 2004.02 - 2008.01. Moholdt et al. (2012) recently estimated regional mass budget of these glacier systems using ICESat laser altimetry and GRACE gravimetry, and reported the total ice loss rate of 9.8 ± 1.9 Gt yr^{-1} (ICESat) and 7.1 ± 5.5 Gt yr^{-1} (GRACE) for the period 2004.01 - 2009.10. Their result is consistent with the average of our results over the two periods 2004.02 - 2012.01 and 2004.02 - 2008.01. The study with GRACE by Jacobs et al. (2012) suggested the rate of -5 ± 6 Gt yr^{-1} for the period 2003.01 - 2010.12, which is consistent with our result for the period 2004.02 - 2012.01.

4. DISCUSSION

4.1 Sources of Error for the Ice Loss Rate

We considered three possible sources of estimation errors; error in the linear regression for the GRACE EWT time-series, uncertainty in the GIA models, and mass changes in terrestrial water storage.

Figure 6 shows the distributions of one-sigma uncertainty for the trends for the period 2004.02 - 2012.01 and 2004.02 - 2008.01. These were obtained a-posteriori by bringing the chi-square of the post-fit residuals to unity. The error in the period 2004 - 2008 would be larger than that in

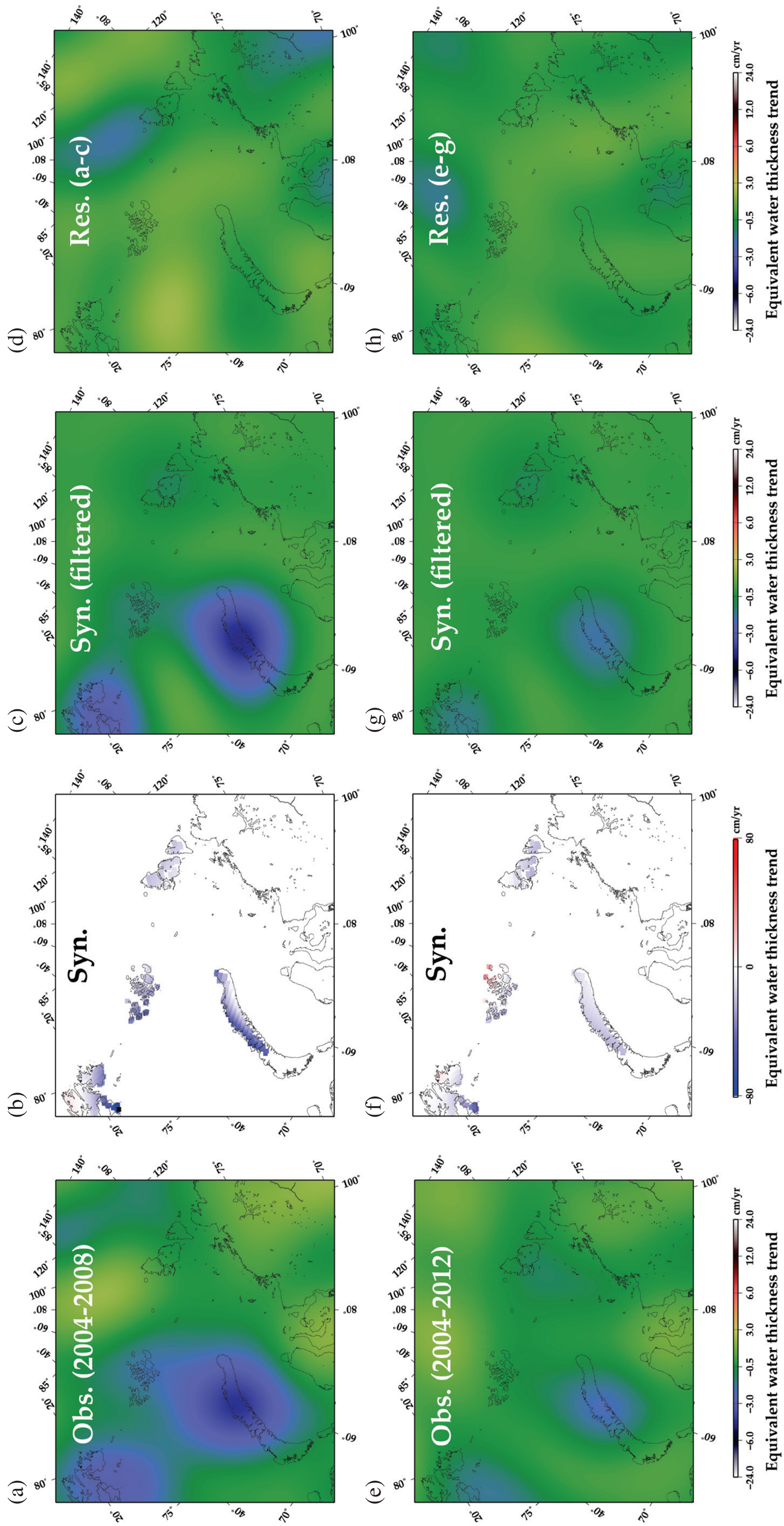

Fig. 5. Distributions of the EWT linear trend in the Russian High Arctic. See Fig. 3 for detail.

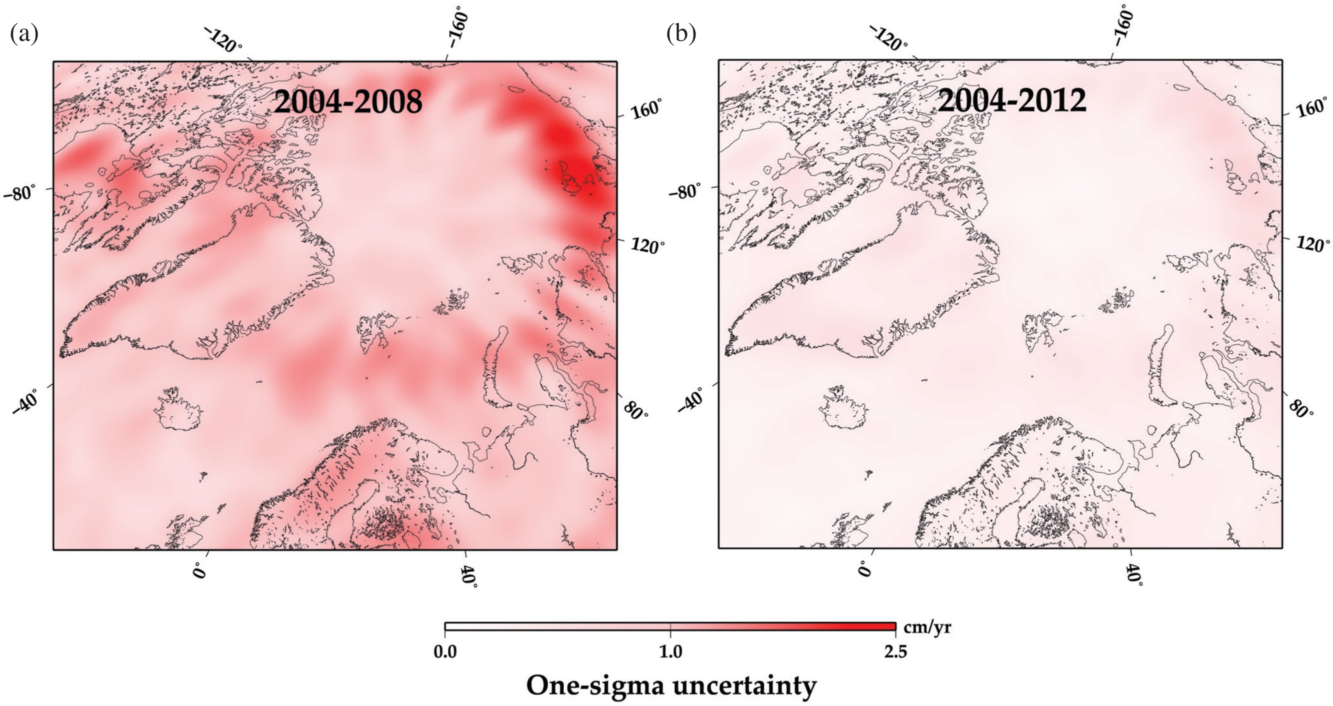

Fig. 6. Distribution map of the one-sigma uncertainty of GRACE linear fitting for the period 2004.02 - 2008.01 (a) and 2004.02 - 2012.01 (b).

2004 - 2012 because of the shorter time span of the data. The contributions of this type of error to the estimated ice loss rate were evaluated from the changes in the inversion results of point-mass modeling by including these errors. They are shown in Table 1.

The GIA correction is important to correctly estimate actual glacial mass changes. As for the region studied here, significant GIA signatures can be found around the Barents Sea and Kara Sea, and they largely affect the glacial mass change estimations in Svalbard and Russian High Arctic. In order to assess the uncertainty of GIA models, we used four GIA model proposed by Peltier (2004), Paulson et al. (2007), Schotman et al. (ftp://dutlru2.lr.tudelft.nl/pub/wouter/pgs/), and Spada and Stocchi (ftp://dutlru2.lr.tudelft.nl/pub/wouter/pgs/) (Fig. 7). The first two models are based on the ICE-5G ice loading history model (Peltier 2004), and the last two models are based on the ICE-3G model (Tushingham and Peltier 1991). The details and differences of these GIA models are discussed in Guo et al. (2012). We investigated the differences in the estimated mass changes using these four GIA models for each glacier system following the method described in section 3. The results are shown in Table 1. Significant variations are found especially in Svalbard, Novaya Zemlya, and Severnaya Zemlya. They are all located around the Barents Sea, where the GIA contributions are large and not well constrained (e.g., Svendsen et al. 2004).

Natural changes in terrestrial water storage may obscure ice loss signals. We assessed their mass changes using the Global Land Data Assimilation System (GLDAS) Noah model (Rodell et al. 2004). Figures 8a and b represent the predicted linear mass changes in land hydrology from GLDAS in the period 2004.02 - 2008.01 and 2004.02 - 2012.01. Their total mass changes were also estimated in the same manner as section 3, and the results are shown in Table 1. Here we did not correct the ice loss rate with these values but included them in the estimation errors because the reliability of long-term trend in the GLDAS model is not well known.

4.2 AO and the Temporal Variability of the Ice Loss Rates

As described in sections 3.3 and 3.4, the observed temporal variability of the ice loss in Svalbard and Novaya Zemlya might reflect AO. To evaluate the relationship between the observed mass changes and AO, we analyzed their statistical correlation using the AO index (AOI). AOI are derived as the first leading mode of empirical orthogonal function of monthly mean sea-level pressure anomaly field north of 20°N, which represents the scale and phase of AO.

We followed the method of Matsuo and Heki (2012) to evaluate the relationship between GRACE mass changes and AO; removing linear, quadratic, and seasonal components from the EWT time-series of GRACE by least-squares method (here we refer to the residual as the EWT deviation), calculating averages of the three winter months (JFM; January, February, and March), and computing correlation

Table 1. Glacial mass losses in the Arctic glacial system.

Glacial system	Mass loss (Gt yr-1)	Fitting error (Gt yr-1)	GIA uncertainty (Gt yr-1)	Hydrology (Gt yr-1)	Mass loss (Gt yr-1)	Fitting error (Gt yr-1)	GIA uncertainty (Gt yr-1)	Hydrology (Gt yr-1)
	2004 - 2008				2004 - 2012			
Iceland	10.6 ± 3.4	2.3	0.8	0.6	10.9 ± 2.1	1.2	0.8	0.2
Svalbard	6.9 ± 3.6	1.6	1.9	0.1	3.6 ± 2.9	0.5	1.9	1.0
Novaya Zemlya	11.2 ± 5.5	3.7	1.7	0.2	5.2 ± 3.9	2.0	1.7	0.3
Severnaya Zemlya	0.7 ± 3.2	1.5	1.7	0.0	0.9 ± 2.2	0.4	1.7	0.2
Franz Josef Land	3.5 ± 3.2	2.3	0.9	0.0	0.8 ± 1.3	0.3	0.9	0.1
Total	**32.9 ± 18.9**				**21.4 ± 12.4**			

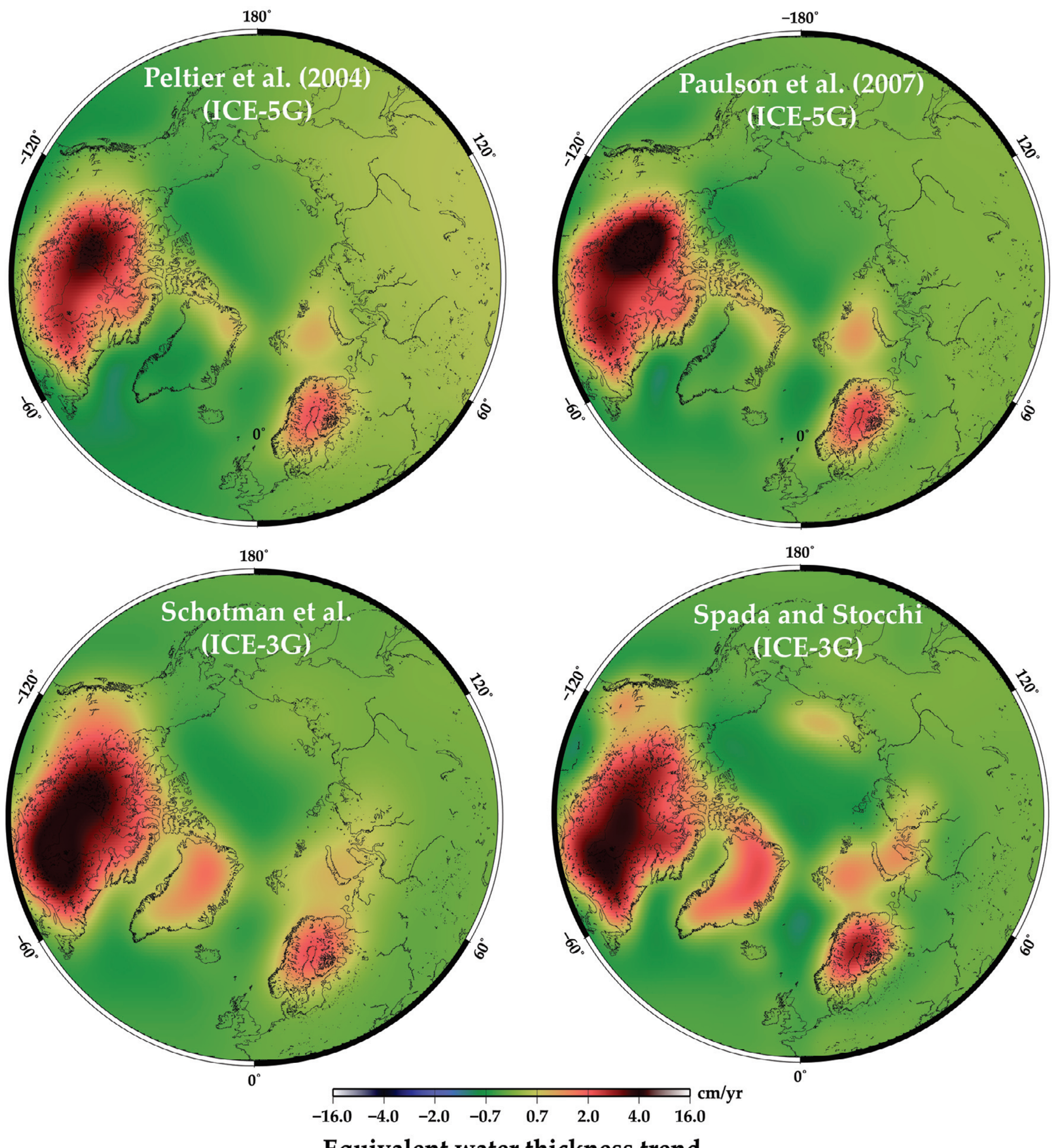

Fig. 7. Linear mass trends predicted using four different GIA models, Peltier (2004), Paulson et al. (2007), Schotman et al. and Spada and Stocchi. The 150 km fan filter and the P3M15 de-correlation filter are applied. All GIA models are downloaded from their webpage.

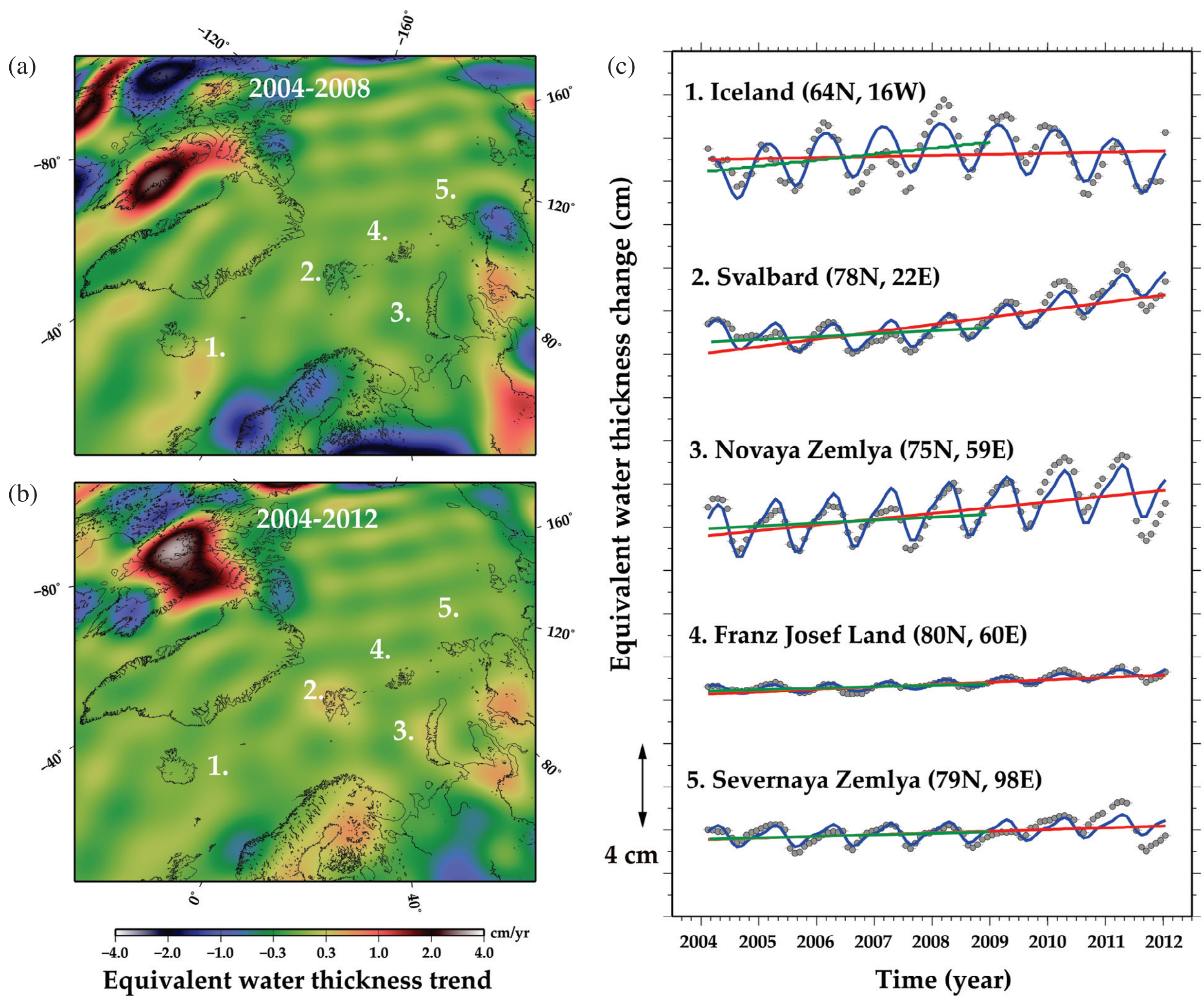

Fig. 8. (a) Map of the linear trends for the GLDAS EWT in NH during 2004.02 - 2012.01. (b) That during 2004.02 - 2008.01. The same filters as GRACE were applied. We excluded Greenland because of relatively poor reliability there. (c) Time-series of the GLDAS EWT at each glacier system. The smooth curves with blue color indicate best-fit models by least-squares method assuming linear, quadratic and seasonal changes. The red and green lines show the linear components during 2004.02 - 2012.01 and 2004.02 - 2008.01.

coefficients between the wintertime EWT deviation and AOI. As for 2004, we used only two months' data, i.e., February and March, because of the availability of the GRACE data. As for 2012, we used three months' data. The results for each glacier system are shown in Fig. 9. High correlations are found in Svalbard (-0.75), Novaya Zemlya (-0.62), and Franz Josef Land (-0.64). This suggests that the mass balances of these glacier systems are significantly influenced by AO.

In fact, the EWT time-series for the land hydrology inferred from the GLDAS model (Fig. 9c) showed the positive and negative deviation from the model curves in Svalbard and Novaya Zemlya in the winter of 2009/2010 and 2006/2007, characterized by the strong negative and positive AOI. Positive/negative precipitation anomalies are considered to be caused by negative/positive AO in these two glacier systems. As for the EWT in Franz Josef Land, it would be difficult to discuss its relationship with AO due to small signals and the leakage from Novaya Zemlya.

5. CONCLUSIONS

Most ice sheets and glaciers worldwide have experienced a substantial amount of ice loss over the last decade. Small glacier systems in the Arctic Islands have also followed this trend. GRACE observation during 2004 - 2012 suggested the average ice loss rates of 10.9 ± 2.1 Gt yr^{-1} in Iceland, 3.6 ± 2.9 Gt yr^{-1} in Svalbard, and 6.9 ± 7.4 Gt yr^{-1} in the Russian High Arctic. The total ice loss rate is 21.4 ± 12.4 Gt yr^{-1}, equivalent to ~0.06 ± 0.03 mm yr^{-1} sea level rise. The observed mass changes by GRACE can be well explained by point-mass changes distributed over these glaciers.

We should note that the mass balance of particular glacial regions is influenced by climatic fluctuations like

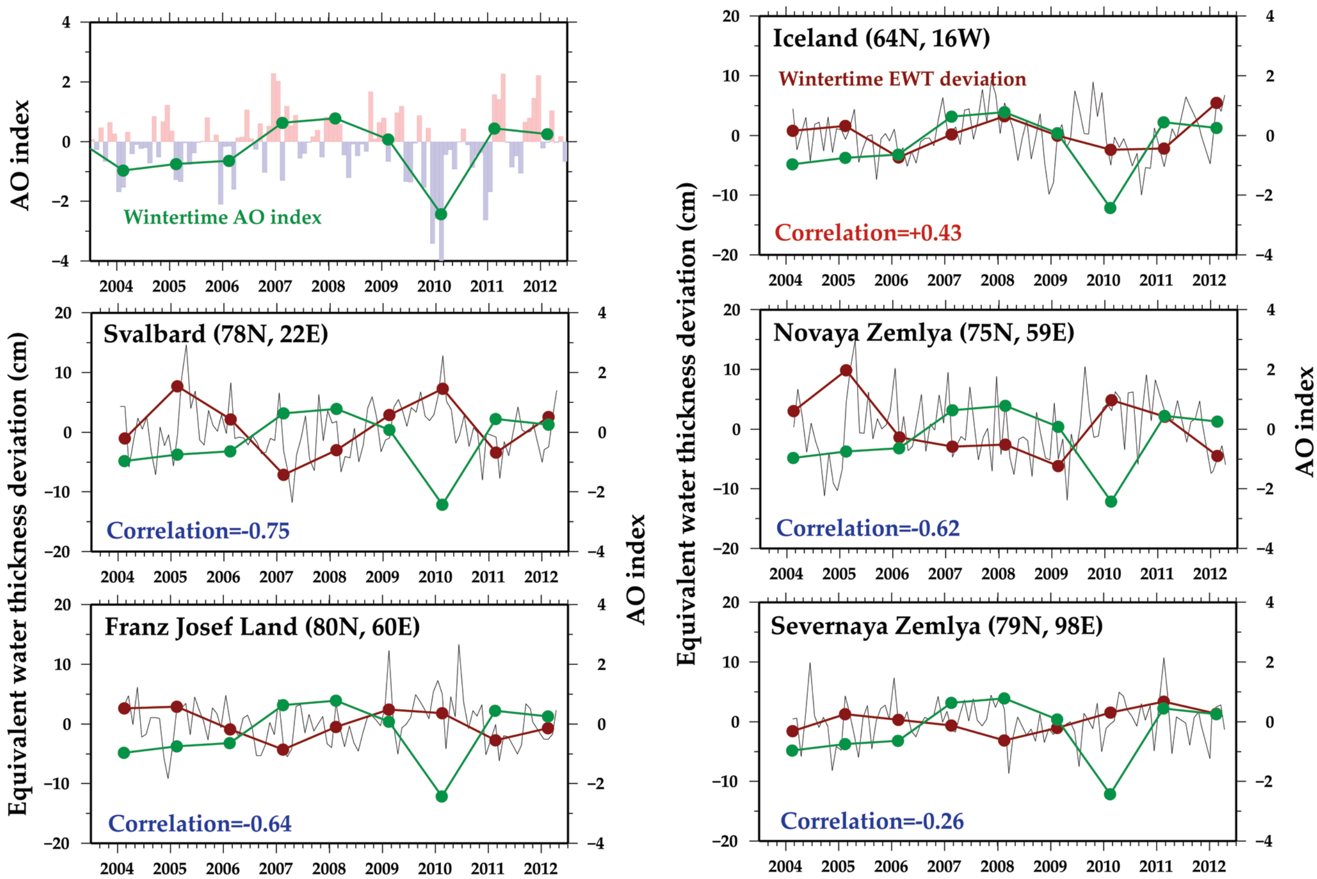

Fig. 9. Time-series of AO index and GRACE EWT deviation in each glacier system, which are calculated by removing linear, quadratic, and seasonal components from the EWT time-series using the least-squares method. AO index are provided by National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml). Grey lines are monthly values of EWT deviation. Red curves are the three month (January, February, and March) averages of the EWDs. Green curves show winter AO index. The correlation coefficient between EWDs and AO index are given in the lower left corners (red and blue characters show positive and negative correlations, respectively).

AO and regional differences in the responses to such fluctuations. For example, the mass in Iceland shows a steady negative trend in the studied period, but those in Svalbard and the Russian High Arctic (especially Novaya Zemlya) behave differently: a significant decrease prior to 2008 and increase around the 2009/2010 winter. This transition coincides with the occurrence time of the strong negative AO. The extreme AO in the winter of 2009/2010 brought a significant increase in surface temperature in and around Svalbard and the Russian High Arctic (Cohen et al. 2010). The observed surface temperature there in January-March 2010 was ~2.5°C higher than that of a 30 year (1971 - 2001) mean. This increased surface temperature would have produced the increased atmospheric moisture and regionally enhanced the winter precipitation in these islands and caused temporary positive trends in the mass of these glaciers. In addition, anomalous wind patterns around this area may also bring enhanced precipitation.

In fact, the EWT time-series of GLDAS, which is based on meteorological data including snow accumulation, showed a positive mass anomaly in Svalbard and Novaya Zemlya in the 2009/2010 winter, suggesting that the strong negative AO brought anomalous precipitation there. It is known that the April ice extent in the Nordic Seas has a strong negative correlation with the winter AOI (Vinje 2001), suggesting that the AO largely control the climate in this region. The average ice loss rates during 2004 - 2008 (i.e., excluding the 2009/2010 winter) are 10.6 ± 3.4 Gt yr^{-1} in Iceland, 6.9 ± 3.6 Gt yr^{-1} in Svalbard, 15.4 ± 11.9 Gt yr^{-1} in the Russian High Arctic. The total ice loss rate is 32.9 ± 18.9 Gt yr^{-1}, 1.5 times as large as the 2004 - 2012 rate.

According to the field observation during 1961 - 2003, the average ice loss rates were 2.4 ± 2.2 Gt yr^{-1} in Iceland, 6.1 ± 1.3 Gt yr^{-1} in Svalbard, 4.0 ± 1.8 Gt yr^{-1} in the Russian High Arctic, respectively. The total ice loss rate was 12.5 ± 5.3 Gt yr^{-1} (Dyurgerov and Meier 2005): about one half of the GRACE results in 2004 - 2012. However, these *in-situ* results are highly uncertain because they rely on extrapolation of a handful of measurements (e.g., Dyurgerov 2010). Though the spatial resolution is limited, GRACE can directly measure such mass changes over extensive glacier systems. Our GRACE estimates suggest that the ice loss rate in the Arctic Islands, as a whole, seems to have doubled in the last decade.

This apparent acceleration matches with the global tendency toward increasing glacial loss in Alaska, Patagonia, and the Asian High Mountain Ranges in comparison with the period 1961 - 2003 (Matsuo and Heki 2010). Gardner et al. (2011) revealed that the glaciers in the Canadian Arctic Archipelago also followed this trend during these years. Our study confirms that the recent global warming enhanced ice melting also occurred in small glacier systems in the Arctic Islands. However, as described above, the ice loss in this region is fairly variable in time. Thus the assessment of their mass balance should be repeated in various time windows in order to correctly understand their long-term behavior. GRACE and future satellite gravimetry missions will remain a powerful tool to enable quantitative assessment of such time-variable mass changes in glaciers and ice sheets all over the world, especially where *in-situ* observations are limited, e.g., the polar and high mountain regions.

Acknowledgements We thank Prof. Benjamin. F. Chao, Academia Sinica in Taiwan, for valuable comments. We also thank Dr. Weijia Kuang, NASA, and the geodetic group in IES, Academia Sinica, for discussion. We also express our gratitude to two anonymous reviewers for their constructive comments, and the editors Prof. C. K. Shum and Prof. C. Hwang for their thoughtful cooperation.

REFERENCES

Amante, C. and B. W. Eakins, 2009: ETOPO1 1 arc-minute global relief model: Procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp.

Baur, O. and N. Sneeuw, 2011: Assessing Greenland ice mass loss by means of point-mass modeling: A viable methodology. *J. Geodesy*, **85**, 607-615, doi: 10.1007/s00190-011-0463-1. [Link]

Chao, B. F., 2005: On inversion for mass distribution from global (time-variable) gravity field. *J. Geodyn.*, **39**, 223-230, doi: 10.1016/j.jog.2004.11.001. [Link]

Chen, J. L., C. R. Wilson, B. D. Tapley, D. Blankenship, E. R. Ivins, 2007: Patagonia Icefield melting observed by Gravity Recovery and Climate Experiment (GRACE). *Geophys. Res. Lett.*, **34**, L22501, doi: 10.1029/2007GL031871. [Link]

Chen, J. L., C. R. Wilson, D. Blankenship, and B. D. Tapley, 2009: Accelerated Antarctic ice loss from satellite gravity measurements. *Nat. Geosci.*, **2**, 859-862, doi: 10.1038/ngeo694. [Link]

Cohen, J., J. Foster, M. Barlow, K. Saito, and J. Jones, 2010: Winter 2009-2010: A case study of an extreme Arctic Oscillation event. *Geophys. Res. Lett.*, **37**, L17707, doi: 10.1029/2010GL044256. [Link]

Dyurgerov, M. B., 2010: Reanalysis of Glacier Changes: From the IGY to the IPY, 1960-2008. Data of Glaciological Studies, Publication 108, Moscow, October 2010, 116 pp.

Dyurgerov, M. B. and M. F. Meier, 2005: Glaciers and the Changing Earth System: A 2004 Snapshot, Occasional Paper 58, Institute of Arctic and Alpine Research, University of Colorado, Boulder, 118 pp.

Gardner, A. S., G. Moholdt, B. Wouters, G. J. Wolken, D. O. Burgess, M. J. Sharp, J. G. Cogley, C. Braun, and C. Labine, 2011: Sharply increased mass loss from glaciers and ice caps in the Canadian Arctic Archipelago. *Nature*, **473**, 357-360, doi: 10.1038/nature10089. [Link]

Guo, J. Y., Z. W. Huang, C. K. Shum, W. van der Wal, 2012: Comparisons among contemporary glacial isostatic adjustment models. *J. Geodyn.*, **61**, 129-137, doi: 10.1016/j.jog.2012.03.011. [Link]

Jacob, T., J. Wahr, W. T. Preffer, and S. Swenson, 2012: Recent contributions of glaciers and ice caps to sea level rise. *Nature*, **482**, 514-518, doi: 10.1038/nature10847. [Link]

Koch, K.-R., 1999: Parameter Estimation and Hypothesis Testing in Linear Models, Springer, Berlin, 333 pp.

Koryakin, V. S., 1986: Decrease in glacier cover on the islands of the Eurasian Arctic during the 20th century. *Polar Geogr. Geol.*, **10**, 157-165, doi: 10.1080/10889378609377283. [Link]

Luthcke, S. B., A. A. Arendt, D. D. Rowlands, J. J. McCarthy, and C. F. Larsen, 2008: Recent glacier mass changes in the Gulf of Alaska region from GRACE mascon solutions. *J. Glaciol.*, **54**, 767-777, doi: 10.3189/002214308787779933. [Link]

Matsuo, K. and K. Heki, 2010: Time-variable ice loss in Asian high mountains from satellite gravimetry. *Earth Planet. Sci. Lett.*, **290**, 30-36, doi: 10.1016/j.epsl.2009.11.053. [Link]

Matsuo, K. and K. Heki, 2012: Anomalous precipitation signatures of the Arctic Oscillation in the time-variable gravity field by GRACE. *Geophys. J. Int.*, **190**, 1495-1506, doi: 10.1111/j.1365-246X.2012.05588.x. [Link]

Mémin, A., Y. Rogister, J. Hinderer, O. C. Omang, and B. Luck, 2011: Secular gravity variation at Svalbard (Norway) from ground observations and GRACE satellite data. *Geophys. J. Int.*, **184**, 1119-1130, doi: 10.1111/j.1365-246X.2010.04922.x. [Link]

Moholdt, G., B. Wouters, and A. S. Gardner, 2012: Recent mass changes of glaciers in the Russian High Arctic. *Geophys. Res. Lett.*, **39**, L10502, doi: 10.1029/2012GL051466. [Link]

Paulson, A., S. Zhong, and J. Wahr, 2007: Inference of mantle viscosity from GRACE and relative sea level data.

Geophys. J. Int., **171**, 497-508, doi: 10.1111/j.1365-246X.2007.03556.x. [Link]

Peltier, W. R., 2004: Global glacial isostasy and the surface of the ice-age earth: The ICE-5G (VM2) model and GRACE. *Annu. Rev. Earth Planet. Sci.*, **32**, 111-149, doi: 10.1146/annurev.earth.32.082503.144359. [Link]

Rasmussen, L. A. and J. Kohler, 2007: Mass balance of three Svalbard glaciers reconstructed back to 1948. *Polar Res.*, **26**, 168-174, doi: 10.1111/j.1751-8369.2007.00023.x. [Link]

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll, 2004: The global land data assimilation system. *Bull. Amer. Meteorol. Soc.*, **85**, 381-394, doi: 10.1175/BAMS-85-3-381. [Link]

Sasgen, I., M. van den Broeke, J. L. Bamber, E. Rignot, L. S. Sørensen, B. Wouters, Z. Martinec, I. Velicogna, and S. B. Simonsen, 2012: Timing and origin of recent regional ice-mass loss in Greenland. *Earth Planet. Sci. Lett.*, **333-334**, 293-303, doi: 10.1016/j.epsl.2012.03.033. [Link]

Seager, R., Y. Kushnir, J. Nakamura, M. Ting, and N. Naik, 2010: Northern hemisphere winter snow anomalies: ENSO, NAO and the winter of 2009/10. *Geophys. Res. Lett.*, **37**, L14703, doi: 10.1029/2010GL043830. [Link]

Svendsen, J. I., V. Gataullin, J. Mangerud, and L. Polyak, 2004: The glacial history of the Barents and Kara sea region. In: Ehlers, J. and P. L. Gibbard (Eds.), Quaternary Glaciations: Extent and Chronology: Part I: Europe, Volume 2, Elsevier Science, Amsterdam, 488 pp.

Swenson, S. and J. Wahr, 2006: Post-processing removal of correlated errors in GRACE data. *Geophys. Res. Lett.*, **33**, L08402, doi: 10.1029/2005GL025285. [Link]

Swenson, S., D. Chambers, and J. Wahr, 2008: Estimating geocenter variations from a combination of GRACE and ocean model outpu. *J. Geophys. Res.*, **113**, B08410, doi: 10.1029/2007JB005338. [Link]

Thompson, D. W. J. and J. M. Wallace, 1998: The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297-1300, doi: 10.1029/98GL00950. [Link]

Tikhonov, A. N., 1963: Regularization of incorrectly posed problems. *Soviet Math. Dokl*, **4**, 1624-1627.

Tushingham, A. M. and W. R. Peltier, 1991: ICE-3G: A new global model of late pleistocene deglaciation based upon geophysical predictions of post-glacial relative sea level change. *J. Geophys. Res.*, **96**, 4497-4523, doi: 10.1029/90JB01583. [Link]

Velicogna, I., 2009: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE. *Geophys. Res. Lett.*, **36**, L19503, doi: 10.1029/2009GL040222. [Link]

Vinje, T., 2001: Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic Seas during the period 1864-1998. *J. Climate*, **14**, 255-267, doi: 10.1175/1520-0442(2001)014<0255:AATOSI>2.0.CO;2. [Link]

Wahr, J., M. Molenaar, and F. Bryan, 1998: Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res.*, **103**, 30205-30229, doi: 10.1029/98JB02844. [Link]

Wouters, B., D. Chambers, and E. J. O. Schrama, 2008: GRACE observes small-scale mass loss in Greenland. *Geophys. Res. Lett.*, **35**, L20501, doi: 10.1029/2008GL034816. [Link]

Zhang, Z. Z., B. F. Chao, Y. Lu, and H. T. Hsu, 2009: An effective filtering for GRACE time-variable gravity: Fan filter. *Geophys. Res. Lett.*, **36**, L17311, doi: 10.1029/2009GL039459. [Link]