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Изменения высоты поверхности и баланс массы ледникового купола Академии Наук на Северной Земле

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Surface-elevation changes and mass balance of the Academy of Sciences Ice Cap, Severnaya Zemlya

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Summary

We have determined the surface-elevation change rates of the Academy of Sciences Ice Cap, Severnaya Zemlya, Russian Arctic, for two different periods: 2004–2016 and 2012/2013–2016. The former was calculated from differencing of ICESat and ArcticDEM digital elevation models, while the latter was obtained by differencing two sets of ArcticDEM digital elevation models. From these surface-elevation change rates we obtained the geodetic mass balance, which was nearly identical for both periods, at −1,72±0,67 Gt a^{-1}, equivalent to −0,31±0,12 m w.e. a^{-1} over the whole ice cap area. Using an independent estimate of frontal ablation for 2016–2017 of −1,93±0,12 Gt a^{-1} (−0,31±0,12 m w.e. a^{-1}), we get an estimate of the climatic mass balance not significantly different from zero, at 0,21±0,68 Gt a^{-1} (0,04±0,13 m w.e. a^{-1}), which agrees with the near-zero average balance at a decadal scale observed during the last four decades. Making an observationally-based assumption on accumulation rate, we estimate the current total ablation from the ice cap, and its partitioning between frontal ablation, dominated by calving (~54%) and climatic mass balance, mostly surface ablation (~46%).

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На основе разновременных ЦМР установлены скорости изменения высоты поверхности ледникового купола Академии Наук на Северной Земле за два периода: 2004–2016 и 2012/2013–2016 гг. и определён геодезический баланс его массы (−1,72±0,67 Гт/год). Сделан расчёт климатического баланса массы (0,21±0,68 Гт/год) и полной абляции (−3,18 Гт/год) ледника, где на отёл приходится ≈54%, а на поверхностную абляцию – ≈46%.

Introduction

The Russian Arctic, which is made up of the archipelagos of Novaya Zemlya, Severnaya Zemlya and Franz Josef Land, had a total glacierized area of 51 592 km^2 in 2000–2010 [1] and an estimated total ice volume of 16 839±2205 km^3 [2]. In spite of current regional climate warming [3], the recent ice-mass losses from the Russian Arctic have been moderate, at ~11±4 Gt a^{-1} over 2003–2009 [4], which is much lower than other Arctic regions such as the Canadian Arctic, the Greenland periphery or Alaska, even when specific (per unit area) losses are considered. However, the mass losses from the Russian Arctic to the end of the 21st century have been projected to increase considerably [5], with an expected contribution to sea-level rise varying between 9.5±4.6 and 18.1±5.5 mm in sea-level equivalent over 2010–2100, depending on the emission scenario [6]. Hence the interest of an accurate knowledge of the current mass losses from the Russian Arctic. There are, however, substantial differences among the various estimates of current mass losses, not only among those obtained using different techniques, such as ICESat altimetry versus GRACE gravimetry, but also among those obtained using a common technique. For instance, Moholdt et al. [7]

found mass changes of -9.8 ± 1.9 Gt a^{-1} using ICESat data and -7.1 ± 5.5 Gt a^{-1} using GRACE data, both for the same period October 2003 – October 2009. The spread among the GRACE estimates is also rather large. For instance, mass changes of -4.6 ± 5.4 Gt a^{-1} have been found for April 2003 – March 2011 [7], of -5 ± 3 Gt a^{-1} for January 2003 – December 2010 [8], of -15.4 ± 11.9 Gt a^{-1} for February 2004 – January 2008 [9], and of -6.9 ± 7.4 Gt a^{-1} for February 2004 – January 2012 [9]. These differences among the GRACE estimates can be attributed to the non-overlapping study periods, to GRACE's large footprint (~250 km), and to uncertainties in the glacier-isostatic adjustment correction, which is known to be poorly constrained in this region [10].

Since most of the recent ice-mass losses in the Russian Arctic have occurred in Novaya Zemlya (~80%), while only the the remaining ~20% correspond to Severnaya Zemlya and Franz Josef Land [7], most recent studies have focused on Novaya Zemlya. A particular aim has been to determine the main drivers (climate, glacier dynamics) of the large ice-mass losses from Novaya Zemlya [7, 11, 12]. Recent work has revealed that the retreat rates of the marine-terminating outlet glaciers of Novaya Zemlya's may have slowed down [13]. The study of the mass balance of Severnaya Zemlya glaciers [14–16] or Franz Josef Land [17] has received comparatively lower attention by the western literature. This motivated our work in a previous paper [18], which had a wider scope, dealing with the short-term and long-term variations of ice-surface velocity, and associated ice discharge variations, the stress regime, the surface-elevation changes and their associated mass-balance changes. In the present paper, we expand the discussion by Sánchez-Gámez et al. [18], focusing on the surface-elevation changes and the geodetic mass balance of the Academy of Sciences Ice Cap, and, in particular, on the possible factors controlling its long-term changes and trends in climatic mass balance.

Study site

General data for the Academy of Sciences Ice Cap has been presented in the companion paper [19], so we will not repeat it here. We will focus here on presenting the climatic conditions of Severnaya Zemlya, and the Academy of Sciences Ice Cap in particular, as these are most relevant for mass balance, which is the focus of this paper. We will also briefly outline the main previous studies on regional mass balance available in the literature.

The climate of Severnaya Zemlya can be considered as a polar desert with both low temperatures and low precipitation [7]. The atmospheric circulation is dominated by high-pressure areas over Siberia and the Arctic Ocean, and low pressure over the Barents and Kara seas [20, 21]. There is a south-north gradient in precipitation, with the Kara Sea as a probable moisture source [21, 22]. This precipitation gradient is demonstrated by the decrease of the ELA in Severnaya Zemlya, as we move from south to north, from ~600 m for the Vavilov Ice Cap, ~400 m for the Academy of Sciences Ice Cap and ~200 m for Schmidt Island [16, 23].

There are two permanent weather stations in the region, Golomyanny and Fedorova (Fig. 1, a of [19]), providing meteorological records from the 1930s to the present [20, 24]. The mean annual surface air temperatures recorded at these stations are of −14.7 and −15 °C, respectively, with Fedorova registering a mean July temperature of 1.5 °C for the period 1930–1990 [24]. Mean annual precipitation is also similar for both weather stations, at ~0.19 m w.e. for Golomyanny and ~0.20 m w.e. for Fedorova [20, 24]. However, Zhao et al. [22] showed that NCEP-NCAR reanalysis summer temperatures at free air 850 hPa geopotential height over Severnaya Zemlya [25] have weak correlations with the summer mean temperatures measured at Golomyanny Island station. They noted that this station is located within the Severnaya Zemlya archipelago 130 km away from the ice cap to the southwest into the Kara Sea, at only 7 m a.s.l., and is strongly influenced by the ocean environment due to sea-ice melting in summer. Additionally, Opel et al. [26] found no correspondence between the number of melt layers in an ice core drilled at the Academy of Sciences Ice Cap summit and the Golomyanny station summer surface air temperatures. On the other hand, Zhao et al. (2014) found that the total number of melt days on Severnaya Zemlya was strongly correlated with NCEP-NCAR reanalysis summer temperatures. For these reasons, we have not used in our analysis the temperature data from Golomyanny and Fedorova stations, but, instead, the NCEP-NCAR reanalysis temperatures. Neither the precipitation data at Golomyanny and Fedorova stations are representative of the conditions at the ice cap, which receives a higher amount of precipitation of ~0,4 m w.e. a^{-1} [21] than the amount recorded at Golomyanny and Fedorova stations.

An automatic weather station installed close to the summit of Academy of Sciences Ice Cap between May 1999 and May 2000 provided temperature information for the air and the shallow snow [27]. The mean annual air temperature was −15.7 °C, whereas the average temperature of the uppermost 10 m of snow/firn was warmer at −10.2 °C, because of the latent heat released by the refreezing of percolating surface meltwater. During the summer months of July and August temperatures were commonly above the freezing point, causing snowmelt and a decrease in snow height [27].

Regarding longer-term past temperature evolution, an ice core drilled at the summit of the Academy of Sciences Ice Cap has provided a temperature record for the last 275 years, inferred from $\delta^{18}O$ concentrations in the ice core. This record shows a minimum in 1790 followed by an increasing overall trend up to present but with a double maximum in the first half of the 20th century [28, 29]. This increasing temperature trend helps explaining the role of the Kara Sea as a moisture source in the area [26, 22]. It also explains the increase in sea-salt content at low altitudes on the ice cap, especially during warm summers [29]. The increase in moisture in the region has also been influenced by the decreasing trend of sea-ice cover in the Arctic beginning in the 1980s [30]. The overall picture of temperature change in the last decades is especially critical for the Arctic region, with a tipping point at the beginning of the 1980s [31].

The mass balance of the ice caps on Severnaya Zemlya and their response to climate change has been addressed by a set of papers by Bassford et al. [14–16]. For the Academy of Sciences Ice Cap in particular, Moholdt et al. [32], using ICESat altimetry together with older DEMs and velocities from Landsat imagery, calculated the geodetic mass balance and the calving flux for various periods during the last three decades, showing that variable ice-stream dynamics dominated the mass balance of the ice cap.

Data and methods

Ice-surface elevation data. We used surface-elevation data from various sources and periods to derive surface-elevation change rates and volume changes. In particular, we used ICESat elevation data from version 34 of the GLAH06 altimetry product [33], based on acquisitions by the Geoscience Laser Altimeter System (GLAS) onboard ICESat [34]. ICESat altimetry is very accurate (~15 cm) where gently sloping topography is present [34]. Most observations used in our study correspond to spring 2004 (see further details in [18]). We also used the ArcticDEM derived from high-resolution submetre satellite imagery from the WorldView and GeoEye satellite constellations [35]. The surface heights retrieved from this imagery are adjusted using ICESat-derived altimetry as a reference [36, 37]. Ice-free land surrounding the ice cap served to vertically adjust the strips, and as a reference to check the quality of the DEMs. The horizontal resolution of the strip DEM product is 2 m, whereas that of the mosaic DEM product is 10 m. The vertical accuracy of these datasets depends on the use of ground-control points as a final step for DEM vertical position refinement. When no ground control is available, the DEM accuracy relies on the accuracy of the sensor's rational polynomial coefficients, and is typically in the order of 4 m [36, 37]. The DEM strips used for this study correspond to the years 2012, 2013 and 2016 (see further details in [18]).

Ice-surface elevation change rates and associated mass changes. We estimated decadal-scale average surface-elevation change rates for 2004–2016 by differencing ICESat altimetry data form 2004 and ArcticDEM strips from 2016. We also calculated short-term elevation changes using pairs of ArcticDEM strip products from 2012/2013–2016. The elevation change rates were split into 25-m height bins using an ice-cap hypsometry calculated from the ArcticDEM mosaic product. Mean elevation change rate values were calculated for individual drainage basins and for increments of ice-cap hypsometry. Volume change rates were converted to mass loss rates (geodetic mass balance) using an ice density of 900 kg m^{-3}. This assumes Sorge's law [38], i.e. that there is no changing firn thickness or density through time and that all volume changes are of glacier ice. Two error sources were considered: the error derived from the differencing of the two datasets and, for calculations involving ICESat data, the extrapolation error associated to an estimation made in an area outside of the region covered by the ICESat altimetry data. The error of the elevation difference was calculated as the square root of the sum of the squares of the measurement errors of the two elevation sources involved. Dividing this error by the number of years between the acquisitions considered provided the elevation change rate error. The extrapolation error was estimated from the difference, within the same height bins, of the calculated point-wise elevation change rates from ICESat altimetry and the mean elevation change rate from the

Table 1. **Mean annual surface-elevation and mass-change rates for the main marine-terminating drainage basins of the Academy of Sciences Ice Cap. Mass-change rates are calculated assuming an ice density of 900 kg m^{-3}.**
Values were calculated from both ICESat-ArcticDEM and ArcticDEM-ArcticDEM differencing, which represent decadal (2004–2016) and recent, shorter-term (2012/13–2016) average values, respectively. ICESat elevation changes were extrapolated hypsometrically. The rates for some basins during 2012/13–2016 are not given because of insufficient coverage of the WorldView images (which are the basis for the ArcticDEM) in 2012/13

Таблица 1. **Среднегодовые значения скоростей изменения высот поверхности и массы для основных ледосборных бассейнов купола Академии Наук, заканчивающихся в море. Скорости изменения массы рассчитаны исходя из плотности льда 900 кг/м^3.**
Значения были рассчитаны по разностям ЦМР ICESat-ArcticDEM и ArcticDEM-ArcticDEM. Эти разности характеризуют средние изменения соответственно за более чем десятилетний период (2004–2016 гг.) и более короткий современный период (2012/13–2016 гг.). Изменения высот ICESat экстраполировались гипсометрически. Скорости изменения высот для некоторых бассейнов в 2012/13–2016 гг. не приведены из-за недостаточной обеспеченности космическими снимками WorldView (которые служат основой для ArcticDEM) для 2012/13 г.

Drainage basin	Surface-elevation change rate		Mass-change rate	
	ICESat-ArcDEM 2004–2016, m a^{-1}	ArcDEM-ArcDEM 2012/13–2016, m a^{-1}	ICESat-ArcDEM 2004–2016, Gt a^{-1}	ArcDEM-ArcDEM 2012/13–2016, Gt a^{-1}
North	−0,05±0,10	–	−0,05±0,12	–
West	0,06±0,07	–	0,05±0,06	–
A	−0,10±0,10	−0,12±0,11	−0,06±0,07	−0,07±0,07
B	−0,28±0,11	−0,58±0,18	−0,10±0,04	−0,21±0,08
South	−0,20±0,13	–	−0,02±0,01	–
BC	−1,31±0,33	−1,21±0,24	−0,33±0,08	−0,30±0,06
Southeast	−0,14±0,08	–	−0,05±0,03	–
C	−1,00±0,14	−0,95±0,26	−0,75±0,11	−0,71±0,17
D	−1,02±0,13	−0,84±0,21	−0,44±0,06	−0,36±0,10

WorldView strip DEMs. In the case of the short-term changes in surface elevation, which were calculated by differencing pairs of ArcticDEM strips, the errors in elevation change rate were estimated by comparing two ArcticDEMs on ice-free land. This analysis provided an RMSE value of 0,91 m for the height differences. Finally, the errors for the basin-wide mass change rates were calculated using error propagation.

Climatic mass balance. Neglecting basal melting or freezing, the mass-balance rate $\dot{M}$ for a given basin is calculated as

$$\dot{M} = \dot{B} + \dot{D} = \int_S \dot{b}\, dS + \int_p \dot{d}\, dp, \quad (1)$$

where $\dot{B}$ is the climatic mass-balance rate (surface mass balance plus internal balance) and $\dot{D}$ is the calving flux, calculated as a surface integral of its local value $\dot{b}$, over the area S of the glacier basin, and a line integral of the local value $\dot{d}$, along the perimeter P of its marine-terminating margin, respectively [39]. The calving flux term $\dot{D}$ is always negative, as it represents a rate of mass loss. If we know the calving flux (given in the companion paper [19]) and the mass-balance rate derived from the surface-elevation changes (calculated in this paper), then we can use Equation 1 to estimate the climatic mass balance for each basin and thus the partitioning of total mass balance into climatic mass balance and frontal ablation. The latter term refers to the ice mass losses by calving, subaerial frontal melting and sublimation, and subaqueous frontal melting at the nearly-vertical calving fronts [39]. Subaerial frontal melting and sublimation can be neglected in comparison with the other terms. Submarine melting is assumed to be small for the Academy of Sciences Ice Cap, because no substantial retreat has been observed along the ice fronts of its nearly-stagnant parts [32]. Consequently, in our case study total frontal ablation can be considered nearly equivalent to calving flux or to ice discharge.

Results

Surface-elevation changes and associated mass changes. The calculated surface-elevation change rates, together with their associated mass change rates (geodetic mass balance) are shown in Table 1 and Figs. 1–3. The surface-elevation changes, at a decadal scale during 2004–2016, and at a shorter-term scale during 2012/2013–2016, are similar, except for Basin B. The thinning rate for Basin B during the most recent period is double than that of the first

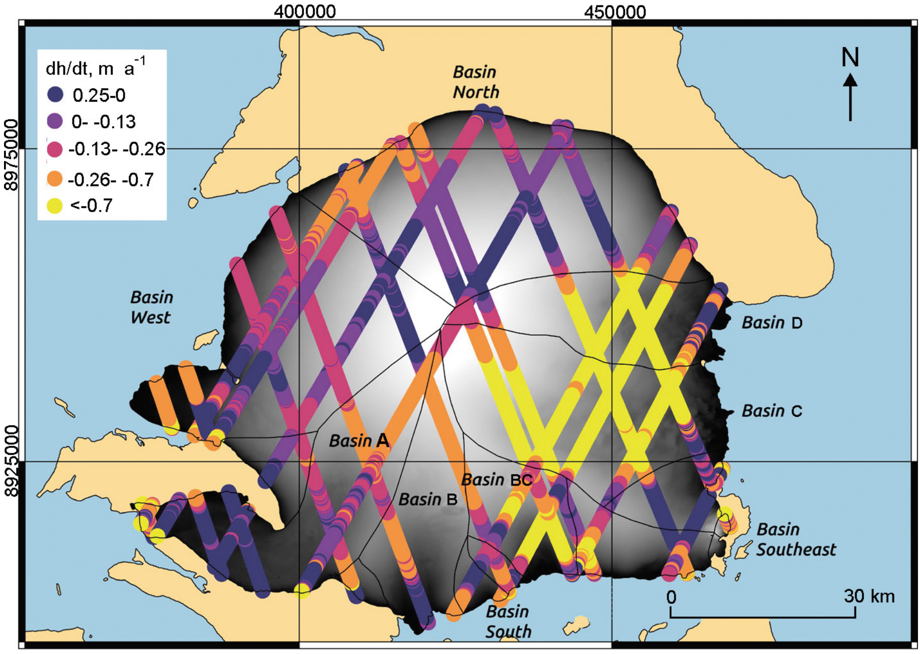

Fig. 1. Surface-elevation change rates 2004–2016 for the Academy of Sciences Ice Cap derived from ICESat-ArcticDEM differencing.
The background image of the ice cap is the ArcticDEM mosaic product

Рис. 1. Темпы изменения высот поверхности в 2004–2016 гг. ледникового купола Академии Наук, полученные на основе разности данных ICESat-Arctic DEM.
Фоновое изображение ледникового купола представляет собой мозаику ArcticDEM

period. The decadal-scale surface-elevation change-rate map displayed in Fig. 1 shows a general thinning pattern for all marine-terminating basins and a state close to balance for the land-terminating northern and marine-terminating western drainage basins. Comparing Fig. 1 with the surface velocity field in Fig. 2 of the companion paper [19], we note that the thinning is largest for the basins with ice streams draining to the southeast and east (Basins BC, C and D). Drainage Basin A, which has the slowest ice-stream flow, shows only limited average thinning, though with greater thinning in its upper part and thickening at lower elevations. The thinning pattern is similar for all fast-flowing basins. The highest thinning rates occur where flow converges from the accumulation areas at the heads of the major ice streams (see Figs. 2 and 3).

Mass balance. As discussed in the Methods section, we calculated the climatic mass balance from the total mass balance and the calving flux using Equation 1. The total mass balance was obtained from surface-elevation changes using the geodetic method. As we are interested in the current climatic mass-balance, we took the geodetic mass balance for the period 2012/13–2016. However, no geodetic mass-balance data were available for certain basins (North, West, South, Southeast) because of the lack of coverage by WorldView images. For these basins, we took the geodetic mass balance for the period 2004–2016. We assume that this does not imply a significant difference, because the changes in surface-elevation change rates between

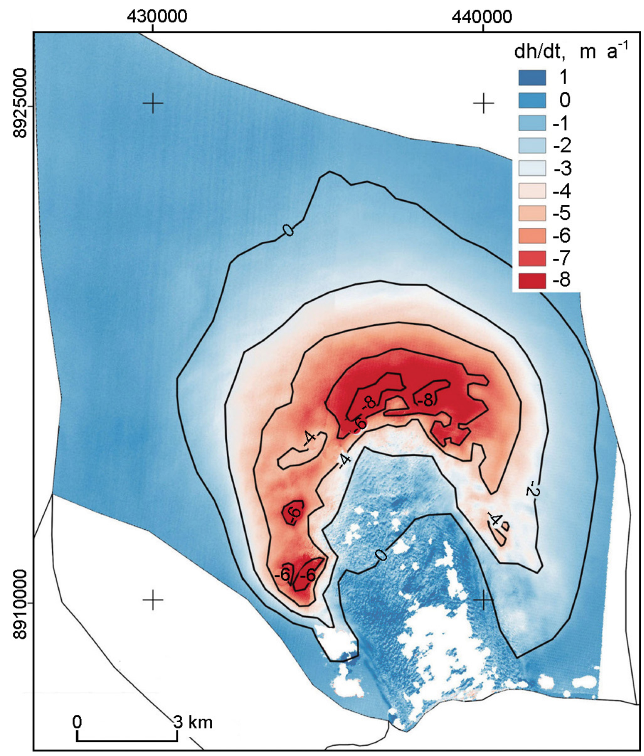

Fig. 2. Surface-elevation change rates of Drainage Basin BC for 2012/13–2016, derived from ArcticDEM-ArcticDEM strip differencing.
White represents no data

Рис. 2. Темпы изменения высот поверхности ледосборного бассейна BC за 2012/13–2016 гг., полученные на основе вычисления разности ArcticDEM-ArcticDEM.
Белым цветом показаны участки, где данные отсутствуют

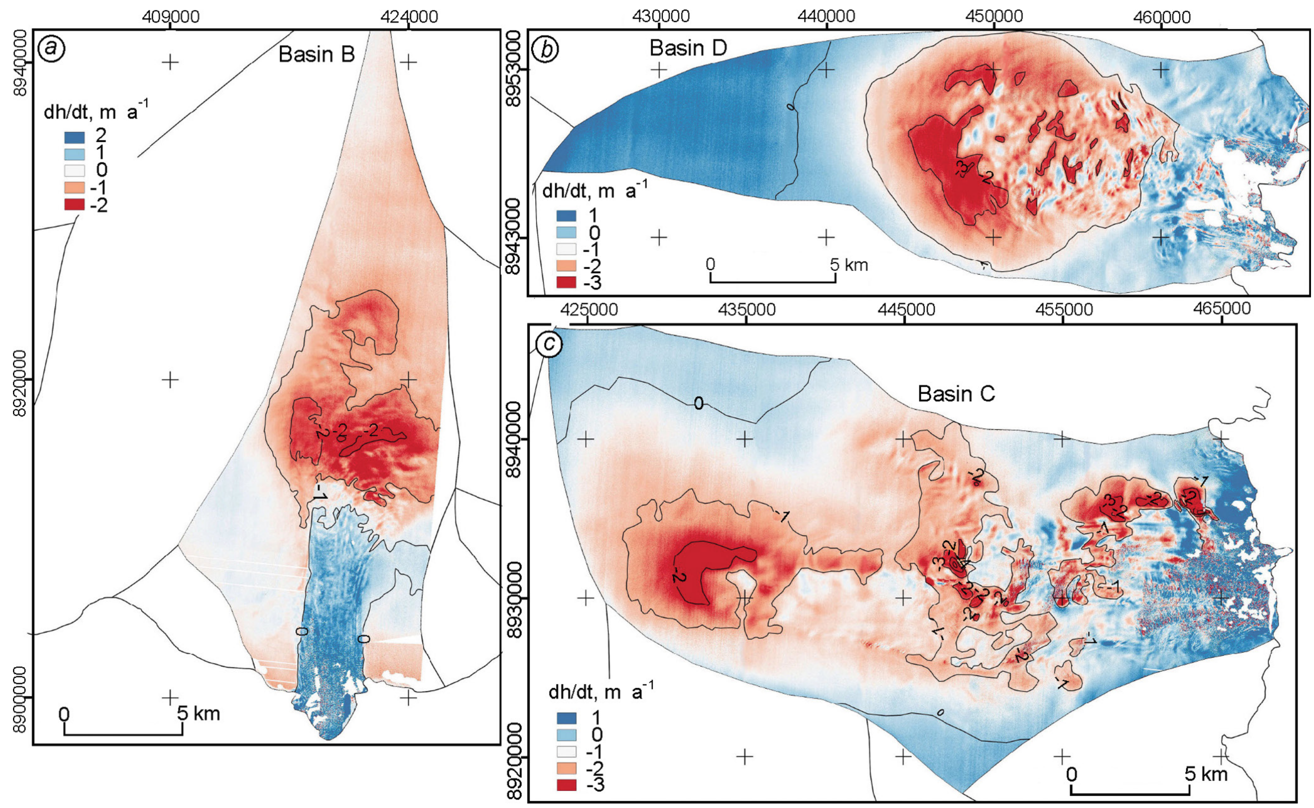

Fig. 3. Surface elevation change rates 2012/13–2016 for basins B (*a*), D (*b*) and C (*c*), derived from ArcticDEM-ArcticDEM strip differencing.
White represents no data

Рис. 3. Темпы изменения высот поверхности в 2012/13–2016 гг. для ледосборных бассейнов B (*a*), D (*b*) и C (*c*), полученные на основе вычисления разности ArcticDEM-ArcticDEM.
Белым цветом показаны участки, где данные отсутствуют

both periods were very small, almost negligible, for the drainage basins with WorldView coverage in both periods. The results for the geodetic mass balance, with detail by basin, are shown in Table 2. For the whole ice cap, we obtained a total geodetic mass balance $\dot{M} = -1.72 \pm 0.67$ Gt a^{-1} (-0.31 ± 0.12 m w.e. a^{-1}). Since the calving flux calculated in the companion paper [19] is $\dot{D} = -1.93 \pm 0.12$ Gt a^{-1} (-0.35 ± 0.02 m w.e. a^{-1}), we get a climatic mass balance $\dot{B} = 0.21 \pm 0.68$ Gt a^{-1} (0.04 ± 0.13 m w.e. a^{-1}), not significantly different from zero. The total mass balance of the ice cap is therefore dominated by the calving flux.

Discussion

Evolution of the surface-elevation change rates during recent decades. As mentioned in the results section, the changes in thinning rate between our study periods (2004–2016 and 2012/13–2016) have been negligible, except for Basin B. Therefore, we focus here on analysing, at a basin scale, the main changes in thinning rates between the two periods studied by Moholdt et al. [32] (1988–2006 and 2003–2009) and our own results. Note that our study period 2004–2016 partly overlaps with one of the periods (2003–2009) analysed by Moholdt et al. [32]. When comparing Moholdt's data with our own data, it is important to be aware that our Basins North and West are grouped together as 'North' in Moholdt et al. [32] study, while our basins South, BC and Southeast are grouped as 'Others' in their study.

The basins North (land-terminating) and West (marine-terminating, but with slow flow), have remained fairly stable along the whole set of periods analysed by Moholdt et al. [32] and ourselves. Basin A presents in 2004–2016 thinning at its upper part and thickening at lower elevations, as it did during both periods analysed by Moholdt et al. [32], who indicated a surge-like elevation change pattern,

Table 2. **Partition of the total mass balance (calculated by the geodetic method) into climatic mass balance and frontal ablation for the drainage basins of the Academy of Sciences Ice Cap.**
The geodetic mass balance has been derived from ArcticDEM-ArcticDEM differencing for 2012/13–2016, except for the basins marked with an asterisk, for which ICESat-ArcticDEM differencing for 2004–2016 has been used. The frontal ablation data correspond to the period November 2016 – November 2017 (see the companion paper [19])
Таблица 2. **Разбиение общего баланса массы (рассчитанного геодезическим методом) на климатический баланс массы и фронтальную абляцию для ледосборных бассейнов ледникового купола Академии Наук.**
Геодезический баланс массы получен на основе разности ArcticDEM-ArcticDEM за 2012/13–2016 гг., за исключением бассейнов, отмеченных звёздочкой, для которых использовалась разность ICESat-ArcticDEM за 2004–2016 гг. Данные по фронтальной абляции соответствуют периоду ноябрь 2016 – ноябрь 2017 (см. сопутствующую статью [19])

Drainage Basin	$\dot{M}$		$\dot{B}$		$\dot{D}$	
	Gt a^{-1}	m w.e. a^{-1}	Gt a^{-1}	m w.e. a^{-1}	Gt a^{-1}	m w.e. a^{-1}
North*	−0,05	−0,04	−0,05	−0,04	0	0
West*	0,05	0,05	0,11	0,11	−0,06	−0,06
A	−0,07	−0,11	−0,04	−0,04	−0,03	−0,06
B	−0,21	−0,52	−0,03	−0,07	−0,18	−0,44
South*	−0,02	−0,18	0,02	0,23	−0,04	−0,46
BC	−0,3	−1,09	0,11	0,4	−0,41	−1,49
Southeast*	−0,05	−0,13	0,03	0,08	−0,08	−0,21
C	−0,71	−0,86	−0,02	−0,02	−0,69	−0,83
D	−0,36	−0,76	0,08	0,17	−0,44	−0,93
Ice cap total	**−1,72**	**−0,31**	**0,21**	**0,04**	**−1,93**	**−0,35**

in agreement with the surface velocity fields of the 1995 InSAR data of Dowdeswell et al. [23]. Moholdt et al. [32] also noted a decrease in ice flow, and correspondingly in dynamic instability, between 1988–2006 and 2003–2009, indicating glacier deceleration. Our own data suggest continued deceleration during the period 2004–2016, with differences in surface-elevation change rates between the upper and lower parts greater than 0.8 m a^{-1} (see Fig. 1).

The surface-elevation change rate in Basin B decreased, from −1.26±0.31 m a^{-1} in 1988–2006, to −0.28±0.11 in 2004–2016 and to –0.58±0.18 m a^{-1} in 2012/13–2016. The structure of its spatial changes (see Figs. 1 and 3, *a*) is of special interest, because it shows a surge-like pattern, with current marked thinning in the upper part of the basin (ca. −2 m a^{-1}) and thickening in the lower part of the ice stream (ca. 1 m a^{-1}).

Basins South, BC and Southeast showed a transition from a near-balance value of −0.02±0.10 m a^{-1} in 2003–2006 to thinning in 2004–2016 (surface-elevation change rate of −0.59±0.17 m a^{-1}). This transition is more marked if Basin BC is considered separately, as its surface-elevation change rate is of −1.31±0.33 m a^{-1} for 2004–2016, due to the initiation of ice stream flow in this basin sometime between 2002 and 2016, as discussed in the companion paper [19].

Basin C presented widespread thinning during all periods, but with largest changes during the earliest period, of −2.56±0.26 m a^{-1} on average in 1988–2006, compared with ca. −1 m a^{-1} in the two most recent periods (see Fig. 3, *b* and Table 3, the latter in terms of mass balance). Basin D has also shown widespread thinning in all periods, but with a slowly decreasing trend, which is an indication of sustained fast flow and results in large cumulative thinning (see Fig. 3, *c*).

Overall, we observe a larger dynamic thinning and a larger contribution to mass loss by the marine-terminating southern and eastern drainage basins for 2004–2016 and for 2012/13–2016, in comparison with the results of Moholdt et al. [32] for 2003–2006. This largest thinning, most relevant at the zones of onset of ice-stream flow, is an indication of dynamic instability.

Evolution of the mass-balance rates during recent decades. The estimates of the total mass balance of the Academy of Sciences Ice Cap during the last three decades, with detail by basin, are shown in Table 3. All mass balances were obtained by the geodetic method, which has the limitations derived from the use of Sorge's law. Possible changes in the area of the ice cap, if significant, would involve a further limitation. Dowdeswell et al. [23] reported an ice-cap area of 5575 km^2, based on Landsat images from 1988. Moholdt et al. [32], analysing multitemporal satellite imagery from Corona and Landsat satellites acquired between 1962 and 2010, concluded that there have been no clear trends in the fluctuations of terminus posi-

Table 3. **Mass balance rates (geodetic mass balance) for the main drainage basins of the Academy of Sciences Ice Cap and over different periods.**
Basin «North» here groups our basins North and West, and «Others» groups our basins South, BC and Southeast. These names are used for compatibility with Moholdt et al. [32]. The values used for computing the Ice Cap total in this study are marked with an asterisk, i.e. we have taken the values for 2012/13–2016 and, when unavailable, those for 2004–2016. All values are given in m w.e. a^{-1} except those in the last row, given in Gt a^{-1}

Таблица 3. **Значения баланса массы (геодезический баланс массы) для основных ледосборных бассейнов ледникового купола Академии Наук и разных периодов.**
Здесь бассейн «North» включает в себя наши бассейны North и West, а бассейн «Others» – наши бассейны South, BC и Southeast. Эти названия были использованы для возможности сравнения с данными Мохолдта с соавторами [32]. Значения, используемые для вычисления общей величины Ice Cap total в данном исследовании, отмечены звёздочкой, т.е. мы взяли значения за 2012/13–2016 гг. и, если они отсутствуют, за 2004–2016 гг. Все значения даны в метрах водного эквивалента в год, за исключением значений в последней строке, приведённых в Гт/год

Drainage Basin	Moholdt et al. [32]		This study	
			ICESat-ArcDEM	ArcDEM-ArcDEM
	1988–2006 m w.e. a^{-1}	2003–2009 m w.e. a^{-1}	2004–2016 m w.e. a^{-1}	2012/13–2016 m w.e. a^{-1}
Basin North	0,03±0,18	0,07±0,06	0±0,08*	–
A	0,14±0,23	0,14±0,09	−0,09±0,09	−0,11±0,10*
B	−1,13±0,28	−0,23±0,12	−0,25±0,10	−0,52±0,16*
C	−2,30±0,23	−0,86±0,09	−0,90±0,13	−0,86±0,23*
D	−1,57±0,26	−1,11±0,11	−0,92±0,12	−0,76±0,19*
Others	−0,29±0,23	−0,02±0,09	−0,53±0,15*	–
Ice Cap total	**−0,55±0,16**	**−0,19±0,05**	**−0,31±0,12**	
Ice Cap total	**−3,06±0,89 Gt a^{-1}**	**−1,06±0,28 Gt a^{-1}**	**−1,72±0,67 Gt a^{-1}**	

tions of the various basins of the Academy of Sciences Ice Cap. They calculated a total area loss of the marine-terminating glaciers of 5 km^2 during 1988–2009, including several cases of small local advance and retreat. The corresponding rate of ice-volume loss was of only 0.02 km^3 a^{-1}, which is insignificant in terms of ice-cap mass balance. Our own observations, using Landsat-7 and Sentinel-2 optical images from July 2002 and March 2016, respectively, showed local advances and retreats of the eastern and southern marine margins of up to ca. 1–2 km with respect to the margins of Moholdt et al. [32], but the net change in area was negligible and thus we used their same ice-cap area of 5570 km^2.

The total mass balances shown in Table 3 are similar, although with reversed sign, to those of the calving fluxes presented in Table 2 of the companion paper [19]. The largest difference (ca. 0.3–0.4 Gt a^{-1}, for 2003–2009), is attributed to the use by Moholdt et al. [32] of Basin North as an analogue for the climatic mass balance of the whole ice cap (the slightly positive climatic mass balance of Basin North multiplied by the area of the whole ice cap accounts for this difference). The second largest difference corresponds to the most recent period, and it could be attributed to two facts: 1) the periods analysed in both tables are close but not equal (2016/17 vs. 2012/13–2016); 2) the mass balances given for certain basins for 2012/13–2016 actually correspond to 2004–2016, due to unavailability of WordView images for those basins in 2012/13–2016. Taken together, the results in Table 2 of [19] and Table 3 of this paper indicate that the total mass balance of the ice cap is nearly equivalent to the calving losses, which means that the long-term climatic mass balance has remained close to zero since 1988.

The scarce earlier observations of climatic mass balance available for the Vavilov Ice Cap on October Revolution Island, some 120 km to the south of the Academy of Sciences Ice Cap, also indicate a near-zero average balance of –0.03 m a^{-1} for the periods 1975–1981 and 1986–1988 [40]. Mass-balance modelling experiments by Bassford et al. [14], also for the Vavilov Ice Cap, give a similar value of −0.02 m a^{-1} for the whole period 1974–1988. Although all of these estimates suggested a large interannual variability, such year-to-year variations have limited interest in the context of this discussion, as we only have available average mass-balance estimates over periods of several years, up to more than a decade. Therefore, me may conclude that the climatic mass balance of the Academy of Sciences Ice Cap has remained close to zero on average for the last four decades.

Possible factors controlling long-term changes and trends in climatic mass balance. Thinking of possible controlling factors, summer air temperature and precipitation seem the most evident to analyse. Using NCEP-NCAR and ERA-Interim reanalysis data for Novaya Zemlya and Severnaya Zemlya from 1995–2011, Zhao et al. [22] studied the influence of summer (June-September) mean 850 hPa geopotential height temperature on snowmelt. They analysed the trends of both total melt days (TMD) and melt offset date (MOD). For Severnaya Zemlya, the temperature trends during 1995–2011 were of 0.80 °C decade^{-1} (NCEP-NCAR, p-value < 0.05) and 0.88 °C decade^{-1} (ERA-Interim, p-value = 0.065). Zhao et al. [22] found a positive correlation between mean TMD and the average June-September NCEP-NCAR air temperature at 850 hPa, with the slope of the linear regression of 10 days °C^{-1} ($r = 0.843$, p-value < 0.0001). Using simple regression, they also found that the TMDs of Severnaya Zemlya are significantly anti-correlated to the Laptev Sea ($r = -0.735$, p-value < 0.001) and Kara Sea ($r = -0.678$, p-value < 0.003) September sea-ice extent. However, since sea-ice extent and glacier surface melting can correspond to the regional temperature increase, Zhao et al. [22] used additionally partial correlation analysis to remove the large-scale influence of air temperature on both variables. Upon removal of these effects, partial correlation analysis suggested that glacier melt on Severnaya Zemlya was still statistically anti-correlated to the Laptev Sea and Kara Sea sea-ice extent. An explanation can be that reduced offshore sea-ice concentration, i.e. increased open-water fraction, can enhance onshore advection of sensible and latent heat fluxes [41]. However, even if long-term changes in summer (and annual) temperatures have been observed during our analysed period [18], and regional sea-ice concentration has also shown a clear decreasing trend [18], these changes seem to have exerted only a minor impact on the long-term climatic mass balance estimates for the Academy of Sciences Ice Cap, which remain close to zero. An explanation suggested by Zhao et al. [22] is that sea-ice reduction exposes larger areas of open water in summer to evaporation and change the large-scale atmospheric circulation, which results in increased summer precipitation over the Arctic [42, 43].

For the Academy of Sciences Ice Cap, the influence of sea-ice concentration on precipitation has been observed by Opel et al. [26], through their analysis of the deep ice core drilled at the ice-cap summit in 1999–2001. Deuterium excess (the difference between the two stable water-isotope ratios $\delta^{18}O$ and δD) in precipitation depends mainly on the evaporation conditions in the moisture-source region, and to a lesser extent on the condensation temperatures. The main factors controlling the process are the relative air humidity and the sea-surface temperature (SST) and, to a lesser degree, the wind speed during evaporation. Based on the relationship between deuterium excess and SST, Opel et al. [26] observed that in hemispherically warmer periods the Academy of Sciences Ice Cap receives more precipitation from moisture evaporated at lower SSTs, for example due to a northward shift of the moisture source. Since most precipitation on Severnaya Zemlya is brought by air masses moving from the south and southwest, the Kara Sea is likely to be a regional moisture source and its sea-ice cover would be the main factor influencing summer and autumn evaporation. Lower sea-ice cover in the Kara Sea would allow higher evaporation rates and enhance the contribution of regional moisture to precipitation over the Academy of Sciences Ice Cap. Moholdt et al. [32] searched for some evidence of this precipitation increase for Novaya Zemlya and Severnaya Zemlya, finding a slightly higher precipitation rate in 2004–2009 with respect to the mean for 1980–2009, especially for Novaya Zemlya. For Severnaya Zemlya, its climatic mass balance close to zero suggests that the recent precipitation anomaly is also likely to be real, as it provides the most reasonable mechanism to counterbalance the observed increasing melt trend. In summary, the near-equilibrium climatic mass balance of the Academy of Sciences Ice Cap (and most generally of Servernaya Zemlya) is probably the result of two opposing effects. On one hand, sea-ice cover loss would enhance precipitation by exposing larger areas of open water to evaporation. On the other, these larger areas of open water would allow onshore advection of heat fluxes from warming mixed ocean layers, accelerating surface melt on the ice cap. With the climatic mass balance remaining near zero, the role of the calving flux is critical in determining the total mass balance of the Academy of Sciences Ice Cap.

Total ablation and its partitioning between frontal ablation and surface ablation. For the projections of future contributions of glacier wastage to sea-level rise, it is of interest to know the relative contributions of surface ablation and frontal ablation to the total ablation. Frontal ablation is equivalent, in our case study, to calving flux, which has been calculated in the companion paper [19]. But we also need an estimate of surface ablation. To get it, we subtracted from our calculated climatic mass balance for 2012–2016 (0.21±0.68 Gt a^{-1}; see section 'Results') an estimate of the total accumulation over the ice cap. This estimate of accumulation was based on the measured net accumulation at the ice-cap summit and its variation with altitude, as done by Dowdeswell et al. [23], and is described below.

At the summit of the Academy of Sciences Ice Cap, analysis of an ice core detected the layers of maximum radioactivity (in terms of Cesium^{137}) corresponding to the 1963 atmospheric nuclear tests and to the 1986 Chernobyl event. The resulting average net accumulation rates were 0.45 m w.e. a^{-1} from 1963 to 1999, and 0.53 m w.e. a^{-1} from 1986 to 1999 [44]. Later analyses by Fritzsche et al. [28] gave an average accumulation rate of 0.46 m w.e. a^{-1} over 1956–1999 based on stable-isotope investigations. These values are also in agreement with the mean annual net mass balance of 0.43–0.44 w.e. a^{-1} observed by Zagorodnov [45] for 1986/87 using structural-stratigraphic methods, although in disagreement with the annual-layer thickness of 0.26–0.28 m suggested by Klementyev et al. [46] and used by Kotlyakov et al. [47] for dating the Academy of Sciences ice core drilled in 1986/87. On the other hand, measurements elsewhere in Severnaya Zemlya suggest that annual precipitation decreases with altitude from 0.45 at the ice-cap summit to 0.25 m w.e. a^{-1} close to sea level [48]. Assuming, a value of 0.30 m w.e. a^{-1} as average accumulation rate over the entire ice cap, as done by Dowdeswell et al. [23], we obtained a total accumulation of 1.67 Gt a^{-1}. If, instead, we had used as ice-cap averaged accumulation rate its upper bound, given by the net accumulation rate at the ice cap summit of 0.46 m w.e. a^{-1} [28], the total accumulation over the ice cap would have been of 2.56 Gt a^{-1}.

Since our estimate of climatic mass-balance is of 0.21 Gt a^{-1}, the surface ablation will thus be of −1.46 Gt a^{-1}. If we add the frontal ablation (mostly calving) of −1.72 Gt a^{-1}, we get a total ablation of −3.18 Gt a^{-1}. This implies that iceberg calving represents, on average, ~54% of the mass losses over 2012–2016, with the remaining 46% corresponding to surface ablation. If we had considered, instead, the upper bound for the accumulation rate of 0.46 m w.e. a^{-1} [28], frontal ablation would have represented ~42% of the total ablation over the period 2012–2016, with the remaining ~58% corresponding to surface ablation. We conclude that calving losses are a substantial component, in fact about half of the total mass loss from the Academy of Sciences Ice Cap. This value is higher than a previous estimate by Dowdeswell et al. [23] for the Academy of Sciences Ice Cap in 1995, of ~40%. It is also higher than the available estimates for other large Arctic ice caps such as Austfonna, for which Dowdeswell et al. [49] estimated that calving accounted for 30–40% of total ablation, or Svalbard as a whole, for which Błaszczyk et al. [50] gave an estimate of 17–25%.

Conclusions

Our analysis leads to the following main conclusions:

1. The average total geodetic mass balance of the ice cap during 2012–2016 was of −1.72±0.27 Gt a^{-1}, which is equivalent to −0.31±0.05 m w.e. a^{-1} over the entire ice cap area.

2. The average climatic mass balance of the ice cap during 2012–2016 (similar to that for 2004–2016), was not significantly different from zero, at 0.21±0,68 Gt a^{-1}, or equivalently 0.04±0.13 m w.e. a^{-1}. This agrees with the scarce in-situ observations in the region during the 1970s and 1980s, and with remote-sensing estimates by other authors for 1988–2006 and 2003–2009. The average climatic mass balance has thus remained around zero during the last four decades.

3. Our estimated average total ablation (surface ablation plus frontal ablation) over the period 2012–2016 is of −3.18 Gt a^{-1}, of which frontal ablation (dominated by calving) accounts for ~54% and the remaining ~46% corresponds to surface ablation. Calving losses are, therefore, an important contributor to the mass losses from the Academy of Sciences Ice Cap.

4. Since the climatic mass balance has remained close to zero over the last four decades, in spite of regional warming, the total mass balance of the ice cap has been driven mainly by calving.

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Расширенный реферат

Определены скорости изменения высоты поверхности ледникового купола Академии Наук на о. Комсомолец (архипелаг Северная Земля в Российской Арктике) за два периода: 2004–2016 и 2012/13–2016 гг. Скорости для первого периода рассчитаны на основе разности цифровых моделей высот ICESat и ArcticDEM, а для второго периода – на основе разности двух наборов цифровых моделей высот ArcticDEM. Исходя из этих скоростей изменения высоты поверхности и предполагая, что плотность льда равна 900±17 кг/м^3, оценён геодезический баланс массы купола, который был почти одинаков для обоих периодов и составил −1,72±0,67 Гт/год, что эквивалентно потерям −0,31±0,12 м вод. экв./год на всей площади ледникового покрова, равной 5570 км^2. Используя независимую оценку фронтальной абляции за 2016–2017 гг., которая равна −1,93±0,12 Гт/год (−0,31±0,12 м вод. экв./год), получаем оценку климатического баланса массы ледникового купола, существенно не отличающуюся от нуля и равную 0,21±0,68 Гт/год (0,04±0,13 м вод. экв./год), что вполне согласуется с почти нулевым средним балансом, наблюдавшимся в течение последних четырёх десятилетий. Обсуждаются также возможные факторы, которые управляют долгосрочными изменениями и трендами климатического баланса массы, включая температуру, осадки, сплочённость морских льдов, относительную влажность воздуха, температуру поверхности моря и скорость ветра. Используя данные об аккумуляции, измеренной на вершине ледникового купола, и высотный градиент аккумуляции накопления, оцениваются полная аккумуляция и, следовательно, полная абляция ледникового купола как −3,18 Гт/год. Далее рассчитывается, в какой пропорции полная абляция распределяется между фронтальной абляцией, в которой преобладает отёл (≈54%), и климатическим балансом массы, в основном поверхностной абляцией (≈46%).

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