KAJ SMO SE NAUČILI PRI SPREMLJANJU LEDENEGA POKROVA NA GRENLANDIJI Z ICESAT IN KAJ LAHKO PRIČAKUJEMO OD ICESAT-2

WHAT HAVE WE LEARNT FROM ICESAT ON GREENLAND ICE SHEET CHANGE AND WHAT TO EXPECT FROM CURRENT ICESAT-2

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IZVLEČEK

Obseg ledenikov in spremembe v njihovi masi je mogoče učinkovito spremljati s tehnologijo laserskega satelitskega daljinskega zaznavanja, to je s satelitskim laserskim višinomerstvom, in/ali satelitsko gravimetrijo. ICESat, ki je bil izstreljen leta 2003, je prvi satelit za lasersko višinomerstvo, s katerim je zbranih mnogo podatkov o višinah na površju Zemlje z visoko časovno in prostorsko ločljivostjo, kar se uporablja tudi za spremljanje ledenikov. ICESat-2 je bil izstreljen leta 2018. Na primeru Grenlandije podajamo oceno o spreminjanju njenega ledenega pokrova na podlagi podatkov ICESat, kar primerjamo z ocenami o spremembi ledeniške mase na podlagi sprememb težnostnega polja na tem območju z uporabo podatkov satelita za spremljanje težnostnega polja Zemlje GRACE. Analiza podatkov ICESat za obdobje 2004–2008 kaže, da je povprečna sprememba višine ledu na Grenlandiji ± 0,60 m na leto. Večje izgube mase ledu so zaznavne na južnih obalnih predelih otoka, v notranjosti otoka v tem obdobju spremembe v masi ledenega pokrova skoraj niso nezaznavne. Za isto obdobje so tudi gravitacijski satelitski podatki pokazali, da ustrezajo spremembe težnostnega polja spremembi v masi ledenega pokrova na južni obali Grenlandije od nekaj centimetrov do –0,36 metrov vodnega ekvivalenta na leto (angl. water equivalent per year), medtem ko spremembe v masni bilanci v notranjosti otoka kažejo pozitivni trend. Na podlagi podatkov GRACE se tudi v obdobju 2009–2017 kaže negativni trend letne masne bilance ledenikov na obalnih območjih.

ABSTRACT

Ice-sheet mass balance and ice behaviour have been effectively monitored remotely by space-borne laser ranging technology, i.e. satellite laser altimetry, and/or satellite gravimetry. ICESat mission launched in 2003 has pioneered laser altimetry providing a large amount of elevation data related to ice sheet change with high spatial and temporal resolution. ICESat-2, the successor to the ICESat mission, was launched in 2018, continuing the legacy of its predecessor. This paper presents an overview of the satellite laser altimetry and a review of Greenland ice sheet change estimated from ICESat data and compared against estimates derived from satellite gravimetry, i.e. changes of the Earth's gravity field obtained from the GRACE data. In addition to that, it provides an insight into the characteristics and possibilities of ice sheet monitoring with renewed mission ICESat-2, which was compared against ICESat for the examination of ice height changes on the Jakobshavn glacier. ICESat comparison (2004–2008) shows that an average elevation change in different areas on Greenland varies up to ±0.60 m yr^{-1}. Island's coastal southern regions are most affected by ice loss, while inland areas record near-balance state. In the same period, gravity anomaly measurements showed negative annual mass balance trends in coastal regions ranging from a few cm up to -0.36 m yr^{-1} w.e. (water equivalent), while inland records show slightly positive trends. According to GRACE observations, in the following years (2009–2017), negative annual mass balance trends on the coast continued.

KLJUČNE BESEDE

GRACE, Grenlandija, ledeniški pokrov, ICESat, ICESat-2, lasersko višinomerstvo, satelitska gravimetrija

KEY WORDS

GRACE, Greenland, ice-sheet, ICESat, ICESat-2, laser altimetry, satellite gravimetry

1 INTRODUCTION

Changes in the glaciers and ice sheet directly influence the balance between the solar radiation reflected and absorbed by the Earth system, affecting the Earth's energy budget and, consequently, the global climate (Budyko, 1969). Climate changes then further affect the ice sheet in a closed loop. Changes of the ice-covered areas can be quantified with respect to the area changes, elevation changes due to the seasonal variations, and by analysing the mass balance change. The latter describes new ice formation from snowfall and ice loss through melting and iceberg calving. Recent studies have shown significant deviation from the normal ice loss-gain cycle due to the rapid glacial melt in Antarctica and Greenland (e.g. Velicogna and Wahr, 2006; Rignot et al., 2008; Paolo et al., 2015; Gomez et al., 2015). Simultaneously, the global sea level is rising caused by seawater thermal expansion and melting of the ice sheets (Zou and Jin, 2018). According to Mouginot et al. (2019), glacial melt in Greenland has raised global sea level by 13.7 mm since the early 1970s, half of which has taken place between 2010 and 2018. Besides causing the sea level rise that endangers coastal zones, ice loss influences ocean currents (Joughin et al., 2012), threatens animal habitats (e.g. Amstrup et al., 2010), destroys historical data on the environmental conditions of the Earth captured inside ice (e.g. Bintanja et al., 2013), and likely provokes new outbreaks of diseases (Wu et al., 2016).

Remote sensing methods are commonly used to observe large-scale changes in ice-sheet related studies providing high spatial and temporal resolution data. Space-borne laser ranging technology has been designed to enable the assessment of ice sheet mass balance changes and monitor the ice spatial-temporal behaviour. This technology was first used in 2003 within ICESat (*Ice, Cloud, and land Elevation Satellite*) mission, which provided laser measurements captured by GLAS *(Geoscience Laser Altimeter System*) instrument operating as a space-based lidar (Schutz et al., 2005). Following the success of the first mission that ended in 2009, its successor, ICESat-2, was launched in 2018 (Markus et al., 2017). The renewed mission retained the same general goals and focused on delivering the data of higher accuracy and reliability using the redesigned Advanced Topographic Laser Altimeter System (ATLAS) instrument. Beside satellite laser altimetry, the satellite gravimetry, especially GRACE (*Gravity Recovery and Climate Experiment*) mission, proved to be very efficient in detecting and quantifying the ice mass balance change (see, e.g. Chen et al., 2006; Velicogna and Wahr, 2006; Wouters et al., 2008; Loomis et al., 2019).

This study presents a review of the ICESat satellite laser altimetry mission and a summary of studies and their findings regarding the ice sheet change in Greenland. Furthermore, it gives an insight into ICESat-2, enlightening the possibilities and future perspectives of laser altimetry data applications.

2 SATELLITE LASER ALTIMETRY CONCEPTS

The basic principles of satellite laser altimetry originate from aerial laser scanning, which provides detailed information about the Earth's surface (Fras et al., 2007). It measures the travelling time of the light pulse to calculate range, angle and intensity. The calculated range is the slant range from the satellite position at the time of pulse emission to the target and back. The spatial position of the measured points in the reference coordinate system can be determined if the position and orientation of the satellite are known. This concept was implemented on space-borne satellites so ICESat can be considered as a satellite lidar system (Cohen, 1987; Fras et al., 2007; Wang et al., 2011).

2.1 Technology

ICESat marked a milestone in ice sheet observation in the field of laser altimetry using a single beam profiling laser altimeter called GLAS (Schutz et al., 2005). The main science objectives of ICESat mission were determination of the ice sheet mass balance and estimation of the present and future contributions of the ice sheets to global sea-level rise (Zwally et al., 2002). However, ICESat data demonstrated interdisciplinary applications providing global measurements of cloud heights and the vertical structure of clouds and aerosols; precise measurements of land topography and vegetation canopy heights; measurements of sea ice roughness and thickness, ocean surface elevations, as well as surface reflectivity. GLAS provided global, high-quality data using three lasers that operated alternately throughout the mission (Wang et al., 2011). However, due to a series of laser malfunctions, the mission terminated in 2009 (Wang et al., 2011).

ICESat-2 is built upon the heritage of the previous mission. Still, many improvements were integrated into the design to meet the science objectives and requirements, such as quantifying polar ice-sheet contributions to recent and current sea-level change, estimating sea-ice thickness (Neumann et al., 2019), and measuring vegetation canopy height for estimation of large-scale biomass change (Narine et al., 2019). The most notable improvement is increasing the number of laser beams from three that worked alternately to six, which work simultaneously, enabling necessary accuracy and precision for monitoring rapidly changing polar regions (Markus et al., 2017). The arrangement of the beams allows measurement of the surface slope in along- and across-track directions with a single pass (Neumann et al., 2019). Thereat, beam pair separation is set at approx. 3.3 km and beams within a pair at approx. 90 m (Smith et al., 2019). Smaller footprint size and higher pulse repetition frequency result in overlapping footprints which ensures better coverage and represents a significant enhancement compared to ICESat. Technical characteristics and differences between the two satellites are summarised in Table 1.

Table 1: Characteristics of ICESat and ICESat-2 (Zwally et al., 2002; Abshire et al., 2003; Markus et al., 2017; Neumann et al., 2019).

	ICESat	**ICESat-2**
Instrument	GLAS	ATLAS
Operational period	2003–2009	2018–present
Number of lasers	3	6
Laser wavelength	1064 nm, 532 nm	532 nm
Laser pulse width	6 ns	1.5 ns
Laser pulse energy	75 mJ, 35 mJ	0.2 to 1.2 mJ
Orbital altitude	600 km	500 km
Inclination	94°	92°
Coverage	up to 86° N and S	up to 88° N and S
Track repeat period	183-day	91-day
Pulse repetition rate	40 Hz	10 kHz
Footprint diameter	60 m	17 m
Sampling interval	172 m	0.7 m
Telescope diameter	1 m	0.8 m

Consequently, various designs of spacecraft and different methods of collecting elevation data are reflected in error budgets. Table 2 presents the single pulse error budget for ICESat elevation measurements as well as the estimated error budget for ICESat-2 measurements.

Table 2: Single-shot error budget for ICESat and ICESat-2 elevation measurements (Zwally et al., 2002; Abdalati et al., 2010; Markus et al., 2017; Ma et al., 2018; Neumann et al., 2019).

GLAS (ICESat)		ATLAS (ICESat-2)	
Range measurement precision	10 cm	Range measurement precision	7.5 cm
Precision orbit determination (POD)	5 cm	Precision orbit determination (POD)	2 cm
Pointing determination (PAD)	7.5 cm	Ocean loading	6 cm
Atmospheric delay	2 cm	Solid Earth pole tide	1.5 cm
Atmospheric forward scattering	2 cm	Ocean pole tide	0.2 cm
Other (tides, etc.)	1 cm	Total atmospheric correction	2.6 cm
Residual sum of squares (RSS)	13.8 cm		

2.2 ICESat data acquisition

NSIDC (National Snow and Ice Data Center) distributes 15 different data products from the GLAS instrument. The most significant one regarding the ice sheet monitoring is GLAH 12 level 2 altimetry data set in HDF5 (Hierarchical Data Format) format. It contains surface elevations for ice sheets of polar regions (Greenland and Antarctica) above the "TOPEX/Poseidon" ellipsoid after instrument corrections, atmospheric delays and tide corrections have been applied. Each elevation estimate has been flagged for quality, which can later be used for data filtering (Zwally et al., 2014). A significant number of ICESat observations were impacted by GLAS detector saturation due to stronger than expected received laser energy, resulting in deviated range measurements. Hence NSIDC recommends applying the provided saturation correction to the flagged measurements for the studies of high-albedo targets as it is not automatically applied to elevation data (for details, see Sun et al., 2017).

2.3 ICESat-2 data acquisition

Currently, there are ten different data sets available that can be used for a variety of applications. For ice sheet studying, the ATL06 level 3A data set is the most interesting one since it provides land-ice surface heights derived from ATL03 containing global geolocated photon data and can be omitted and expressed above the WGS84 ellipsoid in the ITRF2014 reference frame (Smith et al., 2019). Within the data file, each granule contains segments of each individual satellite track over a specific area on the Earth's surface for a specific RGT (Reference Ground Track) with associated data for all six laser beams. Standard surface elevations within the ATL06 product are, by default, corrected for tidal and atmospheric corrections except for the ocean tide and dynamic atmospheric correction. Ocean tide and dynamic atmospheric correction should be carefully applied because the locations of ice-sheet grounding lines are not always precisely known and also may change over time. The data also contain additional parameters that can help in the assessment of the quality of the elevation estimates, among which the most frequently used is quality summary (ibid.).

2.4 Related data

Ice sheet mass balance change influences the gravity field strongly, so the common validation of the ICESat data is performed by comparisons to the satellite gravity data. GRACE was specially designed to provide global gravimetric measurements with a spatial resolution of 400 km to 40,000 km every 30 days (Tapley et al., 2004). It consisted of two identical satellites in an almost circular, near-polar orbit at approximately 500 km altitude with an inclination of 89.5°. The satellites were separated by 220 ± 50 km along the path and were connected by a highly accurate K-band microwave ranging system whose purpose was to continuously determine the distance between two satellites with one micron precision. When moving around the Earth, they accelerate and slow down depending on the gravity field anomalies. These perturbations are observed as changes in the distance between the two satellites and can be used to determine the Earth's gravitational field and, consequently, the mass of ice on polar ice sheets (ibid.). In May 2018, a successor mission GRACE-FO was launched (Kornfeld et al., 2019). The primary goal of this mission is to continue the successful legacy of the previous mission built on the original GRACE design. However, it counts with several improvements based on learned lessons from GRACE mission. GRACE-FO is the first-ever inter-satellite interferometric mission since it contains a laser ranging interferometer, which was added as a technology demonstration to serve as a pathfinder for future gravity mapping missions.

Gravity field monitoring using GRACE data relies on the utilisation of standard along-track data and usage of the mascons (mass concentrations). The mascons used in this study represent discrete cells covering the entire surface of the Earth and, when observed as a whole, they form the gravitational field of the Earth. Each mascon represents a gravitational signal of a particular area and indicates an addition or reduction of water/snow/ice given in units height of water equivalent (Luthcke et al., 2013). Mascon solutions computed by GSFC (*Goddard Space Flight Center*) were derived from GRACE K-band range rate (KBRR) observations taking into account full Stokes noise covariance and are used to estimate global mass change. Firstly, mascon parameters are calculated as a set of (differential) potential coefficients representing a change in the gravitational potential. The estimated height of water equivalent can be equated from known surface mass density and represents a scale factor on the set of differential Stokes coefficients. Therefore, the result gives a surface mass change in centimetres of water equivalent (for details, see, e.g. Luthcke et al., 2013; Croteau et al., 2020). The estimation of the mascons is done with a temporal resolution of 30 days and spatial resolution of 1 arc degree in both latitude and longitude. One degree of longitude at 60° latitude (south of Greenland) equals 56 km, while at 80° latitude (north of Greenland) it is equal to 19 km. Due to the modest spatial resolution of the derived gravity products, which is essentially the same as the other GRACE solutions (~300 km), mascons show averaged values for a certain area.

3 AN OVERVIEW OF THE PREVIOUS RESEARCH OVER GREENLAND

Due to the vast size of ice sheets, inhospitable environment and harsh climate, complete monitoring of these ice-covered regions is possible only using airborne and satellite remote sensing technologies (Zwally and Schuman, 2002). The concepts of the satellite laser altimetry/ranging technology were designed in the 1980s, shortly after significant improvements were seen in Satellite Laser Ranging (SLR), Very-Long-Baseline-Interferometry (VLBI) and Global Navigation Satellite Systems (GNSS) (Cohen et al., 1987). At the same time, the ice-sheet mass balance on the Earth started to deviate from its natural variability (Mouginot et al., 2019). Observations show that the cryosphere has been in transition during the last few decades and that the strong and significant changes, which are the result of an integrated response to climate, have continued, and in many cases, accelerated (Mouginot et al., 2019).

3.1 Greenland ice sheet change

Greenland is the largest island globally, and almost 80 % of its area is covered by ice, while coastal regions are mostly ice-free (Statistics Greenland, 2008). It is characterised by an arctic climate with strong spatial and temporal variations. Therefore, significant climatic differences between coastal and inland areas are observed. These differences are caused by the cold and ice-filled water, temperature inversions, precipitation, the circulations of surface waters and ice transport. Also, there is a difference in climate between north and south as well as large imbalances between the east and west coasts, caused by a different pattern of sea currents (Nielsen, 2010). Most of Greenland's features are geographically dependent; for instance, central parts of Greenland are less sensitive to ice melt since temperatures in that part are never above freezing due to the higher elevation and high albedo effect of the snow surface. Therefore, the response of different regions on the island to climate changes depends on their location. Satellite missions served as a great source of information regarding Greenland's ice sheet change, and since its launch, a number of research studies were published on the ice loss on Greenland. Table 3 presents some of the most significant studies conducted using ICESat data with or without GRACE satellite gravimetric data and their most important findings.

Table 3: Ice-sheet related studies based on ICESat data and their findings on Greenland.

Study	Period considered	Additional data used	Important findings
Slobbe et al., 2008	2003–2007	-	Positive elevation change rate of 0.02 m yr^{-1} is detected for the regions above 2000 m; for the other areas, the estimated rate is –0.24 m yr^{-1}.
Slobbe et al., 2009	2003–2007	GRACE	Estimation of the elevation change rate from ICESat equals –0.09±0.04* m yr^{-1} and from GRACE ranges between –0.08* and –0.14* m yr^{-1}.
Sandberg Sørensen et al., 2011	2003–2008	-	Using three different methods, annual elevation change estimates ranging from –0.11±0.01* m yr^{-1} to –0.14±0.02* m yr^{-1} are obtained. Thinning is recorded along the margin of the ice sheet, while interior parts indicate a slight elevation increase.
Ewert et al., 2012	2003–2008	GRACE	ICESat shows a rate of a mean surface elevation change of –0.12±0.006 m yr^{-1}, but the most significant changes could be identified at coastal areas, with rates of more than –2 m yr^{-1}. GRACE shows an overall elevation change of –0.12±0.01* m yr^{-1}.
Sasgen et al., 2012	2003–2009	GRACE	Both ICESat and GRACE indicate an elevation change for all the basins in Greenland of –0.16±0.01* m yr^{-1}.
Forsberg et al., 2013	2002–2012	Radar altimetry (CryoSat), GRACE	GRACE, ICESat and CryoSat show consistent estimates of elevation change with average values around –0.14* m yr^{-1}. Also, variations from year to year are large, but 2012 proved to be another record melt year in Greenland.
Bolch et al., 2013	2003–2008	-	The results indicate a mean surface lowering of around –0.45 m yr^{-1}; the most significant values are recorded in the south with –0.90 m yr^{-1} and the smallest in the north with –0.18 m yr^{-1}.

Study	Period considered	Additional data used	Important findings
Sørensen et al., 2015	2002–2010	Radar altimetry (Envisat)	Envisat shows an average elevation change between –1 m yr^{-1} and 1 m yr^{-1}. The parts that experience the most significant thinning are located near great outlet glaciers. However, in some parts of the island, laser and radar altimetry results are in contradict.
Zou and Jin, 2018	2003–2008	-	The elevation change varies from about –2 m yr^{-1} up to 1.5 m yr^{-1}. The elevation change rate is around zero in the northern parts of the island, while in most of the inland, the values are slightly positive with about 0.02 m yr^{-1}. Height decrease is visible in the western and southeastern areas where the elevation change rate reaches a value of –2 m yr^{-1}.
Smith et al., 2020	2003–2019	ICESat-2	The largest thinning is observed in Jakobshavn and Kangerdlungssuaq glaciers ranging from 4 to 6 m yr^{-1}, while the largest thickening of less than 0.15 m yr^{-1} is detected inland.

*Rates recomputed from gigatons to meters of ice thickness.

3.1.1 Regional studies over Greenland – Jakobshavn glacier example

Although the ice sheet change is rather a large-scale phenomenon, it is often studied for the local, smaller area. Many studies have thus reported on the Jakobshavn glacier change. The Jakobshavn glacier is a large, fast-moving outlet glacier that currently flows approx. 1250 m yr^{-1} (Lemos et al., 2018). It is located on the west coast of Greenland, where it ends at a floating, calving front extending from 10 to 14 km beyond the grounding zone that drains about 6.5 % of the area of the Greenland ice sheet (Echelmeyer et al., 1991). Its surface is very steep (0.01–0.03) and thick (2600 km) with relatively high driving stresses (200–300 kPa). This area has been the single largest source of Greenland's mass loss over the past two decades. In this period, it exhibited a persistent pattern of frontal retreat, flow acceleration and thinning (Moon et al., 2012). During 1986–2016 Jakobshavn retreated by more than 15 km. It retreated slightly during 1986–1997 with a rate of 66.13 m yr^{-1}. The fastest retreat happened between 1998 and 2016, with a much faster rate of 1337.6 m yr^{-1} (Wang et al., 2018). From 2003 to 2016, the surface of the lower parts of the glacier dropped by approx. 160 m and only between 2000 and 2010, the Jakobshavn contributed the equivalent of nearly a millimetre to global sea-level rise. However, since 2014, thinning has slowed down, and the glacier significantly thickened between 2016 and 2018 (Khazendar et al., 2019). Between 2016 and 2017, it thickened by 20 to 30 m, and the measurements from 2018 confirm that its thickening continued at a similar rate. Scientists explain that the ocean temperatures have cooled by nearly 2°C in the vicinity of the glacier over the last several years (Gladish et al., 2015a; Gladish et al., 2015b). As a result, colder water is not melting the ice from the front and underneath the glacier as quickly as the warmer water did before. Despite the slowdown retreat and thickening, glacier flow still exceeds the velocities of the early 1990s when the mass balance of Jakobshavn was nearly in equilibrium and continues to contribute to Greenland's net ice mass loss (ibid.).

4 GREENLAND CASE STUDY – ICESAT RECOMPUTED OVER GREENLAND

This study encompasses the recomputation of the ICESat data over Greenland, which illustrates laser altimetry data use and related methodology. Here we describe the data processing methods and obtained results which were afterwards compared against satellite gravity data. In addition to that, we compared ICESat and ICESat-2 data as a part of a regional study on the Jakobshavn glacier since it has been the focal point of many researchers for its significance in Greenland's discharge and dynamic changes observed over the years.

As previously said, before any analysis, it was crucial to exclude outliers and insufficient quality data. Preprocessing of ICESat data was done using the parameters obtained empirically by an iterative procedure conducted in order to remove the data points affected by scattering or saturation. Table 4 presents data filtering parameters used in this study. In total, 14 % of the measurements were excluded by omitting the data from L1, L2E and L2F campaigns, and 35 % were eliminated by the data filtering (see Table 5).

Table 4: Data filtering parameters.

Parameter	Description	Value
d_IceSVar	The standard deviation of the difference between the functional fit and the received echo using standard parameters	≤ 0.035 Volts
i_gval_rcv	The gain value used for a received pulse – uncalibrated	≤ 200
d_reflctUC	Reflectivity, not corrected for atmospheric effects	< 1
i_numPk	The number of peaks in the return echo found by the Gaussian fitting procedure, using standard parameters	= 1
elv_cloud_flg	Cloud contamination	= 0

Table 5: Number of measured elevations after applying each filtering criteria.

	Amount of input measurements	Percentage of remained dana
All data	10,126,258	100 %
After excluding L1, L2E, and L2F data	8,721,852	86 %
After filtering	5,653,389	51 %

Since the individual ICESat tracks are not precisely repeated and can be up to several hundred metres apart, a strict analysis of repeated measurements on the same locations could not be performed (Sandberg Sørensen et al., 2011). Instead, elevation variation was computed with respect to the digital elevation model (DEM), which integrates SRTM (*Shuttle Radar Topography Mission*) and GTOPO30 (*Global 30 Arc-Second Elevation*) along with the DEM data derived from aerial photogrammetry and GNSS measurements (Zwally et al., 2014). SRTM provides data with a 1 arc second resolution (about 30 m) and GTOPO30 with 30 arc second resolution (about 1 km). Filtered and processed data were divided into month-solutions for the ICESat operational periods. The month-solutions were afterwards gridded into grids with 30" × 30" resolution using the Inverse Distance to a Power Interpolation method. That resulted in several grids representing Greenland elevation change during the considered period. Due to the data outage during some periods of the year, for each operational year, elevation representations were computed for February, March, April, May, June, September, October, November and December. After that, combined models were computed based on spotted seasonal effects on Greenland driven by temperature changes (see, e.g. Zwally and Jun, 2002). As a result, three combined models were computed per year. The first one refers to the period between February and April, the second to May and June, and the third one to the winter months between September and December. Also, Greenland DEM was calculated using the same resolution (30" × 30") and interpolation method (Inverse Distance to a Power) and was compared to the available DEM by subtracting the latter values from the values obtained with ICESat.

In order to enable direct comparison of ICESat and GRACE data, grids containing ICESat data were extracted to match the mascon locations. Afterwards, the mean surface elevation change was calculated for these specific parts. Since ICESat provides elevation measurements expressed in meters and GRACE shows the mass balance (change in mass per unit time) expressed in the change of height of water equivalent, the recomputations have to be done. Various approaches can be used to convert the estimated elevation change with ICESat to the mass change. The main problem is the fact that information about the density of snow/ice is needed, but the density of newly fallen snow is about three times smaller than the density of ice (Slobbe et al., 2009). According to Thomas et al. (2006), different densities can be used depending on the average elevation. For the region with an elevation below 2000 m, they used a density of 900 ± 300 kg m^{-3} since the mass is primary lost by ice discharge and melting. On the other side, for the region with elevations above 2000 m, a density of 600 ± 300 kg m^{-3} was used because elevation changes are mainly caused by snowfall. Their approach was confirmed by observations indicating that the volume variations in regions with elevations below 2000 m are caused by fluctuations in flow velocity, which consequently provoke variations in the amount of ice (Howat et al., 2007). We adopted this approach for recomputations from elevation change derived from ICESat to mass change to compare the results.

For the study concerning the Jakobshavn glacier, we used ICESat-2 data, which was afterwards compared to ICESat data. The first step is filtering using the ATL06_quality_summary parameter, which identifies potential problems for each segment. ICESat-2 data processing was done using the same interpolation method as in the case of ICESat data but with 1" × 1" resolution, which is equal to 11.06 m × 11.06 m at the latitude of 69° (Jakobshavn area). Produced DEM was used to inspect the changes that happened on the glacier between the two ICESats and enable direct comparison of elevations. To allow that, we derived another DEM of the Jakobshavn glacier from ICESat data. Additionally, ICESat data were recomputed from TOPEX/Poseidon to WGS84 ellipsoid, which was used as the reference for ICESat-2 measurements (for details, see, e.g. Bhang et al., 2007; Xie et al., 2019).

4.1 Results

We have estimated elevation changes on Greenland using satellite laser altimetry data from ICESat mission. Figure 1 shows elevation change derived from ICESat during 2004–2008 for the three defined periods of the year.

Greenland's ice sheet experiences the most significant negative elevation change during summer months, especially in the southern coastal regions (Fig. 1, B). This is expected because the south is characterised by milder climate conditions and more significant temperature changes compared to northern areas. On the other hand, during colder months, ice loss is less notable but still significant in some parts of the island (Figure 1, A, C). Inland areas show certain stability and do not indicate more significant ice loss as much as margins of the ice sheet do.

Obtained results were compared against satellite gravimetry data derived from the GRACE mission. The first selection of mascons for this analysis is based on the division of Greenland into seven weather- and climate regions. Cappelen et al. (2001), as cited in Nielsen (2010), divided the island into the following climate regions: North (N), Northeast (NE), Northwest (NW), Southeast (SE), Southwest (SW), South (S) and Ice cap. Additionally, we divided the Ice cap region into the Center/North (C/N) and Center/

South (C/S) region. Moreover, in the second case, we divided Greenland into two regions, above and below 2000 m. Figure 2 presents selected mascon locations on Greenland for the analysis based on two previous divisions.

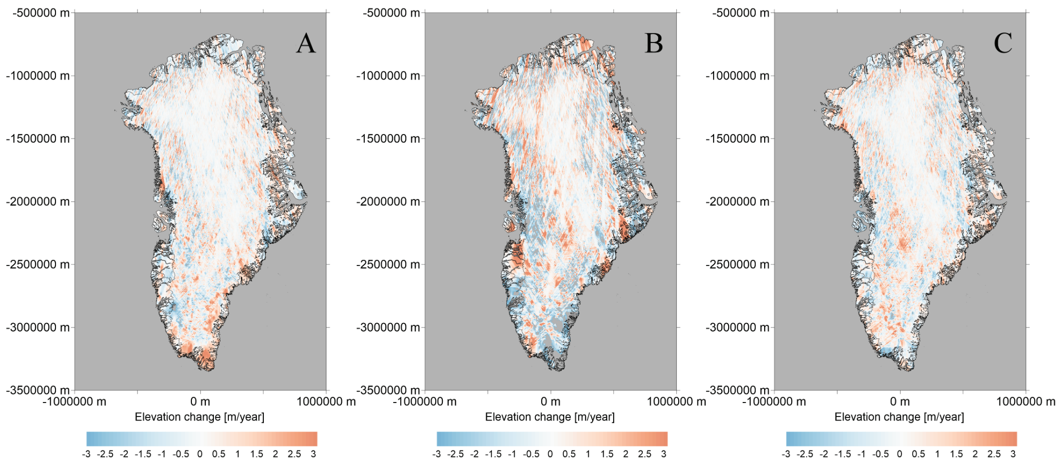

Figure 1: Average annual change in elevation for February, March and April (A); May and June (B); September, October, November and December (C) over the period 2004–2008 derived from ICESat data.

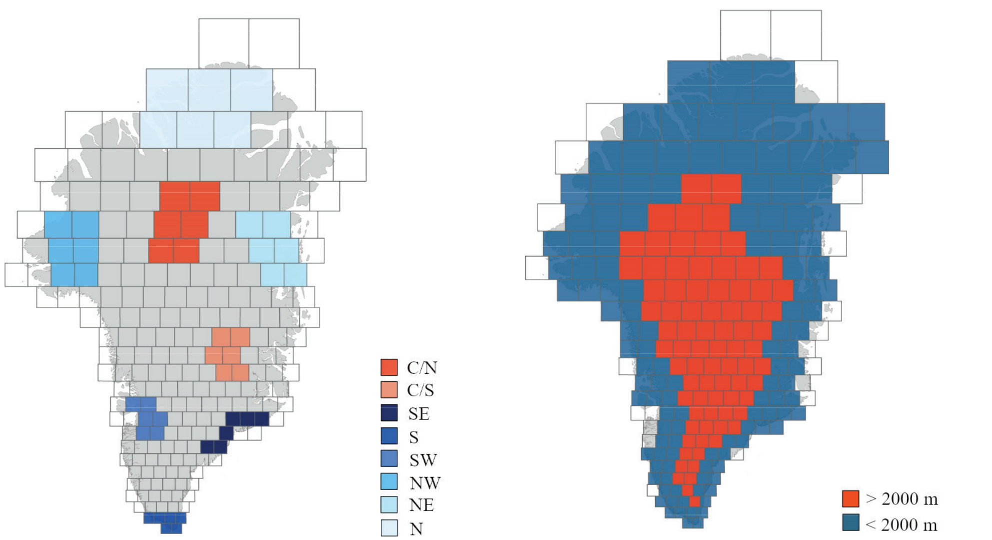

Figure 2: Selected areas for mascon analysis in different climate regions (left); Selected areas for mascon analysis in regions with elevations above and below 2000 m (right).

Table 6 presents the mean surface annual mass balance computed from ICESat and GRACE observations. ICESat recorded the most significant value of negative annual mass balance in the south of –0.34 m yr^{-1} w.e. (e.g., water equivalent) in 2004–2008, while inland parts show positive mass balance values reaching up to 0.36 m yr^{-1} w.e (Figure 2, left). In the same period, GRACE observations show that southern parts indicate negative values of annual mass balance where the greatest value is recorded in the southeast of –0.36 m yr^{-1} w.e. Still, both ICESat and GRACE show that coastal regions record negative mass balance, while inland parts indicate positive mass balance values. All of the above leads to a conclusion that inland and coastal areas have different patterns of behaviour regarding snow and ice accumulation.

Table 6: Comparison of results obtained by ICESat and GRACE for the selected mascons based on the spatial and climatic variability in the period 2004–2008.

Location	Mean surface annual elevation change (m) ICESat	Mean surface annual mass balance* (m yr^{-1} w.e.) ICESat	Surface annual mass balance (m yr^{-1} w.e.) GRACE	Surface mass change (Gt yr^{-1}) GRACE
Center – north (C/N)	2.40	0.36±0.18	0.06	0.73
Center – south (C/S)	1.59	0.24±0.12	0.03	0.34
Southwest (SW)	–1.41	–0.32±0.11	–0.24	–4.84
South (S)	–1.51	–0.34±0.11	–0.25	–3.14
Southeast (SE)	–0.16	–0.04±0.01	–0.36	–3.02
Northeast (NE)	–0.74	–0.17±0.06	–0.04	–2.11
Northwest (NW)	1.17	0.26±0.09	–0.17	–0.45
North (N)	–0.53	–0.12±0.04	–0.04	–0.42

* Mean surface annual mass balance computed from mean surface elevation change for period 2004–2008.

Table 7 shows the results obtained using ICESat and GRACE observations for the regions below and above 2000 m. ICESat records a negative annual mass balance in the regions below 2000 m of –0.15 m yr^{-1} w.e. while at the same time GRACE notes a mass balance of –0.17 m yr^{-1} w.e. (Figure 2, right). On the other hand, in the regions above 2000 m, ICESat shows a positive annual mass balance of 0.35 m yr^{-1} w.e and GRACE of 0.01 m yr^{-1} w.e.

Table 7: Comparison of results obtained by ICESat and GRACE for the selected mascons in regions above and below 2000 m in the period 2004–2008.

Location	Mean surface elevation change (m) ICESat	Mean surface annual mass balance* (m yr^{-1} w.e.) ICESat	Surface annual mass balance (m yr^{-1} w.e.) GRACE	Surface mass change (Gt yr^{-1}) GRACE
> 2000 m	2.35	0.35±0.18	0.01	9.41
< 2000 m	–0.67	–0.15±0.05	–0.17	–266.30

* Mean annual surface mass balance computed from mean surface elevation change 2004–2008.

Since the GRACE mission was active until 2017, we analysed the changes that happened on Greenland's ice sheet between 2009 and 2017 in the regions below and above 2000 m (Figure 3).

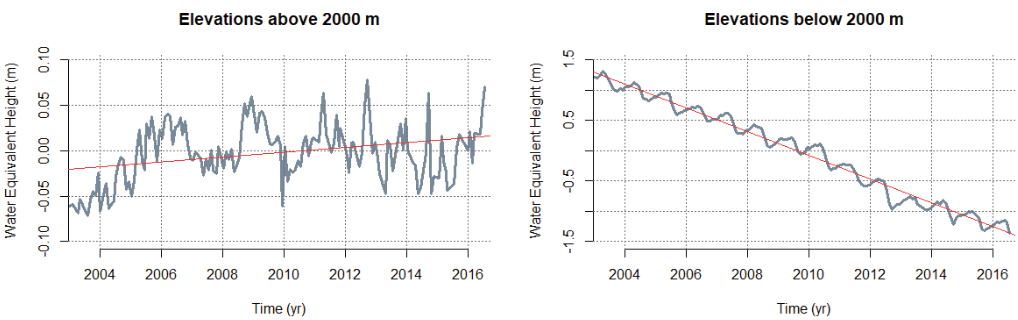

Figure 3: Cumulative mass balance in the basin with elevations above 2000 m derived from GRACE data during 2003–2017 (left); mass balance in the basin with elevations below 2000 m (right).

As we said before, in the period between 2004–2008, GRACE shows that areas above 2000 m register a slightly positive annual mass balance of 0.01 m yr^{-1} w.e. Looking only at the GRACE data from 2009 to 2017, it can be seen that annual mass balance is less than 1 cm yr^{-1} w.e. Taking into consideration all available data for the region above 2000 m, the annual trend of mass balance is still below 1 cm yr^{-1} w.e (Figure 3, left). This area shows a certain balance between accumulation and ablation. On the other hand, for the period between 2004 and 2008, GRACE recorded negative mass balance values of –0.17 m yr^{-1} w.e. while between 2009 and 2017, this value was –0.21 m yr^{-1} w.e, which means that mass loss accelerated in this period of time (Figure 3, right).

4.1.1 Jakobshavn glacier change

The recently launched mission, ICESat-2, promises some breakthroughs in comparison to ICESat due to a number of technical improvements incorporated in its design. Figure 4 presents four elevation profiles on four locations on the Jakobshavn glacier derived from ICESat and ICESat-2 data to compare the two missions and elucidat the topographic changes that happened in the area.

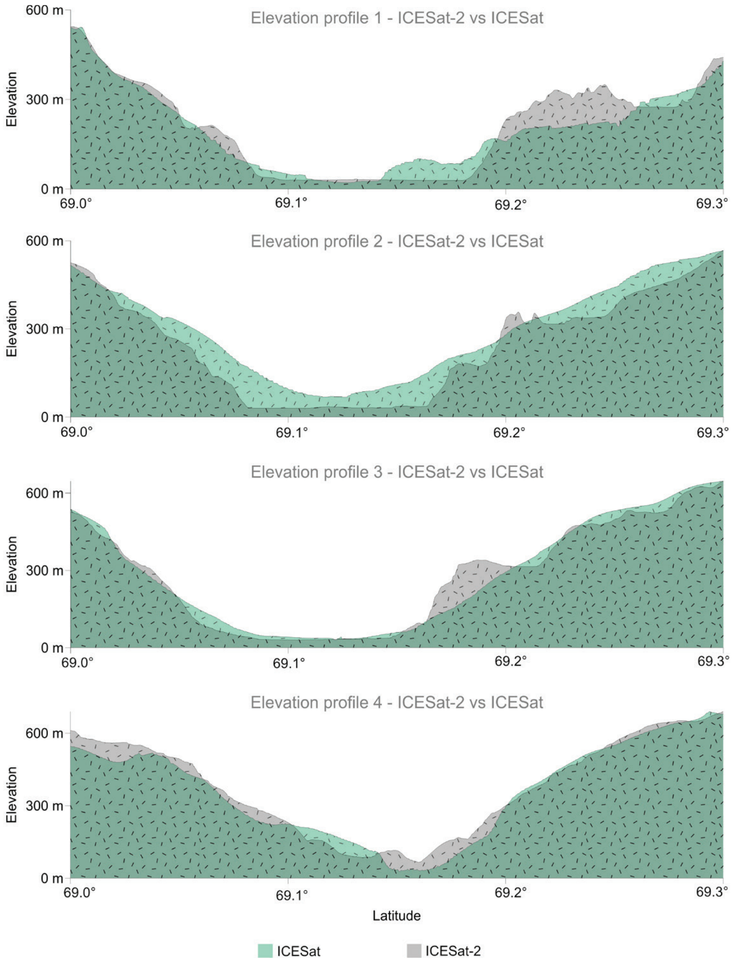

Figure 4: Elevation profiles along the Jakobshavn glacier derived from ICESat (2008) and ICESat-2 data (2018).

Elevation profiles show that in ten years (2008–2018), the topography of glacier has been significantly modified. The glacier has been in constant downward movement under its own weight, and the participation patterns changed due to changes in the temperature of the surrounding waters. ICESat-2 shows that some parts of Jakobshavn gained mass (cross-sections 3 and 4) which is in line with the latest research showing that the glacier thickened in the last few years (e.g. Lemos et al., 2018). On the other hand, cross-sections 1 and 2, which are located closer to the sea, indicate mass loss probably due to the ice calving and glacier's overall retreat.

5 DISCUSSION AND CONCLUSION

Greenland ice sheet has been the focus of many scientists because of its potential contribution to global sea-level rise, and in the last few decades, it experienced substantial changes (results summarised in Table 3). ICESat data (2004–2008) revealed that thinning is observed along the margin of the ice sheet, mainly in the western and southeastern parts, reaching the values of –2 m yr^{-1} (e.g. Ewert at al., 2012; Zou and Jin, 2018). However, inland regions above 2000 m record a positive elevation change rate of a few cm yr^{-1} (Slobbe et al., 2008). According to Bolch et al. (2013), the mean surface lowering is around –0.45 m yr^{-1}. The results we obtained using ICESat showed that the region that records the biggest negative annual mean surface elevation change is south of the island with –0.38 m yr^{-1}. Since strong spatial and temporal variations characterise Greenland, elevation change rates vary depending on the location on the island. The thinning is most evident along the coastline, especially during summer months, which decreases inland at elevations above 2000 m.

The results of GRACE analysis for the period 2004–2008 show that the overall annual elevation change rate ranges from –0.08 to –0.16 m yr^{-1} (e.g. Slobbe et al., 2009; Ewert et al., 2012; Sasgen et al., 2012). Our analysis confirms that coastal areas experience melting with surface annual mass balance values from a few cm to –36 cm yr^{-1} w.e., while the highest parts of the island indicate a balance between mass accumulation and ablation with slightly positive values reaching up to 0.06 m yr^{-1} w.e. Comparing the results from ICESat (–0.15 m yr^{-1} w.e.) and GRACE (–0.17 m yr^{-1} w.e) for the regions below 2000 m, we obtained similar values from the two missions. Looking at more recent GRACE data (2009–2017), it is visible that in coastal areas, the negative trend of annual mass balance reduction is continuing, while inland is still stable.

The greatest mass loss is observed in coastal regions, particularly in the vicinity of glaciers. A recent study of comparison between ICESat and ICESat-2 data shows that in the period 2003–2019, the largest thinning is observed in the Jakobshavn glacier with values from 4 to 6 m yr^{-1} (Smith et al., 2020). However, taking into account only the last few years, studies show that from 2016 to 2018, Jakobshavn significantly thickened (Khazendar et al., 2019) due to the cooling of surrounding waters (Gladish et al., 2015a; Gladish et al., 2015b). We confirmed this fact for the upper part of the glacier. Nevertheless, calving and retreat are still visible in the parts closer to the sea, and even though thinning has slowed down, the Jakobshavn glacier continues to contribute to Greenland's discharge significantly.

To conclude, in a constantly changing world, there is a need for continuous monitoring, peculiarly of polar regions. Satellite data have provided the ability to observe large-scale decadal changes in the cryosphere at a high temporal and spatial resolution as well as to determine the contribution of glaciers and ice sheet to global sea-level rise. In addition, they have been demonstrated as a very useful tool for examining and understanding these changes. However, a longer record of measurements will increase the confidence in the results, reduce uncertainties in the long-term trends, and bring more insights into the geophysical and other processes controlling the changes, which is exactly what ICESat-2 and GRACE-FO aim to do.

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