Surface elevation changes of the Patagonian Icefields: Insights from an ICESat(-2) crossover analysis

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Abstract

The Patagonian Icefields, located in southernmost South America, are the biggest extrapolar concentration of ice in the southern hemisphere. As such, they are of strategic and environmental importance, which will increase even more as freshwater reserves become scarcer around the world. This encourages a detailed study of the conditions and temporal evolution of the icefields, determining with high precision the area, volume and mass changes of the glaciers that compose the icefields. However, glaciological in-situ measurements are unable to provide results representative for the entire region, because of the difficult access to the icefields, harsh physical conditions, and the large spatio-temporal variability among the Patagonian glaciers. While all regional scale studies of the Patagonian Icefields find a significant mass loss, different methods arrive at different rates. This calls for the inclusion of additional, independent observation techniques, and laser satellite altimetry is a prime candidate for it. Satellite altimetry, traditionally employed for sea-level monitoring, determines accurate surface elevations along the ground track of the satellite's repeat-orbit. Therefore, most altimetry missions do not provide a continuous areal coverage, impeding the separation between spatial and temporal elevation changes. Crossover analysis isolates temporal variations in the intersections of tracks observed at different epochs. In this work, ICESat and ICESat-2 data is used, and a crossover analysis is performed, in order to determine seasonal and long-term elevation changes of the ice surface of the Patagonian Icefields. The results are presented and discussed, along with an explanation of the applied methods.

1. Introduction

Glaciers and ice bodies exist in a fragile equilibrium, where temperature variations of tenths of a degree can be the difference between growing or disappearing. As such, they are referenced as one of the most important proxies for climate change studies, both providing insight on paleoclimatic conditions and serving as an indicator of temperature changes over the last century of detailed glaciological records (Zemp et al, 2015). In spite of this, the relation between climate and ice-mass balance is complex, as glaciers are sensitive not only to temperature, but also precipitation with moisture transport intricately dependent on a variety of climate variables and atmospheric circulation (Sauter 2020; Carrasco-Escaff et al. 2023). In addition to this, while glacier mass balance “… is a direct and undelayed response to the annual changes in atmospheric conditions” (Ruiz et al. 2022), the observability of these changes can be limited by the methodology, the observer, and its associated reaction time (Cogley et al. 2011). Moreover, some observable quantities, while seemingly a direct effect of glacier mass balance, can be controlled by other causes. For instance, local changes in ice-surface elevation may be indicative of changes in ice-flow dynamics in addition to ice-mass changes. As a matter of fact, the ice-mass flux, and thus observable area and surface elevation changes, of many glaciers draining the Patagonian Icefields are governed by their calving regime (Minowa et al. 2021).

For these reasons, on-site measurements of glaciers provide, arguably, the most reliable results on the conditions and temporal evolution of many physical parameters, such as flow velocity, rate of ablation and accumulation along the glaciers, density and ice thickness, with some that can hardly be measured any other way. However, the logistical limitations inherent to them make it impossible to get complete coverage of icefields on a regional scale. The Patagonian Icefields in particular are located in the Southern Andes mountains, a very sparsely populated region with the biggest settlements being thousands of meters below the highest altitude in the icefields. To complement this, the rough geography and harsh meteorological conditions make even reaching most of the Patagonian Icefields a challenge. Therefore, most regional scale ice-mass balance estimates include data from either aerial surveys or satellite observations, which allow for a greater coverage of the area of interest at the cost of a lower precision and spatio-temporal resolution.

Different studies based on distinct remote sensing techniques implemented over the Patagonian Icefields find varying estimates on surface elevation changes and mass loss. Gravimetric mass balance estimates based on GRACE (Follow-On) satellite gravimetry and DEM (digital elevation model) differencing using Cryosat-2 swath altimetry tend to indicate more intense ice-mass loss over the Patagonian icefields than DEM differencing based on InSAR (synthetic aperture radar interferometry) and optical imagery (e.g. Table 1 in Richter et al. 2019).

Deviations may be anticipated based on the difference in physical quantity observed by each technique, with gravimetry being sensible to mass changes and DEM differencing considering only elevation changes, calling for additional information or assumptions regarding ice and snow density in order to be comparable. Furthermore, the inherent properties of each signal considered (gravity measurements or electromagnetic wave reflections) impact each method’s resolution and penetration, while among one technique the derived rates differ according to the analyzed time span and the applied processing methods. The need for a better understanding of these systematic differences

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between techniques and a more consistent quantification of the ongoing contribution of the Patagonian icefields to sea-level rise motivates the introduction of an independent observational method in order to help select the most reliable results, with satellite laser altimetry being a prime candidate.

2. Methods

The principle of satellite altimetry consists of a precisely geolocated satellite which sends electromagnetic pulses towards the Earth’s surface, then captures their reflection. The time it takes for those reflections to travel towards the surface and back to the satellite is proportional to the distance between the two, so measuring the time is equivalent to measuring the distance, and by incorporating a reference system, ellipsoidal surface elevations can be determined. The electromagnetic pulses allow for a very precise measurement of said elevations, but are limited by two main physical traits. First, the altimeters work in nadir direction, and surface elevation profiles are available only along the sparsely spaced groundtracks of the satellite. Second, every pulse or shot provides information of the area or footprint where it is reflected in the Earth’s surface, the dimensions of which depend on the wavelength of the pulse utilized.

The limitations described present challenges for the application of satellite altimetry on the Patagonian Icefields. The footprint of traditional radar altimeters is over two kilometers wide, which in the region of interest is too big to accurately represent the topography. However, the laser satellite altimetry missions utilized, ICESat and ICESat-2, have a much smaller footprint (60 m and 13 m, respectively), which makes it possible to study such rugged terrain. Another important advantage of laser altimetry over radar techniques is that the laser signals do not penetrate into ice or snow. On the other hand, altimetry data not having a continuous areal coverage makes comparing observations from different epochs harder, as they correspond to different ground tracks that can be kilometers apart. The points of intersection or crossovers between the different ground tracks were calculated and selected, guaranteeing the observations at those points are comparable, and the difference between them is due to temporal and not spatial changes. This method takes advantage of ICESat-2’s migrating ground tracks, generating an unprecedented number of high precision crossovers.

ICESat-2’s data set ATL06, distributed by NSIDC, provides geolocated land ice surface elevations with centimeter-scale precision and several-meter horizontal positioning accuracy (Brunt et al., 2021) along 40 m segments of ground track, spaced 20 m apart. ICESat’s data set GLAH06, on the other hand, provides shots spaced 180 m apart. This data was downloaded and filtered through, keeping only the high-quality shots inside carefully mapped polygons representing the Patagonian Icefields. This resulted in over 5 million usable ICESat-2 shots, and over 2 thousand ICESat shots. This discrepancy, visualized in Fig. 1, is a consequence of the high quality of ICESat-2’s data, the higher shot frequency, the longer and continuous operation period and the fact that six ground tracks are produced in every orbit, compared to ICESat’s one. While ICESat-2 remains in continuous operation since 2018, ICESat was operational intermittently from 2003 to 2010, with an average of 3 33-day acquisition periods per year.

Ground track crossovers were calculated utilizing the x2sys package from PyGMT (Wessel, 2010), taking into consideration the specifics of each data set. While looking for crossovers between ICESat-2 ground tracks, every ground track was considered continuous and its data usable if the two shots adjacent to the crossover point were less than 50 meters apart.

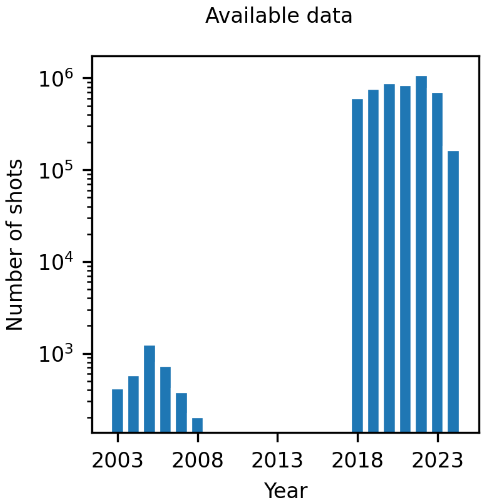

Figure 1. Time distribution of ICESat and ICESat-2 shots.

For crossovers between ICESat and ICESat-2 data, a 200 m spacing was considered continuous for ICESat due to its lower shot frequency. If a crossover was found and both ground tracks satisfied the continuity condition, it was added to a database along with the elevation registered along each ground track, linearly interpolated to the exact crossover location. This makes the crossover analysis more suitable for the elevation change determination in steep terrain than other altimetric methods (e.g. repeat-track analysis), because high-resolution altimetric information on surface slope is exploited along two directions. The residual contribution of topography to uncertainty is thus restricted to deviations from a linear slope, that is, the impact of surface curvature, within a 50 m interval (in the case of inter-mission crossovers, 200 m in the direction of the ICESat track). Over a sample size as large as the available crossovers, this residual topographic effect has an uncorrelated, random impact on integral estimates (e.g. mean surface elevation change), independent of the observation time interval. We estimate that this source of uncertainty contributes with a standard deviation below 1 m to the noise of the results presented in Figs. 2-8, but with a negligible impact on the derived mean values of elevation change or rate.

3. Results

The methodology previously described was implemented, resulting in over 10 thousand crossovers distributed along the Northern and Southern Patagonian Icefields (Fig. 2). This distribution already shows some characteristics of the region, including a rough image of the topography, while the western side of the Southern Patagonian Icefield having less data points is indicative of its constant thick cloud coverage, which laser pulses cannot penetrate.

The elevation differences measured in these crossovers, calculated as the “second minus first observation”, are indicative of ice-surface elevation changes of the icefields between both observations. Figure 3 shows ICESat-2 crossovers with up to a year between observations, and although the biggest scatter could be expected on opposite seasons with a decrease when getting closer to 365 days, we see this is not the case for ICESat-2 data in the region, indicating that surface elevation changes are influenced to a high degree by secular and random effects.

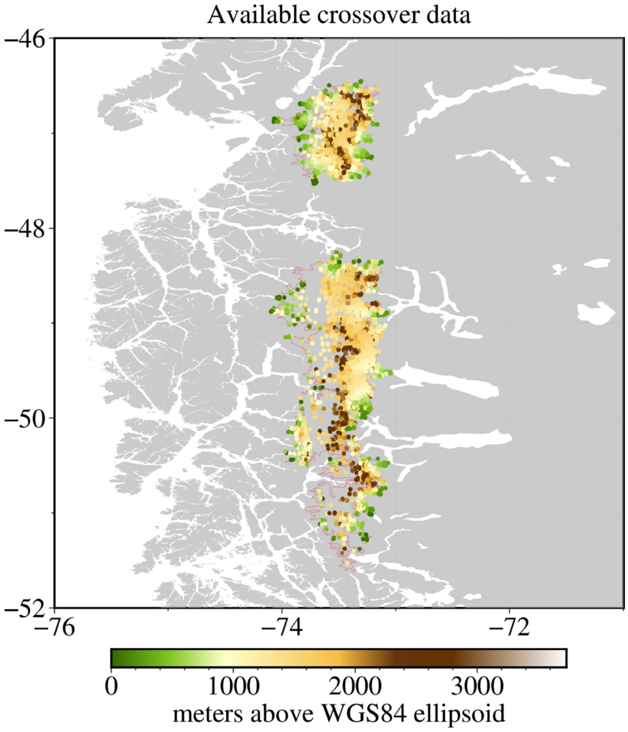

Figure 2. Location and mean elevation of ICESat-2 crossovers. Red polygons show the NPI and SPI contours.

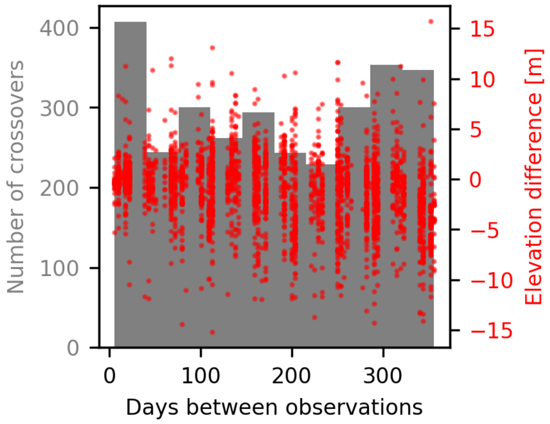

Figure 3. Number of crossovers with up to a year between observations. Red dots show the derived surface elevation difference.

The effect of secular variations can be noticed in the central value for each time period, trending towards negative values when reaching a year between observations. In order to confirm the previously stated hypothesis, a more detailed analysis of the seasonal distribution of crossovers was performed, presented in Figures 4 and 5.

The statistical estimators confirm the previous analysis, as the standard deviation of elevation differences between observations appears to increase with the time window. Crossovers with less than 45 days between observations have a 2.11 m standard deviation, for the ones between 155 and 205 days it is 3.87 m, and from 340 to 390 days it results in 4.01 m. These results can be interpreted as a combination of effects: the surface elevation of the glaciers’ accumulation zone can increase several meters after a single snowfall, while in the ablation zone it can drop by more than 10 m per year.

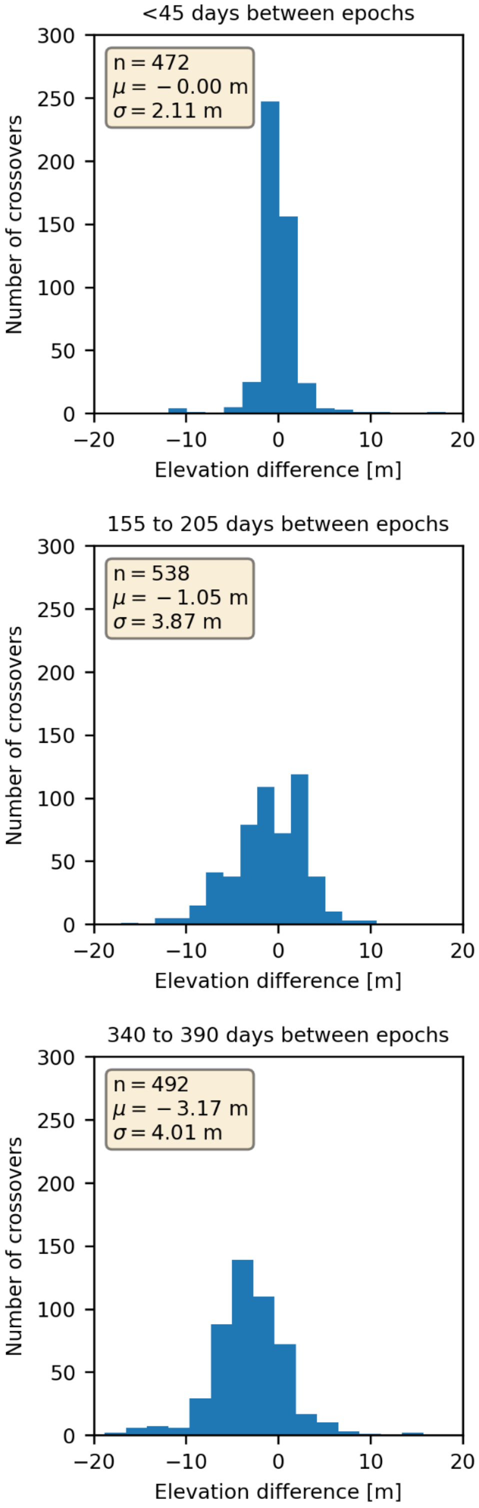

Figure 4. Histogram of ICESat-2 crossover elevation differences over NPI and SPI. The three diagrams correspond to crossovers within one season (top), between opposite seasons (center), and over one year (bottom).

Another important result is found when analyzing the mean elevation difference for different time spans. As expected, for intervals of less than 45 days, the mean value is around 0, indicating that the variations seen in the same season are equally likely to be positive or negative.

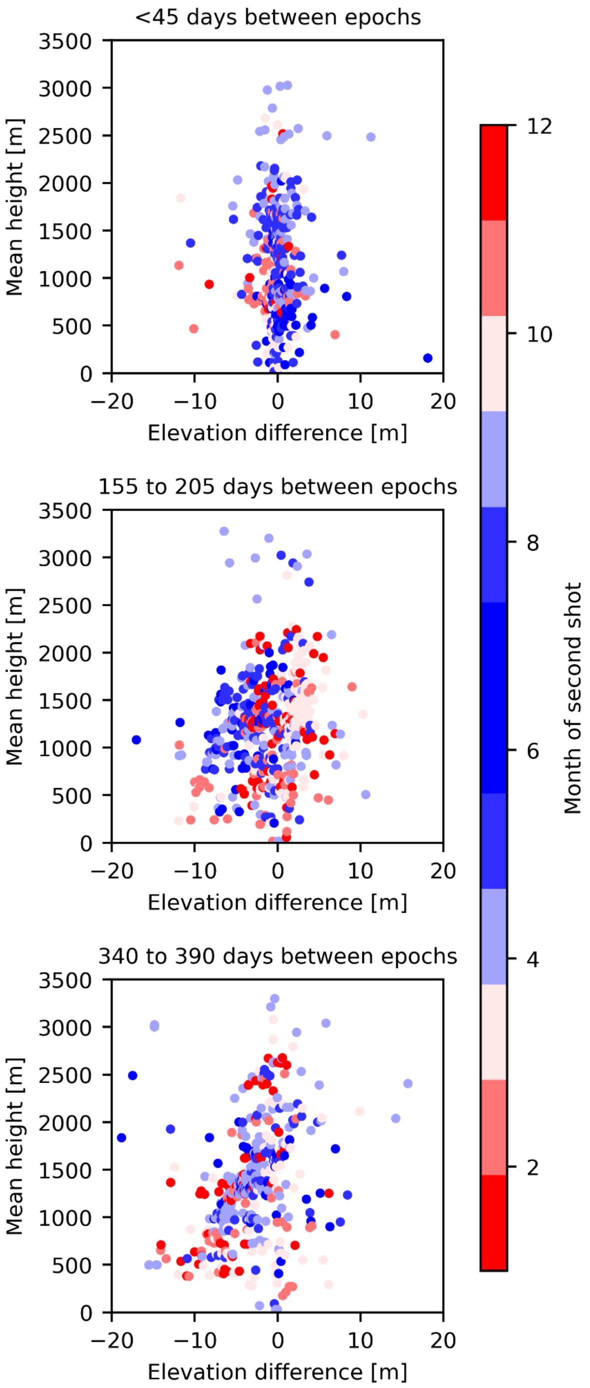

Figure 5. Elevation difference versus mean elevation for the same crossovers as in Fig. 4, colors indicate the seasonal distribution of the second observation.

For opposite seasons, a trend is already visible, with the mean elevation change being -1.05 m, and becoming clearer on the intervals around one year long, with a value of -3.17 m. This shows the influence of the previously observed secular variations, trending towards a reduction in the ice-surface elevation.

The altitudinal distribution of the differences (Fig. 5) shows the expected increase in variability from the top of the icefields (accumulation zone) downward. The differences over half a year (central panel) show an asymmetric seasonal distribution: red dots prevail in the positive difference range, while negative differences are dominated by blue shades. This is consistent with the expected seasonal surface elevation variation: during austral summer (red dots) the snow and ice accumulated during the previous winter has not yet melted away and is higher than after the melt season, resulting in positive differences. Likewise, when the second observation is made during winter, the accumulation period has not yet finished or is just starting, resulting in lower elevations.

These results give interesting insight on short term variations in the Patagonian Icefields, and although secular effects are also present in the data, the effect of short-term influences is significant. Extrapolating elevation surface change rates from them can propagate these effects into the estimations. Consequently, long term variations can be considered more important, as short-term influences are mitigated and results become more representative of climatic trends, along with being more comparable to results from other remote sensing techniques. For this goal, crossovers on a longer time basis were analyzed, starting with ICESat-2 ground tracks with 4 years between observations, as shown in Figure 6.

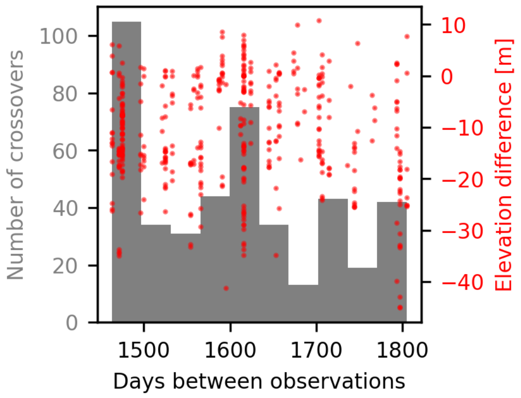

Figure 6. Number of crossovers with 4 years (1460 to 1825 days) between observations. Red dots show the derived surface elevation difference.

While high deviations from the mean are still present, the effect of secular variations following long term climatic trends become even more prevalent, with 85% of crossovers showing a negative ice-elevation change. The 443 crossovers yield a mean surface elevation change of -2.59±2.42 m/yr. Figure 7 shows the elevation surface change rate calculated from these crossovers, revealing the expected outcome: the subsidence rate increases from the top of the icefields downward. However, the highest values signal a faster decrease than previously found.

In order to get the longest time intervals possible, and calculate estimates comparable with previous works using ice-surface change rates since the year 2000, crossovers between ICESat and ICESat-2 ground tracks were produced, with the first being operational from 2003 to 2008, and the second one having been operational since 2018. Figure 8 shows the surface elevation change rates obtained by these crossovers, where all derived differences “second minus first observation” are negative. The 349 inter-mission crossovers yield a mean surface elevation change rate of -2.57±1.37 m/yr. The rates obtained coincide with both climatic trends and the rates found by previous works (e.g., Malz et al. 2018; Braun et al. 2019; Farias-Barahona 2021). Moreover, the mean surface elevation change rate is almost identical to the one determined through ICESat-2 4-year crossovers, signaling the detection of the same trend in both cases, while the significant decrease in standard deviation shows the effect of averaging short-term variations over longer time periods.

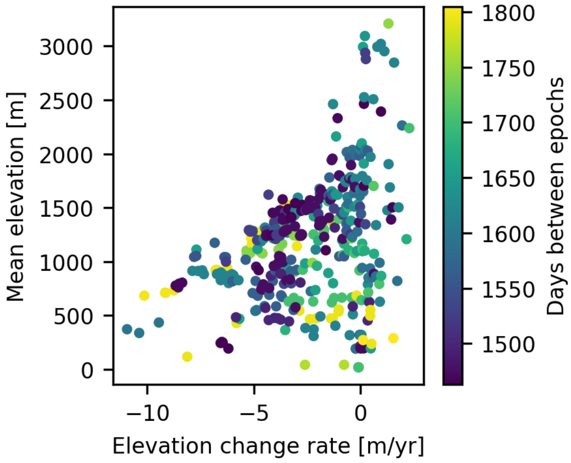

Figure 7. Elevation surface change rate from ICESat-2 4 year interval crossovers.

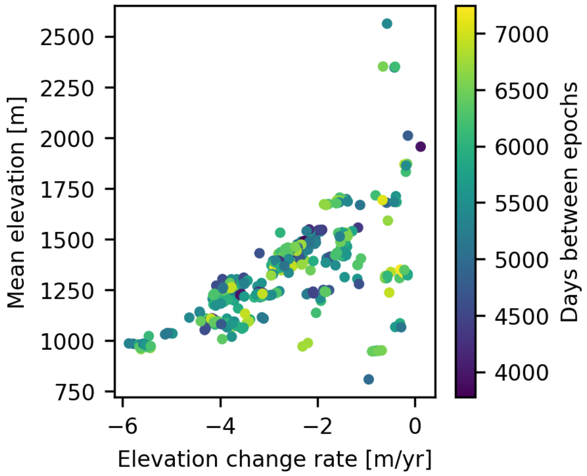

Figure 8. Elevation surface change rate from ICESat and ICESat-2 crossovers.

While these results confirm the quality of ICESat and ICESat-2 data and the crossover products obtained through the methodology described, it is crucial to keep in mind the limitations of this implementation. Using the definition of mass balance as “The change in the mass of a glacier, or part of the glacier, over a stated span of time” (Cogley et al., 2011), an issue with the implementation of crossover analysis towards the determination of said mass balance can be identified, apart from the previously mentioned restriction of the areal coverage not being complete enough to classify the entirety of the Patagonian Icefields. The main limitation that arises regards the “stated span of time” over which the glacier mass balance is defined. While Figures 3, 4 and 6 show a significant number of crossovers for certain time intervals, these do not all correspond to the same span of time. Figures 9 and 10 show the difference in data availability between all crossovers with 340 to 390 day intervals, and the ones that correspond to the span of time with the most crossovers (340 to 390 days from 2021-05-04).

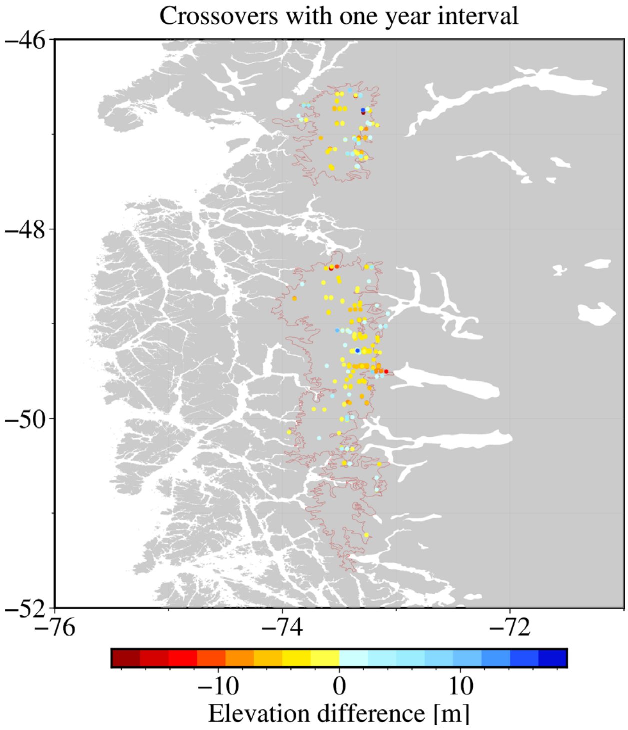

Figure 9. Spatial distribution and elevation difference of crossovers with one year between observations.

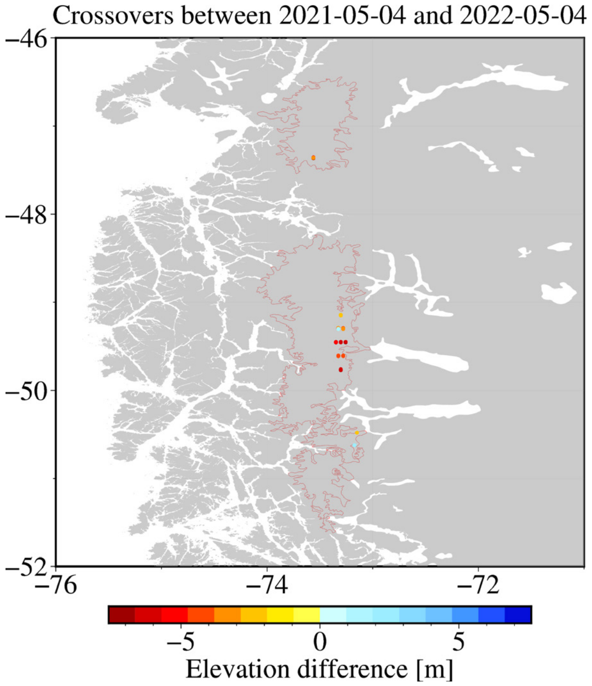

Figure 10. Spatial distribution and elevation difference of crossovers between 2021-05-04 and 2022-05-04.

Altough the 42 one-year-crossovers of this most frequently sampled time span might be sufficient for certain implementations; their spatial distribution is insufficient for deriving the mass balance of an entire glacier. This illustrates the potential of satellite laser altimetry crossovers for glacier mass balance determination, but also the need for complementary data.

4. Conclusion

The results obtained from applying a crossover analysis of ICESat and ICESat-2 data to the study of the Patagonian Icefields prove both the capabilities and limitations of the method. It is capable of reproducing long term trends with high accuracy but is limited in the areal coverage and number of data points provided. While crossovers between ICESat and ICESat-2 reproduce with high accuracy long-term trends derived by different techniques, the low number of ICESat observations limit their representativity on a regional scale. On the other hand, ICESat-2-only crossovers provide a wide coverage of short-term variations, but surface elevation variations over sub-annual periods are highly stochastic. Longer interval crossovers allow a better determination of surface elevation change rates, but the influence of short-term variations is still higher than when combining data from both missions.

For now, this data and method in the Patagonian Icefields serve as an independent technique to compare results to. But further data collection from the still operational ICESat-2 and potential follow up missions will extend the time period, and thus increase the accuracy and coverage of derivable elevation change rates. An increased spatial coverage of long-term crossovers, in turn, could eventually allow to differentiate elevation changes between individual glacier basins and serve towards glacier mass balance determinations.

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