https://doi.org/10.5194/egusphere-2023-2408
Preprint. Discussion started: 7 November 2023

Brief Communication: Recent estimates of glacier mass loss for western North America from laser altimetry

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Abstract. Glaciers in Western North American outside of Alaska are often overlooked in global studies, because their potential to contribute to changes in sea level is small. Nonetheless, these glaciers represent important sources of freshwater, especially during times of drought. Differencing recent ICESat-2 data from a digital elevation model derived from a combination of synthetic aperture radar data (TerraSAR-X/TanDEM-X), we find that over the period 2013-2021, glaciers in western North America lost mass at a rate of -12.3 ± 3.5 Gt yr^{-1}. This rate is comparable to the rate of mass loss **(**-11.7 ± 1.0 Gt yr^{-1}**)** for the period 2018-2022 calculated through trend analysis using ICESat-2 and Global Ecosystems Dynamics Investigation (GEDI) data.

1 Introduction

Western North American glaciers outside of Alaska cover 14,384 km^2 of mountainous terrain (Pfeffer et al. 2014). Although the global sea level equivalent of these glaciers is only 2.6 ± 0.7 mm (Farinotti et al., 2019), these glaciers provide important thermal buffering capacity during late summer or during times of drought (Moore et al., 2009). Early attempts to define regional estimates of glacier mass change suffered from sparse, in-situ glaciological observations, non-uniform distribution of geodetic measurements, and uncertainties in gravimetric assessments due to changes in seasonal water storage (Jacob et al., 2012;

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Gardner et al., 2013; Zemp et al., 2019). Two recent studies combined publicly-available geodetic datasets and statistical methods to yield mass change estimates with much less spatial bias and lower overall uncertainties (Menounos et al., 2019; Hugonnet et al., 2021). Both of these studies rely on DEMs generated from NASA's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor aboard the Terra satellite. Unfortunately, Terra's orbit is degrading and will reach its end of life within the next 3-4 years. Additional datasets are thus required to quantify glacier mass loss in mountain environments where glacier loss is accelerating (Hugonnet et al., 2021), but recent studies leveraging laser altimetry in global glacier assessments have excluded glaciers in western North America (Jakob and Gourmelen, 2023). Here we provide new estimates of recent glacier mass loss based on laser altimetry data for the western United States and Canada which is Region 02 of the Randolph Glacier Inventory (Pfeffer et al., 2014).

2 Data and methods

2.1 Altimetric data (ICESat-2 and GEDI)

Altimetric data include observations made by NASA's Advanced Topographic Laser Altimeter System (ATLAS), which is a 532 nm photon-counting laser system aboard the ICESat-2 satellite that operates between 88° N/S (Markus et al., 2017, (Markus et al., 2017, Smith et al., 2021). We use version 5 of the ATL06 (land-ice surface heights) dataset that includes laser shots from 13 October 2018 to 12 October, 2022. We also used Global Ecosystem Dynamics Investigation (GEDI) laser data (Liu et al., 2021, Dubayah et al. 2021) acquired between 1 January, 2018 and 1 January, 2022 (GEDI02_A release 2). GEDI is a 1064 nm, full-waveform laser that, because of its operation aboard the International Space Station, operates between 51.6° N/S.

2.2 Digital elevation model

The mass change estimate for approximately the last decade (2013 to 2020), herein referred to as the decadal estimate, uses the global, 30 m Copernicus DEM elevation data derived from the TanDEM-X Synthetic Aperture Radar (SAR) mission (Rizzoli et al., 2017) and made publicly available as the Glo30 product, herein referred to as COP-30 (European Space Agency, 2023). Acquisition of the data used in COP-30 DEM occurred between 2010 and early 2015 and coverage represented about five individual SAR tiles in our study region. Because no gridded acquisition date exist for COP-30, we use an acquisition date of 2013, which coincides with the midpoint for the majority of DEM acquisitions (Rizzoli et al., 2017). As described below, we use the ambiguity of DEM acquisition dates as one source of uncertainty in our mass change estimate.

For each subregion, we reprojected the COP-30 into the local UTM zone. The COP-30 vertical datum is EGM96 which we converted to match the vertical datum of ICESat-2 (WGS84). ICESat-2 data for a given acquisition date were clipped to a

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region of interest and the closest elevation of the COP-30 was extracted for a given laser shot. Elevation of both COP-30 and ICESat-2 were retained, as was the derived elevation change [m], rates of elevation change [m yr^{-1}]. Other original attributes present with the ICESat-2 data (e.g. track number, effective laser shot radius, slope) were retained to maintain metadata continuity. Elevation change values that exceeded -20 or 20 m yr^{-1} were excluded from subsequent analysis as it was assumed that these signals exceed the range of what is physically attributable to glacier processes.

For the decadal estimate of mass change, each glacier polygon (RGI-6.0) within the study region was buffered by 1 km and then masked from the original glacier polygon, to capture areas adjacent to glaciers that we considered to be areas of stable terrain. Due to the buffer, we expect results to be robust to glacier polygon updates. Note that the recently released RGI-7.0 has no changes from RGI-6.0 in our study area. Inspection of elevation change over stable terrain for all ICESat-2 laser shots (2.24×10^6) reveals a positive bias for almost every subregion, typically on the order of 0.1-0.5 m yr^{-1} (ICESat-2 minus COP-30); this bias, however, did not substantially vary with elevation for a given region. Visual inspection of elevation change maps and review of acquisition dates of ICESat-2 data suggests this positive bias arises by laser shots over snow-covered terrain (Enderlin et al., 2022). We therefore limit our analysis to the ablation season when the positive bias associated with snow-covered terrain is minimized. Confirmation of the source of this bias is revealed when the analysis of rates of elevation change is limited to ICESat-2 laser shots acquired between 1 August and 1 October. For these late summer laser shots, we respectively observe a mean bias and uncertainty (± 1 sigma) over stable terrain of 0.038 and 1.53 m yr^{-1}.

2.3 Recent rate of elevation change from ICESat-2 and GEDI

For the period 2018-2022, herein referred to as the recent period, we first create altimetry anomalies by differencing ICESat-2 and GEDI laser shots to the COP-30 DEM. A least squares regression that includes an offset, trend and seasonal sinusoidal terms is fit to anomalies within a 250 m radius search window. The y-intercept of the regression is set to the year 2020. We exclude any ICESat-2 or GEDI laser shots if they deviate more than 250 m from the COP-30 DEM, or if they deviate by more than 150 m from the median anomaly within the 250 m search radius. The search radius and median anomaly threshold were selected to omit elevation change signals that were not physically realistic. Regression fits were excluded from further analysis if: (i) there were fewer than five data points for given search window; (ii) the temporal span of observations is less than three years; (iii) the root mean squared error (RMSE) of the fit residuals exceed 5.0 m yr^{-1} and (iv); the seasonal amplitude of the least squares fit exceeds 10 m yr^{-1}. This did not disrupt the representation of glacier hypsometry, i.e. results were well distributed across glacierized elevations in the study region. We use the trend obtained from the regression to the 250 m radius to represent elevation change.

2.4 Mass change uncertainty

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Uncertainty in mass change originates from errors in rates of elevation change and volume-to-mass conversion factor. We use 850 kg m^{-3} and its associated uncertainty term (±60 kg m^{-3}) for mass conversion (Huss, 2013). We generate bootstrapped errors in total volume change using a Monte Carlo method (Chernick et al. 2011). We first temporally randomize the laser altimetric data, randomly choose the acquisition date of the COP-30 DEM (2012, 2013, 2014) and sample 5% of the data with replacement 10,000 times. Total volume change over glacierized terrain is calculated for each synthetic dataset by multiplying the rate of elevation change by the area of glaciers within a given elevation bin (100 m bins). We then take 5% and 95% modelled volume change as our uncertainty.

Error in mass change is then calculated from:

$$\sqrt{(dV_\sigma \cdot \rho)^2 + (\rho_\sigma \cdot dV)^2} \quad (1)$$

Where dV_σ is the uncertainty of volume change generated from the Monte Carlo method, ρ is material density (850 kg m^{-3}), ρ_σ is uncertainty of density (60 kg m^{-3}) and dV is the change in volume.

3.0 Results

To minimize the impact of the seasonal snow signal, we limit our analysis of mass change using ICESat-2 and COP-30 elevation changes to ICESat-2 data acquired during the latter half of the ablation season (1 August - 1 October). Glaciers throughout the western United States and Canada thinned both during the decadal and recent period with prominent thinning within the Southern Coast Mountains, a region that contains nearly one half of the total ice cover of the study region (Fig. 1. For the period 2013-2021 (median date of ICESat-2 data is 26 August, 2020), we estimate a rate of mass change of -12.3 ± 3.5 Gt yr^{-1} (Fig. 1). This measurement agrees within the rate of mass change [−12.3 ± 4.6 Gt yr^{-1}] reported for the period 2009–2018 (Menounos et al., 2019) and the estimate [−12.3 ± 3.0 Gt yr^{-1}] for the period 2015-2019 based primarily on ASTER data (Hugonnet et al., 2021). Comparable estimates of mass loss exist for western North America for the period 1961-2016 [-12 ± 6 Gt yr^{-1}] and for the period 2002-2009 [-14 ± 3 Gt yr^{-1}] respectively from Zemp et al., (2019) and Gardner et al., (2013). Figure 2 shows results using only ICESat-2 and GEDI laser shots and rates of elevation change determined through least squares fitting (i.e. the recent period), glaciers lost -11.7 ± 1.0 Gt yr^{-1} of mass for the period 2018-2022 (Fig. 2). Mass change rates per subregions (Fig. 1) are summarized elsewhere (SM Table 1). The effect of small sample size is evident in the larger uncertainty of elevation change at highest and lowest elevations, but the contribution of this error to total mass change is small since little total glacierized area exists at these elevations.

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4.0 Discussion and Conclusion

Our geodetic balance obtained from laser altimetry using least squares fitting provides the most recent mass change update for western North America, a region excluded in a recent global assessment of glacier mass loss using laser altimetry from CryoSat-2 data (Jakob and Gourmelen, 2023). While our trend analysis provides a robust estimate of recent glacier mass change, insufficient sampling precludes our assessment of mass loss for regions where laser altimetry data are sparse. This sparseness is especially pronounced in regions north of GEDI data coverage (51.6° N) and regions characterised by small glaciers (Fig. 2). Our decadal estimates of glacier mass loss provide more insight into sub-regional patterns of glacier mass loss, but insight is offset by the additional uncertainty of radar penetration at highest elevation and the ambiguity of the acquisition data for the COP-30 DEM. Others report penetration of the Tandem-X radar signal into high elevation firn and snow surfaces (Abdullahi et al., 2019). The potential of this penetration bias to greatly affect our results is limited since it is spatially limited to elevation zones that typically represent < 1-2% of the total areas within a given region, based on the elevation distribution of glaciers in the western United States and Canada and assumptions of the associated distribution of firn and/or snow.

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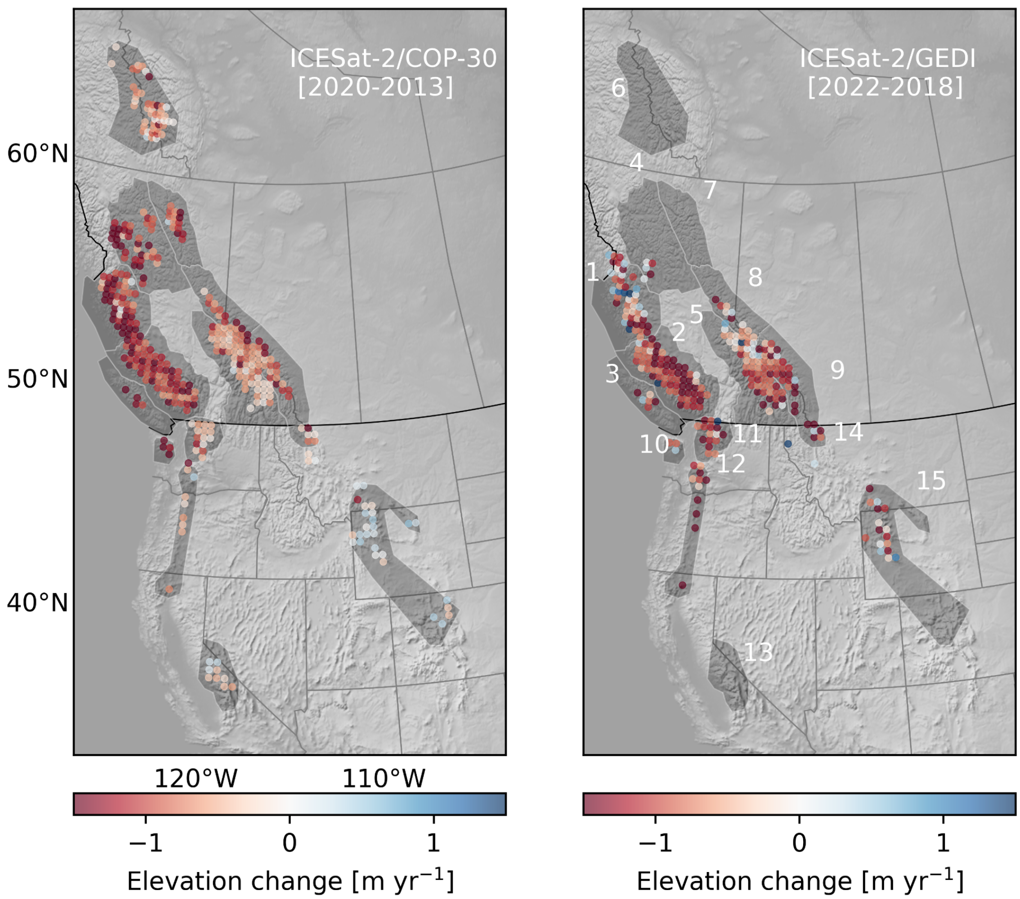

Figure 1: Elevation change [m yr^{-1}] for western North American glaciers. Data aggregated to points with 50 km spacing. Left panel: Elevation change [m yr^{-1}] determined from ICESat-2 and COP-30 data (2022 - 2013); Right Panel: Elevation change [m yr^{-1}] from trend analysis over period 2022-2018 from ICESat-2 (Smith et al. 2021) and GEDI laser altimetric (Dubayah et al. 2021) data. Numbers refer to glacierized regions of Western North America (RGI region 02, Pfeffer et al. 2014). The regions include: (1) Central Coast (1,692 km^2); (2) Southern Coast (7,181 km^2); (3) Vancouver Island (15 km^2); (4) Northern Interior (572 km^2); (5) Southern Interior (1,959 km^2); (6) Nahanni (657 km^2); (7) Northern Rocky Mountains (415 km^2); (8) Central Rocky Mountains (422 km^2); (9) Southern Rocky Mountains (1,350 km^2).

The regional pattern of elevation change obtained for the recent period shows areas of neutral or slight elevation gain (e.g. regions 1 and 5) that are not apparent in the map of decadal elevation change (Fig. 1). The most parsimonious explanation for these differences is the influence of spatially variable snow accumulation in these regions, though we cannot rule out the possibility of changing balance between ice dynamics and mass balance to explain the observed elevation changes. In addition, the decadal pattern largely accords with the notable zonal difference in elevation change observed by Menounos et al., (2019). A key finding of Hugonnet et al., (2021) was the notable accelerated mass loss in western North America during the period

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2015-2019 relative to the start of the 21st century. Our recent and decadal estimates of glacier mass loss using independent datasets confirms the magnitude of recent mass change for a comparably recent period (2018 to 2022), corroborating the finding of accelerated mass loss from this previous study.

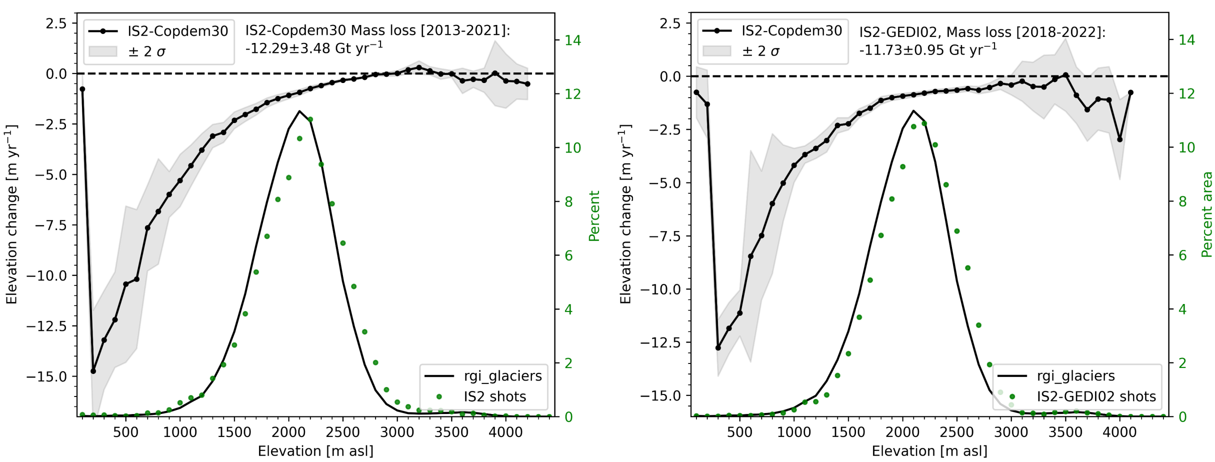

Figure 2: Left Panel: Rates of elevation change [m yr^{-1}] versus elevation for the period 2013-2021. Only laser shots from 1 August-1 October (n=347,630) used in analysis. Light grey shading denotes uncertainty (5-95%) of elevation change. Black line and green dots respectively indicate percent area of RGI ice and percentage of ICESat-2 laser shots within a given elevation bin. Right Panel: Rates of elevation change [m yr^{-1}] versus elevation for the period 2018-2022 from ICESat-2 and GEDI laser shots from least-squares trend analysis (n=66,201). Light grey shading denotes uncertainty (5-95%) of elevation change. Black line and green dots respectively indicate percent area of RGI ice and percentage of ICESat-2 (Smith et al. 2021) laser shots within a given elevation bin.

Code/Data availability

Data reported in this paper is available upon request.

Author Contribution

Menounos proposed the study, completed the Copdem30 and ICESat-2 analysis and wrote the initial draft of the contribution and Gardner completed the ICESat-2 and GEDI analysis. All authors provided input, and commented on drafts of the manuscript.

Acknowledgements

The authors acknowledge constructive input from Rainey Aberle and Albin Wells which improved the quality and clarity of this manuscript. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This study was supported by the National Sciences and Engineering Research Council of Canada, the Tula Foundation, and the Canada Research Chairs Program.

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Preprint. Discussion started: 7 November 2023

2019.