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Brief communication: The Glacier Loss Day as indicator for extreme glacier melt in 2022

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Abstract. In the hydrological year 2021/22 Alpine glaciers showed unprecedented mass loss. On Hintereisferner (Ötztal Alps, Austria), the glacier-wide mass balance was -3319 kg m^{-2}. Near-daily observations of surface elevation changes from a permanent terrestrial laser scanning setup allowed determining the day when the mass balance of Hintereisferner started to become negative. This Glacier Loss Day (GLD) was already reached on 24 June in 2022 and gave way to a long ice ablation period. In 2021/22, this and the high cumulative positive degree days explain the record mass loss. By comparing the GLDs of 2019/20-2021/22, we found a gross yet expressive indicator of the glacier's imbalance with the persistently warming climate.

1 Introduction

During recent decades, climate-induced annual mass balances were persistently negative on most glaciers worldwide (Hugonnet et al., 2021). In the European Alps, the glaciers' mass loss was particularly outstanding in the hydrological year 2021/22[1,2,3] as, in our example, shown in the 70 years long record of annual mass balances on Hintereisferner (HEF, Ötztal Alps, Austria) in Figure 1.

Early in the summer 2022 it became obvious that the day would soon be reached when all mass gained from the accumulation period would be lost. By assuming that after this day, during summer, the glacier loses mass irrecoverably for the rest of the mass balance year, we call this day the glacier loss day (GLD) in an approximate analogy to the Earth Overshoot Day (e.g. Wackernagel et al., 2002; Collins et al., 2020), which marks the date when humanity's annual consumption of ecological resources exceeds what Earth can regenerate in the same year. By reaching a GLD, the glacier obviously leaves the state of balance with the environmental conditions. The earlier the GLD is reached, the higher is the probability of massive mass loss. The key to interpret and use the GLD as near real-time gross but expressive indicator for a glacier's state of "illness" is to record its progressing mass loss during an ablation season at daily resolution.

A daily mass loss record of a glacier and the respective detection of a GLD can be retrieved from mass balance modelling in daily time steps at near real-time. Cremona et al. (2022) upscaled the mass loss on three Alpine glaciers from automated ablation

[1]https://scnat.ch/de/uuid/i/2e076759-0234-567e-9bfb-2cdfebd6ff34-Schlimmer_als_2003_Schweizer_Gletscher_schmolzen_wie_noch_nie, last accessed: 28 February 2023
[2]https://www.uibk.ac.at/de/newsroom/2022/rekordschmelze-gletschereis-auf-dem-ruckzug/, last accessed: 28 February 2023
[3]https://www.lefigaro.fr/sciences/rechauffement-climatique-apres-une-saison-seche-les-glaciers-alpins-plus-que-jamais-menaces-par-la-fonte-20220711, last accessed: 28 February 2023

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stake readings at one point to the full glacier area by applying a mass balance model. The authors do, however, not explicitly indicate a GLD. A second way is to measure daily volume changes over an entire glacier, as was done on Hintereisferner (HEF) in the three consecutive mass balance years 2019/20, 2020/21 and 2021/22 from daily terrestrial laser scanning (TLS) acquisitions (Voordendag et al., 2021, 2023). By assuming that the mass and volume of a glacier change analogously in a first approximation, we derive mass balance variations from respective volume change records, identify the GLD, and compare the extremely negative mass balance of 2021/22 with the two precedent "normally" negative mass balance years for which near daily TLS data are available. By analyzing these records in the light of temperature and winter mass balance records, we explore the GLD's potential for serving as a nearly instant indicator for a glacier's state under the respective year's climatic conditions.

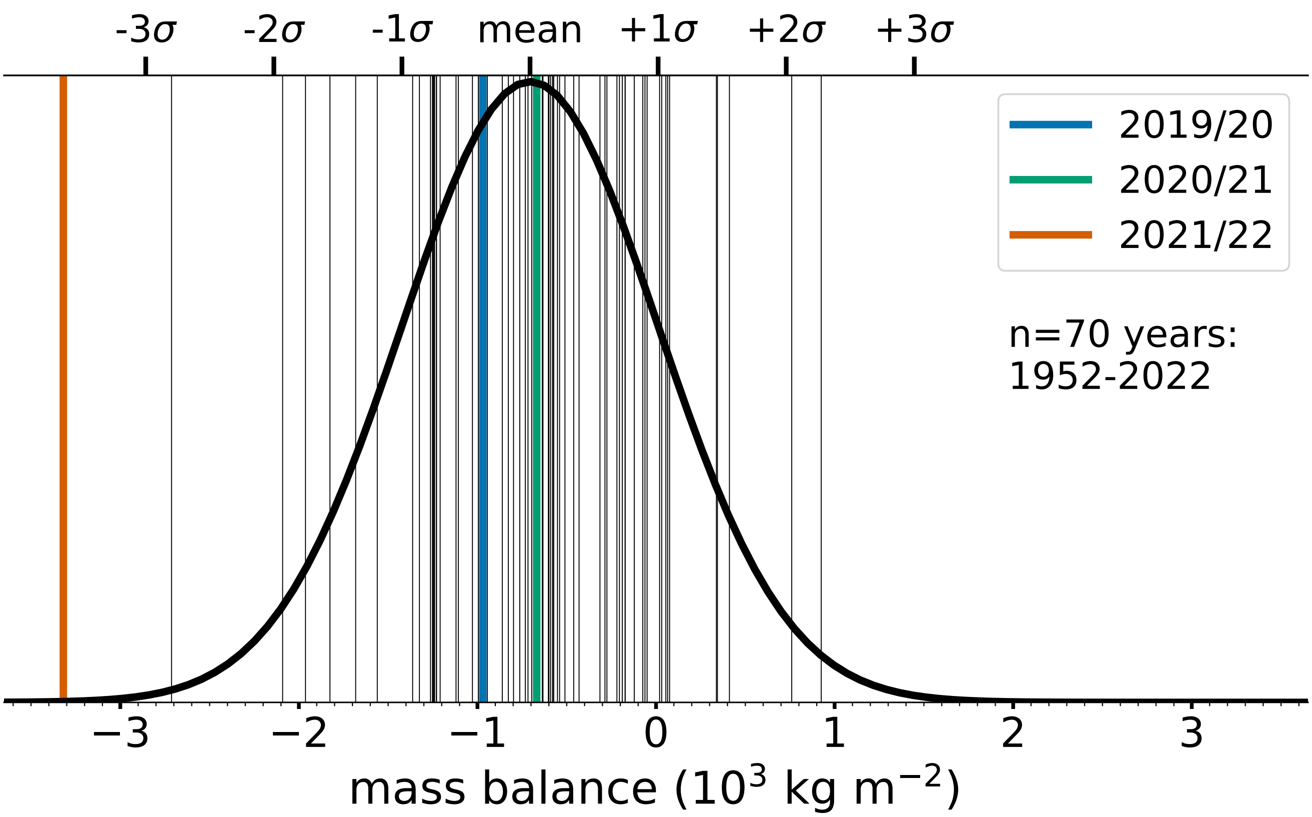

Figure 1. The annual mass balance observations of Hintereisferner (in 10^3 kg m^{-2}) over the full 70 years record are depicted as vertical lines. A fitted normal distribution of these observations is added to emphasize the extremity of the year 2021/22. The hydrological years used in this study are given in blue (2019/20), green (2020/2021) and red (2021/2022). The idea of this figure was inspired by a Twitter post from Matthias Huss (https://twitter.com/matthias_huss/status/1575539821493293058).

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2 Data and methods

The well-studied HEF is a valley glacier in the Ötztal Alps, Austria with continuous mass balance observations since 1952/53 and a rich set of glacier, atmosphere and hydrology data (Strasser et al., 2018), which makes it one of the key 'reference glaciers' by the World Glacier Monitoring Service (WGMS Zemp et al., 2009). A permanently installed long-range TLS system Im Hinteren Eis (Voordendag et al., 2021) allows the acquisition of a daily Digital Elevation Model (DEM) of HEF. The TLS system was permanently installed in 2016, has been in daily operational use since March 2019, and has been automated in June 2020 (Voordendag et al., 2021). The data from the TLS is acquired as point clouds and registered manually in the RiSCAN Pro software (RIEGL, 2019). After registration and rasterization, one-by-one metre DEMs with an accuracy of ±10 cm are acquired (Voordendag et al., 2023). This accuracy is within previously reported errors of airborne laser scanning acquisitions (Klug et al., 2018) and enables the calculation of volume change rates and, ultimately, the GLD. Additionally, common meteorological observations are available from *Station Hintereis* (3026 m a.s.l.), located on the slope opposite to the TLS system (Strasser et al., 2018).

By omitting scans disturbed by clouds or technical problems (e.g., a power shortage in winter 2019/20 and the impossibility of reaching the setup during the Covid-19 lockdown) 151 to 225 scans are available for each of the three years. Each DEM is cropped to the 2018 glacier outlines of HEF. The DEM of difference (DoD) between each registered DEM to the reference DEM of 1 October of the corresponding hydrological year is calculated. Given the scanning geometry of the system, around 67% of the glacier area is covered, but this slightly varies over time and glacier conditions. Thus, the DEMs have different areal distributions of data points, and these heterogeneities reduce coverage further after calculating the DoD. Therefore, only DoDs above a coverage threshold of at least 45% are kept. This results in 133 usable DoDs in 2019/20, 171 in 2020/21 and 208 in 2021/22, with an average glacier coverage of 55%, 55% and 53%, respectively. The coverage seems to have limited influence on the GLD analysis, as our geodetic and glaciological mass balances observations over the last six hydrological years on HEF agree in their mean seasonal and annual values within the uncertainty range found by Klug et al. (2018) of ±210 kg m^{-2}.

Subsequently, the average elevation change weighted over the covered glacier area is calculated and plotted over the hydrological year. The day when the elevation change graphically crosses the zero surface elevation change line is assigned the GLD. As data points may not always be exactly available at the GLD, we interpolate linearly between the last positive and first negative surface elevation change to assign the GLD. Finally, a linear trend is calculated between the first day of the melt season and the GLD, to calculate the melt rate until the GLD is reached. The first day of the melt season is defined as the first maximum after 1 May that is followed by seven consecutive days of surface elevation decrease of at least 4 cm day^{-1}.

Volume and mass are related via the density which is rather constant for glacier ice but varies for snow. The assumption that the GLD measured with elevation changes corresponds to the mass changes is based on the accumulation area ratio (AAR) observations. The AAR on HEF at years with equilibrium mass balance conditions of ±100 kg m^{-2} is 0.69, meaning that at the date of the GLD, the glacier is still 69% snow-covered. In the hydrological years of this study, the snow-covered area at the GLD is also approximately 69%, observed from the time-lapse cameras. The GLD and years with equilibrium mass balance conditions thus have a similar density distribution and we therefore assume a linear correlation between volume and mass changes. Moreover, only small inter-annual variations in the snow line retreat pattern occur during the ablation season, indicating a persistence in this correlation.

3 Results and discussion

A given GLD is the result of i) the amount of mass gained during the accumulation season starting with 1 October, ii) the start of the ablation season and iii) the strength of the ablation rate until the GLD is reached (Figure 2a).

i) At the end of the accumulation season, a maximum of only 2.2 m of snow had been deposited on average over HEF in 2022 (Figure 2a), which equals a winter mass balance of only 691 kg m^{-2}. In 2020 (2021), the winter accumulation was significantly higher with an average elevation change over HEF of 3.2 m (3.7 m) at maximum, which resulted in a long-term "normal" winter mass balance of 1396 (1219) kg m^{-2}. The winter mass balance of 2022 was 47% below the decadal average of 2011-2020. Additionally, the day of peak snow height was 29 April in 2022, whereas this was on 7 (28) May for 2020 (2021). However, we also note that the measurements in 2020 are sparse due to problems with the power supply, and thus the day of peak snow height might have occurred later in May 2020. The low winter mass accumulation in 2022 paved the ground for an early GLD and an extreme glacier mass loss.

ii) In addition, the melting season started earlier in 2022, i.e. on 11 May compared to 23 June 2020 and 26 May 2021, providing a second reason for an extraordinary early GLD. Figure 2b shows the cumulative positive degree days (CPDD) calculated starting from 1 May with air temperature measurements from the automatic weather station *Station Hintereis*. The first positive degree days (PDD) already occurred on 11 May in 2022, which initiated a nearly uninterrupted melting season. In 2020 and 2021, PDDs were also measured in May, but often followed by cold days halting ablation. The period with continuous significant PDDs started at the end of June in 2020 and at the end of May in 2021.

iii) The surface elevation change rate between the start of the melting season and the GLD for 2020 (2021) was 5.8 (5.1) cm day^{-1}, but only 4.7 cm day^{-1} in 2022. The surface elevation change rates until GLD are a combination of compaction of fresh snow and melt. Compaction of fresh snow was likely the case in May/June 2021, as strong snowfall occurred just before this period. The potential for melt in this period is generally a combination of positive air temperatures, global radiation, albedo, clouds, and event-based heat release from rain on snow. In 2022, the lower surface elevation change rate was caused by the early start of the ablation season, when potential melt energy is generally lower due to lower radiation receipts, but high PDDs in that year.

The GLD of the extreme hydrological year 2021/22 is reached on 24 June and on 5 August in 2019/20 and 2020/21. Years with an early GLD allow for more ice exposed to high potential melt energy and a longer ice ablation season and thus, generally offer more negative mass balances. However, the course of the ablation season might be variable and periods with strong melt alternate with periods of no melt or even slight accumulation. Thus, a mass balance prediction from GLD alone seems questionable and mass balance projections must follow scenarios of assumed ablation conditions. In 2022, 99 days

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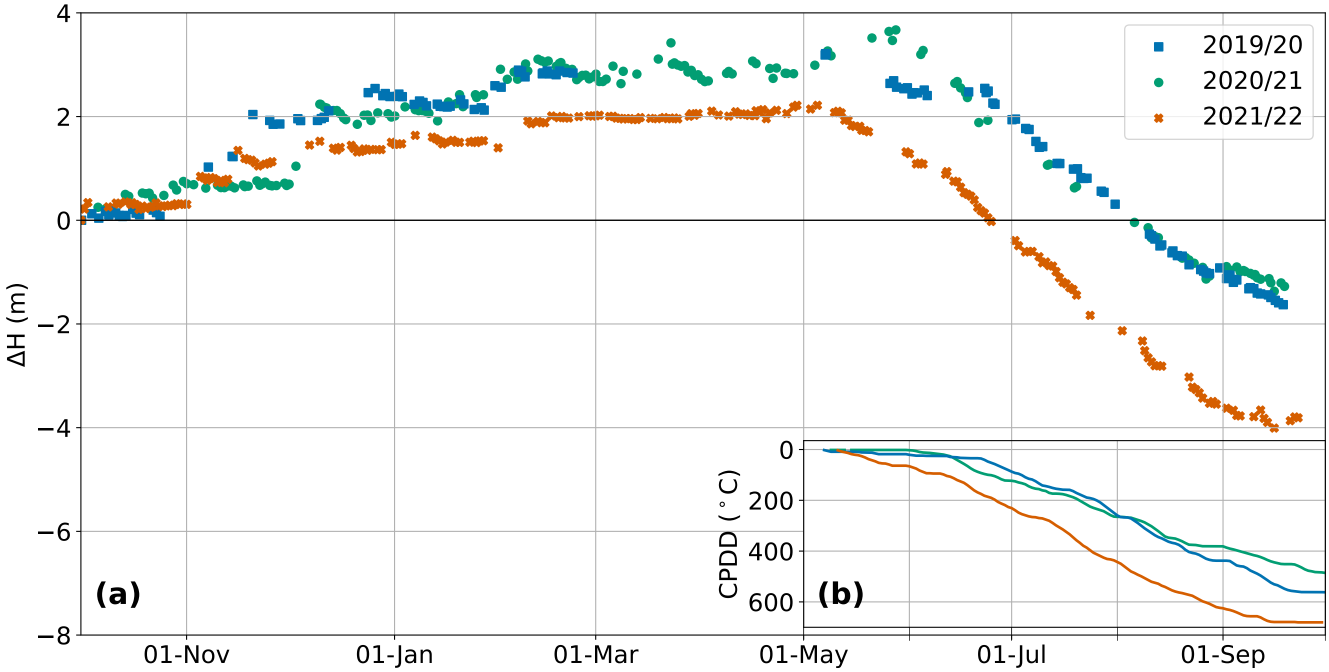

Figure 2. (**a**) The average surface elevation change ΔH over HEF for the hydrological years 2019/20 (blue), 2020/21 (orange) and 2021/22 (green). (**b**) The Cumulative Positive Degree Days (CPDD) calculated from 1 May until 30 September for the same hydrological years.

remain from the GLD until the end of the hydrological year, whereas only 57 days remain in the two preceding years. The end of the ablation season, which is here defined as the minimum surface elevation change, is almost equal in the three studied years, i.e. on 18 September 2020 and on 16 September both in 2021 and 2022. Note, that the end of the ablation season is variable, as it can either end with late summer snow fall and/or low temperatures or can extend into the following hydrological year. In 2021/22, the early GLD, enabling a long ice ablation season, and the high CPDD (Figure 2b) explain the record mass loss of 3319 kg m^{-2}, which is 3.4 and 5.0 times higher than in the two preceding years (Figure 1) and 3.2 times higher than the long-term mean of 1991-2020.

4 Summary and conclusions

Tracking the volume and mass changes of a glacier in daily time steps allows for a nearly instant evaluation of the state of a glacier in a particular year. We introduce the glacier loss day (GLD) as the day in the hydrological year when the mass accumulated during winter is lost and the glacier loses mass irrecoverably for the rest of the mass balance year. Near-daily TLS observations of glacier surface elevation changes at HEF are used and three years of GLD observations are available. The GLD of the extreme hydrological year 2021/22 was already reached on 24 June, whereas this was 42 days later in 2019/20 and 2020/21 on 5 August. In 2021/22, the low winter accumulation, the early start of the ablation season, and the surface elevation

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change rate define the early GLD and give way to a long ice ablation period. This and the high CPDD in 2021/22 explain the record mass loss of 3319 kg m^{-2}. The information on the GLD allows a projected annual mass balance under assumed ablation rates and duration. The GLD contains high public information content and it is, similar to the Earth Overshoot Day, a valid and powerful communication tool. Additionally, the GLD could serve for water management strategies and help to schedule scientific field work.

Nevertheless, we are aware that a setup such as at HEF is unique and only feasible on specific glaciers. However, with ongoing developments in glaciological and geodetic measurements, mainly with automated ablatometers (e.g. Cremona et al., 2022; Carturan et al., 2019; A2 Photonic Sensors, 2022), uncrewed aerial vehicles and the increasing availability of high-resolution satellite data in conjunction with modelling approaches (e.g. Landmann et al., 2021), the GLD of other glaciers can be studied and communicated in the future.

Code and data availability. The RiSCAN PRO software is used to register the TLS point clouds and can be obtained from the manufacturer (RIEGL, 2019). The meteorological data of *Station Hintereis* can be retrieved from https://acinn-data.uibk.ac.at/pages/station-hintereis.html. The data and script to reproduce the plots in this article are publicly available via Zenodo: https://doi.org/10.5281/zenodo.7684348.

Author contributions. AV registered the TLS point clouds and prepared the data for Figure 2. RP is responsible for the glaciological monitoring at HEF. LS provided Figure 1. AV, RP, LS and GK prepared the manuscript together.

Competing interests. The authors declare that they have no conflict of interest.

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