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Temporal downscaling of glaciological mass balance using seasonal observations

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Abstract

Glaciological mass-balance measurements have been the backbone of internationally coordinated glacier monitoring. The resulting annual observations have been used to understand glacier reactions to climate change, and to assess both regional and global glacier mass changes and related contributions to runoff and sea-level rise. However, the comparability of annual observations is hampered by differences in survey periods and mass-balance amplitudes between glaciers, regions and hemispheres. This study presents a simple approach to temporally downscale glaciological mass balance using seasonal observations and sine functions. The proposed analytical model allows reconstruction of the seasonal course of glacier mass balance at weekly to monthly resolution from only annual or seasonal observations. Strengths and limitations of this analytical approach are discussed and compared with results from numerical mass-balance modelling. Potential applications include seasonal corrections of glaciological and geodetic observations and comparisons to monthly results from spaceborne gravimetry and altimetry.

1. Introduction

The glaciological method determines mass balance in situ on the glacier surface by observations of accumulation and ablation (Cogley and others, 2011). Generally, this includes measurements at stakes and in snow pits, which are interpolated to glacier-wide balance estimates (Østrem and Brugman, 1991). Pioneer research measuring annual mass balances at individual stakes was carried out already at the end of the 19th century (Mercanton, 1916; Chen and Funk, 1990). Glacier-wide observations of annual or seasonal mass balances using the glaciological method (based on Ahlmann, 1948) have become the key component of internationally coordinated glacier monitoring since the mid-20th century (Zemp and others, 2015). Annual mass-balance estimates have been used to understand glacier reactions to climate change (Kuhn, 1981; Vincent and others, 2017), and to assess regional to global glacier mass changes as well as related contributions to runoff (Huss and Hock, 2018) and sea-level rise (Meier, 1984; Kaser and others, 2006; Gardner and others, 2013; Zemp and others, 2019). The vast majority of regional to global studies have focused on annual mass balances, while only a few studies have made use of seasonal mass-balance observations (e.g. Dyurgerov and Meier, 1999; Braithwaite, 2009; Barandun and others, 2015; Azam and others, 2016; O'Neel and others, 2019; Braithwaite and Hughes, 2020; Mukherjee and others, 2023). However, the use of annual mass-balance observations comes with some limitations. The comparability of annual results is hampered by differences in survey periods and in mass-balance amplitudes between glaciers, regions and hemispheres. For example, glaciers in the Canadian Arctic and in New Zealand can record the same annual balance despite mass-balance amplitudes ranging from less than half a metre in the Canadian Arctic to a few metres in New Zealand. Their survey periods are also shifted by half a year. Corresponding seasonal observations provide information on winter and summer balances but are only conducted on a subset of glaciers and years for financial or logistical reasons (Braithwaite, 2009), or because of an absence of a climatic winter and summer cycle (e.g. in the tropics or in monsoon areas). Similarly, glaciological observations following different time systems (i.e. fixed date, floating date, stratigraphic; Cogley and others, 2011) as well as temporal differences between glaciological and geodetic surveys can result in mass-balance differences of more than 0.5 m w.e. a^{-1} (Huss and others, 2009; Zemp and others, 2013). Numerical modelling of glacier mass balance (e.g. Huss and others, 2015; Maussion and others, 2019; Rounce and others, 2020) can address these issues but requires computational resources, programming knowledge and meteorological input data. In this study, we present a simple analytical approach to 'temporally downscale' (cf. von Storch and Zorita, 2019; Finkenbiner and others, 2021) seasonal mass balances using sine functions. Two versions of the approach allow accommodating observational gaps in the glaciological records. The first version scales the sine wave from winter and summer balance observations of the corresponding hydrological year (Cogley and others, 2011). For years with only annual balances, seasonal balances are estimated from the long-term mean mass-balance amplitude calculated from years with seasonal balances. The two versions of the analytical model are illustrated and discussed together with results from numerical modelling by Huss and others (2015) estimating the daily mass-balance evolution of Basòdino Glacier, Switzerland, for the hydrological years from 1991/92 to 2021/22.

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2. Data and methods

Glaciological observations have been compiled and made available by the World Glacier Monitoring Service (WGMS; https://wgms.ch) and predecessor organizations since 1894 (Forel, 1895; WGMS, 2021 and earlier reports). The mass-balance measurements of Basòdino Glacier are carried out by Glacier Monitoring Switzerland (GLAMOS, 2022) and the observational series has recently been extended back in time through data rescue and data homogenization efforts (Huss and others, 2015; Geibel and others, 2022).

The latest version of the WGMS Fluctuations of Glaciers database (WGMS, 2022) contains ~7600 glaciological mass-balance records from 480 glaciers. These data come with five main limitations as schematically illustrated in Table 1: (1) 40% of the glaciological data lack seasonal balances, either because they were not measured, not reported or not defined by climate. Of the 270 glaciers with seasonal balances, only half have them throughout their series. The other half lack seasonal values for 30% of the years. (2) In total, 23% of the records provide seasonal balances but do not report dates, only the hydrological year. (3) In total, 17% of the records provide dates based on the stratigraphic system (cf. Cogley and others, 2011). In this system, observations refer to stratigraphic horizons of the previous annual minima (i.e. 'the last summer horizon') and, hence, come without exact begin dates. (4, 5) In total, 20% of the records come with seasonal balances and are based on either the (4) fixed-date or (5) floating-date system (cf. Cogley and others, 2011), providing exact dates referring to the hydrological year or to the field surveys, respectively. Glaciological observations are synchronized with the natural progression of the hydrological year that begins near the start of the accumulation season and ends near the end of the ablation season (cf. Cogley and others, 2011). As such, the hydrological year is defined to run from 1 October to 30 September in the mid-latitudes of the Northern Hemisphere.

In order to exploit the full observational sample, we need an analytical function that can temporally downscale mass balance for years with seasonal observations but also for years with only annual balances. In both cases, the function should be able to deal not only with observations that have exact dates but also with observations that come with fuzzy or no dates.

Glaciological balances are strongly correlated with air temperature and global solar radiation (Ohmura and others, 2007), which can be idealized over the annual cycle by sine waves (Fujita, 2008). Hence, we use sine waves to represent the instantaneous mass balance (b) as a function of time over the hydrological year. Winter and summer, defined as the intervals $[0, m]$ and $[m, 1]$, are each represented by one hump (or half-cycle) of a sine wave of the form:

$$b(t) = A \sin(\omega(t - \varphi)), \tag{1}$$

where t is time, φ and ω are chosen to match the start and width of the season and A is chosen such that the integral over the season equals the seasonal balance. The mass balance for an arbitrary time interval $[i, j]$ is then the integral of $b(t)$:

$$B(i, j) = \int_i^j b(t)\mathrm{d}t = \frac{A}{\omega}(\cos(\omega(i - \varphi)) - \cos(\omega(j - \varphi))). \tag{2}$$

The parameter values for winter (w) and summer (s) are as follows:

$$\varphi_{\mathrm{w}} = 0, \tag{3}$$

$$\omega_{\mathrm{w}} = \frac{\pi}{m}, \tag{4}$$

$$A_{\mathrm{w}} = \frac{B_{\mathrm{w}}\omega_{\mathrm{w}}}{2}, \tag{5}$$

$$\varphi_{\mathrm{s}} = m, \tag{6}$$

$$\omega_{\mathrm{s}} = \frac{\pi}{1 - m}, \tag{7}$$

$$A_{\mathrm{s}} = \frac{B_{\mathrm{s}}\omega_{\mathrm{s}}}{2}, \tag{8}$$

For years with only an annual balance (B_{a}), we prescribe a mass-balance amplitude (α) – defined as half the difference between the winter (B_{w}) and summer (B_{s}) balances (Braithwaite and Hughes, 2020) – from which we calculate seasonal balances:

$$\alpha = \frac{|B_{\mathrm{w}} - B_{\mathrm{s}}|}{2}, \tag{9}$$

$$B_{\mathrm{w}} = \frac{B_{\mathrm{a}}}{2} + \alpha, \tag{10}$$

$$B_{\mathrm{s}} = \frac{B_{\mathrm{a}}}{2} - \alpha. \tag{11}$$

α corresponds to the climatic amplitude of the glacier mass balance. It can be estimated from years with seasonal balances from the same glacier, or, if not available, from neighbouring glaciers with similar mass turnover (Braithwaite and Hughes, 2020). In our example for Basòdino Glacier, we upscaled B_{w}, B_{s} and B_{a} from daily balances computed by Huss and others (2015) in order to ensure consistency in long-term trends with our sine

Table 1. Schematic overview of the glaciological observations available from the Fluctuations of Glaciers database (WGMS, 2022).

#	Year	Time system	Begin period	End winter	End period	B_{w} mm w.e.	B_{s} mm w.e.	B_{a} mm w.e.	Sample %
1	YYYY	–	–	–	–	NULL	NULL	−500	40
2	YYYY	–	NULL	NULL	NULL	500	−1000	−500	23
3	YYYY	stratigraphic	YYYY-??-??	YYYY-05-05	YYYY-09-25	500	−1000	−500	17
4	YYYY	fixed-date	YYYY-10-01	YYYY-04-30	YYYY-09-30	500	−1000	−500	12
5	YYYY	floating-date	YYYY-09-14	YYYY-05-25	YYYY-09-21	500	−1000	−500	8

Each sample (#) illustrates a typical issue: (1) annual (B_{a}) without winter (B_{w}) and summer (B_{s}) balances; (2) seasonal balances without dates; seasonal balances based on (3) stratigraphic, (4) fixed-date and (5) floating-date systems.

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wave approach. α was calculated as the mean of the mass-balance amplitudes from each year with seasonal balances.

3. Results and discussion

The characteristics of the sine wave approach are illustrated in Figure 1. We can scale the two sine functions to fit winter and summer balances separately. The integrals over each season equal the seasonal balances, and the sum of these equals the annual balance. Years with only annual observations are treated in the same way by calculating seasonal balances from an assumed mass-balance amplitude estimated from other years (or neighbouring glaciers) with seasonal balances.

The results from the analytical model are now compared to the output from a numerical model, employing the example of Basòdino Glacier, Switzerland (Fig. 2), in order to illustrate the strengths and limitations of the sine wave approach. The distributed accumulation and temperature-index melt model by Huss and others (2015) uses daily air temperature and precipitation data as forcing and has been calibrated with seasonal glaciological balances from GLAMOS (2022). The plots of the daily balances (Figs 2a, b) illustrate that the numerical model is able to estimate daily accumulation and ablation events thanks to the meteorological forcing, whereas the sine wave approach can reasonably downscale glacier mass balance to weekly to monthly resolution, but has no information about daily events. The cumulative plots (Figs 2c, d) nicely illustrate the ability of the sine wave approach to well represent the seasonal course of glacier mass balance within and between years. As expected, the cumulative values of both models match at the start dates of the winter and of the summer seasons due to the calibration to the same glaciological observations. The zoom to the hydrological years 2020/21 and 2021/22 (Figs 2b, d) shows that the sine wave approach scaled with seasonal balances performs better in years (e.g. 2020/21) where the annual mass-balance amplitude is close to mean amplitude, which was used to estimate the seasonal balances. In 2021/22, the strongly-negative summer balances resulted in an underestimation of the amplitude.

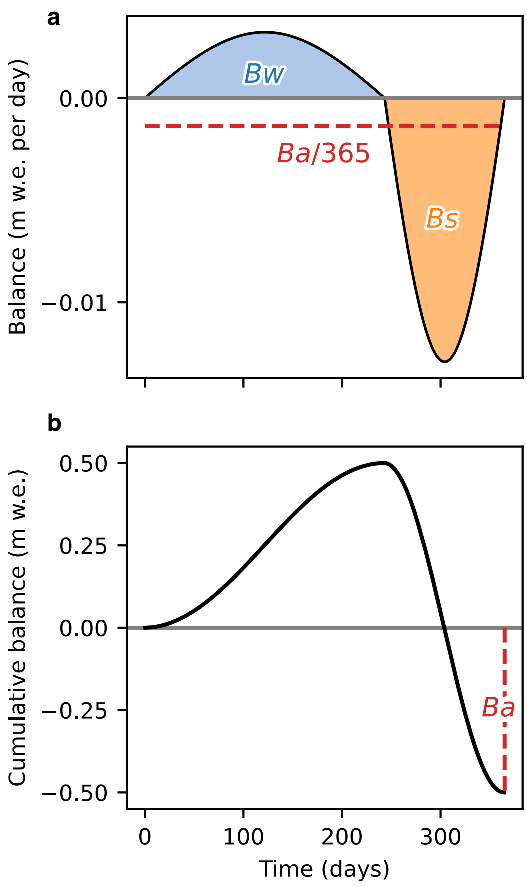

Figure 1. Representation of glaciological mass balance using sine waves (a) together with corresponding cumulative balances (b). The illustrated example is given for daily balances downscaled from $B_w = 0.5$ m w.e., $B_s = -1.0$ m w.e. and $B_a = -0.5$ m w.e., and for a hydrological year of 365 days with eight winter and four summer months (i.e. $m = 8/12$).

A quantitative comparison of the results (Figs 3a–d) shows that the sine wave approach performs similarly with or without seasonal balances over the full 30-year period, and better matches the numerical model results with increasing temporal aggregation. At daily resolution, the balances of the sine wave approach follow a mean seasonal course and, hence, are not able to reproduce high-frequency meteorological events. Averaged over longer time periods, the model performance improves, with RMSE decreasing by one order of magnitude from daily to seasonal aggregation. The comparison for cumulative balances (Figs 3e–h) shows an overall good model fit, independent of the temporal aggregation, and a better performance of the sine wave approach from seasonal balances (RMSE between 0.23 and 0.29 m) than the one from annual balances and balance amplitude (RMSE between 0.30 and 0.35 m). With regards to applications, it can be stated that the sine wave approaches can reliably estimate balances over weeks or months while daily variations cannot be reproduced. As such, the approach has the potential to correct cumulative differences in survey periods between glaciers, regions and hemispheres.

Temporal downscaling of glaciological observations – using analytical or numerical models – offers the possibility to compute continuous time series and provides a richer view of glacier mass changes (Braithwaite, 2009). As such, these time series clearly demonstrate that the seasonal variability of glacier mass balance can be orders of magnitude larger than the long-term trend (Braithwaite and Hughes, 2020), and differences in survey periods can hamper direct comparison of annual balances (Huss and others, 2009). The proposed analytical model based on sine functions provides an approach to deal with these issues, especially for users without access to numerical models and for cases that need to be independent of meteorological forcings. It can be applied to all glaciers with seasonal mass-balance observations and might be extended to other glaciers with similar mass-balance variability and amplitudes (Braithwaite and Hughes, 2020), which typically are well correlated over several hundred kilometres (Letréguilly and Reynaud, 1990; Cogley and Adams, 1998). The main strength and – at the same time – limitation of the analytical approach is its sole dependency on glaciological input data and its basic assumption of distinct seasons of winter accumulation and summer ablation. As such, the approach is restricted to regions with available seasonal glaciological observation but cannot resolve the course of balances in tropical or monsoonal climate regimes, which is not captured in the traditional glaciological observations of winter, summer and annual balances.

Potential applications include the illustration of seasonal balances of glaciers, especially when located at different latitudes, for educational and outreach purposes (e.g. WGMS, 2021; C3S, 2022); seasonal corrections of glaciological and geodetic observations covering different survey periods (e.g. Zemp and others, 2013), although not solving issues related to density conversion (cf. Huss, 2013); and comparison of glaciological results with those from other methods that provide results at monthly time resolution, such as spaceborne gravimetry (e.g. Wouters and others, 2019) or altimetry (e.g. Jakob and others, 2021).

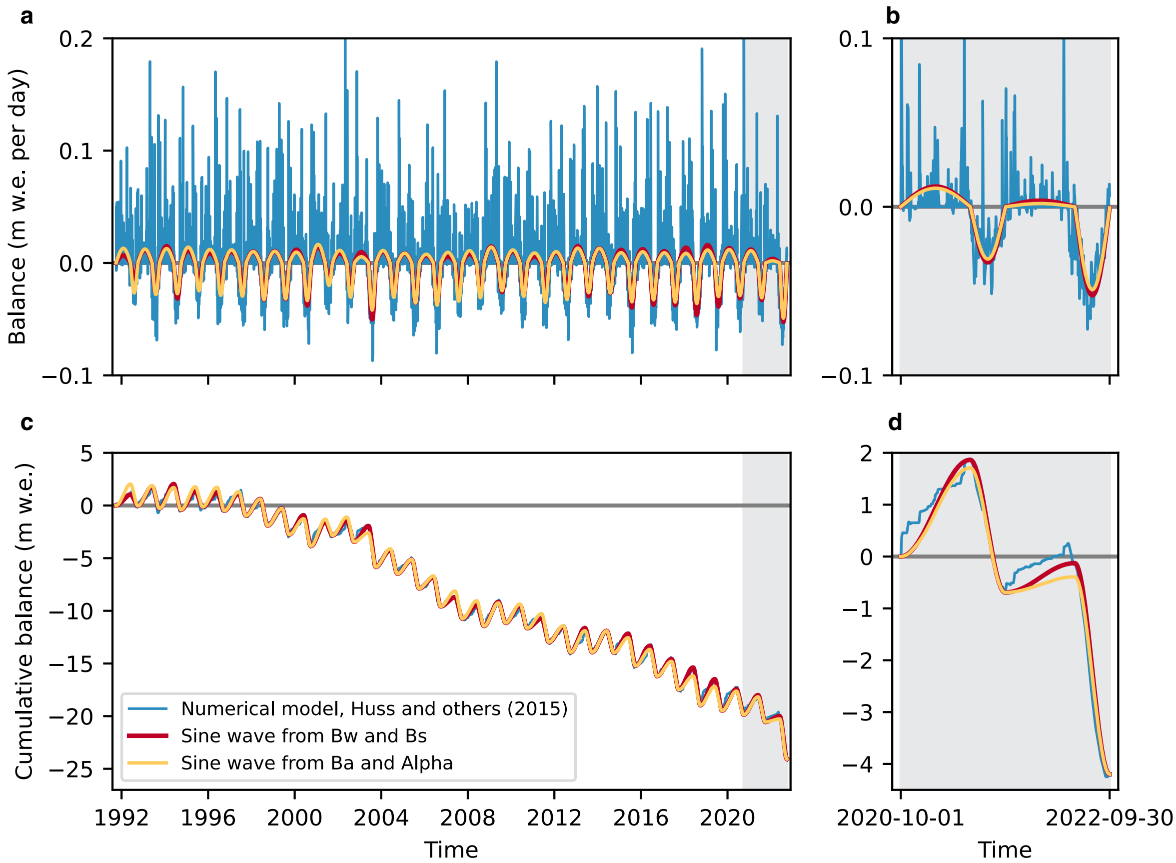

Figure 2. Model comparison between sine wave approaches (this study) and a numerical model run (Huss and others, 2015) using glaciological observations (GLAMOS, 2022) from Basòdino Glacier, Switzerland, for the hydrological years from 1991/92 to 2021/22. The results are shown as daily balances (a, b) and cumulative daily balances (c, d), with a zoom to the hydrological years 2020/21 and 2021/22 (b, d) as indicated by the grey shading.

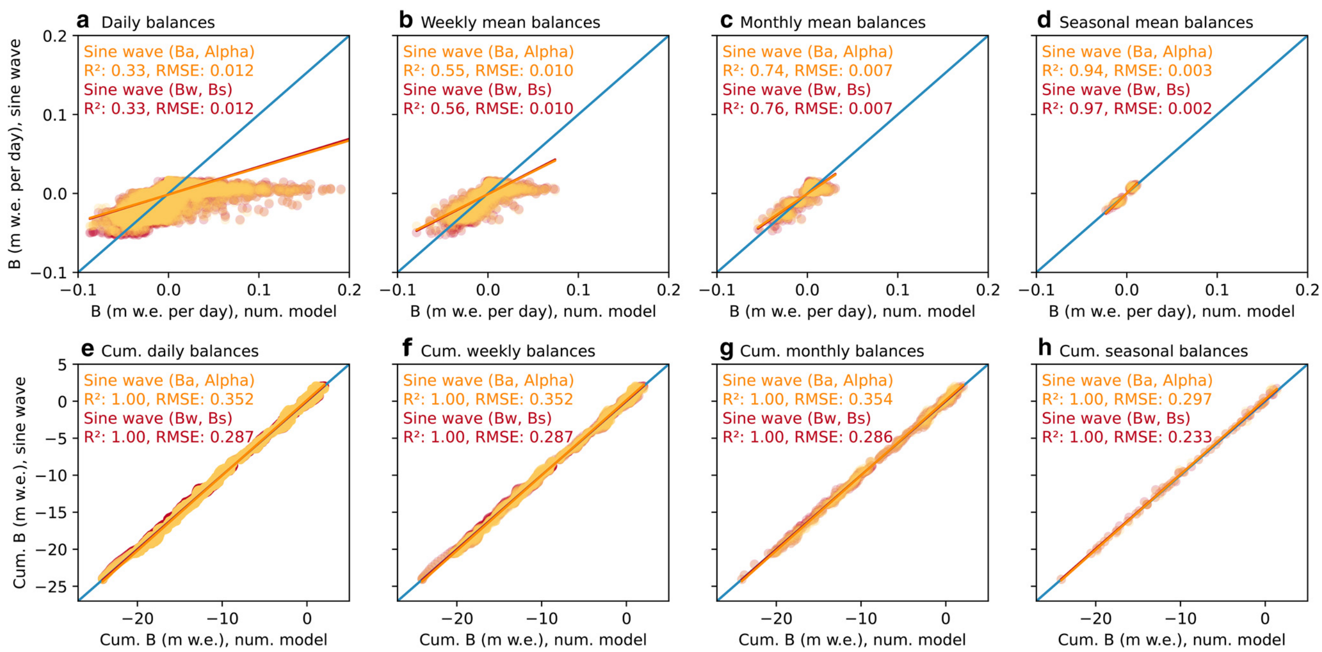

Figure 3. Model comparison between sine wave approaches (this study, *y*-axis) and a numerical model run (Huss and others, 2015; *x*-axis). The results are shown as mean daily balances aggregated at daily (a), weekly (b), monthly (c) and seasonal (d) resolution as well as corresponding cumulative balances (e, f, g, h). Linear regressions between the sine wave approaches and the numerical model are shown with corresponding regression statistics (R^2, RMSE). The blue line indicates the predicted values for a perfect model fit.

4. Conclusions

Temporal downscaling of glaciological observations – using analytical or numerical models – allows the calculation of continuous time series and provides a more comprehensive picture of glacier mass-balance variability. The proposed analytical model uses sine functions and seasonal mass-balance observations to temporally downscale the seasonal course of glacier mass balance at weekly

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to monthly resolution; it can deal with observational gaps as well as with different durations of winter and summer periods. The approach allows estimations of the seasonal variability of glacier mass balance to be made, which can be orders of magnitude larger than the long-term trend; it can also contribute to the correction of differences in survey periods, which hamper direct comparison of results from different glaciers or observational sources. The presented sine wave can provide a much richer view of glaciological observations, especially for users without access to numerical models and for use cases that need to be independent of meteorological forcings.

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Data. Access to glaciological observations is provided by GLAMOS (https://doi.org/10.18750/massbalance.2022.r2022) and by WGMS (https://doi.org/10.5904/wgms-fog-2022-09).

Code availability. Code implementing our analytical sine wave approach is available on GitHub: https://github.com/wgms-org/mb-downscaling.

Author contributions. M.Z. developed the concept of the study, wrote a first version of the code, carried out the analysis, prepared figures and tables and wrote the manuscript. E.W. revised the method, polished the code, and contributed to the revision of the manuscript.

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