2 Data and methods for surge-type glacier identification

We propose to identify surge-type glaciers from distinct widely used criteria (Dowdeswell and Williams, 1997; Copland et al., 2003; Grant et al., 2009), directly contrasting with regional trends of glacier mass loss (Brun et al., 2017; Shean et al., 2020; Bhattacharya et al., 2021), slowdown (Dehecq et al., 2019) and retreat (Li et al., 2019). First, substantial and spatially concentrated surface elevation changes (over 1–10 years), either in the reservoir zone or at lower elevations (near the glacier terminus), are assumed to be typical of surge-type glacier ice mass redistribution. Then, substantial variations in a glacier's velocity field over a similar time period are taken as indicative of surging. Finally, we consider chaotic glacier-wide crevasse patterns mixing longitudinal and transverse crevasses at low altitudes (typically close to the front) as diagnostic of active glacier surges. While terminus advance is often a consequence of glacier surges, not all surge-type glaciers display terminal advance during the active phase, and it is therefore not considered as a discriminating criterion for surge identification (Mukherjee et al., 2017; Paul et al., 2017; Steiner et al., 2018).

2.1 Glacier surface elevation changes

We considered two contrasting patterns of glacier surface elevation change to be diagnostic of surge-type glaciers. We aimed to identify glaciers which exhibited substantial and widespread surface elevation gain (thickening) over their receiving zone, which is also commonly accompanied by surface elevation decrease (thinning) over a glacier's reservoir zone due to the flux of ice between the two areas (Fig. 1a). We consider this pattern of elevation change to be diagnostic of the active phase of a glacier's surge cycle. We also aimed to identify glaciers which exhibited substantial and widespread reservoir zone thickening and concomitant terminal thinning, which we attribute to quiescent phase ice build-up occurring alongside post-surge phase ice loss at lower elevations (Fig. 1b). To identify the mass displacement associated with the active phase of a glacier's surge cycle or substantial ice mass build-up associated with the quiescent phase of the surge cycle, we examined multi-temporal datasets of surface elevation change (dH) over HMA glaciers. We primarily used the dH data generated by Shean et al. (2020), which cover the period 2000–2018, to identify the elevation change patterns described above. To aid the identification of surge-like behaviour which may have occurred at the beginning of the period covered by Shean et al. (2020), the signal of which may have been obscured by subsequent long-term thinning, we also examined dH data generated by Hugonnet et al. (2021) over the periods 2000–2004 and 2005–2009 and by Brun et al. (2017) over the period 2000–2016. Distinctive surface elevation patterns were identified manually and corroborated by multiple users.

2.2 Glacier surface velocity

The NASA MEaSUREs ITS_LIVE project (Gardner et al., 2019) provides measurements of glacier surface velocity at monthly to yearly temporal resolution over all major land ice regions, with a resolution of 240 m. Glacier surface velocities were estimated over the 1985–2018 period from Landsat 4, 5, 7 and 8 images using the auto-RIFT feature tracking algorithm (Gardner et al., 2018). As a consequence of unequal data quality and scarcity in the years covered by the earlier Landsat data archives, we only considered yearly glacier surface velocity derived from Landsat 7 and 8 imagery, between 2000 and 2018, which also matches the period covered by surface elevation change datasets.

The ITS_LIVE yearly glacier surface velocity data are provided with an associated error map. From the collection of yearly glacier surface velocity and their respective error maps, we then form V_0, the error-weighted mean velocity map for the study period, as follows:

$$V_0 = \frac{\sum_{i=1}^{n} w_i V_i}{\sum_{i=1}^{n} w_i}, \tag{1}$$

where V_i is the glacier surface velocity dataset for year i, and the weights w_i are defined as

$$w_i = \frac{1}{\epsilon_i^2}, \tag{2}$$

with ϵ_i being the error map for year i.

The yearly map of velocity change (dV) is computed as the difference between V_0 and V_i for each year i. We then follow the method from Mouginot and Rignot (2015) and eliminate potential outliers using a 3×3 median filter.

From these data, we aim to identify positive velocity anomaly with a magnitude commensurate to that of a glacier surge. We thus assume the distribution of dV to be a zero-mean Gaussian distribution for glaciers with stable flow over the studied period (Fig. 2a). Surging behaviour typically displays more complex patterns, and one can expect the distribution of surface velocity variations to be either positively (during the active phase) or negatively (quiescent phase) heavy-tailed (Fig. 2b). In the present work, we aim to identify glaciers displaying strong positive heavy tails resulting from active surges on particular years. We thus compute the range between the median (P_{50}) and the percentile 95 (P_{95}) for each glacier and year:

$$\mathrm{IPR}_i = |P_{95i} - P_{50i}|, \tag{3}$$

where IPR_i is the inter-percentile range for year i. From Eq. (3), we propose to quantify surge magnitude as a surge index, defined as follows:

$$s_i = \frac{\mathrm{IPR}_i}{k \cdot V_0}, \tag{4}$$