Considerations for setting up new long-term mass balance monitoring programmes in the Reuss and Inn basin

View over Hüfifirn from Gross Düssi

Piz Palü and the accumulation area of Vadret Pers

1. Introduction

The effect of climate change on long-term glacier mass balance monitoring series in the Swiss Alps has been evident since the acceleration of glacier melting in the late 1980s. Traditionally, many of the most important measurement series of surface mass balance are located on medium-sized or small glaciers that are easily accessible and can be covered in their entirety by direct observations. These glaciers have shown massive wastage during the last years with a high frequency of extreme melting conditions (GLAMOS, 2018). On some glaciers, measurements are difficult, or they are increasingly losing their regional representativeness due to glacier wastage and decay. The most prominent example is Pizolgletscher, Eastern Swiss Alps, where detailed mass balance monitoring was performed since 2006, and continuous length change observations date back until the late 19th century. In summer 2018, Pizolgletscher has shown a far-reaching decay into individual remnants of ice, losing around 40% of its surface area only during a single year. Monitoring will be abandoned after 2019/2020.

The case of Pizol indicates the pressing need of replacing important direct mass balance observations on small glaciers as soon as possible in order to guarantee a continuity of the monitoring. According to the GCOS climate monitoring principle No. 2 “a suitable period of overlap for new and old observing systems (monitoring series) is required”. In response to this, two large glaciers (Findelengletscher, Rhonegletscher) have already been included in the monitoring programme in 2005/2006. However, as Glacier Monitoring Switzerland (GLAMOS) aims at a complete coverage of all regions / hydrological drainage basins of the Swiss Alps, an in-depth assessment of the need and the feasibility of new mass balance series acting as a replacement of glaciers that will soon be impossible to be measured was performed. The results are described in the present internal GLAMOS report, which mainly investigates the potential of setting up new monitoring programmes with a temporal perspective of several decades in the Reuss and Inn basins.

The selection of long-term mass balance monitoring sites follows five objective criteria that need to be optimal and – if possible – equally-weighted before a site should be considered for long-term monitoring activities. The following criteria have been compiled by the GLAMOS office (based on guidelines in the GCOS monitoring principles) and are used for the detection of potential monitoring sites in the Swiss Alps:

1. **Local and regional representativeness:** The monitoring site should be located in a region with presently lacking information on glacier mass balance and should be representative.
   ⇨ ***Provision of climate-relevant information***
2. **Accessibility:** Field-site accessibility (e.g. road, cable car, reasonably short walking distance) should be ensured to allow an efficient conduction of the field work.
   ⇨ ***Efficiency***
3. **Objective dangers:** Most of the glacier surface should be accessible with limited objective danger, which favours glaciers with little crevassing, rather gentle slopes and limited rockfall hazard.
   ⇨ ***Safety***
4. **Previous measurements:** If possible, long-term monitoring sites should be installed at glaciers with previous direct observations.
   ⇨ ***Continuity***
5. **Maximal resilience to climate change:** To ensure long-term perspective of the monitoring, glaciers expected to withstand climate change the longest should be selected, i.e. large/thick glaciers.
   ⇨ ***Secured observations for next decades***

2. Evaluating potential losses of long-term series and detection of potential replacement sites

For all glaciers with ongoing long-term monitoring programmes within GLAMOS their likely *survival time* was estimated (Fig. 1). Here, we define *survival time* as the period for which *reasonable* measurements are possible on the respective glaciers. Our *survival time* is thus different from the complete loss of all remnants of glacier ice but targets the feasibility of a mass balance programme delivering data that are useful for climatic interpretation. The estimates of *survival time* shown in Figure 1 are based on current climate scenario and corresponding projections of glacier evolution (Zekollari et al., 2018), but are to be understood as rather rough and only half-quantitative estimates that do not account for diverse uncertainties (e.g. uncertain evolution of temperature and precipitation, uncertainty in glacier model). Whereas most glaciers in the Rhone basin are expected to still deliver reasonable data after the mid-21st century, thus indicating no need for immediate action, several other long-term monitoring sites are expected to be lost within the coming years to decades (Fig. 1).

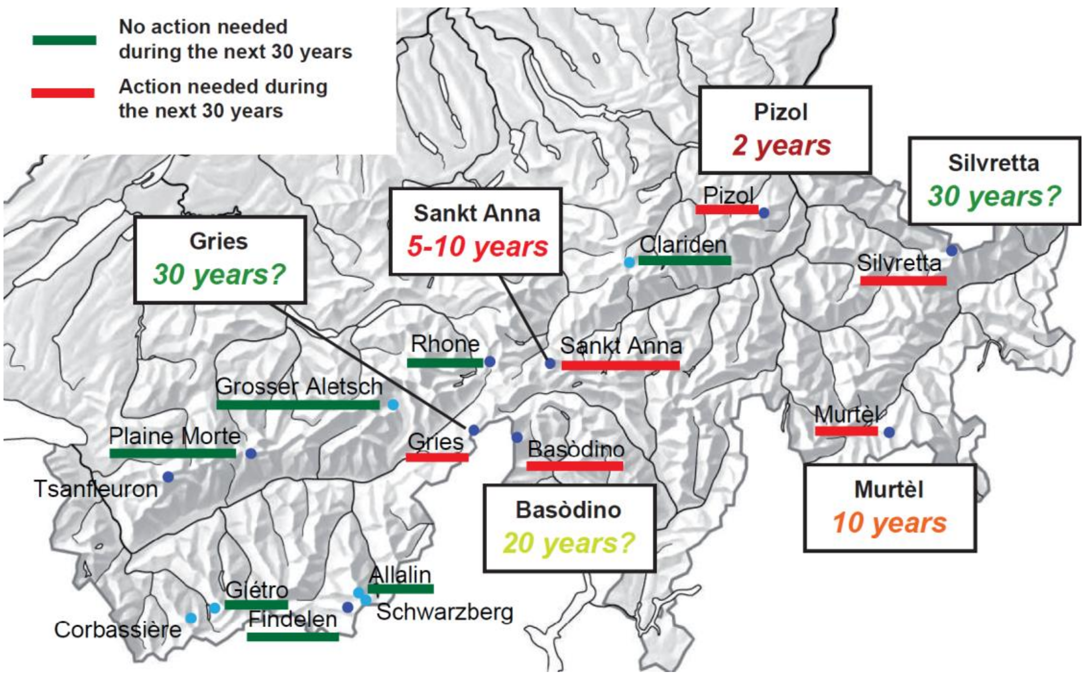

Figure 1: Evaluation of the estimated "survival time" of long-term mass balance monitoring sites included in GLAMOS. Glaciers that can still be measured after 2050 are classified in green.

GLAMOS aims at covering all regions of Switzerland and hydrological drainage basins (often representative for regional climate regimes) with long-term mass balance series. For each basin, the need of shifting monitoring from a possibly disappearing glacier to a larger, more climate-change resilient one has been assessed (ordered for regional glacier area):

- **Rhone basin:** Several large glaciers in the network. No need for action although a previous reference glacier (Griesgletscher) is expected to be lost towards 2050.
- **Aare basin:** One of the largest glaciers (Glacier de la Plaine Morte) is expected to remain in the network for several decades. No need for action.
- **Reuss basin:** The present representative (St. Annafirn) is expected to be lost within a few years. *A replacement glacier is necessary.*

- **Inn basin:** The present representative (Vadret dal Murtèl) is expected to be lost within a few years. *A replacement glacier is necessary.*
- **Alpenrhein basin:** Monitoring is performed on the largest glacier in the region at the moment (Silvrettagletscher). If this glacier is lost (in 30 years?) there is no need / possibility for continued glacier monitoring. No replacement is required for Pizolgletscher as glaciation in this region is very limited already now.
- **Linth basin:** One of the largest glaciers (Claridenfirn) is expected to remain in the network for several decades. No need for action.
- **Ticino / Maggia basins:** Monitoring is performed on the largest glacier in the region at the moment (Ghiacciaio del Basòdino). If this glacier is lost (in 20 years?) there is no need / possibility for continued glacier monitoring.

The above assessment clearly indicates that replacement glaciers are needed for the Reuss and the Inn basins, as presently monitoring is performed on two very small glaciers where direct mass balance observations will have to be abandoned within the next 5-10 years. In most basins, significantly larger glaciers are present emphasizing the need of shifting activities to sites that are more resilient to climate change.

The selection of potential new sites for long-term glacier monitoring should follow the criteria formulated in Chapter 1. Many of the present monitoring sites have not been selected based on such a detailed evaluation process as measurements were often started in relation to specific projects and other local interests and were subsequently continued / integrated into national monitoring activities. Furthermore, the selection strongly depends on the weighting of the five criteria. For the present selection process, we attribute a high weight to the resilience of the glaciers to climate change. Whereas for the Reuss basin, two potential glaciers were detected for closer inspection (Hüfifirn, Brunnifirn), one glacier was detected for the Inn basin (Fig. 2). A more detailed description of these sites is provided in Chapter 3.

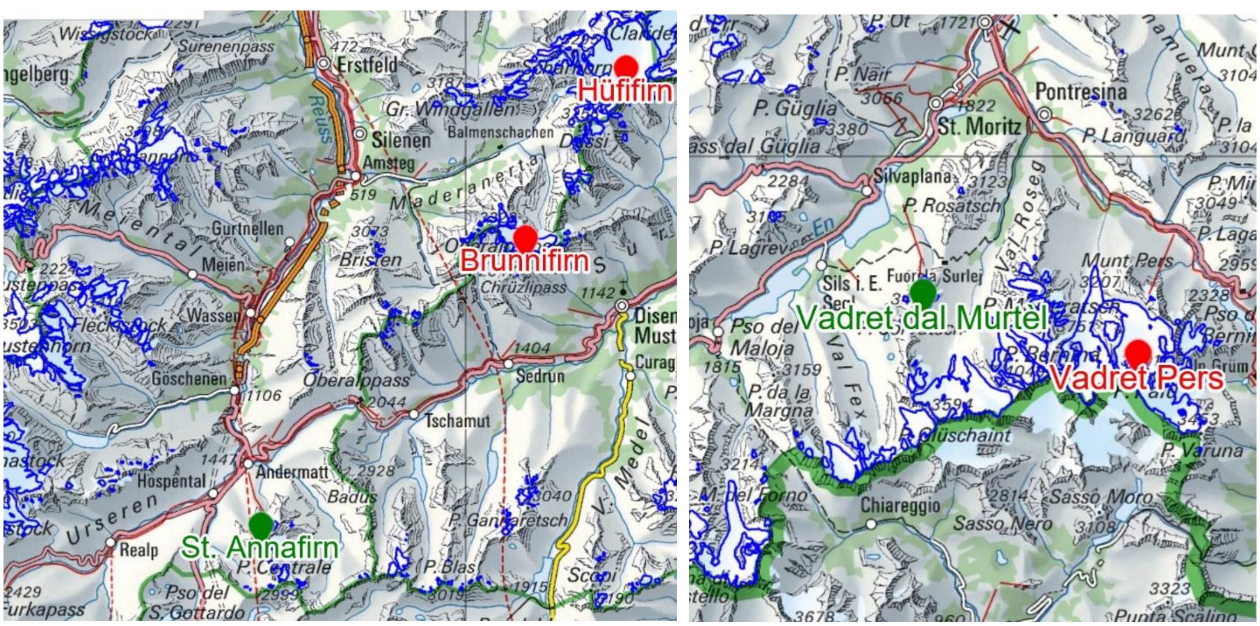

Figure 2: Regional overview of the Reuss basin (left) and the Inn basin (right). St. Annafirn (previous representative within GLAMOS for the Reuss basin) is indicated in green, Hüfifirn and Brunnifirn, potential replacement glaciers in red. Vadret dal Murtèl (previous representative within GLAMOS for the Inn basin) is indicated in green, Vadret Pers, a potential replacement glacier, in red.

3. Description of potential sites and assessment of available data

Table 1 summarizes the topographical characteristics of the three sites selected for closer inspection (*Reuss*: Hüfi, Brunni; *Inn*: Pers) and the sites are described below. **For both basins no other similarly suitable sites given the above criteria have been detected and the detailed assessment is limited to these three glaciers.** The *survival time* is estimated as a lower bound. With a favourable evolution of climate, longer *survival times* are possible.

Glacier	Area	Elevation range	*Survival year/time*
Hüfifirn (Reuss)	12.7 km^2	1840-3180 m a.s.l.	2080 (60 years)
Brunnifirn (Reuss)	2.3 km^2	2560-3280 m a.s.l.	2050 (30 years)
Vadret Pers (Inn)	7.0 km^2	2360-3900 m a.s.l.	2070 (50 years)

Table 1: Characteristics of the three glaciers selected for in-depth evaluation of suitability. Areas and elevation ranges refer to approx. 2015.

3.1. Hüfifirn

Hüfifirn is by far the largest glacier in Reuss basin with a current area of almost 13 km^2. It is located in the eastern part of the Reuss basin, in the Maderanertal, at the border between the cantons of Uri and Glarus (Fig. 3). In its accumulation area, the glacier is partly connected to Claridenfirn (Linth basin) that is already included in GLAMOS. Hüfifirn is a schoolbook type of a glacier with a wide and gently-sloping accumulation area and a well-developed glacier tongue. Although the glacier only reaches barely above the level of 3000 m a.s.l. (Table 1) the region is characterized by high snow accumulation rates and a relatively low equilibrium line altitude. The accumulation area and most of the glacier tongue only show limited crevassing, whereas the lowest part of the glacier is presently inaccessible due to an ice fall. General field-site accessibility is moderate – no roads or other touristic transportation are nearby. Two mountain huts close to the glacier offer lodging (Planurahütte, Hüfihütte).

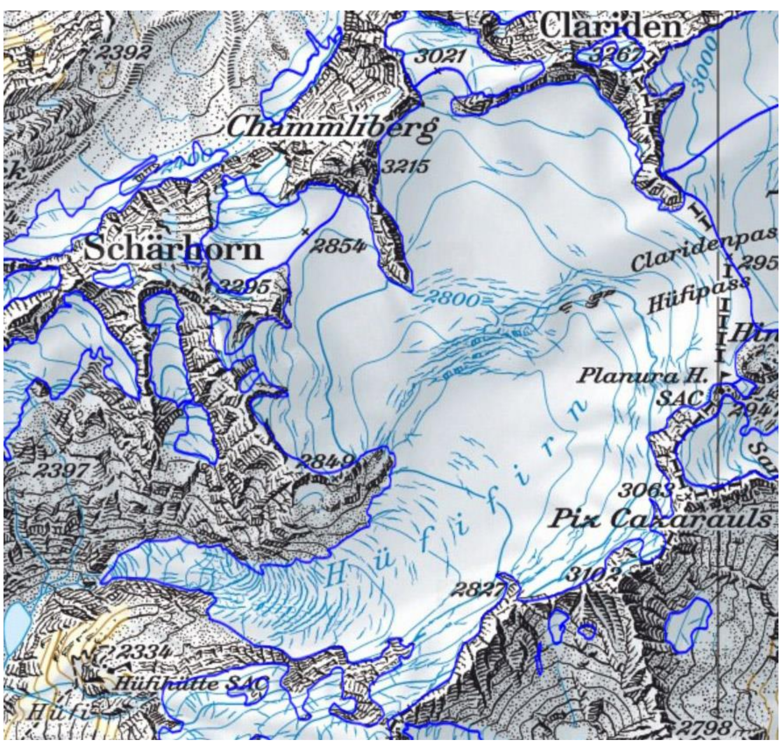

Figure 3: Overview map of Hüfifirn. The map and the outline refer to about the year 2010 (Fischer et al., 2014).

No direct observations of mass balance are available for Hüfifirn. Length change measurements were performed continuously between 1882 and 2010 but are interrupted since then due to inaccessibility of the glacier terminus. An evaluation of geodetic mass balances acquired by Fischer et al. (2015) by comparing the DHM25 digital elevation models from the 1980s with the swissALTI^{3D} product (around the year 2010) for all Swiss glaciers allows assessing the regional representativeness of Hüfifirn (Fig. 4). For the Reuss basin, the long-term average mass balance of Hüfifirn is more negative than the median relative to all 161 glaciers, but at the median value for large glaciers. Hüfifirn can therefore be considered as suitable for monitoring the regional mass balance at seasonal/annual resolution. Moreover, the value for 1980-2010 agrees well with the long-term mass balance of the current representative for the Reuss basin (St. Annafirn).

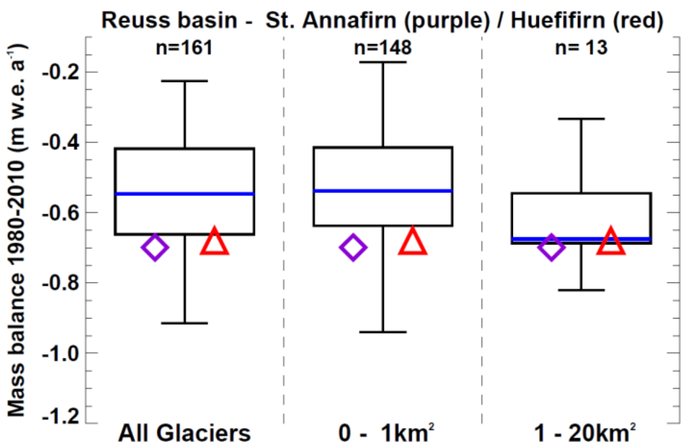

Figure 4: Statistical distribution of geodetic glacier mass balances between 1980-2010 (Fischer et al., 2015) in the Reuss basin, for all glaciers, as well as specified for glaciers smaller or larger than 1 km^2. Boxes show the 25% and 75% quantiles, bars include 95% of the data. The median is given by the blue line. The value for St. Annafirn (current representative for the Reuss basin within GLAMOS) is shown with the purple diamond, the mass balance 1980-2010 for Hüfifirn is indicated with the red triangle.

3.2. Brunnifirn

Brunnifirn is a medium-sized glacier with an area of somewhat more than 2 km^2 in the southeast of the Reuss basin, also located in the Maderanertal. The glacier is characterized by a wide and gently-sloping lower part of the glacier and a relatively steep and narrow, southeast-facing upper part towards the summit of Oberalpstock (Fig. 5). The glacier is located at the border between the cantons of Uri and Graubünden. With an elevation range of between 2600 and 3200 m .a.s.l. the glacier is located rather low. Crevassing is relatively limited on the entire glacier. The glacier is relatively well-accessible during winter from the Disentis ski area but is quite remote during summer. A mountain hut close to the glacier (Cavardirashütte) provides lodging.

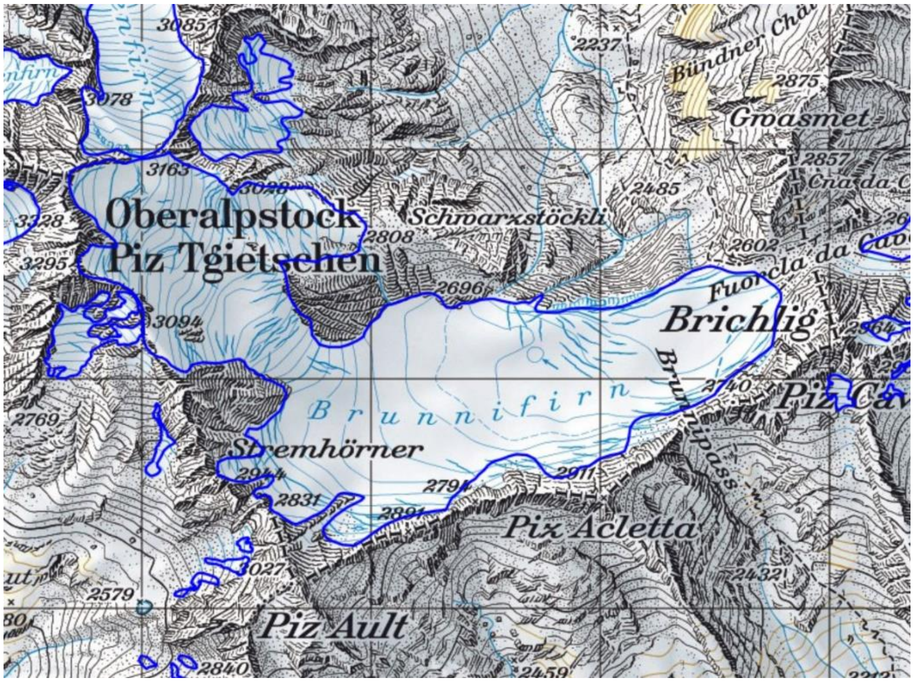

Figure 5: Overview map of Brunnifirn. The map and the outline refer to about the year 2010.

No direct observations of mass balance are available for Brunnifirn. Length change measurements were performed almost continuously between 1882 and 2017. Geodetic mass balances indicate that the long-term average mass balance of Brunnifirn is more negative than the median relative to all 161 glaciers, but at the median value for large glaciers. Brunnifirn can therefore be considered as suitable for monitoring the regional mass balance at seasonal/annual resolution (Fig. 6). Moreover, the value for 1980-2010 agrees well with the long-term mass balance of the current representative for the Reuss basin (St. Annafirn).

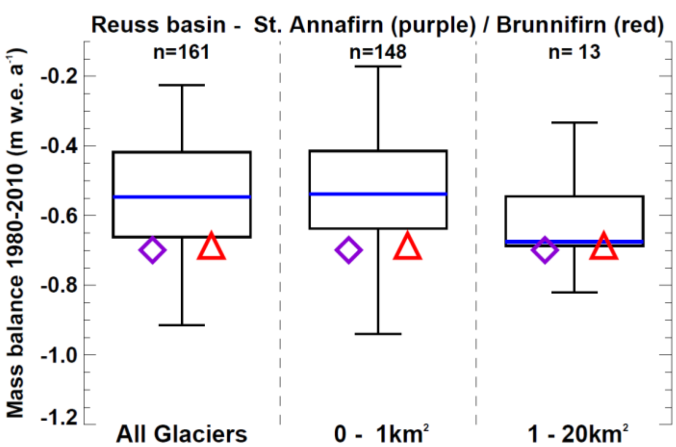

Figure 6: Statistical distribution of geodetic glacier mass balances between 1980-2010 (Fischer et al., 2015) in the Reuss basin, for all glaciers, as well as specified for glaciers smaller or larger than 1 km^2. Boxes show the 25% and 75% quantiles, bars include 95% of the data. The median is given by the blue line. The value for St. Annafirn (current representative for the Reuss basin within GLAMOS) is shown with the purple diamond, the mass balance 1980-2010 for Brunnifirn is indicated with the red triangle.

3.3. Vadret Pers

Vadret Pers is the largest tributary to Vadret da Morteratsch, but its tongue is now detaching from its parent glacier. Therefore, Vadret Pers can be considered as a new and separate glacier from now on. The Morteratsch glacier system contains by far the largest ice volume in the Inn basin and is therefore attractive for monitoring. Vadret Pers currently has an area of about 7.0 km^2. It has a narrow and relatively steep and crevassed tongue, a wide and gently-sloping central part, encompassing most of the glacier area, and very steep and mostly inaccessible accumulation area (Fig. 7). Crevassing is relatively limited over most of the glacier but high above an elevation of 3100 m a.s.l. strongly limiting accessibility. Field-site accessibility is facilitated by the cable car to Diavolezza, where also lodging is available.

Figure 7: Overview map of Vadret Pers. The map and the outline refer to about the year 2010.

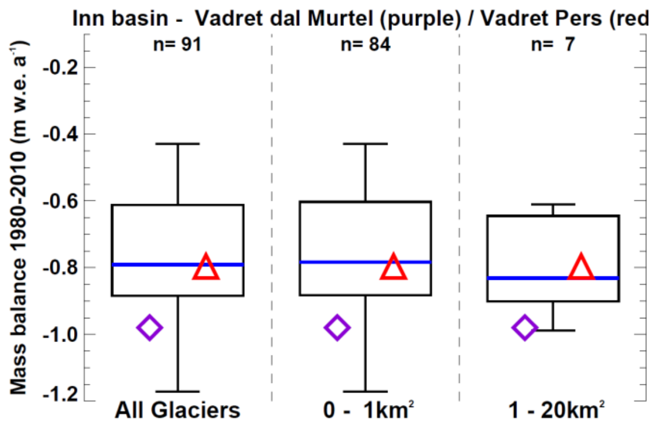

Figure 8: Statistical distribution of geodetic glacier mass balances between 1980-2010 (Fischer et al., 2015) in the Inn basin, for all glaciers, as well as specified for glaciers smaller or larger than 1 km^2. Boxes show the 25% and 75% quantiles, bars include 95% of the data. The median is given by the blue line. The value for Vadret dal Murtèl (current representative for the Inn basin within GLAMOS) is shown with the purple diamond, the mass balance 1980-2010 for Vadret da Morteratsch (parent of Vadret Pers) is indicated with the red triangle.

For Vadret Pers (and Vadret da Morteratsch) direct mass balance measurement are available. Since 2002 Belgium scientists are observing annual mass balance at a network of about 15 stakes over the Morteratsch glacier system (e.g., Nemec et al., 2009; Zekollari et al., 2014; Zekollari&Huybrechts, 2018). These observations were never intended as a full mass balance monitoring programme, and measurement sites are only in the ablation area and not all stakes have continuous time series. So far, these measurements were not included in the activities of GLAMOS but are publicly available now (Zekollari&Huybrechts, 2018). An evaluation of the glacier-wide mass balance of Vadret Pers / Vadret da Morteratsch back to 2002 would thus be possible based on established methods (Zemp et al., 2013; Huss et al., 2015), thus strongly extending the overlap with measurements on other glaciers.

In addition, length change measurements are available for the terminus of Morteratsch over the period 1878-2017, as well as geodetic mass changes over the period 1935-2015. Geodetic mass balances indicate that the long-term average mass balance of the Morteratsch glacier system corresponds well to the median of all 91 glaciers in the Inn basin, both for small and large glaciers. It can therefore be considered as suitable for monitoring the regional mass balance at seasonal/annual resolution (Fig. 8).

4. Potential monitoring programmes

4.1. Hüfifirn

4.1.1. Measurement network

Figure 9 shows a proposed potential monitoring network on Hüfifirn. The nine mass balance stakes are distributed over the entire glacier except for the very lowest part of the glacier tongue (inaccessible). All potential monitoring sites are well-accessible and are located in regions with few crevasses and small surface slopes. In a typical year (no extreme melt rates), it is expected that four stakes are in the accumulation area (Table 2). The stakes are located between 2350 and 2950 m a.s.l. The point measurement density of 0.7 per km^2 is relatively small but comparable to monitoring programmes on other glaciers larger than 10 km^2 (e.g. Rhone, Findelen). Expected rates of mass gain/loss at the potential measurement sites (Table 2) have been estimated based on observations on nearby Claridenfirn.

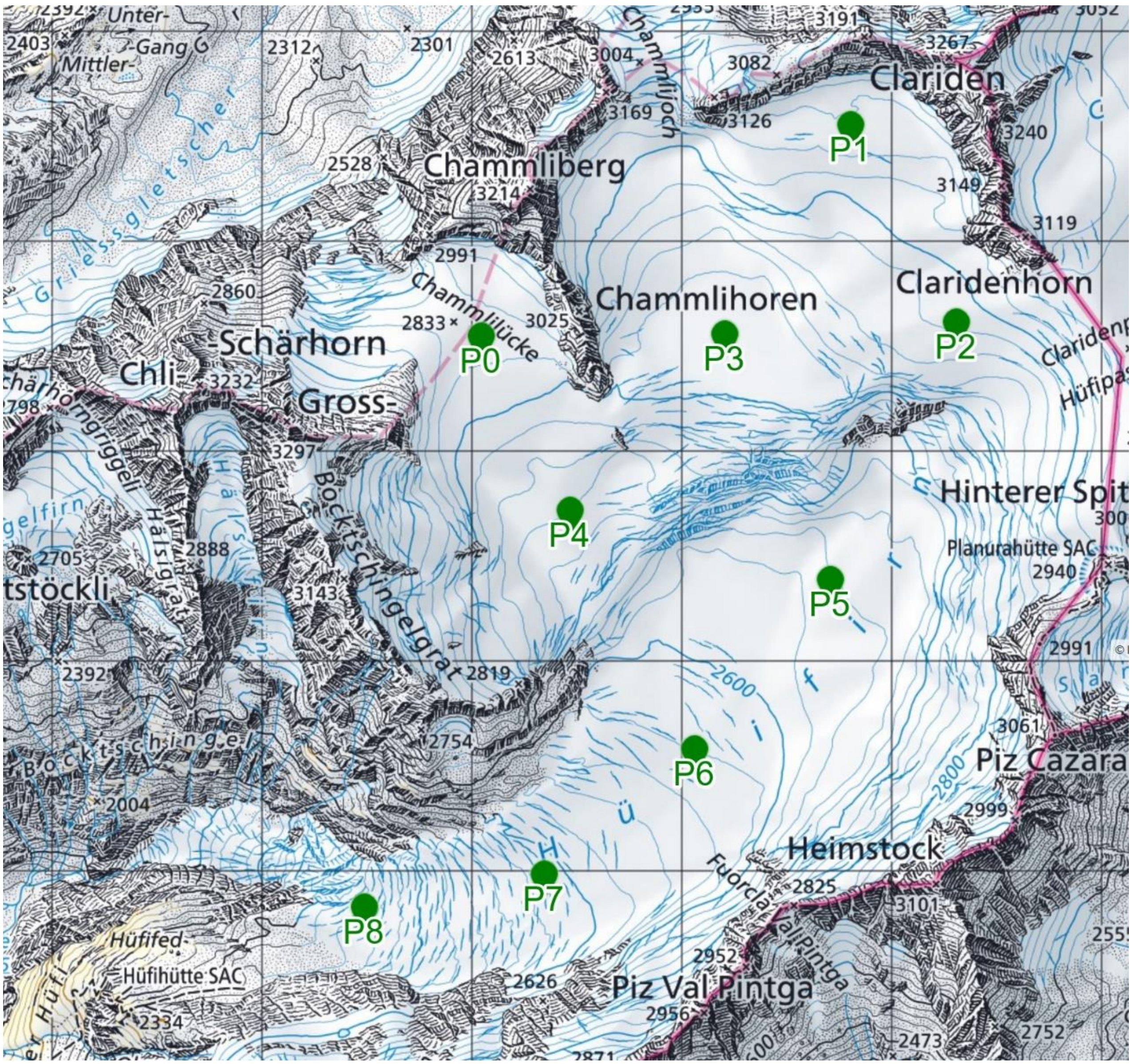

Figure 9: Potential stake network on Hüfifirn.

No. of sites in accumulation area	**4**
No. of sites close to ELA	**2**
No. of sites in ablation area	**3**
Measurement point density	**0.7 km^{-2}**
Highest measurement site	**2950 m a.s.l.**
Lowest measurement site	**2350 m a.s.l.**
Expected mass balance at highest site	**+1 m w.e.**
Expected mass balance at lowest site	**–4.5 m w.e.**

Table 2: General statistics on the potential stake network on Hüfifirn.

4.1.2. Field campaign logistics

Hüfifirn is a relatively remote glacier where efficient and safe measurements are only possible with helicopter support (Fig. 10). For both the winter and the late summer field campaigns, **three to four persons and one day** is required.

Winter campaign:

1. Helicopter transport to P1
2. Snow probings (**two teams**) on the entire glacier with snow density measurements at P1, P5, P8
3. Helicopter transport from P8

Remarks: Alternatively, lodging at Planurahütte after the measurements could be considered with an early descent to Klausenpass the next day, or combination with the Clariden field campaign.

Late summer campaign:

1. Helicopter transport to P1
2. Visit and redrill all stakes (**one team**, three persons), firn density measurements at P1, (P2, P3, P0)
3. Helicopter transport from P8

Remarks: Alternatively, lodging at Hüfi-/Planurahütte after the measurements could be considered with a combination with the Clariden field campaign.

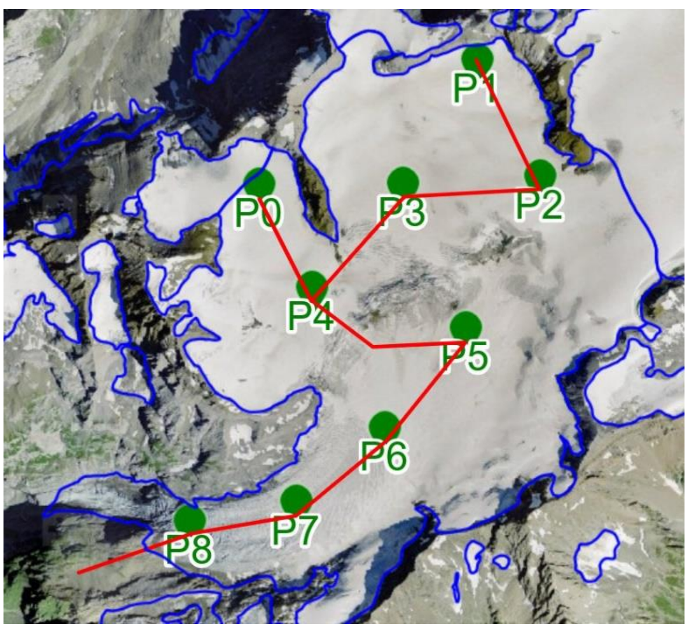

Figure 10: Potential route for visiting all measurement sites during the late summer field survey for Hüfifirn.

4.1.3. Potential opportunities and problems (advantage / disadvantage)

Advantages:

1. By far the largest glacier in the Reuss basin; observations are likely to be possible for a long period
2. Hüfifirn is typical for a Swiss valley glacier, and its past geodetic mass balance was representative
3. Almost the entire glacier surface can be covered by direct measurements; limited crevassing, gentle slopes
4. Possible synergies with monitoring of Claridenfirn due to connection in the accumulation area

Disadvantages:

1. Due to the remoteness of the site, an efficient and safe monitoring requires up to four helicopter flights per year (in/out in winter/summer). This causes higher costs and a significant dependence on weather conditions. Ground-access would be feasible but difficult with field equipment (via Klausenpass) and double the work duration.
2. Hüfifirn is very close to the existing long-term observations on Claridenfirn (although located in a different hydrological catchment). Thus, the spatial distribution of measurements is not optimal regarding the overall network.
3. Potential formation of new glacial lakes, influencing ablation rates (see Section 4.2.3 for details).

4.2. Brunnifirn (Reuss)

4.2.1. Measurement network

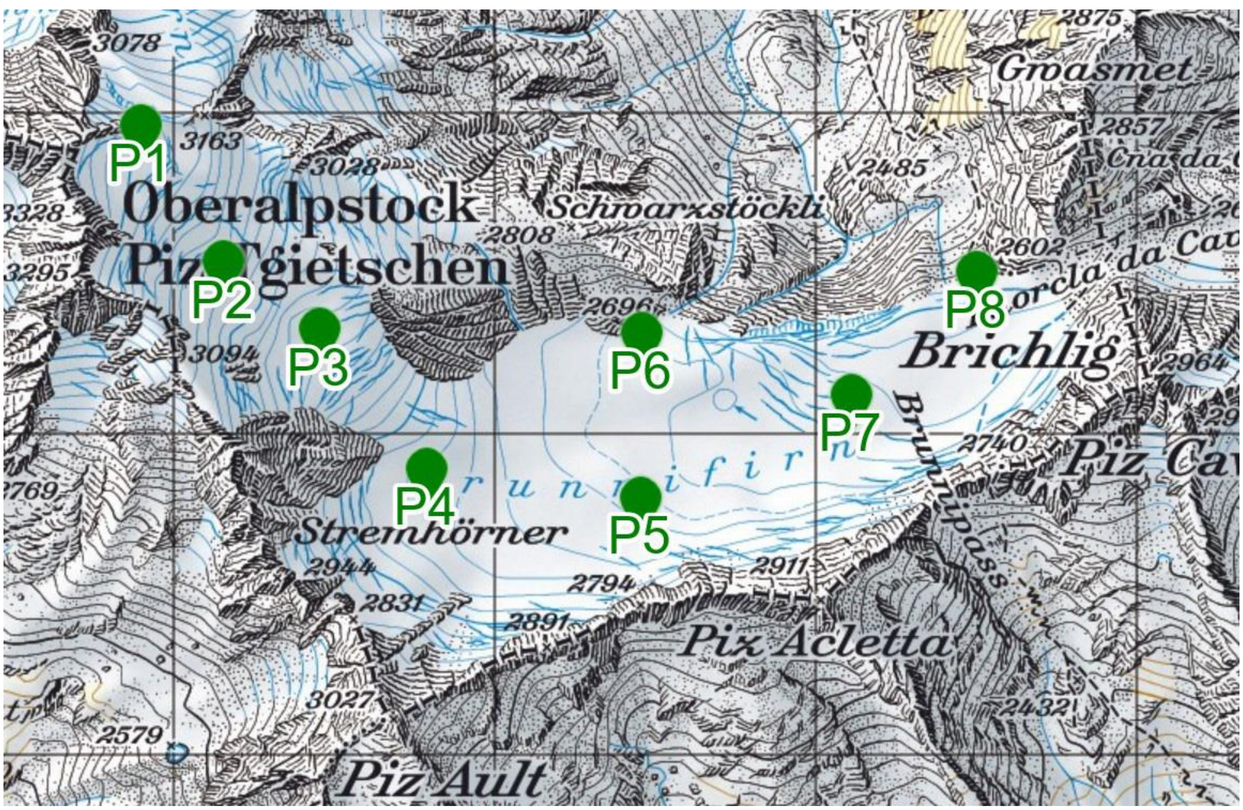

Figure 11: Potential stake network on Brunnifirn.

Figure 11 shows a proposed potential monitoring network on Brunnifirn. The eight mass balance stakes are distributed over the entire glacier. All potential monitoring sites are well-accessible and are located in regions with few crevasses and relatively small surface slopes. In a typical year (no extreme melt rates), it is expected that two stakes are in the accumulation area (Table 3). The stakes are located between 2580 and 3180 m a.s.l. The point measurement density is 3.4 per km^2 and, thus, similar as on other glaciers in this size class (e.g. Silvretta, Gries, Basòdino). Expected rates of mass gain/loss at the potential measurement sites (Table 3) have been estimated based on the location of the equilibrium line altitude and mass balance gradients.

No. of sites in accumulation area	**2**
No. of sites close to ELA	**2**
No. of sites in ablation area	**4**
Measurement point density	**3.4 km^{-2}**
Highest measurement site	**3180 m a.s.l.**
Lowest measurement site	**2580 m a.s.l.**
Expected mass balance at highest site	**+0.5 m w.e.**
Expected mass balance at lowest site	**–3.5 m w.e.**

Table 2: General statistics on the potential stake network on Brunnifirn.

4.2.2. Field campaign logistics

Brunnifirn is relatively well-accessible in winter, but remote during summer, thus requiring helicopter support (Fig. 12). For both the winter and the late summer field campaigns, **two to three persons and one day** is required.

Winter campaign:

1. Helicopter transport to P1
2. Snow probings (**one team**) on the entire glacier with snow density measurements at P1, P4, P8
3. Via Brunnipass or Piz Ault back into the ski area of Disentis

Remarks: Alternatively, ascent to P1 without helicopter support via Piz Ault would be possible, but time-consuming and probably only feasible with subsequent lodging at Cavardirashütte.

Late summer campaign:

1. Helicopter transport to P1
2. Visit and redrill all stakes (**one team**, 2-3 persons), firn density measurements at P1, (P3)
3. Walk to Caischavedra (1862 m a.s.l.) via Brunnipass (2-3h)

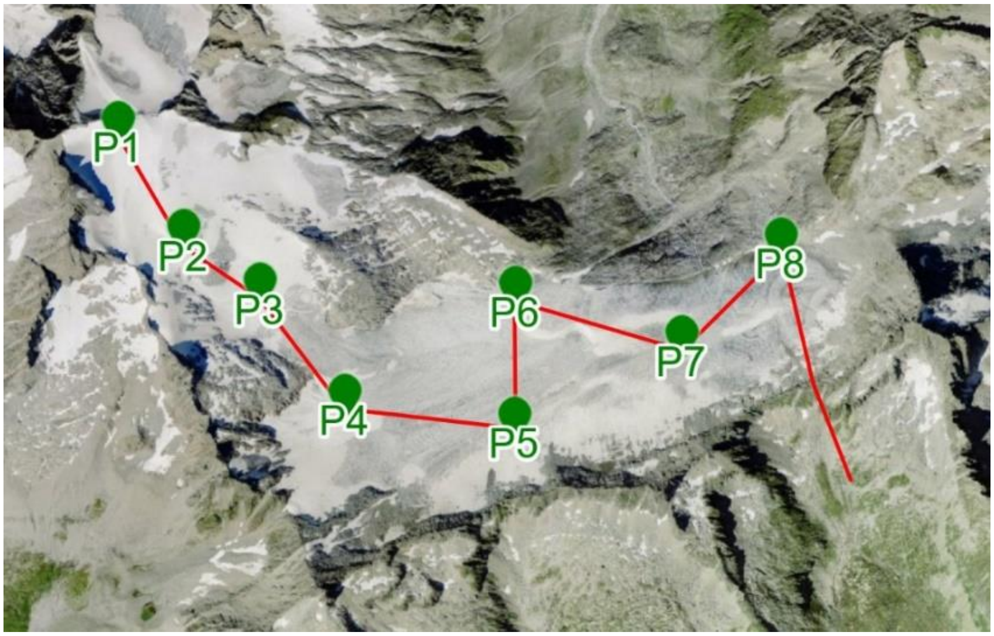

Figure 12: Potential route for visiting all measurement sites during the late summer field survey for Brunnifirn.

4.2.3. Potential opportunities and problems (advantage / disadvantage)

Advantages:

1. The entire glacier surface can be covered by direct measurements; limited crevassing, gentle slopes.
2. Although located in the Reuss basin, Brunnifirn also covers a current geographical gap in the monitoring strategy between the Gotthard region and the Engadin (Vorderrheintal).

Disadvantages:

1. Brunnifirn is only the fifth-largest glacier in the Reuss basin. Measurements are expected to be possible until somewhat after 2050, but not much longer. A detachment of the steeper accumulation zone below Oberalpstock from the flat and lower-lying main part of the glacier will likely occur in about a decade.
2. The formation of new lakes in present overdeepenings of the bedrock is likely with future glacier retreat (e.g. Haeberli et al., 2016). Studies based on the GlabTop approach (Linsbauer et al., 2012) to infer bedrock topography from ice surface features indicate that a substantial glacier lake might emerge in already a few years at the terminus of Brunnifirn (Fig. 13, Haeberli, 2016). A proglacial lake might importantly impact on ablation rates which would be difficult to be quantified. Although the size and the depth of the potential future lake at Brunnifirn is uncertain, it might have a relevant impact on a possible mass balance programme, and is considered as a disadvantage.

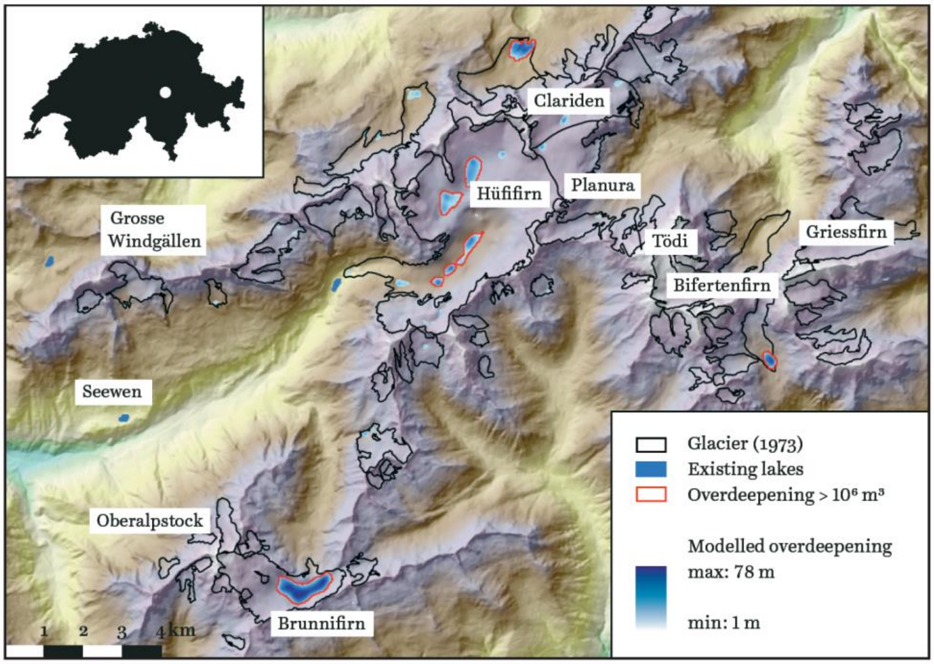

Figure 13: Potential sites for the formation of new lakes with retreating glacier termini at Brunnifirn and Hüfifirn according to Haeberli (2016).

4.2. Vadret Pers

4.2.1. Measurement network

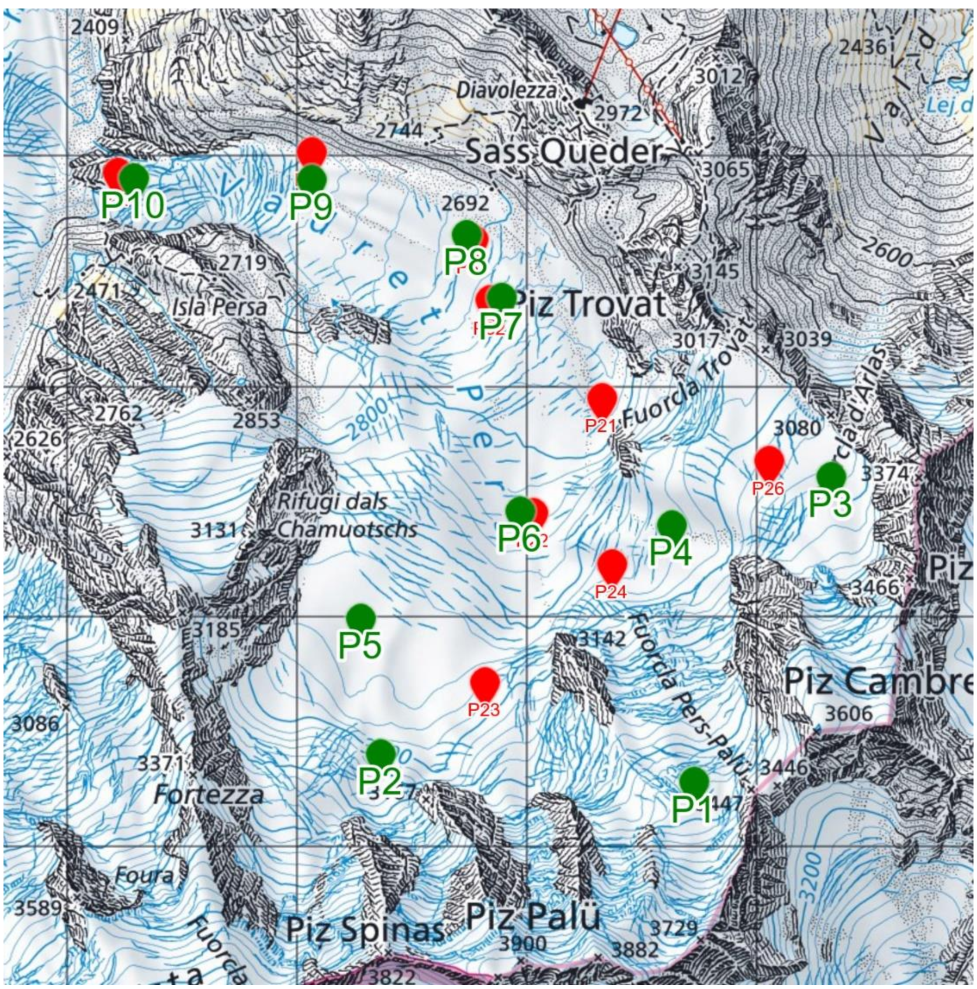

Figure 14: Potential stake network on Vadret Pers (green). Red dots indicate the location of previous stakes, partly since 2001 by Zekollari&Huybrechts (2018).

Figure 14 shows a proposed potential monitoring network on Hüfifirn. The ten mass balance stakes are distributed over the entire glacier except for the very steep upper part of the accumulation area. All potential monitoring sites are mostly well-accessible, but some are located in regions with crevasses (P1, P10). In a typical year (no extreme melt rates), it is expected that three stakes are in the accumulation area (Table 4). The stakes are located between 2460 and 3380 m a.s.l. The point measurement density of 1.4 per km^2 is in between that of large and medium-sized glaciers. Expected rates of mass gain/loss at the potential measurement sites (Table 3) have been estimated based on the observations from Zekollari&Huybrechts (2018).

No. of sites in accumulation area	**3**
No. of sites close to ELA	**2**
No. of sites in ablation area	**5**
Measurement point density	**1.4 km^{-2}**
Highest measurement site	**3380 m a.s.l.**
Lowest measurement site	**2460 m a.s.l.**
Expected mass balance at highest site	**+1.5 m w.e.**
Expected mass balance at lowest site	**–6.5 m w.e.**

Table 4: General statistics on the potential stake network on Vadret Pers.

4.2.2. Field campaign logistics

Vadret Pers is efficiently accessible via Diavolezza (Fig. 15). No helicopter support is thus necessary. For both the winter and the late summer field campaigns, **three to four persons and 1.5 days** are required. At present, monitoring at a small stake network (ablation area) at annual resolution is still carried out by the Vrije Universiteit Brussel (Belgium). A collaboration is envisaged, reducing the current efforts needed on the GLAMOS side. However, an early involvement of GLAMOS is considered important to guarantee continuity into the future and to upgrade the previous measurements to a full monitoring programme. The campaign planning below relates to the case without support from the Belgium side.

Winter campaign:

1. Night at Diavolezza and early start to P1 (alpine equipment required)
2. Snow probings (**two teams**) on the entire glacier with snow density measurements at P1, P6, P9
3. Descent to Morteratsch

Remarks: Helicopter transport to P1 would reduce the time for the entire campaign to one day.

Late summer campaign:

1. Night at Diavolezza and early start to P1 (alpine equipment required)
2. Visit and redrill all stakes (**one team**, three persons), firn density measurements at P1, (P2, P4)
3. Descent to Morteratsch, or ascent to Diavolezza

Remarks: It has to be evaluated whether the lowest stake (P10) needs to be maintained (high melt rates, difficult accessibility, not very representative within the ice fall). Helicopter transport to P1 would reduce the time for the entire campaign to one day.

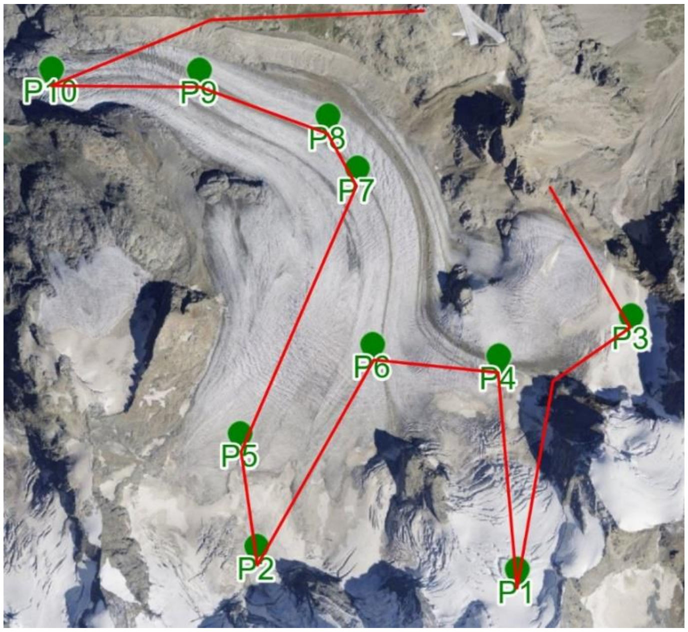

Figure 15: Potential route for visiting all measurement sites during the late summer field survey for Vadret Pers.

4.2.3. Potential opportunities and problems (advantage / disadvantage)

Advantages:

1. Largest accessible glacier in the Inn basin (Morteratsch, Roseg, Tschierva are too crevassed)
2. Excellent field-site accessibility via Diavolezza
3. Long-term mass balance measurements (16 years) already available from previous projects (Belgium scientists)
4. Most of the potential measurement sites are easily accessible (limited crevassing, gentle slopes)

Disadvantages:

1. The accumulation area of Vadret Pers is steep, subject to avalanches in winter and has many large crevasses in summer. Measurements (both in winter and summer) in the accumulation area are thus only possible at a limited extent (P1 is on a plateau on the normal route to Piz Palü).
2. Snow-/ice-avalanches might lead to a loss of some stakes (e.g. P2)

5. Conclusions

Due to the imminent loss of glacier mass balance monitoring series in the Reuss and Inn basin, potential replacement glaciers have been evaluated. Three potentially suitable sites (Hüfifirn, Brunnifirn, Vadret Pers) have been detected by applying five defined selection criteria. The feasibility of setting up long-term monitoring programmes on these sites has been assessed in detail, including the planning of field campaigns at seasonal resolution and the related efforts (in terms of time, manpower and transportation).

All sites have been found to be suitable in general, and the set-up of mass balance monitoring programmes with a perspective of several decades is feasible. Relevant drawbacks are however present for all glaciers:

- **Hüfifirn:** remoteness, need for substantial helicopter support
- **Brunnifirn:** comparably small, measurements only until 2050 (?)
- **Vadret Pers:** Difficult access to the accumulation area

Evaluations within the GLAMOS Office, the GLAMOS Scientific and Steering Committees will indicate which glacier(s) will be chosen for an onset of the monitoring in 2020.

GLAMOS Office, March 2019

(Responsibility: M. Huss)

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