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Surface mass balance monitoring of the peripheral glaciers of the Antarctic Peninsula in the context of regional climate change

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Abstract

During the second half of the 20th century, the Antarctic Peninsula region has undergone a long and sustained warming period, followed by a shorter but also sustained cooling period, and then a very recent return to warming conditions. All of these have profoundly impacted the glaciers peripheral to the Antarctic Peninsula. This paper focuses on the analysis of the surface mass balance monitoring of such glaciers by the glaciological method, complemented by the analysis of mass-balance estimates by geodetic methods, as well as frontal ablation estimates. We aim to summarize the current knowledge and outline the main challenges faced by investigating the mass balance of such peripheral glaciers and their current contribution to sea-level rise.

Motivation and current knowledge

Due to the peculiar recent climate evolution of the Antarctic Peninsula (AP) region, and the forecast of significantly changing conditions in the forthcoming decades, the studies focused on the mass balance of the AP ice sheet (APIS) and its peripheral glaciers, and their contribution to sea-level rise (SLR), are highly relevant. From the climatic point of view, the AP region showed, during the second half of the 20th century, one of the strongest warming trends on Earth, of 0.57 ± 0.2°C decade^{-1} during 1951–2001 recorded at Faraday/Vernadsky station (Vaughan and others, 2003). This was followed by a relatively short but sustained cooling period between the end of the 20th century and the mid-2010s (Turner and others, 2016), which was mostly focused on the northern AP and the South Shetland Islands (SSI) (Oliva and others, 2017), where winter (summer) temperature drops in the order of 1.0°C (0.5°C) per decade were observed between the decades 1996–2005 and 2006–15. This cooling period was followed by a return to warming conditions (Carrasco and others, 2021). Simultaneously, snowfall changes have played a dominant role in the surface mass balance (SMB) changes in the region, with multi-decadal increases inferred since the 1930s (Medley and Thomas, 2019).

From the point of view of SLR contributions, the APIS has been a significant contributor over the last few decades (Shepherd and others, 2018; Otosaka and others, accepted), mostly due to the acceleration of the outlet glaciers feeding the ice shelves following the main atmosphere-changes-driven ice-shelf disintegration events in 1995 (Larsen A) and 2002 (Larsen B) in the eastern coast of the AP (e.g. Meredith and others, 2019), with losses partially offset by increased snowfall (Fox-Kemper and others, 2021). These losses were accompanied, in the south-western coast of the AP, by ocean-induced thinning of ice shelves and their tributary glaciers, and acceleration of the latter, as well as marine-terminating glacier front retreat by increased calving (e.g. Cook and others, 2016; Hogg and others, 2017; Verfaillie and others, 2022). However, the contribution of APIS wastage to SLR to the end of the 21st century is predicted to be relatively small due to an approximate cancellation of model projections of snowfall accumulation and ice loss (Edwards and others, 2021). By contrast, the current contribution to SLR of the glaciers in the Antarctic periphery (Region 19 – Antarctic and Subantarctic in the Glacier Regions classification (GTN-G, 2017)), most of them (63% by glacier area) situated in the AP region, is currently small (Zemp and others, 2019; Hugonnet and others, 2021), but is projected to increase substantially to the end of the 21st century (Edwards and others, 2021).

In this paper, we focus on the current state and perspectives of the SMB measurements by the glaciological method on the glaciers peripheral to the AP, mostly located on its surrounding islands. The monitoring of the SMB of such glaciers is particularly relevant for various reasons:

(1) They have been shown to be extremely sensitive to changes in air temperature. For instance, distributed temperature-radiation index melt modelling by Jonsell and others (2012) on Livingston Island glaciers, SSI (Fig. 1), indicated that an increase (decrease) in mean summer surface temperature by 0.5°C implied a 56% increase (44% decrease)

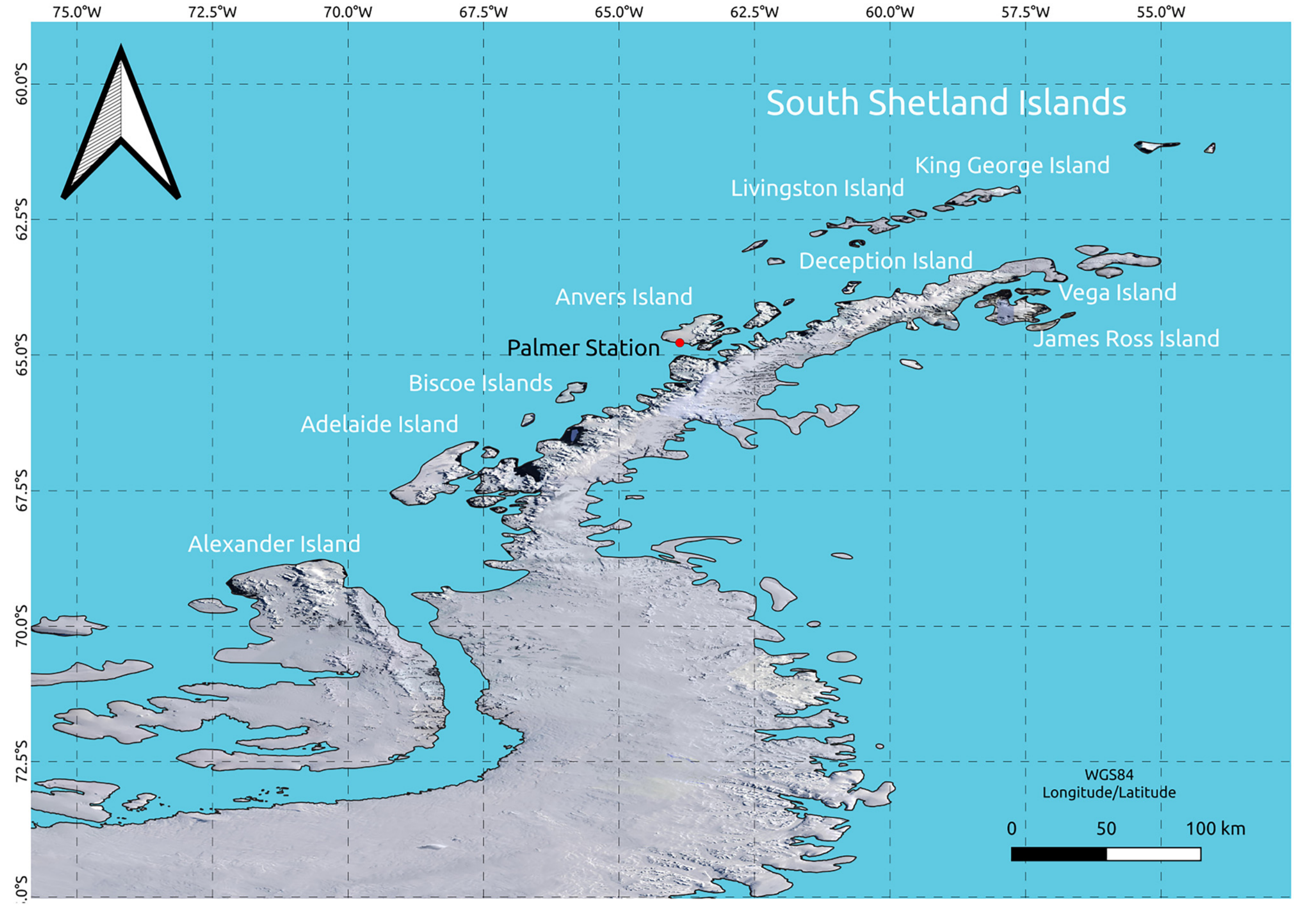

Fig. 1. Location of the various study sites mentioned in the text within the AP and the SSI.

in surface melt. The reason for this extremely high sensitivity of melt, to summer temperatures is that glacier hypsometry in the SSI is limited to a few hundred metres, and the typical mean summer surface temperatures on a large fraction of the glacier area are very close to the melting point of ice. Therefore, a small temperature change implies a shift from non-melting to melting conditions or vice versa over large areas. Precisely, as noted earlier, a ~0.5°C temperature drop in average summer surface temperature was observed in the northern AP and the SSI between the decades 1996–2005 and 2006–15 (Oliva and others, 2017).

(2) To our knowledge, only three main long-term SMB-monitoring programmes are active in the northern AP and SSI. Glaciar Bahía del Diablo, on Vega Island (since the hydrological year 2000 of the Southern Hemisphere) (Skvarca and others, 2004; Marinsek and Ermolin, 2015), Hurd and Johnsons glaciers, Livingston Island (since 2002) (Navarro and others, 2013; Recio-Blitz, 2019) and Whisky Glacier, Davies Dome and Triangular Glacier, James Ross Island (Whisky and Davies, since 2010; Triangular since 2014) (Engel and others, 2018, 2023) (Fig. 1). Of these, only Bahía del Diablo, Hurd and Johnsons data are currently reported to the Global Glacier Change Bulletin of the World Glacier Monitoring Service (WGMS, 2021). SMB fieldwork measurements on Vega and James Ross islands are carried out only once per year, so only annual SMB can be reported, while the glaciers on Livingston Island are visited at the beginning and end of each melting season, so winter and summer balances can be retrieved in addition to the annual SMB (Fig. 2). This is important for climate-related analyses, as it allows to understand whether an increase (decrease) in annual SMB is due to an increase (decrease) in winter accumulation, a decrease (increase) in summer melting or a combination of both (Navarro and others, 2013). A further interest of these measurements is that, while Hurd Glacier is land-terminating, Johnsons is a tidewater glacier, so that, while being next to each other, they have different mass loss mechanisms and dynamical responses to SMB changes. Ablation and accumulation measurements at the point level from this region are currently supplied to the WGMS database only for Glaciar Bahía del Diablo. Other regional glaciers that had brief SMB measurement periods (at the whole glacier basin level) in the past are reported in Navarro and others (2013) and Recio-Blitz (2019), and include Glacier G1, Deception Island, SSI (1969–74) (Orheim and Govorukha, 1982), Spartan Glacier, Alexander Island (1971–74) (Jamieson and Wager, 1983; Wager and Jamieson, 1983) and Bellingshausen Dome, King George Island, SSI (2008–14) (Mavlyudov, 2014) (Fig. 1).

(3) The SMB data are very useful for the calibration and/or validation of melt models. Notable examples in this region are the modelling exercises by Jonsell and others (2012), for Johnsons Glacier, Livingston Island, Falk and others (2018), for Fourcade Glacier, King George Island, and Costi and others (2018), covering most of the AP and the SSI.

(4) The SMB of land-terminating glaciers is equivalent to total mass balance (which can be determined e.g. by the geodetic method, obtaining the so-called geodetic mass balance, GMB), provided that internal and basal mass balances are negligible. Therefore, SMB and GMB of land-terminating glaciers can be used to validate each other as they employ two independent techniques (glaciological and geodetic methods,

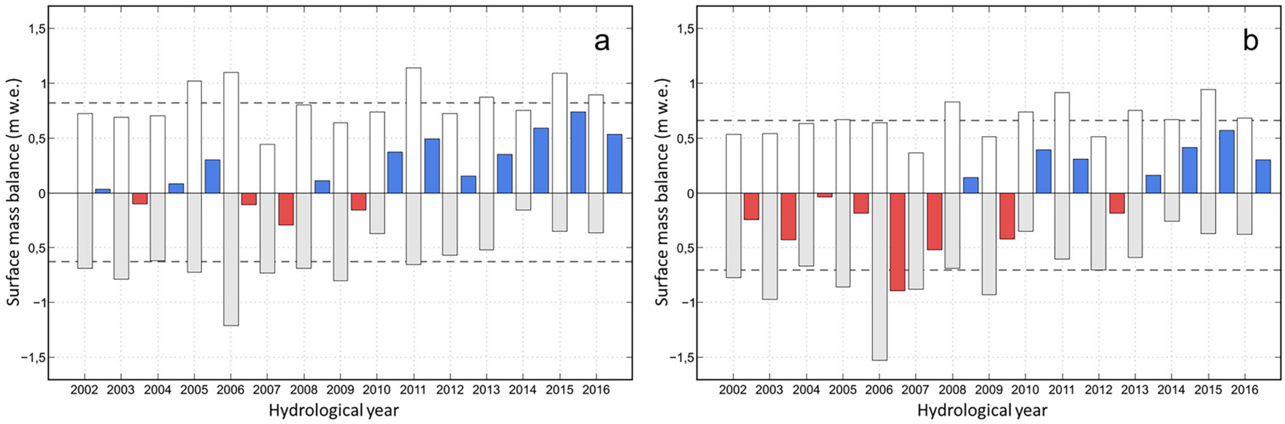

Fig. 2. SMB 2002–16 by the glaciological method of Johnsons (a) and Hurd (b) glaciers. White bars represent the winter balance, grey bars the summer balance; blue/red bars represent positive/negative (respectively) annual balance; top/bottom dashed lines indicate the average winter/summer (respectively) balances. Hydrological years are for the Southern Hemisphere (e.g. 2016 indicates the year beginning on 1 April 2015 and ending on 31 March 2016) (modified from Figs 5.6 and 5.7 of Recio-Blitz, 2019).

respectively; see e.g. Cogley and others, 2011). In particular, Zemp and others (2013) proposed a framework for reanalysing glacier mass-balance series, including tools for random and systematic error assessment, and for validation and calibration (whenever needed) of the glaciological balances using the geodetic ones.

(5) In the case of tidewater glaciers assuming the internal and basal balances are negligible, the GMB can be compared with the SMB less the frontal ablation, which can be approximated by the ice discharge if the front position changes are negligible, as done by Navarro and others (2013) for Johnsons Glacier, Livingston Island, thus providing an independent estimate of the total mass balance of the glacier.

(6) When no total mass-balance estimate is available but its two main components have been measured separately, their addition provides the missing total balance estimate. This was done e.g. by Osmanoğlu and others (2014), who combined their calculated ice discharge for the whole ice cap of Livingston Island with an estimate of the SMB across the entire glacierized area of the island. Conversely, an estimate of total mass balance can be combined with one of its measured components to obtain another, unmeasured component. For instance, the total ice discharge from King George Ice Cap computed by Osmanoğlu and others (2013) could be combined with the later estimate of GMB by Shahateet and others (2021) to get an order-of-magnitude estimate of the SMB of King George Island. Just an order-of-magnitude estimate was possible in this case because the measurement periods were very close to each other but did not overlap (2008–11 vs 2013–17, respectively), although the climate conditions in both periods were relatively similar (both within the regional cooling period). In either of the mentioned ice discharge estimates for a whole island ice cap (Livingston and King George), the main problem was the limited availability of suitable ice-thickness data close to the calving fronts. Ice discharge is computed as the flux of ice through a cross section of a glacier near its calving front (the so-called 'flux gate') (Cogley and others, 2011), so it requires the availability of ice-thickness data and a velocity field in the vicinity of the glacier terminus. Though critical, ice-thickness data are very scarce in most of the periphery of the AP. James Ross, Anvers, Biscoe, Adelaide and Alexander islands (Fig. 1) have been partially covered by airborne Alfred Wegener Institute and Operation Icebridge radar soundings (MacGregor and others, 2021), which have been used for bed reconstructions of the entire Antarctica such as Bedmap2 (Fretwell and others, 2013) or BedMachine V2 (Morlighem and others, 2020), or in bed reconstructions of the AP such as that of Huss and Farinotti (2014). Aside from these, the widest relative coverage of ground-penetrating radar (GPR) profiles on the peripheral glaciers of the AP corresponds to King George (Rückamp and Blindow, 2012) and Livingston (Macheret and others, 2009; Navarro and others, 2009) ice caps, but even for these ice caps the data coverage is incomplete.

Outlook: perspectives and challenges

From the above discussion certain research subjects arise which have great interest in the context of the glacio-climatic evolution of the glaciers peripheral to the AP. Some of them pose important challenges, as discussed below:

(1) It is critical maintaining the currently ongoing programmes of SMB measurements in the northern AP and the SSI. Losing any of them would pose severe limitations to the studies based on observations, including the calibration and validation of surface melt models, which are fundamental for estimating mass losses resulting from climate change. In particular, Glaciar Bahía del Diablo, Vega Island, programme should continue as currently executed. Given the logistic requirements, asking for measurements at the beginning and end of each melting season would be unrealistic. This glacier could be the first in the region to become a reference glacier of the WGMS (which requires 30 years of continued SMB measurements by the glaciological method). It would be of great interest that the SMB monitoring of Hurd and Johnsons glaciers, Livingston Island, would also provide to the WGMS database point data on accumulation and ablation. These two glaciers could also soon become reference glaciers of the WGMS. In the case of the SMB-monitoring programmes of Whisky Glacier, Davies Dome and Triangular Glacier, James Ross Island, it is critical that their data be supplied to the WGMS database. Having made the strong effort required to maintain such a monitoring programme for more than a decade, it makes no sense failing to invest the little added effort required to make such data part of the WGMS database.

(2) The current SMB measurement sites by the glaciological method are limited to the northern AP and the SSI. It would be interesting to incorporate additional sites at more southern locations, such as the southwestern coast of the AP. However, this poses serious difficulties, as many research stations in this region are located on small islands without access to neighbouring glaciers, or the glaciers nearby are too large to be suitably covered by glaciological method measurements at a whole-basin level or, if smaller, are not so easily accessible (e.g. the case of Rothera station, on Adelaide Island). A possibility would perhaps be Palmer station, in Anvers Island (Fig. 1), though still some of the difficulties mentioned for Rothera station remain. The inventory of peripheral glaciers of Antarctica by Bliss and others (2013) could help choose some convenient locations, provided that the logistic requirements for the deployment of a SMB-monitoring programme could be met.

(3) Given its importance for calibration and validation of SMB series, it would also be of interest to expand the set of available GMB measurements at the level of whole glacier basins (e.g. Molina and others, 2007; Navarro and others, 2013; Recio-Blitz, 2019). Also, for its importance concerning regional mass-balance estimates and contributions to SLR from glacier wastage, it would be recommended to also expand the available GMB estimates at the level of whole island ice caps (e.g. Osmanoğlu and others, 2013, 2014) or entire archipelagos (e.g. Shahateet and others, 2021). Such studies are a perfect complement to validate at the regional level global GMB estimates such as that of Hugonnet and others (2021).

(4) Analysing the mass-balance estimates of land-terminating glaciers by glaciological and geodetic methods occasionally reveals certain inconsistencies in the results (Navarro and others, in preparation). Possible reasons for this would be the fact of neglecting the internal and basal mass balances. In particular, it is difficult to estimate how much of the snow melted at the surface on the accumulation zone, which percolates into the snow or firn layers, refreezes within the current year snow layer (in which case this amount of refreezing meltwater is not accounted for as surface ablation) or within the firn layer (in which case it is accounted as internal accumulation). This is not, however, particularly relevant (except for detailed quantification of the individual mass-balance components), because the associated mass is not lost in either case. More relevant from the point of view of total mass-balance estimates is quantifying the share of surface ablation by melted – and then percolated – snow and by sublimated snow (on the ablation zone this does not matter, as both quantities eventually become part of ablation, either by surface runoff or by sublimation). Estimating sublimation requires the use of surface ablation models, which in turn require a good deal of automatic weather station data on surface temperature, wind regime and radiation components. For this reason, further modelling studies such as those done by Jonsell and others (2012) or Falk and others (2018), and references therein should also be encouraged. A second reason for the discrepancies between GMB and SMB estimates would be the failure to properly set the apparent density for converting volume changes to mass changes. It is becoming increasingly common the use of a constant factor of $850 \pm 60\ \mathrm{kg\,m^{-3}}$ for the entire glacier area, as suggested (as a general recommendation) by the excellent study of Huss (2013). However, this value could be overestimating the accumulation under a cooling climate, such as that present in the northern AP and SSI regions during the beginning of the 21st century. Perhaps a more reasonable approach would be using, as done by Recio-Blitz (2019), a factor of $600\ \mathrm{kg\,m^{-3}}$ on the accumulation zone (as a local average value for the density of the end-of-summer snow layer and that of the uppermost layer of firn) and another of $900\ \mathrm{kg\,m^{-3}}$ on the ablation zone (to account for the ice lost), or other similar values depending on the study site. In fact, Huss (2013) pointed out that the conversion factor from volume to mass changes could range, for periods with limited volume change (as is our case), between 0 and $2000\ \mathrm{kg\,m^{-3}}$ and beyond.

(5) Most of what has been discussed in (4) also applies to tidewater glaciers. However, comparing SMB and GMB estimates for the latter requires a separate estimate of frontal ablation to be subtracted from the GMB, as done in this region e.g. by Navarro and others (2013). Unfortunately, such separate estimates do not always overlap in time. On the other hand, there is a large interannual variability of ice velocity, and hence ice discharge in this region. For instance, Osmanoğlu and others (2014) quantified this interannual variability as 47% for Livingston Island glaciers during the period 2007–11. Additional analyses of temporal velocity variations in Livingston Island can be found in Sugiyama and others (2019). This large variability implies that further local estimates of frontal ablation are envisaged, which in turn require further ice discharge and front position change measurements. These are also of much interest for regional mass-balance estimates.

(6) For both land-terminating and marine-terminating ice masses, the temporal changes of the glacier outlines pose additional challenges to the mass-balance estimates using either geodetic or glaciological techniques (combined with frontal ablation estimates, for marine-terminating glaciers). Further studies such as those undertaken by Rodríguez-Cielos and others (2016), at a local level (for Hurd Peninsula glaciers, Livingston Island), or by Silva and others (2020), at the regional level, are highly recommended.

(7) The ice discharge computations, both at the level of individual glaciers (for process-oriented or detailed mass-balance studies) and at the regional level (for regional mass-balance calculations), have a major problem in this region, namely the scarcity of ice-thickness data close to the marine termini. The highly crevassed calving fronts make GPR measurements from the glacier surface nearly impossible, while from a helicopter are logistically complex and extremely expensive. Moreover, multiple diffractions from the crevasse fields and the fact that many crevasses are partially water-filled during the summer season (only period with limited helicopter availability in this region) cause a strong backscatter of the radiated energy, preventing it from reaching the glacier–bed interface. In theory, this lack of ice-thickness data could be alleviated by the use of ice-thickness inversion from other available surface data such as surface topography, surface velocity, surface elevation change rates or SMB, as done for the SSI by Osmanoğlu and others (2013, 2014). However, this is also challenging because ice-thickness data are still required for calibration of the inversion models, and it happens that (i) near the calving fronts, where good remotely sensed surface velocities are available, proper ice-thickness data are unavailable, whereas (ii) near the ice divides, where good ice-thickness data have been properly retrieved from GPR records, surface velocity is not only very small (by definition of ice divide) but also nearly impossible to retrieve from remote-sensing data. The latter is due to the gentle slopes and the homogeneity of the snow surfaces, which make both D-InSAR and offset-tracking techniques inefficient or impossible. For this reason, ice velocities determined from observations at the glacier surface using GNSS techniques

(e.g. Machío and others, 2017) are useful. They can also be used for the calibration of velocities determined from satellite observations. In any case, the collection of further ice-thickness data for the AP peripheral glaciers is urgently needed. It is also strongly recommended that any new data acquisition be made part of the Glacier Ice Thickness Database (GlaThiDa Consortium, 2020; Welty and others, 2020).

In summary, we face many challenges in estimating the mass balance of the glaciers in the periphery of the AP and its current contribution to SLR. This brief paper was envisaged as a contribution to outline which are, in our opinion, the most critical ones, as well as providing some hints for tackling them.

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