The Cryosphere Discuss., 6, 3667–3702, 2012
www.the-cryosphere-discuss.net/6/3667/2012/
doi:10.5194/tcd-6-3667-2012

The Cryosphere Discussions

An updated and quality controlled surface mass balance dataset for Antarctica

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Received: 31 July 2012 – Accepted: 1 August 2012 – Published: 3 September 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We present an updated and quality controlled surface mass balance (SMB) database for the Antarctic ice sheet. We retrieved a total of 5284 SMB data documented with important meta-data, to which a filter was applied to discard data with limited spatial and temporal representativeness, too small measurement accuracy, or lack of quality control. A total of 3438 reliable data was obtained, which is about four times more than by applying the same data filtering process to previously available databases. New important data with high spatial resolution are now available over long traverses, and at low elevation in some areas. However, the quality control led to a considerable reduction in the spatial density of data in several regions, particularly over West Antarctica. Over interior plateaus, where the SMB is low, the spatial density of measurements remained high. This quality controlled dataset was compared to results from ERA-Interim reanalysis to assess model representativeness over Antarctica, and also to identify large areas where data gaps impede model validation. Except for very few areas (e.g. Adelie Land), the elevation range between 200 m and 1000 m a.s.l. is not correctly sampled in the field, and measurements do not allow a thorough validation of models in regions with complex topography, where the highest scattering of SMB values is reported. Clearly, increasing the spatial density of field measurements at low elevations, in the Antarctic Peninsula and in West Antarctica remains a scientific priority.

1 Introduction

In the context of global warming, particular attention is being paid to the mass balance of the Antarctic ice sheet (AIS) and its impact on sea level rise (Lemke et al., 2007). A recent study by Rignot et al. (2011) suggests that the Antarctic surface mass balance (SMB) decreased in the last decade, contributing 5.5 ± 2 Gt yr^{-2} to sea level rise since 1992. However, interpreting this result as definitive would be premature given the uncertainty of SMB measurements and interpretations. For instance, other studies (e.g. Monaghan et al., 2006b) suggested that precipitation over Antarctica has been stable since the 1950s. While on the other hand, a slight increase in surface elevation has been observed in the interior of the continent, suggesting a recent mass gain (e.g. Helsen et al., 2008). These contradictions underline the lack of reliable information concerning the Antarctic SMB and its recent variations.

Even though several techniques have been developed to assess the SMB in the field (see Eisen et al., 2009, for a review), direct SMB measurements are rare in Antarctica and those that exist are generally local (e.g. stake and ice core measurements). The size and remoteness of the AIS and the harsh climatic conditions make long-term measurements difficult. All the available data have only been compiled once previously by Vaughan and Russel (1997). This Antarctica database (hereafter referred to as V99) was described in detail by Vaughan et al. (1999). With 1860 field data, the V99 database legitimately became a reference for climate studies in Antarctica and was regularly used for model validation (e.g. Van de Berg et al., 2006; Krinner et al., 2007, 2008; Lenaerts et al., 2012). However, only partial updates have been undertaken since 1999 (e.g. Magand et al., 2007; Van de Berg et al., 2006; Lenaerts et al., 2012), even if important new datasets have been compiled since 1999. For instance, during the last international polar year 2007–2008 (IPY), several inland traverses were performed with a range of scientific goals, including filling the gaps in SMB measurements.

Based on the V99 database, several authors interpolated the SMB data to the whole AIS. The current surface accumulation value integrated over the grounded ice-sheet is generally assumed to range between 143 mm w.e. a^{-1} (Arthern et al., 2006) and 168 mm w.e. a^{-1} (Van de Berg et al., 2006). These two studies are generally considered to be the most reliable because computations included interpolation methods to accurately fit the observed SMB from the V99 database (Monaghan et al., 2006a). However, these values should be considered with caution because a reliability check of the data in the V99 dataset, as proposed by Magand et al. (2007), was not performed before interpolating field data. Indeed, different problems affect estimates of the

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Antarctic SMB, particularly limited or unwarranted spatial and temporal coverage and measurement inaccuracy (Magand et al., 2007). Biased surface measurements can strongly affect the final estimation of the SMB for the whole of Antarctica (e.g. Genthon et al., 2009; Lenaerts et al., 2012). Such a bias was observed by Verfaillie et al. (2012) who identified a serious discrepancy between the SMB of Arthern et al. (2006) and recently updated SMB estimates for Adelie Land.

Here, we present an updated SMB database for Antarctica. An important part of the work was documentation of so-called "meta-data" (e.g. time coverage, measurement methods, altitude), which is required when using data, especially to check the quality of the SMB values. Next, in Sect. 2, we present the updated database, and we describe the improvements in spatial coverage and compare the data with the V99 dataset (Sect. 2.2). A quality control was conducted by rejecting all unreliable data (Sect. 2.3). The impact of this quality control on the spatial distribution of reliable data over Antarctica is discussed in Sect. 2.4. In Sect. 3, we compare the data with ERA-Interim reanalysis, and show the importance of the selected data for climate model validation. The comparison highlights the remaining gaps in the spatial coverage of surface mass balance data in Antarctica and biases that can occur when interpolating these data. Finally, in Sect. 4, we discuss the main gaps in the SMB database and suggest ways to achieve a better estimate of the Antarctic SMB.

2 The new "SAMBA-LGGE" SMB database

2.1 Definitions

The surface mass balance (or net accumulation of snow/ice; hereafter referred to as SMB) can be expressed as the balance between the accumulation and ablation terms as follows:

$$\mathrm{SMB} = P_\mathrm{S} + P_\mathrm{L} - E - S - R \quad (\text{in mm w.e. a}^{-1}) \tag{1}$$

where P_S, P_L, E, S and R are solid precipitation, liquid precipitation, erosion by the wind, sublimation and runoff, respectively. If E is negative at some place, it represents drifting snow deposition. Hence, SMB is the result of the competition between accumulation and ablation terms. Knowing the values of erosion or deposition is crucial in windy areas where these processes lead to extremely high spatial variability of SMB values. For instance, in the coastal area of Adelie Land, the SMB may change from negative to highly positive values within a distance of one or two kilometers (Agosta et al., 2012).

2.2 The fully updated database

Because the international polar year (IPY) recently provided a large amount of new SMB data, an update of existing SMB compilation is now timely. We consequently updated the V99 database by including the large amount of new SMB data obtained since 1999 (Fig. 1a). Important new information was obtained during the European EPICA and international TASTE-IDEA (Trans-Antarctic Scientific Traverse Expeditions – Ice Divide of East Antarctica) programs, when isolated measurements and traverses were performed, including in Dronning Maud Land (e.g. Rotschky et al., 2007), from Ross Sea to Talos Dome (French–Italian contribution to ITASE, Frezzotti et al., 2004). Measurements were also taken along the French traverse to Dome C (Agosta et al., 2012; Verfaillie et al., 2012), and from South Pole to Dronning Maud Land (Anschütz et al., 2009). A large new dataset was acquired from Zhongshan station to Dome A by the Chinese Antarctic research center (Ding et al., 2011). Traverses have also been revisited, including the Japanese traverse from Syowa (also spelled Showa) to Dome Fuji (e.g. Motoyama and Fujii, 1999; Motoyama, personal communication), resulting in a major update of SMB data from Fujiwara and Endo (1971). The SMB measurements for the Syowa to Dome Fuji traverse in the V99 database were not located exactly as described by Motoyama and Fujii (1999). We chose to not include this part of the V99 data because (1) full information on the data was not provided in Fujiwara and Endo (1971) and (2) Japanese traverses are expected to follow an almost fixed trajectory and the updated information provided by Motoyama (personal communication) was believed to be more accurate than previous information. Finally, we also present unpublished stake data from the coast to Princess Elizabeth station resulting from collaboration between the Belgian Antarctic expeditions and the French Polar Institute (IPEV) in the framework of the GLACIOCLIM observatory.

In addition to SMB values, information is also provided that is essential for a quality control, i.e. location, methodology, altitude, local mean temperature, distance to the coast, dates of measurements, SMB units in the primary data sources, time period covered by the SMB values, and primary data sources. This primary information was retrieved for both new data and for previous V99 data, which enabled the correction of several data. For instance, correction of longitude for measurements on Siple Coast was possible, thanks to the primary publication (Bindschadler et al., 1988). In some cases, if measurements were a short distance apart (within approx. 20 × 20 km), the V99 database only gives their averaged values. Instead, we documented each data point. This was mainly the case at the South Pole and along traverses around Lambert Glacier, in Wilkes Land and from Syoma to Dome Fuji (Table 1). This increases the number of available measurements by 1973 (even though data did exist in the V99 database, it was at a lower spatial resolution). Of these 1973 data, 719 from around Lambert Glacier and from Syowa to Dome A were updated using new measurements made since 1999. So we now have a more accurate description of small scale SMB spatial variability. We also added crucial information to interpret the data, for instance the snow density used for SMB calculation when the data were not expressed in mm w.e. a^{-1} (several data were originally presented in cm of ice per year). Other specific characteristics were also added, for instance, the presence of blue ice or of megadunes.

Retrieving the primary information was complex because all the information is not usually available in a single publication. After tracking down previous publications, we were able to select the most relevant data for a particular application, together with precise information on the method used and the location. This included digitalizing data from figures or maps when necessary, which is clearly indicated in the final database.

Finally, when different time periods were available for a single location (for instance, when several layers were reliably dated in ice cores), SMB estimates are given for each period.

This involved compiling and documenting more than 5539 SMB data distributed over the whole continent (Fig. 1a). Following Magand et al. (2007), we rejected data that did not correspond to measurements of annual SMB. This was the case of 255 data provided by Bull (1971) which were interpolated values from a SMB map. Moreover, as pointed out by Vaughan and Russell (1997), Bull's (1971) SMB map contains no information on references or data sources. We rapidly investigated Bull's (1971) data between Dome Fuji and South Pole and concluded that they are probably deduced from a single traverse undertaken in the area before 1971 (Fujiwara and Endo, 1971). However, according to the latter publication, these data are from stakes measured twice in less than one year, suggesting that they are not reliable, which also justified our rejection of Bull's (1971) digitalized data.

The full updated surface mass balance of Antarctica (SAMBA-LGGE) database now contains 5284 data (Table 2). This database is fully and freely available on the GLACIOLIM-SAMBA Observatory website: http://www-lgge.ujf-grenoble.fr/ServiceObs/SiteWebAntarc/database.html.

2.3 A reliable dataset extracted from our database

A first update and improvement of the V99 database was performed by Magand et al. (2007), who focused on a limited part of Antarctica (90°–180° East Antarctic sector). These authors applied a quality control to SMB estimates based on objective criteria of reliability, as initially suggested by Bull (1971). We applied the quality rating based on measurement techniques provided by Magand et al. (2007). We do not discuss the quality and reliability of the method here because this has already been done by Magand et al. (2007), but the main explanations for the data rating are summarized in Table 3. The quality control enabled us to select only reliable SMB values. The measurement techniques we considered to be very reliable are rated "A".

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Techniques judged to be less reliable are provisionally accepted and rated "B", while those deemed unreliable are rated "C" (Table 3). Like Magand et al. (2007), we also rejected data when information that was crucial for the quality control was missing, i.e. location, SMB value and unit, method and period covered (for stake data).

Results rated "A" form a new dataset of 3438 very reliable SMB values (Table 2, Fig. 1b). This is about four times more than the 745 reliable data obtained by Lenaerts et al. (2012), who conducted a similar quality control on the V99 database. Since our aim was to retrieve a high quality dataset, our data filtering may be too restrictive. Note that the fully documented database is available on the GLACIOCLIM-SAMBA website, so that any other control can be applied to the data.

2.4 Analysis of the reliable dataset

The impact of the quality control on the distribution of available data over Antarctica was tested by comparing the full database with the reliable dataset (data rated "A", Table 2). The quality control led us to remove data from large areas (Fig. 1b), mainly in West Antarctica. For instance, no measurements are available for a large area between Marie Byrd Land and the coast. This is particularly important because modelswere initially suspected to have common positive biases (i.e. overestimated SMB) comparedto surface accumulation compilations (Genthon and Krinner, 2001; Van de Berg et al., 2006). Since data are not reliable, it is difficultto know whether the models are correct or not for this area. Data availability is also particularly poor for the region from the Filchner-Ronne ice shelf to the South Pole, and for Pine Island glacier catchment, which was the site of considerable research in the past but where SMB values were usually obtained through snow stratigraphy studies (e.g. Pirrit and Doumani, 1961; Shimizu, 1964). Stratigraphy data are generally assumed to be ambiguous because precipitation is low, presents high annual variability, and is affected by strong surface snow metamorphism, resulting in partial or sometimes total obliteration of annual layering (e.g. Magand et al., 2007). Other large datasets from traverses to and around the South Pole were also excluded because the data were originally obtained from

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digitalized maps (e.g. Bull, 1971) or from snow stratigraphy studies (Brecher, 1964). Finally, the quality control resulted in a huge reduction in available SMB values at Siple Coast and on Ross ice-shelf because the data were mainly stake measurements made over a period of only one year (Bindschadler et al., 1988; Thomas et al., 1984). Because inter-annual variability of snow accumulation is large in Antarctica, a one year SMB estimate cannot be representative of the mean local SMB, and more than a 3-yr average SMB (Magand et al., 2007) is required to obtain an accurate estimate. However, this data gap is not as serious because snow accumulation on the Ross Ice Shelf does not affect the grounded ice SMB so that changes in accumulation in this area do not directly affect sea level rise. Nevertheless, surveying possible future melting over the ice shelf is an important scientific concern and obtaining SMB data there is indispensable. The proximity of the main Antarctic station (Mac Murdo station) is an ideal opportunity to plan future studies since it is the departure point for scientific research on the ice shelf.

The removal of suspicious data considerably modified the spatial distribution of the SMB. For instance, we computed the mean SMB as a function of elevation over Antarctica before and after the quality control process. There was a significant difference between 200 m a.s.l. and 2000 m a.s.l. over East Antarctica (Fig. 2a), because few observations are made in this elevation range and removing incorrect data thus had a significant impact on the mean SMB. There was a significant difference at every elevation over West Antarctica (Fig. 2b) because the number of unreliable observations is high for all elevation ranges on this side of the continent. The mean SMB of areas with field measurements (Table 4, see values in italics) over Antarctica differed significantly before (159 mm w.e. a^{-1}) and after the quality control (144 mm w.e. a^{-1}), and the difference was even higher in West Antarctica (244 versus 159 mm w.e. a^{-1}) than in East Antarctica.

After the removal of unreliable data, the SMB of Antarctica may be studied in detail. The SMB significantly increases from 200 m to 1000 m a.s.l., associated with marked scattering (Fig. 3). At higher elevations, the SMB and its scattering decreases

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progressively (between 1800 and 4000 m a.s.l.), as the SMB is very low over interior plateaus. The frequency distribution of surface elevation for the entire continent or for only the observation points differs (Fig. 4a), which means that the observations are not equally distributed as a function of altitude. Indeed, the frequency of surface elevations in Antarctica peaks at around 0 m a.s.l. (ice shelves) and at 3200 m a.s.l., with a very broad maximum between 1800 m a.s.l. and 3400 m a.s.l., whereas a narrow maximum appears at 2800 m a.s.l. in the case of SMB measurements. Although new data at low elevation were added to this dataset, low elevation areas are not sufficiently documented, considering their contribution to the total SMB and to the high spatial variability of their SMB. There is still insufficient available data and measurements were mainly made in East Antarctica. The low density of field measurements is a serious obstacle to accurately assessing the Antarctic SMB (e.g. Van de Berg et al., 2006).

Each SMB value was measured over a different period of time. Ninety percent of the periods covered less than 20 yr and 43 % less than 5 yr (Fig. 4c, d). The period the data covered is closely related to the methods used to estimate the SMB. Dating of known horizons in cores or snow pits (volcanic eruptions, nuclear tests) is accurate and provides good estimates of the SMB over long periods (15 to 60 yr). But these observations are isolated because they are difficult to perform at a high spatial density. On the other hand, stake measurements are very useful because they are generally made at a high spatial density, which allows correct sampling of the actual SMB distribution in the field. This is particularly useful in coastal areas, because stake networks provide relevant information over a wide range of elevations, and enable the increase in SMB caused by orographic precipitation to be sampled correctly (e.g. Agosta et al., 2012a,b). Stake networks also allow information to be collected on the inter-annual variability of the SMB. However, acquiring long time series requires the maintenance of a regular stake network with regular renewal of the stakes and annual assessment of stake height and density, which is difficult over long periods. For this reason, stake measurements generally cover periods of less than 10 yr. Hence, stake measurements represent the largest proportion (82 %) of observations, because several large stake networks (containing many stakes) exist but were measured only a few times.

3 Comparison of the reliable dataset with results of ERA reanalysis

3.1 A subset of our SMB database was used for the comparison with model outputs

Although inaccurate, model outputs are useful because of their global coverage and their ability to predict the future. Combining real world data with model outputs is essential both to identify biases in various models and also biases due to heterogeneous data coverage.

It is difficult to compare spotty field data and model outputs on a regular grid. For this reason, we defined a special dataset for a (basic) model validation. Because climatic models generally focus on climatic conditions at the end of the 20th century, we filtered the database for this period, to avoid possible secular climate variations. Here, we only considered data covering the last 70 yr, leading to a slight reduction in the database (52 data were removed). We are aware that this process does not remove the decadal bias of each datum because data present distinct time coverage. Now, this sub-dataset should be rescaled to a reference time period to produce a homogeneous climatology. But our purpose here was not to provide an accurate SMB map at the scale of Antarctica, but to compare the available field information with ERA-Interim data to judge if their spatial distribution is correct (or not) for model validation. In a future work, data will be rescaled against a common period to remove regional trends caused by heterogeneous coverage of time.

Several data were further left aside because the elevation (as given in published works) differed from the local elevation (in the reference concerned) was not the same as the local elevation given by the 1-km resolution digital elevation model (DEM) of Bamber et al. (2009). Differences may result from errors in compiling field data (for instance, if an elevation or geographic location was incorrectly estimated in the field). Differences can also be due to the DEM resolution (1 km), because local variations in topography may be smaller than those of the real terrain. A significant error in the DEM which may apply to several points is also possible when the slope is very steep. Consequently, we removed data for which the difference in elevation exceeded a 200 meter threshold (Fig. 5). This led to the removal of 44 observations. Finally, when validating the climate model, we noted that a few points still require a detailed analysis: 26 observations by Sinisalo et al. (2003) and 164 observations on Taylor glacier by Bliss et al. (2011) were in blue ice areas and should not be included in a validation process unless the climate model concerned took erosion and sublimation processes into account (Fig. 3).

These additional removals led to a sub-dataset totaling 3152 observations for comparison with model outputs (Table 2). In the following section, ERA-Interim SMB values are tested against this subset.

We also chose to focus on low elevation areas of Antarctica where much of the snow accumulation occurs. Seventy percent of the Antarctic SMB accumulates below 2000 m a.s.l., although this elevation range represents only 40 % of the total area of Antarctica. Low elevation areas are those where spatial variability in the SMB are the highest and where largest future changes in SMB are expected to occur in the 21st century (e.g. Krinner et al., 2007, 2008; Genthon et al., 2009; Agosta et al., 2012b). Conversely, accumulation over interior plateaus is very low (less than 50 mm w.e. a^{-1}) and rather homogeneous over long distances as the topography is flat. Thus, using dense field observations over low elevation networks is most appropriate for model validation, as already demonstrated in coastal Adelie Land where data from the GLACIOCLIM-SAMBA observatory allowed us to identify a number of discrepancies in the model (Agosta et al., 2012a). Because low elevation areas (that is, where high SMB values are observed, Fig. 4b) are under-sampled, a focus on specific areas was necessary.

We selected datasets, starting from coastal regions and extending inland, to include a high topographic contrast (between 0 m a.s.l. and 2000 m a.s.l., but sometimes extending up to 3000 m a.s.l. when data from a continuous traverse were available). Data cover the peripheral regions and key catchments of Antarctica. We also selected homogeneous data in terms of temporal coverage and methodology, and gathered data resulting from the same initial publications and origin. This led us to select the 10 datasets listed in Table 5 (Fig. 1b) along traverse lines in Adelie Land (GLACIOCLIM-SAMBA dataset), around Law Dome, from Zhongshan to Dome A, around the west side of Lambert glacier (above Mawson station), from Mirny to Vostok and from Syowa station to Dome F. Considering the spatial density of measurements, these data are particularly appropriate for model validation in coastal areas. We also selected three datasets not from traverses but from points located in Byrd region, along the Antarctic Peninsula and in Dronning Maud Land.

For Dronning Maud Land, Mirny to Vostok and Peninsula, the observations covered a wide range of elevations (Fig. 6a) and presented a very low spatial density. These values thus provide important information on the regional increase in the mean SMB, and data are also highly impacted by small scale variability due to local erosion or deposition processes (e.g. Eisen et al., 2009; Agosta et al., 2012a). Nevertheless, Byrd, Peninsula and Dronning Maud Land are useful to characterize atypical climate settings and to study these particular areas because considerable environmental changes are expected to occur there in the future. For instance, the Byrd dataset presents the particularity that SMB values are low in low elevation areas (Fig. 6b).

Among these datasets, data from the GLACIOCLIM-SAMBA dataset and at Law Dome are particularly appropriate for model validation because they have a high spatial resolution and cover a long observation period. Data from Zhongshan to Dome A (CHINARE in Fig. 6) and the west side of Lambert glacier (above Mawson station) are mainly located above 1500 m a.s.l. (Fig. 6a), which reduces their usefulness for studies on processes that take place at low elevations. Data from Showa station to Dome F traverse cover a more interesting range of elevations, but 75 % of these observations are also above 1500 m (Fig. 6a) where SMB is already low (Fig. 6b).

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3.2 Comparison between our subset of SMB data and ERA-Interim outputs

3.2.1 Available SMB from ERA-interim reanalysis

We compared the subset (i.e. the 3152 data) from our SMB database with ERA-Interim data to judge the accuracy of the ECMWF global atmospheric reanalysis data, or conversely, to correctly validate models by checking whether any areas are insufficiently documented in the database. We then focused on the datasets for elevations between 0 and 3000 m a.s.l. (Table 5).

ERA-Interim (Simmons et al., 2006) is an improved form of operational analysis for which efficient four-dimensional variational data assimilation (4-D-Var) is performed by taking additional data into account. ERA-Interim data are produced by applying the IFS model (Cy31r2 version), running in spherical harmonic representation (T255, nominal resolution of 80 km). Calculations are performed on 60 vertical levels (hybrid pressure-sigma coordinates) from the surface to the mesosphere at 0.1 hPa or 65 km. Here, we used ERA-Interim for the period 1989–2010, even though data are now available for the period 1979–1988. Data were interpolated over a 15-km Cartesian grid resulting from a stereographic projection with the standard parallel at 70° S and the Central meridian at 15° W. The liquid phase (P_L and R, see Sect. 2.1 for abbreviations) is assumed to refreeze entirely. The final SMB is thus the balance resulting from precipitation (P_S and P_L) and sublimation (S). In ERA-Interim, the model used does not account for wind erosion or deposition processes (E). Snow drift and wind processes are expected to have significant effects on SMB when wind speed is high (e.g. Gallée et al., 2012). These processes introduce a major uncertainty in SMB computations by ERA-Interim in low elevation areas. Hence, we did not focus on areas where snow erosion is the main SMB process over long distances – in this case, blue ice areas.

To compare simulated and observed SMB values, we extracted grid boxes including at least one field measurement. Each field datum was then compared to the simulated SMB of the grid cell that contained it. We also estimated the average observed SMB values included in the same model grid cell, and compared it to the SMB simulated by ERA-Interim. Finally, we compared observed and model data as a function of elevation.

3.2.2 Results

The Antarctic SMB simulated by ERA-Interim for the current period (1989–2010) was compared to our subset of measurements. Averaging ERA-Interim simulated data over the grounded ice sheet led to a mean value of 128 mm w.e. a^{-1} (4.4 mm a^{-1} in terms of sea level equivalent). This estimate is among the lowest published values (Monaghan et al., 2006a), and is well below estimates by Vaughan et al. (1999) and Arthern et al. (2006). This low value is mainly due to very low accumulation modeled at high elevations (above 2000 m a.s.l.) where ERA-Interim is known to considerably underestimate the actual amount of solid precipitation, and below 1000 m a.s.l., where ERA overestimates ablation (Fig. 7). The areas located below 1000 m a.s.l. cover a narrow belt around Antarctica in mountainous regions (the Antarctic Peninsula, in Palmer Land, along the Transantarctic mountains at 160° E and in Mary Byrd Land). This elevation range is crucial for the Antarctic SMB because it concentrates most of the total accumulated SMB.

In grid cells containing measurements, ERA-Interim values were lower than but close to mean measurements. This shows that SMB measurements are correctly reproduced by ERA-Interim. Nevertheless, for each elevation range between 200 and 1000 m a.s.l., the mean simulated SMB computed over all grid cells was significantly higher than the one computed over grid cells containing measurements (Fig. 7: red circles versus red squares). In other words, even though the ERA-simulated SMB values agree with measurements, field data mainly reflect the low SMB areas and poorly constrain areas where SMB values are high, suggesting that observations do not correctly sample the SMB between 200 and 1000 m a.s.l. (as already suggested in Sect. 3.1). Above 2500 m a.s.l., mean values (computed over Antarctica or only where observations exist) are similar, suggesting that the observation may be representative of the entire range of elevations over the icecap.

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The datasets selected at low elevations also provide interesting information. The Era-Interim simulation fits observations acceptably despite significant differences (Fig. 8). A large proportion of SMB differences are due to the biases in the surface elevation used by the model. Indeed, temperature and all related energy fluxes depend directly on elevation. However, some of the differences are directly related to the model's inability to accurately represent the actual SMB distribution in the field. For instance, ERA-Interim assumes too low albedo values at low elevations (values between 0.1 and 0.75) and calculates too high runoff and sublimation. Overestimation of melting by ERA-Interim has already been demonstrated (Agosta et al., 2012a) and the SMB in coastal areas is usually calculated by considering that liquid water entirely refreezes. However, incorrect albedo values have serious consequences for the entire surface energy balance (SEB), for instance on sublimation. Finally, this comparison provided useful information on how to design a network for correct estimation of SMB at regional scale. Because at a 1-km scale, SMB variability is very large in coastal areas (see GLACIOCLIM-SAMBA, Showa station to Dome F, and Zhongshan to Dome A traverses for instance, Fig. 8a, f, e), using point data every 10 or 50 km (see Law Dome for instance, Fig. 8c) does not distinguish the regional mean from local variability. A survey of dense stake networks is clearly better in such cases. Another way to obtain a better estimate of spatial variability may be to use ground penetration radar (GPR) data to interpolate SMB point estimates from ice cores (e.g. Verfaillie et al., 2012).

4 Discussion and conclusion

In this paper, we present an up-to-date surface mass balance database for the entire Antarctic continent, including relevant information about the data (location, measurement methods, time period covered, specificity of the data, references) and recommendations for the use of data in particular regions. This database was carefully checked with a quality control. This method of selection was designed to keep only highly reliable data. The quality control led to a significant change in data distribution over Antarctica

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and in mean regional values. But, as already shown by Magand et al. (2007), this process removes suspicious data that could have a major impact on any kind of SMB interpolation (e.g. Magand et al., 2007; Genthon et al., 2009; Verfaillie et al., 2012).

Inspection of our reliable dataset showed that our knowledge of SMB distribution is even weaker than we supposed, because for large areas data were shown to be unreliable. This is particularly true in the Antarctic Peninsula, in West Antarctica, and along the margins of the ice sheet. Large scale field campaigns in these regions should thus be a scientific priority, with particular focus on elevations between 200 and 1000 m a.s.l., because measurements are currently mainly located in low SMB areas and no measurements are available in large areas in which a significantly higher SMB is expected.

Despite these limitations, the present work allowed us to obtain a new and more reliable database for climate model validation. The datasets described in this paper should enable correct assessment of model quality in several specific areas (see Table 5). For model validation, similar approaches to those performed by Agosta et al. (2012a) with the GLACIOCLIM-SAMBA network should be extended to the whole of Antarctica, using any climate model and the selected datasets. In the present study, we demonstrated the interest of comparing field data with ERA-Interim outputs. On one hand, our comparison confirmed that ERA-Interim correctly fits observations, even though the computed SMB presents significant dry biases. On the other hand, the comparison demonstrated that observations do not correctly sample the SMB between 200 and 1000 m a.s.l., and that very few data are available for high SMB areas. New field data along the AIS margin and new traverses in unexplored areas are thus still required to validate climate models for Antarctica.

Correctly estimating the Antarctic SMB is still a complex issue, which will require both field data and modeling results. The first step will be rescaling the dataset to obtain a timely unbiased SMB climatology for the end of the 20th century. In a future work, this rescaling step will be performed against ERA data. For this task, field data from each specific period and each region will be rescaled assuming the SMB difference

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given by ERA between this specific period and a reference period. A modeling step at a high resolution (∼10–20 km) is required to correctly account for the effects of local topography on precipitation and ablation processes, because the computed SMB is tightly linked to model resolution (e.g. Krinner et al., 2008; Genthon et al., 2009). Regional circulation models (e.g. MAR, RACMO2, PMM5) are good candidates for this task. The selected model should correctly model surface processes such as snow metamorphism and albedo, refreezing, and erosion or deposition of drifting snow. This is particularly important below 2000 m a.s.l. where strong katabatic wind cause considerable snowdrift (erosion or deposition processes), and also where melting may be significant but not always generate surface runoff. The selected models will have to correctly account for cloud physics to accurately reproduce precipitation over interior plateaus. Finally, a better estimate of the Antarctic SMB will also require the use of remote sensing data, and again, the first step should be applying the method of Arthern et al. (2006) to the current updated and quality controlled dataset. This method should allow the treatment or removal of serious biases in passive microwave data due to steep slopes and melting at low elevations (Magand et al., 2008).

This paper presented the most recent updated surface mass balance dataset for Antarctica. The database is freely available on the GLACIOCLIM-SAMBA website (http://www-lgge.ujf-grenoble.fr/ServiceObs/SiteWebAntarc/database.html) for any scientific use. Continuous updating of the database is planned but will require data owners to share their published data. This will also be possible on the GLACIOCLIM-SAMBA website.

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Acknowledgements. The GLACIOCLIM-SAMBA observatory is supported by IPEV (*Institut Polaire Paul-Emile Victor*) and INSU (*Institut National des Sciences de l'Univers*). We acknowledge the ice2sea project funded by the European Commission's 7th Framework Programme through grant number 226375, ice2sea manuscript number ice2sea128. We thank Jérôme Chappellaz, Kenji Kawamura and Kumiko Azuma who helped us contact data owners to obtain new unpublished data. We thank M. Fily and ANR fundings ("VANISH" project no. ANR-07-VULN-013) for providing several new unpublished data around Dome C. Finally, we are grateful to O. Magand and P. Smeets who provided partially updated databases, and we particularly thank A. Bliss, M. Ding, and H. Motoyama who gave us access to the full information on published datasets over long traverses.

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The publication of this article is financed by CNRS-INSU.

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Table 1. List of sectors where data are presented separately instead of their average over $20 \times 20\,km^2$ grid cells given in V99.

	Number of data in databases			
	This paper	V99	References	Comments
South Pole	280	6	Mosley-Thompson et al. (1995, 1999)	N.A.
Syowa to Dome Fuji	504	30	Fujiwara and Endo (1971)	Update/longer time coverage
Lambert Glacier	997	73	Higham and Craven (1997)	N.A.
Lambert (traverse to Dome A)	215 data are redundant with Higham and Craven (1997)	not in V99	Ding et al. (2011)	redundant data from Higham and Craven (1997) are stakes measurements spanning only 1 yr: these redundant data disappear after the quality control
Wilkes Land	394	99	Goodwin (1988)	N.A.
Total	2175	202		

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Table 2. SMB datasets, and available data at each step.

Name in the text	Filtering	No. of observations
Full SAMBA-LGGE database	Full updated database before any filtering (but excluding digitalized data from Bull, 1971)	5284
"A" rated data	Basic quality (see Table 3) control, only "A" rated data are retained	3438
For 20th century model validation	Blue ice data, data covering more than 70 yr, and data with differences in elevation of more than 200 m from the Digital elevation Model from Bamber et al. (2009) were excluded	3152

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Table 3. Reliability and applicability conditions of SMB measurement methods (see Magand et al., 2007, for details on reliability criteria).

SMB measurement methods	Applicability conditions	Reliability[a] Annual	Multi-annual	Decadal[b]
Anthropogenic radionuclides	Dry snow facies, little mixing, absolute calibration and dating tools with reference horizon levels	/	A	A
Stake measurements	Everywhere, annual and multi-year averaged SMB variability studies	C[c]	A	A
Natural 210Pb	Dry snow facies, little mixing, less accurate than anthropogenic radionuclides	/	/	B[d]
Stable isotope content and chemical markers	Dry snow facies, annual to multi-year averaged SMB variability studies, clear observations difficult in areas with very low SMB values (Central Antarctic plateau), subjectivity in counting annual layers	/	B	B
Snow stratigraphy	Dry snow facies, "low" reliability and accuracy	C	C	C
Precipitation gauges	Unreliable, inaccurate	C	C	C

[a] The methods deemed very reliable are rated "A", methods judged reliable are provisionally accepted (rated "B"), unreliable data are rated "C".
[b] Over one or several decades,
[c] Applicable to single stakes and stake networks,
[d] The natural 210Pb SMB method is reliable only over 4 to 5 decades (∼ two half life periods).

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Table 4. Mean SMB computed from field observations for Antarctica, and for the eastern and western parts of Antarctica. Note that these SMB averages are only for areas with observation, and do not represent a mean SMB for the whole continent.

	"A" rated data	Full database
Antarctica (Grounded area: 12.2 10^6 km^2)	146[3] (**144**[4])	177 (**159**)
East Antarctica[1] (Grounded area: 8.5 10^6 km^2)	139 (**132**)	142 (**122**)
West Antarctica[2] (Grounded area: 3.7 10^6 km^2)	168 (**159**)	228 (**244**)

[1] More precisely, for the 0° E–180° E sector of Antarctica.
[2] More precisely, for the 0° W–180° W sector of Antarctica.
[3] Mean SMB value, assuming that each observation has the same weight.
[4] We first computed the average SMB for each 15 × 15 km^2 grid cell (values from points located in the same grid cell are averaged), and then computed the mean SMB over Antarctica, assuming that each grid cell has the same weight.

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Table 5. Description of selected datasets in low elevation areas for comparison with ERA-Interim reanalysis.

Name	Location	No. of observations	No. of cells 15 × 15 km*	Time coverage (start-end)	Mean elevation (m a.s.l.)	Mean SMB (mm w.e. a^{-1})
Byrd	Byrd	143	15	1955–1994	700	100
CHINARE	Zhongshan – Dome A	249	40	1994–2008	2216	120
DDU-DC	Dumont d'Urville – Dome C	27	18	1955–2009	1815	298
DML	Dronning Maud Land	22	21	1948–1999	1385	200
GS	Glacioclim-SAMBA	90	11	2004–2010	990	357
LD	Law Dome	29	9	1973–1986	1207	704
MNR-VTK	Mirny – Vostok	9	8	1955–1998	2215	215
MWS-LBw	Mawson – Lambert West	249	40	1990–1995	2531	100
Peninsula	Antarctic Peninsula	26	22	1953–1986	1212	546
SHW-DF	Showa – Dome Fuji	245	37	1955–2010	2068	106

* Number of 15 × 15 km^2 grid cells containing field measurements.

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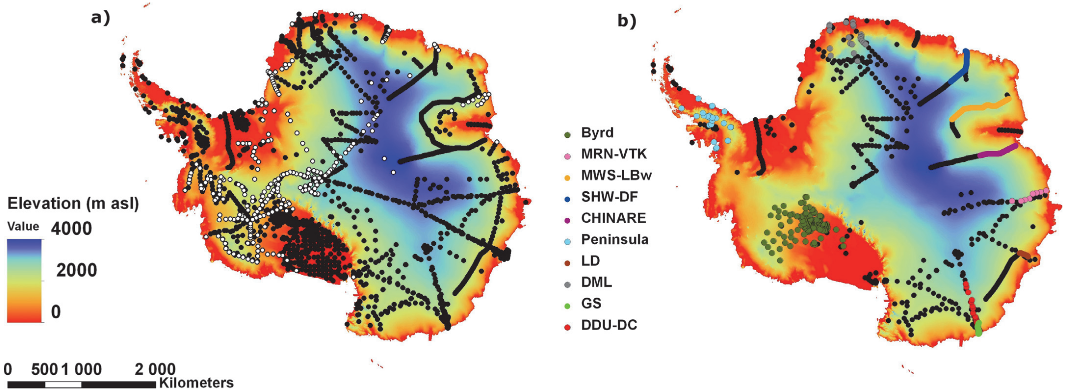

Fig. 1. (a) Location of available SMB data in Antarctica. Black dots represent available data before quality control, white dots represent data from Bull (1971) which were directly excluded from the Vaughan et al. (1999) database due to their low reliability (digitalized from maps). Background map is elevation according to Bamber, 2009. **(b)** Location of reliable field data (black dots) and selected datasets for model validation. Background map is elevation according to Bamber, 2009. Abbreviations. CAS: Casey (Vincennes Bay, Australia), DC: Dôme C (Antarctic Plateau, France/Italy, DDU: Dumont d'Urville (Adelie Land, France), DF: Dome Fuji (Dronning Maud Land, Japan), LD: Law Dome (Wilkes Land, Australia), GS: GLACIOCLIM-SAMBA network, MRN: Mirny (Davis Sea, Russia), MWS: Mawson (Mac Robertson Land, Australia), NMY: Neumayer (Atka-Bay, Germany), SHW: Showa (East Ongul Island, Japan), SP: Amundsen-Scott South Pole (South Pole, USA), TRL for Troll (Dronning Maud Land, Norway), VTK: Vostok (Antarctic Plateau, Russia), ZGS: Zhongshan (Prydz Bay, China).

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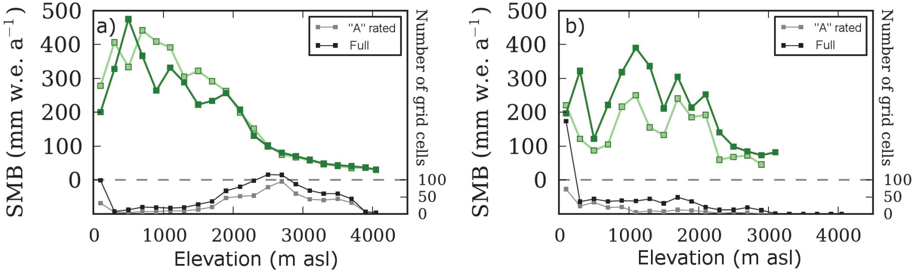

Fig. 2. Mean SMB computed using field data measured within each 200 m elevation range on the grounded ice sheet, **(a)** for the Eastern Antarctic sector (longitude between 0° E and 180° E), and **(b)** Western Antarctic sector (longitude between 0° W and 180° W). We first computed the average SMB for each 15 × 15 km^2 grid cell (values from points located in the same grid cell are averaged), and then the mean SMB every 200 m in elevation, assuming that each grid cell had the same weight. Dark green squares are mean SMB computed with the full database, and light green squares are mean SMB computed with "A" rated data only. Gray and black dots are the number of observations within each elevation range for the "A" rated data and the complete ("full" SAMBA-LGGE) database respectively.

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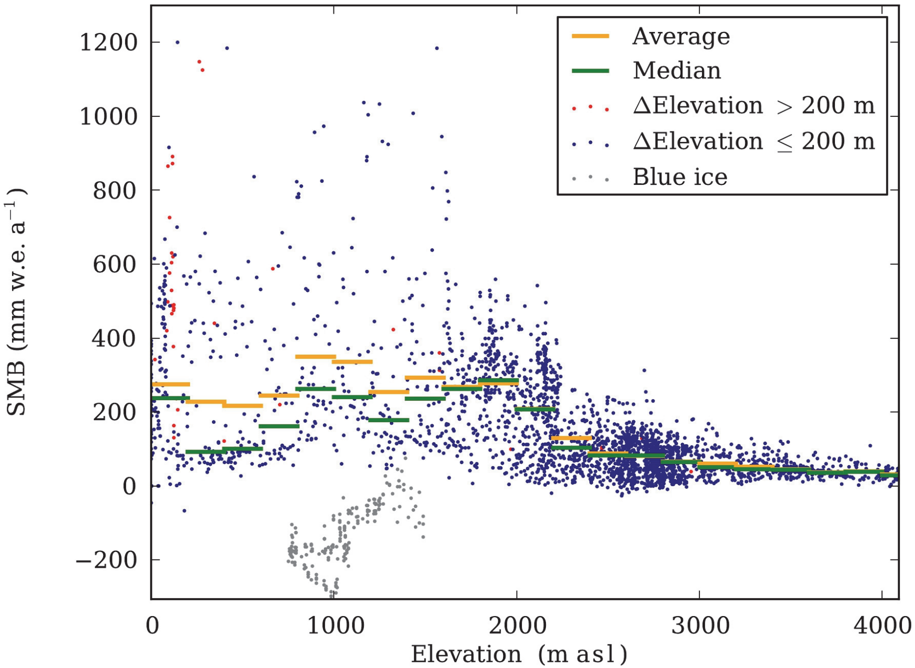

Fig. 3. Variation in SMB according to elevation based on reliable data. Data spanning a period of more than 70 yr are not shown. Elevations are from Bamber et al. (2009) digital elevation model (DEM). Blue dots are the selected observations for comparison with ERA-Interim, red dots are observations presenting a difference in elevation greater than 200 m compared with Bamber et al. (2009) DEM, and gray dots are data from blue ice areas described in Sinisalo et al. (2003) and Bliss et al. (2011). Horizontal bars are the mean (orange) and 50 % occurrence (green) of blue dots for each 200 m elevation range.

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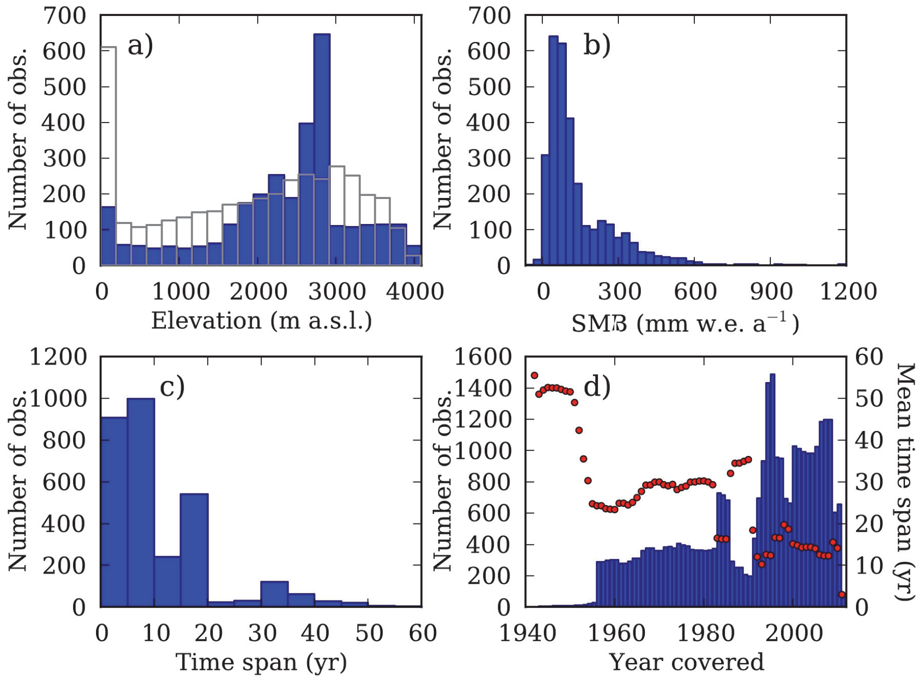

Fig. 4. Main characteristics of reliable SMB data. **(a)** Comparison between distribution of elevation in the database (blue histograms) and distribution of surface elevation of Antarctica (white histograms). Elevation are deduced from Bamber et al. (2009) DEM, **(b)** number of observations as a function of SMB values, **(c)** number of observations as a function of time coverage, **(d)** variations in the number of observations over time (vertical bars) and in the time period used for their average since 1940 (red dots).

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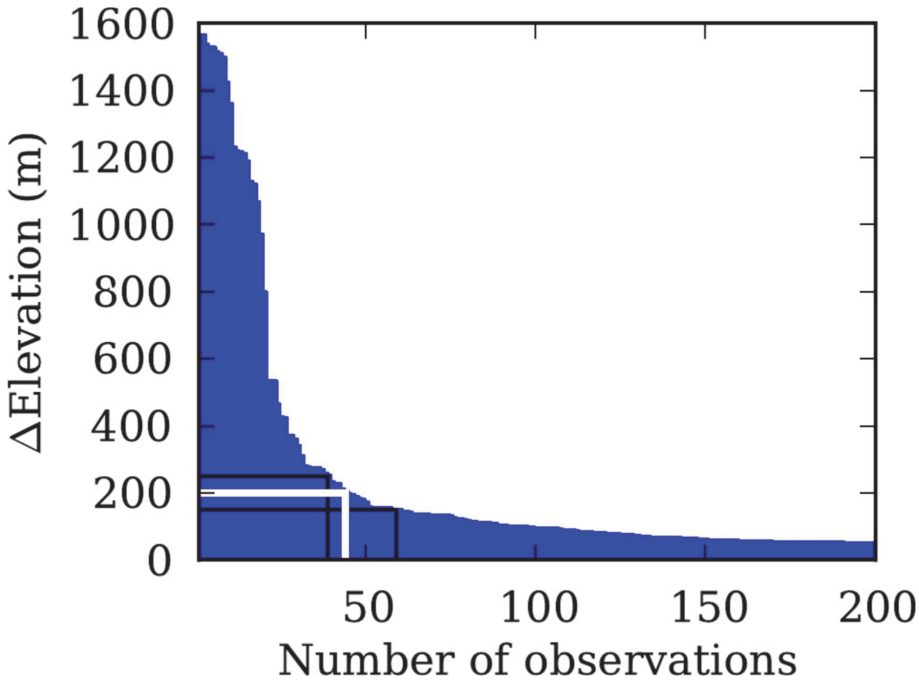

Fig. 5. Distribution of the difference in elevation between observed data and data from the digital elevation model of Bamber et al. (2009). The white lines represent the 200 m threshold, which led to the rejection of 44 observations.

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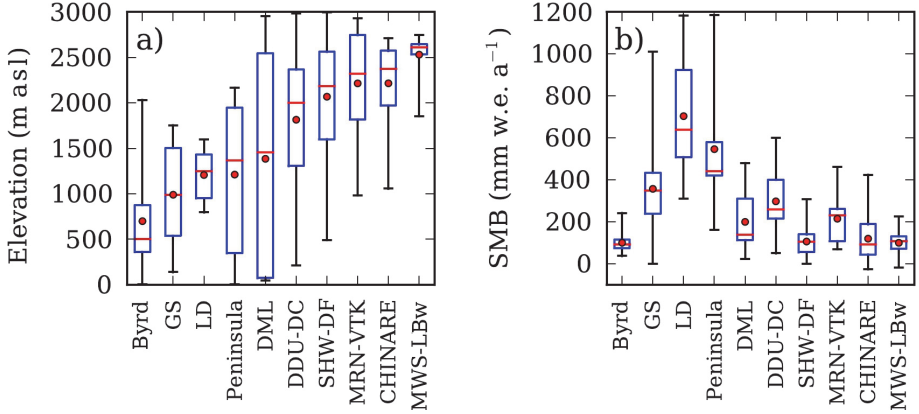

Fig. 6. Distribution of **(a)** elevation and **(b)** SMB values for each selected dataset. Red lines represent 50 % occurrence, red dots are mean values, and the first and third quartiles are represented by box extremities. Minimum and maximum values are the extremities of the black lines.

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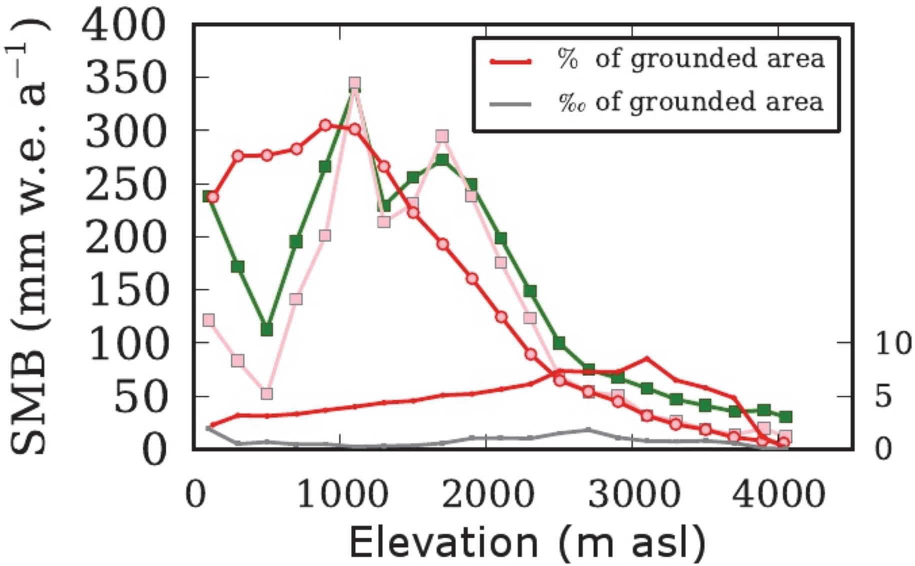

Fig. 7. Mean SMB over the grounded ice sheet as a function of elevation. Pink squares are the mean SMB calculated by ERA-Interim for grid cells containing observations within each elevation range. Red circles are mean SMB calculated by ERA-Interim over each entire range of elevations. Green squares are mean observed SMB from grid cells containing observations within each elevation range. The gray line represents the contribution of areas with observation to the grounded ice sheet area (for each elevation range). The red line represents the contribution of entire elevation range to the grounded ice sheet. Each elevation range is 200 m.

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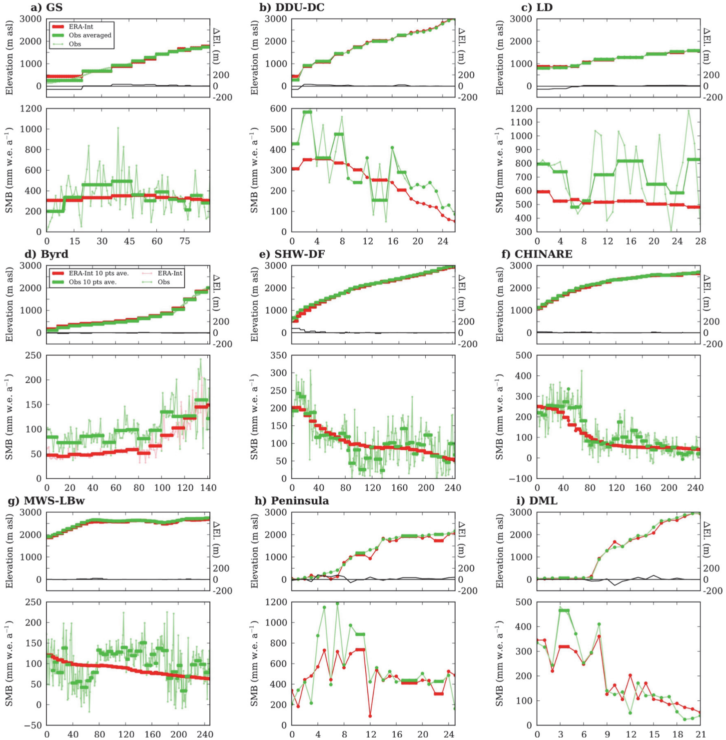

Fig. 8. Surface elevation ("sh") and variations in the SMB in specific areas and along traverses from the coast to plateaus where field data are available: **(a)** along the GLACIOCLIM-SAMBA observation transect in Adelie Land, **(b)** between Dumont d'Urville (DDU) station and Dome C (DC), **(c)** around Law Dome, **(d)** in Byrd Station region and on Ross ice shelf (Byrd), **(e)** between Showa (SHW) and Dome Fuji (DF), **(f)** along the traverse route from Zhongshan station to Dome A (CHINARE), **(g)** along the west side of Lambert glacier (LBw) close to Mawson station (MWS), **(h)** in the Antarctic Peninsula, and **(i)** in Dronning Maud Land (DML). For each region, surface elevation values are presented in the upper panel and SMB values in the lower panel. Values calculated by ERA-Interim (thick red line) are compared with the mean of field data included in each EAR-Interim grid cell (thick green line). Point field data before averaging are represented by a thin light green line. The surface elevation of field observations is from Bamber et al. (2009) digital elevation model (DEM). Also shown in the upper panels are the differences in surface elevation between ERA-Interim and Bamber et al. (2009) DEM (Δsh, black line, right axis).