An up-to-date quality-controlled surface mass balance data set for the 90°–180°E Antarctica sector and 1950–2005 period

Olivier Magand, Christian Genthon, Michel Fily, Gerhard Krinner, Ghislain Picard, Massimo Frezzotti, A. A. Ekaykin

An up-to-date quality-controlled surface mass balance data set for the 90°–180°E Antarctica sector and 1950–2005 period

O. Magand,[1] C. Genthon,[1] M. Fily,[1] G. Krinner,[1] G. Picard,[1] M. Frezzotti,[2] and A. A. Ekaykin[3]

Received 23 June 2006; revised 16 November 2006; accepted 14 December 2006; published 19 June 2007.

[1] On the basis of thousands of surface mass balance (SMB) field measurements over the entire Antarctic ice sheet it is currently estimated that more than 2 Gt of ice accumulate each year at the surface of Antarctica. However, these estimates suffer from large uncertainties. Various problems affect Antarctic SMB measurements, in particular, limited or unwarranted spatial and temporal representativeness, measurement inaccuracy, and lack of quality control. We define quality criteria on the basis of (1) an up-to-date review and quality rating of the various SMB measurement methods and (2) essential information (location, dates of measurements, time period covered by the SMB values, and primary data sources) related to each SMB data. We apply these criteria to available SMB values from Queen Mary to Victoria lands (90°–180°E Antarctic sector) from the early 1950s to present. This results in a new set of observed SMB values for the 1950–2005 time period with strong reduction in density and coverage but also expectedly reduced inaccuracies and uncertainties compared to other compilations. The quality-controlled SMB data set also contains new results from recent field campaigns (International Trans-Antarctic Scientific Expedition (ITASE), Russian Antarctic Expedition (RAE), and Australian National Antarctic Research Expeditions (ANARE) projects) which comply with the defined quality criteria. A comparative evaluation of climate model results against the quality-controlled updated SMB data set and other widely used ones illustrates that such Antarctic SMB studies are significantly affected by the quality of field SMB values used as reference.

Citation: Magand, O., C. Genthon, M. Fily, G. Krinner, G. Picard, M. Frezzotti, and A. A. Ekaykin (2007), An up-to-date quality-controlled surface mass balance data set for the 90°–180°E Antarctica sector and 1950–2005 period, *J. Geophys. Res.*, *112*, D12106, doi:10.1029/2006JD007691.

1. Introduction

[2] Loss of mass of the majority of Earth's glaciers and ice sheets is known to have played a major role in the sea level rise of the recent decade [*Miller and Douglas*, 2004], but the contribution of the Antarctic ice sheet to this rise is difficult to assess. During the last 10–15 years, the numerous imbalances (i.e., a nonzero mass balance of the grounded ice sheet) observed in several Antarctic ice drainage basins from interferometric (InSAR), altimetric (ICESat, ERS-1 and -2) and gravimetric measurements [*Rignot and Thomas*, 2002; *Thomas et al.*, 2004; *Davis et al.*, 2005; *Vaughan*, 2005; *Zwally et al.*, 2006; *Velicogna and Wahr*, 2006] suggest a net loss from West Antarctica (WA) contributing to global sea level rise, and a recent mass increase in East Antarctic (EA) ice sheet which slows global sea level rise. In the context of climate change debate, a better estimate of the present-day and future contribution of the Antarctic ice sheet to global sea level rise is therefore needed. This concerns a more precise determination of input (annual snowfall on Antarctic ice sheet) and output (loss by melting, iceberg calving, and snow blowing in coastal areas) terms. As shown by *Thomas et al.* [2004] and *van de Berg et al.* [2006], numerous technical advances, notably with satellite measurements, have been realized during recent years to quantify solid ice fluxes and melting in coastal areas, contributing to better estimates of output terms. Similar progress determining surface mass balance (SMB), which cannot directly be measured by satellites, has not been achieved [*van de Berg et al.*, 2006]. Assessments of the integrated SMB over the grounded ice sheet rely on interpolation of observed SMB data sets [*Giovinetto and Bentley*, 1985; *Vaughan et al.*, 1999; *Giovinetto and Zwally*, 2000]. *Giovinetto and Zwally* [2000] visually interpolated the observed SMB data, while *Vaughan et al.* [1999] used passive microwave satellite data for their interpolation. However, there are still large gaps in the spatial coverage of SMB data, and available data can be of poor quality. This is due to the very sparse distribution (especially in East Antarctica) of field SMB measurements with around 2000

[1] Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, Université Joseph Fourier-Grenoble, St. Martin d'Hères, France.
[2] Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, Rome, Italy.
[3] Arctic and Antarctic Research Institute, St. Petersburg, Russia.

0148-0227/07/2006JD007691

observed SMB points for about 13 million km^2, corresponding to one SMB data point every 6500 km^2 on average.

[3] The interpolated SMB map by *Vaughan et al.* [1999] suggested a mean Antarctic SMB exceeding earlier widely accepted estimates [*Giovinetto and Bentley*, 1985] by 15%, with revisions in excess of 50% at the drainage basin scale. Even the sign of the contribution of Antarctica to the current sea level change is not known with certainty yet [*Church et al.*, 2001], but considering the accumulation term alone, the best estimate has decreased by 0.7 mm yr^{-1} because of the recent reevaluations of the SMB. Using almost the same observed SMB values as *Vaughan et al.* [1999], *Giovinetto and Zwally* [2000] applied different sorting and interpolation techniques. Their deduced Antarctic SMB reevaluation appears to better agree with *Vaughan et al.* [1999] than with the older evaluations [*Giovinetto and Bentley*, 1985]. However, they still differ by as much as 30% at drainage basin scales, and even by 15% at the scale of East Antarctica as a whole [*Rignot and Thomas*, 2002]. On the basis of meteorological analysis and climate models results, recent work [*Genthon and Krinner*, 2001] questioned the reliability and accuracy of the Antarctic interpolated SMB map of *Vaughan et al.* [1999]. *Genthon and Krinner* [2001] argued that substantial inaccuracies occurring in interpolated Antarctic SMB maps may be due to the spatial interpolate techniques applied. They showed that the microwave interpolant used to build the Antarctic SMB map [*Vaughan et al.*, 1999] may be in error by as much as some of the largest systematic model biases, especially in Antarctic sectors devoid of field SMB measurements. In some of these data-sparse regions, meteorological and climate models display coherent differences with respect to the interpolated SMB maps, and it is uncertain whether the climate models share systematic errors or whether the interpolate of the observed SMB data is inaccurate [*Genthon and Krinner*, 2001].

[4] *Arthern et al.* [2006] have recently produced a new interpolated Antarctic SMB map. They used the same observed SMB data as *Vaughan et al.* [1999] but applied a new interpolation technique based on an empirical relationship between mean annual temperature, accumulation rate and a polarization ratio of thermally emitted microwaves [*Arthern et al.*, 2006]. They also empirically reduce possible biases from observational data using weighting factors related to data variance at 100 km scale. The authors suggest that the new interpolated SMB map may eliminate some of the discrepancies between model results, earlier compilations and interpolation of observed SMB data as suggested by *Genthon and Krinner* [2001]. According to *Arthern et al.* [2006], their new map describes the average accumulation rate to an accuracy of 10% or better at an effective spatial resolution of 100 km. They judged the mean annual accumulation of snow over the major drainage sectors of Antarctic ice sheet to be representative of the second half of the 20th century [*Arthern et al.*, 2006].

[5] A potential source of error is that the methods that have been used to measure SMB in field, yielding data that were then used to produce interpolated SMB maps, are not equally robust and reliable. Therefore compiling all observed SMB data available in the literature yields a data set of heterogeneous quality, with the values of lowest quality being likely to contaminate the information provided by more reliable methods, thereby making large-scale interpolation and synthesis questionable. How can one certify the reliability and accuracy of an interpolated Antarctic SMB map if the underlying observed SMB data used to produce these maps, largely compiled from the published and unpublished literature as well as from personal communication, may be in error and inaccurate? The quality of SMB data is also related to the "availability" of essential information as the geographical coordinates (longitude, latitude), dates of measurements and time period covered by the SMB estimation, as well as references to the primary data sources.

[6] The main aim of this paper is to deliver a new data set of SMB reports which, contrary to others largely used in the literature, e.g., to extrapolate into accumulation maps [*Vaughan et al.*, 1999; *Giovinetto and Zwally*, 2000; *Arthern et al.*, 2006] or to directly compare with climate models [*van de Berg et al.*, 2006], is built on restrictive quality control criteria based on observation methods and availability of information on how data have been obtained. We acknowledge that fully objective criteria cannot be appropriately adapted to each individual report considering all possibly pertinent local parameters like, e.g., topography and orography, meteorological environment, seasonality, and so on. Rather, we deliberately use common restrictive criteria that are probably too extreme in a number of cases and thus unnecessarily blacklist some of the available reports but which, compared to other SMB data set that compile all available reports regardless of data quality, result in a new data ensemble of a radically different nature. The new data set is not meant to compete or replace with other data sets, but rather to provide a complementary view for data users, and to evaluate how sensitive to data quality our best evaluations of the Antarctic SMB may be. It is expected that, as an outcome of this work, more high-quality data will be obtained and made available along with more comprehensive information to contribute better quality and better assessed SMB data sets. We focus on a sector of East Antarctica (EA) sector, from Queen Mary to Victoria lands (90°–180°E) (Figure 1), where recent satellite radar altimetry measurements suggest an important mass gain, linked to a precipitation increase, during the last decade [*Davis et al.*, 2005]. The chosen period of observation is from the 1950s to nowadays. SMB data sources treated in this work, are mainly issued from *Vaughan et al.*'s [1999] data set (V99), in which most of the references containing SMB data across Antarctica, from 1950s to 1997, has been compiled. Some SMB data from *Lorius et al.* [1968], *Pourchet et al.* [1983, 1997], *Lipenkov et al.* [1998], *Stenni et al.* [2000], and *Pourchet et al.* [2003] along the Dumont–d'Urville–Dome Concordia (Ddu-DC) and Mirny-Vostok (MNY-VK) routes which were not included in V99 data set are added. We finally improve and complete this compilation by addition of new observed SMB data produced by the Italian and French ITASE activities [*Frezzotti et al.*, 2004; *Magand et al.*, 2004; *Frezzotti et al.*, 2005], the Russian Antarctic Expeditions (RAE) with intensive pit studying program from 1998 to 2000, in the vicinity of Vostok station [*Ekaykin et al.*, 2002, 2005] and the Australian National Antarctic Research Expeditions (ANARE) [*Smith et al.*, 2002; *Goodwin et al.*, 2003] in our study sector since 1998. In particular, some of these new observed SMB data fill large spatial gaps in the data sets previously available for this area.

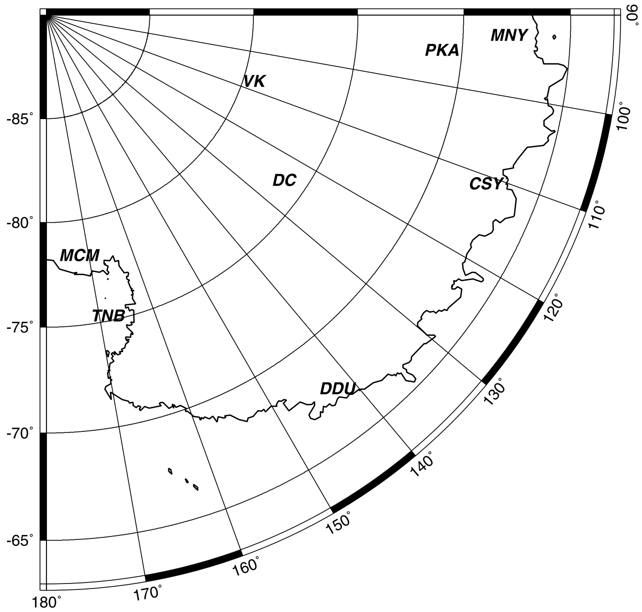

Figure 1. Study region in East Antarctica, from Queen Mary to Victoria lands (90°–180°E). Scientific stations: CSY, Australia, Casey; DDU, France, Dumont d'Urville; DC, France-Italy, Dôme Concordia; MCM, United States, McMurdo; MNY, Russia, Mirny; PKA, Russia, Pionerskaya; SP, United States, South Pole; TNB, Italy, Terra Nova Bay; VK, Russia, Vostok.

[7] Section 2 discusses the reliability and accuracy of methods used to estimate SMB, and provides a quality rating of the various techniques. In section 3, we describe procedures applied to select the most reliable observed SMB data in our study sector since the 1950s, using the quality criteria. In section 4, we finally compare (1) older (and unfiltered) observed SMB values from V99, (2) up-to-date but unfiltered values gathered in the present work, and (3) the quality-controlled data set to simulated SMB values by the LMDZ4 atmospheric general circulation model [*Hourdin et al.*, 2007; *Krinner et al.*, 2007]. Rather than rating the model, this comparison is designed to help evaluate the impact of the quality selection process on the observed SMB data sets. A general conclusion is provided in section 5.

2. Review and Quality Rating of SMB Measurement Techniques

[8] A variety of methods has been used to directly or indirectly evaluate SMB in Antarctica. All methods are not equally robust and reliable. Therefore compiling all observed SMB data in the literature without selection yields a data set of heterogeneous quality, with the values of poorest quality being likely to contaminate both the information provided by more reliable methods and any large-scale extrapolation and synthesis. *Bull* [1971] provided an extensive critical review of the relative characteristics and qualities of the various SMB measurement methods commonly used in the 1950s and 1960s. In this section, we (1) attempt to provide an up-to-date review of the various field methods for estimating local SMB, by partly drawing on the work of *Bull* [1971] and (2), as a result, establish a final quality rating of the various methods (Table 1). This rating is then used to decide on the eventual rejection of observed SMB data, and thus to build a SMB data set with a high level of confidence. We are mainly interested in evaluations of the recent mean SMB, i.e., representing the period from 1950 to 2005. Thus we do not evaluate methods that yield SMB evaluations on centennial timescales. In this section, we address only the methodological aspects. The methods deemed very reliable are accepted and given a mark "A." Methods judged reliable are conditionally accepted (marked "B"), while those, which are deemed unreliable, are marked "C." Method rating is summarized in Table 1, while the reasons for this rating are described below.

2.1. Direct in Situ SMB Measurement Methods

2.1.1. Snow Stratigraphy: Rate C

[9] SMB measurement by snow stratigraphy is based on the identification of annual layers in the dry snow facies in

Table 1. Reliability and Applicability Conditions of SMB Measurement Methods[a]

SMB Measurement Methods	Applicability Conditions	Reliability: Annual	Multiannual	Decadal[b]
Anthropogenic radionuclides	dry snow facies, little mixing, absolute calibration and dating tool with reference horizon levels	/	A	A
Stake measurements	everywhere, annual and multiyear averaged SMB variability studies	C[c]	A	A
Natural ^{210}Pb	dry snow facies, little mixing, less accurate than anthropogenic radionuclides	/	/	B[d]
Stable isotope content and chemical markers	dry snow facies, Annual and multiyear averaged SMB variability studies, difficulty for clear observations in areas with very low SMB values (central Antarctic plateau), subjectivity in annual layers counting	/	B	B
Snow stratigraphy	dry snow facies, "low" reliability and accuracy	C	C	C
Precipitation gauges	not reliable, not accurate	C	C	C

[a]The methods deemed very reliable are accepted and given an "A." Methods judged reliable are conditionally accepted (marked "B"), while those that are deemed unreliable are marked "C."
[b]The term "decadal" means one or several decades.
[c]Applicable to single stakes and stake networks.
[d]The natural ^{210}Pb SMB method is reliable only from 4 to 5 decades (≈ two half-life time periods).

the accumulation zones of ice sheets [*Benson*, 1962; *Giovinetto*, 1964]. Numerous criteria for the identification of these annual layers have been established for dry snow facies in Greenland and Antarctica [*Giovinetto*, 1960, 1963; *Koerner*, 1964; *Vickers*, 1966], and they have yielded a large number of net accumulation values during the fifties and sixties [*Picciotto et al.*, 1971; *Bull*, 1971]. However, in the central region of the East Antarctic plateau, these criteria are difficult to apply, and the observed SMB data derived from pit stratigraphy alone involve personal and subjective interpretation usually leading to unreliable estimates [*Shimizu*, 1964; *Bull*, 1971]. This major problem originates from the low and variable annual precipitation in the central plateau and by the strong metamorphism of the upper snow and firn layers, resulting in a partial or sometimes total obliteration of the annual layering [*Aver'yanov*, 1969; *Picciotto et al.*, 1971; *Bull*, 1971; *Ekaykin*, 2003]. Several authors considered also that this technique may also not be reliable in areas of very high snowfall, near the coast [*Schytt*, 1958; *Shimizu*, 1964; *Cameron*, 1964; *Bull*, 1971]. Following *Oerter et al.* [1999], we argue that a detailed stratigraphic description of firn layers is difficult, time-consuming and not always unambiguous.

2.1.2. Precipitation Gauges: Rate C

[10] It is accepted that, except under unusual meteorological conditions, modified or standard snow gauges do not yield accurate and reliable measurements of the true precipitation, as described by *Aver'yanov* [1963], *Swithinbank* [1957], *Black and Budd* [1964], and *Bull* [1971]. As a consequence, even if some new precipitation gauges series are currently developed and tested, they are still not applied and validated in polar regions. In the present work, we argue that this measurement method cannot not be used to determine local SMB.

2.1.3. Stakes Measurements (Stake Farms and Single Stakes): Rates A or C

[11] The simplest method for measuring SMB at a repeatedly visited site or continuously occupied station, or along transect is by direct measurements from stakes [*Bull*, 1971]. The method is based on the field measurements of stake height changes, reflecting accumulated or ablated snow layer thickness in the study area. Many precautions must be taken to obtain accurate and reliable measurements [*Bull*, 1971]. For example, in an accumulation zone, one of the main measurement errors is the settling of snow that normally occurs around the pole. Even if allowances are made for this "error," *Schytt* [1962] and *Bull* [1971] pointed out that measurement issued from a single stake may not be representative of the net accumulation occurring in the studied area, because of errors produced by surface irregularities and thermal effects around the stakes. To limit the errors due to morphological features and local meteorological processes, a large variety of stake farms and single stakes has been established and tested at permanent scientific stations or during traverses from the 1960s to now [*Schytt*, 1962; *Shimizu*, 1964; *Bull*, 1971; *Petit et al.*, 1982; *Goodwin*, 1988; *Mosley-Thompson et al.*, 1995, 1999; *Frezzotti et al.*, 2005]. It is clear from most of the references cited above that the accurate estimation of annual positive balance is not so easy even with such a simple technique as stake measurements. This difficulty does not prevent from obtaining reliable observed SMB data in studied areas, as attested by other reliable SMB measurement methods in most of the previous cited works. However, several authors showed very large standard deviations (up to 150%) in the accumulation pattern derived from annual SMB stake farms (or single stake) measurements [*Petit et al.*, 1982; *Pettre et al.*, 1986; *Mosley-Thompson et al.*, 1999; *Goodwin et al.*, 2003; *Frezzotti et al.*, 2005]. As pointed out by *Fisher et al.* [1985], the observed variability limits the degree to which a single annual snow accumulation value may be temporally representative of the local SMB on longer period. As a consequence, stake measurement methods are rated A when time period SMB measurements cover more than one year. We rate C for a unique year SMB measurement by this method.

2.2. Indirect SMB Measurements From Pits and Cores Chemical Profiles Interpretation

2.2.1. Oxygen and Hydrogen Isotope Ratios: Rate B

[12] The ratio of the two most common stable isotopes of oxygen, ^{16}O and ^{18}O, and of the two stable hydrogen isotopes, ^{1}H and ^{2}H, depends on the temperature at which the snow condenses at cloud level [*Dansgaard*, 1964; *Bull*, 1971]. It results that, at a given location, it is possible to distinguish winter (light isotopic composition) from summer (heavy isotopic composition) snow precipitation and thus to evaluate annual and multiyear averaged positive SMB from profiles of the ^{18}O: ^{16}O or ^{2}H: ^{1}H ratios recorded in the snow [*Bull*, 1971]. A large number of oxygen and hydrogen isotope ratio profiles have now been made on Antarctic snow and ice samples from the 1960s to the present [*Epstein et al.*, 1963; *Picciotto et al.*, 1968; *Petit et al.*, 1982; *Grootes and Stuiver*, 1984; *Lyon*, 1986; *Morgan*, 1988; *Oerter et al.*, 1999; *Smith et al.*, 2002; *Ekaykin et al.*, 2002, 2005]. However, the determination of local SMB by identifying annual isotope content variation is only valid in case the distinctive seasonal signal is preserved. At different spatial and temporal scales, the isotope composition of snow layers analyzed can be different from that of the original snow deposited, due to several postdepositional processes [*Bull*, 1971; *Ekaykin*, 2003]. This implies a distortion of the original seasonal signal, which biases the estimation of local SMB. The seasonal variations are difficult to clearly observe at sites characterized by low accumulation rates, such as in central Antarctica plateau. Finally, while the ratio measurements themselves are objective, the interpretation of the variations is still to some extent subjective, especially in areas of lower accumulation, and wide ranges of annual positive balance values may be obtained by different observers studying the same snow deposit.

2.2.2. Anthropogenic Radionuclide (Gross β Activity, Pu Isotopes, and Tritium): Rate A

[13] Artificial radioisotopes from atmospheric nuclear weapon tests carried out between 1953 and 1980 were deposited in Antarctica after transport in the upper atmosphere and stratosphere [*Picciotto and Wilgain*, 1963; *Wilgain et al.*, 1965; *Feely et al.*, 1966; *Picciotto et al.*, 1971; *Lambert et al.*, 1977; *Carter and Moghissi*, 1977; *Jouzel et al.*, 1979; *Oerter et al.*, 1999; *Stenni et al.*, 2002]. Moreover, the dates of arrival and deposition of radioactive debris in Antarctica are well known [*Wilgain et al.*, 1965; *Feely et al.*, 1966; *Pourchet et al.*, 2003; *Magand et al.*,

2004], and the resulting main 1954–1955 and 1965–1966 maximum radioactivity peaks provide two very convenient horizons for dating snow and ice layers and measuring snow accumulation rates. In summary, the accurate knowledge of the history of artificial radioactive fallout over Antarctica since the 1950s and behaviour of radioactive debris leave no doubt about the reliability, accuracy and validity of the method of radioactive reference levels measurements for estimating snow accumulation rates in accumulation areas with no melting.

2.2.3. Natural Radionuclide (Case of ^{210}Pb): Rate B

[14] Lead 210, a natural beta emitter, is a long-lived daughter nuclide (half-life 22.3 years) belonging to the ^{238}U family [*Picciotto et al.*, 1971]. Its presence in the atmosphere is a result of the alpha radioactive decay of gaseous radon (^{222}Rn).The atmosphere, via tropospheric and stratospheric transport, is the major source of ^{210}Pb deposited in Antarctica ice sheet. Because of the properties of radioactive decay, the continuous deposition flux of natural ^{210}Pb over the Antarctic ice sheet can thus be used for dating purposes over periods of the past 100 years. The first attempts at dating firn or ice layers with the ^{210}Pb method in polar regions were successfully operated and validated by other direct measurements [*Goldberg*, 1963; *Picciotto et al.*, 1964; *Crozaz et al.*, 1964; *Nemazi et al.*, 1964; *Crozaz and Langway*, 1966]. Accurate dating in snow by ^{210}Pb is possible under the following assumptions: (1) the mean ^{210}Pb activity in precipitation has remained constant over the time period covered by the samples, (2) the ^{226}Ra concentrations within the firn/ice samples are negligible, (3) no diffusion of air into the ice sheet occurs (bearing additional ^{222}Rn), and (4) ^{210}Pb remains at its initial place of deposition (no vertical transportation by water from melting snow). Evaluation of SMB over the past few decades by this method usually lead to these values being judged reliable in melt-free areas [*Pourchet et al.*, 1997, 2003], even if none of the previous assumptions was perfectly fulfilled.

2.2.4. Chemical Markers: Rate B

[15] The various chemical species (Cl^-, NO_3^-, SO_4^{2-}, SO^+, NH_4^+, H^+, K^+, Mg^{2+}, Ca^{2+}, F^-, Br^-, PO_4^{3-}, CH_3COO^-, $HCOO^-$, $CH_3SO_3^-$, H_2O_2) that could be used for dating purposes, and thus for the evaluation of net annual and multiyear averaged mass balance, come from a variety of sources including marine, crustal, volcanic, anthropogenic and cosmogenic processes [*Allen et al.*, 1985; *Piccardi et al.*, 1994]. Source discrimination and the determination of seasonal concentration peaks are based on studies of Antarctic glaciochemical records [*Herron*, 1982; *Legrand and Delmas*, 1985; *Allen et al.*, 1985; *Saigne and Legrand*, 1987; *Legrand and Kirchner*, 1988; *Lyons et al.*, 1990; *Minikin et al.*, 1994; *Piccardi et al.*, 1994; *Mulvaney and Wolff*, 1994; *Oerter et al.*, 1999; *Kaspari et al.*, 2004]. As previously discussed in oxygen and hydrogen isotope ratios studies, we have to keep in mind that numerous postdepositional processes (not described in the present work), highly variable depending on the chemical species considered, may affect the original seasonal signal in the snow/firn layers, resulting of dating and SMB evaluation uncertainties. Moreover, because of low snowfall in central Antarctic plateau, the observation and counting of seasonal oscillations may be difficult to operate. This implies that much caution is required in the interpretation of the seasonal variations of chemical markers and the deduced net SMB values. However, some studies show clearly that the chemistry of the firn layers could be a more helpful tool for dating than the isotope content, when a very distinct and known seasonal cycle occurred as observed in Amundsenisen, Dronning Maud Land [*Oerter et al.*, 1999], near Neumayer station [*Minikin et al.*, 1994], and in West Antarctic areas comprising the Pine Island–Thwaites and Ross drainage systems [*Kaspari et al.*, 2004].

3. Quality Selection of SMB Data: Procedures and Results

[16] In this section, we describe procedures and successive steps to select the most reliable SMB data in the 90°–180°E Antarctic sector, for the last 5 decades (1950s to the present).

3.1. Step 1: Collection and Description of Observed SMB Data

[17] The aim of the first step (hereafter referred to as S1, for "step 1") is to collect the maximum existing and available SMB field data corresponding to the SMB study in the 90°–180°E sector between 1950 and 2005. Despite intensive research of primary data sources references, few SMB field data may have not been collected and then, compiled in the S1 SMB data set. These values could be further reintegrated to the data set if information becomes available. As previously cited, location (longitude, latitude), elevation, field and/or laboratory measurement methods applied to SMB evaluation, dates of measurements and time period covered by the SMB data, and primary data sources references are the most important collected information, and considered as essential parameters. When available, elevation, distance from the coast, temperature at the site (at 10 or 15 m depth), topographical and meteorological information, and estimated uncertainties of the calculated SMB data are also collected, and cited as secondary parameters. A digital elevation model [*Bamber and Gomez-Dans*, 2005] is used when in situ elevation measurements are lacking. SMB data reported in the data set are the mean values corresponding to the multiyear period of observation. The complete resulting data set comprises 652 SMB values nonhomogeneously distributed between Queen Mary and Victoria Lands (90°–180°E) (Figure 2).

[18] Unsurprisingly, the SMB measurements are concentrated along the well-known routes (Ddu–DC, MNY-CSY–Ddu, CSY–VK, MNY–VK, MNY–CSY and VK-SP axis) linking the main scientific stations that have been operated for several decades. Many scientific traverses took place in these areas since the 1960s and are still going on, especially along the MNY-VK route [*Lipenkov et al.*, 1998; *Ekaykin et al.*, 1998, 2002]. Even if we take into account the significant improvement in spatial coverage of ice cores and new SMB measurements in recent years [*Frezzotti et al.*, 2004; *Magand et al.*, 2004; *Frezzotti et al.*, 2005] in the Georges V land basin along the Ddu–TNB and TNB-DC axes (solid circles in Figure 2), these areas (and especially the Eastern Dome C drainage basin) still remain sparsely covered. The field measurement density differs strongly between the coastal and polar plateau areas. More than 61% (i.e., 402 measurements) of

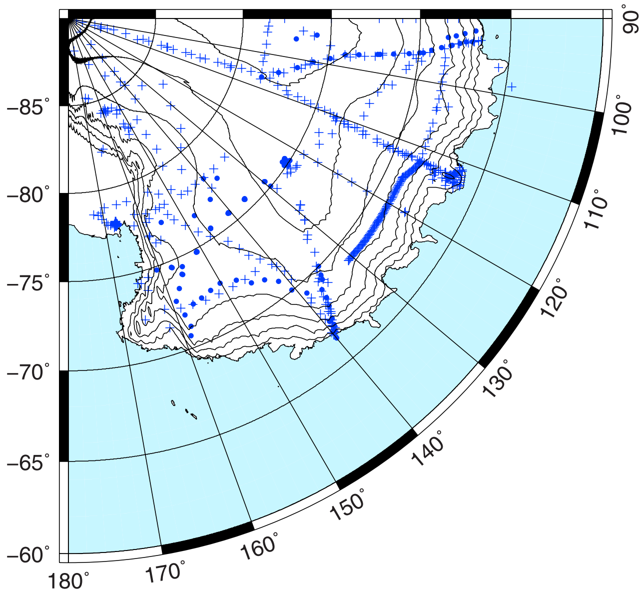

Figure 2. Distribution pattern of all observed SMB data (652 points) gathered in the present work for the 1950–2005 period in the 90°–180°E Antarctica sector. The blue crosses correspond to observed SMB data used by *Vaughan et al.* [1999] and *Arthern et al.* [2006], and solid blue circles represent new observed SMB data obtained from ITASE, RAE, and ANARE projects. Elevation contour lines are represented every 500 m.

the observed SMB data were obtained on the polar plateau (elevation more than 2000 m asl), approximately 24% (i.e., 157 measurements) between 1000 and 2000 m asl, and less than 15% (i.e., only 93 measurements distributed near Ddu, CSY, MNY and MCM stations) close to the coast, below 1000 m asl. This was recently pointed out by the ISMASS committee [*ISMASS Committee*, 2004] which recommended the need to increase SMB measurements near the coast, because of the expected accumulation variation that will occur at low elevations in next decades due to climatic change.

[19] As described in Table 2, SMB data mostly stemmed from stake observations (single stakes and stake farms) and radioactive measurements (β and γ radioactive counting). These represent 157 and 143 individual values, respectively, i.e., $\approx$ 46% of complete data set. More than 15% of the SMB data are issued from stratigraphic observations, chemical marker measurements, or from a combination of different methods (essentially stakes measurements + radioactive reference level and stable isotope content + snow stratigraphy). Some published SMB data were also obtained by digitization of SMB interpolated map (15%) [*Bull*, 1971]: These data will be discussed in a further paragraph. Finally, methods of SMB evaluation are unknown or not precisely detailed for almost a quarter of the SMB values (i.e., 162 SMB measurements), despite careful checking of primary data sources references.

3.2. Step 2: Selection of the Most Reliable SMB Data

[20] The second step (S2) is a quality selection of the previously gathered (S1) SMB data depending on the following quality criteria.

Table 2. Distribution of SMB Measurement Methods Identified in the Complete S1 Data Set

SMB Measurement Methods	Data Number (Percent of S1 Data Set)
Stakes measurements (stake farms and single stakes)	157 (24%)
Radioactive measurements (anthropogenic and natural radionuclides)	143 (22%)
Digitization from map	96 (15%)
Mixed methods	76 (12%)
Chemical markers plus stable isotope content	11 (2%)
Snow stratigraphy	7 (1%)
Unknown	162 (25%)
All methods	652

[21] 1. For S2a, in step 1, we include 96 SMB data from the mass balance map published by *Bull* [1971]. This map is based on linear interpolation over large spatial scales (50 km^2 areas) of any types of SMB field observations (365 measurements for whole Antarctica) realized between 1950 and 1970. These 96 SMB data are not direct or indirect SMB field measurements, but correspond to interpolated values from field measurements which are extracted from *Bull*'s [1971] SMB map. Moreover, as pointed out by *Vaughan and Russell* [1997] when they published their data set, *Bull*'s [1971] SMB map is presented without detailed information on references to the primary data sources. As no detailed information is given on the measurement methods and on their quality, we decide to reject these 96 SMB data.

[22] 2. For S2b the SMB data for which essential parameters (location, field and/or laboratory measurement methods used, dates of measurements and time period covered

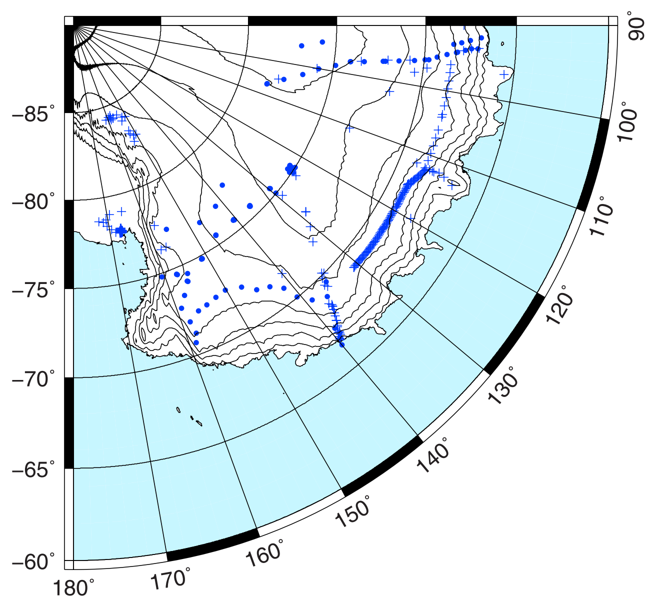

Figure 3. Distribution pattern of SMB data set after S2 quality-controlled selection (365 observed SMB data) for the 1950–2005 period in 90°–180°E Antarctica sector. The blue crosses correspond to observed SMB data used by *Vaughan et al.* [1999] and *Arthern et al.* [2006], and solid blue circles represent new observed SMB data obtained from ITASE, RAE, and ANARE projects. Elevation contour lines are represented every 500 m.

Table 3. Distribution of SMB Measurement Methods After S2

SMB Measurement Methods	Data Number (Percent of S2 Data Set)
Stakes measurements (stake farms and single stakes)	157 (43%)
Radioactive measurements (anthropogenic and natural radionuclides)	140 (38%)
Mixed methods	68 (19%)
All methods	365

by the SMB data, and references to the primary data sources) are missing or not verifiable are also eliminated because of uncertain reliability and validity. 173 SMB data are thus rejected. Some of these values could be further reintegrated to the data set if new additional information becomes available, but at this stage, we decide not to keep them.

[23] 3. For S2c, according to discussions in section 3, SMB measurement methods deemed very reliable (i.e., rate A) are retained. Methods rated B are conditionally accepted, i.e., if the related SMB data is attested in the same work by another reliable method (rates A or B). This concerns the methods based on natural radionuclide (^{210}Pb), stable isotopes and chemical markers (Table 1). Observed SMB data issued from snow stratigraphy are retained only if confirmed and controlled, in the same work, by one very reliable SMB measurement method (rate A), or by at least two reliable ones (rate B). We finally reject SMB data issued only from direct and unique snow stratigraphy observations, chemical markers or stable isotope content measurement. This lead to the rejection of only 18 additional SMB data.

[24] The second SMB data list resulting from this primary quality selection contains 365 SMB values, implying the rejection of approximately 44% of the SMB data from list 1 (Figure 3 and Table 3). This second list constitute our "reference SMB data set", that is to say it is the data set containing SMB data in 90°–180°E sector in which we have high confidence in terms of reliability and accuracy according to quality criteria previously described. In this quality controlled data set, SMB data from both stakes and radioactive measurements include more than 81% of all values; stake measurements remain the most representative method (43%). Simultaneous use of several SMB measurement methods on the field from the 1950s to now is less frequent (19%).

[25] Concerning the geographical distribution of SMB measurements, applying the quality criteria to select trustworthy values induces a significant loss of spatial coverage (Figures 2 and 3), essentially along the CSY–VK and VK-SP transects, between McMurdo and Dome C stations, in sectors south of the 80°S parallel and in the eastern portion of the Dome C drainage area.

[26] Concerning the temporal distribution, we observe that the number of SMB data in S2 decreases rapidly as the time period covered by the SMB estimation increases (Figure 4 and Table 4). However, this decrease is not regular. There are relatively sharp decreases of the number of SMB data between (1) 3 and 5 years of time period covered by the measurements, (2) 10 and 15 years, and finally (3) from 30 to 40 years.

[27] 1. Significant fraction of the observed SMB data in the 3 year range (i.e., 3 year and more) originates from stake

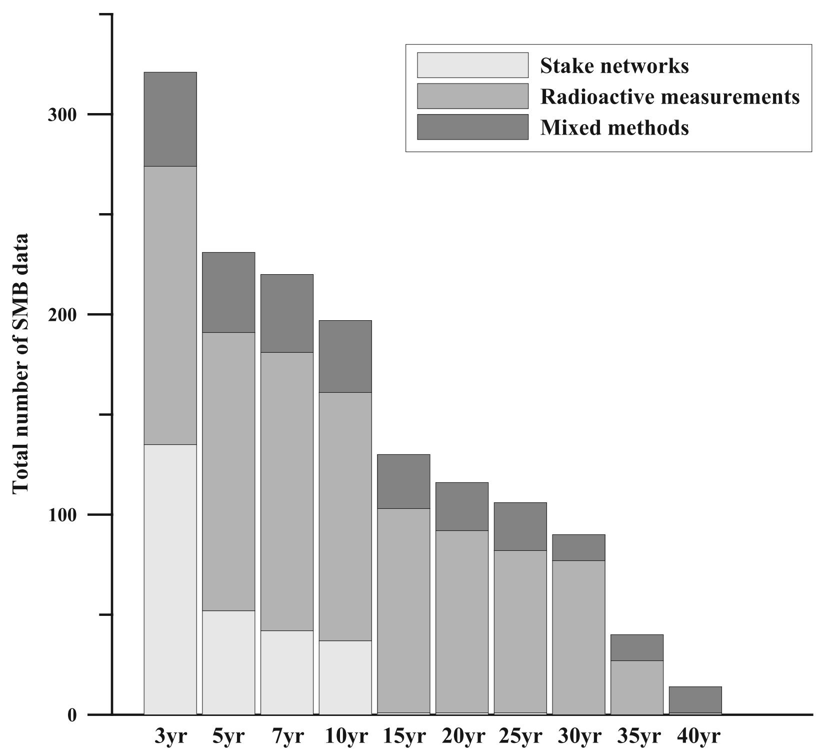

Figure 4. Temporal distribution of number of observed SMB data for three SMB measurement method categories (stakes and radioactive measurements as well as mixed methods) as a function of time period covered by the SMB measurements (3, 5, 7, 10, 15, 20, 25, 30, 35, and 40 years).

Table 4. Temporal Distribution of Number of Observed SMB Data (and Frequency Distribution) as a Function of Associated Measurement Method Types After S2[a]

	3 years	5 years	7 years	10 years	15 years	20 years	25 years	30 years	35 years	40 years
Stakes measurements	135 (42)	52 (23)	42 (19)	37 (19)	1 (<1)	1 (<1)	1 (<1)	1 (<1)	/	/
Radioactive measurements	139 (43)	139 (60)	139 (63)	124 (63)	102 (78)	91 (78)	81 (76)	77 (86)	27 (67)	1 (7)
Mixed methods	47 (15)	40 (17)	39 (18)	36 (18)	27 (21)	24 (21)	24 (23)	13 (14)	13 (33)	13 (93)
Total	321	231	220	197	130	116	106	90	40	14

[a]In parentheses, the frequency distribution is expressed in percentage of the number of observed SMB data associated to each measurement method.

measurements in Australian sector (ANARE Expeditions from 1980 to 1985, 110°–135°E). These data do not contribute in the 5 year range.

[28] 2. Between 10 and 15 years, the sudden decrease of the total number of SMB data is explained in particular by the disappearance of all stake measurements (except one stake network near the Vostok station).

[29] 3. The reduced number of field campaigns organized between 1990 and 2005 for the SMB study on the last 4–5 decades explains the small number of SMB data with periods of observations longer than 30 years.

4. Impact of Quality-Controlled SMB Data Selection

[30] One of the main uses of observed SMB data sets is to evaluate the ability of climate models to simulate the present SMB of Antarctica [*Krinner et al.*, 2007; *van de Berg et al.*, 2006]. Confidence in model predictions of Antarctic mass balance changes in response to climate change depends on the models' ability to reproduce past and present SMB. However, model validation is subject to uncertainties associated with the observed SMB data used in the validation process. By analyzing the apparent common systematic biases of several climate models compared to a same observation-based reference data set, *Genthon and Krinner* [2001] conclude that besides being the signature of common model shortcomings (resolution limitations, missing processes like blowing snow), it appears possible that the reason for some of the apparent model biases are in fact errors of the observational data used in the model assessment.

[31] Here we analyze how our filtering observed SMB data using quality control criteria affects the evaluation of the Antarctic SMB as simulated by climate models. We are not evaluating the models themselves. Rather, we want to see to what degree model evaluation can depend on the quality of the observation reference SMB data set. To carry out this exercise, we principally focused on results from the LMDZ4 atmospheric general circulation model (AGCM). LMDZ4 [*Hourdin et al.*, 2007] is a typical state-of-the-art stretchable grid high-resolution AGCM, latest in a suite of AGCMs regularly evaluated for their ability to simulate the climate and SMB of the polar ice sheets [*Krinner et al.*, 1997, 2007; *Genthon and Krinner*, 2001; *Genthon et al.*, 2002]. Spatial resolution over the Antarctic region is 60 km on average, which is quite high for an AGCM and of the order of that of limited area regional climate models used in climate mode [*Van Lipzig*, 1999; *van de Berg et al.*, 2006]. The evaluation of LMDZ4 itself was carried out recently [*Krinner et al.*, 2007] along with predictions of the impact of climate change of ice sheets mass balance for the 21st century. Results from model composite SMB assembled by *Genthon and Krinner* [2001] from several high-resolution AGCMs and meteorological analyses are also presented. The composite is an average of the SMB simulated by seven finest resolution models, including ARPEGE T106 and T79, ECHAM T106, HADAM 0.833° × 1.25°, LMDZ (versions 1 and 4) and ERA (noted as AGCMs composite) from 1979 to 2001. Table 5 summarizes the main characteristics of the different models. Further explanations and description of model's characteristics and quantitative assessment of model performances were described by *Genthon and Krinner* [2001].

4.1. Methodology

[32] We compare observed SMB data in 90°–180°E sector from the S1 (up-to-date but unfiltered) and S2 (quality control filtered) data sets to 20-year (1981–2000) LMDZ4 and 21-year (1979–2001) AGCMs composite simulations. In addition, the less recent and thus not quite up-to-date (and unfiltered) data set used by *Vaughan et al.* [1999] and *Arthern et al.* [2006], referred here as data set V99, is also used in the process. The comparison is carried out separately in 500 m elevation bins from 0 to 4000 m asl, altitude being used as a common sorting criterion, which allows roughly gathering regions and grid points of similar climate.

[33] Comparing model results and observed SMB data over periods that do not strictly coincide (1979–2001 for the models, various periods in the last 50 years for the

Table 5. List and Characteristics of General Circulation Models Used to Construct AGCMs Composite[a]

Model/Forecasts	Type	Resolution	Levels	Period
ARPEGE HIRETYCS (version 1)	spectral	T106/T42	30	1979–1988
ECHAM HIRETYCS (ECHAM 4)	spectral	T106	19	1979–1988
HADAM HIRETYCS (HADHAM2b)	grid point	0.833° × 1.25°/2.5° × 3.75°	19	1979–1988
ARPEGE version 0	spectral	T79	30	1979–1988
LMDZ (version 1), Antarctic zoom	grid point	Irregular, ≈ 100–200 km over the Antarctic ice sheet	15	1987–1991
LMDZ (version 4), Antarctic zoom	grid point	irregular, ≈ 60 km	19	1981–2001
ECMWF ERA	spectral	T106	19	1979–1993

[a]See *Genthon and Krinner* [2001] for further explanation. Type is the numerics used to solve the dynamic equations. Resolution is the horizontal resolution or truncation. Levels in the number of layers in the vertical. Period is the period of integration.

Table 6. Mean Absolute SMB Values From V99, S1, and S2 SMB Data Sets in Each 500 m Elevation Bin as Well as Corresponding Mean Absolute SMB Values of LMDZ4 Model (1981–2000 Time Period) and AGCMs Composite Results (1979–2001 Time Period)[a]

	V99 Mean A, kg m^{-2} yr^{-1}				S1 Mean A, kg m^{-2} yr^{-1}				S2 Mean A, kg m^{-2} yr^{-1}			
Elevation Bins, m	n	V99	LMDZ4	AGCMs Composite	n	S1	LMDZ4	AGCMs Composite	n	S2	LMDZ4	AGCMs Composite
0–500	53 (53)	+231 (±229)	+176 (±198)	+143 (±151)	55 (54)	+234 (±227)	+180 (±197)	+150 (±152)	36 (35)	+231 (±117)	+82 (±76)	+80 (±90)
500–1000	29 (28)	+472 (±471)	+370 (±140)	+323 (±108)	32 (31)	+457 (±452)	+368 (±133)	+322 (±102)	10 (9)	+444 (±173)	+355 (±60)	+322 (±42)
1000–1500	40 (38)	+367 (±297)	+441 (±132)	+337 (±91)	54 (44)	+359 (±281)	+423 (±138)	+330 (±95)	23 (14)	+399 (±153)	+344 (±101)	+307 (±108)
1500–2000	82 (76)	+330 (±142)	+203 (±72)	+224 (±63)	94 (86)	+318 (±142)	+201 (±75)	+223 (±70)	79 (71)	+324 (±128)	+201 (±70)	+235 (±65)
2000–2500	125 (119)	+209 (±114)	+130 (±62)	+152 (±86)	177 (152)	+189 (±113)	+122 (±62)	+140 (±86)	118 (96)	+225 (±118)	+143 (±57)	+174 (±83)
2500–3000	56 (55)	+101 (±47)	+60 (±34)	+56 (±36)	83 (69)	+95 (±51)	+59 (±38)	+54 (±39)	30 (20)	+98 (±70)	+69 (±48)	+63 (±50)
3000–3500	67 (65)	+55 (±24)	+32 (±16)	+25 (±14)	112 (88)	+51 (±26)	+32 (±17)	+26 (±14)	52 (31)	+45 (±28)	+32 (±18)	+27 (±13)
3500–4000	24 (23)	+54 (±13)	+26 (±8)	+19 (±7)	33 (31)	+52 (±13)	+27 (±9)	+20 (±8)	11 (10)	+44 (±12)	+27 (±12)	+20 (±9)

[a]See explanation in section 4. Mean A is the mean absolute SMB value expressed in kg m^{-2} yr^{-1} (1σ standard deviation is indicated in parentheses); n values correspond to number of available observed SMB values in each elevation bin (number of measurement sites are indicated in brackets).

observations) may be considered as a limitation to our study. However, this is typically the way model validations are carried out in the literature, and almost all data in our observational set do not cover the whole 50 year period either. It is very likely that models/data mismatches shown in the following are larger than any mismatch that would be related to inconsistent time sampling, in particular, because SMB tendencies during the 5 last decades in Antarctica are insignificant [*Monaghan et al.*, 2006]. Data from S1, S2 and V99 SMB data sets are compared with modeled result at the nearest grid point. In 3 instances for LMDZ4 simulation, the nearest model grid point is a fully oceanic grid point for which the model provides no evaluation of evaporation/sublimation or melting over snow/ice surfaces. As a consequence, these 3 coastal observations are not used in the comparison.

[34] Table 6 and Figure 5 show mean absolute SMB values (expressed in kg m^{-2} yr^{-1}) of observed SMB data from V99, S1 and S2 SMB data sets in each 500 m elevation bins, as well as corresponding mean absolute SMB values of LMDZ4 model and AGCMs composite. Mean absolute SMB results of LMDZ4 and AGCMs composite models are sampled at the same sites than observational data sets. We express the comparison results between the different observed SMB data and LMDZ4 simulated SMB data as mean absolute SMB differences (in kg m^{-2} yr^{-1}) (Table 7) and also as mean relative SMB differences (in percentage) (Figure 6 and Table 7). Here, the mean relative difference is defined as follows:

$$R = \left(\overline{\frac{x_i - x_{si}}{x_{si}}}\right) \times 100$$

With X_i, the observed SMB data and X_{si}, the simulated SMB data from LMDZ4 and associated to each x_i.

4.2. Results and Discussion

[35] Mean absolute SMB values of LMDZ4 and AGCMs composite model results are sampled at the same sites as V99, S1, and S2 SMB observations (Figure 5 and Table 6) in each altitudinal bin. They show that altitudinal distribution of the SMB is almost insensitive to data sampling, except in 0–500 m and 1000–1500 m elevation bins (see explanations below). As a consequence, much of the change of the estimate of the mean absolute (and then relative) SMB values after filtering is a result of SMB data quality control. In the present section, we principally focus on results from observational SMB data/LMDZ4 model simulation comparison.

[36] Except from 1000 to 1500 m elevation, the mean differences between observed and modeled SMB data in our study sector are positive, suggesting a general underestimation of the 90°–180°E sector SMB by the LMDZ4 model (Figure 6 and Table 7).

[37] For the lowest elevation bin, the mean model/observed SMB data differences are more than twice higher for S2 than for V99 and S1 respectively (Figure 6 and Table 7), showing a very large impact of the data selection. This is also where the relative differences with all data sets are largest. Poor model resolution of the ice marginal slope and the fact that coastal grid points are generally mixed land/sea grid points (for which the mass balance calculations are not valid) limit the pertinence of the comparison in this altitude bin.

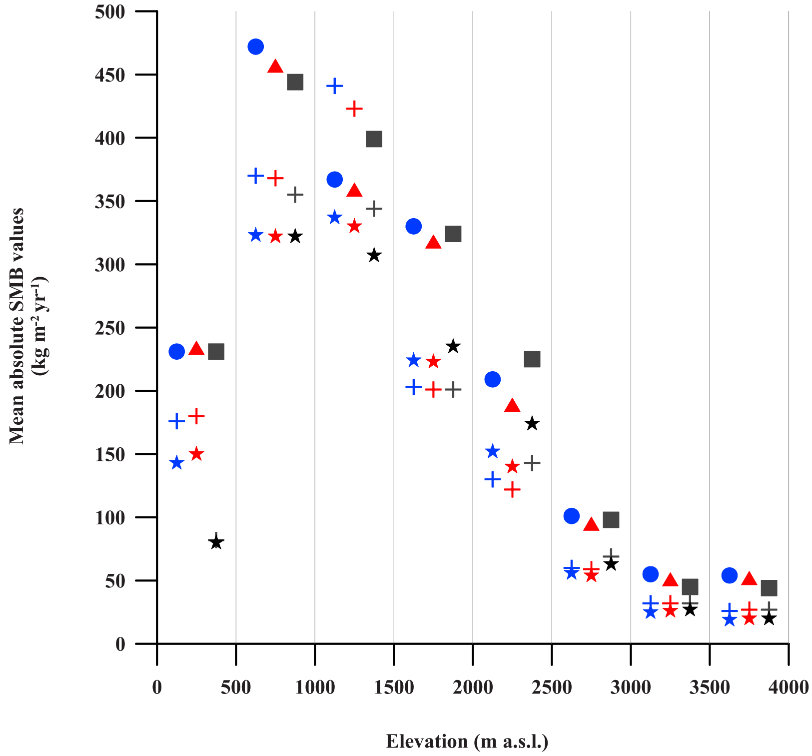

Figure 5. Mean absolute SMB values from V99 (blue circles), S1 (red triangles), and S2 (grey squares) SMB data sets in each 500 m elevation bin (0–4000 m elevation) as well as corresponding mean absolute SMB values issued from LMDZ4 model (blue, red, and grey crosses, respectively) and AGCMs composite model (blue, red, and grey stars, respectively) results (see explanation in section 4 and specific numbers in Table 6). Mean absolute SMB values are expressed in kg m^{-2} yr^{-1}.

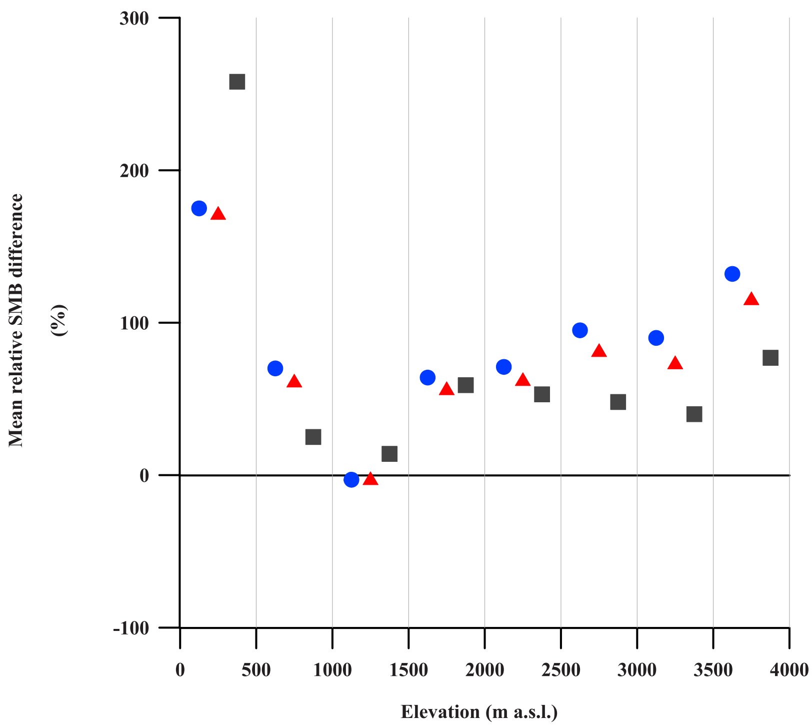

Figure 6. Relative mean SMB differences between mean observed SMB data in V99 (blue circles), S1 (red triangles) and S2 (grey squares) SMB data sets and LMDZ4 SMB simulations over 1981–2000 time period in each 500 m elevation bin (0–4000 m elevation) (see explanation in section 4 and specific numbers in Table 7). Relative mean SMB differences are expressed in percentage.

Table 7. Comparison Results Between Observed SMB Values from V99, S1, and S2 SMB Data Sets to LMDZ4 Model Results Over 1981–2000 Time Period Every 500 m Elevation Bin[a]

	V99			S1			S2		
Elevation Bins, m	n	Mean Difference, kg m^{-2} yr^{-1}	R, %	n	Mean Difference, kg m^{-2} yr^{-1}	R, %	n	Mean Difference, kg m^{-2} yr^{-1}	R, %
0–500	53 (53)	+55 (±299)	+175 (±222)	55 (54)	+54 (±296)	+172 (±221)	36 (35)	+149 (±140)	+258 (±207)
500–1000	29 (28)	+101 (±474)	+70 (±223)	32 (31)	+90 (±454)	+62 (±213)	10 (9)	+90 (±146)	+25 (±40)
1000–1500	40 (38)	−74 (±357)	−3 (±78)	54 (44)	−64 (±334)	−2 (±73)	23 (14)	+55 (±99)	+14 (±28)
1500–2000	82 (76)	+126 (±123)	+64 (±83)	94 (86)	+117 (±121)	+57 (±74)	79 (71)	+123 (±109)	+59 (±73)
2000–2500	125 (119)	+79 (±77)	+71 (±109)	177 (152)	+67 (±77)	+63 (±103)	118 (96)	+82 (±84)	+53 (±66)
2500–3000	56 (55)	+41 (±35)	+95 (±98)	83 (69)	+35 (±36)	+82 (±99)	30 (20)	+29 (±41)	+48 (±74)
3000–3500	67 (65)	+23 (±17)	+90 (±74)	112 (88)	+19 (±17)	+74 (±70)	52 (31)	+13 (±16)	+40 (±40)
3500–4000	24 (23)	+28 (±13)	+132 (±92)	33 (31)	+25 (±13)	+116 (±87)	11 (10)	+17 (±11)	+77 (±61)

[a]See explanation in section 4. Mean difference is the mean absolute SMB difference between observed SMB values and simulated SMB values, expressed in kg m^{-2} yr^{-1}; R is the mean relative difference, expressed in percentage (in mean difference and R columns, 1σ standard deviation are indicated in parentheses); n values correspond to number of available observed SMB values in each elevation bin (number of measurement sites are indicated in parentheses).

[38] For the 500 to 1000 m elevation bin, the mean differences are 20–30% and 30–45% smaller with S2 SMB data sets than with S1 and V99 SMB data sets respectively.

[39] The 1000–1500 m bin is the only one where data selection inverts the sign of the model/observed SMB data mean difference, possibly because of a relatively large concentration of observed SMB data in a single region, the Law Dome area (∼112°E, Figure 2). The mean relative difference in this elevation bin is very small though (Figure 6 and Table 7).

[40] For the 1500 to 2500 m elevation bin, the mean model/observed SMB data differences are similar for the 3 observational data sets. In these altitude ranges, the quality selection does not greatly modify the results (Figure 6 and Table 7).

[41] Between 2500 m and 4000 m, the mean absolute SMB values seem similar for all the SMB data sets (Figure 5 and Table 6) but, as the SMB values are small in these elevation bins, the relative SMB differences are large: from 20–30% to 30–45% smaller with S2 SMB data sets than with S1 and V99 SMB data sets respectively (Figure 6 and Table 7). As the plateau area is large, the impact of the choice of the reference data set on the integrated mass balance could be very important above 2500 m elevation.

[42] Except in the lowest bin, and from 1500 to 2000 m, the mean SMB difference resulting from S1 SMB data sets (V99 SMB data sets plus new SMB values) lie between the V99 and S2 ones (Figure 6 and Table 7).

[43] The appreciation of the performance of a climate model thus depends on the quality of the SMB reference data set used. This is particularly clear for the plateau region above 2500 m where quality control filtering of the reference SMB data results in a significant "improvement" of the model. The analysis and comparison between observational data sets and AGCMs composite yields very similar results than those shown with LMDZ4 model (Figure 5 and Table 6). Climate model quality evaluation and assessment is sensitive to the selection process applied to the observed SMB data used as reference. Since this is a rather perturbing issue, the observed SMB data/AGCMs composite results ensure that it is not a model-dependent improvement that would result from some peculiarity of LMDZ4. It is questionable, and would be worth verifying, to which extent interpolating observed SMB data to build global maps and evaluations of the Antarctic SMB [*Vaughan et al.*, 1999; *Arthern et al.*, 2006] is equally affected if data preprocessing for quality control is carried out.

5. Conclusion

[44] From the 1950s to the present, more than 650 field SMB measurements were carried out in 90°–180°E Antarctic sector using different techniques: stakes, annual layer counting, visual, chemical or isotopic markers, or identification of radioactively marked well-dated horizons (from atmospheric nuclear test explosions). Arguing that all these observed SMB data are of heterogeneous reliability, with a fraction of data of lowest quality being likely to contaminate the information provided by more reliable methods, we suggest a new quality-controlled SMB data set for this sector of Antarctica. This data set may be used along with

existing more comprehensive but quality-controlled data set to better evaluate the characteristics of the Antarctic SMB.

[45] We first provide an up-to-date short review of the various field methods for estimating local SMB, by partly drawing on the work of *Bull* [1971] and establish a "quality" rating of the various methods. Then we collect most available observed SMB data in our study sector for the 1950–2005 time period and check them carefully for potential errors. More than 40% of the SMB data originally gathered are identified as unreliable and/or inaccurate. 269 SMB data (~41% of S1) are rejected because not enough information is available to check their accuracy and reliability, and only 18 SMB data (~3% of S1) are rejected due to the SMB measurement method used. The new suggested observed SMB data set (S2) contains 365 SMB data. 84% of the selected values represent more than 3 years of SMB, 52% more than 10 years and only 24% more than 30 years. As previously recommended by *ISMASS Committee* [2004] and *van de Berg et al.* [2006] in their Antarctic SMB studies, we point out that new observations of SMB from the coastal zones of Antarctica are urgently required.

[46] We then investigate the "impact" of the quality selection process by comparing simulated SMB from AGCMs to recent SMB data sets and the new suggested one. All the comparisons show clearly that the selection process proposed in this paper has a significant impact on the inferred model biases. The "impact" is the largest above 3000 m elevation where the mean filtered SMB data is 20–30% less than the mean original SMB data. Therefore we point out the necessity to take into important consideration the reliability and accuracy of all observed SMB data before using them to calibrate and validate SMB simulation models, as well as to construct interpolated SMB maps. Even if the number of observed SMB data available in East Antarctica, and more generally in all Antarctica, is low, we expect that systematic use of all available SMB data without preliminary selection of SMB measurements depending on their quality (reliability and accuracy) could induce large errors in the quantification of the Antarctic SMB.

[47] **Acknowledgments.** The French ministry of research is acknowledged for financial support and ACI Climate Change is acknowledged for funding the analytical equipment of the LGGE underground laboratory (radioactive measurements). In Wilkes and Victoria Land sectors, most of observed surface mass balance data were obtained from recent research carried out in the framework of the Project on Glaciology of the PNRA-MIUR and financially supported by PNRA consortium through collaboration with ENEA Roma and supported by the French Polar Institute (IPEV). This work is a French-Italian contribution to the ITASE project. The authors are grateful to all colleagues who participated in field work and sampling operations.

References

Allen, B., et al. (1985), Glaciochemical studies and estimated net mass balance for Rennick glacier area, Antarctica, *Ann. Glaciol.*, *7*, 1–6.

Arthern, R. J., et al. (2006), Antarctic snow accumulation mapped using polarization of 4.3 cm wavelength microwave emission, *J. Geophys. Res.*, *111*, D06107, doi:10.1029/2004JD005667.

Aver'yanov, V. G. (1963) On the methods of precipitation measurements in the central Antarctica, report, pp. 195–197, Russian Acad. of Sci., Moscow.

Aver'yanov, V. G. (1969), Problem of the amount of snow accumulating in central Antarctica, *Sov. Antarct. Exped. Inf. Bull., Engl. Transl.*, *73*, 285–287.

Bamber, J. L., and J. L. Gomez-Dans (2005), The accuracy of digital elevation models of the Antarctic continent, *Earth Planet. Sci. Lett.*, *237*, 516–523.

Benson, C. S. (1962), Stratigraphic studies in the snow and firn of the Greenland Ice Sheet, *SIPRE Res. Rep. 70*, U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H.

Black, H. P., and W. Budd (1964), Accumulation in the region of Wilkes, Wilkes Land, Antarctica, *J. Glaciol.*, *6*, 3–16.

Bull, C. (1971), Snow accumulation in Antarctica, in *Research in the Antarctic*, pp. 367–421, Am. Assoc. for the Adv. of Sci., Washington, D. C.

Cameron, R. (1964) Glaciological studies at Wilkes Station, Budd Coast, Antarctica, in *Antarctic Snow and Ice Studies*, *Antarct. Res. Ser.*, vol. 2, edited by M. Mellor, pp. 1–36, AGU, Washington, D. C.

Carter, M. W., and A. A. Moghissi (1977), Three decades of nuclear testing, *Health Phys.*, *33*, 55–71.

Church, J. A., et al. (2001) Changes in sea-level, in *IPCC Third Scientific Assessment of Climatic Change*, edited by J. T. Houghton et al., chap. 11, pp. 641–693, Cambridge Univ. Press, New York.

Crozaz, G., and C. C. J. Langway (1966), Dating Greenland firn-ice cores with ^{210}Pb, *Earth Planet. Sci. Lett.*, *1*, 194–196.

Crozaz, G., et al. (1964), Antarctic snow chronology with ^{210}Pb, *J. Geophys. Res.*, *69*, 2597–2604.

Dansgaard, W. (1964), Stable isotopes in precipitation, *Tellus*, *16*, 436–468.

Davis, C. H., et al. (2005), Snowfall-driven growth in East Antarctic Ice Sheet mitigates recent sea-level rise, *Science*, *308*, 1898–1901.

Ekaykin, A. A. (2003), Meteorological regime of central Antarctica and its role in the formation of isotope composition of snow thickness, Ph.D. thesis, 123 pp., Univ. Grenoble 1, Grenoble, France.

Ekaykin, A. A., et al. (1998), Prostranstvennovremennaya struktura poly snegonakopleniya v rayone stantsii Vostok, Tsentral'naya Antarktida (The spatial and temporal structure of snow accumulation field in the vicinity of Vostok station, central Antarctica), *Vestnik St. Petersb. Un ta, Ser. 7*, *4*, 38–50.

Ekaykin, A. A., et al. (2002), Spatial and temporal variability in isotope composition of recent snow in the vicinity of Vostok station, Antarctica: Implications for ice-core record interpretation, *Ann. Glaciol.*, *35*, 181–186.

Ekaykin, A. A., et al. (2005), The changes in isotope composition and accumulation of snow at Vostok station over the past 200 years, *Ann. Glaciol.*, *39*, 569–575.

Epstein, S., et al. (1963), Oxygen-isotope ratios in Antarctic snow, firn and ice, *J. Geol.*, *71*, 698–720.

Feely, H. W., et al. (1966), Transport and fallout of stratospheric radioactive debris, *Tellus*, *18*, 316–328.

Fisher, D. A., et al. (1985), Stratigraphic noise in time series derived from ice cores, *Ann. Glaciol.*, *7*, 76–83.

Frezzotti, M., et al. (2004), New estimations of precipitation and surface sublimation in East Antarctica from snow accumulation measurements, *Clim. Dyn.*, *23*, 803–813, doi:10.1007/s00382-00004-00462-0038500803-00813.

Frezzotti, M., et al. (2005), Spatial and temporal variability of snow accumulation in East Antarctica from traverse data, *J. Glaciol.*, *51*, 113–124.

Genthon, C., and G. Krinner (2001), Antarctic surface mass balance and systematic biases in general circulation models, *J. Geophys. Res.*, *106*, 20,653–20,664.

Genthon, C., et al. (2002), Free and laterally-nudged Antarctic climate of an Atmospheric general circulation model, *Mon. Weather Rev.*, *130*, 1601–1616.

Giovinetto, M. B. (1960), Glaciology report for 1958, South Pole Station, *Res. Found. Rep. 825-2 IV*, Ohio State Univ., Columbus.

Giovinetto, M. B. (1963) Glaciological studies on the McMurdo–South Pole traverse, 1960–1961, *Inst. Polar Studies Rep. 7*, Ohio State Univ., Columbus.

Giovinetto, M. B. (1964), Distribution of diagenetic snow facies in Antarctica and in Greenland, *Arctic*, *17*, 32–40.

Giovinetto, M. B., and C. R. Bentley (1985), Surface balance in ice drainage systems of Antarctica, *Antarct. J. U. S.*, *20*, 6–13.

Giovinetto, M. B., and H. J. Zwally (2000), Spatial distribution of net surface accumulation on the Antarctic ice sheet, *Ann. Glaciol.*, *31*, 171–178.

Goldberg, E. D. (1963), Geochronology with lead-210, in *Radioactive Dating: Proceedings of a Symposium, Athens, 19–23 November 1962, Jointly Sponsored by the IAEA and ICSU, Vienna*, pp. 121–131, Int. At. Energy Agency, Vienna.

Goodwin, I. D. (1988), Ice sheet topography and surface characteristics in Eastern Wilkes Land, East Antarctica, *ANARE Res. Notes 64*, 100 pp., Antarct. Div., Kingston, Tas., Australia.

Goodwin, I. D., M. de Angelis, M. Pook, and N. W. Young (2003), Snow accumulation variability in Wilkes Land, East Antarctica, and the relationship to atmospheric ridging in the 130°–170°E region since 1930, *J. Geophys. Res.*, *108*(D21), 4673, doi:10.1029/2002JD002995.

Grootes, P., and M. Stuiver (1984), Oxygen isotope studies at the South Pole, *Antarct. J. U. S.*, *19*, 62–63.

Herron, M. M. (1982), Impurity sources of F−, Cl−, NO3− and SO_4^{2-} in Greenland and Antarctic precipitation, *J. Geophys. Res.*, *87*, 3052–3060.

Hourdin, F., et al. (2007), The LMDZ4 general circulation model: Climate performance and sensitivity to parameterized physics with emphasis on tropical convection, *Clim. Dyn.*, *27*, 787–813, doi:10.1007/s00382-006-0158-x.

ISMASS Committee (2004), Recommendations for the collection and synthesis of Antarctic Ice Sheet mass balance data, *Global Planet. Change*, *42*, 1–15.

Jouzel, J., et al. (1979), A continuous record of artificial tritium fallout at the South Pole (1954–1978), *Earth Planet. Sci. Lett.*, *45*, 188–200.

Kaspari, S., et al. (2004), Climate variability in West Antarctica derived from annual accumulation-rate records from ITASE firn/ice cores, *Ann. Glaciol.*, *39*, 585–594.

Koerner, R. M. (1964), Firn stratigraphy studies on the Byrd-Whitmore Mountains, 1962–1963, in *Antarctic Snow and Ice Studies*, *Antarct. Res. Ser.*, vol. 2, edited by M. Mellor, pp. 219–236, AGU, Washington, D. C.

Krinner, G., et al. (1997), Studies of the Antarctic climate with a stretched grid GCM, *J. Geophys. Res.*, *102*, 13,731–13,745.

Krinner, G., et al. (2007), Simulated Antarctic precipitation and surface mass balance at the end of the 20th and 21st centuries, *Clim. Dyn.*, *28*, 215–230, doi:10.1007/s00382-006-00177-x.

Lambert, G., et al. (1977), Accumulation of snow and radioactive debris in Antarctica: A possible refined radiochronology beyond reference levels, in *Isotopes and Impurities in Snow and Ice: Proceedings of a Symposium Held During the XVI Assembly of the International Union of Geodesy and Geophysics at Grenoble, August–September 1975*, *IAHS Publ.*, *118*, 146–158.

Legrand, M., and R. J. Delmas (1985), Spatial and temporal variations of snow chemistry in Terre Adelie (East Antarctica), *Ann. Glaciol.*, *7*, 20–25.

Legrand, M., and S. Kirchner (1988), Polar atmospheric circulation and chemistry of recent (1957–1983) south polar precipitation, *Geophys. Res. Lett.*, *15*, 879–882.

Lipenkov, V. Y., et al. (1998), O svyazi plotnosti poverhnostnogo sloya snega v Antarktide so skorost'yu vetra (On the relationship of surface snow density in Antarctica and Wind speed), *Glyatsiologicheskih Issled.*, *85*, 148–158.

Lorius, C., et al. (1968), Dating of firn layers in Antarctica: Application to the determination of the rate of snow accumulation, paper presented at International Symposium on Antarctic Glaciological Expedition, Int. Counc. of Sci. Unions, Hanover, N. H., 3–7 Sept.

Lyon, G. L. (1986), Stable isotope stratigraphy of ice cores and the age of the last eruption at mount Melbourne, Antarctica, *N. Z. J. Geol. Geophys.*, *29*, 135–138.

Lyons, W. B., et al. (1990), Nitrate concentrations in snow from remote areas: Implication for the global NO_x flux, *Biogeochemistry*, *9*, 211–222.

Magand, O., et al. (2004), Climate variability along latitudinal and longitudinal transects in East Antarctica, *Ann. Glaciol.*, *39*, 351–358.

Miller, L., and B. C. Douglas (2004), Mass and volume contributions to twentieth-century global sea level rise, *Nature*, *428*, 406–409.

Minikin, A., et al. (1994), Spatial and seasonal variations of the snow chemistry at the central Filchner-Ronne Ice Shelf, Antarctica, *Ann. Glaciol.*, *20*, 283–290.

Monaghan, A. J., et al. (2006), Insignificant change in Antarctic snowfall since the International Geophysical Year, *Science*, *313*, 827–831.

Morgan, V. I. (1988), Snow accumulation and oxygen-isotope records at the Law Dome Summit, Antarctica, *Ann. Glaciol.*, *11*, 220.

Mosley-Thompson, E., et al. (1995), Recent increase in South Pole snow accumulation, *Ann. Glaciol.*, *21*, 131–138.

Mosley-Thompson, E., et al. (1999), Late 20th century increase in South Pole snow accumulation, *J. Geophys. Res.*, *104*, 3877–3886.

Mulvaney, R., and E. W. Wolff (1994), Spatial variability of the major chemistry of the Antarctic ice sheet, *Ann. Glaciol.*, *20*, 440–447.

Nemazi, M., et al. (1964), Mesure du taux d'accumulation de la neige au bord du continent Antarctique par la méthode du Plomb-210, *C. R. Hebd. Seances Acad. Sci.*, *259*, 3319–3322.

Oerter, H., et al. (1999), Accumulation studies on Amundsen, Dronning Maud land, Antarctica by means of tritium, diellectric profiling and stable-isotope measurements: First results from the 1995–96 and 1996–97 field seasons, *Ann. Glaciol.*, *29*, 1–9.

Petit, J. R., et al. (1982), A detailed study of snow accumulation and stable isotope content in Dome C (Antarctica), *J. Geophys. Res.*, *87*, 4301–4308.

Pettre, P., et al. (1986), Accumulation in Terre Adelie, Antarctica: Effect of meteorological parameters, *J. Glaciol.*, *32*, 486–500.

Piccardi, G., et al. (1994), Spatial and temporal trends of snow chemical composition at northern Victoria Land (Antarctica), *Terra Antarct.*, *1*, 134–137.

Picciotto, E., and S. Wilgain (1963), Fission products in Antarctic snow, a reference level for measuring accumulation, *J. Geophys. Res.*, *68*, 5965–5972.

Picciotto, E., et al. (1964), Rate of accumulation of snow at South Pole as determined by radioactive measurements, *Nature*, *203*, 393–394.

Picciotto, E., et al. (1968), Determination of the rate of snow accumulation at the pole of relative inaccessibility, eastern Antarctica: A comparison of glaciological and isotopic methods, *J. Glaciol.*, *7*, 273–287.

Picciotto, E., et al. (1971), Accumulation on the South Pole–Queen Maud Land traverse, 1964–1968, in *Antarctic Snow and Ice Studies*, *Antarct. Res. Ser.*, vol. 2, edited by A. P. Crary, pp. 257–315, AGU, Washington, D. C.

Pourchet, M., et al. (1983), Some meteorological applications of radioactive fallout measurements in Antarctic snows, *J. Geophys. Res.*, *88*, 6013–6020.

Pourchet, M., et al. (1997), Distribution and fall-out of ^{137}Cs and other radionuclides over Antarctica, *J. Glaciol.*, *43*, 435–445.

Pourchet, M., et al. (2003), Radionuclides deposition over Antarctica, *J. Environ. Radioact.*, *68*, 137–158.

Rignot, E., and R. H. Thomas (2002), Mass balance of the polar ice sheets, *Science*, *297*, 1502–1506.

Saigne, C., and M. Legrand (1987), Measurements of methanosulphonic acid in Antarctic ice, *Nature*, *330*, 240–242.

Schytt, V. (1958), *Norwegian-British-Swedish Antarctic Expedition, 1949–52*, *Scientific results*, vol. 4, *Glaciology II*, Norsk Polarinst., Oslo.

Schytt, V. (1962), Mass balance studies in Kebnekajse, *J. Glaciol.*, *4*, 281–286.

Shimizu, H. (1964), Glaciological studies in West, 1960–1962, in *Antarctic Snow and Ice Studies*, *Antarct. Res. Ser.*, vol. 2, edited by M. Mellor, pp. 37–64, AGU, Washington, D. C.

Smith, B. T., et al. (2002), Distribution of oxygen isotope ratios and snow accumulation rates in Wilhelm II Land, East Antarctica, *Ann. Glaciol.*, *35*, 107–110.

Stenni, B., et al. (2000), Snow accumulation rates in northern Victoria Land, Antarctica, by firn-core analysis, *J. Glaciol.*, *46*, 541–552.

Stenni, B., M. Proposito, R. Gragnani, O. Flora, J. Jouzel, S. Falourd, and M. Frezzotti (2002), Eight centuries of volcanic signal and climate change at Talos Dome (East Antarctica), *J. Geophys. Res.*, *107*(D9), 4076, doi:10.1029/2000JD000317.

Swithinbank, C. (1957) The regime of the ice shelves at Maudheim as shown by stake measurements, in *Norwegian-British-Swedish Antarctic Expedition, 1949–52, Scientific Results*, vol. 3, pp. 41–75, Norsk Polarinst., Oslo.

Thomas, R., et al. (2004), Improved estimation of the mass balance of glaciers draining into the Amundsen Sea sector of West Antarctica from the CECS/NASA 2002 campaign, *Ann. Glaciol.*, *39*, 231–237.

van de Berg, W. J., M. R. van den Broeke, C. H. Reijmer, and E. van Meijgaard (2006), Reassessment of the Antarctic surface mass balance using calibrated output of a regional atmospheric climate model, *J. Geophys. Res.*, *111*, D11104, doi:10.1029/2005JD006495.

Van Lipzig, N. P. M. (1999), The surface mass balance of the Antarctic ice sheet: A study with a regional atmospheric model, Ph.D. thesis, 155 pp., Univ. Utrecht, Utrecht, Netherlands.

Vaughan, D. G. (2005), How does the Antarctic Ice Sheet affect sea level rise?, *Science*, *308*, 1877–1878.

Vaughan, D. G., and J. Russell (1997), Compilation of surface mass balance measurements in Antarctica, *Internal Rep. ES4/8/1/1997/1*, 56 pp., Br. Antarct. Surv., Cambridge, U. K.

Vaughan, D. V., et al. (1999), Reasessment of net surface mass balance in Antarctica, *J. Clim.*, *12*, 933–946.

Velicogna, I., and J. Wahr (2006), Measurements of time-variable gravity show mass loss in Antarctica, *Science*, *311*, 1754–1756, doi:10.1126/science.1123785.

Vickers, W. W. (1966), A study of ice accumulation and tropospheric circulation in western Antarctica, *Antarctic Snow and Ice Studies II*, *Antarct. Res. Ser.*, vol. 16, edited by M. J. Rubin, pp. 135–176, AGU, Washington, D. C.

Wilgain, S., et al. (1965), Strontium 90 fallout in Antarctica, *J. Geophys. Res.*, *70*, 6023–6032.

Zwally, H. J., et al. (2006), Mass changes of the Greenland and Antarctic ice sheets and shelves and contributions to sea-level rise: 1992–2002, *J. Glaciol.*, *51*, 509–527.

A. A. Ekaykin, Arctic and Antarctic Research Institute, 199397, St. Petersburg, Russia.

M. Fily, C. Genthon, G. Krinner, O. Magand, and G. Picard, Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS, Université Joseph Fourier-Grenoble, 54, Rue Molières, BP 96, F-38402 St. Martin d'Hères Cedex, France. (magand@lgge.obs.ujf-grenoble.fr)

M. Frezzotti, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, P.O. Box 2400, I-00100 Rome A.D., Italy.