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A synthesis of the antarctic surface mass balance during the last eight centuries

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Abstract

Global climate models suggest that Antarctic snowfall should increase in a warming climate and mitigate sea level rise, mainly due to the greater moisture-holding capacity of the warmer atmosphere. Several processes act on snow accumulation or surface mass balance (SMB), introducing large uncertainties in the past, present, and future ice sheet mass balance. To provide an extended past perspective of the SMB of Antarctica, we used 66 firn/ice core records to reconstruct the temporal variability over the past eight centuries and in greater detail over the last two centuries. Our SMB reconstructions show that the changes over most of Antarctica are statistically negligible and the current SMB is not exceptionally high compared with the last eight centuries. However, a clear increase in accumulation of more than 10 % has occurred in high SMB coastal regions and over the highest part of the East Antarctic ice divide since 1960s. To explain the different behaviours between the coastal/ice divide sites and rest of Antarctica, we suggest that a higher frequency of blocking-anticyclones increases the precipitation at coastal sites, leading to the advection of moist air at the highest areas, whereas blowing snow and/or erosion have significant negative impacts on the SMB at windy sites. Eight centuries of SMB stacked records mirror the total solar irradiance, suggesting a link between the southern position of the Pacific Intertropical Convergence Zone and atmospheric circulation in Antarctica through the generation and propagation of a large-scale atmospheric wave train. Decadal records of the last eight centuries show that the observed increase in accumulation is not anomalous at the continental scale; indeed, high accumulation periods have also occurred in the past, during the 1370s and 1610s.

1 Introduction

Sea level rise is among the major long-term consequences of climate change. Determining the future contribution of the Antarctic Ice Sheet (AIS) to global sea level rise is likely to be complex. The AIS is constantly adjusting its mass in response to changes in snow accumulation on its surface. These changes occur on annual to millennial time scales, with a concomitant effect on global sea level.

The SMB results from precipitation in the form of snow (snowfall and diamond dust/clear sky precipitation), which is then modified by surface sublimation, erosion/deposition of snowdrift transport, sublimation of drifting/blowing snow particles (wind-driven sublimation) and melting. Wind erosion, wind redistribution and sublimation as well as other processes during or after a precipitation event lead to a deposition at the surface, which is spatially much less homogeneous than the original precipitation (e.g., Eisen et al., 2008).

The SMB of the grounded AIS is approximately 2083 $\mathrm{Gt\,yr^{-1}}$, with a large interannual variability, year-to-year changes as large as 300 $\mathrm{Gt\,yr^{-1}}$ (15 % of the annual SMB) and a standard deviation of 121 $\mathrm{Gt\,yr^{-1}}$, which represents approximately 6 % of the 1989–2009 average (Van den Broeke et al., 2011). Moreover, despite recent advances, the SMB uncertainty is significant and is estimated to more than 10 % (equivalent to nearly 0.6 $\mathrm{mm\,yr^{-1}}$ of sea level rise), which represents a greater degree of uncertainty than any other component of the ice sheet mass balance (Frezzotti et al., 2007; Magand et al., 2007). Modern altimetry and gravimetric technologies are now strongly improving mass balance detection possibilities at shorter (decadal) time scales. However, several processes that act on the SMB at different temporal scales (from seasonal to decadal/centennial) introduce significant uncertainty into the cross-comparison of rates of change in ice-surface elevation (e.g., from satellite altimetry measurements) and mass (gravimetric satellite), with in situ measurements of SMB and with the precipitation fields that are output from climate models and reanalyses.

Global climate models suggest that Antarctic snowfall should increase in a warming climate, mainly due to the greater moisture-holding capacity of the warmer atmosphere, and thus, the SMB of the AIS will contribute negatively to sea level rise (Monaghan et al., 2008; Gregory and Huybrechts, 2006; Krinner et al., 2007; Uotila et al., 2007). Approximately 75 % of the predicted precipitation increase will fall in the peripheral area with surface elevations below 2250 m (Genthon et al., 2009). However, snow precipitation reflects not only air temperature variations but also conditions at the ocean surface, atmospheric teleconnections and circulations shift, as well as other climatologic/environmental effects. Recent observations from satellite data point to an accelerating ice loss from these peripheral areas that is caused by on-going and past glacier acceleration, implying that the contribution of ice sheets to sea level rise increases with time (Velicogna, 2009; Rignot et al., 2008; Pritchard et al., 2009).

Even insignificant trends in the SMB can cause considerable change in the mass balance of the AIS. Information about the temporal and spatial variability of the SMB is essential not only for the input term of the mass balance (component approach, SMB minus ice discharge at the grounding line) but also for interpreting the surface elevation/mass change signals from satellites (integrated approach, elevation or mass change) and for improving climate and meteorological models (ISMASS Committee, 2004). The combination of a firn densification model with time series of accumulation and temperature of the last 15 yr indicates that the SMB over a wide range of time scales has a significant influence on ice sheet elevation changes and needs to be taken into account for the assessment of the AIS mass balance (Helsen et al., 2008). The interannual mass variability along the Antarctic Peninsula (AP) and in the Amundsen Sea Sector of the West Antarctica Ice Sheet (WAIS) obtained from GRACE after removing offset, linear trend and annual harmonic, are mainly a consequence of accumulation variations governed by changes in precipitation rates (Sasgen et al., 2010).

The combination of satellite-derived temperature data with meteorological observation shows significant warming of surface temperatures across the AP and, to a lesser extent, in WAIS since the early 1950s, with little change across the rest of the AIS (Steig et al., 2009). The warming rate since the 1950s is approximately 0.082 °C decade^{-1} as a mean value for the whole of Antarctica (Chapman and Walsh, 2007). In the troposphere above the surface of Antarctica, a fairly strong winter warming has occurred since the early 1970s (Turner et al., 2006). Winter is the season in which much of Antarctica receives its maximum snowfall (Marshall, 2009). There is evidence of a warming and freshening trend in the ocean waters of the Southern Ocean and a reduction of the sea ice extent during the 1950s and 1960s (Curran et al., 2003; Abram et al., 2010). However, firn cores coupled with an atmospheric reanalysis model over the AIS indicate statistically insignificant or slightly negative SMB changes over the AIS since the 1950s (Monaghan et al., 2006). SMB research in recent decades using firn/ice core records of the last several centuries and beyond shows a variety of changes and trends, from slight increases (Thompson et al., 1994; Morgan et al., 1991; Mosley-Thompson et al., 1999; Frezzotti et al., 2005; Goodwin et al., 2003; Stenni et al., 2002; Urbini et al., 2008; Igarashi et al., 2011; Fujita et al., 2011) to doubling (Thomas et al., 2008), to decreases (Spikes et al., 2004; Kaspari et al., 2004; Schlosser and Oerter, 2002; Kaczmarska et al., 2004; Ren et al., 1999) and to no significant trend in the SMB (Frezzotti et al., 2007; Ruth et al., 2004; Anschütz et al., 2009, 2011; Sommer et al., 2000; Karlöf et al., 2005; Stenni et al., 1999).

The main purpose of this paper is to evaluate how the SMB affected the volume of the AIS at centennial scale and to provide an extended past perspective. For this reason we used seven new firn/ice records of Northern Victoria Land and Wilkes Land together with the existing firn/ice records (No. 59) to reconstruct the temporal variability of the SMB over the past eight centuries and in greater detail over the last two centuries. In Sect. 2 we described the various methods applied in order to evaluate the SMB values and its temporal variability from firn measurements and ice cores. In Sect. 3 we presented the results obtained by comparing SMB average values in three different time windows: the last 40 yr, the last 150 yr and last eight centuries, in order to highlight the SMB temporal and spatial variability at continental and regional scale. Finally, in the last paragraph, we discussed the possible climatological/environmental reasons of the SMB temporal variability and their spatial distribution.

2 Data and methods

The available dataset (66 records; Fig. 1; Table 1 Supplement) at the centennial scale is spatially widely representative of the entire Antarctic continent, with approximately 3 records in the AP, 14 records in the WAIS and the other records in the East Antarctic Ice Sheet (EAIS). However, the distribution of the SMB dataset is not completely balanced, with inadequate SMB records in coastal and slope areas with high accumulation, particularly in the WAIS and in the Indian Sector of the EAIS between 30° E and 110° E.

The WAIS presents SMB time series records that are younger than 500 yr, and Dronning Maud Land (DML) and Wilkes Land (WL) present 4 and 2 records that are longer than 800 yr, respectively.

The SMB temporal variability is evaluated in firn and ice cores (from annual to centennial scales) by counting the seasonal cycle of various parameters (physical, chemical and isotopic) and by identifying prominent horizons of known age, such as the fallout of acid layers from dated volcanic eruptions (e.g., 1964, Agung; 1887, Krakatua; 1816–1809, Tambora-Unknown; 1601, Huaynaputina; 1460, Kuwae; 1259, Unknown) or radioactive fallout (e.g., 1955, 1966) from atmospheric thermonuclear bomb tests (Eisen et al., 2008). Most recently the SMB has been evaluated at selected sites using stake farms (Frezzotti et al., 2007; Urbini et al., 2008; Kameda et al., 2008; Ding et al., 2011a). In general, however, seasonal cycles are difficult to observe at sites with low accumulation (below approximately 70 $\mathrm{kg\,m^{-2}\,yr^{-1}}$), such as the polar plateau of the EAIS, because the seasonally deposited chemical or physical signals have often been erased or changed by the action of the surface wind (Eisen et al., 2008). For the entire record, the two most valid reference horizons in the 1960s (atomic bomb and Agung eruption reference layers), the Tambora-Unknown volcanic explosions at the beginning of the XIX century and the oldest dated volcanic explosions (e.g., 1460 Kuwae, 1259 Unknown) are used when seasonal stratigraphy is unavailable or uncertain. Where available, stake farm measurements have been used to cover the most recent record (from the 1990s to the present) of previous firn/ice core measurements.

The snow redistribution process and relative surface roughness (e.g., sastrugi formation) have a strong impact on the annual variability of the SMB at the annual/metre scale (i.e., noise in ice cores). The accumulation/ablation pattern emerging from the stake farm measurements makes it possible to survey the accumulation values and noise on an annual scale by comparing the variations in the accumulation at each stake with the average across the stake farm. The detected "noise", represented by the standard deviation of the measured values, largely reflects the snow surface roughness (sastrugi) and limits the degree to which a single annual SMB value may be considered representative (Frezzotti et al., 2007; Kameda et al., 2008; Ding et al., 2011a).

Stake farm measurements show that accumulation hiatuses and/or erosion can occur at sites with accumulation rates below 120 kg m^{-2} yr^{-1} (Frezzotti et al., 2005, 2007; Ding et al., 2011a). Differences between cores and stakes can lead to the statistical misidentification of annual layers determined from seasonal signals at sites with SMB rates below 200 kg m^{-2} yr^{-1} because of the non-detection of higher and lower values. Achieving ±10 % accuracy in the reconstruction of the SMB from single cores requires high accumulation for an average roughness height of 20 to 40 cm (>700 kg m^{-2} yr^{-1}). Low-accumulation sites are representative if cumulative rates are computed over several years. Variation in the multi-year averages of the annual SMB decreases with the square root of the number of observation years (McConnell et al., 1997; van der Veen et al., 1999b; Goodwin et al., 2003; Frezzotti et al., 2007; Kameda et al., 2008; Banta et al., 2008). SMB records have been computed using cumulative rates over several years to reach an approximately 700 kg m^{-2} yr^{-1} threshold, allowing the estimation of annual SMB at ±10 % accuracy, which is comparable to that of instrumental measurements (e.g., those measuring rain precipitation).

The snow radar survey shows that spatial variability of SMB at the kilometre scale is one order of magnitude higher than the temporal variability at the multi-decadal/centennial scale. Depending on the study area, the distributions can be homogeneous over hundreds of kilometres on the polar plateau, particularly at ice divides and domes, or could vary considerably at places with high spatial accumulation variability due to strong wind erosion (e.g., Eisen et al., 2008; Frezzotti et al., 2005, 2007; Anschütz et al., 2008, 2011; Fujita et al., 2011). Therefore, the reconstruction of past climates based on firn/ice cores drilled in areas with spatial variability in SMB is complicated (Eisen et al., 2008). Several authors note the importance of conducting ancillary spatial SMB measurements as part of ice-coring programs so that topographic effects can be deconvolved from potential climate signals (e.g., Hamilton, 2004; Frezzotti et al., 2005, 2007; Anschütz et al., 2008; Spike et al., 2004; Kaspari et al., 2004). To avoid such a misleading issue, it is important that SMB records of insufficient or unassessed reliability (high variability or unknown SMB upstream of the core site) are discarded, even at the cost of a strong reduction in spatial and temporal coverage (Magand et al., 2007). To disregard artificial results, most of the analyses presented in this paper are applied for the entire dataset (66 ice cores) and for a restricted ensemble of 51 ice cores, hereafter called the assessed dataset (Ω), which is unaffected by upstream topographic/wind erosion effects (Fig. 1 and Table 1 Supplement).

The SMB has been analysed by comparing average values in three different time windows: the last 40 yr, from the present day to the 1960s (β40); from 1960s to 1815 (β150); and from 1960s to approximately the last eight centuries (βtot). The variations from one period to another are also studied.

To study the temporal variability of the SMB, different staked records at the continental and regional scale with decadal temporal resolution were created from the available ice core time series records with accumulations higher than approximately 70 $\mathrm{kg\,m^{-2}\,yr^{-1}}$. To homogenise the dataset and disregard noise due to post-depositional effects, the SMB records were smoothed with a 13-yr backward average. The 13-yr smoothing window was chosen because it is the minimum number of years needed for the core with the smallest accumulation (Talos Dome, B31, B32, B33) to arrive at the threshold accumulation value of 700 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ to ensure that the accumulation variability is within ±10 % of its mean value. In a second step, the cores were normalised (anomaly from the mean divided by the standard deviation) to allow comparison between sites with very different accumulation values. Finally, the mean continental values were created by averaging all the available data in each single year from 1200 to 2010. With the same methodology, three regional patterns were also created by averaging the WAIS (180–60° W), DML (60° W–90° E) and WL (90–180° E) records.

The possibility of representativeness of the calculated means decreasing going back in time and the consequent decrease of the available data was evaluated using a Kruskal-Wallis H-Test. This statistical non-parametric test ensures that the 21 cores have the same mean of distribution against the hypothesis that they differ within a confidence level of 95 %. Moreover, the longest ice core time series results are within one standard deviation for 87 % (1980–1918) for entire continent, 85 % (1980–1918) for the WAIS, 75 % (1980–1766) for DML, and 78 % (1990–1882) for WL. These time windows represent where the maximum number of ice cores for each average record is available.

3 Results

In the AP region, Thomas et al. (2008) show evidence indicating a doubling of the SMB since 1850 at the Gomez site, with acceleration in recent decades. Additionally, the Southern Annular Mode (SAM) variability is suggested to be responsible for more than a quarter of this SMB increase over the past 50 yr (Fig. 2). A much smaller rate of increase in the SMB since the 1930s has been observed in other high SMBs of the AP (Aristrarain et al., 2004; Raymond et al., 1996), suggesting that the doubling of the Gomez site appears to be unique. Additionally, a high SMB of the Amundsen Sea area of the WAIS (Kaspari et al., 2004) has been observed since the 1970s, whereas in the same period, a decrease in the SMB occurs in the south eastern area of the WAIS (Kaspari et al., 2004). The WAIS records present a decrease in the SMB between 1650 and 1725; after 1725, up to beginning of the XX century, a slight increase occurs, and a stable condition is maintained for most of the XX century (Banta el al., 2008).

Recent results (Anschütz et al., 2009, 2011) of the Norway-US traverse between DML and the South Pole, south of the ice divide of East Antarctica (IDEA), show that the temporal variability does not present an overall clear trend in the area (Fig. 2). The survey reveals a decrease in accumulation from 1963–2007 in accordance with previous research (Isaksoon et al., 1999), and westerly and lower elevations show an increase over the same period in accordance with other results from EPICA-DML (Mosley-Thompson et al., 1999; Oerter et al., 2000; Hofstede et al., 2004). The largest changes seem to have occurred in the most recent decades, with the longer time pattern being mostly stable. However, a different pattern has been observed between the more easterly and higher elevation sites along the IDEA. Fujita et al. (2011) note that the accumulation rate in the second half of the XX century is higher by approximately 15 % compared with the average over longer periods of 722 yr Before Present (BP) and 7900 yr BP along the highest part (> 3450 m) of the IDEA from Dome Fuji and EDML. A different result is found on the leeward sides of the ice divide with respect to the moisture source, where a decrease or no significant change was reported from the southern part of ice divide Dome Fuji-EDML (Anschütz et al., 2009, 2011; Fujita et al., 2011) or at lower elevations (< 3450 m). Dome A (Ding et al., 2011a; Hou et al., 2009) and Dome C (Frezzotti et al., 2005; Urbini et al., 2008) show similar higher accumulations since the 1960s observed at the highest part of the IDEA. The SMB at the South Pole shows that during 1050–1956, no significant change in accumulation occurred (van der Veen et al., 1999a), whereas stake farm measurements suggest an increase in SMB between 1965 and 1997 (Mosley-Thompson et al., 1999). However, Hamilton (2004) has noted a topographic control of the regional accumulation rate variability at the South Pole.

The results of the temporal variability of the SMB in WL do not show an overall clear trend for the last centuries (Fig. 2). An increase occurred from 1960 to 1970 and during the 1990s (Morgan et al., 1991; Goodwin et al., 2003; Stenni et al., 2002; Frezzotti et al., 2005). Since the 1990s, however, a decrease in accumulation with values close to a long average has been observed in the records (Frezzotti et al., 2007; van Ommen and Morgan, 2009; this study).

The $\beta 40$ record shows an accumulation increase of approximately 10 % (R^2 0.98; significance level > 99 %, $n = 66$) with respect to $\beta 150$ and an increase of approximately 15 % (R^2 0.97; significance level > 99 %, $n = 66$) with respect to βtot (Fig. 2). The difference between $\beta 40/\beta 150$ and $\beta 40/\beta$tot shows variations reaching approximately ±50 % of the SMB in close areas. This very high temporal variability can be correlated with spatial variability at the kilometre scale upstream of the core site; however, this variability is still observed if the same method is applied to the Ω dataset (51 records). No clear geographical spatial distribution of increasing/decreasing value could be observed on the Antarctic continent (WAIS and EAIS), whereas only a positive increase of the SMB is present in the AP. A detailed comparison between the total and the Ω dataset shows that the increase occurs mainly in records with high SMB values of > 300 kg m^{-2} yr^{-1} (+22 % $\beta 40/\beta$tot; +28 % $\beta 40/\beta 150$) and along the IDEA, whereas values of < 300 kg m^{-2} yr^{-1} do not show significant variations of the SMB (+2 % $\beta 40/\beta$tot; −1 % $\beta 40/\beta 150$). These clear differentiations of the base of the SMB are still present for the assessed record but with a low increase of SMB for values > 300 kg m^{-2} yr^{-1} (+5 % $\beta 40/\beta$tot; +8 % $\beta 40/\beta 150$) and no variation for an SMB < 300 kg m^{-2} yr^{-1} (+1 % $\beta 40/\beta$tot; −1 % $\beta 40/\beta 150$).

Analysis of the continental and regional staked time series shows a coherent pattern at the centennial scale with three periods with lower accumulation (1250–1300; 1420–1550; 1660–1790), interrupted by higher accumulation reaching a maximum around the 1370s and 1610s (Fig. 3). We can observe a value close to the average during the XIX century and the first part of the XX century, a trend of increasing accumulation is apparent from the 1950s up to the 1990s; but a decrease has been measured during the last 10 yr, with values that are approximately equal to the long period average. The regional patterns (WAIS, WL and DML) show antiphasing/dephasing between the different regions, mainly before the XIX century, but no clear antiphasing/dephasing patterns have been observed between the three different stacked records.

4 Discussion

Climate models suggest that snow precipitation in Antarctica should increase in a warming climate, mainly due to the greater moisture-holding capacity of the warmer atmosphere. The stable isotopic composition of snow precipitation is the closest proxy of air temperature. However, snow precipitation reflects not only air temperature variations but as well as other climatologic/environmental effects and moreover SMB represents the snow precipitation minus ablation driven mainly by wind.

The available $\delta O^{18}/\delta D$ and SMB annual records, from the annual to decadal scale, were not correlated as expected, assuming that precipitation increases with temperature (Thompson et al., 1994; Stenni et al., 2002; Fernandoy et al., 2010).

Our SMB stacked records show cyclic variations at continental and regional scale (Fig. 4) during the last eight centuries, especially between the XIII and XIX centuries. These cyclic variations do not mimic the temperature recostruction at continental or global scale but mirrored the total solar irradiance (TSI) based on the 10Be data of GRIP (Greenland Ice Core Project) and the South Pole (Steinhilber et al., 2009). A comparison of the two records shows low accumulation during low solar activity (Fig. 4), particularly during the Wolf minimum (1280–1359 AD) and the Spörer minimum (1420–1540 AD). The correlation between the SMB and TSI is less significant during the Maunder (1645–1715 AD) and Dalton (1790–1820 AD) minimums but nevertheless are well inside the 1σ uncertainty. Using staked records of ^{10}Be of the South Pole and Dome Fuji, Delaygue and Bard (2010) noted that the lowest solar activity is found during the Spörer minimum. Radiative forcing evolves with the cosine of the latitude and is thus at its maximum at the equator. A recent study indicates that variations in solar ultraviolet irradiance may be larger than previously hypothesised (Harder et al., 2009). The ultraviolet band contributes strongly to solar heating in the middle atmosphere, largely through ozone absorption. Sachs et al. (2009) provide strong evidence that during the past millennium, the southernmost position of the Pacific Intertropical Convergence Zone (ITCZ) occurred at the Spörer minimum. The central tropical

Pacific is a critical region that has a significant influence on atmospheric circulation in the Southern Hemisphere through the generation and propagation of a large-scale atmospheric wave train during winter (Lachlan-Cope and Connolley, 2006). Ekaykin et al. (2004) show that at Vostok Station, the variation of the SMB and snow isotope composition is significantly correlated with the Pacific Decadal Oscillation (PDO). Their results are confirmed by other studies that note that more intense (and fewer) cyclones and anticyclones are observed during the positive PDO (Pezza et al., 2007). Moreover, over the past 30 yr, anomalous sea surface temperatures in the central tropical Pacific have generated an atmospheric Rossby wave response that influences atmospheric circulation over the Amundsen Sea, causing increased advection of warm air to the WAIS and the AP (Ding et al., 2011b).

Intermittent blocking-anticyclone events in the Southern Ocean have caused significant precipitation events along the coast and slope of the AIS by conveying warm and moist deep air masses into the continental interior. The formation of the blocking ridge is associated with the wave activity propagation of quasi-stationary Rossby waves from the lower latitudes (Noone at al., 1999; Hirasawa et al., 2000; Goodwin et al., 2003; Massom et al., 2004; Scarchilli et al., 2011; Schlosser et al., 2011). The amount of snowfall related to blocking conditions is two times greater at high accumulation coastal sites (Law Dome 40 %) than at inland sites (20 % Dome C and Taylor Dome; 25 % Talos Dome; Scarchilli et al., 2011). Moreover, Sodemann and Stohl (2009) note that the highest altitudes of the EAIS have mean moisture source latitudes that are father north (45°–40° S) than coastal and slope areas (55°–60° S).

Wind-driven ablation greatly affects the SMB, and one of the largest areas of uncertainty regarding present and future SMB calculations is the role of wind-driven sublimation. Spatial variations in accumulation are well correlated with surface slope changes along the wind direction, and windy areas represent 90 % of the Antarctic surface (Frezzotti et al., 2004). Wind-driven sublimation rates are less than 50 kg m^{-2} yr^{-1} in plateau areas and up to 260 kg m^{-2} yr^{-1} in slope areas, and they account for 20–75 % of the precipitation (Frezzotti et al., 2007).

Turner et al. (2005, 2009) report that all continental stations have shown a negative trend in mean sea level pressure during the last 50 yr, that most coastal stations have recorded increasing mean wind speeds over recent decades, and that some EAIS and AP sites have shown a significant increase of strong wind events during the last 50 yr. These changes have been correlated to the shift of SAM into more positive conditions (Marshall, 2003). This shift has resulted in a decrease in mean sea level pressure over the Antarctic/Southern Ocean with a consequent increase of westerly winds over the Southern Ocean. Around the slope and coastal area of EAIS, the significant majority of strong wind events are associated with the enhancement of the downslope katabatic flow by broad-scale synoptic circulation involving a deepening of pressure off the coast and an increase of pressure inland (Turner et al., 2009). Simmonds et al. (2003) noted that the intensity of the mean cyclone activity has increased in the Southern Ocean since the 1990s.

To explain the different behaviours between the high accumulation/IDEA site and the rest of Antarctica, we suggest that the higher frequency of blocking-anticyclones increases the precipitation at coastal sites and leads to the advection of moist air at the highest area of the IDEA, whereas blowing snow and/or erosion have significantly negative impacts on the SMB of windy sites when katabatic strong wind events are enhanced by a deepening of pressure off the coast and the increase of pressure inland.

The highest IDEA site represents less than a few % of the lowest SMB of the EAIS ($< 30\,\mathrm{kg\,m^{-2}\,yr^{-1}}$), whereas the region with $> 300\,\mathrm{kg\,m^{-2}\,yr^{-1}}$ represents less than 15 % of the area but more than 25 % of the precipitation occurring over entire continent of Antarctica. However, we must take in account that the SMB in coastal areas is strongly influenced by wind erosion and blowing directly towards the ocean. Ablation by wind-driven processes represents from 20 % to more than 80 % of the solid precipitation in coastal areas (Frezzotti et al., 2004, 2007; Scarchilli et al., 2010). The SMB records with assessed reliability are located in relatively low wind speed areas and therefore are not representative of the SMB in windy areas.

5 Conclusions

In total, 66 SMB records of the last eight centuries from the Antarctic Ice Sheet have been analyzed to assess temporal variability of accumulation rates. The temporal and spatial variability of the last eight centuries pointed out that SMB change over most of Antarctica are statistically negligible and does not show an overall clear trend. This result is coherent with the results of Monaghan et al. (2006) that show statistically insignificant changes along the last 50 yr. However, a clear increase in accumulation of more than 10 % has occurred in high SMB coastal regions where the accumulation is higher than 300 kg m^{-2} yr^{-1} and over the highest part of the East Antarctic ice divide since 1960s. Decadal records of the last centuries show that the observed increase in accumulation is not anomalous at the continental scale, that high accumulation periods have also occurred during the 1370s and 1610s, and that the current SMB has not been exceptionally high over the last eight centuries.

The different behaviours between the coastal/ice divide sites and rest of Antarctica could be explained by a higher frequency of blocking-anticyclones increases the precipitation at coastal sites and leading to the advection of moist air at the highest areas, whereas blowing snow and/or erosion have reduced the SMB at windy sites. Eight centuries of SMB stacked records have mirrored the total solar irradiance, suggesting a link between the southern position of the Pacific Intertropical Convergence Zone and atmospheric circulation in Antarctica through the generation and propagation of a large-scale atmospheric wave train.

Small changes in the Earth's radiation budget may profoundly affect the atmospheric circulation and SMB of Antarctica. To predict future trends in ice sheet mass balance, models must reliably reproduce present-day and recent past patterns (from years to millennial scales) of SMB. Future scenarios from global climate models suggest that Antarctic snow precipitation should increase in a warming climate, but this increase could be offset by enhanced loss due to wind blowing ablation.

Supplementary material related to this article is available online at: http://www.the-cryosphere-discuss.net/6/821/2012/tcd-6-821-2012-supplement.pdf.

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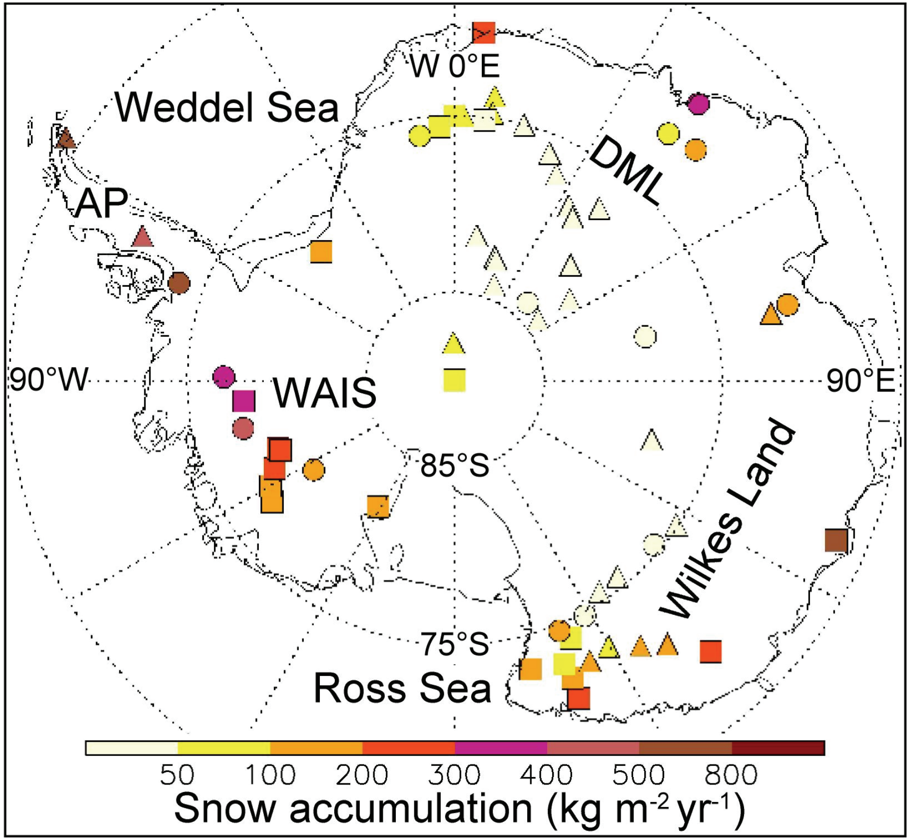

Fig. 1. Geographical distribution of firn/ice core records used in this study with snow accumulation values (kg m^{-2} yr^{-1}) and their reliability (square: assessed data (Ω) of annually resolved time series used for stacked records of Fig. 3; triangle: assessed data (Ω) without temporal series at the annual scale; circle: unassessed data with unknown SMB conditions upstream of the core site or sites affected by high SMB spatial variability).

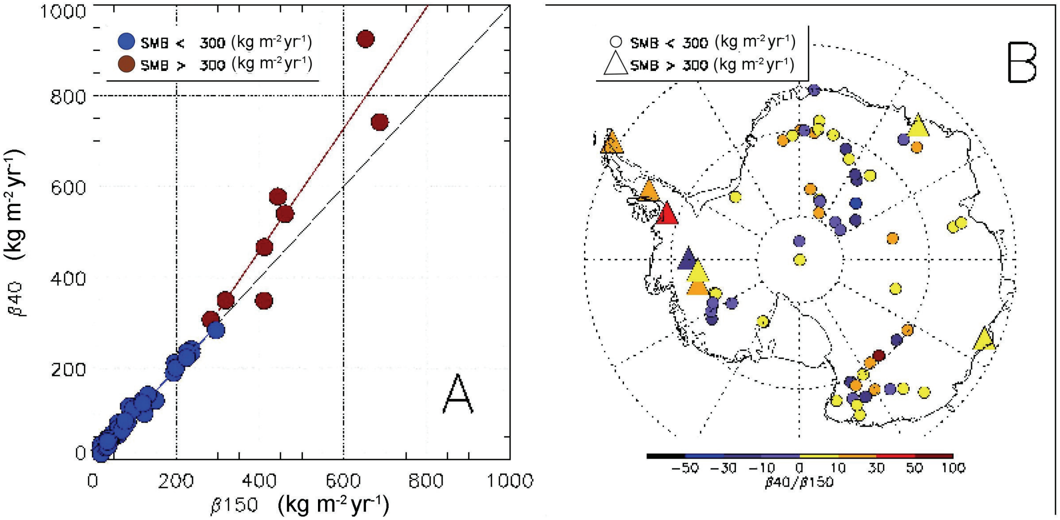

Fig. 2. (A) Relationship between 1960s-present (β40) and Tambora-1960s (β150) SMB values for sites included in the assessed (Ω) dataset (blue and brown circles for sites with an SMB lower and greater than 300 kg m^{-2} yr^{-1}, respectively); **(B)** Geographical distribution of % ratio between 1960-present (β40) and Tambora-1960s (β150) SMB values, triangles represent sites with SMB < 300 kg m^{-2} yr^{-1}.

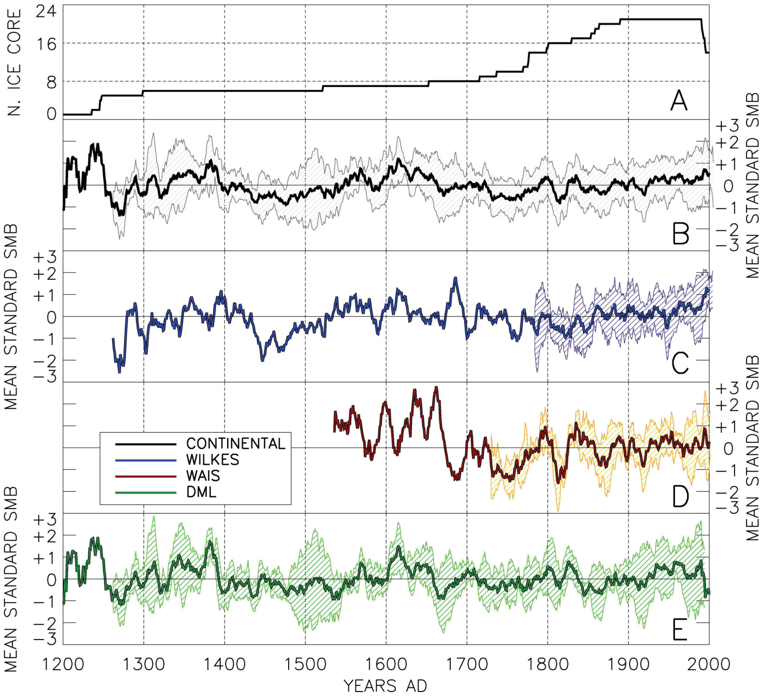

Fig. 3. Normalised annual resolved SMB time series smoothed at 15 yr using a backward running average for Antarctic sites included in the assessed (Ω) dataset. **(A)** Number of records used for each year; **(B)** Mean normalised SMB time series averaged over all the sites (21 cores) with their ±1σ uncertainty (grey filled). **(C)** the Wilkes Land sites (Hercules Névé, 31Dpt, Talos Dome, GV5, GV7, D66; Law Dome); **(D)** The West Antarctic Ice Sheet sites (Siple Dome; ITASE00_5, ITASE00_4, RIDSA, DC05A, DC05Q, ITASE00_1 and ITASE01_3); **(E)** The Dronning Maud Land sites (South Pole; Berkner B25, B31, B32, B33 and S100); with ±1σ uncertainty standard deviation (light blue-, orange- and light green-filled contours, respectively).

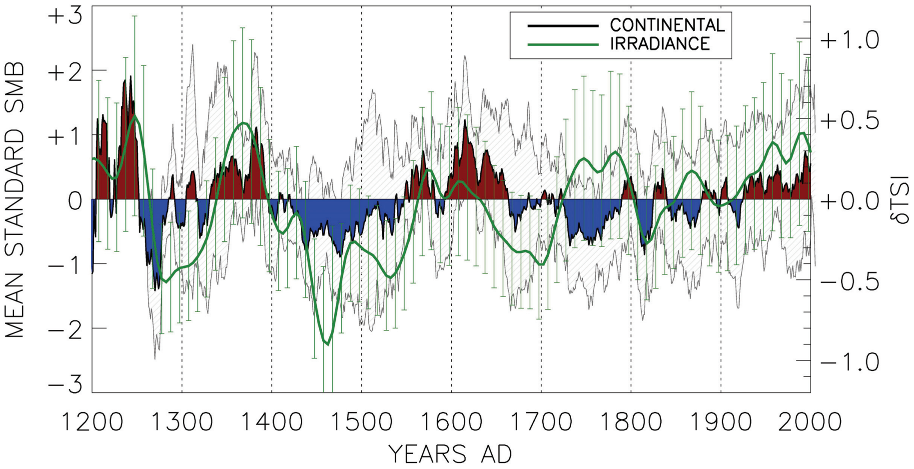

Fig. 4. Normalised annual resolved SMB time series smoothed at 15 yr using a backward running average for Antarctic sites included in the assessed (Ω) dataset (21 cores, black filled lines with positive and negative values filled in red and blue contours, respectively) and total solar irradiance (green line) with their ±1σ uncertainty (grey filled area and green vertical bars, respectively).