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The Cryosphere Discussions

Interactive comment on "Snow melting bias in microwave mapping of Antarctic snow accumulation" *by* O. Magand et al.

O. Magand et al.

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Comments from referees are in italic, responses are below and added text in the manuscript in bold

Comments from anonymous referee 1

General: The paper by Magand and others deals with surface mass balance in East Antarctica. The main tool used in this study is satellite record of microwave surface emission and surface observations. Surface mass balance of Antarctica is a great challenge due to both spatial and temporal variability and this work improve our knowledge. The paper contributes to ongoing debate concerning the estimation of uncertainty in the measurement of spatial variability in snow accumulation using remote sensing data tuned by in situ observation. Authors point out that regions potentially affected by melt-

ing should be masked out in microwave-based interpolation schemes.

The manuscript subject is very appropriate for The Cryosphere Discussion; Analysis are very accurate and the results are sufficient to support the interpretations and conclusion. However authors have taken in account only the melting process whereas pronounced density constrasts within the snow pack is also due to the outcrop of ice. Most of outcrops of blue ice area occur in coastal region due to intense wind scouring.

The paper indeed focus on the errors on A06's map due to surface melting as clearly stated in the title Snow melting bias in microwave mapping of Antarctic snow accumulation. However, we agree with the reviewer that the map is probably also inaccurate in the regions where the snow-pack layering is absent or not related to the snow accumulation but due for instance to strong wind. This includes blue ice areas as noted by the reviewer, as well as the wind-glazed / megadune areas. During our analysis, we tried to evaluate the accuracy of A06 map in the megadune areas but, the weak number of surface mass balance measurements in these areas does not allow statistically significant analysis. The same problem would arise in the blue ice regions.

According to the reviewer's comment, the text was carefully improved by including a comment (**bold text hereafter**) about blue ice and megadune areas in the section 5. Conclusion, first paragraph:

The disagreement in melt areas is a consequence of the fact that melt-refreeze layers affect the microwave emissivity in horizontal polarisation more strongly than accumulation does. **In some other places, the polarisation ratio may be unrelated to the accumulation. This includes the blue ice area (Bintaja, 1999; Winther et al., 2001) where no snowpack layering is present, and the megadune areas. The morphology of megadunes is complex (Frezzotti et al., 2002) but the snowpack seems to be weakly structured as revealed by the lower polarisation ratio (around 0.05 in the megadune field South of Dome C) than in the surrounding (around 0.07) or on the ice divide (around 0.09). Since a low polarisation ratio is interpreted as an**

high accumulation, it is not surprising that A06 map shows larger accumulation in the megadune field South of Dome C than around although the accumulation is probably lower there (Courville et al., 2007). Further statistical analysis is however difficult given the lack of in situ SMB measurements in these areas. The surface melting in the 90 - 180°E sector in East Antarctica observed by microwave radiometers (Picard and Fily, 2006) represents more than 0.6 x 106 km2 i.e. approximately 14% of the sector (about 4.4 x 106 km2). . .

We also added the following new references in the revised manuscript:

A) Bintaja, R.. On the glaciological, meteorological and climatological significance of Antarctic blue ice areas, Rev. of Geophysics, 37(3), 1999.

B) Courville, Z.R., Albert, M.R., Fahnestock, M.A., Cathles IV, L.M., and Shuman, C.A.. Impacts of an accumulation hiatus on the physical properties of firn at a low-accumulation polar site, J. Geophys. Res., 112, F02030, doi:10.1029/2005JF000429, 2007.

C) Frezzotti, M., Gandolfi, S., and Urbini, S.. Snow megadunes in Antarctica: Sedimentary structure and genesis, J. Geophys. Res., 107(D18), 4344, doi:10.1029/2001JD000673, 2002.

D) Winther, J.G., Marint, M.J., and Glen, E.L.. Blue-ice areas in Antarctica derived from NOAA AVHRR satellite data, J. Glaciol., 47, 325-334, 2001.

Specific comment:

(1) - In figure 1, TransAnarctic mountains of Victoria Land are mapped as area with 30 melting days, all these mountains present blue ice area and melting area is very limitated due to high elevation.

Surface melting detected by passive microwave satellite is indeed uncertain in regions with a complex topography or where rocks emerge such as in the TransAntarctic Mountains of Victoria Land. Three reasons may explain the over-estimation of the melting days in these regions:

1)The effective resolution of the satellite date used for the melt detection is about 40x60km. Even if a pixel is partially melted, it is likely detected as melted. Hence, in region with complex topography, if the valleys experience surface melting while mountains don't, the pixel is labelled as melted. 2)Melt mapping is based on the detection of snow emissivity increase associated with the presence of liquid water in the first meter of the snowpack. However, to our experience, when emerging rocks are present in a pixel, the emissivity also tends to rapidly increase during summer and is then detected as a melt event by our algorithm. We currently don't know if this is actually due to melt at the rock surface (because of their low albedo, melt is more frequent than in snow) or due to another phenomenon not associated with melting. Hence, surface melting is often detected in Mountains and especially in the TransAntarctic Mountains of Victoria but the validity of the detection is not as certain as in other areas. 3)To avoid erroneous detection, our melt detection algorithm is only applied where the altitude is below 1500m (Torinesi et al., 2003). The topographic mask used in the present paper was developed by Torinesi et al. (2003). We have recomputed a new mask with an up-to-date DEM (Bamber, personal communication) and find some differences in the northern part of Victoria Land.

As a conclusion, we agree with the reviewer that the melting map is questionable in the Transantarctic Mountains but this has no consequence on the present paper as no accumulation measurements are available in the area. In the revised manuscript, the figure 1 was then updated with the mask derived from the new DEM , but large melting processes are still detected in the region.

(2) *-Page 260 it is not clear 'The typical length of accumulation variability is about 10 km' Please explain.*

According to the comment of the reviewer, the text was carefully improved by including more detailed explanations (**bold text hereafter**) concerning Law Dome area special feature, in second paragraph in section 3.1. A06-100 versus MO7 SMB:

This is not surprising since the Law Dome region is characterized by strong precipitation, and then SMB, gradients due to the topography (Goodwin, 1991; Goodwin et al., 2003). **The typical length scale of elevation and spatial accumulation variability is about 10km (Van de Berg et al., 2006). The present-day accumulation at Law Dome is marked by a very sharp east-west gradient; high accumulation on the east side is the result of dominant cyclonic flow from the south-east and the orographic effect of the dome (Van Ommen et al., 2004). Due to the large SMB gradients occurring in such small area, the 100 km resolution A06's SMB map may hardly be consistent with the local SMB observations.** These two outliers are then discarded from our analysis and in particular the statistics (Table 2).

We hope that the new paragraph in the corrected manuscript is now more easily readable, and understandable. We also added the following new references in the revised manuscript:

E) Van de Berg, W.J., Van den Broeke, M.R., Reijmer, C.H., and Van Meijgaard, E.. Reassessment of the Antarctic surface mass balance using calibrated output of a regional atmospheric climate model, J. Geophys. Res., 112, doi 10.1029/2005JD006495, 2006.

F) Van Ommen, T.D., Morgan, V., and Curran, M.A.. Deglacial and Holocene changes in accumulation at Law Dome, Annals of Glaciology, 39(1), 359-365, doi 10.3189/172756404781814221, 2004.

(3) Page 260. On the base of figure 2 A06 Maps overestimate observed SMB values lower than 200mm WE and underestimate value higher than 200mm WE and A06 is not able to detect value higher than 400mm WE. Accumulation is clearly correlated to elevation, distance from coast, however, there is clear difference in the area East and West of Dumont D'Urville - Dome C Ice Divide, with higher accumulation in Western part. I suggest to Authors a geographical distribution analysis together with elevation analysis that could improve the analysis.

We agree with the reviewer's comment and we tried to see if any difference was clear between East and West of the Dumont d'Urville - Dome C transect. Therefore we selected all SMB data located between 90° and 170° East and between 1500m and 2500m asl elevation in order to minimize the altitude effect. Those data correspond mainly to Australian and Italian-French traverses from 1950s to nowadays. Results are given below as the difference ([A06-100 SMB data] minus [observed SMB data] in kg m-2 y-1) as a function of longitude (figure A available on request to the author).

No clear difference is seen between East and West of the 140° longitude. Then we conclude that A06 map apparently performs similarly East and West of the Dumont D'Urville - Dome C Ice Divide, and no useful conclusion can then be given in the paper.

(4) Page 261 last line and Page 262 first line, it is not clear the region where calculation is not performed and why?

A06 map is based on 6.9 Ghz microwave emission that comes from the first 10-20 top meters of the snowpack. Hence, to estimate the number of melt events seen by the satellite, we calculate the age of the layer at 10 meters (using accumulation and density), and sum the number of melt events from 2006 back in the past, up to the age of the 10 m deep layer. However, in low accumulation regions, the 10m deep layer may be older than 1979, the starting date of the melting dataset. In such a case, the number of melt events seen by the satellite can not be calculated. Fortunately, low accumulation regions usually corresponds to high-elevation and thus infrequent or no melting. And indeed, the calculation appears to be always possible in the 90°E-180°E sector as shown in figure B (available on request to the author).

Since the calculation is always possible in our study sector, we have decided to remove the sentence (second paragraph in section 3.2. Snow melting areas and microwave signatures) rather than to lengthen the paper for explaining a problem that does not concern our sector.

(5) Page 262 First paragraph of discussion, RMS relative % values are different be-

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tween text and table 2.

According to the comment of the reviewer (and we are sorry to have confused him), the text was corrected and we confirm that there are no differences between the RMS relative % values in the text and in the table 2.

(6) Reference Page 261 Surdyk and Fily, 1995. Page 263, Cavalieri and Comiso, 2004.

According to the comment of the reviewer, we corrected the references in the new manuscript.

Comments from anonymous referee 2

General: This paper describes the impact of (sparse) melt events on accumulation retrieval from microwave mapping in Antarctica. This is a particularly important topic. To date, no remote sensing technique exists to map absolute accumulation rate from space. That is why microwave-based interpolation of in-situ accumulation observations is used to construct accumulation compilations over the ice sheets. These accumulation compilations may be then used to assess the ice sheet mass balance, by comparing basin-integrated accumulation amounts to the solid ice fluxes from InSAR, for instance. This paper convincingly shows that irregular melts events destroy the correlation between microwave surface emission and accumulation, leading to systematic underestimates of accumulation in the coastal zones. In these regions, accumulation rates are highest. Given the significant and increasing fraction of the ice sheet that experiences occasional melting, this may lead to a systematic underestimation of basin-integrated and ice sheet integrated accumulation. The paper is original and significantly advances our understanding of Antarctic accumulation. It is well written, concise and the figures are of good technical quality. I have some small comments listed below and recommend publication after these have been addressed.

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Interactive Discussion

Discussion Paper

Station	Latitude	Longitude	SMB value	Elevation
GF11	-68,50000	98,40361	530	2048
GF10	-68,50000	99,67028	610	1983
E010	-68,49580	112,63380	542	1636
GF01	-68,50000	110,86667	520	1789
BO29	-68,50000	112,06667	640	1668
E015	-68,52570	112,86760	508	1612

Table 1: Detailled information on accumulation measurements far from the 1:1 line in Figure 3 (see Reviewer 2 - Comment 1)

Specific comments:

(1) - Figure 3 shows that some but not all data that lie outside the 1:1 line have been identified by the melt map. Please, comment on possible reasons, e.g. were these points missed by the melt algorithm?

The data points showing high observed SMB values (more than 500mm.yr-1) in figure 3, and not affected by melting processes are located along the ANARE Australian traverse (see coordinates and SMB values in the table, below) realized during the 1980s. These data points are located far from the melt zone detected by the satellite (see figure 1 in the revised manuscript, as well as, figure B in the present document) and their altitude ranges between 1600 and 2100m asl elevations. We are then confident that they are not affected by surface melting.

The short time period (less than 3 years) during which the SMB values of the 6 data points described above have been estimated as well as the SMB measurements methods (stake farms, single stake and/or Oxygen and Hydrogen isotope ratios) used for these estimation may explained the fact that the resulting observed SMB values are largely higher than those issued from the A06 interpolated SMB map. Indeed, as described in Magand et al. (2007), several authors showed very large standard deviations (up to 150%) in the accumulation pattern derived from very short time period (1-3 years) 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. It implies that high SMB values estimated on the 6 previous data points in the Australian sector are issued from accumulation area exempted of melting process, but were observed during a very short time period maybe not representative of the local SMB value on longer period. This may explain the discrepancy between SMB measurements and A06 SMB map. This is not discuss in the present paper that focuses on assessing the impact of melting on the A06 map.

(2) - Recently, Antarctic accumulation maps based on regional climate models have been published, showing significantly higher accumulation rates in the coastal regions of Antarctica compared to A06 (e.g. Van de Berg and others, JGR 2006). Is this difference a manifestation of the effect described in this paper? (...)

Both Van de Berg et al. (2006) and Figure 3 in the present paper indeed show that A06's map under-estimate the accumulation for the high accumulation. We are however not able to confirm that both are due to the same cause. In the submitted version of the manuscript, we were very careful in our conclusion about the direction of the effect of melting on A06 predictions (over or under-estimate of the accumulation) for the reason given line 12 page 264: The results presented in this paper strongly suggest the background model is inaccurate in the melt areas even if the background model also uses other information (i.e. thermal infrared). How this inaccuracy translates into the A06 map is difficult to quantify as the accumulation measurements are the primary source of information to build the map and the background model is only used for the interpolation.

In the revised manuscript, we have decided to add Van de Berg et al. (2006)'s findings as they corroborate with the effect of melting but are still careful not to conclude that there is a common cause. The text (**bold text hereafter**) is modified as follow (last paragraph, section 4. Discussion):

How this inaccuracy translates into the A06 map is difficult to quantify as the accumulation measurements are the primary source of information to build the map and the background model is only used for the interpolation. **However, the main effect seems to be an under-estimation of the accumulation in the melt areas. This may be explained by the fact that icy layers tend to increase the polarisation ratio and thus to decrease the accumulation estimation. Van de Berg et al (2004) also noticed that in the coastal regions, Vaughan et al (1999)'s microwave based map is under-estimated with respect to SMB predicted by a calibrated regional climate model. However, this is only partially supported in figure 3 which shows that not all the points affected by surface melting are below the 1:1 line. In any cases, we recommend polarisation ratios should not be used in melt areas to infer the SMB.**

(...) It would be interesting to see how these maps perform in this region, when checked against the new observations. Has any attempt been made at this?

Unfortunately, the number of new SMB observations (i.e. those not used to build A06's map) in the coastal regions is very limited (14 SMB data points) and the comparison with independent data is then very difficult.

Interactive comment on The Cryosphere Discuss., 2, 255, 2008.