Response to Referees' comments

Timo Vihma, Olli-Pekka Mattila, Roberta Pirazzini, and Milla M. Johansson, 24 January 2011

We thank both Referees for their efforts and constructive criticism. We have followed their recommendations as well as we can and the data available allow. Only in very few cases we disagree with the Referees, and explain our arguments below.
Our responses are marked in red.

Anonymous Referee #1

Received and published: 1 September 2010

Review comments
Spatial and temporal variability in summer snow pack in the Dronning Maud Land, Antarctica T. Vihma, O.-P. Mattila , R. Pirazzini and M.M. Johansson

This paper describes a data set of snow pit observations obtained on Antarctica. The presented subject fits well in the general scope of the journal and the data set itself is new and interesting.

The authors describe a large data set of snow temperature and density observations on Antarctica. They present a detailed analysis of the observed temporal and spatial variability of their observations. My only main remark on this paper is that due to the large amount of observations described, the paper is not always easy to read. Most of my remarks are therefore intended to improve the readability of the paper, in addition to some questions for clarification.

General remarks

- The link between cloud cover and snow temperature is through the surface energy balance, and more specific through the radiation budget. You use cloud cover as an indication of the near surface radiative budget. Make that more clear especially in the first part of the manuscript.
We have added text on the link between radiation and clouds.

- You refer to a weather station close to the Basen observations, but you do not present any observations of that station. Adding the observations can give more information about the radiation budget, mass balance and temperature at that site.
Unfortunately we have not (at least not yet) obtained data from the AWS that located 10 km south of Basen (operated by another institute), and therefore we considered it clearer not to mention this AWS in the revised text. Instead, we have added information on the air temperature and radiative fluxes on the basis of our measurements next to the snow pit

site close to Basen. Instead of an AWS, we trust much more on radiation measurements at manned stations, where we frequently checked the sensors for ice/snow accretion and horizontal leveling. These observations are now utilized to support the snow data analyses. There is an automatic weather station also at Aboa, operated by our institute, but the conditions on the nunatak differ from those on the glacier 250 m below. We did not have accurate data on the mass balance.

- Check when to use the word 'In' or 'On'.
Corrected.
- Make more clear when you refer to horizontal, vertical or temporal variability.
Corrected.
- Try not to use too long sentences.
Corrected.

Specific remarks

Title
I recommend a small change to the title: Spatial and temporal variability in the snow pack in Dronning Maud Land, Antarctica.
Corrected.

Abstract

P1108
- The general goal of the research is missing from the abstract.
Added.

L2-5: reverse the sentence: ...showed that horizontal gradients...largest in the escarpment region, and the most homogeneous snow pack was found on the Riiser-Larsen Ice Shelf.
Corrected.

L6, L11, L12: On the .... scale.
Corrected.

L16: write out: 101 to 102.
Corrected.

Study area and its climate

P1112
L6-9: Split long sentence at 'This effect'
Corrected.

L19: Replace 'Based' by 'Basen'
Corrected.

Observations and methods

P1113
L18: Explain 'traverse', or remove remark, Suggestion: start by explaining in a few sentences the different years, then explain how the different observations are made during the different projects. Is the meaning of transect the same as traverse in this manuscript?
Corrected. Now we only use the term 'transect'.

P1114
L2: Do you mean you determine the water mass and then use the known volume of the box to determine the density? Yes
Is it correct that in the Basen measurements the snow from the box was not measured but weighed directly? Yes. During the Basen measurements we had an accurate balance available to directly weigh the sample at the measurement site.

L1-5: Have you tried to resample the snow fork observations to the same spatial resolution as the cylinder observations? How well do they match in that case?
We made a new Figure 2 on the basis of a larger set of measurement from same snow pits with snow fork and a traditional density cylinder. The comparison yielded a root-mean-square error of 24.40 kg/m^3 and a correlation coefficient of 0.78.

L21: Add 'vertical' before 'profiles'.
Corrected.

L23: Replace 'to' by 'into' behind horizontally.
Corrected.

P1115
L8: Add 'vertical' before 'density profiles'.
Corrected.

L14: Were the horizontal profiles measured in 2006-2007 or 2007-2008 or both years?
On both years, but more in 2007-2008. Information on the measurements is now collected in Table 1, as suggested by the Referee.

L15: Were the cloud fraction observations done in both years?
Yes, clarified.

L18-28: In the previous section you describe in detail at what depth etc you measured temperature and density. This information is completely missing in this paragraph.
Information is added

P1116
L1: In the rest of the manuscript no data is used from this AWS, while the information might be of use for validation of the ECMWF output.

See above. Instead of the AWS, we have now applied data from our measurements close to Basen. The validation results are presented in Section 3.4.

L4-12: Add information about the reliability of the ECMWF output. To my knowledge, ECMWF is not very reliable in precipitation over Antarctica.
Information added.

Data analyses and results

Make subsections for the description of the temperature and density profiles in sections 4.1 and 4.2.
Done.

P1116
L17-22: It is not completely clear to me how the different standard deviations presented in e.g. figure 3 are calculated. Please rephrase this sentence, maybe split up in more sentences to explain the procedure in more detail.
Clarified.

L23: Remove 'Further'
Removed.

L23-25: I assume the classification is based on observed cloud fractions?
Yes, clarified.

P1117
L2-3: Were there no observations carried out between 11 UTC and 18 UTC? Explain why it is interesting to make this distinction.
Only very few observations were made between 11 UTC and 18 UTC, which made it natural to make the distinction: the results demonstrate that the morning and evening conditions were clearly different.

L5: Start new sentence and change sentence to 'In the summer of 2007-2008 no evening profiles were measured during cloudy days.
Corrected.

L7-10: Very long sentence, please split in shorter sentences.
Corrected.

L7: I assume with small scale you mean spatial scale on order of m?
We have simplified the sentence.

L12: Explain the exponential decrease with depth.
Explained.

L13: Remove 'however'

The sentence represents an exception to the exponential decrease. Hence, we kept the word ‘however’ but moved it in a more proper place.

L18: Split sentence at ’which demonstrates’.
Corrected.

L22: What were the average temperatures in the year/months preceding the observations? Do you have observations from AWS5 (air and/or snow temperature)?
On the basis of our observations at the snow pit site close to Basen, the air temperature in January 2008 was 2.6°C lower than in January 2007 (2.3°C according to the ECMWF). According to the ECMWF, 1-6 month periods preceding the observations were, however, warmer in 2007 than in 2006. The difference was 0.6°C for 1-2 preceding months and 1.9°C for 6 preceding months. The uppermost 50 cm of the snow pack reacts so fast to the atmospheric forcing, in particular during summer with strong solar radiation, that the mean temperature during the month of observations was more important than that during the preceding months.

L27-28: Replace ’that’ by ’the’ and add ’of 2007-2008’ behind ’summer’.
Corrected.

P1118
L8: See remark about connection of clouds with snow temperature.
We have added a note on the role of cloud in controlling variability in radiative fluxes.

L8-21: How many days/observations are included in the clear and cloudy subset?
We have added the information in the legend of Figure 4.

L8-21: Do you have any information about the actual diurnal cycle of the radiation components at the observation site from the AWS?
We made detailed radiation measurements at the snow observation site close to Basen. Information on the results is added.

L24-28: Explain the difference.
The reasons for the difference are explained in the end of Section 5.5.

P1119
L17-25: How reliable are the ECMWF analyses? Do you have mass balance observations available from the AWS?
We have added text on the reliability of ECMWF output in the end of Section 3. Unfortunately we do not have mass balance observations available.

P1120
L6-8: Is there any evidence of melting actually occurring? And how can melting result in lower densities?
The downward looking pyrgeometer frequently indicated periods with the surface temperature at zero. Melting takes place every summer at the measurement site close to

Basen, seen as annual ice layers (refreezing) in the snow pack. Melting can result in lower near-surface densities, when mass is moved from the surface layer via downward percolation of melt water, which refreezes deeper in the snow pack. We have clarified these issues in the text.

L4-12: How many days/observations are included in the clear and cloudy subset?
We have added the information in the legend of Figure 6.

L21: Replace ’in’ by ’on’ behind ’snow’ and before ’escarpment 2’
Corrected.

P1121
L27: Any information available about the snowfall event from local observations?
No, there were observers neither on the ice shelf nor at Aboa on 28-30 November, and we dropped this text. The other snow-fall event on 7-8 January was observed at Aboa.

L29: Is there any evidence of melting actually occurring? And how can melting result in lower densities?
We do not have actual evidence of melting over the ice shelf, and have therefore slightly reworded the sentence. We think that melting was very probable, as it occurs every summer close to Basen, and the climate on the shelf is a few °C warmer on the basis of the ECMWF analyses and literature (references in Section 2). See above for the mechanism resulting in lower densities.

P1123
L21-25: Consider moving this paragraph to the discussion section.
Moved.

Discussion

P1124
L3-8: Very long sentence, please split in shorter sentences.
Splitted.
L11-12: replace 102 by 100.
Replaced.
P1125, P1126
-Replace 10x by corresponding number in m or km.
Replaced.
P1126
L14: Replace ’Reijemer’ by ’Reijmer’
Replaced.
P1127
L11: Replace ’that that’ by ’that’
Replaced.
P1128
L16: See general comment about energy balance and clouds.

We have added discussion on radiation measurements in Section 5.4.

Conclusions
P1132
-Replace 10x by corresponding number in m or km.
Replaced.

Tables
- Add table with the technical information about the density and temperature observations.
Please add accuracy information on the 3 density observational methods.
You can remove part of the information from the main text and refer to the table.
- Consider adding a table with all the measurement information, time, location, depth, number of observations etc. Especially when you present averages it could be useful to know how many observations are used in order to asses the reliability/significance of the results.
We have added a new Table 1 which presents all the information requested by the reviewer.

Figures

Figure 1.
Add small inset map of Antarctica to denote the general location of Dronning Maud Land. Mark AWS 5 in the map. Add the names of the 3 regions in figure 1b.
Check spaces between words in the caption. Remark that the numbering is based on mass balance stake numbers.
Corrected.

Figure 2.
Add legend to the figure and remove legend information from caption.
Corrected.
Suggestion: add lines denoting sample size of the snow cylinder observations.
Different dataset for showing snow fork accuracy used. Figure changed.

Figure 3 and 5.
Remove title from panel a, add this information as a legend in the figure. Replace ’daily’ by ’diurnal’ in the legends of panels b and c. In the caption add the information that these profiles are for the Basen small spatial scale experiment.
Corrected.

Figure 7 and 8.
Dotted lines for escarpment 1 are not visible.
Corrected.

Figure 9.

The color scale includes higher and lower values than shown in the figure. Add information about latitude longitude location of the plotted area. Mention the origin of the data in the caption.
Corrected.

Figure 10.
The horizontal axis labels mention accumulation stake, replace with snow pit id. Add comment in caption that the figure illustrates the whole transect.
Corrected.
Figure 13.
Add legend to the figure and remove legend information from caption.
For clarity of the figure, we found it better to keep the information in the caption.

Anonymous Referee #2

Received and published: 21 October 2010
The paper provides new observations of spatial and temporal variability of snow temperature and density of coastal and slope area of Dronning Maud Land (East Antarctica).

The main tool used in this study is snow pit observations integrated with operational analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF).

Snow density measurement in Antarctica is a great challenge due to both spatial and temporal variability and difficulty to collect data due to environmental and logistical constrain. The paper contributes to ongoing debate concerning the snow density variability and its implications on integrated mass balance measurements using altimetry satellite.

The manuscript subject is appropriate for journal and data set is new and significant, but the analysis of data, result and discussion are partially adequate. Description and interpretations of data are not well organised and Authors should improve the readability writing more concisely.
We have organized the presentation better and rewritten several parts of the manuscript more concisely. See detailed information below.

Temperature gradient from daily to seasonal is one of the dominant process changing the structure of snow close to surface, and diurnal cycle have very important impact on snow temperature in the upper 50 cm of snow.

Authors analysed the data of temperature and density without taking in appropriate consideration the time and meteorological condition prior the measurements. Temperature and density of the first 50 cm of snow are strongly depended by previous

meteorological condition from hourly to week time scale. The Authors must analysed the data taking in account the air temperature in the previously hours and week. Analogously, in the first decimetres the density of snow, in the area with a snow accumulation up to meter per year, is strictly correlated to the last snow fall and the duration of densification process and correlated meteorological condition. Due to the fact that the sampled area extends for more than 300 km and 1200 m in elevation and only an AWS is available, the analysis of meteorological condition should performed using ECMWF, after a comparison of representativeness using AWS present along the traverse. Moreover the analysis of data should be performed with more attention to the different geographical/climatological condition along the traverse that strongly influence the temperature (e.g. melting on coastal area and absence in escarpment 2, katabatic wind absent in coastal and important in the escarpment) and density process.
We have added analyses on the meteorological conditions prior to the observations. We address this in Section 4.1 for the local measurements close to Basen nunatak (see the new Figure 5), and in Section 4.2 for the transect measurements. In the case of the transect measurements, we can only compare the effects of inter-annual variations in meteorological conditions prior to the observation periods. An analysis similar to that made for Basen (Figure 5) was not possible, because we basically had only one observation from each site in each year. If data from several snow pit sites would be merged together in the analyses, we could not reliably distinguish between the effects of spatial variability and weather history. The 50-km sub-section was an exception, but even from there we only had 4 snow pits from fixed locations (compared to 45 snow pits close to Basen in summer 2006-2007). Hence, the analyses did not add anything essential to the results presented in the new Figure 5. Unfortunately we have not (at least not yet) obtained data from the AWS that located 10 km south of Basen (operated by another institute).

Considering the effect of weather history on snow density, see our response below.

In the comparison with previous study (Granberg et al., 2009) should be taken in account the different scale of measurements and representativeness of the data analysed.
See our response below.

General comments:

The analysis and discussion would be improved by going further into the drivers of density variability in terms of local meteorological parameters, such as temperature (for melting using positive degree days/hours), snow accumulation rate and precipitation, and wind scouring. Some of these data could be available from previous research (eg. snow accumulation see, Karkas et al., 2005; Richardson PhD thesis 2001, Rotschky et la., J. Glacol. 2007 and reference therein) and from AWS data and ECMWF.
We have made much more analyses on the drivers of density variability. We analysed the effect of the history of air temperature, wind speed, solar radiation and precipitation on the density measured at the uppermost 50 cm close to Basen nunatak. These analyses were based on our own observations next to the snow pit site. We applied both bilateral and multilateral regression analyses. The analyses did not, however, reveal as clear

results as the analogous analyses for snow temperature (added in the end of Section 4.1.1). This was probably due to the following. First, related to summer season and the vicinity of the open sea, the density of newly fallen snow varied a lot from event to event. Under warm weather, snow fall did not always result in smaller density at the surface layer. Second, melting had different, even opposing effects on snow density in different layers. Sometimes melting resulted in lower near-surface densities, when mass was moved from the surface layer via downward percolation of melt water, which refroze deeper in the snow pack. Sometimes surface melting and sometimes sub-surface melting occurred. A significant relationship was that the density at the depth of 0.3 m correlated with the mean solar radiation during 10 days preceding the density observation ($r = 0.60$). We have also added comparisons against Rotschky et al. (2007).

Introduction should be reduced significantly; most of pag 1110 is not pertinent to the manuscript (air mass trajectory, snow on sea ice, etc.).
We have dropped much of the text that was in the previous version of the Introduction.

Most of previous authors that analysed the temporal and spatial variability of snow density (Sugiyama et al., 2010, Takahashi & Kameda, 2007) and their implication for surface mass balance and for satellite altimeter are not take appropriately in account (Helsen et al., 2008; Arthern etl al. 2010; Arthern and Wingham, 1998; Wingham, 2000; McConnell et al., 2000; Zwally and Li, 2002; Li and Zwally, 2004). Analogously the measurements conducted at South Pole for temperature (e.g. Brandt & Warren, 1997; Town et al., 2008). In the discussion should be describe the result of present manuscript and their implications on integrated mass balance measurements.
We have added most of the above-mentioned references into the Introduction, and added aspects of mass balance measurements in the Discussion.

Specific Comments:

pag 1110 line 4-7 snow density and hardness increase during summer, but also at onset of fall season. On the plateau the hardness is higher during winter and spring time .....
We have dropped this part of the text while shortening the Introduction (as requested above)

pag 1110 line 24 explain error source or delete?
Deleted

pag 1111 line 5 -9 The spatial variability is performed at scale 100 km scale, all the profile is 300 km long. The temporal variability is not analysed at diurnal scale.
Spatial variability is analysed both at 100 km and 300 km scale (see e.g. Figures 8 and 9. The temporal variability is analysed both at diurnal scale (within a day) and inter-diurnal scale (see e.g. Figures 3 and 6 and related text in Sections 4.1 and 5).

pag 1113 1-5 taking in account the snow distribution of the area from previous snow accumulation study (eg Rotschky et al., 2007 and reference within)

Reference added.

Methods

Error in snow density must be provided, and the large difference and the anomalous high value (up to 700 kg/m3) using box must be explained.
We have added information on the error in snow density measurements.
See below for explanation of the high value.

Pag 1115 line 1 to 15 Are spatial and temporal distribution of profile homogenous between during the different campaigns? The difference should be analysed and their implication on the analysis and comparison discussed.
The profile measurements were made at the same site in the two summers. The number and temporal interval of the measurements of vertical profiles were so similar in the two summers that it was not possible to detect any effects of the small differences on the results. On the other hand, most of the horizontal profiles of snow temperature and density were measured in summer 2007-2008. To avoid problems due to the small sample in 2006-2007, in the revised manuscript we only analyse data from summer 2007-2008.

Data analyses and results paragraph should be revised and organised more concisely and describe only the data used in the discussion.
We have dropped a lot of text from the previous version the of the data analyses and results paragraphs, and written the remaining parts more concisely. On the other hand, we also needed to add a lot of new material to satisfy the requests of both referees.

Pag 1118, should be reduced drastically.
One of the main requests of Referee 1 was that we should pay more attention to the effects of clouds and radiative fluxes. Hence, we have added text on radiative fluxes, but we have also dropped part of the old text.

Pag 1119 line 1-25, The snow precipitation conditions are not comparable in space/time during different campaign, this should be put in evidence and analysed in detail.
The measurements were made at the same place in summers 2006-2007 and 2007-2008. We have analysed the inter-annual differences in snow precipitation on the basis of ECMWF output. We reported the results as follows: “According to the ECMWF operational analyses, the amount of snow fall in the Basen region in December-January 2007-2008 was 130% larger than during the same period in the previous summer. The large accumulation of new snow has probably been the main reason for the lower density in summer 2007-2008. In addition, the colder weather with less metamorphosis in the snow pack may have contributed to the lower density. The large accumulation of new snow may also have contributed to the large day-to-day std in snow temperature in 2007-2008: new snow with low heat conductivity makes the near-surface snow temperatures more sensitive to synoptic-scale changes in the air temperature.”

Pag 1120 line 19-27 why use 9.8_K/km and not others value? The dry-adiabatic lapse rate is not in agreement with the observed value.

Dry-adiabatic lapse rate of 9.8 K/km comes from the definition of potential temperature. The observed temperature differences are reported a few lines above in the same paragraph. Calculation of the potential temperature is essential to interpret the reasons for the variations along the slope, as discussed in Section 5.2.

Pag 1120 line 27 and pag 1121 line 1, The horizontal std is controlled by std of altitude, which is the scale of analysis? Is and obvious observation, or is a new result?
We have dropped this text, as the result was rather obvious.

pag 1121 line 12. How much snow precipitation occurred on 7 and 8 January? Which implication for the measurements? analogously for line 27.
We have added information on the amount of snow fall on the basis of the ECMWF. This probably generated noise in the std profile, as the depths of different layers changed and new surface micro-topography was created.

Pag 1121 line 17 The value of 700 kg/m3 is close to ice value, whereas the density of 150 kg/m3 could be explained only with a recent snow precipitation, the data must be discussed and explained.
Both snow fall and melting-refreezing took place in the study region, which explains the extreme density values. We have modified the text accordingly.

Pag 1124 line 24-28 The research of Japanese colleagues are very important, but why quote here?
Citation dropped.

Pag 1127 It is not clear why Authors are against the conclusion of Granberg? Data from Granberg derived from fall and winter katabatic season and deeper measurements. These data are more close to climatic condition than meteorological condition of the Authors. The observations of Authors are strictly during summer and due to shallow depth represent the meteorological condition of summer season. Katabatic wind is a clear driver of climate along the escarpment area during fall, winter and spring. Comparison with Granberg study should be revised taking in account the different time/depth measurements.
We are aware of the differences between the time and depth of measurements (one of us was a co-author in Granberg et al.). Although the observation seasons and measurement depths were different, our results were similar to those of Granberg et al. (2009): the potential temperatures in the snow pack decreased from inland towards the coast in both data sets. The disagreement is in the interpretation of reasons for this. We present several arguments supporting our interpretation. None of these arguments is based on our summer-time data from upper snow layers. We have clarified the text to emphasize this.

Pag 1128 Is it melting an important factor on snow metamorphism and temperature? or not? where (elevation/distance) melting occurs?
Here we discuss the effects of melting on the diurnal cycle of snow temperature. We only had data from the site close to Basen (500 m above sea level, 120 km from the ice-shelf

edge). Melting was so limited that it did not have detectable effects of the diurnal temperature cycle.

The discussion and conclusion should be revised taking in account the previous comments.
We have revised the Discussion and Conclusions.

Fig 2 revised the X scale, hundred kg, described the site.
Corrected

Fig 9 and 11 Lat and Long
Added.