Interactive comments on "Representative surface snow density on the East Antarctic Plateau" by Alexander H. Weinhart et al.

Comments by the referees will be displayed in italics, the response from the authors in normal font.

1 Review by Anonymous Referee #1

This paper describes density observations along two over-ice transects from Kohnen station to Dome F on the plateau of the East Antarctic ice sheet. The observational techniques are state-of-the-art, resulting in small errors and highly significant results. These results show that 0-1 m average density shows little variation along the traverse, with a mean value of about 355 kg m^{-3}. This is an important result, as it can be used to improve the snow/firn modules in (regional) climate models and the interpretation of satellite altimetry observations. However, the writing needs to be improved, as many formulations are unclear (for some examples, see below, but this listing is not exhaustive). The figure quality can also be improved in places.

We thank the anonymous referee for his feedback on our manuscript. We carefully went through the manuscript again, clarified unclear passages and elaborated further on the influence of the presented data on satellite altimetry. Generally we included axes in the figures where missing.

1.1 Major comments

p. 1, l. 25: "The difference in the total mass equivalent of measured and modelled density yields a 3% underestimation by models, which translates into 5 cm sea level equivalent." It is unclear how these numbers are obtained, see comment below on Section 4.3.

See comment on section 4.3.

p. 2, l. 3: "Accurate quantification of the current state and rate of change of SMB is therefore one of the most important quantities..." A quantification is not a quantity. Please critically re-assess your formulations to improve this throughout the paper.

Thank you very much for this advice. We reassessed unclear wording or passages in the text, for example the terms quantification/quantity and precision/accuracy/representativeness. Necessary improvements were done especially in section 2.4, where we added a more in-depth explanation of stratigraphic noise, and section 4.3 (see also comment on section 4.3).

p. 3, l. 5: "The coldest 10 m firn temperature is recorded at Plateau Station (...), which makes the area the best modern analog of glacial firn." This is another example of a sentence that is really hard to understand. Coldest on Earth? What do you mean by "an analogue of glacial firn"? Please clarify.

We do not have access to glacial-climate firn but firnification during glacial climate periods is modelled to calculate for example the Δage (the gas age-ice age difference), and to infer the phase relationship between temperature derived from the isotopes and the CO_2 concentration measured in ice cores. Modelling glacial-climate firn faces some problems, e.g. at the pore close off (firn to ice transition). Firnification models simulate a deeper pore close off than $\delta^{15}N$ data predict. In this sense we understand modern firn from the coldest regions of the EAP as the best modern analogue of glacial-climate firn (for some regions, e.g. Kohnen station). The acronym CoFi stands for Coldest Firn. Within the project, five 200 m firn cores have been drilled on the EAP to investigate the firn densification.
We moved the project description to section 2.1 and added climatic information about the area. The snow profiles presented here were taken in the framework of this project. But as this information about the project itself is not necessary for the further manuscript, we decided to remove this sentence.

Section 4.3: It is unclear to me how the density errors in previous studies lead to the SMB error results in a 5 cm sea level equivalent? Over what period? SMB is usually derived from regional climate models that quantify mass directly, i.e. irrespective of density. Mass changes by GRACE are also direct mass measurements, only satellite altimetry suffers from uncertainties in the density of the material at which the elevation change takes place, but this is valid for changes in elevation, not for steady densities as presented here.

This comment also refers to your general comment on a proper use of terms, here we refer to simply mass instead of a mass balance (4.6 in the revised manuscript). We want show the underestimation in mass in the firn column running the model by Herron and Langway (1980) with two different initial densities. According to our calculation, this underestimation (3% of the firn column) in East Antarctica is equivalent to a total mass of 5 cm sea level equivalent. We updated the section with proper terms and described our line of thoughts at length. We also added another section (4.4 in the revised manuscript) with focus on the impact of our findings on satellite altimetry of ice sheets.

Section 4.4: Are the Ligtenberg et al. (2011) data also valid for the first 1 m? I think they use a simple parametrization to calculate surface density, hardly a 'model' as it is called here. It would also be valuable to provide the time span covered by the first 1 m of snow, this will vary with accumulation. In how far can climate variability be responsible for part of the differences with other studies? Based on its findings, does the current paper recommend to redefine 'surface density' as the average density of the first m? If so, this is an important recommendation that could be made more explicit.

According to the dataset description, the data from Ligtenberg et al. (2011) are modelled (IMAU Firn Density Model) for the near-surface (0-1 m depth) and gridded to 33 km resolution. We added this information in the manuscript.

Also in preparation of this manuscript we stumbled upon several opinions about how ‘surface snow density’ is defined (‘fresh snow density’, ‘near surface density’ and ‘density of the uppermost snow layer’ are used sometimes arbitrary for different purposes). For practical reasons, 1 m intervals are not only a commonly used interval for density, but also stable water isotopes in surface snow (e.g. Masson-Delmotte et al., 2008). The suggestion to redefine the term surface snow density is an important point that was addressed. We elaborated a bit more on the advantages of 1 m surface snow density.

The problem of time span and the – in turn – advantage of 1 m density compared to smaller intervals, is tackled in the conclusion, but we emphasised in the discussion a bit more. As mentioned before, we added a section about the climatic setting of the area. This includes information about accumulation rates as well as temperature. At Kohnen station the accumulation rate is 64 mm we a^{-1} (we = water equivalent) (Oerter et al., 1999) with increasing tendency over the last decades (Medley et al., 2018), at Dome Fuji 27.3 mm we a^{-1} has been measured (Hoshina et al., 2016). For the locations along the traverse a precise value is difficult to obtain. A 1 m snow profile therefore can cover a time period of four years at Kohnen station to 20 years on the remote Plateau.

Regarding your comment on climate variability: if we understood correctly, you ask whether changing temperature can be responsible for a difference between two density datasets. Here we want to refer to section 4.3 (revised manuscript), in which we elaborate on this thought. We show, that climatic driven changes in density are too low to ascribe the difference in density between the datasets only to temperature.

1.2 Minor comments

p. 1, l. 10: "Wrong estimates of snow and firn density can lead to significant underestimations of the surface mass balance." underestimations of → uncertainties in

p. 1, l. 17: "liner"? This has not been explained yet, so please don’t use it here.

p. 1, l. 23: "provided by a regional climate model" These models usually don’t ’provide’ density, but either prescribe it or use a simplified expression based on temperature, wind etc. Suggest to replace by ’used’.

p. 1, l. 25 and further: Note that regional climate models DO explicitly calculate accumulated mass, so using a wrong surface density does not influence the surface mass balance directly, only indirectly (through blowing snow threshold friction velocity, vertical heat transport in snow affecting surface temperature and hence sublimation etc.).

p. 2, l. 2: on → of; Greenlandic → Greenland.

p. 2, l. 5: "Satellite altimetry is state of the art" → Satellite altimetry is a state of the art method/technique...

p. 2, l. 13: "snow density is parameterized" → snow density in models is often parameterized

p. 2, l. 30: This sentence is unclear, please reformulate.

p. 3, l. 4: Remove "In order to avoid misunderstandings" *p. 3, l. 5: coldest/warmest temperatures → lowest/highest temperatures (change this throughout the text, please)*

p. 9, l. 8: good → well

p. 18, l. 23: This AWS has been installed and serviced by Utrecht University and AWI; please provide proper credit.

Figures: Please include solid axes where missing.

All minor comments were taken as suggested by the referee.

2 Review by Eric Keenan, Nander Wever, Jan Lenaerts

The authors present a suite of highly accurate surface density measurements taken during a traverse in Dronning Maud Land, East Antarctica. These observations have the potential to offer the ice sheet scientific community a unique and very useful dataset to evaluate and improve snow and firn densification models. The authors present principally interesting spatial analysis of the measured snow density, which adds to the presented data. That said, we have significant concerns that should be addressed before publication, namely

1) a more detailed description of density uncertainty quantification,

2) the method used to quantify the impact of density on surface mass balance retrieval, and

3) a more detailed description of observed small scale density variability in the top 1 m presented in Figure 5, as well as its potential drivers and implications for interpretation of satellite altimetry observations.

Please find a more detailed description of these suggestions and others broken into major and minor comments below.

We kindly thank Eric Keenan, Nander Wever and Jan Lenaerts for their detailed and productive feedback. The deliberate comments definitely helped to improve this manuscript, in particular the discussion and application of the presented dataset.

Regarding the impact on satellite altimetry, we added another section in the manuscript.

2.1 Major comments

Section 2.1: This section would benefit from a general discussion of weather and climate conditions in the area, in relation to how they may impact surface density (in terms of variability of yearly accumulation rates, wind speed and temperature). This would help setting the stage for the discussion in section 4.4.

We agree, rearranged section 2.1 and added a climatic overview about the area (especially regarding temperature and accumulation rate). This should also clarify unclear passages in the text (see also minor comment on P3, L3-6).

P7, L12: "Breaks and lost snow in the snow profiles haven been corrected." This needs more explanation.

s. comment on P8, L15

P8, L9-11: "It is generally possible that at the liner top and bottom some snow is lost, but as the exact snow volume is determined with the µCT, we overcome this error source." It's not clear how the microCT can compensate for errors due to lost snow. It's the same liner that's measured by microCT and the scale, so if the snow is lost, both methods should be affected.

s. comment on P8, L15

P8, L15: "Therefore…" I don't see how this sentence follows logically from the previous section.

We realized that parts of section 2.3 were not coherent enough and updated it. Now the logical sequence as well as the description of uncertainty in snow density should be clearer.

Regarding the missing snow: For the calculation of the µCT density only the central segment of the liner is used as scattering effects at the outer parts of the liner occur. The used segment corresponds to less than half of the snow volume in the liner. Missing snow at the edges of the profile does not influence the µCT scan.

It is generally possible that the snow profiles are subject to compression during sampling or transport. Therefore the exact snow volume determined with the µCT is rescaled to the original 1 m length (length of every single snow profile is determined individually) to avoid this potential error source. But lost snow in the liner (or at top or bottom) e.g. in non-cohesive layers (such as depth hoar layers) can lead to lower densities for the volumetrically calculated snow density.

Still, for 1 m segments, the volumetrically derived density has a higher precision as Fig. 7 shows; we added more details the text.

P8, L19: "spatially independent" Not really clear. Is the measurement setup in Fig.3 considered spatially independent? I.e., are liners X, A, B, C considered spatially independent? According to the text they are, but those four liners are not really independent.

Fisher et al. (1985) defined local noise as "random element caused by the surface irregularities", which is present in any taken snow profile or ice core. Stratigraphic noise and depositional noise are used as equivalent terms for local noise as they are more descriptive. This noise is mainly caused by spatially inhomogeneous deposition in combination with wind, leading to snow patches or dune structures that usually have a spatial extent of several meters.

To still be able to get a representative value or profile (of density or other parameters) at a given spot, several samples have to be taken at a distance, at which they have not recorded the same depositional (or stratigraphic) noise. For example, samples should not be taken from the same dune or snow patch. By stacking or averaging the samples, the noise is minimized. The (minimum) sampling distance between two samples was quantified by Laepple et al. (2016) with 5-10 m, as the correlation factor between single profiles decreases with increasing distance. Also the sampling distance in this study was chosen according to this finding. In an (unpublished) test using our density profiles we also come to a similar result. Note: Laepple et al. (2016) sampled perpendicular to the dune direction like we did in the OIR trench. For sampling parallel to the wind, the sampling distance between two samples should be higher.

This condition (not recording the same depositional noise several times) was called 'spatially independent' in our manuscript. The problem of stratigraphic noise is generally higher in regions with low accumulation and has also been recorded for e.g. isotopes (Karlöf et al., 2006; Münch et al., 2016).

For a better understanding, we added passages of the explanation above in the text.

Section 2.4: This section is difficult to comprehend, and is written very compact. Particularly, please expand on: "This way we use the maximum sample size without an artificially caused bias in the data."

For the whole section, there might be many different approaches to determine a certain number of precision for our data. The method we use has also recently been applied in a study by Dallmayr et al. (in review). We are aware of the not-straightforward method and tried to explain in more detail. With 'artificially caused bias' we mean the instance of arbitrary picking sets of different numbers of ρ_L (e.g. a certain number of independent profiles out of the 30 trench profiles). Instead we suggest to take the maximum possible number from the beginning. For more clarity, we also put the formula

$$\sigma_n = {\sigma_H^{1m}} \Big/ \sqrt{[2; n\text{-}1]}$$

in a more explicit position in the manuscript and changed x to [2;n-1], which makes is more understandable.

Figure 5: The large variability in observed density, particularly in the top meter, is very interesting and is a very nice inclusion in this paper. Can you please elaborate on what might cause this (surface topography? winds?) and what this variability means for interpretation of satellite altimetry. In particular, the observed variability is in apparent contrast with the title of this paper "Representative surface snow density...". If surface density is highly variable, is a representative density truly the best approach or should the scientific community make an effort to model this variability? A related comment is that Section 3.5 is really short and only mentions results. It's not clear which conclusions the authors draw from this and how it is important to understand surface density variability.

The surface topography is definitely one of the driving factors for the high horizontal variability of density we see in the top 20 cm in the OIR trench. It can be seen as a complex interaction between accumulation (a combination of calm diamond dust deposition as well as event-based accumulation), redistribution of soft snow by moderate wind and the existing topography, with the topography being the dominant factor (height & shape). Additionally, long residence time of snow at the surface due to low accumulation rates enhances the chance of metamorphism and sublimation (due to the vertical temperature gradients and low humidity), which also can have an impact on the surface snow density. We expanded the discussion of the driving factors in section 4.1.

Indeed, the high (local) variability at the snow surface (especially in the upper 20 cm) is a major finding of this manuscript. But as a consequence this is also the reason, why we argue for the use of a 1 m mean density as a more robust parameter for surface snow density. This way the density variability at the uppermost surface is compensated by using enough depth (or "annual layers", in other terms) without having the influence of a densification effect. We emphasized this statement in the discussion and the conclusion.

Otherwise, the high variability at the surface can also be an argument for a representative density obtained with the method we presented. Especially as altimetry measurements have a certain footprint area, representative regional density values can be of particular interest.

Despite the argument for the 1 m snow density, from our point of view a representative vertical variability is a more important aspect than modelling the horizontal variability. This is why we included the density distribution of density (Figure 9) in the manuscript and calculated the distribution also according to the presented subareas. The vertical variability can be interpreted as a measure of snowpack layering (i.e. layers of high and low density). The layering definitely has a strong influence on the densification from snow to ice on one hand (and therefore also on the bubble close-off at the firn-ice transition and subsequent effects). On the other hand, also satellite altimetry can use this information of vertical layering due to penetration depth into the snow and reflection at layer boundaries, but the topic of snowpack layering demands another dimension (esp. further parameters to describe the snowpack) that goes beyond the current manuscript frame.

Regarding section 3.5: We included this – indeed – very short section as a baseline for the argument of dune height and surface topography on the East Antarctic Plateau. We mention the relation of dune height to accumulation rate later in the manuscript. One might argue, that the dune height of 30-40 cm is not that high. But in contrast to the annual accumulation of ~10 cm, the dune height becomes enormous. We marked in the text when we refer to the measured surface heights.

P11, L1-3 and in the following sections: If the standard deviation for 1m sampling intervals is 5-10 kg/m3, how can the error quantification for the average be only +/- 2 kg/m3?

We assume, you refer to the horizontal standard deviation, as also displayed in Fig. 5.

The horizontal standard deviation (σ^{1m}_{H}) for the liner mean density (ρ_L) in the OIR trench is 9.63 kg m^{-3}. The standard error then is defined as the standard deviation divided by the square root of the samples size: (σ^{1m}_{H} / √30) = 1.76 kg m^{-3} ≈ 2 kg m^{-3}

Figure 8: Observations report a near uniform mean density in the four different subregions. For me, this is a surprising result. How might the different dates the observations were taken affect the measured density, i.e. do you expect a seasonal cycle in surface density. The way this dataset is currently presented, does not take into account this possibility. Additionally, if you are not already planning on doing so, can you please include exact observations date and time in the final dataset publication on Pangaea?

To be honest, we also expected to see a larger difference between the subregions (in both, mean density (Fig. 8) and density distribution (Fig. 9)) and a clearer trend along the traverse before the measurements.

To clarify your remark we added the sampling date at each location in table 2 (we planned to add the sampling date to the Pangaea dataset). From first (14.12.2016) to last (28.01.2017) sampling date we do not expect to see a seasonal cycle or bias due to sampling, especially as we did not notice significant accumulation during the traverse (main synoptic features: some diamond dust above 3500 mSL during the nights, during some days moving/drifting snow. The temperatures varied between -20 and -40°C during the night). We also added a sentence on that to section 4.4. From extensive sampling programs at Kohnen station we can generally say, that it is possible to detect seasonal cycles in density profiles – but only with a sufficient amount of samples (if local noise can be eliminated) (Laepple et al., 2016). On the EAP, this may be more difficult as the accumulation rate is much lower. To derive a representative density profile from the OIR trench can be a part of a future study.

P18, L18: This line mentions natural variability due to antecedent weather conditions. Section 4.2 needs to put the analysis based on climatological trends in perspective to possible year-to-year variability due to antecedent weather conditions. Since accumulation depths in dunes could be up to 30cm, this may impact top 1m density significantly.

In this context, high mean density of single profiles can also be explained with a high percentage of dune snow in a profile. A major problem here is that we do not know anything about the persistence of the surface roughness or surface features. If the surface is reshaped once or twice a year by stronger wind (>10 ms^{-1}), it is hard to attribute this variability to a variability of climate. Also the distribution of snow accumulation during the year is poorly known (keeping in mind the differences at Kohnen station with higher synoptic influence than the remote plateau with diamond dust deposition).

We elaborated on the year-to-year variability a bit further by comparing samples from Kohnen station from different seasons (16/17 and 18/19). Please note here, that the temporal and spatial variations cannot be decoupled completely, as we cannot sample the exact position again. But as the samples are taken as close as possible to the original sampling positions (several cm), we consider the spatial variation to be very low.

For further discussion about the climatic influence on surface snow density, we want to refer to section 4.3. (revised manuscript), where we test, whether the discrepancy in density between two datasets can be ascribed to rising temperatures in DML. We come to the conclusion, that the warming of 1°C alone cannot explain the difference in 1 m surface snow density and ascribe this to the stratigraphic noise.

Section 4.3: The authors aim to provide the impact of density on the uncertainty in SMB, but they fail to do this correctly. First of all, 3% uncertainty in the firn column does not directly translate to a 3% uncertainty in the overall firn+ice column (since there is much more ice than firn on East Antarctica). Secondly, this calculation pertains to mass, not mass balance (i.e. the change in mass per unit time). Instead, the authors should think about focusing on the application to altimetry, which needs surface density to convert volume to mass. As most of the elevation changes on East Antarctica measured by altimetry are SMB-driven, the observed elevation change will be associated to the layer of recently accumulated/ablated snow/firn, with an extremely spatially and temporally variable density. Since this (near-)surface density is much more variable than at 1 m, this volume-to-mass conversion is highly uncertain, especially when focusing on small scales such as in this study. The error here *is directly proportional to density, i.e. there will be 100% error in mass change if the assumed density is 100% different than it is in reality.*

We admit using wrong terms (especially in the section head) as well as unclear explanation in this section. Instead of a SMB, we rather want to show a simple underestimation of mass of East Antarctica here. Our calculation has been very simplistic, but regarding mass only we consider it to be principally correct.
We assumed an average thickness of 2000 m of firn and ice combined in East Antarctica. The firn column has a length of 93 m according to Herron and Langway (1980) with an initial density of 320 kg m^{-3}. This corresponds to 59 mWE. Calculating the water equivalent with our presented surface snow density, we get 61 mWE, meaning +3% mass for the same depth as above. This again corresponds to +0.11% in relation to the 2000 m of firn and ice combined. This 0.11% of the water equivalent of East Antarctica (51.69 m SLE (Rignot et al., 2019)) leads to a ~5 cm SLE estimation.
We made section 4.6 (revised manuscript) more comprehensive and added another section specifically discussing the applications of this dataset for satellite altimetry on ice sheets.

Figure 11: How is surface roughness and sub-grid topography, e.g. using REMA, related to observed density in this figure? It is recommended to analyze the liners from Kohnen station from different seasons (as mentioned P9,L15/16) to show to what extent there is year-to-year variability.

We also thought about this aspect in preparation for this manuscript and compared REMA surface and bedrock topography with our dataset. The resolution is simply a limiting factor here (in both dimensions, depth and space). For drawing a significant conclusion from the comparison, we consider the local sampling distance (10 m) as too small and the regional distance (100 km) as too large. Still, this would make sense for adjusted sampling intervals (like 10 km or so) along transects with samples of representative density.
Your idea for samples on Kohnen station has been implemented (see your comment on P18, L18).

P21, L5-8: First of all, a primary source of error in modelled snow density by the Ligtenberg et al. (2011) model could as well result from the meteorological driving data for the FDM simulations. Second, the text now seems to imply that more snow redistribution leads to lower densities. However, it has been demonstrated that snow redistribution tends to increase hardness/density (see Sommer at al. 2017, 2018).

We mentioned the meteorological forcing as a potential error source in our discussion.
Regarding the influence of snow redistribution on surface snow density, the wind speed and surface topography have to be taken into account. In wind speed maps (Parish, 1988; Sanz Rodrigo et al., 2012; van Lipzig et al., 2004), we see low wind vectors or mean wind speed from Kohnen station along the ice divide up the EAP and even lower values for the region around Plateau Station. Rather than with only the mean wind speed, we also want to argue with the distribution of wind speed instead of average wind speed (generally low wind speeds on the East Antarctic Plateau

with occasional strong winds causing drifting snow; the latter can happen more often at Kohnen station). We backed our discussion with the cited wind maps.

We are aware of the mentioned article (Sommer et al., 2018) and included it into the discussion as an example for wind packing with (in contrast to the remote plateau) relatively high wind speed. Knowing that there are many complex possibilities for depositional processes, we want to contrast two scenarios:

1) At higher wind speeds, snow gets redistributed and sorted, after deposition that snow has a higher density mainly due to wind packing (sorted, high density, example by Sommer et al. (2018)).
2) Soft snow (low density) gets deposited at low wind speeds, which causes a high variability (not sorted, low density) over depth in a given period of time.

Scenario 2) is the explanation we give for the lower densities in the major part of the interior plateau, as we sum up in section 4.4.

We thank the authors for taking the substantial time and effort to collect, describe, and distribute these density observations. That said, we believe these observations would best serve the community if they were also included in a unified and publicly available dataset such as SUMup (Montgomery et. al., 2018).

The data will be available on open-access repository Pangaea. We are happy to collaborate with our data on further datasets.

2.2 Minor comments

P1, L11: Underestimations or overestimations.

At the introductory part of the abstract, we kept the term 'uncertainties' deliberately as a general term. The under- or overestimations are dependent on the density measurements, of course. In our case, with higher density than assumed, we speak of an underestimation (s. same page, line 26).

P1, L25: Density errors can be due to errors in parameterizations or atmospheric forcing.

Added.

P2, L3: "Greenland Ice Sheet"

Corrected.

P2, L3-5: Please reformulate. Either "accurate quantification is important" or "The current state and rate are some of the most important quantities…"

Corrected as suggested.

P2, L11: "Especially in the interior of the ice sheets, the exact surface snow density is a limiting factor in precision." Please amend why that is, with appropriate references if available.

This sentence originated from a discussion with colleagues working with altimetry data. We found the following passage in Thomas et al. (2008) and included it as reference: "Radar return-pulse waveforms from high-elevation parts of Antarctica are affected by various characteristics of the snowpack, such as snow density, distribution of ice, wind-crust and depth-hoar layers (…), and by wind-induced surface roughness. (…) Near the coast, radar penetration into the snow is of far less concern than the local surface topography, which becomes quite rough, particularly in the most active parts of outlet glaciers where thinning rates are highest."

P2, L23: "Small variability" → "A small part of variability" I assume.

Corrected as suggested.

P3, L1 and L9: "stratigraphic noise" please explain.

Please see our answer to your major comment on P8, L19.

P3, L3-6: "In this paper, we present surface snow density data with high precision from a traverse covering over 2000km on the East Antarctic Plateau (EAP). In order to avoid misunderstandings we follow Stenni et al. (2017) using the term EAP for the region higher than 2000m above sea level (asl). The coldest 10m firn temperature is recorded at Plateau Station (Picciotto et al., 1971), which makes the area the best modern analog of glacial firn." Don't understand this section. Please explain in more detail.

We do not have access to glacial-climate firn but firnification during glacial climate periods is modelled to calculate for example the Δage (the gas age-ice age difference), and to infer the phase relationship between temperature derived from the isotopes and the CO_2 concentration measured in ice cores. Modelling glacial-climate firn faces some problems, e.g. at the pore close off (firn to ice transition). Firnification models simulate a deeper pore close off than $\delta^{15}N$ data predict. In this sense we understand modern firn from the coldest regions of the EAP as the best modern analogue of glacial-climate firn (for some regions, e.g. Kohnen station). The acronym CoFi stands for Coldest Firn. Within the project, five 200 m firn cores have been drilled on the EAP to investigate the firn densification.
We moved the project description to section 2.1 and added climatic information about the area. The snow profiles presented here were taken in the framework of this project. But as this information about the project itself is not necessary for the further manuscript, we decided to remove this sentence.

P3, L10 Average local snowpack density.

Corrected.

P4, Fig 1: Please add elevation contour labels.

Added.

P6, L20: The sentence “The trench surface was measured…” needs to be placed before P6, L19: “The total height difference between the lowest…”

Corrected.

P7, L9 weighted → weighed?

Taken as suggested.

P8, Fig 4: What explains the occasional large difference? Please add linear regression statistics.

We added linear regression and elaborated on the snow density uncertainty in more detail in the text (see also comment on P8, L9-11).

P8, L15: "Therefore, to quantify the 1m snowpack density we use L, to investigate smaller intervals we use the 1mμCT (Tab.1)" Since 1mμCT is CT density over 1m, and L the liner density over 1m, how should it be interpreted that 1mμCT can assist in investigating smaller intervals? Or should it read 0.1mμCT.

The latter, it was a typo. Corrected.

P8, L17: Snow density profiles?

Replaced.

P9, Section 2.6 Optical levelling needs to be placed before Section 2.2.3., since the optical levelling is already mentioned there.

We carefully thought about this suggestion, and discussed a suitable solution.
The profiles investigated with optical levelling are completely independent from the liner sampling procedure and should be seen as an additional information, with which we want to address the topic of surface roughness. As the snow liners are the main samples in this study, we want to keep them as the first method presented.
We moved the levelling of the OIR trench into section 2.6.

P9, L17: "Furthermore, a possible effect of the station itself should not be migrated into the other subsets." Please explain what effects are meant here.

Around Kohnen station an effect of increased accumulation has been observed, which might influence density as well.

We erased this sentence, as the samples at Kohnen (previous studies) have an adequate distance to the station itself.

P10, Figure description: What is meant by raster?

We started a common depth scale for the whole trench at the top of the highest (relative) snow profile. Then we calculated the mean value in 0.1 m intervals of each profile but according to the common depth scale (as visible in Fig. 5, bottom left). We used the term raster (or grid) as a more descriptive term, but added a sentence like above for clarity.

P12, Table 2: Can you create maps of p_loc and sigma_1m?

We included a map in the appendix of the manuscript.

P18, L9: Please quantify dune height

Dune heights on EAP can be up to 30-40 cm, we included concrete values from section 3.5 here.

P19, L4: What exactly leads you to make this claim. Could density errors be due to errors in atmospheric forcing? Temporal variability in snow density?

As mentioned in your comment on P21, l5-8, atmospheric forcing was neglected in our manuscript as an error source and was added to the discussion, without being able to determine the exact contribution.
The large difference we observed between our dataset and Kaspers et al. (2004) & Ligtenberg et al. (2011) should at least be partly accounted to the parameterization of surface snow density.
Regarding temporal variability we refer to the comments above (P18, L18).

Many figures have missing axes. Please correct.

Missing axes added.

References: please provide doi's for easy lookup of literature.

We have added the DOIs to the references, but also want to mention, that the original template for EndNote did not show DOIs by default. This should be updated by Copernicus.

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Representative surface snow density on the East Antarctic Plateau

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Abstract

Surface mass balances of polar ice sheets are essential to estimate the contribution of ice sheets to sea level rise. Uncertain snow and firn densities lead to significant uncertainties in surface mass balances, especially in the interior regions of the ice sheets, such as the East Antarctic Plateau (EAP). Robust field measurements of surface snow density are sparse and challenging due to local noise. Here, we present a snow density dataset from an overland traverse in austral summer 2016/17 on the Dronning Maud Land plateau. The sampling strategy using 1 m carbon fiber tubes covered various spatial scales, as well as a high-resolution study in a trench at 30°E 79°S. The 1 m snow density has been derived volumetrically, vertical snow profiles have been measured using a core-scale microfocus X-ray computer tomograph. With an error of less than 2%, our method provides higher precision than other sampling devices of smaller volume. With four spatially independent snow profiles per location we reduce the local noise and derive a representative 1 m snow density with an error of the mean of less than 1.5%. Assessing sampling methods used in previous studies, we find the highest horizontal variability in density in the upper 0.3 m and therefore recommend the 1 m snow density as a robust measure of surface snow density in future studies. The average 1 m snow density across the EAP is 355 kg m^{-3}, which we identify as representative surface snow density between Kohnen Station and Dome Fuji. We cannot detect a temporal trend caused by the temperature increase over the last two decades. A difference of more than 10% to the density of 320 kg m^{-3} suggested by a semi-empirical firn model for the same region indicates the necessity for further calibration of surface snow density parameterizations. Our data provide a solid baseline for tuning the surface snow density parameterizations for regions with low accumulation and low temperatures like the EAP.

1 Introduction

Various future scenarios of a warming climate as well as current observations in ice sheet mass balance indicate a change in surface mass balance (SMB) of the Greenland and Antarctic ice sheets (IPCC, 2019). Accurate quantification of the SMB is therefore one of the most important tasks to estimate the contribution of the polar ice sheets to the global sea level rise (Lenaerts et al., 2019). Satellite altimetry is a state of the art technique to measure height changes of the major ice sheets on large spatial scales (McMillan et al., 2014; Schröder et al., 2019; Sorensen et al., 2018). These changes are converted to a respective mass gain or loss, which are directly linked to an eustatic change in sea level (Rignot et al., 2019; Shepherd et al., 2018). But this volume change converted to a mass change is subject to large uncertainties (Shepherd et al., 2012). In altimetry, at the margins of the ice sheets the local surface topography is a limiting factor in accuracy, while in the comparably flat and high-elevation interior part of the ice sheets snow properties like density have a much larger influence on the accuracy (Thomas et al., 2008). Therefore, an accurate snow and firn density on top of the ice sheets, which undergoes constantly the natural process of densification, is crucial. Given the large extent of the ice sheets, the spatial coverage of ground truth snow and firn density data is still sparse. To overcome this shortcoming, snow density in firn models is often parameterized as a function of climatic conditions, such as temperature, wind speed and accumulation rate (Agosta et al., 2019; Kaspers et al., 2004) and validated by field measurements. Then, this parameterized approach is implemented in firn models leading to a surface snow density (e.g. Ligtenberg et al., 2011). But the modeled density seems to underestimate the snow density when compared to independent ground truth data from Antarctica (Sugiyama et al., 2012; Tian et al., 2018). Inaccurate snow density, especially in the uppermost meter, leads to significant surface mass balance uncertainties (Alexander et al., 2019). Accordingly, ground truth density data are urgently needed to optimize densification models, which are crucial to convert height changes to mass changes in altimetry and therefore reduce the uncertainties in ice sheet mass balance estimates.

One source of uncertainty in the assessment of ground truth density data is the representativeness of the derived density values mainly due to the sampling strategy and sampling tools, as the snow surface on the ice sheet is spatially inhomogeneous at all scales. Apart from climate-induced (e.g. seasonal or event-based) density fluctuations, surface snow density is also influenced by topographic changes of the ice sheet surface and underlying bedrock on small (tens of meters) and large spatial scales (up to hundreds of kilometers) (Frezzotti et al., 2002; Furukawa et al., 1996; Rotschky et al., 2004). On the local scale, surface roughness and the surface slope in combination with dominant wind regimes and varying accumulation rates (Fujita et al., 2011), causes the main variations in density.

Arthern et al. (2006) derived snow accumulation in Antarctica from available field measurements of accumulation and density. To obtain this density, sampling is usually conducted in snow pits with discrete sampling over depth. Between Kohnen Station and Dome Fuji, snow density has been sampled in discrete depth intervals by Sugiyama et al. (2012), who report a high spatial variability on a kilometer scale. A small part of the variability can be attributed to the sampling method. Conger and McClung (2009) compared different snow cutting devices with various volumes between 99 cm³ and 490 cm³. The combination of under-sampling (usually negligible), variation of the device itself (0.8-6.2%) and the weight error of the scale can add up to a significant error (dependent on the type up to 6%). Box- or tube-type cutters with larger sampling volumes are suggested for more precise measurements, with the disadvantage of coarser sampling intervals. Other commonly used devices to derive snow density in discrete intervals use dielectric properties of snow (Sihvola and Tiuri, 1986) or penetration force into the snow (Proksch et al., 2015).

In this paper, we present surface snow density data from a traverse covering over 2000 km on the East Antarctic Plateau (EAP). We show snow density data using the recently introduced liner sampling method (Schaller et al., 2016). The focus of this study is on the uppermost meter, resonating the study of Alexander et al. (2019) who emphasized the importance of an accurate 1 m density of polar snowpack. To reduce the stratigraphic noise we show a strategy with multiple samples per location. This allows a more representative local 1 m snow density. The spatial representativeness of density profiles in East Antarctica has been recently addressed at the local scale (Laepple et al., 2016), but correlation studies for larger scales are currently not available. We discuss the representativeness of density on small and large spatial scales as well as on the temporal variability of density. Beyond improving density retrieval, our results can be of particular interest for calibration of snow density parameterizations in firn models for this part of the East Antarctic ice sheet.

2 Material and methods

2.1 Study area

We performed an overland traverse in austral summer 2016/17 – a joint venture of the Coldest Firn (CoFi) project and the Beyond EPICA – Oldest Ice Reconnaissance (OIR) pre-site survey (Karlsson et al., 2018; Van Liefferinge et al., 2018) (Fig. 1). The CoFi project aims at an improved understanding of firn densification with samples from the EAP. In its framework, five firn cores have been drilled, referred to as B51, B53 (both drilled in 2012/13), and B54, B55 and B56 (drilled on the traverse in 2016/17).

From Kohnen Station the traverse went to former B51 drill site. Right after B51 the traverse split up and followed two different legs, to reunite at the OIR field camp at 79°S, 30°E. After accomplishing the OIR survey and drilling the firn core B54, the traverse continued to the former Plateau Station (abandoned in 1969) and then returned back to Kohnen Station.

We follow Stenni et al. (2017) using the term EAP for the region higher than 2000 m above sea level (asl).

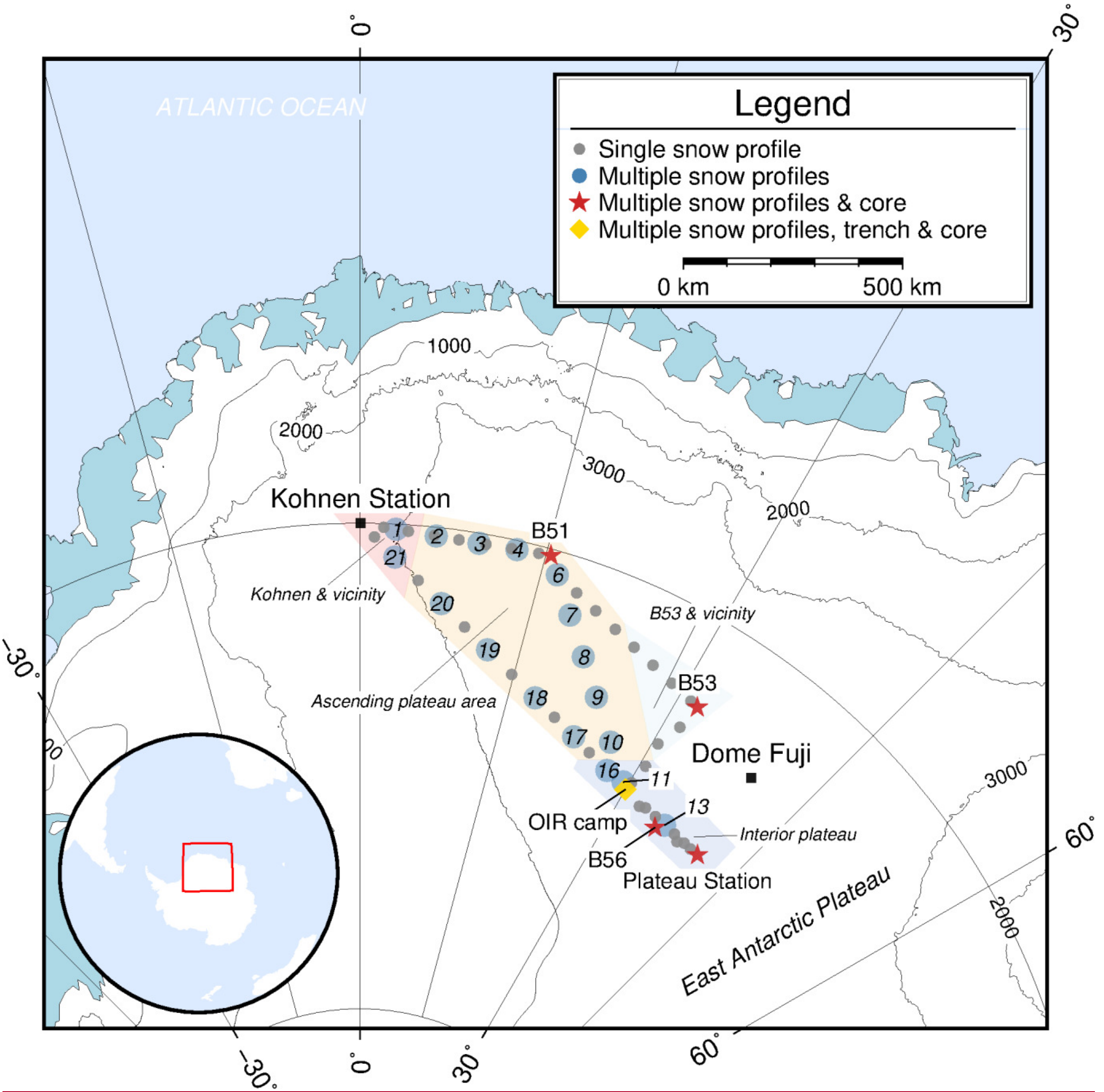

Figure 1: Overview map of the traverse route and sampling locations, inset shows location in Antarctica. Contour lines are given in 1000 m asl intervals. The first sampling position with multiple liners after Kohnen Station is named location 1. Following the traverse route, B51 is also called location 5, OIR camp location 12, Plateau Station location 14, B56 location 15 and B53 location 22 (s. Tab. 2). 200 m firn cores were drilled at locations indicated with a red star. Subregions defined in chapter 2.5 are colored differently (Kohnen and vicinity: purple, ascending plateau area: orange, B53 and vicinity: light blue, interior plateau: lavender).

The traverse covers a region with an annual mean temperature range of about -43°C at Kohnen Station (Medley et al., 2018; Oerter et al., 2009) to -58.4°C at Plateau Station (Kane, 1970; Picciotto et al., 1971), which belongs to the lowest firn temperatures ever recorded in 10 m depth (cf. Dome A: -58.3°C (Cunde et al., 2008)).

At Kohnen Station the accumulation rate used to be 64 kg m² a^{-1} (Oerter et al., 1999) with increasing tendency to over 80 kg m² a^{-1} over the last decades (Medley et al., 2018). At Dome Fuji 27.3 kg m² a^{-1} was measured (Hoshina et al., 2016). For the locations along the traverse an accurate value is difficult to obtain. Large-scale accumulation estimated based on remote sensing techniques (Arthern et al., 2006) are assumed to be too high for the EAP (Anschütz et al., 2011). Karlof et al. (2005) determined an accumulation rate of ~45 kg m²a^{-1} close to location 5 (Fig. 1), Anschütz et al. (2009) published ~20 kg m²a^{-1} for sites between location 8 and B53 as well as OIR camp and Dome Fuji. A high inter-annual variability of accumulation rate is observed in several places on the EAP (Hoshina et al., 2016; Hoshina et al., 2014; Oerter et al., 2000). A 1 m deep snow profile can therefore cover a time period of about four years at Kohnen Station and up to 20 years on the interior plateau.

While the Northern part of the traverse (Kohnen Station – B51) is more strongly influenced by synoptic activities with periodic snowfall (Birnbaum et al., 2006), the interior plateau (OIR camp to Plateau Station) is characterized by diamond dust deposition from a clear sky atmosphere (Schwerdtfeger, 1969), which was described by Furukawa et al. (1996) as calm accumulation zone. Wind maps (Lenaerts and van den Broeke, 2012; Parish, 1988; Sanz Rodrigo et al., 2012; van Lipzig et al., 2004) show generally low mean wind speed (around 6 ms^{-1}) from Kohnen Station along the ice divide up the EAP, but lower values for the region around Plateau Station. Due to the prevailing Antarctic high pressure system over the EAP and the gentle slopes, the katabatic winds reach only moderate wind speeds there. While e.g. at Kohnen Station occasionally snow storms with wind speeds exceeding 15 m s^{-1} can happen, this is not the case on the interior plateau.

2.2 Liner sampling

For clarity, we define the terms used in the following paragraphs in Table 1.

Table 1: Definition of terms used in the following sections are listed below

Term	*Symbol*	*Description*
Liner	-	1 m of snow sampled with a carbon fiber tube. This term is used in a methodological context or for the tube itself.
Snow profile	-	(Continuous) snow sample at a given position. It may consist of several consecutively (vertically on top of each other) sampled liners; the length can be 1~~-~~–3 m.
Location	-	A given place with one or several snow profiles taken within a range of 50 m.
Liner ~~mean~~ density	ρ_L	Volumetrically derived 1 m ~~average~~ density of one single liner. Note: for snow profiles over 1 m length, liner ~~mean~~ densities for every meter segment are calculated individually.
µCT^x mean density	$\rho^x_{\mu CT}$	µCT derived mean density for the sampling interval x.
Location ~~liner~~ mean density	ρ_{loc}	Average of liner ~~mean~~ densities at one location for the same depth interval (usually 0-1 m).
Horizontal standard deviation	σ^x_H	Standard deviation of either liner density or µCT density for depth interval x over horizontal distance in a given area. Note: for 1 m we use the liner density, for smaller intervals µCT^x means.
Vertical standard deviation	σ^x_V	Vertical standard deviation of either µCT density over depth interval x or liner density (only for snow profiles >1 m) at a given position.
Standard error	σ_n	Definition in Sect. 2.4

Along the traverse route, vertical snow profiles were extracted using the snow liner sampling technique, also described by Schaller et al. (2016). Each vertical profile was taken using a carbon fiber tube of one meter length and ten centimeters in diameter. The liner was pushed into the snow until the liner top was level with the snow surface. Afterwards, a snow pit next to the liner was dug and the snow was cut at the liner bottom with a metal plate to take the filled liner out of the pit wall. Both ends were covered with a WhirlPack® plastic bag to reduce possible contamination by touching the liner ends and air ventilation. During the sampling process, the liner was handled carefully to avoid concussions that destroy the original snow stratigraphy (e.g. not to bounce against the liner with the shovel and placing it softly into the sample box). A 1 m snow profile can be retrieved within 15 minutes. The liners were stored in isolated polypropylene boxes and shipped to the Alfred Wegener Institute (AWI) in Bremerhaven in a continuous cold chain.

In total 144 snow profiles in different setups and total lengths were taken (Sect. 2.2.1 – 2.2.3). All strategies described in the following sections have been applied independently from each other.

2.2.1 Single snow profiles

Single profiles were taken every 30 km. On the last segment of the traverse (OIR camp to Kohnen Station) the distance increased due to limited liner availability. In total, 31 single snow profiles are available (Fig. 1).

2.2.2 Multiple snow profiles

22 locations with multiple profiles were sampled during overnight stops of the traverse, therefore the distance between the locations varied (roughly around 100 km). Regularly four snow profiles were sampled, at one location three, at two locations only two profiles because of time constraints (s. Tab. 2). The four profiles were arranged in an even-sided triangular setup with one profile in the center (labeled with ‘X’) and three profiles around it (labeled with ‘A’, ‘B’ and ‘C’). The corner profiles A, B, C are on a radius of 10 m to the central profile X (Fig. 2). 83 profiles were retrieved in this setup. The locations are named in ascending order (Fig. 1 and Tab. 2).

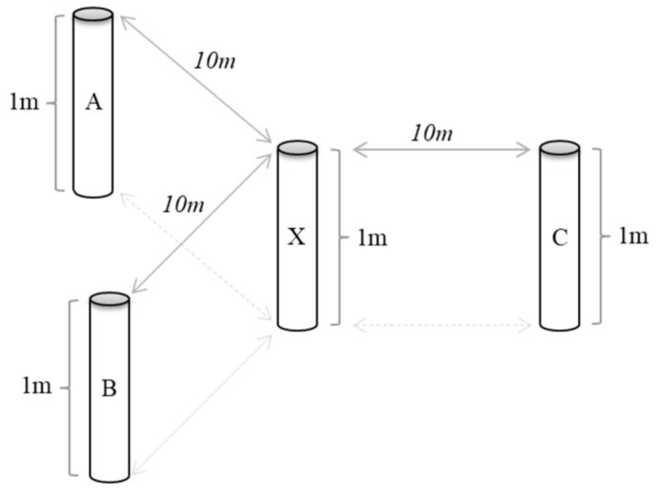

Figure 2: The sampling setup for locations with multiple snow profiles. The profiles A, B and C have a sampling distance of roughly 10 m to the central profile. Due to time constraints, locations 19 (three profiles) 11 and 13 (two profiles) have been sampled differently.

2.2.3 OIR trench

At the OIR camp (Fig. 1), a 50 meter long and ca. 2.3 meter deep trench was excavated by a PistenBully snow vehicle (Fig. 3). The trench orientation was perpendicular to the main wind direction (127° true North). Thirty 3 m snow profiles were sampled directly at the trench wall using the liner technique described above. At every sampling position in the trench three liners were taken below each other. The first liners were pushed into the snow around 0.2 meters behind the trench wall, to ensure an original stratigraphy not disturbed by excavation of the trench. After removal of the snow, the liners were directly taken out of the wall and the next consecutive liner in depth was placed at the same position (see Fig. 3, where the first liner is already in place). The lateral spacing between neighboring liners varied between 0.4 and 2.4 meters, depending on the surface structure. The profiles were taken within two days after excavation of the trench (31.Dec.2016-02.Jan.2017).

Figure 3: Sampling procedure in the OIR trench. The first carbon fiber tube (liner) is pushed into the snow after excavation of the trench. The positions were marked with a small bamboo pole. After retrieval of the first profile, the vertically consecutive second and third liners were taken. Two empty liners lean at the trench wall. The last liner had to be dug out partly as the trench was only 2 to 2.5 meters deep.

2.3 Density measurements

The snow liners have been non-destructively analyzed at AWI with the core-scale microfocus X-ray computer tomograph in a cold cell (µCT), specifically constructed for snow, firn and ice cores. For technical details see Freitag et al. (2013) and Schaller et al. (2016). Before the measurement all liners were weighed. The weight of the carbon fiber tube was subtracted. The exact height of filled snow inside the liner was determined using the µCT. Then, ρ_L was calculated volumetrically. All liners have been measured in a 2D-mode using a setup of 140 kV and 470 µA at -14°C. Breaks and lost snow in the snow profiles haven been spotted during the scan and corrected (set to NaN) in the µCT density profiles, which have a vertical resolution of ca. 0.13 mm (s. Appendix).

For the calculation of the µCT density only the central segment of the liner is used as scattering effects at the outer parts of the liner occur. The used segment corresponds to less than half of the snow volume in the liner. Missing snow at the edges of the profile does not influence the µCT scan. Accuracy of the $\rho_{\mu CT}$ can be affected by the calibration, which is done with three cuboids of bubble free ice with different lengths in every scan individually, or at the horizontal variability on the very small-scale, as the central part of the profile can have a different density than the edges.

It is generally possible that the snow profiles are subject to compression during sampling or transport. Therefore the exact snow volume determined with the µCT is rescaled to the original 1 m length (length of every single snow profile is determined individually) to avoid this potential error source. But lost snow in the liner (or at top or bottom), e.g. in non-cohesive layers (such as depth hoar layers), can lead to lower densities. Thus, ρ_L is also affected by errors. Conger and McClung (2009) reported, that snow sampling devices with larger volumes usually result in higher precision in snow density. The volume of the snow liners (radius: 5 cm, length: 1 m) is 7855 cm³, 16 times the volume with the highest precision in their study. As the volume error among single liners is not known, we assume a 0.3 mm variation in both dimensions (length and radius), resulting in a volume error around 1.2%. As still small parts inside the liner might not be completely filled with snow (e.g. lost snow during the transport) we estimate the under-sampling error of the liner method to be less than 1.5%. Additional error sources are the precision of the used scale (1 g or 0.03% compared to the mean value along the traverse) as well as weight variations among the carbon tubes (<0.1%). The maximum relative error is estimated to be below 1.9%.

Both, $\rho^{1m}_{\mu CT}$ and ρ_L are in good agreement with each other (Fig. 4), the differences between the volumetrically calculated ρ_L and $\rho^{1m}_{\mu CT}$ is on average only 0.6%. As the µCT density is sensitive to calibration, we consider ρ_L to be more accurate for a 1 m interval. Some systematically higher values in the µCT measurements can be caused by low-quality calibration in single measurements. Therefore, for the 1 m surface snow density we use ρ_L. For the comparison of intervals smaller than 1 m we use the µCT-derived density $\rho_{\mu CT}$ (Tab. 1).

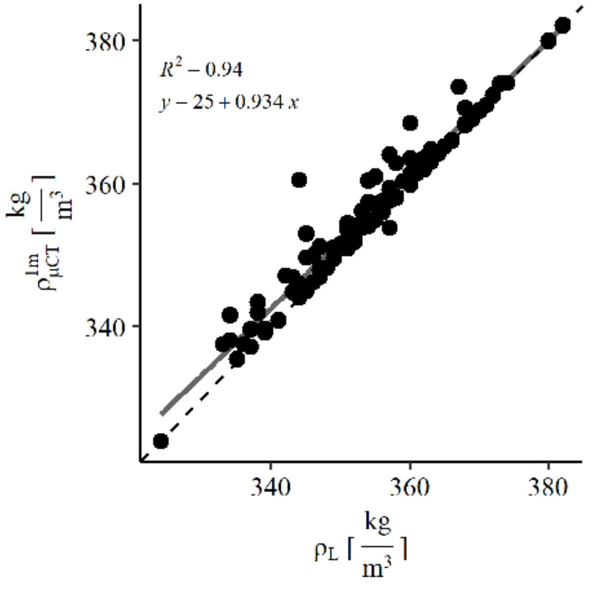

Figure 4: Comparison of liner density (ρ_L) with µCT density ($\rho^{1m}_{\mu CT}$) calculated from the 114 liners along the traverse. Values of both measurements are in good agreement with an R² of 0.94. The linear fit is given with a grey solid line, the dashed black line represents x=y.

2.4 Finding a representative density

Fisher et al. (1985) defined stratigraphic noise as "random element caused by the surface irregularities", which is present in any taken snow profile or ice core. This stratigraphic noise is mainly caused by spatially inhomogeneous deposition in combination with wind, leading to snow patches or dune structures that usually have a spatial extent of several meters. This stratigraphic noise hampers the representative (i.e. for a certain location or area) estimate of surface density, when not considered in the sampling strategy. To still be able to get a representative value or profile (of density or other parameters) at a given spot, several samples have to be taken at a distance, at which they are not subject to the same stratigraphic noise. For example, samples should not be taken from the same dune or snow patch, as these values cannot be considered to be spatially independent. By stacking or averaging independent samples, the stratigraphic noise is reduced. This has also been performed for e.g. isotopes (Karlöf et al., 2006; Münch et al., 2016) and a common (annual or seasonal) climatic signal can be retrieved despite a high level of stratigraphic noise.

The (minimum) sampling distance between two samples was quantitatively described for snow density by Laepple et al. (2016). In a 2D high-resolution trench study at Kohnen Station they have shown, that the correlation coefficient between single profiles decreases rapidly with increasing distance and settles at a constant value after 5-10 m. In the following we refer to samples taken at this distance as ‘spatially independent’. Consequently, we consider the multiple snow profiles at one location to provide spatially independent ρ_L. In the OIR trench, we assume a sampling distance of 5 m between two profiles as sufficient. For a representative 1 m ρ_{loc} we aim for a relative error of less than 2%. To test how many snow samples per location are needed for this representativeness, we calculated σ^{1m}_H of ρ_{loc}. We used the maximum number of spatially independent ρ_L for ρ_{loc} (further called *n*). We did this for both the multiple liners at the traverse locations and the OIR trench. At the locations along the traverse we use all four available ρ_L (*n*=4) to calculate σ^{1m}_H of ρ_{loc}. In the trench, we created two sets of seven ρ_L (*n*=7; maximum possible number with spatial independent samples) with different snow profiles in both sets and calculated the mean value. We then derive the standard error (σ_n), which depends on the number *n* of ρ_L at a given location by

$$\sigma_n = \sigma^{1m}_H / \sqrt{[2; n\text{-}1]} \,, \qquad (1)$$

with the denominator being a varying number of snow profiles from 2 to n-1. This means, for example, when using seven profiles (like one set in the OIR trench) we are able to calculate the standard error for 2 to 6 profiles. In this way we use the maximum sample size without an artificially caused bias in the data. This can happen, for instance, by creating sets with small sample size and picking ρ_L randomly. Accordingly by a) using large volumetric samples we improve the accuracy and by b) using several profiles at each location we improve the representativeness of the density values derived for each location. We are therefore able to deliver a more accurate and representative density of each site, compared to previous studies.

2.5 Definition of subregions on the EAP

We pooled several snow profiles for further investigation to characterize the surface density of a larger (≥10,000 km²) region. We chose a minimum number of 10 profiles (0-1 m) per area. We followed the classification of Furukawa et al. (1996) as well as possible and used the 3500 m asl contour line as approximate boundary between different wind and accumulation regimes on the katabatic wind zone and the interior plateau (calm accumulation zone). This way we classified one major area “Ascending plateau area” (AP) with 64 profiles, covering roughly 140.000 km² between Kohnen Station and OIR camp, and the smaller “Interior plateau” (IP) with 29 profiles between OIR camp and Plateau Station (28,500 km²). We did not include the OIR trench, as this specific location would have been overrepresented. The area around B53 (28,500 km²) was treated as a separate area as it is on the interior plateau close to the ice divide ("B53 and vicinity" – 10 profiles). Additionally, we handled the area around Kohnen Station (Ko) with roughly 10,000 km² as another separate unit ("Kohnen and vicinity" – 45 profiles). The sample availability at Kohnen Station from other studies is sufficient, several liners from other sampling programs in seasons 2015/16 (16 profiles) and 2016/17 (18 profiles) have been added to the evaluation. The areas are color-coded in the overview map (Fig. 1).

As we present density data on different scales, in this context we use the term 'local' scale for distances between profiles at one location and the area around a sampling location (i.e. tens of meters, Tab. 1). In contrast, the term 'regional' scale is used for distances between several locations (100 km to 1000 km) and areas in the dimensions of the subregions defined above. For all subsets, we present a spatial distribution of ρ_L and ρ_{loc}.

2.6 Optical levelling

The relative surface elevation of the OIR trench was measured using optical levelling at each profile position and in between two consecutive profiles. Additionally, at the OIR camp and Plateau Station surface roughness transects were measured. The optical level was placed at the transect starting point. The first height measurement was done in 10 m distance to the starting point and repeated every 2 m up to 58 m distance relative to the start, resulting in 25 measuring points per transect. In total six transects have been done at one location with 1 m lateral spacing between them.

3 Results

3.1 Snow and firn density in the OIR trench

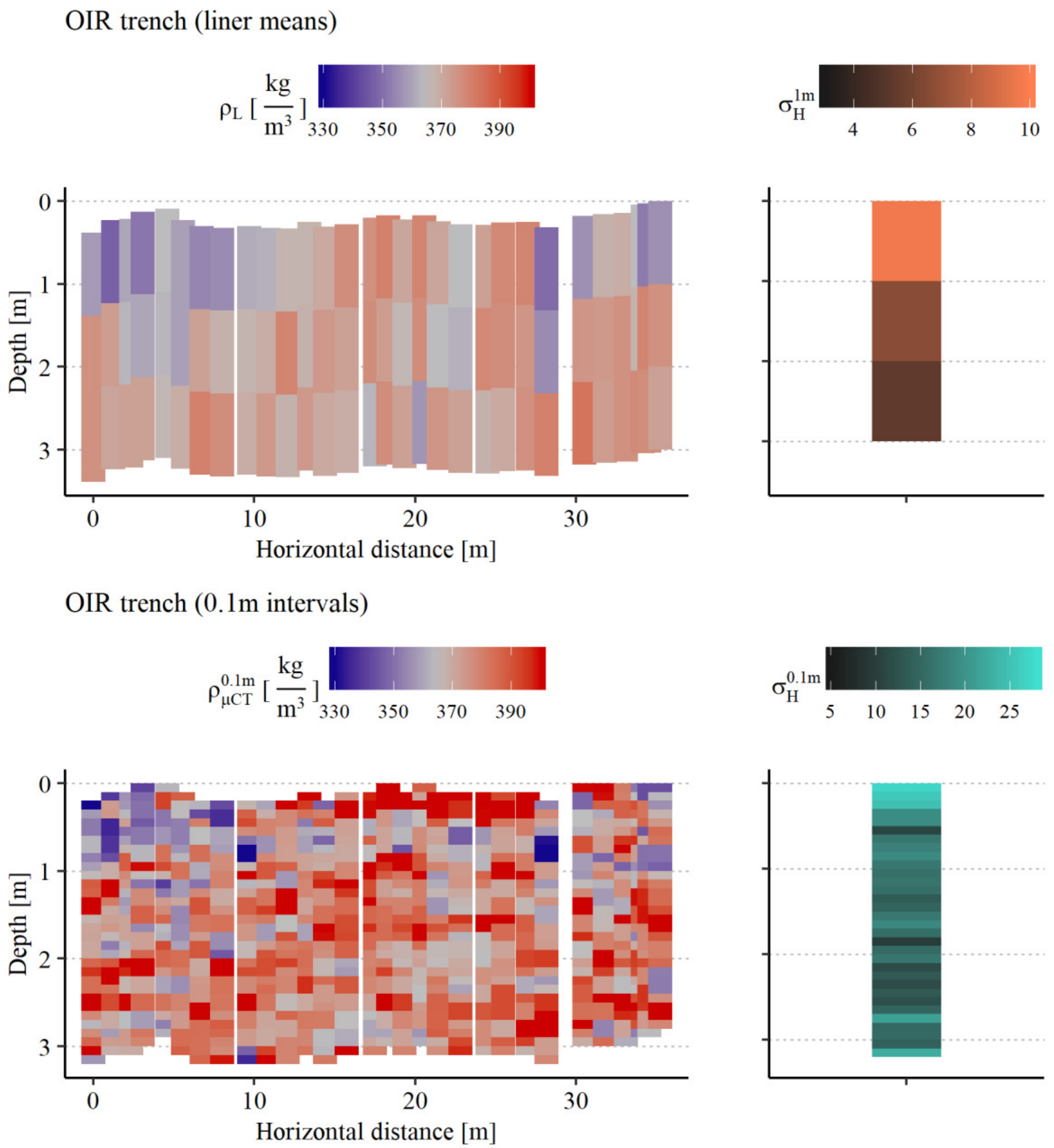

Figure 5: Density of the OIR trench from 30 profiles in vertical 1 m (liner density, top) and 0.1 m sampling intervals (µCT density, bottom) in a color-coded plot. For the profiles in 0.1 m intervals, we used a common depth scale for the whole trench starting at the top of the profile with the highest surface elevation (profile 30), all other liners start at the measured relative height. We then calculated the density of each 0.1 m interval according to the common depth scale. ρ_L and $\rho^{0.1m}_{\mu CT}$, respectively, are given in a blue (low density) to red (high density) color code. On the right of each panel σ_H of the respective depth interval is shown.

ρ_L ranges in the OIR trench from 347 kg m^{-3} to 380 kg m^{-3}. We calculated ρ_{loc} for the OIR trench (± standard deviation) with 365±10 kg m^{-3}, which is 3.1% higher than for the whole traverse (Sect. 3.2). σ_H is between 10 and 27 kg m^{-3} for 0.1 m sampling intervals and between 5 and 10 kg m^{-3} for 1 m sampling intervals (Fig. 5 and Tab. 4). The highest $\sigma^{0.1m}_H$ can be found in the top 0.3 m. σ^{3m}_V of the 3 meter profiles is 34 kg m^{-3} (Tab. 4).

3.2 Snow and firn density along the traverse

Here we present data from Sect. 2.2.1 and 2.2.2. Along the traverse we find ρ_L ranging from 324 kg m^{-3} (pos. 22C) to 382 kg m^{-3} (pos. 16A). The average ρ_L calculated from 114 liners along the traverse is 354 ± 11 kg m^{-3} (Fig. 6).

ρ_{loc} (Tab. 1) is calculated from multiple snow profiles (Sect. 2.2.2) at each location. At location 21 and 1 close to Kohnen Station we find the lowest ρ_{loc} with 344 and 345 kg m^{-3}, respectively. Highest ρ_{loc} is found at position 5 with 372 kg m^{-3} (Tab. 2). The average ρ_{loc} along the traverse is 355 ± 8 kg m^{-3}. To characterize the surface variability, we calculated σ^{1m}_H for each location separately. The minimum σ^{1m}_H is 2 kg m^{-3} at position 20 (and position 13 with only two profiles taken), the maximum σ^{1m}_H is 15 kg m^{-3} at position 22.

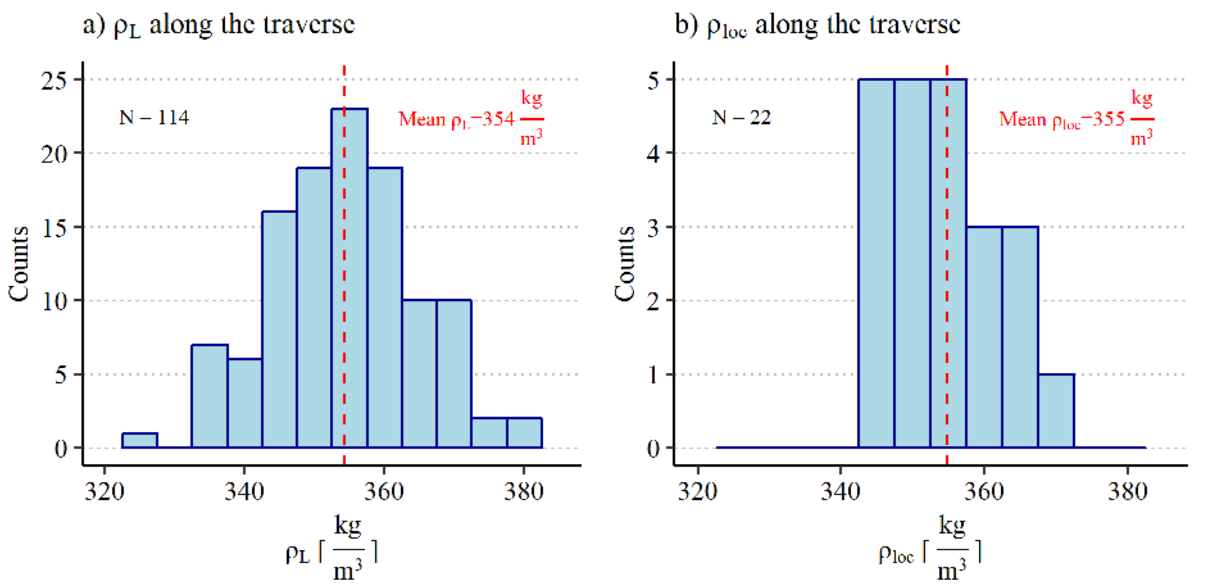

Figure 6: Histogram of a) liner density (ρ_L) and b) location mean density (ρ_{loc}) along the whole traverse route (profiles of the OIR trench not included). For both plots we used a bin width of 5 kg m^{-3}. The average liner density and location mean density, respectively, is given with the red dashed line.

A detailed overview of all ρ_{loc} and σ^{1m}_H along the traverse can be found in table 2 and a visualization in the appendix (Fig. 13).

Table 2: ρ_{loc} at each location with multiple liners and the respective standard deviation. The number of liners at each location is given in brackets. For locations and abbreviations see Fig. 1.

Location (No. of ρ_L)	*Longitude [°]*	*Latitude [°]*	*Elevation [m asl]*	*Sampling date*	*ρ_{loc} [kg m^{-3}]*	*σ^{1m}_H [kg m^{-3}]*
1 (4)	2.89	-75.11	2990	14.Dez.2016	345	8
2 (4)	6.12	-75.18	3146	15.Dez.2016	355	10
3 (4)	9.58	-75.21	3301	16.Dez.2016	360	13
4 (4)	12.66	-75.18	3400	17.Dez.2016	350	9
5 (4) – B51	15.4	-75.13	3470	18.Dez.2016	372	7
6 (4)	16.32	-75.47	3484	19.Dez.2016	353	14
7 (4)	18.33	-76.19	3463	20.Dez.2016	346	8
8 (4)	20.66	-76.9	3456	21.Dez.2016	355	9
9 (4)	23.19	-77.57	3452	22.Dez.2016	351	12
10 (4)	26.3	-78.29	3455	23.Dez.2016	346	5
11 (2)	29.38	-78.89	3461	24.Dez.2016	350	6
12 (4) – OIR / B54	30.0	-79	3473	26.Dez.2016	358	6
13 (2)	35.69	-79.18	3576	06.Jan.2017	362	2
14 (4) – B55	40.56	-79.24	3665	09-11.Jan.2017	352	10
15 (4) – B56	34.97	-79.33	3544	16-18.Jan.2017	351	8
16 (4)	27.28	-78.84	3416	23.Jan.2017	366	11
17 (4)	22.64	-78.5	3325	24.Jan.2017	358	7
18 (4)	17.62	-78.02	3259	25.Jan.2017	356	5
19 (3)	12.03	-77.32	3153	26.Jan.2017	365	6
20 (4)	7.2	-76.54	3067	27.Jan.2017	368	2
21 (4)	2.90	-75.67	2959	28.Jan.2017	344	7
22 (4) – B53	31.91	-76.79	3737	26.Dez.2016	345	15
Whole traverse (22 ρ_{loc})	-	-	-	-	355	8

3.3 Representativeness of surface snow density on local scales

In Fig. 7 we compare the calculated σ_n according to section 2.4. For four spatially independent snow profiles in the OIR trench, we get a value for σ_n of less than 1.5% (4.9 kg m^{-3}) relative to ρ_{loc} (355 ± 2 kg m^{-3}). We note, that on average σ_n in the OIR trench is higher than the average of the four areal subsets (7.0 kg m^{-3} in contrast to 6.1 kg m^{-3} for two profiles and 5.7 kg m^{-3} in contrast to 5.0 kg m^{-3} for three profiles).

Consequently, we consider four snow profiles to be sufficient for a ρ_{loc} with σ_n of less than 2%. Unfortunately, we cannot test a number of profiles higher than six. But assuming a constant σ^{1m}_H, seven spatially independent profiles are needed to assure a relative σ_n of less than 1%.

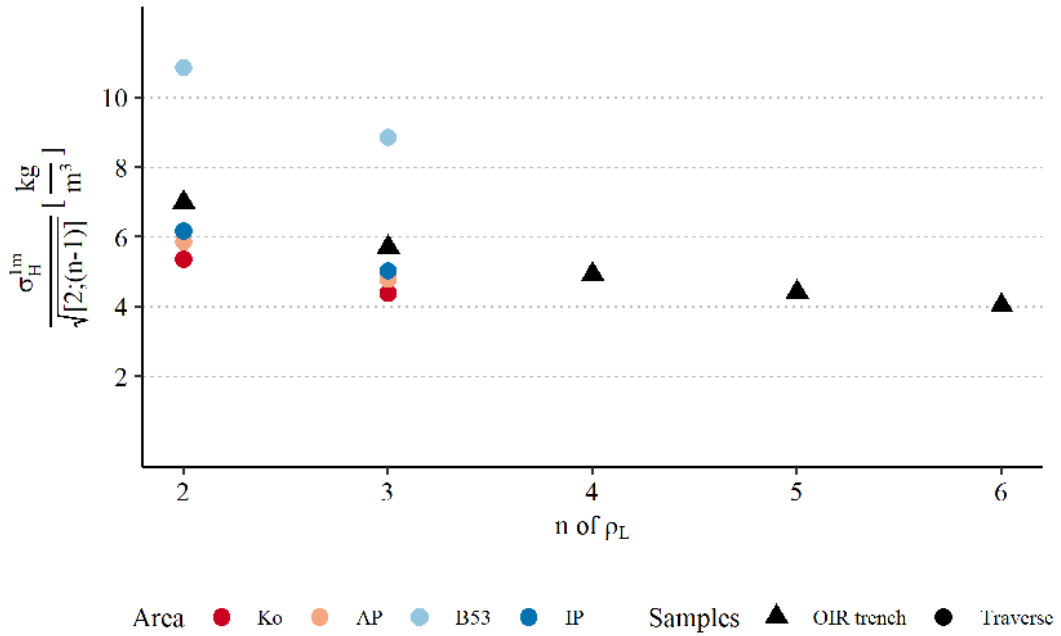

Figure 7: Standard error (σ_n) of the location mean density (ρ_{loc}) as a function of the number of profiles (n). Triangles represent samples from the OIR trench while colored circles show samples along the traverse in the respective subsets (Sect. 2.5).

3.4 Representativeness of surface snow density on regional scales

In the spatial density distribution of ρ_L and ρ_{loc}, find similar values for Kohnen and vicinity (352±1 kg m^{-3}), ascending plateau area (356±1 kg m^{-3}) and the interior plateau (355±2 kg m^{-3}) (Fig. 8). These have less than 1% difference from the average value of the whole traverse. Only B53 and vicinity shows lower density values (349±3 kg m^{-3}, -1.7% compared to the traverse location mean density 355 kg m^{-3}).

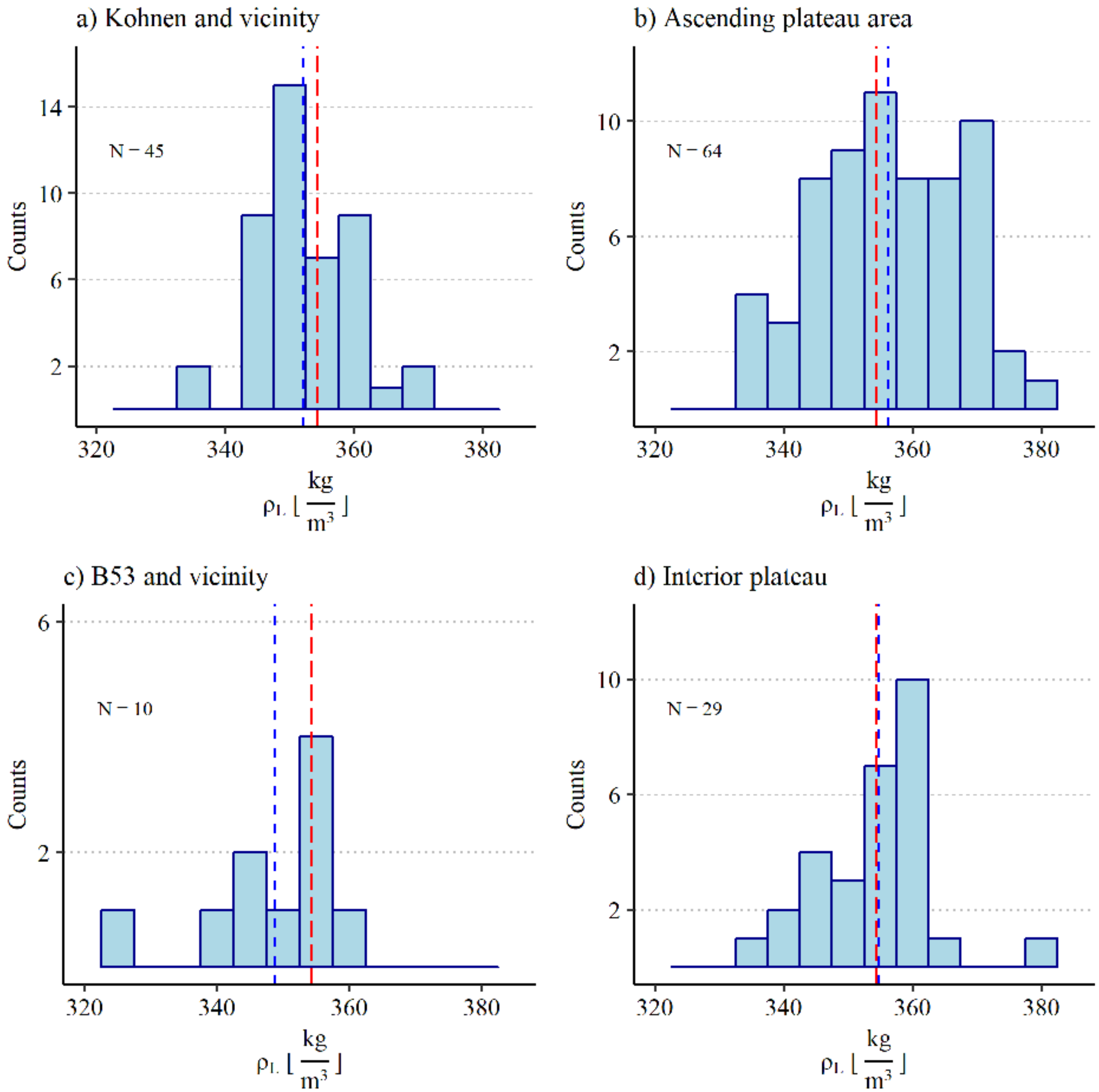

Figure 8: Histograms of the liner density (ρ_L) for the four subregions (Fig. 1). The bin width for each histogram is 5 kg m^{-3}. The average ρ_L (Fig. 6, a) is given in a red dashed line while the liner density of the respective subregion is marked with a blue dashed line.

Looking at the density distribution of the high-resolution µCT density profiles (for details, see Appendix), we find a normal distribution of the snow density in the first meter (Fig. 9). We see a shift towards higher densities in the OIR trench and a higher probability for lower densities in B53 and vicinity, but in general a similar distribution of density in all subregions is found.

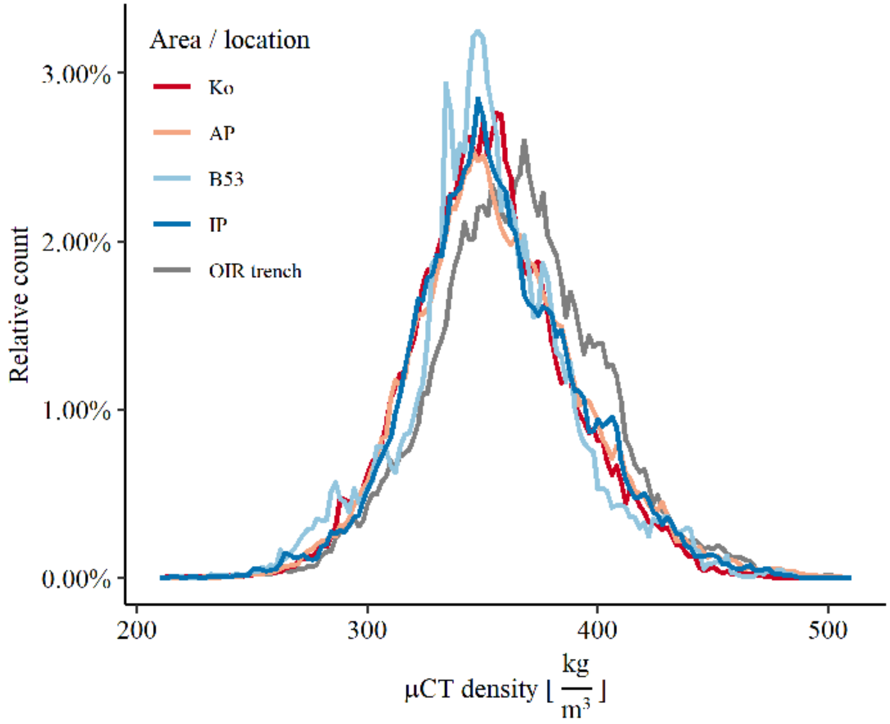

Figure 9: Density distribution from surface to one meter depth of the µCT density. It is based on all available liners - 114 liners from the traverse (according to their subregion), 30 liners for the OIR trench (grey) and 16 liners from Kohnen Station (not this study) with a bin width of 2 kg m⁻³. We used the same color code for the subregions (Sec. 2.5) as in Fig. 1.

We calculated the confidence interval (95%) of ρ_L for each respective subregion (Tab. 3). We want to stress that the number of samples of "B53 and vicinity" is lower than recommended for this method. The mean value for the traverse is represented in all four intervals of the subregions. We note, that the interval for Kohnen and vicinity just includes this value.

Table 3: Confidence intervals of 95% for each pooled area.

Area (number of samples)	*Lower boundary [kg m^{-3}]*	*Upper boundary [kg m^{-3}]*
Whole traverse (114)	352	356
Kohnen and vicinity (45)	350	354
Ascending plateau area (64)	353	358
B53 and vicinity (10)	341	357
Interior plateau (29)	351	358
OIR trench (30)	361	368

The snow density directly measured at the surface in general shows high spatial variability (Figs. 5 and 10). To characterize the spatial variability of density in a given area (tens of meters for traverse locations and trenches, hundreds of meters for Kohnen Station), we use the parameter σ_H. For a comparison we used snow liners along the traverse (liners sampled at OIR trench presented in a separate column), liners from Kohnen Station (Schaller, 2018) and from East Greenland ice core project

(EGRIP) camp site (75°37′N, 35°59′W; 2702 m asl). Shown is also σ_V for the respective areas, which can be interpreted as temporal (seasonal or annual) variations in density. We computed both (σ_H and σ_V) for 0.1 m, 0.5 m and 1 m intervals each (Tab. 4).

Table 4: Comparison of σ (horizontal and vertical) for each depth interval (from surface to respective depth) of samples from the traverse and OIR trench (this study), Kohnen Station and a trench from EGRIP (Schaller, 2018).

σ^{0-X} [kg m^{-3}]	σ_V Traverse (22 locations, 4 profiles)	σ_H Traverse (22 locations, 4 profiles)	σ_V OIR trench (30 profiles)	σ_H OIR trench (30 profiles)	σ_V Kohnen Station (16 profiles)	σ_H Kohnen Station (16 profiles)	σ_V EGRIP trench (22 profiles)	σ_H EGRIP trench (22 profiles)
0.1 m	24	23	19	25	31	23	24	17
0.5 m	33	11	33	14	31	9	33	9
1.0 m	34	8	34	10	33	6	43	7

3.5 Small-scale topography at OIR camp and Plateau Station

The maximum height difference between the lowest (first) and highest (last) profile in the OIR trench is 38.5 cm. The height values of each position are given in the appendix (Tab. 6). We find significant differences in the surface topography at both places. At OIR camp the height differences between the lowest and highest point of the measured transects are 60% larger than the height differences at Plateau Station (Tab. 5). The variation of height differences between the six transects at each location is low with a standard deviation of 2.4 cm (OIR camp) and 2.0 cm (Plateau Station).

Table 5: Maximum height differences [m] along the transects one to six at Plateau Station and B56

	1	*2*	*3*	*4*	*5*	*6*	*Mean*
OIR camp	0.268	0.280	0.310	0.330	0.319	0.310	0.303
Plateau Station	0.180	0.211	0.180	0.174	0.150	0.212	0.184

4 Discussion

4.1 Liner method vs. discrete sampling

To discuss the 1 m snow density using the liner technique, we compare our dataset with data by Oerter (2008). In that study, snow pits with 20 km spacing have been dug and sampled along a small transect from Kohnen Station upstream towards B51 (comp. Fig. 1). A detailed map of the sampled region by Oerter (2008) is available in Huybrechts et al. (2007). Snow density has been measured volumetrically in each snow pit using discrete samples in 0.1 m depth intervals. We compare our results with density data from locations 1 to 4 (including single snow profiles in between) in two different depth resolutions (0.1 m and 1 m). For our study, we use $\rho^{0.1m}_{\mu CT}$ and ρ_L. For the 1 m interval from Oerter (2008) we use the average density value of all discrete samples between 0 and 1 m.

ρ^{1m} from both studies are in good agreement with each other. ρ^{1m} derived with the liner method tends to be 1-5% higher than the one from Oerter (2008) (Fig. 10). Higher discrepancy can be seen in the mean density of the upper 0.1 m. While we find on average $\rho^{0.1m}_{\mu CT}$=349 kg m^{-3} from liner measurements, $\rho^{0.1m}$ for Oerter (2008) is 293 kg m^{-3}. The calculated $\sigma^{0.1m}_H$ over the whole distance is 31 kg m^{-3} for our study and 25 kg m^{-3} for Oerter (2008). Interestingly, $\rho^{0.1m}$ in Oerter (2008) is always lower than ρ^{1m}, which is not the case in samples from our study. Due to the soft and unconsolidated snow at the surface we assume that the under-sampling error is higher at the surface for small sampling devices, which forces a systematic error towards smaller values (Fig. 10). Snow in greater depth has undergone sintering processes and is more coherent, therefore also the under-sampling error should be smaller. Additionally, a systematic error with increasing depth in the data by Oerter (2008) cannot be excluded, as the sampling device (core cutter) might densify the snow with each interval due to the thick wall in relation to the sampling volume. In contrast to other devices, the liner method preserves the original stratigraphy of the snow column. In combination with the µCT-measurement on different chosen depth intervals, this results in a density value with less uncertainty, especially for small sampling intervals at the snow surface. Despite from the sampling strategy, the difference between both datasets can be caused by different weather conditions during the sampling. This affects in particular the upper cm of the snow column.

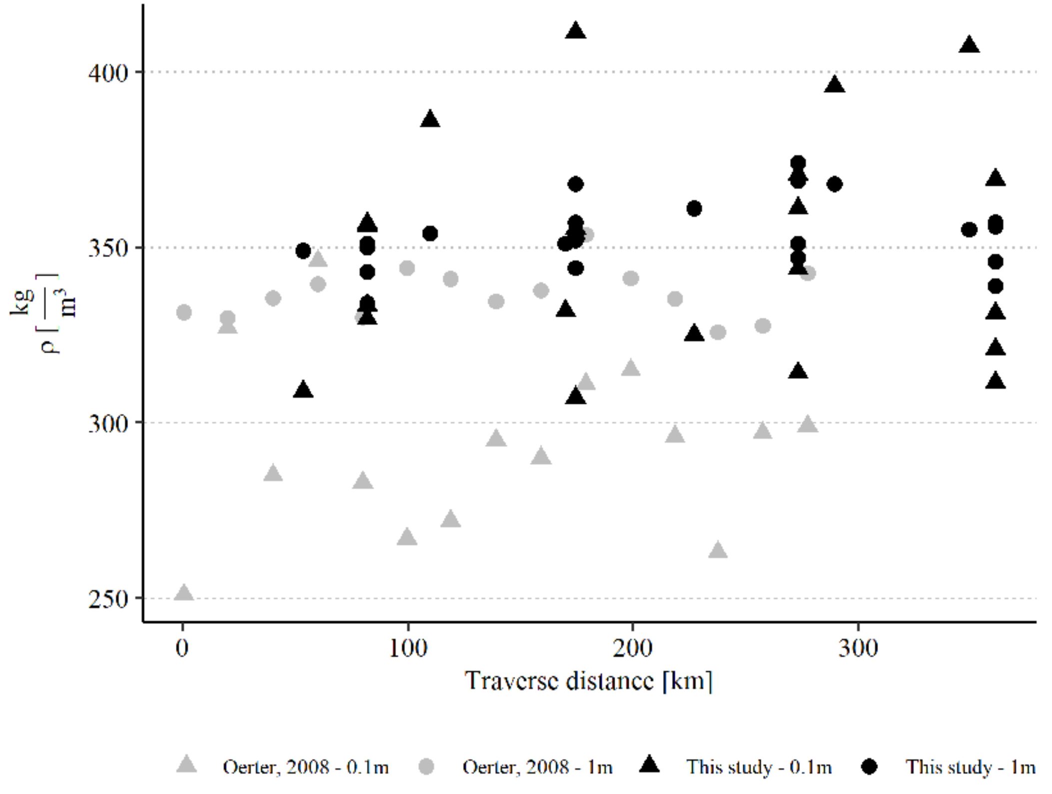

Figure 10: Density values of this study (black) in comparison with those from snow pit sampling by Oerter (2008) (grey). The samples are taken along a comparable transect line. Density is given as mean value from the snow surface to the respective depth. The spatial variability in both, 1 m and 0.1 m intervals, can be seen by the spread of points in data of this study at one sampling location (comp. Tab. 3).

4.2 Comparison of different sampling intervals

In the following we discuss the advantages of a 1 m snow density in contrast to smaller depth intervals. In this context we refer to the data presented in Tab. 4. At sites with accumulation rates higher than 100 kg m^{-2} a^{-1} (e.g. EGRIP), small sampling intervals (<0.5 m) do not contain the seasonal or annual variability over several years (see also data by Oerter (2008) in Fig. 10), at sites with lower accumulation (in this context <60 kg m^{-2} a^{-1}) the density might be masked by the high stratigraphic noise. Both effects can be seen in the low $\sigma^{0.1\,m}{}_V$ in contrast to $\sigma^{1m}{}_V$ looking at data from different sites in Tab. 4. Higher $\sigma^{1m}{}_V$ in snow profiles from EGRIP are caused by a clearer seasonal density cycle, which is barely or not detectable on the EAP. This can be explained with higher temperatures as well as higher accumulation rates at EGRIP. In case of surface melting like in year 2012 (Nghiem et al., 2012), $\sigma^{1m}{}_V$ can be even higher. We find lower σ_H at the surface in samples from EGRIP in contrast to EAP. This can be explained with the non-uniform deposition causing high undulations in the surface topography. We measured the topography in form of dune heights (Tab. 5), which are often 30 to 40 cm high and exceed the yearly accumulation by far. Snow layers do not form as spatially consistent as at sites where the (predicted) yearly layer thickness is larger than the amplitude of dunes. This also affects the snow density as the signal cannot form homogenously over a larger distance and causes larger σ_H. For all presented sites, the $\sigma^{0.1m}{}_H$ is 2.4 to 4 times higher than the $\sigma^{1m}{}_H$, which is explainable by the more comprehensive density spectrum over larger depth intervals. This high horizontal variability is mainly caused by the existing small-scale topography, in particular dunes. The variability decreases below the maximum measured dune heights of 30-35 cm below the surface. These dunes have a higher snow density (Birnbaum et al., 2010) than snow that gets deposited in local depressions due to enhanced wind packing (cf. Sect 4.3).This is also visualized for the OIR trench in Fig. 5. A snow patch of low density can be seen at the surface between 0 and 5 m (horizontal distance) and rather high density between 18 and 25 m (horizontal distance) (Fig. 5, bottom left). This illustrated well to choose a far enough distance to reduce the effect of stratigraphic noise (Sect. 2.5).

The temperature dependent densification effect does not affect the 1 m snow density substantially. By comparing all µCT density profiles over depth we cannot see a significant increase in density over the first meter. Also according to the model by Herron and Langway (1980), at a temperature of -43°C (annual mean air temperature at Kohnen Station after Medley et al. (2018)), the increase in snow density by densification from the surface to 1 m depth is 10 kg m^{-3}. At a -53°C annual mean air temperature (-10°C compared to Kohnen Station) the densification is roughly 8.3 kg m^{-3}. A temperature change of -1°C would lower the densification induced density by about 0.17 kg m^{-3}.

In summary, due to the high snow density variability in the upper decimeters of the snowpack, we suggest the 1 m density as a feasible approach to derive the surface snow density independent from local recent weather conditions. For a representative value, at least four samples should be taken per location with the respective sampling distance. The densification of snow over the first meter is negligibly small. Furthermore, we want to advert to the time efficiency of the liner method here. A 1 m snowpack density with four samples can be obtained within 1 h. Even if a high-resolution study in a snow pit is done, a snow profile using a liner can always be added to the discrete sampling in a snow pit for comparison.

4.3 Temporal and vertical variation of density along the traverse

Also long-term changes in temperature, accumulation rate or wind systems can affect fluctuations in density. At Kohnen Station a 1°C temperature rise per decade has been recorded by an automatic weather station, jointly operated by the Institute for Marine and Atmospheric Research (IMAU) and AWI (Reijmer and van den Broeke, 2003) over the past 20 years and discussed by Medley et al. (2018). Recent studies postulate in some areas of Antarctica, partly also on the EAP, an increase in the accumulation rate (Frieler et al., 2015; Medley and Thomas, 2019) caused by a temperature rise. However, accurate accumulation rates for the interior EAP are hard to determine and are generally overestimated (Anschütz et al., 2011).

We test the impact on surface snow density of a 1°C temperature rise as well as a 15% increase in accumulation rate at Kohnen Station. We use the parameterization after Kaspers et al. (2004):

$$\rho = 7.36 \times 10^{-2} + 1.06 \times 10^{-3}\,\mathrm{T} + 6.69 \times 10^{-2}\,\dot{\mathrm{A}} + 4.77 \times 10^{-3}\,\mathrm{W}, \qquad (2)$$

where T is the annual mean temperature [K], $\dot{A}$ the accumulation rate [kg m² a^{-1}] and W the mean wind speed [ms^{-1}]. For comparison we also use the parameterization after Sugiyama et al. (2012), as this one has been calibrated in particular with samples along a traverse over the EAP:

$$\rho = 305 + 0.629\,\mathrm{T} + 0.150\,\dot{\mathrm{A}} + 13.5\,\mathrm{W}, \qquad (3)$$

with T in [°C], $\dot{A}$ in [kg m² a^{-1}] and W in [ms^{-1}] at the given location.

A temperature rise of 1°C and an increase in accumulation rate of 15% at Kohnen Station would increase the surface snow density by 1.7 kg m^{-3} according to Kaspers et al. (2004) and by 2.0 kg m^{-3} according to Sugiyama et al. (2012). According to both parameterizations, the difference in density between this study and Oerter (2008) cannot be solely attributed to these climatic changes as both potential increases are inside the error range of ρ_{loc}. Despite of uncertainties in the precision of the sampling method or natural (climatic) variability, the discrepancy in surface density between both datasets can also be caused by stratigraphic noise over time. To give an example here, we compare ρ_{loc} of snow profiles from Kohnen Station taken in two different seasons at the same position. We use 17 profiles along a transect line with 0.5 m spacing from season 16/17, which were resampled in season 18/19 (both unpublished). The climatic conditions during this time span did not change significantly. ρ_{loc}(16/17) and ρ_{loc}(18/19) both have the same value and the same standard deviation 350±6 kg m^{-3}. Although this example can give an estimate for the robustness of our density measurements using the liner method, we are not able to completely decouple the spatial variability and the temporal variability as we cannot resample the exact same position (and thus the exact same snow).

In a second test, we use an annual mean temperature of -50°C (223.15 K), accumulation rate of 40 kg m² a^{-1} (0.05 m.w.eq a^{-1}) and a wind speed of 6 m s^{-1}, which are roughly the mean values of the area covered with the traverse. While the parameterization by Sugiyama et al. (2012) is fairly accurate compared to our 1 m snow density (+5 kg m^{-3}), keeping the temperature and accumulation rate constant we have to increase the wind speed to 9 m s^{-1} to reach the surface snow density along the traverse using the parameterization by Kaspers et al. (2004).

In general we conclude, that several parameterizations for the surface snow density (Kaspers et al., 2004; Sugiyama et al., 2012) need further tuning for regions with low accumulation and low temperatures like the EAP. Rather local parameterizations should be used for regions with similar environmental conditions instead of continent-wide parameterizations.

4.4 A representative surface snow density on the EAP

In order to overcome the sparsity of ground truth surface snow density, regional climate models and derivatives with adequate snow deposition modules are often used to obtain estimates of accumulation and surface snow density on a full regional scale. Ligtenberg et al. (2011) presented firn density averaged from surface to 1 m depth over a period from 1979-2011. It is forced by RACMO2.3p1 mass fluxes and skin temperature and gridded at 33 km resolution.

Compared to the firn densification model presented by Ligtenberg et al. (2011), we find systematically higher values for density on the interior EAP than the model predicts for the same locations. While ρ_{loc} spans the range from 346 to 372 kg m^{-3}, the firn model provides a range from 308 to 332 kg m^{-3} (Fig. 11). Having a sound statistics at these locations, we exclude the systematic bias to be caused by our observations, but rather assume a shortcoming of the model to yield densities which are about 10% too low. This could be caused by a multitude of reasons, e.g. model physics, spatial and temporal resolution or forcing. As the parameterization by Kaspers et al. (2004) provides density values closer to our ground truth data than the model output by Ligtenberg et al. (2011), we suggest to revise the used slope correction (Helsen et al., 2008) for the EAP.

Our observation is consistent with recent field observations on the EAP (Sugiyama et al., 2012) or snow density collections from over two decades (Tian et al., 2018). Sugiyama et al. (2012) found a density around 350 kg m^{-3} for the same depth interval (0-1 m) along a traverse between Dome F and Kohnen Station, with a similar spatial variability. Nevertheless, we cannot detect a clear trend in density along the whole traverse route. A potential reason might be the increase in elevation, distance to the coast and major Dronning Maud Land (DML) ice divide on one hand and the decrease in temperature as well as accumulation rate (Fig. 11) on the other hand. As the sampling took six weeks in total (Tab. 2), we exclude an effect of seasonal density variability as well as a significant effect of accumulation during the traverse (as the only observed accumulation on the traverse was few diamond dust events above 3500 m asl during the nights and some drift snow). We explain the increase in surface density along the ice divide from Kohnen Station towards B51 (Figs. 8, b and 11) by smaller grain sizes due to decreasing temperature. The combination with the lower accumulation rate and longer exposition and mixing at the snow surface seems to create a higher surface snow density here. The observation of this systematic change in density is also visible in results of Sugiyama et al. (2012) and not captured by firn models. In fact, the model by Ligtenberg et al. (2011) shows the opposite trend along this traverse section (km 0-500 in Fig. 11). High density at B51 goes along with stronger dune formation than at Kohnen Station, which was observed to increase along this traverse part, and higher potential for wind packing due to lower accumulation rates. This is consistent with observations of dune formation at wind speeds exceeding 10 m s^{-1} (Birnbaum et al., 2010) or observation of wind packing events (Sommer et al., 2018) causing increased snow density.

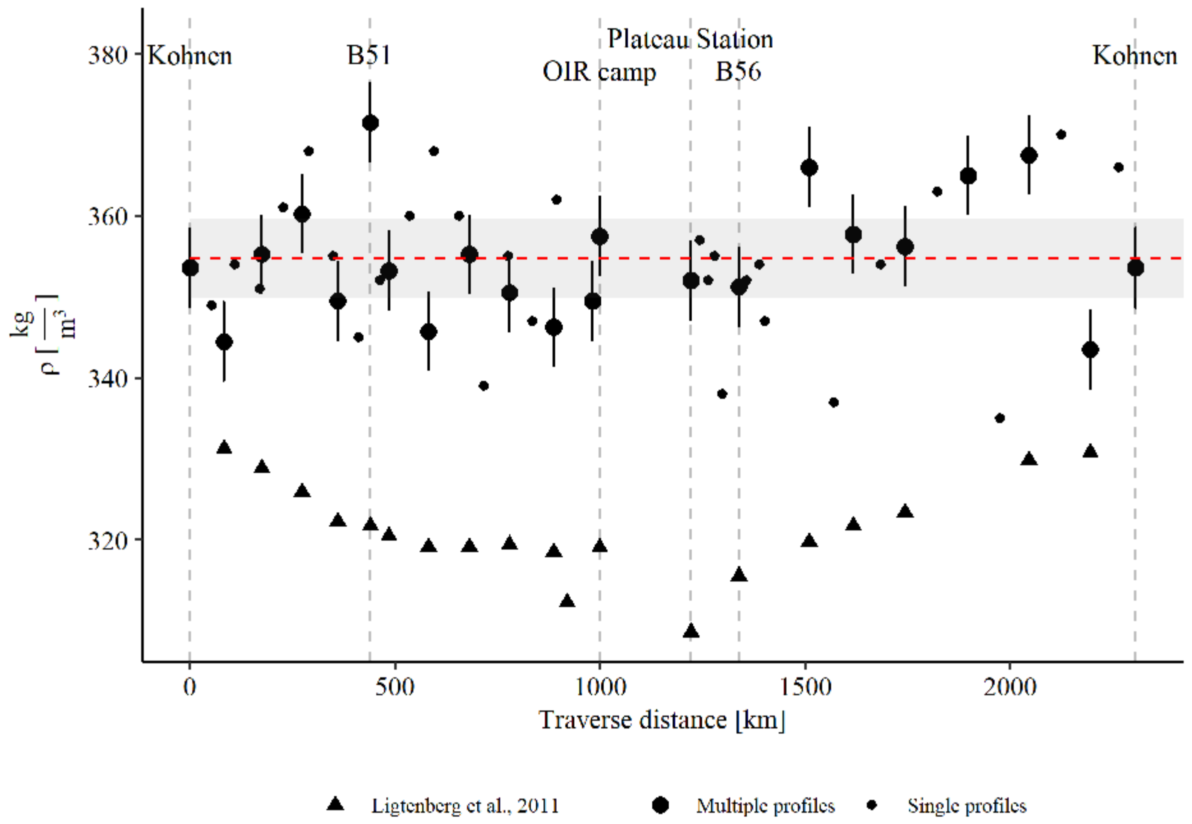

Figure 11: Location mean density (ρ_{loc}) as well as liner density (ρ_L) along one leg of the traverse route, from Kohnen Station to B51, further along the ice divide to B53 and from Plateau Station straight back to Kohnen Station. σ_n calculated from the OIR trench (Sect. 3.3) is given by vertical error bars at each location. A mean density value for Kohnen Station was calculated from samples not collected in this study (s. 2.5). The red dashed horizontal line indicates the mean density along the whole traverse, the standard error (σ_n) is indicated with a grey shade. The triangles show the parameterized density values according to Ligtenberg et al. (2011).

Modelled density is parameterized by wind speed, but the process of denser packing by wind scouring and redistribution over the time until the snow is finally buried might be underestimated. We assume that the modelled low density values for the locations 14 and 15 (Plateau Station and B56, Fig. 11) in the calm accumulation zone are caused by the relatively low wind speed (Lenaerts and van den Broeke, 2012; Sanz Rodrigo et al., 2012), in combination with low temperatures and humidity (Picciotto et al., 1971). But the wind on the interior plateau is not strong enough to cause wind packing and sintering of snow crystals. It rather redistributes them smoothly at the surface, which also happens at low wind speeds. This process is significantly different from wind packing at high wind speeds. Thus the sintering process is prolongated it increases the density on the long term, which also causes an increase in density variability at the surface. But as the low densities cannot be seen for the whole interior plateau region (Fig. 8, d), we consider it rather as a process that needs very specific settings on the high plateau than an average characteristics. The abundance of wind speeds higher than 10 m s^{-1} might be a limiting factor in this context.

Different environmental conditions at B53 and vicinity might cause lower density here as well (Fig. 8, c). High σ_n for subset B53 and vicinity should not be over-interpreted, as only one sampling location with four profiles is present there. Still, σ_{loc} is highest here amongst all locations with multiple liners along the traverse (comp. also σ^{1m}_H in Tab. 2). An explanation can be a different wind and accumulation regime at the distant side of the ice divide causing high heterogeneity on a very small-scale. Small fluctuations in density within the error range at nearby locations can be explained by stratigraphic noise (Laepple et al., 2016; Münch et al., 2016). Stronger variations in density, e.g. beyond one standard variation, can be caused by a complex interaction between wind speed and surface roughness on the small-scale but also have been shown to originate from dynamic interaction of ice flow over bedrock undulations, thus altering surface slope and in turn elevation and accumulation rate on the large-scale in this region (Anschütz et al., 2011; Eisen et al., 2005; Rotschky et al., 2004). For a detailed conclusion regarding the influence of bedrock topography on the density fluctuations in our data, we consider the local scale (10 m) as too small and the regional scale (100 km) as too large. We suggest a different sampling scale (i.e. 10 km spacing of representative density) for this purpose.

As already stated above, we cannot conclusively attribute a cause to the model behavior as we also neglected the atmospheric forcing of the firn densification models, which could explain parts of the density discrepancy between field data and modeled values. Unfortunately, it is also difficult to pin down the mechanism for the observed systematic spatial distribution of density. As the snow density parameterizations are mainly dependent on temperature and wind speed, the influence of both might be too high while processes acting on the snow surface like snow redistribution and packing play a major role on snow density. Obviously, a dedicated sensitivity study with a snow deposition and firn model is needed to discriminate the various processes affecting postdepositional snow metamorphism and densification. We suggest to set up a specific model test designed for the EAP and use data sets like ours and those from comparable studies as the standard against which to evaluate model outcomes.

4.5 Application to satellite altimetry of ice sheets

Firn densification models are used in altimetry, to convert height changes of the ice sheets to mass changes. The more accurate the modelled firn density provided by these models is, the lower the uncertainties in the calculated mass changes will be. Therefore, our presented density data can be of particular interest to improve the accuracy of ice sheet mass balances.

One way in altimetry is to use a simple density mask as input parameter (e.g. McMillan et al., 2014; Schröder et al., 2019). In regions with a strong influence of ice dynamics, only the density of ice is used. In the remaining areas, also in large parts of East Antarctica where the ice flow velocities are low (Rignot et al., 2011), the density of firn is used. In this conversion, uncertainties in snow density have a direct impact on the result in mass. In our case, the 10% density underestimation in previous studies can lead to a 10% mass error (e.g. Alexander et al., 2019). Shepherd et al. (2019), in contrast, use firn or ice density by defining areas of dynamic imbalance, which depend on surface uplift or lowering in relation to firn column changes. This method is even more sensitive to uncertainties in the firn densification models, as it subtracts variations in firn density over time.

Despite the impact of density on the height-to-mass conversion, the snowpack properties can also influence the microwave penetration into the snow and therefore considerably affect the radar altimetric measurements. Generally, snow properties like density, grain size and liquid water content can influence the permittivity (Mätzler, 1996), but also spatio-temporal variations of these parameters influence the measurements (Davis and Zwally, 1993). Furthermore layering of the snowpack seems to affect the penetration depth, like shown in Slater et al. (2019) for Greenland. Interestingly, the density distribution of density (Fig. 9) does not show as much difference between the subregions as previously expected due to different accumulation rates. While we can see differences on the local scale (OIR trench), on the regional scale the vertical density distribution of the subregions is very congruent. Therefore further high-resolution studies on the vertical variability of the snowpack are needed on the EAP, especially with regard to high surface variability.

4.6 Mass estimate of East Antarctica

In the following we provide an idea how the mass of the firn column depends on the choice of the surface density using the commonly used firn densification model by Herron and Langway (1980).

Based on our findings we employ a simple quantitative calculation of the underestimated mass in the firn column with the density data presented in this study (average ρ_{loc}) using the semi-empirical firn densification model by Herron and Langway (1980). We use an annual mean temperature of -50°C and an accumulation rate of 0.04 m we a^{-1} as input parameters. We use the two different surface densities $\rho_0(1)$=320 kg m^{-3} (Ligtenberg et al., 2011) and $\rho_0(2)$=355 kg m^{-3} (this study) and sum up the water equivalent in the firn column.

We calculated 59.0 m we for $\rho_0(1)$ and 61.0 m we for $\rho_0(2)$ in the firn column down to the firn-ice-transition in 92.9 m, where scenario $\rho_0(2)$ reaches the critical density of 830 kg m^{-3}. The calculation is in good agreement with firn density (µCT) measured in core B53 (unpublished data). This is roughly an underestimation in mass of 3% for the firn column only. Other effects like an overestimation of the accumulation rate on the interior plateau are not taken into account. We extrapolate this underestimation to the East Antarctic ice sheet, assuming an average ice sheet thickness of 2000 m. This results in a total underestimation of mass in the order of 1‰. Using the sea level equivalent for East Antarctica published by Rignot et al. (2019), this corresponds to about 5 cm sea level equivalent, which is more than twice as high as the sea level rise over the last four decades (-13.9±2.0 mm, Rignot et al. (2019)). As the firn-ice-transition is not as deep at the coast as on the EAP, we consider this calculation to be somewhat overestimated.

5 Conclusion

We presented surface snow density data along a traverse route from Kohnen Station to former Plateau Station on the EAP using the time efficient liner method. We can reduce the sampling error from up to ±4% (Conger and McClung, 2009) by the liner technique (this study and e.g. Schaller et al., 2016) to less than 2% relative error for a 1 m snow density. The method covers seasonal and annual variations at sites of high accumulation and reduces the influence of high surface roughness in relation to the annual accumulation in low accumulation areas. Especially in the upper 30 cm we see the highest stratigraphic variability in snow density. As long as the accumulation does not exceed 0.5 m of snow per year (independent of the snow density), we suggest a 1 m snow density using the liner method as the best way to quantify surface snow density as the 1 m interval offers high accuracy and is representative when repeated several times. It is not biased by the seasonal density variations or weather conditions, balances high surface roughness with multiple samples, has negligible under-sampling errors as well as snow compaction and is very time efficient.

We compared the presented snow profiles to density data from snow pits by Oerter (2008). We found 1-5% lower 1 m snow densities, which cannot be attributed to a temperature change between the sampling dates only. For the density from surface to 0.1 m depth we find a considerable 16% difference in density, that we explain with a systematic sampling error. This systematic error makes comparisons of old and new datasets with different sampling devices difficult, as an increase in mass in Antarctica or an underestimation of mass in the past is hard to detect.

Especially on the EAP, field data are sparse. We conclude, that four spatially independent snow profiles are necessary to determine a snow density value with an error lower than 1.5% of the mean. To further verify this result in future studies, we suggest to test this with a similar sampling scheme with five and more profiles using the liner technique. A circular setup with one profile in the midpoint and four to six profiles along a circle with a radius of 10 m to keep spatial independency might be a feasible approach.

Our results are in good agreement with earlier density studies partly made in the same region (Sugiyama et al., 2012). We suggest a representative mean density of 355 kg m^{-3} for surface snow on regional scales on the EAP. As we find a high variability on different spatial scales, we suggest to average point measurements for snow density over regional scales to find a spatially representative density value for surface snow instead of using single measurements. We divided the area covered by the traverse into subregions due to different environmental regimes, but we cannot find significant differences in surface snow density among them. Natural variability in snow density seems to be higher than previously assumed. Especially on the regional scale, we cannot see a clear correlation between temperature and accumulation rate with snow density. For future studies we therefore suggest to sample transects of 50-100 km with representative density samples every 1 km to investigate the influence of topography changes on snow density in more detail.

We also suggest further tuning of parameterizations of the surface snow density in firn models, especially for regions with environmental conditions like the EAP, which currently produce densities which are almost 10% lower than our observed values. We did not test the climatic forcing in firn models, which also can contribute to this significant offset. Neglecting the forcing, an underestimation of surface snow density can lead to a 3% mass underestimation in the firn column of East Antarctica, which roughly corresponds to a 5 cm sea level equivalent. These errors or biases in 1 m snow density can lead to large uncertainties in SMB. Improving densification models with the presented density data can also increase the accuracy of ice sheet SMB derived by altimetry, as a 10% offset in snow density, as presented in this study, can lead to a 10% error in mass. We suggest further investigation of the density variability in depth (temporal variability) with local snowpack studies in high-resolution and whether this can affect altimetry measurements.

6 Data availability

Datasets will be uploaded to the open-access repository Pangaea.

7 Author contributions and conflict of interest

JF and SK were in charge for the planning of the scientific expedition. AW and SK conducted the field work. AW performed the majority of the µCT measurements, subsequent analysis and wrote the manuscript. All authors discussed the results and contributed to revising the manuscript.

OE is Co-Editor-in-Chief of The Cryosphere.

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10 Appendix

10.1 Appendix A: Snow density profile

For a better understanding of Fig. 9, we show a density profile over depth measured with the µCT. In the radioscopic image the stratification of the snowpack is visible. In Fig. 9 we took all high resolution µCT density profiles along the traverse, according to their subregion, as well as the OIR trench and plotted the relative abundance of the density values in 2 kg m^{-3} intervals.

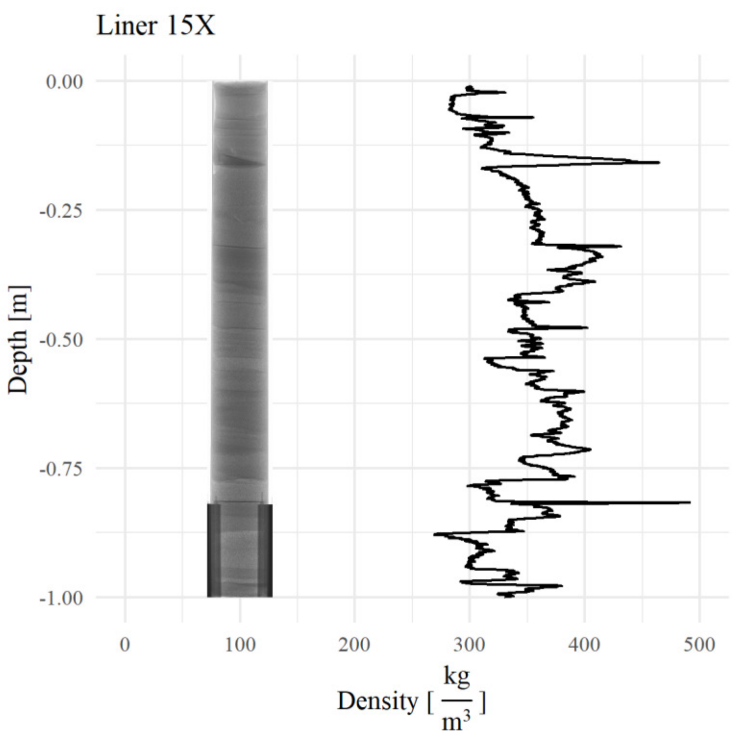

Figure 12: µCT density of a snow profile at position 15X. On the left the radioscopic image of the snow profile is visible. Dark grey colour represents high density, bright grey represents low density values. On the right, the corresponding density profile over depth is shown.

10.2 Appendix B: Geographical map of ρ_{loc} and σ^{1m}_H

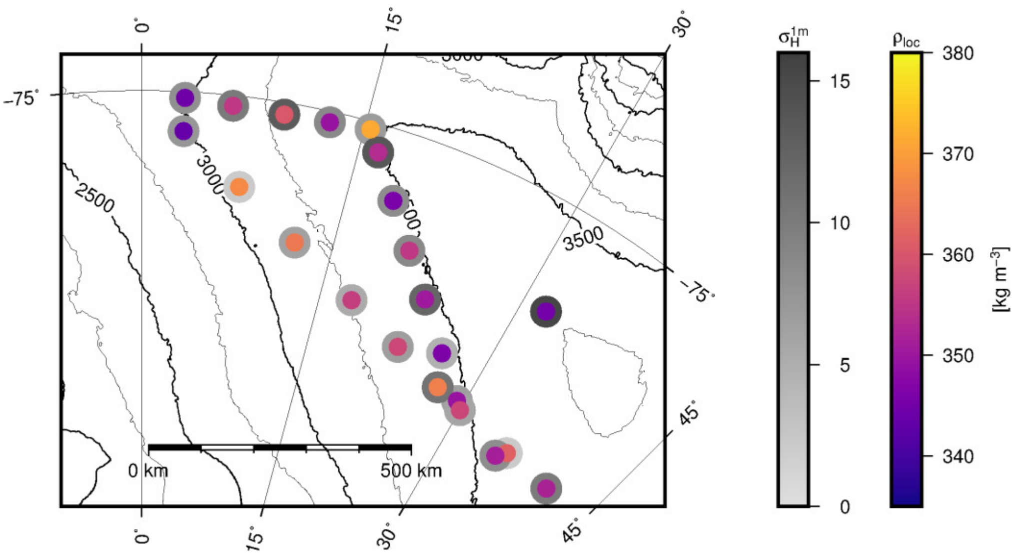

Figure 13: Location mean density (ρ_{loc}) and the horizontal standard deviation (σ^{1m}_H) along the traverse. The according values can be found in table 2. Colored points show ρ_{loc}, grey edges σ^{1m}_H.

10.3 Appendix C: Height measurements along the OIR trench surface

Table 6: Surface levelling along the OIR trench. Surface height was measured at and in between subsequent sampling positions. In column two we show the distance along the trench, in column three the relative surface height in relation to the last profile.

Sample position	*Distance [cm]*	*Relative surface height (to profile 30) [cm]*
1	0	-38.5
	59	-31
2	125	-23.4
	178	-33
3	237	-21.6
	274	-16.1
4	309	-12.7
	391	-17.8
5	462	-9.7
	510	-19.3
6	556	-22.7
	610	-30.1
7	672	-30.2
	740	-34.7
8	800	-32.1
	895	-35.7
9	970	-30.5
	1030	-32.6

10	1088	-32.3
	1150	-35
11	1209	-33.4
	1278	-33.5
12	1343	-24.9
	1395	-30.4
13	1440	-31.3
	1510	-29.6
14	1575	-28.4
	1675	-30.4
15	1750	-20.2
	1790	-19.6
16	1832	-17.6
	1880	-20.4
17	1934	-22.6
	1998	-25.2
18	2056	-17.1
	2100	-25
19	2145	-24.6
	2230	-27.9
20	2282	-28.2
	2380	-30
21	2449	-28.9
	2500	-26.8
22	2545	-25.6
	2619	-27.8
23	2700	-25.2
	2760	-29.9
24	2815	-31.8
	2940	-30.9
25	3051	-18.3
	3120	-21.9
26	3177	-16
	3245	-12.7
27	3310	-14.6
	3368	-8.7
28	3412	-4.6
	3432	-4.2
29	3453	-3.2
	3488	-1.1
30	3522	0