Interactive comment on "Measurement of fracture toughness of an ice core from Antarctica" by J. Christmann et al.

Anonymous Referee #1

general comments:
The paper by Christmann et al. presents an interesting data set on fracture toughness of bubbly ice (not an ice core). The carefully measured data add
to the knowledge on fracture properties of ices. This preliminary study, where samples were measured at one temperature and one strain rate, supports earlier data.

specific comments:
The title is misleading. The data are from an ice core, but only a very short section! "Measurement of fracture toughness of bubbly ice from Dronning Maud Land, Antarctica" would be more appropriate.
You are right. The new title reads:
"Measurement of fracture toughness of polycrystalline bubbly ice from an Antarctic ice core"

The introduction is very short, a reader not familiar in fracture mechanics will have difficulty to follow.
The following sentences (p.613, l.3ff):
"In the presence of cracks, the stress field is singular at the crack tip for linear elastic materials, thus stress based criteria fail to predict crack growth.
However, the asymptotic behavior is given by the stress intensity factors (SIFs), usually denoted by K_I, K_II or K_III. "
are expanded by
"For linear elastic materials the stress intensity factor (SIF) determines the criticality of the crack due to mechanical loading on the basis of macroscopic behavior and therefore predicts the stress intensity around the tip of the crack. The reason for this is, that in a linear elastic model the stress field is singular at the crack tip, thus stress based criteria fail to describe crack growth. In the presence of cracks, there are three different possibilities for further crack opening. Mode I describes the symmetric crack opening perpendicular to the direction of the largest tensile stress. Additionally, mode II characterizes the sliding fracture mode, causing shear stresses, and mode III denotes the tearing mode. In all loading cases, the asymptotic behavior is given by the SIFs, usually denoted by K_I, K_II or K_III. For details on fracture mechanical concepts …."

It would also be a welcome addition to hint the reader to the rather special properties of ice, namely its extremely high temperature and plasticity. It is by no means clear at which strain rate the plastic component of ice fracture can be neglected, and this section should be extended.

Additional comments in the introduction
"The measurement of fracture toughness is performed at high deformation rates in order to trigger the brittle response of ice. In this measured regime the theory of linear elastic fracture mechanics can be applied ignoring the viscous and plastic properties of ice, see Schulson and Duval (2009)."
are added after the sentence (p.612, l 24)
"...and the relevant parameters are fracture and rupture."

The author should be very clear that the data presented by Schulson and Duval (2009) are copy-paste from the Rist et al (1999) data set. I suggest that the authors only cite the Rist et al data, as this is the original source.
This is true and the revised version of the manuscript contains only the reference of data determined by Rist et al. (1999).

I was also slightly puzzled by the last sentence of the introduction. Are the measurements purely estimates? So then there would be no need to measure again the fracture toughness of ice at all, and even less to get this article published. Please explain and detail the limitations, and explain the expected uncertainty.
The word "estimates" was misleading in this context, "dependent on the determination method" would be better. The sentence should clarify, that the method to determine the fracture toughness is not unique and that different methods result in slightly different fracture toughnesses.
Therefore, the sentence
"Rice (2000) had analyzed for the case of ceramics, that there do not exist one single and perfect method, so the results of the fracture toughness are only estimates."
is replaced by:
"For the case of ceramics Rice (2000) states, that there does not exist a unique method to measure the fracture toughness of a material. According to the ASTM standards several experimental setups are possible. In this investigation the ASTM standard for a four-point bending technique on single edge v-notched beam samples was applied to ensure plane strain conditions. The measured parameters, which determine the fracture toughness, are assumed to be independent of the geometry and the loading situation. The advantage of this method is that the measured data of Section 2.2 (load-deflection curves) are not sensible to small changes in the alignment of the ice sample. In addition, the fracture toughness measurements show a high amount of repeatability, verifying the insensitivity to geometry variations."

The density measurement using X-ray adsorption across the core diameter should be explained in more detail and referenced (p 614, l 13).
The density-depth profile also shows several missing parts, but in line 16 it is mentioned that the entire core was weighted? So it remains unclear why there are missing parts in the radiographic density measurements.
I am also wondering why there were not micro-CT measurements of the samples performed, as AWI is well equipped with such instruments? This would give a much more detailed and complete bubble size distribution and statistics. In this context the spatial variability of the density within the used samples would be of interest - the

figure shows relatively large variations? Could you characterize the trend and variability within your samples?
A volumetric scan of the ice core was not performed, as two dimensional X-ray scans are sufficient to select vertical density variations with a resolution of approximately 0.11mm. Subsequently, the density near the prefabricated crack is sufficed for the realized measurements of the critical fracture toughness. Therefore, the focus for the determination of the critical fracture toughness lies on the density near the crack and we are not interested in additional structure parameters as the bubble size and distribution. The missing parts in the density measurements are based on breaks or notches. We think that these regions are uncritical for the calibration of the absolute density and the error in this density is estimated with 1-2% as the ice core is not perfect cylindrical. The relative error is more precisely, since we remove the parts near breaks or split-offs.
The standard deviation within the samples range from 4.06kg m^{-3} to 8.7kg m^{-3} , if the density is averaged over 2mm in order to exclude the noise of the measurement. The standard deviation ranges from 5.15kg m^{-3} to 9.25kg m^{-3} for the density measurements without smoothing. A slight trend is seen in the variability of the density, since the standard deviation is getting smaller for deeper parts of the ice core. The density analysis of an ice core, located nearby the one investigated in this context, shows a similar layering for the density variability at comparable depths, see Freitag et al. (2013).
Therefore, the sentences in the manuscript (p.614, l.13):
"Prior to testing an X-ray computed tomography (CT scanner) was used to determine the density as a function of depth, shown in Fig.2. During analysis each 1m long ice core was weighted to estimate the mean density used for the CT analysis calibration." are modified in the following way:
"Prior to testing an X-ray microfocus computer tomograph (ICE-CT) was used to determine the density as a function of depth with a high vertical resolution, shown in Fig. 2. Freitag et al. (2013) demonstrate that the variability of the density measurements, using two dimensional X-ray scans, is less than other previously used methods as the noise level is smaller. During analysis each 1m long ice core was weighted to estimate the mean density from the ratio of weight to volume, the so called volumetric method. This density is used as a calibration parameter for the two dimensional X-ray scans. Regions of anomalies, conditioned by for example breaks or notches in the ice, are automatically detected and removed, see the missing parts in Fig. 2. For a detailed description of the construction and practical application of such a X-ray scan, see Freitag et al. (2013). The density profile shows, that for greater depth the density slightly increases, whereas the density variability decreases, including standard deviations ranging from 5.15kg m^{-3} to 9.25kg m^{-3}. The ice core was then cut into 12.6cm …"

The paragraph (p. 614 l 22 ff) is clearly of introductory nature.
In order not to overload the introduction (which has been prolonged in the revision) the authors prefer to leave this paragraph in Section 2.1.

The section Results and Discussion is very short and results superficially described. Especially p 618, l 25 ff

"... the critical fracture toughness values is relatively small,..."
When I compare this statement with Fig. 7, then the distribution for one density shows a variation of almost 40%? I think this is not "small" and needs more explanation.
Replace the following sentence (p.618, l.25)
“Nevertheless, the distribution of the critical fracture toughness values is relatively small, demonstrating the repeatability of the current measurements.”
with
“The average standard deviation for a four-point-bending technique is assumed to be in between 2% and 7% for homogeneous ceramics as a given estimate in literature, see Gogotsi (2003). This spread will be much larger, if the material is relatively heterogeneous or full of defects (like ice-core ice). The standard deviation of the critical fracture toughness for the current measurements was approximately 17.5%. Nevertheless, the maximum absolute variation of 0.017 MPa m^1/2 for fracture toughness measurements of any sort is relatively small, if this is, for example, compared to other materials such as structural ceramics, where an absolute deviation of several MPa m^1/2 is possible, see Gogotsi (2003). However, the absolute value of the critical fracture toughness for ice, here 0.095 MPa m^1/2, is small compared to other materials, which results in an absolute distribution of 40% is significant. Wei et al. (1991) also studied the influence of different notches in artificial ice using a four-point-bending experimental arrangement, resulting in an average standard deviation of 33.95%. However, the larger number of tested samples, with the comparable distribution of critical fracture toughness variations for given scattering for ice in literature, demonstrates the repeatability of the current measurements. It should also be considered that (i) the measurements were performed on natural materials with various impurities and (ii) that a relatively small number of grains were tested in each sample due to the grain size. Both of these factors can lead to an increased sample-to-sample variation.”

New reference:
“Fracture toughness of ceramics and ceramic composites”, George A. Gogotsi, Ceramics International 29, 777-784, 2003.

The comparison between the Rist data set and this new data set is also necessarily biased because Rist et al measured at -20°C, while the measurements here were at -15°C. A direct comparison, without taking into account a temperature correction, seems to me not correct and needs explanations.
The following sentences are added in the manuscript (p. 618, l. 21):
“The temperature of -15°C was prescribed due to the conditions in the ice lab. Rist et al. (1999) measured the critical fracture toughness in an ice lab at -20°C and stated “we believe that within experimental error, temperature would have no significant effect on our measured values of fracture toughness for shelf ice” (Rist et al., 1999). Therefore, it is possible to compare those results to the one obtained by the presented four-point-bending technique here.”
Due to this statement, the authors are convinced that a temperature correction is not necessary, since Rist et al. (1999) explains more precisely that the fracture toughness of granular ice was not influenced by a temperature variation between -5°C and -20°C.

A similar point is that Rist et al had an almost 10-times smaller strain rate than in this paper, also a point that requires detailed comment and discussion.
The higher the strain rates are, the higher are the influences of the brittle properties of ice and therefore only the elastic response is the crucial factor for the samples to break. A faster failure time of approximately 1 second indicate that viscous and plastic effects are neglectable and therefore the results are comparable to those described by Rist et al. (1999).

("technical corrections": typing errors, etc.):

p 613, l 21ff: The sentence is not logical,
"where ... has a completely different subject than the main sentence".

The second part of the sentence is shifted to Section 2.1 and therefore the sentence read:
"Their results are used as reference values in the present investigation.
The mechanical testing ..."

The description of the location of the core belongs to section 2 (including coordinates),

The coordinates are included in section 2 in the following sentences (p. 614, l. 13):
"Bar shaped samples for fracture testing were obtained from the B34 ice core, originally from a depth between 94.6m and 96m. This core was drilled at Kohnen station (75°00' S, 00°04' E, 2882m) on the East Antarctic plateau, a site of low accumulation rates and temperatures. Prior to testing ..."

Fig. 1 can be deleted, as of no use to the reader.

Figure 1 is deleted in the revised version.

p 613, l 13: experientially -> experimentally

corrected

p 613, l 20: circulatory notch -> peripheral notch

corrected

p 616, l 10: I can't understand the sentence
"... that the states grain size distribution is representative..."
What do you mean by "states"?

This was a typing error and the word states is corrected by stated:
"The grain size was not found to vary in other analyzed sample sections, indicating that the stated grain size distribution is representative of the entire B34 ice core."