

Reply to the re-submission report for the manuscript titled "In-situ estimation of ice crystal properties at the South Pole using LED calibration data from the IceCube Neutrino Observatory" received on the 14th of September 2023

The IceCube Collaboration

September 30, 2023

Comments from the editor

Dear authors,

Both reviewers and I agree that the manuscript has improved considerably and that it should be accepted for publication in The Cryosphere. We also agree that it will be a pity that such a interesting paper may not be as accessible as it could have been.

There are obvious reasons for that. The paper deals with a topic not common in glaciology, and it is long and technical. However both reviewers are pointing at making even more accessible the introductory sections of the paper by improving terminology and language.

I ask the authors to step back for a second: no new runs, figures or equations, but edit the introductory sections of the manuscript (Abstract and Sections 1 and 2) so that they are more readable. The reviewers have given several suggestions in that direction.

Thank you again for your efforts, Carlos Martin

We would like to thank the editor for the timely evaluation of the reviewers comments, his patience in the sometimes slow editing process and the overall encouraging words regarding the evolution of the manuscript.

The introductory sections have been reworked as detailed below and we hope to have now reached an overall satisfactory manuscript.

Comments from Anonymous Reviewer #1

Dear authors,

The authors considered many points that I raised last time. I found the paper excellent. Very frankly, I believe that not many readers can follow the entire details of the paper, as subjects are deep and complex. In addition, as for the numerical simulation, readers must just trust the given results. I could read it from a viewpoint of a glaciology scientist. I must confess that very details of the physical calculations were hard to follow. For these points, I let further criticisms be done by future readers. The section "Outlook" became more sound; unknown or unclear points were described concretely. I will write some comments that I ask to the authors to consider before finalizing the paper. They are basically minor points on introductory part related to glaciology.

We would like to thank the reviewer for the time invested, the encouraging words and the additional comments, which we hope to have adequately addressed.

L1-L2: I did not understand the grammatical structure of the sentence.

Sentence has been split in two.

L22: A term recrystallization suddenly appeared. Basically, crystal rotation due to strain and recrystallization is related but different phenomena. I guess that the authors wanted to say non-isotropic c-axes distribution here. If it is so, please rephrase.

This was also pointed out by the second reviewer, who enforced that the IceCube side is probably dominated by rotation instead of recrystallization. The paragraph has been modified to avoid potential errors and to de-emphasize the importance of the type of mechanism leading to a non-isotropic fabric. Please see the new paragraph in the response to the second reviewer.

L24-25: The authors' expression seem complex. I believe that the expression will confuse readers. An expression unimodal fabric is new for me. At the same time, I feel the expression is a bit tricky. Both single pole fabric and girdle fabric are caused by uniaxial strain (from compression and extension). With a view point of a-axis, single pole c-axes fabric is girdle type a-axes. I feel that single pole fabric or girdle fabric is good enough. The expressions in this paper makes meaning unnecessarily complex.

We wanted to borrow the term from statistics, referring to a distribution having a single mode/local maximum, as is the case in axis space for single pole fabrics. To conform with the more common terminology single pole has been adopted here and in most other instances, with some exceptions in Appendix B where the statistical term is more appropriate.

L26: Again, the term "recrystallization". Was it intended to discuss recrystallization as used in crystal physics? Recrystallization is related to molecular diffusion, grain growth, grain boundary migration or polygonization. Were these intended in the manuscript? Or do you intend to mean evolution of microstructures and ice fabrics? Please clarify. Possibly, misunderstanding is going on.

The possible connection of grain sizes and shapes to the fabric evolution has now been removed so to not include any potentially false/misleading information.

L26: “Alternatively” I did not understand the context. What do you compare, method or phenomena?

This was intended to compare methods. Simply dropped the ” *alternatively*” here.

L25-L32: I find that negative tones for introduction of ice core studies drilled for climate research purposes. Sampling volume limitation is OK. Core orientation can be deduced from ice fabric or other methods. Grain volume or elongation can be deduced from analysis of 3D thin sections. Ground truth is very important. I prefer more positive tone.

Deducing the core orientation from the fabric (while certainly good to first order) becomes a circular argument when trying to understand the interplay between present day flow and fabric. While we are certainly not intimately familiar with the glaciological literature, we have in our studies also so far not encountered ”3D thin sections.” Information on this would be appreciated.

Regarding the discussed section, the tone was certainly not meant to be negative and we absolutely agree on the value of ground-truth information. Yet we believe the limitations as outlined to be fairly described and these were all limitations which we also encountered in modeling the ice optical anisotropy.

The wording of the paragraph has been slightly altered and it now reads as:

While ice core analysis uniquely delivers ground-truth information, it is limited by its small sampling volume, and often unable to resolve the absolute direction of fabric orientation as the core orientation is not preserved in the drilling process. Volumetric quantities such as grain volumes and shapes are generally not directly accessible through the commonly employed techniques. Grain sizes and elongations evaluated through the microscopy of thin slices cut from ice cores in turn often depend on the sample plane.

L31: In firn, grain boundaries are still undetectable by X-ray CT. Thus, it does not seem an exception. We can observe just boundaries of pore structure and ice matrix. It is so in bubbly ice zone (100-1300 m depth), too.

Fair enough. X-ray only sees density fluctuations and even in the firn it may not be single but grains with air pockets in between. We have omitted the X-ray tangent.

L50 and at many points in the manuscript: What do you mean with a term “Grain boundary crossings”? Is it your original term? Is the widely used term “grain boundaries” not suitable? Do you specifically mean triple junctions?

” *Grain boundary crossings*” was meant to denote the process of a photon traversing/crossing the grain boundary. The term was replaced in all instances, in this case simply switching to ”... *is refracted or reflected on many grain boundaries ...*”.

L51-53: Did Chirkin and Rongen investigate effects from shapes of grain boundaries? Please specify.

Yes, but only on length scales larger than 400 nm. On the length scale relevant to individual refractions/reflections, that is the wavelength of light, the grain boundaries are assumed to be simple planes (see section 5.2). The macroscopic shape is accounted for in the probability density of encountered grain boundary orientations, as elaborated on throughout the manuscript and detailed in Appendix C. To

emphasize the connection between the grain shape and the distribution of grain boundary orientations the paragraph has been updated as follows:

Thus, the spacing of grain boundaries and the distribution of encountered grain boundary orientations, both of which are a function of the average grain shape, must be accounted for in addition to the fabric.

L51: Light propagation is along the preferred orientation of the a-axes. It seems meaningful to let readers know about it.

We do not understand this comment, could the referee clarify? The model accounts for light propagating in any direction as is also the case in reality. (With the initial emission being random and scattering being present.)

L547: The term "crystal realizations" is not a standard term in physics but might be used in specific contexts to refer to particular instances or examples of crystalline structures. Please specify your intended meaning to readers.

Changed here to "*configurations/realizations*" to specify the intent going forward.

L150: Soot does not have volcanic origin. Please find a review paper below. Bond, T. C., et al. (2013), Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos.*, 118, 5380–5552, doi:10.1002/jgrd.50171. If you still claim that soot is from volcanic eruptions, please provide convincing reference paper.

Thank you for noticing this. This was an oversight. Volcanic ash layers are detectable for example with the dust logger but were not meant to be mentioned in this context. The "*(volcanic)*" has been deleted.

L492: Crystal dielectric tensor can change both gradually and also abruptly. Please find Figure 7 in the following paper.

Saruya, T. et al.: Development of crystal orientation fabric in the Dome Fuji ice core in East Antarctica: implications for the deformation regime in ice sheets, *The Cryosphere*, 16, 2985–3003, <https://doi.org/10.5194/tc-16-2985-2022>, 2022.

In terms of radar sounding, it will be a topic of further discussions.

That is an interesting plot. We have omitted the statement about gradual changes for correctness.

Section 2.3 Size distributions of sea salts and terrestrial dusts in ice sheets are well described in the paper below. It will give more concrete information to readers. Oyabu, I., Iizuka, Y., Kawamura, K., Wolff, E., Severi, M., Ohgaito, R., et al. (2020). Compositions of dust and sea salts in the Dome C and Dome Fuji ice cores from Last Glacial Maximum to early Holocene based on ice-sublimation and single-particle measurements. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD032208. <https://doi.org/10.1029/2019JD032208>

There is a LOT of literature on particle sizing of impurities in ice cores. Since in this context only the conceptual connection to the scattering asymmetry as well as order of magnitudes are of relevance, we would prefer to not include papers of specific measurements here.

Comments from Reviewer #2, David Lilien

This is my second review of this paper, and I would like to thank the authors for carefully responding to all my comments. I still think it will be a valuable contribution well-suited to The Cryosphere.

I find the manuscript to be significantly improved, although I still struggled a bit with what I view as a lack roadmap and lack of clarity on what exactly was done in the present work (or the proceedings which it collects for a geophysical audience). As the paper goes on, I think that this improves somewhat, and so this general comment focuses on the abstract and sections 1 and 2.

We would like to thank the reviewer for the time invested, the encouraging words and the additional comments, which we hope to have adequately addressed.

I recognize that it is not really my role as a reviewer to demand grammatical changes that are a matter of preference, but I think that one reason that clarity is still an issue is the almost exclusive use of present and present perfect tenses and the heavy use of passive voice. Those choices make it very, very difficult for somebody without intimate knowledge of the various efforts by the IceCube team to know what happened when and what is really part of the current ice model or current study. I do not think there is anything technically wrong with using present tense, but it causes confusion. Take, for example, line 3: does “has been examined” mean we will read about it here or that it was in previous work? Or line 60: between two sentences I think there is a transition between a pre-existing truth and a roadmap of the present paper, but I would not have known that without having read the whole paper previously. Or 682, where the authors write “could” to describe something that they actually did. I think one way to address the lack of clarity is by hewing closer to common scientific use of tenses (i.e., present for pre-existing truths, past for things that happened in the past, including work that has been completed for the present paper). That is one suggestion for improving clarity, and I imagine there would be a number of other ways to reach the same goal of clarifying what is “this paper” and what not. However, if this suggestion is not taken, I think there still need to be substantial changes in the abstract and sections 1–2 to distinguish between what is happening in this paper and what was previous knowledge. That is not to say that this should be difficult, a careful edit that considers how little most glaciologists know about Ice Cube should make the start of the paper more readable.

We would like to thank the reviewer to be able to pinpoint specific grammatical structures that he found to hinder the accessibility of the manuscript. We found the specific recommendation (active voice and present for pre-existing truths, past for things that happened in the past, including work that has been completed for the present paper) thought provoking. In particular, active voice has traditionally been somewhat of a taboo. Re-examining some recent literature we agree that this has changed and probably improves clarity overall. While we hesitate to embrace a full rewrite of the manuscript for voice and tense, for fear of adding new inconsistencies, we will certainly take the advice for future publications.

Regarding the specific examples of confusion raised by the reviewer:

- Line 3: The wording has been changed to: “*We here examine birefringent light propagation through the polycrystalline ice microstructure as a possible explanation for this effect.*”
- Line 60: The overall effect was first described in Chirkin and Rongen, 2020, while the parametrization and application in photon propagation is described in Rongen et al. 2021a. To de-emphasize a temporal relation “*The new simulations, ...*” in line 63 has been changed to “*These simulations,*

...”, the tense has been changed to be self consistent with the prior use of present perfect and a further citation of Rongen et al. 2021a has been added.

- Line 682: Yes this could easily be misread as ”to be done in the future”. The wording has been changed to: *”This has been improved upon by ...”*

The following further clarifications have been added:

- Line 75: Changed *”prior to this work”* to *”prior to the discovery of the ice optical anisotropy”*
- Line 150: Added a further reference to Ackermann et al., 2006.
- Line 180: Changed *”This leaves 6 global parameters ... to be determined.”* to *”Thus 6 global parameters ... are required to describe the layered ice properties.”* so to not give the impression that these parameters are of primary interest in this manuscript.

At this point, other than a couple of the detailed comments below, I do not have qualms that would prevent publication, but I think it would be a missed opportunity not to further improve the clarity of the manuscript.

L18: The introductory phrase is misleading—the reason for ease of deformation is not the crystal shape

Fixed by omitting the shape:

The viscosity of an individual ice crystal strongly depends on the direction of the applied strain and it will most readily deform as shear is applied orthogonal to the c-axis

L20: This is still incorrect; it describes the mechanism of migration recrystallization but not lattice rotation. At IceCube, ice is cold and flow is reasonably slow, so lattice rotation is the likely cause of fabric development (the circa 1990 Alley papers are still fine references for this). That is to say, the crystals are not reorganizing to minimize strain energy, they are simply being rotated by the physical deformation changing place; to the extent that they minimize strain energy, in this case that is incidental.

Thank you for elaborating on this. This actually sheds some light on the apparently missing quantitative relationship between fabric strength and grain elongation, which is something we have been looking for in the literature for a while... The paragraph has been rephrased so not to be explicit on the fabric forming mechanism (as it does not directly matter for the optical properties) and now reads as (without citations):

Ice flows under its own weight, either through basal sliding or through plastic deformation, which is mediated by the deformations of individual grains as well as interactions between grains. The viscosity of an individual ice crystal strongly depends on the direction of the applied strain and it will most readily deform as shear is applied orthogonal to the c-axis (crystal symmetry axis, normal to the hexagonal basal planes), leading to slip of the individual basal planes. In polycrystalline ice subjected to strain the crystals may undergo lattice rotation or recrystallization, both of which result in non-isotropic c-axes distributions and a bulk anisotropic viscosity. In this work we only consider scenarios where the c-axes are distributed isotropically (uniform fabric), are aligned in a single direction (single pole fabric) or lie in a plane (girdle fabric). The

later is of primary importance for the studied ice.

The crystal orientation fabric is experimentally most commonly observed through the use of polarized light microscopy on thin sections of ice core samples.

L60: Combination of passive voice and present tense with a mid-paragraph transition in topic make this hard to parse

Please see the response above.

L167-180: This is really the start of the development of a model of this particular parcel of ice, whereas the rest of the section is more about physical properties of glacial ice in general. I would suggest making these two paragraphs a separate section, since they do not really describe “ice as an optical medium”—maybe consider moving them to 3.2 if not.

Point taken. In isolation these paragraphs probably fit best into section 3.4, yet the concepts introduced here are already required going into section 3.2. With section 3.2 being dedicated to light curves and photon propagation, we have decided to give these paragraphs a new subsection titled “*Describing the depth dependence*”.

L320: I think that this is a little deceptive—the azimuthal orientation of a core is not retained but the elevation angle is generally known.

While still potentially of interest, the statement as given was indeed not detailed enough, nor is it actually vital to the rest of the manuscript. The sentence has been removed.

L533 and 570, maybe elsewhere: 2 and 3 should be subscripts on the eigenvalues

This has been fixed.

L659: second clause has no subject

This has been fixed.