Review of *'Evolution of crystallographic preferred orientations of ice sheared to high strains by equal-channel angular pressing'*

TC manuscript egusphere-2024-331

Summary

This study adapts the method of equal-channel angular pressing (ECAP), previously used primarily to study the plastic deformation of metals and alloys, to understand the development of crystal-preferred orientation (CPO) in ice experiencing high strains. The authors generate artificial polycrystalline ice and perform deformation tests at -5 °C. Repeated deformation of the same ice samples allows them to reach higher shear strains, resulting in six analysis samples with equivalent strains ranging from 0.6 to 3.6 in 0.6 increments.

They analyze the samples with cryo-electron backscatter diffraction to obtain c-axes distributions, grain size, and shape. They find that all samples result in two clusters of c-axes, and while one strengthens with increasing strain, the other seems to disappear. At the same time, the angle between the clusters remains unaffected by strain. Based on these observations and a fabric evolution model, the authors suggest that the combined effects of lattice rotation due to dislocation slip and grain growth by strain-induced grain boundary migration can explain the CPO patterns. They conclude that grain-boundary migration becomes progressively less important with increasing strain and that single-cluster fabrics can be generated with high-strain experiments.

I believe this paper is a valuable and relevant contribution to the current understanding of CPO development in ice and other anisotropic materials on Earth and in the Solar System. The manuscript is of good quality and lies well within the scope of The Cryosphere. The text is well written and nicely illustrated with comprehensive figures and photos documenting the experimental process. Although I am not an expert in deformation experiments, I find the methods used sound and well explained for the general reader of The Cryosphere. I, therefore, recommend this article for publication with minor revisions.

This review is structured into general, specific line-by-line, and technical comments. Suggested text edits or quotes are marked in blue, and changes are tracked with strikethrough and italic font.

General Comments

Structure & Text Fluidity:

In general, the text is well written and well-supported by references. However, it seems as if different sections were written by different authors, resulting in some repetition and a lack of logical order. Long, complex sentences could be simplified and broken down to improve readability, particularly in

Sections 1, 2 and 4. The introduction could benefit from a more structured flow, guiding the reader through the background, problem statement, and research significance in a clearer sequence. Some sections could be more specific about the gaps in current research and how this study addresses them. The discussion could be condensed and sentences shortened/simplified. Additionally, it would be helpful to clearly distinguish between the results and conclusions of this study and what is known from previous work.

The structure of the manuscript in sections and subsections seems logical. However, in some areas, these sections mix together. For example, lines 62-70 in the introduction describe the ECAP method in detail, including a reference to Figure 1, which should be part of the methods (e.g., before section 2.1).

Lines 156-183 are difficult to read and repetitive. For example, the orientation data is mentioned three times as being analyzed with the MTEX toolbox: lines 158, 171, and 174. It is also described twice how individual graphite particles can't be detected with EDS: lines 168 and 170. Shortening and simplifying this section would improve readability. The text also jumps between analysis methods and datasets, which is confusing.

See my specific comments for suggested edits at specific lines.

Processes Affecting CPO Development:

In the introduction, I would have liked to see a paragraph focusing on the individual processes affecting CPO and under what conditions they are relevant. You describe (lines 39-41) that "the dominant mechanism for CPO formation changes from grain boundary migration (GBM) to lattice rotation and subgrain rotation (polygonization), with increasing stress, increasing strain or decreasing temperature (Qi et al., 2019; Fan et al., 2020)." However, you do not explain how these processes work. This is somewhat done in Section 4.7 (lines 405-408) and later in that section, as well as in Fig. 12a, but it would be very helpful to have an overview of these processes already in the introduction.

SpecCAF Model:

It is unclear what role the modeling actually plays here. In the methods, you spend some time explaining the SpecCAF model and how you "re-used" the model by Richards et al. (2021), but lack details of how exactly that modeling was done (i.e., parameterization, initial conditions, or what values of β you used, etc.). This makes it seem as if you did simulations in the context of this study. However, no modeling results are shown or mentioned anywhere in the results. The only place modeling results are mentioned is in the discussion, and in Fig. 11 where "outcomes from a recently published numerical model by Richards et al. (2021) are plotted." You should be more clear about what you did in the context of this study and provide the details necessary to reproduce your results, and what is a result by Richards et al. (2021). For modeling done in the frame of this manuscript, its outcome should be shown before the discussion.

Implications:

In the introduction, you outline the broad relevance of CPO development for ice and mantle material on Earth as well as on other planetary bodies. However, the discussion and conclusion sections lack detail on how your work relates to these broader implications and in where this strong shear deformation at relatively warm temperatures used in your experiments is likely to occur in nature. For example, what are the implications of this study for CPO developments in shear margins of ice streams? It would also be helpful to have a brief discussion on limitations of this kind of experiment in representing conditions found in natural ice deformation (e.g. different timescales).

Axes Definition:

Somewhere in the manuscript, you should define a-axes, m-planes, and c-axes with their corresponding Miller indices. It is somewhat defined in line 250, but this is rather late. c-axes are defined in the introduction, so it would make sense for the other two being described there as well.

Specific comments

line 4: To examine the impact of strain *on the relative importance of these two mechanisms,* might be more clear.

line 20: *water* ice or *Ice Ih*.

line 20: '*the most common compound in the universe*' needs citation. Or leave out, I think this is redundant

line 21: satellites, (comma)

line 25-26: I find this sentence wordy and complex. Consider breaking it down to improve readability.

line 27: than on other slip planes (Duval et al., 1983); 0001 is defined as c-axis in line 46?

line 28: 'to ice' is unnecessary and can be omitted.

line 30: Omit 'subsequent'. Not clear what 'response' refers to in this sentence. I suggest rephrasing to something like:

When the stress field driving ice flow changes, the rate of ice deformation depends on the existing CPO and its evolution under the new stress configuration (Hudleston, 2015).

line 31: perhaps add gravitational forcing to the list?

line 34: For CPOs in ice sheets on Earth, radio-echo sounding (RES) is another widely used technique to derive CPOs. You could consider citing e.g.:

https://tc.copernicus.org/articles/16/1719/2022/
https://ieeexplore.ieee.org/document/8755860
https://tc.copernicus.org/articles/17/1097/2023/

line 37-39: What kind of 'transition' have been observed? change in the dominant mechanism for CPO deformation between different experiments? Or with time/increasing strain? Needs to be clarified.

line 42-45: long sentence, consider breaking it down:

While uni-axial compression tests are commonly used to study ice microstructural evolution during deformation, high-strain deformation in ice sheets and glaciers is mainly simple shear (Cuffey and Paterson, 2010). Therefore, understanding CPO evolution under shear is critical.

line 47-49: sentence seems a bit wordy. Suggestion:

The highest shear strain achieved in the lab, 2.6, was reported by Qi et al. (2019) at −30°C. Previous experiments at similar temperatures did not exceed shear strains of 0.12 (Wilson and Peternell, 2012).

line 50: ... cluster. Instead ... (break sentence here).

line 50: Not clear what gamma refers to. Please clarify.

line 49-52: I think this part is a bit confusing. I would suggest first stating that natural ice samples often experience shear strains larger than 5, which leads to the development of a single cluster of [0001] axes. Then go on and explain that this could so far not be reproduced by lab experiments, which even under strains larger than 2 fail to produce such a strong single maximum fabric.

line 53: single, primary cluster *evolving* at smaller...

line 55: omit '*simply*'

line 56: at higher strains

line 57: are needed.

line 59: move the alternative defintition one line up: *Equal-channel angular pressing (ECAP; also known as equal-channel angular extrusion) is a technique for generating severe plastic deformation, resulting in highly strained microstructures with ultra-fine grain sizes and strong fabric. ECAP was initially developed in the 1980s ...*

line 63: intersect at an angle Φ

line 79: it would be nice to have one sentence summarizing the most relevant findings and relevance of this study at the end of the introduction.

Fig. 1: - panel a): arrows are hard to see. Consider a zoom window with a close-up of the shear plane. Photos could be arranged so the load arrow in panel c is not cut off.

- panel b): TEC is not defined in caption.

- panel c)): LVDT is not defined. Processed sample (instead of Sample processed?)

- caption: Photos and dreawings *of* the ECAP apparatus.

- caption: both parts of *the* die are shown with a dummy sample in the channel (omit comma).

- caption: define abbreviations.

- caption: 'all passes are done without changing the orientation of the sample': how do you ensure the orientation is the same during the second deformation?

- panel c, d and caption: Thermistor misspelled (thermister)

line 85: change 'has' to 'have'

line 86: 'for more details please refer to Table 1' or 'more details can be found in Table 1'.

Table 1: I think it would be helpful to describe parameters ε' and φ in the caption.

line 90: This first sentence is not very informative. Remove and change the second sentence to:

'The ECAP die consists of two symmmetrical stainless-steel parts, as shown in Fig. 1a. '

line 92: The diameters of the channel and ice samples is 25 mm ~~along the channel, the same as the diameter of our ice samples~~.

line 92-93: perhaps use dash for 'mirror-finished'. The quotation marks seem strange here, I would simply remove it. Is the soap coating refreshed between experiments? Please clarify.

line 93: The channel *geometry* is defined by two angles

line 94: remove '(equal to 120° in Figure 1(a))' . Instead add '(see Fig. 1a)' at the end of the sentence.

Eq. (1) : I am confused on why strain here is expressed as ε and as ε' in Table 1. I also think it is strange to use '=' for the definition of Φ and '≈' for the definition of ψ. Can the angle ψ be determined less accurately or why is that? In addition to this equation, it might be helpful to state the relationship of the equivalent strain and the shear strain.

line 112-113: Once ~~the temperature of the die stabilized (typically 20 min), indicating~~ the sample temperature had equilibrated with the die *(typically after 20 min)*, a load was applied to the sample using dead weights hung on the aluminum profile

line 115-117: why is that? In some cases (ECAP_19, 21) the load of the second pass decreases by 5kg, while for others (ECAP_34, 38) it decreases by 10 kg and being stable for further passes. Please clarify.

line 116: for *a* single sample; (*for* more details

line 120-123: I think this sentence should be shortened/broken up and simplified.

Fig. 2: - caption: Drawings ~~describing~~ *illustrating* the accumulation of shear straine in a sample deformed from the i-th ~~pass~~ to the (i+2)-th pass *in side view*.

- general: In the case illustrated i=1, right? I am unsure of the generalization with *'i'* since the strain ellipse suggests it has not been deformed previously before pass *i*. I would suggest changing it to first, second, third pass and adding a comment in the bottom of the figure or the caption, stating that for further passes step 3 is repeated with adding additional ice to compensate the length.

line 124-133: This section sounds in parts as if it is a result, rather than experiment set-up or method. For example (line 125) ' indicating shearing' seems redundant when you are describing a shear deformation experiment. See my suggested edits below:

Upon passing through the channel, the sample's diameter ~~remained~~ *remains* unchanged, but the head and tail surfaces ~~were~~ *are* no longer perpendicular to the cylindrical axis~~, indicating shearing~~ (see Figures 2 and 3). *In preparation for additional passes* ~~Subsequently~~, the head and tail surfaces were trimmed ~~flat and parallel~~, restoring the sample's ~~original~~ *cylindrical* shape ~~except for~~ *with* a reduced length *compared to the original sample* (Figure 2). The sample can be reinserted into the channel with the same orientation relative to the corner and deformed again. ~~If the~~ *For* samples ~~became~~ *becoming* shorter than 50 mm, an additional piece *of ice*~~(which won't be analyzed)~~ was added ~~in the channel~~ to achieve the required length *but this extra ice was not considered in the analysis* (Figure 2). This process allows for multiple passes through the channel, accumulating high strains. After reaching the target number of passes, the *samples* ~~was~~ *were* wrapped in aluminum foil and stored in liquid nitrogen. Note that during an experiment, the head part of the sample ~~was~~ *is* exposed to air, while the tail part ~~was~~ *is* deformed in the corner, causing more sublimation in the head part. ~~As a result, the head part was not ideal for microstructural analysis. Instead, the middle part near the tail was used for analysis in the next subsection.~~ *To avoid sublimation bias, we used the middle part near the tail for microstructural analysis.*

line 126-127: How do you ensure that the orientation is preserved? Is it marked by something? Please clarify.

line 128-129: Where is the additional piece of ice added? From Fig. 2 it looks as if it is added at the tail. Since the head part is more prone to be affected by sublimation, why not add this piece at the head? Maybe it is, but please clarify here in the text and mark head and tail in Fig. 2.

line 134-135: To investigate the effect of annealing on pre-existing CPO~~, after ECAP deformation experiment,~~ one sample was annealed at −3.5◦ C for 24 days *after ECAP deformation*. The annealing experiment was done using a similar apparatus described in Fan et al. (2023).

Can you state which of the samples in Table 1 that is?

Fig. 3: - panel c & d): It would be good to have an approximate scale on these photos too. Abbreviation SEM in panel d) needs to be defined in caption.

- caption: Illustration for a sample deformed and prepared for microstructural analysis. ~~In each panel, a drawing is on top and a photo is at bottom.~~ (a) Starting sample before deformation. (b) Sample deformed by ECAP. (c) Sample cut along profile plane. (d) Sample polished and mounted on a copper ingot for analysis. Note that the ~~sample is ice + graphite, so the color is black.~~ *black color stems from graphite powder added to the ice samples.*

line 139: why is sample storage so cold and for how long? Do temperature changes from -5 to -190/-120 to -10 degrees not affect your analysis?

line 140: I think it would be helpful to be more specific here on how the cut is oriented relative to the shear plane. Alternatively, define what you mean with 'profile plane' and indicate in Fig. 1.

How thick is this 'section'?

line 145-146: ~~'To prevent graphite from covering the polished surface, the surface was not polished to high grit sizes that were used for pure water ice (Prior et al., 2015).~~

I don't think this sentence adds much information as it stands now.

line 152: It would be helpful to state the approximate sample size here or somewhere else. Were they all cut to the same size?

line 154: Subsequently, carbon element data were obtained from EDS ~~in the~~ *for the* same *selected* regions with a step size ranging from 3.2 to 6.7 μm. (assuming this is only done for regions with step size of 15 micrometer. Else please clarify)

line 156: I think the first sentence is redundant. Rather than describing what you didn't do, simply describe what you did.

Orientation data obtained from diffraction data with a step size of 30 μm ~~were not processed for extrapolation of unindexed points. These sets of data~~ were used for analyzing the CPO patterns.

line 157-158: Here you say that 15 micrometer data is analyzed with MTEX. In line 176 you mention that 30 micrometer data is analyzed with MTEX toolbox. Why not generalize this in one sentence in the beginning of the paragraph in something like ' We used the MTEX MATLAB toolbox (citations) to process orientation data' or similar.

line 166-167: To match the dimensions of the EBSD data, the pixel size of *the* EDS map was adjusted to match the step size of *the* EBSD. Then these pixels were attributed to *the* graphite phase in *the* EBSD data.

line 168: ~~Combine~~ *By combining* the EBSD data from ice and graphite, a data set with two phases was obtained (Figure 4(e)).

line 168-169: Note that this method cannot identify individual graphite particles, but only ~~revealed~~ *reveals* graphite-rich regions. (mixed tense)

line 169-170: Repeat of previous sentence.

line 171-172: Not very clear what you're doing here. Are you really 'reconstructing grains? Do you mean you locate grain boundaries by looking for orientation changes between pixels of more than 10 degrees? Please clarify.

line 177-179: consider splitting this sentence in two.

line 181-183: We adopted the same method *for cluster identification* used previously in Qi et al. (2019)*, where t*~~T~~he normalized counts of data per orientation in the profile plane were plotted on a histogram. φ was defined as ~~that~~ *the angular width* between the two peaks on the histogram.

line 183: reference to Fig. 7d?

line 185: ~~This~~ *The observed* CPOs were compared to predictions from the *spectral continuum anisotropic fabric evolution (*SpecCAF*)* model (Richards et al., 2021).

line 186: The SpecCAF model cannot directly simulate microstructural *changes* ~~that can be achieved by~~ *like* other models, e.g., ELLE, (Jessell et al., 2001).

line 185-189: I think these section is confusing and should be clarified by being more specific of how 'microstructural processes' are simulated differently between these models. 'The evolution of CPO' which 'SpecCAF simulates' could also be interpreted as 'simulating microstructural changes'.
It could also be mentioned that in contrast to more complex models, such as ELLE, SpecCAF is computationally more effective and more suitable for large-scale CPO modeling.

line 192: The numerical model was ~~the same as those reported in~~ *adapted from* Richards et al. (2021), producing simulated pole figures *representing the distribution of c-axis orientation*, and the angle, φ, *describing the angular distance between clusters.*

line 193: 'φ was compared to model predictions with a variety of β = kβ0 values': I don't understand this. Do you mean experimentally observed φ were compared to modelled? Or do you mean φ was tuned to observations by adjusting β? Either way, needs clarification.

line 195: How many, and in what increments?

Fig. 4: - title of panel c): Combine*d* pixels - combined pixels of what? panel (a) and (b)?

- caption: The caption reads in part as instructions, rather than a description of what is shown. I find the description of panel e) especially confusing ((e) Knowing the coordinates of graphite from (c), create “EBSD” data of graphite. Combine the ice phase and the graphite phase.) Suggested edits:

The example ~~used~~ *shown* here is sample ECAP_38_6P.

(c) Combine*d* pixels so that the pixel size is the same as the *15 μm* step size of *the* EBSD data.~~, which is 15 μm.~~

(e)~~ Knowing the coordinates of graphite from (c),~~ Create*d* “EBSD” data of graphite, *informed by the graphite coordinates in (c), and combined with* ~~Combine~~ the ice phase *in (d)*. ~~and the graphite phase.~~

(f) Denoise*d* ~~the~~ data with grain boundaries tracked by the MTEX toolbox. ~~and reconstruct grains with MTEX toolbox.~~ Note that by this method, the identified graphite phase represents the upper limit of the area fraction of the graphite.

line 198: The ice microstructure of the starting materials was similar in character to that described in ~~(~~*Qi et al., (2017).*

Fig. 5: - panel labels would be helpful.

- colorbar: I would suggest adjusting the colorbar for the stereoplots to range from 0 to 1.6 and add at least one more number between to indicate that it is linear (e.g. 0,0.8,1.6)

- it might be helpful to indicate that [0001] is the c-axis, and [1120] and [1010] are axes in the basal plane of the crystal here.

- the subgrain boundaries look almost white and are hard to see - use a darker gray for better visibility.

- labels of IPF-Y colorscale are very small

- y-axis in caption is undefined. Is it vertical to the sample cut? Please clarify.

- caption: Microstructural analyses of an undeformed ice ~~samples~~ *sample*.

'The grain-size data are calculated from a larger area' - larger than what? how large, and is it the same size for all samples?

', ~~with consisting of~~ 791 grains *in this sample*.'

line 201: ~~rather~~ (better say how much smaller)

line 208: I think you mean the temperature is lower by 0.5°C. Better state -5.5°C to be more clear.

line 214-215: I don't think this is true for ECAP_21 and ECAP_34, while we don't know for ECAP_33. Given that this is only true for 2 out of 5 samples, can you really say that the first pass is 'generally much slower' ?

line 215-227: This section could be shortened and streamlined. Line 215-220 seems more relevant for the discussion, rather than results

Fig. 6: - panel a): increase line thickness in the legend - it is hard to see the colors in such thin lines. A very minor detail: why are the colors in panel (a) in pastel/different from (b) and (c) when denoting the same thing? (same comments for Fig. A1).

- I would adjust the y-axis to min/max achieved temperatures to increase visibility in panel (a)

- green and red lines might be hard to be distinguished by colorblind people.

- panel (c), y-label: *Equivalent nominal strain, ε'*

Fig. 7: - caption: The contours on the stereonets are colored by MUD, values of which ~~are indicated in the color bar at the bottom of the figure.~~ range from 0 to the maximum value indicated on top left of each stereonet.

- panel c): I think the maximum value of the colormap should also be stated here. Please state in the caption how the shear direction is now (from top to bottom? or left to right?). It seems as this has been tried to be indicated by the gray figure on top of panel c, but should be complemented by a unambiguous description.

Fig. 8: - panel labels are missing.

- a legend in each panel would be helpful to see what the plots show faster.

Fig. 9: - why not add the annealed sample to the legend too?

- additional math symbol in x-label would help for faster comparison with e.g. fig. 7, Table 1 and text.

line 257-262: I'm not sure this belongs to 'results'. Since you already have a section in the discussion (4.2) dedicated to the effect of graphite, I would suggest moving this to 4.2.

line 264: more *frequent* in the samples

line 266: deformed ~~to~~ *by* 1-~~to~~-3 passes

line 267: deformed ~~to~~ *by* 4-6 passes

line 270: The distribution of *grain* aspect ratios (I assume? Should be clearly distinguished from cluster aspect ratio) line 270: deformed ~~to~~ *by* 2~~-to-~~6 passes (as above. Notation doesn't matter, but should be consistent).

line 278: multi-pass *samples*

line 280-282: This overview of the discussion sections is very helpful. I suggest using section names to be more specific. I think you should also mention what section 4.3 and 4.7 is about

line 298-299: I think this sentence is redundant: ~~Here, we explore the influence of cyclic annealing on the evolution of CPO during subsequent ECAP passes.~~

line 310: I believe en dashes are used for ranges

line 321-324: repetitive

line 335-340: I suggest mentioning the names and location of the glaciers for natural samples instead of 'a glacier'. For example: Thomas et al. (2021) found a roughly round c-axis cluster in the shear margin ~~of a~~ *Priestly G*lacier *in Antarctica*.

line 357: ~~as pointed out by Qi et al. (2019),~~

line 359: ~~The~~ T~~t~~wo recent studies

line 362-363: It is worth noting that under the same strain, the strength of the CPO in the sample deformed by ECAP is weaker than that in samples deformed continuously *due to effects of annealing discussed in Section 4.1.*

line 369: in *Qi et al. (2019)*

line 375: laboratory samples *from this study*.

line 385: is in good agreement with laboratory data *from this study,*

line 385-386: I'm not sure I understand this second part of the sentence. Do you mean: *and is possibly because the secondary cluster weakens with increasing strain, rather than moving towards the primary cluster. ?*

line 390: define FFT.

line 391-393: The SpecCAF model, incorporating recrystallization, lattice rotation and grain rotation processes, yielded excellent quantitative agreement in the CPOs ~~from~~ with experimental observations ~~and numerical models~~ (Richards et al., 2021).

line395-396: *see* Richards et al. (~~see~~ 2021))

line 408: ~~are~~ have to deform through slip

line 408-409: Is this really your hypothesis? In the introduction you state something similar in line

26-28: 'When deformed by dislocation glide, a single crystal of ice is several orders of magnitude weaker for slip on the basal plane, (0001), than on others (Duval et al., 1983).

need to be clear what is your results or hypothesis and what is known from earlier studies.

line 411: remove double parenthesis around Figure 12(c); check hyphenation in higher-Schmid and lower-Schmid factors

line 429-430: awkward sentence

line 435: ~~Such that~~ *Consequently,* ?

line 430: secondary *clusters*

line 461: We thank ~~to~~ Prof. Jianhua Rao for his help with designing the ECAP die.

Fig. 10: -panel a): I suggest adding the IPF-Y colorbar here as well, else readers have to jump between this Figure and Fig. 5. I would also indicate the shear direction on these figures

- do you have an explanation for why grain size increases in 3p compared to undeformed?

- panel d): legend for red and gray lines?

Fig. 11: - caption: unclear what 'simple models' and 'numerical models' are. What model has been used (reference). Are these both results done in this study or obtaine previously? It is also not clear if 'Model from R21' is a result you obtained in this study or if it was obtained by Richards et al., 2021. Please clarify.

- 'Since the nominal shear strains in this study cannot be directly compared with those in previous experimental studies, a range of φ is marked by a shaded box in the plot, independent of strain.' - I don't understand how this is more helpful than simply plotting your datapoints, and discuss why they differ from e.g. models in the text.

- 'Data *points* at a~~n~~ nominal equivalent strain of 3.6 can be treated as a single c-axis cluster, but a disappearing secondary cluster can still be identified, which gives a value of φ, marked by a shaded marker' - I don't understand this either. Where is this shaded marker? Is this still referring to the results from this study?

- Experimental data are from *the following studies* ~~follows~~:

- three markers (M21, H77 and T21) were placed at the right end of the x-axis suggesting that their *shear* strains are larger than 7.

- Outcomes from a recent*ly* published numerical model by Richards et al. (2021) are marked by colored thick lines.

- The termination of these curves suggests that a single-cluster fabric forms. - unclear what this means. Are you saying that for lines ending before nominal strain of 4 was reached have already developed a single-cluster? Isn't it strange that e.g. for β=0.5βo two clusters develop, separated by 58 degrees and abruptly turn into a single cluster fabric?

Fig. 12: - this figure is almost identical to Fig. 10 in Qi et al., (2019) and should be cited as 'adapted from Qi et al.,(2019)' or similar in the caption.

- panel labels are different from other figures. I think The Cryosphere asks for (a) instead of **a.**

- panel a is a very useful overview. In my opinion this could also be a figure for the introduction, explaining these individual processes and how they work. Whether you move this (part of the) figure or reference it in the introduction is up to you.

- panel d): again it is not clear where these model results come from and how they were obtained.

Fig. A1: - typo in all panels for the temperature panel y-axis
- increase line thickness in legend for temperature plots and adjust y-axis for better visibility.

Technical comments

1. Most citations are lacking a doi.
2. Figure references are usually abbreviated as Fig. 1. Figure is used only in the beginning of sentences (see TC author guidelines https://www.the-cryosphere.net/submission.html)
3. You often use red-green lines in plots - beware colorblindness
4. I think the bullet points in the conclusion are redundant. You can just remove them and write it as continuous text.