Response to RC 1 of 'Mapping age and basal conditions of ice in the Dome Fuji region, Antarctica, by combining radar internal layer stratigraphy and flow modeling' (tc-2023-35)

May 4, 2023

The paper provides an assessment of the distribution of ice that meets the targets of the International Partnerships in Ice Core Science "Oldest Ice Challenge" using a kinematic approach inverting observed englacial isochrons dated using an ice core pinning point for the deep age structure of the ice sheet. This 1-D approach (specifically IsoInv) has been primarily used for the Dome C region, and stands in contrast to 1D thermodynamic approaches that balance both mass and heat through latent heat (eg van Liefferinge et al., 2014, 2018), and 3D full stokes modeling. The approaches are complementary, with their strengths and weaknesses - thermodynamic approaches have to deal with the tremendous uncertainty in the value of geothermal heat flux, while attaining the deep dated isochrons needed for IsoInv is fraught and the computational cost and rheological and boundary condition uncertainties for 3D approaches limit their usefulness.
This paper represents an overall readable contribution to the literature on old ice distribution modeling. I don't have fundamental problems with the conclusion. Aspects of the presentation and discussion would benefit from being made clearer.

We thank Anonymous Referee #1 for taking the time and effort to provide us with the helpful comments. We believe the manuscript will be improved by following these comments. We have discussed on all the comments from referee and will respond to all of them in order. For clear tracking of changes, individual issues raised by the referees are referred to as (**Revision I**) below, where "I" is the number of the comment in the attached table.

Major points:
Gray literature: *The paper does lean on preprints somewhat. The study by Chung et al., submitted is obviously highly coupled with many of the same authors - one would anticipate that the methods this paper refers to will not change greatly, but there is a risk. A larger issue is the pointers to the preprint by Obase et al. 2022, looking at complementary thermodynamic modeling where the reviews indicate that there was an error in the calculation of the basal thermal gradient. Presumably this is addressed in the final accepted (but not yet published) version of that paper. While the Obase paper is obviously very complementary, the Wang paper should either drop the explicit comparisons, or at least provide some caveats on that comparison.*

We thank the reviewer for pointing out the gray literatures.

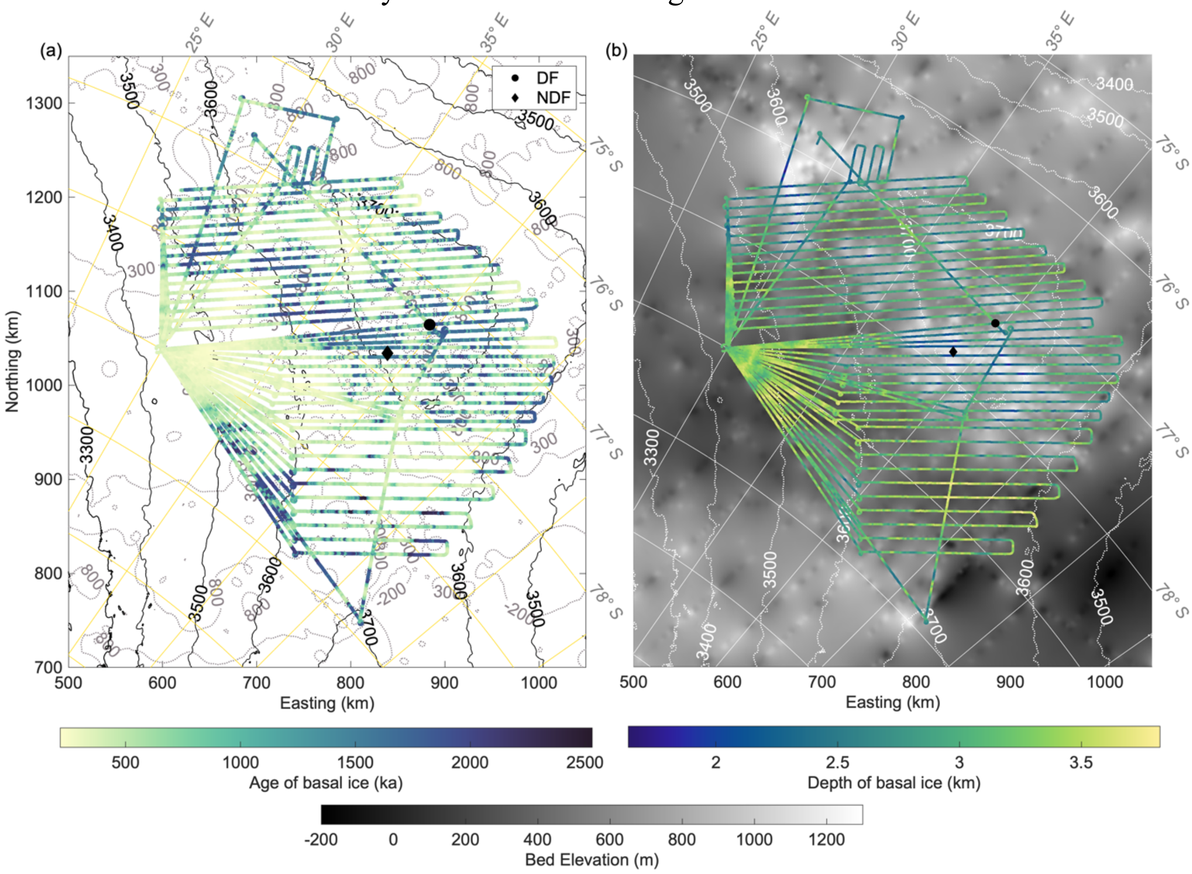
- The study by Chung et al. (2023, in review) is our companion manuscript, the IsoInv model was used in both studies, and Chung et al. (2023, in review) gave a detailed description of the model in their manuscript submitted. In our manuscript, we cited their research for either directing people who is more interested in the model towards their study (Line 69 and Line 162) or compare the basal thermal state (Line 257) and model reliability in the DF and DC region (Line 267). Nevertheless, regarding the gray literature issue, we will add further details of the model, i.e., the optimization algorithm in the Method section. Therefore we can make this part more independent from our companion research. **(Revision 1)**
- As the reviewer has pointed out, the Obase et al. (2022, in review) paper is very complementary by using a 1D temperature and age model which takes geothermal

heat flux into account. We will keep the comparison in our manuscript for the time being and point out the caveats **(Revision 2)**. We will rephrase the comparison in our manuscript depending on the final state of the Obase et al. (2022, in review) manuscript in case our manuscript is accepted before theirs is finally published.

Figures: *The maps are hard to read, especially at printed scale. I recommend removing the greyscale DEM bed elevation background and using some well spaced contours instead in a different color than the surface contours. Increasing the plotted point size of the data point may also help make the ideas conveyed more visible. The authors discuss specific candidate old ice sites in the text - they should indicate them on at least one of the maps. The indicators for DF and NDF are hard to make out at printed scale. More specific points are below.*

Thanks for the suggestions on figures. We follow the suggestions and replot the Fig 1, 4, 5, 6. **(Revision 3, 4, 5, 6)**

- We replace the gray scale bed elevation background with colored contours with different line style in Figure 4a. We haven't adapted this change to other figures yet since we found the corrected one seems less readable. We put the new Figure 4 here as the example, the left one use the contour to replace the gray background. It is very difficult to be concise and at the same time be very inclusive and take into account the needs of colour blind people. We tried to to that but at a certain point a limit is reached. Here we would kindly ask the reviewer for guidance.



- We will increase the size of data points.
- We will add four ellipses to Fig. 5a (Modelled age of basal ice) to clarify the locations of old ice candidates. **(Revision 5)**
- We will increase the size of markers of DF and NDF in the figures.

Flank flow versus divide flow: *1-D models are really only appropriate where ice velocities are very low, as the authors point out, but the case they make for Dome F could be made better. They use the statistical spread of basal ice ages as a function of distance from key Dome points as an indicator for flank flow, but don't make their logic clear on why that should be the case. Isn't this statistical trend just a fractal distribution as you cover more and more area with expanding range from the dome? A map of ice flow velocity, or an indication of ice velocity on the maps would be helpful.*

We agree that 1D is appropriate where ice velocities are low. But how low? That's what we would like to illustrate with this analysis. As the distribution are normalized they should in principle be independent of ice depth and flank flow and thus overlap more strongly than if those regimes are included, where flank flow becomes more dominant. As we consider this a useful and simple illustration of the underlying logic, which we will make more clear in the revision, we can also consider to discard this analysis if the editor or reviewer consider it too far from the main case. We will provide a map with velocities in the revision. **(Revision 7)**

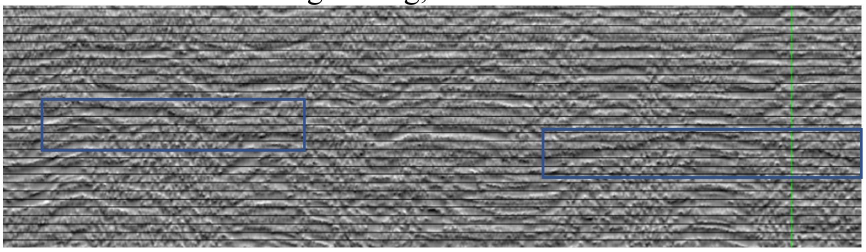
Age uncertainties of internal reflection horizons: *This was confusing. How are depth uncertainty, range precision and best guess uncertainty combined? Is range precision actually calculated from using the SNR? If so, where are the results (which should be different for each IRH).*

Sorry for the confusing description. People have used different methods to evaluate the uncertainty of horizon positions. Lilien et al. (2021) used quarter-wavelength uncertainty and Cavitte et al. (2016) use a concept of range estimate precision. In our research, we follow the latter method, because we want to involve the impact from sub-resolution of different horizons.

The range estimate precision in determining reflection depth is determined by the pulse width of the radar waveform, the signal-to-noise ratio and the sub-resolution reflector fluctuations. The last term could be ignored when the reflections have " continuality of reflection amplitudes and subsequent traceability" (Cavitte et al., 2016), but this is not the case in our study.

We use radar data collected by AWI RES system with 600 ns in this study, which means 50 m vertical resolution in the radargram. The resolution is lower than that of more advanced radar systems, which causes lower subsequent traceability. Moreover, the bedrock topography that is characterized by a series of mountain ranges and valleys and wide melting distribution in the Dome Fuji region, lead to the discontinuity of isochrones at some places, especially near the bottom. These reasons mentioned above could explain that we need to consider the sub-resolution of different reflectors.

We found that the uncertainty caused by the low traceability and continuity is actually large when we traced the horizons semi-automatically, which means we need to choose where to trace the horizons in the disturbed discontinuous places with a few possible trace routes. E.g., in the radar segment shown below, the horizon in the blue frames is easy to be traced, but between the frames, the stratigraphy is harder to follow and we need to interpolate it referring to the shape and pattern of other internal layers. This is a standard approach for instance also used in marine geophysics to interpolate stratigraphic boundaries. The uncertainty of different isochrones ranges from 20 m to 50 m for different horizons. We call it best-guess uncertainty, since it is also impacted by the signal-to-noise ratio (SNR) and resolution. As it is also larger than the range estimate precision calculated from the SNR and range resolution, we finally took it as the uncertainty of horizon positions. To conclude, the tracing process brought larger uncertainty with it mainly because of the resolution of radar system, compared to radar systems used in other research. This large uncertainty needs to be estimated for different horizons during tracing, and considered into the uncertainty part.



We will rephrase this part in a clearer way in revision. **(Revision 8)**

Stagnant Ice: *At Dome C the stagnant layer has a distinctive radar character. The authors should comment either if similar features are seen at Dome Fuji, or if the radars that have been used can even detect it.*

In the radar dataset we used, there is an echo free zone (EFZ) above the bed, with a thickness of several hundreds of meters. EFZ could be caused by a several reasons, e.g., system sensitivity of the radar system, deformation, recirculation and recrystallization of ice (Drews et al., 2009 and Franke et al., 2023). We think the EFZ in our dataset could be caused by the performance of the radar system, since in the same region more sophisticated radar systems can detect deeper signatures, as we have pointed out in our manuscript (L340), 'It implied that at the same depth modern systems would provide not only a higher resolution, but most likely also a deeper detection of continuous IRHs (Rodriguez-Morales et al., 2020).'

We will point it out in the section 4.2 when we discuss the basal thermal state and 4.3.4 when we discuss the limitation of radar system. **(Revision 9)**

Specific points:
Abstract line 6: *probably best to use 'basal unit' to replace 'basal layer' following on Lilien et al., 2021.*

Thank you, a reasonable suggestion. But since the term "basal unit" is defined in the radargram and "stagnant ice" is what we deduce from the model, we will use "stagnant ice" to replace "basal layer" here. **(Revision 10)**

Line 26: *replace ''feasible' with 'useful'*

Done. **(Revision 11)**

Lines 37-39: *The Bo 2014 paper, with the 3-D model, is more of a point to the issue discussed above – they conclude that "Hence, with the observations available now, we cannot constrain the age of the basal ice well.". The 1.5 million year where the ice is not melting from their Figure 6 is an assumption used to drive their model thermodynamics, not a result.*

Thanks for pointing out the misunderstanding. We will change Line 36-39

"In the Dome A region, Sun et al. (2014) estimated ice age around Kunlun station by applying a three-dimensional, thermomechanically coupled full-Stokes model, which indicated that in the area without basal melting the ice age at 95 % depth could be limited to 1.5 Ma."
to
"In the Dome A region, Sun et al. (2014) estimated the age of ice around Kunlun station by applying a three-dimensional, thermomechanically coupled full-Stokes model assuming different geothermal flux and fabrics. They imposed a 1.5 Myr limit to the age solver, thus they did not get the actual age of the oldest ice, but the distribution of ice potentially older than maximum run time of their model." **(Revision 12)**

Lines 40-: *the paragraph starting at line 40 is very long and dense and could be broken up.*

Done. We will split the paragraph to two parts, the researches of the Dome Fuji ice core and in the large Dome Fuji region. In addition, we will also add the conclusions of the previous studies follow the suggestion from another reviewer. **(Revision 13)**

Line 56: *"on an airborne radar surveys" should be "on airborne radar surveys" or "on an airborne radar survey".*

Done. **(Revision 14)**

Line 89: *what is a 'two-dimension filter'?*

It is a particular filter in the software "Echos", which we use for analysis. Since the filter could be adapted to the radar data in both trace direction and time direction, it is called a 2D filter. This filter returns a weighted running average. It is summing up amplitudes at the same travel-time, which could remove the horizontal noise. We will change
"…a low-pass filter and a two-dimension filter are…"
to
"…a low-pass filter and a running average filter are…" **(Revision 15)**.

Line 98: *"in all survey lines, the third IRH H3 is" change to "in all survey lines, however the third IRH H3 is"*

Thanks for the comment, we realized that we have not expressed ourselves clearly enough in the text. We will modify Line 98
"We trace 6 or 7 relatively distinct and continuous IRHs (H1 – H7) in all survey lines, the third IRH H3 is not clear and continuous enough to be traced in some profiles"
to
"We trace 6 (H1, H2, H4 – H7) or 7 (H4 – H7) relatively distinct and continuous IRHs in the radar profiles, since the third IRH H3 is not clear and continuous enough to be traced in some profiles." **(Revision 16)**

Line 128: *"The estimate of the range precision is always higher than the resolution" - the numerical value for precision should be smaller than the resolution for a well behaved echo waveform; I would not use the term "larger" to mean "better". maybe finer verse courser?*

Thanks, we will change
"The estimate of the range precision is always higher than the resolution"

to
"The estimate of the range precision is always numerically smaller than the vertical resolution". **(Revision 17)**

Line 264: *for lazy readers who skip the methods, I would add "We show the reliability index (described in section 2.4)"*

Done. **(Revision 18)**

Data availability: *It would be good to get the IRH data at least in a repository prior to acceptance. Technical issues with getting the radar data are more understandable, but we should as a community be moving toward getting that as well. For the ice thickness product used for the modeling, would it be more appropriate to point to the Eisen et al., 2020 (https://doi.org/10.1594/PANGAEA.920234) product for the line-based data?*

We submitted the IRH data to Pangaea before submitting the manuscript, it took some time to be published and get the registered doi. The data is now available on https://doi.org/10.1594/PANGAEA.958462.

The ice thickness product is provided by Karlsson et al., 2018 (https://doi.pangaea.de/10.1594/PANGAEA.891323). In section 2.2 Line 99, after "Ice–bed returns were picked by Karlsson et al. (2018) through semi-automatic detection routines in MATLAB" we will add "This ice thickness data is available on PANGAEA (Karlsson et al., 2018)". **(Revision 19)**

Figure 1: *While Greene et al., 2017 should be cited if AMT was used for these plots, Greene et al is not an appropriate citation for the surface elevation data. AMT provides at least 3 different surface DEMs for Antarctica, and this paper should reference the one ultimately used.*

We have used the BedMachine plugin in AMT to plot the figure. The BedMachine data has two references, one is a data product, one is a data paper. We will adjust the citations from
"… from Greene et al. (2017) and Morlighem et al. (2017, 2020) …"
to
"… from Morlighem et al. (2020) and Morlighem (2022) ..." **(Revision 20)**

Figure 2: *what is the strong line at ~250 m depth?*

This is the radar blind zone below the surface reflection, due to saturation of the amplifier of the receive channels of the radar. The strong line is the bottom of this blind zone.

Figure 5: *gray polygons (the Van Liefferinge et al., 2018 data) on a gray scale map does not work well*

We will change the gray polygons to another color. **(Revision 5)**

Figure 6: *the patches of blue stagnant ice are nearly invisible in this rendition. It might be better to have a separate figure or indicate existence rather than thickness. The distribution with respect to lakes you have here is interesting with comparison to Dome C where we apparently have lakes under stagnant ice.*

We will increase the size of the scatters and combine the to make stagnant ice clearer **(Revision 6)**.
Sometimes there is basal melting underneath the basal unit, as the basal unit is advected from regions of thinner ice. We will consider this comment and compare the lakes distribution in Dome Fuji and Dome C. **(Revision 21)**

Figure 7: *it's very hard to tell what is going on with the overlapping color zones. Especially if one is color blind - STD and Run III could look identical.*

We will use different color to make figure more visible. **(Revision 22)**

References

Chung, A., Parrenin, F., Steinhage, D., Mulvaney, R., Martín, C., Cavitte, M. G. P., Lilien, D. A., Helm, V., Taylor, D., Gogineni, P., Ritz, C., Frezzotti, M., O'Neill, C., Miller, H., Dahl-Jensen, D., and Eisen, O. (2023): Stagnant ice and age modelling in the Dome C region, Antarctica, EGUsphere, 2023, 1–31.

Drews, R., Eisen, O., Weikusat, I., Kipfstuhl, S., Lambrecht, A., Steinhage, D., Wilhelms, F. and Miller, H. (2009): Layer disturbances and the radio-echo free zone in ice sheets, The Cryosphere, 3, pp. 195-203.

Franke, S., Gerber, T., Warren, C., Jansen, D., Eisen, O., & Dahl-Jensen, D. (2023). Investigating the radar response of englacial debris entrained basal ice units in East Antarctica using electromagnetic forward modelling. IEEE Transactions on Geoscience and Remote Sensing.

Obase, T., Abe-Ouchi, A., Saito, F., Tsutaki, S., Fujita, S., Kawamura, K., and Motoyama, H. (2022): A one-dimensional temperature and age modeling study for selecting the drill site of the oldest ice core around Dome Fuji, Antarctica, The Cryosphere Discussions, 2022, 1–24.

Rodriguez-Morales, F., Braaten, D., Mai, H. T., Paden, J., Gogineni, P., Yan, J.-B., Abe-Ouchi, A., Fujita, S., Kawamura, K., Tsutaki, S., et al. (2020): A Mobile, Multichannel, UWB Radar for Potential Ice Core Drill Site Identification in East Antarctica: Development and First Results, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13, 4836-4847.

Revision number	Reviewer	Position	Before	Rephrase	Revision		
1	1 2	Section 2.4			Add further details of the model		
2	1	Line 211			Add the caveats		
3	1 2	Figure 1				Change the contours color of the surface elevation.	
4	1 2	Figure 4			We increase the size of data points. We increase the size of markers of DF and NDF in the figure. We give the values of colorbars at start and end. We put the ticks outside the color bar to see them clearly.	We replace the gray scale bed elevation background with colored contours with different line style (only in Fig. 4a, test).	
5	1 2	Figure 5				Add ellipses to show the old ice sites.	Change gray polygon to another color.
6	1 2	Figure 6				Make stagnant ice clearer.	
7	1	Flank flow			Rephrase this part and provide velocity map		
8	1 2	Section 2.3			We rephrase this part in a clearer way in revision.		
9	1 2	Section 4.2/4.3.4			We point out the limitation of radar system, i.e., basal unit couldn't be observed in the radargrams.		
10	1	Line 6	basal layer	stagnant ice			
11	1	Line 26	feasible	useful			
12	1 2	Line 37-39	In the Dome A region, Sun et al. (2014) estimated ice age around Kunlun station by applying a three dimensional, thermomechanically coupled full-Stokes model, which indicated that in the area without basal melting the ice age at 95 % depth could be limited to 1.5 Ma.	In the Dome A region, Sun et al. (2014) estimated ice age around Kunlun station by applying a three-dimensional, thermomechanically coupled full-Stokes model assuming different geothermal flux and fabrics. They imposed a 1.5 Myr limit to the age solver, thus they didn't get the actual age of the oldest ice, but the distribution of ice potentially older than maximum run time.			
13	1 2	Line 56-	…Karlsson et al. (2018) presented an updated subglacial topography…	… In the large DF area, Karlsson et al. (2018) presented an updated subglacial topography…	Start a paragraph about the researches in the large Dome Fuji region. Add the conclusions of the previous studies.		
14	1	Line 56	…based on an airborne radar surveys…	…based on airborne radar surveys…			
15	1 2	Line 89	...two-dimension filter...	…running average filter…			
16	1	Line 98	We trace 6 or 7 relatively distinct and continuous IRHs (H1--H7) in all survey lines, the third IRH H3 is not clear and continuous enough to be traced in some profiles	We trace 6 (H1, H2, H4 – H7) or 7 (H4 – H7) relatively distinct and continuous IRHs in the radar profiles, since the third IRH H3 is not clear and continuous enough to be traced in some profiles			
17	1	Line 128	The estimate of the range precision is always higher than the resolution	The estimate of the range precision is always numerically smaller than the vertical resolution			
18	1	Line 264	…We show the reliability index in the…	… We show the reliability index (described in section 2.4) in the…			
19	1	Line 99		Add "This ice thickness data is available on Pangaea (Karlsson et al., 2018)." after "…through semi-automatic detection routines in Matlab..."			
20	1 2	Figure 1 caption	...from Greene et al. (2017) and Morlighem et al. (2017, 2020) ...examplary…	from Morlighem et al. (2020) and Morlighem (2022) ...example…			
21	1	Section 3.3			Compare the lakes distribution with DC.		
22	1	Figure 7			Use different color to make it clearer.		
23	2	Figure 4d			Add figure of age of ice at the depth of 250 m above the bed in results.		
24	2	Section 4.3.3			Rewrite this section.		
25	2	Conclusion			Make it more conclusive		
26	2	Figure 3			We give the values of colorbars at start and end. We put the ticks outside the color bar to see them clearly.		
27	2	Grammer			Revise carefully.		
28	2	Line 26	basal layer	deep ice records			
29	2	Line 70	a (potentially stagnant) basal layer	the stagnant ice			
30	2	Line 153	..there is a basal layer of stagnant ice…	...there is stagnant ice…			
31	2	Line 367	basal layer	bottommost part			
32	2	Figure 4c			Add age uncertainty of basal ice as c in the figure.		
33	2	Line 224			Rephrase the paragraph to show the importance of addiing the comparison with the previous work.		
34	2	Line 39			Add the reference Beem et al., 2021.		
35	2	Line 82	The AWI RES system transmits radar waves with a center frequency of 150 MHz and an amplitude of 1.6 kW	The AWI RES system transmits radar waves with a center frequency of 150 MHz, a band width of 20 MHz and an amplitude of 1.6 kW			
36	2	Figure 2			Remove the black lines. Use plus/minus to replace parenthesis.		
37	2	Line 140			State how accumulation is inferred for ages that predate the oldest ice in the core.		
38	2	Line 141	inverted	inferred			
39	2	Line 147	where H_m is the mechanical ice thickness, which means the effective ice thickness above the stagnant ice, and p is a shape factor controlling vertical deformation (Lilien et al., 2021)	where p is a shape factor controlling vertical deformation (Lilien et al., 2021), H_m is the mechanical ice thickness, which is different to the observed ice thickness H_{obs}, When H_m is greater than the observed ice thickness H_{obs}, we have melting conditions at the base. Otherwise, there is stagnant ice. If the basal ice is melting, the melt rate m can be obtained by…			
40	2	Line157/Fig 5 caption/Line 264/Line 265	reliability index	reliability index σR			
41	2	Line167/168	exemplary	example			
42	2	Line171	where the mechanical ice thickness Hm (purple dash line) is larger (deeper) than the observed ice thickness (black line)	where the mechanical ice thickness Hm is larger than the observed ice thickness			
43		Line 6	...do not exist, the basal thermal conditions, including the thickness of the stagnant ice surface accumulation rates	...do not exist, the surface accumulation rate and the basal thermal condition, including melt rate and the thickness of the stagnant ice.			
44		Line 99	Matlab	MATLAB			
45		Line 52	inverted	inferred			
46		Reference	Chung,A.,Parrenin,F.,Steinhage,D.,Mulvaney,R.,Martin,C.,Cavitte,M.,Lilien,D.,Helm,V.,Taylor,D.,Gogineni,P.,Ritz,C.,Frezzotti,M.,O'Neill,C.,Miller,H.,Dahl-Jensen,D.,andEisen,O.:StagnanticeandagemodellingintheDomeCregion,Antarctica,submitted.	Chung, A., Parrenin, F., Steinhage, D., Mulvaney, R., Martín, C., Cavitte, M. G. P., Lilien, D. A., Helm, V., Taylor, D., Gogineni, P., Ritz, C., Frezzotti, M., O'Neill, C., Miller, H., Dahl-Jensen, D., and Eisen, O. (2023): Stagnant ice and age modelling in the Dome C region, Antarctica, EGUsphere, 2023, 1–31.			
47		Line 75	...BaslerBT-67aircraft…	...BaslerBT-67aircraft (Wesche et al., 2016)…			
48		Reference		Add reference: Wesche, C., Steinhage, D., and Nixdorf, U.: Polar aircraft Polar5 and Polar6 operated by the Alfred Wegener Institute, Journal of large-scale research facilities, 2, 1–7, 2016.			
49		All the orientations			All directions should be referring to true north, thus, we will add "grid" in front of all the words representing orientations, e.g., we will change Line 180 "to the north-west of the DF drill site" to "to the grid north-west of the DF drill site"		