Responses to Comments on the Manuscript:

"A new method of resolving annual precipitation for the past millennia from Tibetan ice cores"

(MS No.: tc-2021-115)

Many thanks for the reviewer's constructive comments. Below a point-to-point response to the comments. The comments are in black, and our response is in blue.

1 General Comments

Zhang et al. "A new method of resolving annual precipitation for the past millennia from Tibetan ice cores" presents a detailed study on the average accumulation rate for 3 epochs in the last 2500 years for an ice core site on the Chongce ice cap, northwestern Tibetan Plateau. The paper combines annual layer thickness data (from ultra-high resolution ice core elemental chemistry) with a flow thinning model (constrained by water-insoluble organic carbon ^{14}C ages) to determine local net accumulation over 3 disjoint epochs. The paper is well written and structured and generally presents sufficient supporting evidence. I recommend minor alterations and corrections detailed below.

2 Specific Comments

2.1 Major specific comment

The most significant problem with the manuscript as it stands is the data fit to the flow model presented in Figure 2 and associated text on P8 L228-229. In particular, it appears that all of the ^{14}C ages are above the nonlinear least squares data fit. This raises questions about the validity of the data fit and if the solution has converged. I would have expected at least some of the ^{14}C ages to be below the data fit. Specially, the data fit line can be moved upward and this would reduce the error at every observational data point, and hence the overall error of the fit. The authors need to verify that the data fit presented is indeed a (near) optimal fit, and redo the accumulation analysis if the data fit needs to be revised and improved.

Response: In this study, the depth-age relationship of the Chongce 135.81 m Core 2 was established by using a two-parameter (2p) model. The 2p model was first constrained by the ^{14}C calibrated ages, together with the β-activity reference horizon of the Chongce 58.82 m Core 3, located only ~ 2 meters apart (Hou et al., 2018; Pang et al., 2020). We found that by using these data only, the 2p model is poorly constrained at the deep section, and giving an estimate bottom age much older than the bottom age ($8.3 \pm _{3.6}^{6.2}$ ka B.P.) estimated for Core 4 (Hou et al., 2018). Therefore, we included the Core 4 bottom age to constrain the final 2p model. Due to its mathematical configuration to account for ice flow dynamics, the 2p model gives more weight to points at deeper sections. Therefore, the inclusion of the Core 4 bottom age (relatively younger than otherwise derived bottom age) pushes the curve towards the left (younger) of most ^{14}C dates. However, we believe this model gives the most reasonable results, compared with several other model fit based on different data combinations (Figure 1). The details of these model fits are provided as follows.

(1) all data (including β-activity peak of Core 3 and nine ^{14}C ages) (Fig. 1a).

Results: The derived annual accumulation rate of 137 ± 54 mm w.e./year is in good agreement with the value of 140 mm w.e./year based on the tritium horizon. But the model is poorly constrained in deeper sections: the derived age estimate at the depth of the deepest ^{14}C sample is $9.1 \pm _{4.0}^{7.2}$ ka B.P.. This is much older than the actual measured ^{14}C age of 6.3 ± 0.2 ka B.P. at that depth (Fig. 1a).

(2) all data (including β-activity peak of Core 3 and nine ^{14}C ages) and constant accumulation rate (140 m w.e./year) (Fig. 1b).

Results: The derived ice age at the bedrock is $30.7 \pm _{18.4}^{44.8}$ ka B.P., which is much older than the bottom age ($8.3 \pm _{3.6}^{6.2}$ ka B.P.) estimated for Core 4. In addition, the derived age estimate at the depth of the deepest ^{14}C sample

is $9.2 \pm^{6.0}_{3.6}$ ka B.P.. This is much older than the ^{14}C age of 6.3 ± 0.2 ka B.P. at that depth. (Fig. 1b).

(3) β-activity peak of Core 3 and oldest six ^{14}C ages (Fig. 1c).

Results: The derived ice age at the bedrock is $22.5 \pm^{34.8}_{13.8}$ ka B.P., which is much older than the bottom age $(8.3 \pm^{6.2}_{3.6}$ ka B.P.) estimated for Core 4. In addition, the derived accumulation (233 ± 104 mm w.e./year) deviates significantly from the β-activity based estimate (140 mm w.e./year) (Fig. 1c).

(4) β-activity peak of Core 3, oldest six ^{14}C ages, and constant accumulation rate (140 mm w.e./year) (Fig. 1d).

Results: The derived ice age at the bedrock is $50.1 \pm^{118.4}_{35.6}$ ka B.P., which is much older than the bottom age $(8.3 \pm^{6.2}_{3.6}$ ka B.P.) estimated for Core 4. In addition, the derived age estimate at the depth of the deepest ^{14}C sample is $9.6 \pm^{7.3}_{4.1}$ ka B.P.. This is much older than the ^{14}C age of 6.3 ± 0.2 ka B.P. at that depth (Fig. 1d).

(5) all data (including β-activity peak of Core 3 and nine ^{14}C ages) plus bedrock estimate from Core 4 (Hou et al., 2018) as an additional model input point (**the method used in this manuscript**) (Fig. 1e).

Results: The derived ice age at the bedrock is $9.0 \pm^{7.9}_{3.6}$ ka B.P., which is roughly consistent with the bottom age $(8.3 \pm^{6.2}_{3.6}$ ka B.P.) estimated for Core 4. The derived accumulation rate (103 ± 34 mm w.e./year) is in relative agreement with the β-activity based estimate (140 mm w.e./year). In addition, the modeled age at the depth of the deepest ^{14}C sample is now $5.2 \pm^{1.9}_{1.2}$ ka B.P. which, with the uncertainty range, is similar to the ^{14}C age of 6.3 ± 0.2 ka B.P. (Fig. 1e). We believe this model provides most reasonable results, and is therefore adopted for this paper.
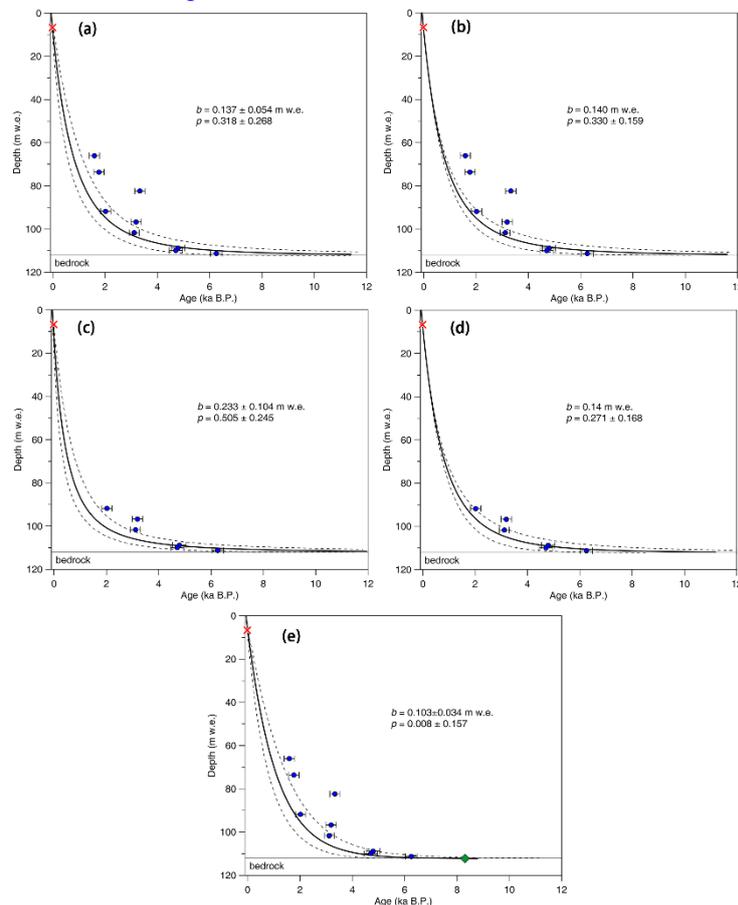

Fig.1. The depth-age relationship of the Chongce Core 2 based on the two-parameter model.

2.2 Minor specific comment

P2 L40 Is Christiansen and Ljungqvist (2017) the correct citation? This paper is about temperature reconstruction, and only mentions precipitation because of its influence on temperature reconstructions.

Response: We replaced this citation with Sun et al., 2018, which presented a comprehensive review of the data sources

and estimation methods of 30 currently available global precipitation data sets, including gauge-based, satellite-related, and reanalysis data sets.

P2 2nd paragraph. This needs a restructure, at the moment, the sentence topics are annual layers, thinning, annual layers then thinning again. Suggest you move the sentence starting "In addition, the nonlinear" to after the sentence starting "The most common approach". Then change "The thinning parameter" → "This thinning parameter".

Response: We agree with the reviewer, and have revised the sentence accordingly. The revised sentence is as follows; *The most common approach is to obtain annual-layer thickness based on the seasonal cycles of ice core parameters such as stable isotope ratio of oxygen in the water ($\delta^{18}O$), the concentration of major ions (e.g. Ca^{2+}, Mg^{2+}, NH_4^+, SO_4^{2-}), and the presence of melt layers (Thompson et al., 2018). In addition, the nonlinear thinning of annual layers caused by ice flow must be suitably constrained (Bolzan, 1985; Henderson et al., 2006; Roberts et al., 2015).*

P3 L80 I think the location map (Fig. S1) should be moved into the main manuscript, as this is key information.

Response: We agree with the reviewer, and have included the location map (Fig. S1) in the main text of the manuscript.

P5 Section 2.3 You do not give the vertical size of the samples required to give the 1kg sample, this is key information for the depth uncertainty estimate of the β-activity dating.

Response: We have given details on ice samples for β-activity measurements (Table S1) in the supporting information.

Table S1. Details on ice samples for β-activity measurements.

Sample #	Depth (m)	Depth (m w.e.)	Length (m)	Length (m w.e.)	β activity (dph kg^{-1})
1	0.000-0.710	0.000-0.406	0.710	0.406	555.1
2	0.710-1.150	0.406-0.771	0.440	0.365	936.5
3	1.150-1.720	0.771-1.253	0.570	0.482	597.9
4	1.720-2.185	1.253-1.648	0.465	0.395	499.2
5	2.185-2.575	1.648-1.981	0.390	0.333	505.6
6	2.575-2.945	1.981-2.297	0.370	0.316	539.1
7	2.945-3.355	2.297-2.648	0.410	0.351	416.7
8	3.355-3.890	2.648-3.110	0.535	0.462	518.4
9	3.890-4.350	3.110-3.504	0.460	0.393	396.1
10	4.350-4.805	3.504-3.889	0.455	0.385	439.4
11	4.805-5.270	3.889-4.288	0.465	0.399	1754.5
12	5.270-5.780	4.288-4.735	0.510	0.447	385.8
13	5.780-6.320	4.735-5.198	0.540	0.463	504.9
14	6.320-6.780	5.198-5.593	0.460	0.395	749.1
15	6.780-7.200	5.593-5.948	0.420	0.355	963.2
16	7.200-7.690	5.948-6.362	0.490	0.414	224.9
17	7.690-8.170	6.362-6.767	0.480	0.406	1709.9
18	8.170-8.630	6.767-7.158	0.460	0.390	1910.3
19	8.630-9.120	7.158-7.571	0.490	0.413	479.9
20	9.120-9.580	7.571-7.977	0.460	0.407	574.2
21	9.580-10.020	7.977-8.361	0.440	0.384	98.6
22	10.020-10.550	8.361-8.819	0.530	0.457	682.8
23	10.550-11.060	8.819-9.254	0.510	0.435	262.6

24	11.060-11.490	9.254-9.618	0.430	0.364	503.8
25	11.490-12.015	9.618-10.061	0.525	0.444	705.8
26	12.015-12.525	10.061-10.494	0.510	0.433	168.7
27	12.525-12.925	10.494-10.833	0.400	0.339	282.9
28	12.925-13.375	10.833-11.203	0.450	0.370	191.8
29	13.375-13.845	11.203-11.608	0.470	0.405	673.8
30	13.845-14.305	11.608-11.999	0.460	0.392	269.3
31	14.305-14.805	11.999-12.410	0.500	0.411	324.3

P5 L130 Was the Argon gas flow purged or was the system purged using Argon gas? If the later, suggest changing "whilst the Argon (Ar) gas flow was purged for two minutes" → "whilst the system was purged with Argon (Ar) gas for two minutes".

Response: We thank the reviewer for clarification, and have revised this sentence accordingly, as "whilst the system was purged with Argon (Ar) gas for two minutes".

P5 Section 2.4 you do not give the vertical size of the samples used for the ^{14}C extraction, this is key information for the uncertainty estimate of the ^{14}C dating, as there is uncertainty in both the age and depth.

Response: We have given the vertical size of the samples used for the ^{14}C extraction in the supporting information.

P6 L188-189 These grouped peaks could also be from independent snow events with dry wind blown dust deposition between these snow events.

Response: We agree with the reviewer, and have revised the text accordingly. The revised sentence is as follows;
These grouped peaks are interpreted as independent snow events with elevated element concentrations or with wind-blown dust deposition between these snow events.

P9 L241-242 Make it clear that you are using the values of "*b*" and "*p*" that you found in Section 3.2.

Response: We have revised this sentence as "where $L_{(Z)}$ is the modeled annual layer thickness (mm w.e.) for the average accumulation rate (*b*, i.e., 103 ± 34 mm w.e.) at the depth of *z* given the thinning parameter of *p* (i.e., 0.008).".

P10 L257 Change "can be securely stored" → "is preserved". In fact your density profiles (Fig. S6) suggest this for Core 2 and 3, which both lack the lower densities near the surface indicative of snow. I suggest you add a sentence at Line 258 making this point.

Response: Following the reviewer's comment, we have revised this sentence as "However, not all snowfall is preserved in high-elevation glaciers, due to wind scouring, snow drifting, and sublimation (Hardy et al., 2003). Moreover, firnification process might develop rapidly as indicated from the lack the lower density layers (indicative of snow) near the glacier surface (Fig. S6)".

P10 L265 You have presented all other accumulation rates as mm w.e./yr, suggest that you do the same for the Thompson et al (2006) results, to allow for easy comparison.

Response: We agree with the reviewer, but because the density profile of the Guliya ice core is not available (Thompson et al., 1995), we are not able to calculate the accumulation rate of the Guliya ice core as mm w.e./yr, but this comparison is still reasonable given the similar density for the periods of 1950-1989 A.D. and 1160-1169 A.D.

P10 L284-286 This statement is not correct. For example, an error in either the ^{14}C dating, or the flow model fit (see main

points above) will introduce an error in the flow thinning model, which due to its non-linear nature will result in different relative average accumulations over various epochs.

Response: We agree with the reviewer. For this reason, we deleted this statement in the revision.

P11 L295-299 In fact you already have 9 such markers from the ^{14}C age ties, which allow you to calculate the average accumulation rate over the 8 epochs these 9 makers define.

Response: This suggestion is theoretically possible, but we are not able to calculate the average accumulation rates over the 8 epochs between the 9 ^{14}C age ties because the errors of the ^{14}C ages cause overlaps of some ages.

Supp info, Figure 1b give details of where the remote sensing data is from, what is the instrument (e.g. optical, SAR) and give a data citation.

Response: We have included details about the remote sensing data, and provided a citation in the supporting information.

Supp info, Figure S8 Give details of which core (or cores) are being compared here.

Response: We have included details of the ice cores in the supporting information.

Supp info, Table S1 is the depth in meters water equivalent? Explain the difference between "^{14}C age" and "cal age".

Response: The depth in Table S2 is the measured depth in the field. For convenience of the readers, we also included the depth in meters water equivalent in the revision after taking account of the density profile.

Regarding "^{14}C age" and "cal age", "^{14}C age" denotes conventional radiocarbon age, which is calculated from the formula below:

$$t = -8033 \times \ln (Fs)$$

where t is conventional radiocarbon age, Fs is the ^{14}C / ^{12}C ratio of the sample divided by the same ratio of the modern standard. "cal age" denotes the calibrated age using OxCal v4.3 (Ramsey and Lee, 2013) with the Northern (IntCal13) calibration curve.

Table S2. Results of radiocabon measurements for the Chongce 135.81 m Core 2 ice core samples. For the calibrated calender year, ranges are given with 68.2% probality.

Sample #	Depth (m)	Depth (m w.e.)	Mass (g)	WIOC (µg)	F^{14}C	^{14}C age (ka B.P.)	Calibrated age (ka B.P.)
CC-1	79.46-80.21	65.74-66.31	307.7	20.3 ± 1.2	0.81 ± 0.01	1.679 ± 0.078	1.445-1.704
CC-2	88.82-89.56	73.31-73.92	302.9	24.3 ± 1.4	0.80 ± 0.01	1.831 ± 0.138	1.572-1.921
CC-3	99.44-100.10	82.12-82.65	304.6	13.8 ± 0.9	0.68 ± 0.01	3.133 ± 0.161	3.157-3.560
CC-4	110.58-111.35	91.48-92.10	342.6	24.9 ± 1.4	0.78 ± 0.01	2.037 ± 0.142	1.827-2.296
CC-5	116.62-117.43	96.39-97.05	330.9	9.1 ± 0.7	0.69 ± 0.01	3.012 ± 0.164	2.978-3.377
CC-6	122.64-123.36	101.40-101.98	338.6	17.6 ± 1.1	0.69 ± 0.01	2.944 ± 0.157	2.892-3.331
CC-7	131.41-132.10	108.54-109.12	324.6	22.6 ± 1.3	0.59 ± 0.01	4.228 ± 0.176	4.451-5.036
CC-8	132.65-133.51	109.59-110.31	392.7	23.6 ± 1.4	0.60 ± 0.01	4.169 ± 0.175	4.424-4.951
CC-9	134.31-135.03	110.98-111.59	292.4	23.0 ± 1.4	0.51 ± 0.01	5.466 ± 0.201	5.997-6.443

3 Technical corrections

P2 L34 Kidd and Hoffman 2011 do not say "most important" only "variable parameter associated with atmospheric circulation". Delete "most important".

Response: Correction has been made accordingly.

P2 L45 "glacier" → "glaciers".
Response: Change has been made accordingly.

P2 L45-47 It is possible to obtain accumulation rates at time-scales other than annual from ice-cores. Suggest changing "obtain reliable annual-layer thickness information"→"obtain reliable layer thickness information for the relevant times-scales (typically annual, but may be centennial for low temporal resolution sites or studies)".
Response: Change has been made accordingly.

P2 L48 You are not constraining the thinning, you are compensating for it, suggest changing "constrained" → "compensated for".
Response: Change has been made accordingly.

P2 L57 There are many more ice core records than just the citations you list, suggest changing "(Alley" → "(e.g., Alley"
Response: Change has been made accordingly.

P3 L62 Change "methods. e.g., the" → "methods, for example the".
Response: Change has been made accordingly.

P3 L64 Remove the full stop after "technology".
Response: Change has been made accordingly.

P3 L65 Maybe change "reveal" to "resolve".
Response: Change has been made accordingly.

P3 L69 Change "parameters" → "parameterisations"
Response: Change has been made accordingly.

P3 L77 Delete the word "parameter".
Response: Change has been made accordingly.

P3 L78 Change "record" → "records"
Response: Change has been made accordingly.

P4 L93 See comment above about moving Fig S1into the main manuscript.
Response: Change has been made accordingly.

P4 L96 Is there a citation for the statement that the local climate is "largely controlled by the mid-tropospheric westerlies"?
Response: Yes, we have added a citation (i.e., Pang et al. (2020)).

P4 L100 Given you have listed the summer (28%) and winter/spring (59%) precipitation percentages, also include for autumn (13%) rather than leave the reader to calculate this. Suggest changing "lowest amount of precipitation." → "lowest amount (13%) of precipitation."
Response: Change has been made accordingly.

P5 L145 There is some ambiguity about what you are removing the 3mm outer layer from, and while the reader can work it out, it is much better to make it easier for the reader to understand. Therefore, suggest changing "decontaminated the ^{14}C samples" $\rightarrow$ "decontaminated the ice for the ^{14}C samples".
Response: Change has been made accordingly.

P5 L147 The more common term is laminar flow "hood" rather than "box".
Response: Change has been made accordingly.

P6 L149 Delete "were"
Response: Change has been made accordingly.

P6 L153 Change "found in the previous studies (Uglietti et al., 2016)." $\rightarrow$ "found in Uglietti et al. (2016). ".
Response: Change has been made accordingly.

P6 S2.5 You talk about verifying your annual-layer identification using StratiCounter, but at this point in the manuscript you haven't described how you did your annual-layer identification. As this description comes later, suggest changing "To verify our annual-layer identifications" $\rightarrow$ "To verify our annual-layer identifications (see Section 3.1)".
Response: Change has been made accordingly.

P6 L166 While CCSM3 might have been "state-of-the-art" when this research was conducted (2006), this is no longer the case, with CCSM3 being replaced by CCSM4 in 2010. Suggest deleting "state-of-the-art".
Response: Change has been made accordingly.

P8 L208-209 Until this point your references have been in alphabetic order, so suggest you swap order of Rapp 2012 and Nye 1963.
Response: Change has been made accordingly.

P8 L225 Change "overweigh" $\rightarrow$ "over emphasise".
Response: Change has been made accordingly.

P9 L236 Change "of the Holocene" $\rightarrow$ "over the Holocene".
Response: Change has been made accordingly.

P9 L245 Change "The initial" $\rightarrow$ "The estimated original (pre-thinning)".
Response: Change has been made accordingly.

P13 L344 Change "Bronk Ramsey, C.," $\rightarrow$ "Ramsey, C. B.,".
Response: Change has been made accordingly.

P13 L350 Delete second, repeated "for large-scale temperature".
Response: Change has been made accordingly.

P15 L412 I don't think Parrenin et al 2004 is cited anywhere in the manuscript.

Response: We have deleted this citation in the revision.

P16 L443 I don't think Tang et al 2015 is cited anywhere in the manuscript.
Response: We have deleted this citation in the revision.

P17 L475 Change "sine" → "since".
Response: Change has been made accordingly.

Supp info, Figure S4 Change "The seasonal precipitation" → "Monthly precipitation".
Response: Change has been made accordingly.

References

Bolzan, J. F.: Ice flow at the Dome C ice divide based on a deep temperature profile, J. Geophys. Res., 90(D5), 8111–8124, https://doi.org/10.1029/JD090iD05p08111, 1985.

Hardy, D. R., Vuille, M., and Bradley, R. S.: Variability of snow accumulation and isotopic composition on Nevado Sajama, Bolivia. J. Geophys. Res, 108(D22), https://doi.org/10.1029/2003JD003623, 2003.

Henderson, K., Laube, A., Gäggeler, H. W., Olivier, S., Papina, T., and Schwikowski, M.: Temporal variations of accumulation and temperature during the past two centuries from Belukha ice core, Siberian Altai, J. Geophys. Res., 111, D03104, https://doi.org/10.1029/2005JD005819, 2006.

Hou, S., Jenk, T. M., Zhang, W., Wang, C., Wu, S., Wang, Y., Pang, H., and Schwikowski, M.: Age ranges of the Tibetan ice cores with emphasis on the Chongce ice cores, western Kunlun Mountains, The Cryosphere, 12, 2341–2348, https://doi.org/10.5194/tc-12-2341-2018, 2018.

Ramsey, C. B., and Lee, S.: Recent and planned developments of the program Oxcal, Radiocarbon, 55, 720–730, 2013.

Roberts, J., Plummer, C., Vance, T., van Ommen, T., Moy, A., Poynter, S., Treverrow, A., Curran, M., and George, S.: A 2000-year annual record of snow accumulation rates for Law Dome, East Antarctica, Clim. Past, 11, 697–707, https://doi.org/10.5194/cp-11-697-2015, 2015.

Pang, H., Hou, S., Zhang, W., Wu, S., Jenk, T. M., Schwikowski, M., and Jouzel, J.: Temperature Trends in the Northwestern Tibetan Plateau Constrained by Ice Core Water Isotopes Over the Past 7,000 Years, J. Geophys. Res. Atmos., 125(19), e2020JD032560, 2020.

Sun, Q., Miao, C., Duan, Q., Ashouri, H., Sorooshian, S., and Hsu, K.-L.: A review of global precipitation data sets: Data sources, estimation, and intercomparisons, Rev. Geophys., 56, 79–107, https://doi.org/10.1002/2017RG000574, 2018.

Thompson, L., Mosley-Thompson, E., Brecher, H., Davis, M., León, B., Les, D., Lin, P.-N., Mashiotta, T., and Mountain, K.:Abrupt tropical climate change: Past and present, P. Natl. Acad. Sci. USA, 103(28), 10536-10543, https://doi.org/10.1073/pnas.0603900103, 2006.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P. N., Dai, J., and Bolzan, J. F.: A 1000 year climate ice-core record from the Guliya ice cap, China: its relationship to global climate variability, Ann. Glaciol., 21, 175–181, https://doi.org/ 10.1017/S0260305500015780, 1995.