Author Reply to the Review Comments by **Dmitry Divine (Referee #2)**

on the manuscript

How precipitation intermittency sets an optimal sampling distance for temperature reconstructions from Antarctic ice cores

by Thomas Münch, Martin Werner, and Thomas Laepple,
submitted to *Climate of the Past* (https://doi.org/10.5194/cp-2020-128).

Thank you very much, Dmitry Divine, for the time you spent on reading and reviewing our manuscript. Below we include a point-by point response to both the major and all minor comments. The original referee comments are set in normal black font, our replies in blue, and suggested changes to the manuscript are shown by citing the manuscript text on a gray background with changes in red.

Major Comments:

My major comment concerns the presentation of the sampling procedure in 2.3.2-2.3.3, which I have found not very straightforward to comprehend. One should admit I have spent quite some time trying to understand the actual details behind the technique, though this difficulty could of course be quite individual. The grip of understanding came later, while reading "Results", yet some questions still remain. A number of minor questions that emerged while reading the manuscript, could therefore be a result of my unclear understanding of the basics of the proposed method.

We are sorry and apologise for the fact that our description of the sampling procedure was not straightforward to comprehend and are grateful to the reviewer that he still spent the time trying to understand our approach. In addition to implementing our suggestions in the below answers to the specific comments, we will thoroughly go through the overall methods text again and revise it in order to improve formulation and clarity. Furthermore, we suggest to include the following figure as an additional part of manuscript Fig. 1 to visualise our approach and hope that is helpful for aiding comprehension:

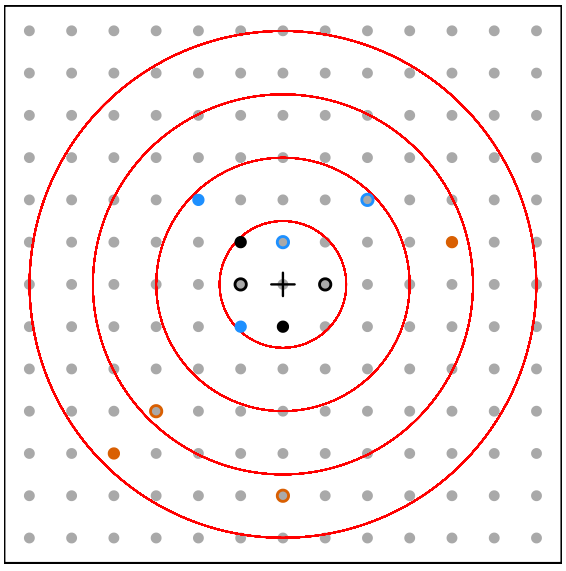

Fig. 1 From an array of grid cells (grey points), we choose sets of grid cells, consisting of N_ℓ cells, around a target site (black cross), which are drawn from radial bins determined by selected combinations of rings (red). As an example for $N_\ell = 2$, possible grid cell sets are shown for the cases of (i) combining the innermost ring with itself (grid cells marked black), (ii) combining the innermost ring with the second ring (grid cells marked blue), and (iii) combining the third and the fourth ring (grid cells marked orange).

I would like to note also that sometimes the discussion around/use of terms like ”target site” or “local site” may appear confusing, same as the actual dimension of the core network being discussed. May be some simplification/clarification of 2.3. can improve the readability?

The target site is always the site from which we use the pure temperature time series as a reference or, in other words, which is sought to be reconstructed from the "ice core" network. We will clarify this in the methods sections. "Local site" is loosely referred to as a site close to the target site, so e.g. the target site grid cell itself or grid cells within the innermost ring. We will go through the manuscript text to check whether certain instances of this use can be improved in terminology. Finally, the "study regions" are areas from which we sequentially use all contained grid cells as target sites. The results with respect to each target site in a study region are then averaged in order to arrive at regional estimates, such as for Figs. 5, 6, and A1. We will clarify this in Section 2.3.4.

In general, with respect to the sampling strategy, the question is why the authors initiated the procedure with these concentric rings used for spatial sampling, instead of just random seeding of the “sampling locations”, calculating the metrics of interest and then ordering them according to the distances between the locations? It sounds way more straightforward to comprehend than via introducing these circular sampling areas with an increment of an arbitrary choice.

Yes, we agree that the approach of randomly seeding the sampling locations and subsequent ordering of the results according to the distances between the locations is, conceptually, a more straightforward procedure. In fact, our approach for N = 1, i.e. sampling one location only, is identical to the random seeding approach, if the latter approach uses a sufficient number of iterations to sample the entire required space.

However, this is also the critical point why we chose the different approach of the ring sampling scheme. While for N = 1 it is compuationally easy and fast to sufficiently sample the required space (e.g. a 2000 km circle around a target site) by random seeding, this is more problematic for N >= 2. Here, the total number of possibilities of combining two, or more, grid cells is much larger than the actual number of grid cells (the more the larger N is), and a random seeding approach of these many possibilities will be strongly limited by available computation time. This will likely lead to an undersampling of the possible relative distances, especially for distances farther away from the target site due to the radially increasing number of grid cells.

Our ring sampling approach circumvents this undersampling: i) Since we sample all possible ring bin combinations, we ensure to sample the entire available sampling space of (binned) relative distances. ii) For each ring combination, we either sample all possible grid cell combinations (N = 1 and N = 2), or we sample a fixed (but large) number of randomly chosen grid cell combinations (N > 2). This ensures that either the entire availble sampling space is actually sampled, or – at least – a fixed number of grid cell combinations for every ring bin combination, so that the expectation value for every ring bin combination builds on the same number of combined grid cells.

We will add this motivation to the manuscript in section 2.3.3.

Also, as a suggestion for the future work, it would be highly useful to test the concept of this method on a different model with enabled stable water isotopes in precipitation in order to see how different the results/inference can be. Testing on the existing ice core network can be fairly problematic due to all the deficiencies (both in the available ice core and instrumental data) mentioned throughout the text.

This is a very good point. Indeed, we tested our concept also on the ECHAM6/MPI-OM-wiso PI-control simulation (unpublished) and obtained comparable results. However, this might also be due to the fact that both models use the same isotope scheme. So testing our results with a completely different isotope-enabled climate model is needed. We will add this suggestion to the conclusions of our manuscript.

Minor Comments (the manuscript text shown in italics):

Line 112: “*...define consecutive rings around this site with a 250 km radial width...*”
Here you refer to these concentric rings with a radius increment of 250 km, used for delimitation of the sampling regions, do I get it right? May be it needs to be specified already here. Can you also provide

any rationale behind the value of 250 km?

Yes, we here refer to the concentric rings (red circles in Fig. 1) with 250 km radial increments which we use to sample grid cell combinations as a function of whether they lie within the same ring or within different rings. We will refine the text here to make this clearer to the reader. We chose the value of 250 km radial extent as a trade-off between achieving a high spatial resolution and ensuring that a sufficient number of grid cells actually lie within the ring bin borders; e.g., the first ring (0–250 km) includes with respect to the EDML site already five grid cells only. Using a smaller radial extent (higher spatial resolution) would thus not be meaningful and would result in statistically less robust results.

Line 118: "*Finally, we report the mean correlation for every ring combination by averaging across all correlations of the analysed grid-cell combinations*." Is this averaging based on the distance between the locations, or just everything? How then the distance-based value is calculated?

The averaging is performed across all analysed grid cell combinations for a given ring combination. The distance information is then "only" given by the radial midpoint distances of the combined ring bins relative to the target site. We will add a sentence here to clarify how we obtain this distance information.

Line 119: "...for sampling N locations from the model field depending on the distances between the locations." See my previous comment. If everything is averaged out, how the distance based sorting/ranking is implemented?

We will clarify here how we obtain the distance information; see our previous answer.

Line 136: "(−78.47 S)». No need in "-" before the latitude value if "S" is explicitly indicated.

Thanks for spotting this inconsistency; we will correct this.

Line 184: "*...depend on the specific simulated climate state or result...*"
It would be meaningful to add that it also includes the actual model used and the stable water isotope scheme applied in the model.

We will add the possible dependence on the climate model isotope scheme here.

Line 212: "*...maximum average correlation is to sample one location from the innermost ring and the second location from the fifth ring*"
this is not entirely apparent as both maxima in Fig 6 seem to be found on the "5th ring".

We are afraid that this is a misunderstanding. There are indeed two maxima visible in Fig. 6c, both between 1000 and 1250 km (i.e. fifth ring), one along the x axis and one along the y axis. However, this is the same information since the locations of the two cores are indistinguishable, i.e., it doesn't matter whether we put the "first core" within the fifth ring and the "second core" within the first ring (maximum along the x axis) or vice versa. In other words, the figure is symmetric along the diagonal and half of the plot already contains the full information. We chose this way of presentation for aesthetic reasons. We will add a sentence to the caption noting that the plot is symmetrical since the locations of the cores are indistinguishable.

Line 255: "*For a conceptual model of the sampling correlation structure, we focus on three processes that influence...*". It is probably would be more relevant to write about focusing on three OF the processes that has an influence, as other processes are discarded in this conceptual model and this is mentioned in the text.

We will edit the text as suggested.

Line 280: "*When fixing one location to the target site and varying the distance from the target site of the second location...*"
This sentence appears again somewhat confusing to me. Do you actually average over "three" locations here or only two? You refer to fixing the core to the target site (first core), and then refer to the "second

site". What then denotes "distance of first core " in the figures (like Fig 6)?

We are sorry for this ambiguity. We indeed average across only two locations. What is meant here in general is to fix one core (the "first core") to the innermost location and only vary the location of the second core. In the conceptual model, which is discussed at this point, the innermost location is identical to the centre of the rings, i.e. the target site (simply due to the fact how the conceptual model is set up numerically). In the climate model results (Figs. 6, A1), however, the innermost location in the ring sampling scheme can only be obtained for putting the first core within the first (innermost) ring (0–250 km). We will revise the text accordingly here:

"When fixing the position of one core to the innermost location..."

and at other respective passages to avoid this ambiguity.

Line 307: "*Our results which we obtained from analysing the climate model data and substantiated with our conceptual model provide guidance on where to drill N = 1,2,3 or more ice cores, or from which locations...*"
This statement is not entirely correct, the presented results tell about the relative distances (dimensions) of the core network optimal for the model, rather than point to specific locations that need to be derived via modelling for every target region.

We do not fully agree. If one believes in the "picking" results of directly analysing the best grid cell combinations (Section 3.2 and Fig. 4), our results can directly advise where to drill cores for a specific target site. This is also elaborated in the following paragraph (LL310–315). But you are correct that one would need to do the analysis for every specific target site one is interested in. In this regard, the ring sampling results are more general since they should apply to a larger region (DML, Vostok region) but with the downside that the results only tell us about the optimal relative distances of the core network, as you correctly observe. We will revise the introductory paragraph of this section in order to better reflect these two different views.

Line 311: *"However, it is unclear whether these results can be one-to-one transferred to the real world, since they might depend on dynamical processes in the atmosphere which could differ between climate states or depend on initial conditions."* Consider adding "...or unaccounted model deficiencies"

We will add this additional information.

Line 328: "*we expect the optimal spatial configuration to be more dependent on the study region*" ... and very likely on the GCMiso model used in the analysis.

Here, we talk specifically about the results for three or more ice cores (N >= 3); your statement rather applies to the results in general. We think it is thus sufficient to revise the text around L184, as suggested above in the respective comment.

Line 331:" *We thus need to create an isotope record that*" Consider adding "As a proof of concept"

We will add the suggested phrase.

Line 352: *...we expect similar results to hold for other parts of Antarctica, and potentially also for other large-scale ice-coring regions such as Greenland"*
One can add that this is conditional on a simplified assumption of a nearly anisotropic exponential decorrelation scale length to be valid

We will add this limitation.

Figure 3: Why the correlation value for a cell at approximately 70 S and 20E stands out?

Inspection of the time series of this grid cell located at ~ 72.4 °S, 22.5 °E shows that the isotope time series exhibits one anomalous time step where the delta value erroneously rises far above 0 permil. This causes the outlier correlation with the temperature time series. We will remove this anomalous

time step from the isotope time series to fix this, and we will carefully check whether there are further anomalies.

Figure 6: The caption is somewhat confusing. Is the "target site" also to be sampled or not? If this is the case, should this be a 3-dimensional case or not?

No, it is the 2-dimensional case, i.e. averaging two locations, as explicitly stated in the first and second sentence of the caption. The grid cell of the target site lies in the centre of the innermost ring, so it is (implicitly) included in the analyses when sampling is performed for combining the innermost ring with itself (distance of both cores <250 km) or with one of the other rings (distance of only one of the cores <250 km). But please note that the results are the average across all grid cell combinations for a specific ring combination, hence the target site grid cell only contributes proportionately to the overall average value for the combinations which include the innermost ring.

Figure 7: what is “Rank” on y-axis? Ranking according to the maximum correlation attained? It should than be mentioned explicitly.

Yes, the "Rank" means ranking according to the maximum attained correlation, with Rank 1 denoting the case with the highest correlation. We will add this information to the figure caption.

Figure B1, caption.
“Note that the plots (a) and (c) are based on the same parameters and therefore identical”.
Why and where they are identical? This is not evident from the plots.

Thanks for spotting this typo, correct is that plots (a) and (d) are identical. We will fix this.