REVIEWER 1 COMMENTS

(Reviewer 2 comments begin on page 9)

All text is copied from RC1, and the authors' comments are preceded by "Response:".

Updates following reviewer comments are preceded by "Final Revision Update".

General Comments

In this study, Nye and Condron consider the Bølling-Allerød (BA) and Younger Dryas (YD) in the broader context of abrupt climate change over the last glacial cycle. They apply an outlier detection algorithm to a number of paleoclimate records in order to test whether the BA/YD is statistically unique from DO events of the last glacial. From the results of this outlier detection method, they suggest that the BA/YD is statistically indistinguishable from other DO events (in Greenland ice core records), raising the question of whether its triggering mechanism is unique.

This paper raises important questions regarding our understanding of the mechanisms of abrupt climate change and applies a novel technique to compare DO events. However, there are several aspects of the paper where more detail/analysis is required. The main components of the paper that I found insufficiently addressed were 1) the use of outlier detection in distinguishing mechanisms of abrupt change, and 2) a more quantitative discussion/demonstration of the (non)uniqueness of the BA/YD, relative to the other 24 considered DO events.

1) Use of outlier detection in distinguishing mechanisms of abrupt change In this study, Nye and Condron use outlier identification (or non-identification) to 1) argue that the BA/YD should be included in the list of DO events, and 2) suggest that it may not have a unique triggering mechanism (when compared to other DO events). However, the study did not address how outlier detection may be used for this second argument. It is unclear if/how a statistical difference (or more accurately, a similarity) in the selected proxy records would indicate a different (or common) triggering mechanism for these events. As noted by the authors, AMOC variability is often invoked to explain the global signature of DO events and the BA/YD, alike. Modeling studies that compare the global imprint of freshwater forced versus spontaneous AMOC variations (see Brown and Galbraith, 2016, https://doi.org/10.5194/cp-12-1663-2016) suggest that forced and unforced AMOC variations have very similar signatures. This would suggest that similarities between climate proxy records during DO events (and the BA/YD) may not necessarily imply that they were triggered by the same mechanism. Please address the suitability (or limitations) of applying this outlier technique in differentiating between the triggering mechanisms for abrupt climate change.

Response: We thank the reviewer for their constructive feedback, and provide some additional details as follows: In our study, we have indeed shown that many proxy-based qualities of the BA/YD are statistically indistinguishable from the other DO events. The fact that the climate response to freshwater forced or spontaneous variations in AMOC is similar is one of key and overarching motivations for our work that a single freshwater forcing mechanism should not be the only triggering mechanism for the BA/YD. Indeed, our main goal with this study is to demonstrate that no assumptions should be made regarding the trigger of the BA/YD, precisely because it bears strong resemblance to other DO events. In so doing, our revision will make clear that the outlier detection technique is not aimed to assess the qualities of DO events as they result from specific triggers, but rather to provide a general framework for situating the BA/YD within a broader context of many other DO events, each of which may (or may not) have the same underlying trigger. In this sense, our outlier technique is limited to that simple conclusion, and is meant to negate any strong favorability for the BA/YD as triggered by a unique mechanism.

Final Revision Update:

- Changed lines 11-12 to emphasize that our results confirm ambiguity of the BA/YD trigger, and highlight a novel statistical method
- Added final sentence of Introduction starting at line 42 to contextualize results
- Changed wording in final paragraph of discussion to emphasize that the proxy *data* is not unique, not necessarily the BA/YD itself (e.g. lines 258 and 264)

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2) Quantitative discussion/demonstration of non-uniqueness of the BA/YD The main conclusions of the study are drawn from the results presented in Table 4, which shows the outlier detection results for a given set of climate proxies and metrics. However, from this table it is not obvious that the results support the conclusion that the BA/YD transition is non-unique, given that the BA/YD was identified as an outlier in most of the tests. It is unclear whether these results are related to the algorithm's relatively high rate of 'false positives' (as the authors mention), or if the BA/YD is actually a statistically unique interval (as defined by the outlier detection algorithm). A fairly simple test of the relative 'non-uniqueness' of the BA/YD would be to perform the same outlier analysis for each of the other 24 events considered in the record.

In Table 4, please include a summary of the results for the other 24 considered DO intervals compared against the 25 DO events. For example, add three columns (and three rows) to the end of the table and include 1) the rate of outlier detections for the BA/YD (for instance, 12/15 or 0.80 for the first column), 2) the average rate of outlier detections for the other 24 events, and 3) the standard deviation of the outlier detections for the other 24 events for each column or row. Including these metrics for how 'unique' the individual DO events are from one another (and the BA/YD) provides a much more direct comparison of the BA/YD to the rest of the DO events. This eliminates the requirement for the reader to have an in-depth knowledge of the nuances of the applied statistical technique to interpret the results for themselves. Without this, it is difficult to assess the 'non-uniqueness' of the BA/YD, and thus the conclusions of the study.

Response: Thank you for this comment. While we believe that Table 4 supports our conclusions, we also agree that the way the results are currently presented could be misleading. In our revised manuscript we will make two additional points to clarify the validity of our conclusions from Table 4. Firstly, we will state explicitly that we are specifically looking for subsets of proxies that PCOut identifies as non-outliers, rather than to compare the results of such subsets to one another. This is motivated by sentiments in the paleoclimate community that treat the BA/YD as outlying from other DO events. Secondly, we will make clear that since we are performing tests on all subsets of our data, tallying the total number of subsets registering as outliers is not a statistically sound way of determine outlier behavior on a large scale. Instead, we are asking if the shape of the BA/YD's Greenland proxies exhibits outlier behavior, for which the answer remains to be no.

We believe that the additional analysis you've proposed is a sound way to add context to our argument, but caution against taking means and standard deviations of the total number of outliers in rows and columns of this data. This is because our goal is not to compare the number of proxy subsets for which the BA/YD is an outlier to other DO events. Rather, our results in Table 4 serve as grounds to support pointed claims about each subset (for example, that the shape of the BA/YD's Greenland proxy data is not an outlier compared to all other DO events). In our revised manuscript, we will certainly perform the PCOut analysis on other DO events as a grounds to discuss the extent to which the general picture of outlier behavior in the BA/YD differs from the other DO events in our study.

We also propose to rework the results section and Table 4 such that the results of PCOut regarding the measurements on proxies of interest (namely, measurements of the shape of Greenland proxies) are highlighted as entirely separate from the other results that indicate the BA/YD as an outlier. This will aid the reader in understanding that the BA/YD may well be an exceptional event in the context of southern hemispheric proxies, but is certainly not when viewed through the Greenland lens.

Final Revision Update:

- Modified Table 4 such that only the columns discussed in the results section are present (the other columns were not interpretable or relevant to our conclusions).
- Added lines 191-194 to explicitly state the purpose of the table and irrelevance of summing outlier results.
- Added paragraph from 233-242 discussing conclusion and relevance of performing same analysis on other D-O events.

Overall, I think that major revisions are required to provide a convincing argument of how outlier detection may be used to differentiate between mechanisms of abrupt change, and to quantitatively demonstrate the 'non-uniqueness' of the BA/YD. Other aspects of the manuscript that need to be addressed (such as the choice in paleoclimate proxies, and a quantitative assessment of uncertainties) are included in the specific comments. Technical corrections are included in a supplementary document.

Specific Comments

Lines 41-43: The authors do not discuss their choice in which paleoclimate proxies to include in this analysis. Please explain the choice in which proxy records were (and were not) included, and why they are well suited for this analysis. For instance, how are the chosen records better suited in this analysis than other available ice core records for this interval (such as Greenland/Antarctic aerosol records)? It is also unclear why proxy records from Greenland ice cores are emphasized in this analysis (see comments on lines 178, 189-191). A more thorough discussion of how the chosen records provide insight into the mechanisms/expressions of abrupt climate change would enrich the manuscript.

Response: Our choice of proxies is based on those with the highest spatial resolution and tradition in the field of paleoclimatology of using these to study climate variability during both DO events and the BA/YD. The high temporal resolution of the ice cores during the last glacial period makes them idea for use in our work. Furthermore, we use both d18O records (NGRIP and EDML) to provide local approximations of climate, whereas CH4 and CO2 are more indicative of global climate fluctuations.

Final Revision Update:
- Added lines 57-61 to explain choice of proxy.

Line 79: What is the age scale for the EDML d18O? Related to the above questions, why EDML d18O? EDML is often considered unique from other Antarctic ice core records because of its close proximity to the Atlantic basin, but this is not mentioned in the manuscript.

Response: The age scale of the EDML record spans from 150kya to the present. It was chosen because it has a spatial resolution comparable with the Greenland ice core records. Indeed, the snow accumulation at EDML is two to three times higher than at other deep drilling sites on the East Antarctic plateau, so higher-resolution atmosphere and climate records can be obtained for the last glacial period, making the EDML core especially suitable for studying decadal-to-millennial climate variations in Antarctica. Including EDML d18O allows us to observe changes in NGRIP d18O as distinct in location but similar in meaning. This allows us to make conclusions about how the BA/YD may not have been a unique event in Greenland, but perhaps was so in the southern Atlantic. We will certainly make note of EDML's special status as close to the Atlantic basin in our revised manuscript.

Final Revision Update:
- Added lines 51-57 to discuss the significance of the using EDML.

Lines 80-81: How were these three metrics selected? Why were the slopes and medians within the stadial (but not the interstadial) considered?

Response: The slope and peak-to-trough metrics are meant to give an idea of the shape of each DO cycle, whereas the median gives us a sense of how cold each stadial became. This latter feature allows us to discuss how larger timescale glacial-to-interglacial changes have the potential to render the BA/YD's average temperature exceptional or not, while the former two (slope and peak-to-trough) allow us to isolate the shape of each DO as an independent feature. We focus solely on the slope and median of the stadial periods because of their known volatility, but will perform an analysis of slope during the interstadials as well in our upcoming revision.

Final Revision Update:
- Lines 107-110 were added to explain the selection of measurements taken and the result of analysis of slope on interstadials.

Lines 85-87: The goal of objectively selecting time windows to compare stadial and interstadial conditions for peak to trough analysis is a worthy one. However, the interval (as defined with water isotopes) may not be appropriate to apply to other variables. For the BA/YD, the selected interval for the stadial (shown in Figure 3, lower left panel) includes the abrupt decrease in CH_4, so the amplitude of the peak to trough change appears to be underestimated. This technique assumes that there is no age uncertainty between the selected climate records. Please consider the influence of age (and delta age) uncertainties in selecting stadial and interstadial intervals for peak to trough analysis.

Response: Thank you for this comment. In our revised manuscript, we will be sure to explore questions of age uncertainty.

Final Response Update:
- Added lines 116-118 to address age uncertainty.

Lines 88-89: Why use a narrower (not wider) filter for CO_2 if the data are sparser?

Response: Using a narrower filter for the sparser CO_2 data ensures that we are not taking too broad of an average, which, when data is sparse, has the potential to erase important trends in the data. In our revision, we will certainly perform this analysis using a wider filter to quantify this.

Final Response Update:
- Lines 119-120: expanded on reasoning for alternate filter.

Lines 90-94: Again, error in the alignment of ice core records may influence the median and slope metrics for the selected stadial intervals. Please consider/discuss how age (and delta age) uncertainties may influence these results. It may also be informative to consider how analytical (measurement) uncertainties may affect these metrics (as well as the peak-to-trough metric), and their comparison between DO events.

Response: We use robust techniques in this paper primarily because of the uncertainties you mention. For example, we take the median of each stadial interval rather than the mean because the mean is far more sensitive to the uncertainties that present themselves when working with proxy data. Further, we take the mean of the top 10% extrema for both interstadials and stadials rather than simply the highest individual value to protect against uncertainty and observation-based variations. In our revised manuscript, we will perform an age uncertainty analysis to see if slight differences in age alter our results significantly.

Final Response Update:
- A basic age uncertainty analysis was performed to test whether shifting our data forward or backward in time would skew our measurements. As lines 125-127 suggest, our data is robust to such shifts of at least 100 years (and in some cases, more).

Lines 95-136: The explanation of the PCOut algorithm is quite detailed, but also important. Please consider shifting some of the details/equations to an appendix.

Response: Thank you for your comment. Although equations (1)-(6) regarding PCOut are detailed, we prefer to leave them in the body of the manuscript.

Final Response Update:
- No changes made.

Lines 146-148: I would caution in generalizing atmospheric CO_2 as a Southern Hemisphere proxy, or at least explain the reasoning (also see comments on line 178).

Response: Noted. In our revised manuscript we will be more specific about the meaning of the CO_2 proxy data.

Final Response Update:
- Line 182 changed “Southern Hemisphere” to “these proxies”.

Line 152: It’s not totally clear what chemical makeup means here. Does this mean the choice in which proxies are included in the analysis? Please clarify.

Response: Chemical makeup is incorrect. We mean “record subset”, and will amend this in the revised version.

Final Response Update:
- Line 186: Change “chemical makeup” to “record subset”.

Line 178: Why are Greenland proxy records prioritized? See also comments for Lines 189-191. I would also caution in referring to the NGRIP CH_4 record as a Greenland proxy. It’s true that the record comes from a Greenland ice core, but it is not a proxy for Greenland climate (and is also available from Antarctic ice core records).

Response: The Greenland proxy records are prioritized in part for their historical significance in terms of looking at DO events, as well as to address the hypothesis that the climatic signature of the BA/YD and DO events centered predominantly on the North Atlantic due to changes in AMOC. In our revised manuscript, we will be more explicit in discussing the NGRIP CH4 proxy.

Final Response Update:

- See lines 57-61 to explain choice of proxy.

Line 183-184: I could be mistaken, but I thought that assessment of leads/lags between CH4 and Greenland temperature came from Baumgartner, 2014, which used d15N-N2 (not d18O) for temperature (so there is no delta age uncertainty).

Response: Thank you for pointing this out. This citation will be fixed in our revised manuscript.

Final Response Update:
- Citation changed from Baumgartner et al. 2012 to Baumgartner et al. 2014 (Line 215).

Lines 189-191: I'm not sure I understand the logic of this argument. Please explain why the NGRIP CH4 and d18O records are particularly well suited to evaluate the (non)uniqueness of the BA/YD in the context of their climatological significance.

Response: The logic of this argument relies on the fact that the pair of these proxies evaluated together are non-outlying behavior across the board. They are both indicators of temperature, yet d18O is generally indicative of local temperature, while CH4 is more global in nature. Thus, the fact that the pair of behaviors of d18O and CH4 during the BA/YD is not unique compared to the pair of behavior for these records in other DO events is a stronger conclusion than if we were to restrict this analysis to only one proxy record from Greenland.

Final Response Update:
- Added lines 222-224 to explain reasoning.

Line 201-202: It is unclear how this degree of similarity (86-93%) is quantified. Please specify how the results (with 25 DO cycles versus 28-30) are compared.

Response: For both the 28 and 30 cycle versions of the data, we create a table in the same format as Table 4, and then count which cells display the same result as our Table 4. By this metric, 93% of the cells in the 28 cycle version are the same as the 25 cycle version, and 86% of the cells in the 30 cycle version are the same as the 25 cycle version. We will include text along these lines to our revised manuscript to clarify this analysis

Final Response Update:
- Added lines 245-246 to further clarify.

Figure 5: It is unclear the direction in which time is moving in this figure.

Response: Noted. It moves right to left, where more recent times are toward the left. This will also be clarified in our revised manuscript.

Final Response Update:
- Clarified in the caption of this figure and the horizontal axes' arrows, which now point left.

Table 2: Please check the signs of the metrics. I would expect that the sign for peak-to-trough changes in d18O and CH4 during DO1 (BA/YD) would be the same.

Response: That's correct, they are the same. We used absolute value for the d18O peak-to-trough measurement because they are all negative, but for the sake of clarity in the revised version we will include the sign.

Final Response Update:
-Negative signs added in Table 2 to the d18O P2T column.

Technical Corrections:

Response: Thank you for your thoughtful technical corrections. All such corrections will be implemented in our revised manuscript. Citations for lines 17-18 and lines 23-24 are Li and Born (2019), and citation for lines 103-104 will be Filzmoser et al. (2008).

Final Response Update:
- All technical corrections implemented.

REVIEWER 2 COMMENTS

Interactive comment on “Assessing the Statistical Uniqueness of the Younger Dryas: A Robust Multivariate Analysis” by Henry Nye and Alan Condron

Anonymous Referee #2

Received and published: 9 May 2020

Review of cp-2020-43

Updates following reviewer comments are preceded by “Final Revision Update”.

General comments:

The paper by Nye and Condon applies statistical analysis to metrics derived from ice core data (δ18O, CH4, CO2) spanning a large group of abrupt climate shifts between 120-11 thousand years ago. The procedure PCOut, essentially a form of principal component analysis that is particularly suited for outlier identification, is relatively novel for paleoclimatology studies. The results are interpreted to mean the BøllingAllerød/ Younger Dryas is not statistically different from 24 other preceding Dansgaard-Oeschger events during the last glacial period in terms of the specific metrics they C1 CPD Interactive comment Printer-friendly version Discussion paper derived from the ice core data (specifically, stadial slope and magnitude of peak-to-trough change). The authors conclude that future work should not focus on identifying a unique cause for the YD cold event, suggesting that similar mechanism(s) may have controlled all of the interstadial-to-stadial transitions in the past.

The manuscript is well written, and the analyses and results are very clearly presented. Researchers will be able to repeat this work or apply the techniques to other datasets, thanks to the clear presentation of the methods. I have no issues with the analysis itself, save for a few minor comments listed below. I do, however, think the underlying motivation for the study – the notion that the paleoclimate community considers the cause of the YD event unique from other D-O/ stadial transitions - is overstated throughout the manuscript. Yes, there are studies proposing “one-off” causal mechanisms; for example, there is a large body of literature debating the bolide impact hypothesis. But many researchers think the reason the YD is unique is not because of its cause necessarily, but because it occurred during the last deglaciation, a sort of “failed” transition back to glacial conditions. Or, by the same token, D-O events were “failed” deglaciations that for some reason reverted to glacial conditions. The YD is also unique because similar “reversals” toward glacial conditions did not occur during other terminations of the last 800,000 years. The authors’ analysis does not consider these aspects, which to me are more fundamental qualities that make the YD unique, more so than the shapes and slopes of the ice core data themselves. If the authors disagree with this assessment, they should make a stronger case in the introduction for why it should be proven the YD is or is not statistically different from other D-O cycles. More specifically, the authors should specify why their outlier test on only three specific metrics – i.e., stadial slope, median, and peak-to-trough magnitude – is a sufficient test of whether the YD is or is not unique. Is there reason to believe these metrics should look statistically different if the YD was in fact caused by something different than other stadial transitions?

Furthermore, I am not fully convinced that the results support the conclusions. The PCOut results in Table 4 show (at face value, at least) that the YD is statistically significantly different from other D-O events. That is, there are 64 instances of yes while only 41 instances of no, and the first column of Table 4 (the all metrics evaluation) points overwhelmingly to outlier status for the BA/YD. The authors' explanation for the median results is that there is significant offset from the rest of the glacial period, but this is precisely why I find the YD is unique and interesting in the first place - not because it looks different from other events in terms of the data, but because it occurred during a deglaciation. That being said, the authors do provide a very clear and thorough discussion of the most interesting aspects of the statistics, which convinced me that the BA/YD is not unique in terms of its expression in NGRIP d18O and CH4. It is useful to point out the statistical likenesses between the BA/YD and other D-O events, as they have done, and I think this paper should be published for this reason, as well as for the reason that the statistical technique is potentially useful for other studies.

I think the manuscript would greatly benefit from revisions such that the paper emphasizes the statistical method rather than the (to me) unsurprising result that the YD is not unique from other stadial events in terms of a few certain patterns resolved in the ice core data. For example, the paper might present the YD/BA is an interesting application of the method, but not an absolute test of YD uniqueness. The description of the method could be bolstered by describing how PCOut might be used for other paleoclimate work, or how it could be adapted to deal with age and measurement uncertainties that are inherent to most paleo datasets. In addition, please see specific comments and technical corrections listed below.

Response: Thank you for your very thoughtful comments. We strongly agree that the result of statistical uniqueness in the NGRIP d18O and CH4 records should be emphasized over the overall uniqueness of the BA/YD with respect to other events. In regards to your first comments, we believe that there is significant treatment of the BA/YD as a unique event in the literature, and seek to broaden the field of considerations for what the BA/YD represents climatologically. In particular, we find it notable that an event so similar in shape to the classic notion of a DO event can occur at a time of deglaciation.

In our revised manuscript, we will emphasize these thoughts in addition to the second meta-purpose of this study, which is to introduce more robust algorithmic outlier detection techniques into the field of paleoclimatology. Indeed, we consider our methods to be incredibly useful when attempting to synthesize and compare climate records that are both uncertain and complex.

Final Revision Update:
- Added sentence at lines 40-41.

Specific comments:

Line 6-7: Freshwater forcing of circulation due to meltwater from ice sheets or iceberg discharge has been proposed as the cause of stadials during the last glacial period as well, not just for the YD.

Response: Noted, this will be corrected.

Final Revision Update:
- De-emphasized uniqueness of trigger hypotheses in line 7.
- Volcanic eruption in line 7 has been deleted.

Lines 58-59: Can you provide any objective reason for choosing these durations? What makes them conservative?

Response: We choose these durations simply because they are at the shorter end of what has previously been accepted as the length of a stadial or interstadial. They are conservative in relation to the Rasmussen et al., 2014 study, which contains many events are that sub-centennial in length. It should also be noted that our results are not very sensitive to the chosen length, and this will be noted in our revision.

Final Revision Update:
- Lines 76-80 are added to justify the conservativeness of our choices.

Line 65: Can you show or say what happens to your final results if you do the extreme scenarios – (1) merge all sub-events into single events, (2) discard all sub-events and only look at the main events, and (3) include all sub-events as their own individual events? This could be in a supplementary section.

Response: Yes. We can certainly perform this analysis for inclusion and discussion in the supplementary section of our revised manuscript.

Final Response Update:
Upon further reflection, we have decided not to include this additional analysis. Although the results would certainly be interesting, they would not pertain directly to our goal of providing a new method for researchers to implement and replicate. Thank you again for this idea, as it is an interesting question for further research.

Lines 74-77: What exactly do “normalize” and “centered” mean in this context?

Response: These lines refer to the creation of Figure 5. “Centering” these time series at their median means computing and subtracting the median value of each record during each DO event, and “normalizing” means stretching or shrinking the time over which each DO event occurred to a consistent number of years for each. These methods allow us to better visualize and compare the shape of each DO event. In our revision we will make it clear precisely what we are referring to in this context.

Final Response Update:
- Added sentence in lines 96-98

Lines 74-77: It is unclear if the “narrowing down” of D-O events applies to the statistical analysis or not. Did you effectively screen the number of events this way? Can you either describe or provide a figure to demonstrate how you narrowed them down, given that this step was done subjectively by eye. Please also state how many events you kept/excluded based on the criteria of visually resembling the BA/YD, assuming you did screen them.

Response: This process does not apply to the statistical analysis that follows it, and we will make this clear in our revision. But, rather, this serves as preliminary evidence for the fact that the BA/YD’s shape in the context of the Greenland records is not unique in terms of the general shape of many DO events. Visually selecting 7 out of 25 DO events that appear indistinguishable in shape from the BA/YD evidences a similarity and a motivation for the following statistical study. We are aware that performing our subsequent analysis on only 8 DO events is not a rigorous test, so use all 25 DO events.

Final Response Update:

- Added sentence in lines 100-102 to clarify.
- Added clause at the beginning of line 103.

Lines 74-77: Another comment here, and I am assuming that the visual selection of events that you described was used as a screen for the statistical analysis (if not, then disregard the following but please simply reword so it is clear in the text). If so, however, this step would strike me as a major weakness of your analysis. The overall conclusions is that the YD/BA is not statistically distinct from other D-O events in terms of shape, structure, and the other metrics described, but in this selection step you intentionally chose to only look at D-O events that visually resemble the YD/BA in the first place? Please address to what degree the selection criteria influence the final statistical result.

Response: N/A, it is not a screen. Our revised manuscript will make sure this section of our methods is much clearer.

Final Revision Update:
- See above revision.

Lines 91-93: Do you have to identify D-O behavior by these criteria for the analysis? I thought you already identified them using the algorithm and the visual resemblance to the BA/YD. If you are just describing the characteristics of D-O behavior, you might change the wording to reflect this so readers are not confused.

Response: Our methods follow two strains of logic: the first concerns the visual selection of 7 DO events to provide evidence for the BA/YD's visual similarity to nearly one third of other DO events studied. Our second, more important line of analysis is that which takes the peak-to-trough, slope, and median measurement in order to implement the PCOut procedure. Both of these analyses are preceded by the algorithmic selection of DO events found in Figure 2. The distinction between different parts of our methods will be made much more clear in the revised manuscript.

Final Revision Update:

- See above revision.
- This is further clarified in the altered wording in lines 104-105.

Lines 138-140: Again, I don't follow why. Is this just for ease of visualization, or is this related somehow to the statistical analysis? Please state so if that is the case.

Response: Yes, correct. We will make it explicitly clear in our revision that this is just for ease of visualization.

Final Revision Update:
- Lines 171-180 edited to make the separateness of this visual analysis clear.

Figure 5 – Is the "BA/YD exclusive mean" the mean of all 24 other D-O events, or just the 7 shown? Please clarify. Additionally, are you sure that the "BA/YD exclusive mean" in the fourth panel (second column, second row) is the mean of EDML d18O? My understanding is this is supposed to be the EDML mean of the 7 events (or 24?), but excluding the BA/YD. . . It doesn't look like the mean of the other colored lines in that panel, and it looks more sawtooth shaped than the normal phasing of Antarctic temperature with respect to the onset of D-O events. Perhaps there is a mistake.

Response: The "BA/YD exclusive mean" is the mean of just the 7 D-O events shown, and our revised manuscript will explore the possibility of changing this mean to reflect the average of all

24 other DO events. The mean of the EDML is incorrect, thank you for spotting that. It will be corrected in our revision.

Final Revision Update:

- Figure 5 is corrected as stated above. The average is now the average of all 24 D-O events, excluding the BA/YD.
- This figure with 24 D-O events is far too cluttered to include, so we stick to our current analysis.

General technical corrections:

There are numerous places in the text where the term "D-O event" is used somewhat loosely to describe a warming event in the NGRIP ice core record, a cold stadial that follows the warming, or the combination of both warm and cold intervals. Technically the D-O events are just the warming events as they are expressed in the Greenland isotope records.

Response: Noted, these will be corrected such that D-O events only refer to the warmings.

Final Revision Update:
- Multiple instances of this error have been corrected.

Specific technical corrections:

Figure 1: The transitions to stadial conditions are marked, but not the transitions to interstadials (i.e. the onset of the D-O events). It is a little confusing when you refer to a specific D-O event. You might consider distinguishing whole interstadial periods versus stadial periods with shading, as in Figure 1 of Rasmussen {Rasmussen, 2014 #751}.

Response: Thank you for this note. For our revised manuscript we will look at different ways of plotting the data so that interstadial periods and stadial periods are easily distinguished.

Final Response Update:
- For ease of viewing, our Figure 1 is left unchanged. After experimenting with shading, we find that it is not viable for a small graph like Figure 1, and prefer to mark the transitions as before.

Lines 17-19: Needs a reference.

Response: Indeed, thank you. In our revision, we will reference Li and Born (2019) for this.

Final Revision Update:

- Li and Born (2019) is referenced for lines 17-19.

Line 39: Suggest changing “paleoclimate research” to “future work.”

Response: Yes, this phrase will be altered in our revised manuscript.

Final Response Update:
- This has been rephrased in line 40.

Line 48: Do you mean, “labeled by lowercase letters” in Rasmussen 2014? Please clarify. Line 67: “of a well-defined and complete record for all four of our chosen proxies, as we restrict our analysis of the last glacial cycle to. . .”

Response: Yes, this is what we mean. We’ll make clear that this labeling comes from the Rasmussen 2014 paper.

Final Response Update:
- This has been made clear in line 65.

Line 76: “NGRIP d18O,” rather than “NGRIP d18”

Response: Thank you, this will be changed.

Final Response Update:
- This has edited in line 95.

Line 106: I am being picky here, but two of the four records – NGRIP CH_4 and composite CO_2 - are not proxies, they are direct measurements.

Response: Correct. The revised manuscript will reflect the correct language for these data.

Final Response Update:
- Line 139 reflects this change.

Line 109: The word “remaining” is confusing to me here? Should it say “resulting,” since the components are the result of the principle component analysis?

Response: Indeed, “resulting” is more intuitive. This change will be made.

Final Response Update:
- Line 142 reflects this change.

Equation 1: In reading Filzmoser 2008, I noticed that equation (1) in this manuscript is different from equation (11) in Filzmoser, which has a fourth power in the denominator. However, I also notice the Filzmoser equation (11) is missing a parenthesis in the numerator. Perhaps the fault is in Filzmoser 2008 and not in this manuscript? Please clarify.

Response: The missing parenthesis in the numerator of Filmozer equation (11) should indeed be present. We have, however, forgotten to include the fourth power in our equation (1) denominator. Thank you for noticing, this will be corrected.

Final Response Update:
- This correction has been made in line 144.

Lines 117-120: Consider dividing this long sentence into two sentences for readability.

Response: Certainly, thank you.

Final Response Update:
- Line 153 reflects this change.

Equation 4: Would be helpful to define M and c immediately after equation 4, not after describing calculation of bi.

Response: Thank you, this will be changed.

Final Response Update:
- This edit can be found in lines 159-162.

Line 138: I think it should be “BA/YD,” not BA/YA. There are other instances of this typo throughout.

Response: This typo will be corrected everywhere it occurs, thank you.

Final Response Update:
- These typos have all been corrected.

Line 145: I disagree with calling the data a CH4 “proxy.” A proxy is when you measure one thing, and the data mean something else – like d18O and temperature. In the case of CH4, it’s a true measurement of the CH4 concentration in the atmosphere in the past, rather than a proxy for it.

Response: Indeed, thank you for this clarification. Our revised language will better reflect this fact.

Final Response Update:
- These errors have all been corrected.

Figure 3: There are some typos in caption and legend.

Response: Noted, thank you. These will be corrected in our revision.

Final Revision Update:
- Caption and legend have been corrected for typos.

Figure 4: Consider numbering the panels, or make them look more distinct. I originally thought the top right panel was panel 2. The arrows are not helpful as they are currently displayed because it took me too long to realize they point to the next step in the procedure. Table 1 caption: “different” rather than “difference.” By “point of departure” do you mean “preferred parameter choices used in the statistical analysis?”

Response: For our revised manuscript we will produce a clearer version of Figure 4; in particular we will emphasize the fact that each panel in Figure 4 is labeled by the equation it corresponds to, and change the “point of departure” phase such that it clearly describes our preferences.

Final Response Update:
- The recommended edits have been made for Table 1’s caption

- The language of figure 4’s caption has been changed to make clear that the figure contains 3 panels, each of which corresponds to an equation in our methods section.

Assessing the Statistical Uniqueness of the Younger Dryas: A Robust Multivariate Analysis

Henry Nye[1] and Alan Condron[2]

[1]Department of Mathematics and Statistics, Haverford College, PA 19041
[2]Geology and Geophysics, Woods Hole Oceanographic Institution, MA 02543

Correspondence: Henry Nye (hnye@haverford.edu), Alan Condron (acondron@whoi.edu)

Abstract. During the last glacial period (c. 120-11 kyr BP), dramatic temperature swings, known as Dansgaard-Oeschger (D-O) events, are clearly manifest in high resolution oxygen isotope records from the Greenland ice sheet. Although variability in the Atlantic Meridional Overturning Circulation (AMOC) is often invoked, a unified explanation for what caused these 'sawtooth shaped' climate patterns has yet to be accepted. Of particular interest is the most recent D-O shaped climate pattern that occurred from ∼14,600 to 11,500 years ago - the Bølling/Allerød (BA) warm interstadial and the subsequent Younger Dryas (YD) cold stadial. Unlike earlier D-O stadials, the YD is frequently considered a unique event, potentially resulting from a rerouting and/or flood of glacial meltwater into the North Atlantic or a meteorite impact~~, or a volcanic eruption~~.Yet, these mechanisms are ~~seldom~~ less frequently considered as the cause of the earlier stadials. Using a robust multivariate outlier detection scheme - a novel approach for traditional paleoclimate research - we show that the pattern of climate change during the BA/YD is not statistically different from the other D-O events in the Greenland record, and that it should not necessarily be considered unique when investigating the drivers of abrupt climate change. Our results thus confirm the ambiguity of the BA/YD's trigger and present a novel statistical framework for paleoclimatic data analysis. ~~Our results thus raise important questions about the ability of glacial meltwater input and other 'one off' events to trigger abrupt, centennial-to-millennial length, changes in climate~~

1 Introduction

First noted in 1985 by Willi Dansgaard as "violent oscillations" in Greenland's DYE-3 and Camp Century oxygen isotope (δ^{18}O) records, Dansgaard-Oeschger (D-O) events are now well known examples of abrupt climate change during the last glacial period (c. 120-11 ky BP) (see Figure 1) (Dansgaard, 1985). These events are characterized by abrupt warmings of ∼ 8-16° C, a subsequent centennial-to-millennial length period of relative warmth (i.e. an interstadial), followed by a gradual, and sometimes abrupt, shift to cooler (stadial) conditions (Li and Born, 2019). Since their discovery three and a half decades ago, countless mechanisms have been proposed to explain D-O cycles (see Li and Born (2019) for a review). Although most hypotheses invoke changes in ocean heat transport as a consequence of variations in the strength of the Atlantic Meridional Overturning Circulation (AMOC) (Broecker et al., 1985), it remains poorly understood as to what would have caused the overturning cell to undergo such large and rapid changes (Lohmann and Ditlevsen, 2019). While variations in atmospheric circulation, sea ice extent, and ice shelf formation/collapse have all been hypothesized as triggers (Li and Born, 2019), a unifying theory has yet to emerge (Lohmann and Ditlevsen, 2018). Given that D-O events provide compelling evidence that the Earth's climate can rapidly switch from one state to another, it is imperative that we determine the causes of this variability if we are to accurately predict future climate.

In the original work of Dansgaard (Dansgaard, 1985), the most recent saw-tooth shaped interstadial stadial sequence of climate change since 120,000 years ago, associated with the Bølling-Allerød warming and Younger Dryas stadial (abbreviated here to BA/YD) from ∼14,600 to 11,700 years BP was labeled as D-O event 1 (Figure 1). Since then, however, a growing body of geological evidence attributing the Younger Dryas cooling to a glacial outburst flood and/or a change in glacial meltwater drainage patterns to the ocean (Broecker et al., 1989; Clark et al., 2001; Keigwin et al., 2018) has often led to this episode being treated as a unique event, rather than as one of the D-O stadials (Li and Born, 2019). Evidence that the YD cooling also might have coincided with a meteorite impact capable of 'blocking out' incoming solar radiation has helped bolster this notion (Firestone et al., 2007). ~~"one-time" events such as a meteorite impact (Firestone et al., 2007) and/or a large volcanic eruption (Baldini et al., 2018) capable of 'blocking out' incoming solar radiation has helped bolster this notion.~~ In this paper, we use a multivariate outlier method to re-examine the extent to which the BA/YD should be considered 'unique' in the context of the other D-O events. The motivation for this study derives from the remarkable similarities in shape (i.e. deviation from center over its timespan) between the BA/YD and other D-O events within the last 120,000 years, which leads us to question the uniqueness of the BA/YD in the Greenland record. Our approach is particularly novel for traditional paleoclimate research and we argue for the increased implementation of similarly robust statistical methods in future research. Indeed, the application of our statistical method to assessing the 'BA/YD uniqueness' is just one example given that it is exceptionally useful when synthesizing and compare climate records that are both uncertain and complex. It should also be noted that modeling studies suggest that forced and unforced AMOC variations have very similar signatures (Brown and Galbraith, 2016), so the outlier detection technique is not aimed to assess the qualities of D-O events as they result from specific triggers, but rather to provide a framework for situating the BA/YD within a broader context of many other D-O events, each of which may (or may not) have the same underlying trigger.

2 Methods

To study abrupt decadal-to-multidecadal changes in climate associated with each of the Dansgaard-Oeschger events, we examined published changes in oxygen isotope ratios (δ^{18}O) and methane (CH_4) from the NGRIP Greenland ice cores (Rasmussen et al., 2014; Baumgartner et al., 2014) and δ^{18}O and carbon dioxide (CO_2) changes from the EDML, WAIS, Siple Dome, and TALDICE ice cores recovered from Antarctica (Barbante et al., 2006; Bereiter et al., 2015) that span the last 120,000 years of Earth's climate history. Our EDML record uses the GICC05 age scale, and it was chosen because it has a spatial resolution comparable with the Greenland ice core records. Indeed, the snow accumulation at EDML is two to three times higher than at other deep drilling sites on the East Antarctic plateau, so higher-resolution atmosphere and climate records can be obtained for the last glacial period, making the EDML core especially suitable for studying decadal-to-millennial climate variations in Antarctica. Including EDML δ^{18}O allows us to observe changes in NGRIP δ^{18}O as distinct in location but similar in meaning. This allows us to make conclusions about how the BA/YD may not have been a unique event in Greenland, but perhaps was so in the southern Atlantic. In general, our choice of records is based on those with the highest spatial resolution and tradition in the field of paleoclimatology of using these to study climate variability during both D-O events and the BA/YD. The high temporal resolution of the ice cores during the last glacial period makes them idea for use in our work. Furthermore, we use both δ^{18}O records (NGRIP and EDML) to provide local approximations of climate, whereas CH_4 and CO_2 are more indicative of global hydrology and temperature, respectively.

For the purposes of our study, the timing of each Dansgaard-Oeschger event is taken from the ages published in the INTIMATE (INTegration of Ice-core, MArine and TErrestrial records) dataset in Table 2 of Rasmussen et al. (2014). We then develop a stratigraphy that emphasizes the large-scale Dansgaard-Oeschger variability as follows: Firstly, as several interstadials in the INTIMATE record of Rasmussen et al. (2014) comprise of sub-events labeled by lowercase letters, for our work we consider these to be part of the larger interstadial, and not unique events. For example, while Greenland Interstadial 1 (i.e. the BA interstadial) comprises of sub-events GI-1a through GI-1e, in our analysis this is simply treated as GI-1. A second set of sub-events in the INTIMATE dataset are also denoted by decimals in Rasmussen et al. (2014). For example, Dansgaard-Oeschger event 2 in the INTIMATE dataset is separated into two sub-events, labeled GS 2.1/GI2.1 and GS 2.2/GI 2.2. Due to their generally high amplitude and tendency to span multi-centennial timescales, these sub-events must at least initially be considered as Dansgaard-Oeschger ‘candidates’, and thus require a more rigorous procedure to be dealt with. Firstly, we consider cases when two sub-events occur in succession and define a duration-based algorithm to determine whether each one should be considered a separate Dansgaard-Oeschger event, both combined into one single event, or omitted from our analysis entirely (Figure 2).

Of the eight Dansgaard-Oeschger events in this period containing two sub-events - namely numbers 2, 5, 15, 16, 17, 19, 21, and 23 - our main analysis ~~- which is founded on conservative duration parameter choices (x = 300 yrs, y = 300 yrs, z = 200 yrs) -~~ leads to the selection of stadial and interstadials found in Table 1. The selection of these events is based on using duration parameter choices: $x = 300$ yrs, $y = 300$ yrs, $z = 200$ yrs, which are at the shorter end of what has previously been accepted as the length of a stadial or interstadial (e.g. Rasmussen et al. (2014)), but our results are not very sensitive to the chosen length. For example, columns 2-3 of Table 1 show that altering these parameters to $(x, y, z) = (90, 100, 140)$ or $(x, y, z) = (90, 100, 90)$ yields results that are 86-93% similar.

Taking D-O event 2 as an example, we observe that GI2.2, GS2.2, and GI2.1 span 120, 200, and 120 years respectively, and thus the algorithm in Figure 2 leads to the combination of GI2.2, GS2.2, and GI2.1 into a single interstadial, since the sub-events are less than the parameter choices $x = 300, y = 300, z = 200$ respectively. In D-O event 5, however, GI5.2, GS5.2, and GI5.1 span 460, 1200, and 240 years, respectively, and thus under the same parameter choices, the interstadial-stadial choice algorithm in Figure 2 dictates that each sub-event should be treated as its own stadial or interstadial. Note that our final results differ minimally based on how sub-cycles are chosen.

Beyond ∼104 kyr BP, the CO_2 record contains only one data point for about every 500 years. Thus, to ensure the existence of a well-defined and complete record for our chose data, we restrict our analysis of the last glacial cycle to the period of 104-11 kyr BP containing D-O events 1-23. Of the eight containing sub-events, our algorithm discards the second sub-event of four D-O events (i.e., 16.2, 17.2, 21.2, and 23.2), includes two second sub-events as distinct (i.e., 5.2 and 19.2), absorbs GI15.1 into the sub-stadials surrounding it, and absorbs GS2.2 into the sub-interstadials surrounding it (see Table 1 for the algorithm's decisions for other parameter values). This amounts to the consideration of 25 D-O events, four of which are sub-events (i.e., events 5.1, 5.2, 19.1, and 19.2).

To initially examine the uniqueness of the pattern of climate change during Dansgaard-Oeschger event 1 (the BA/YD), we overlaid the NGRIP δ^{18}O record of each D-O event over the BA/YD. To better visualize and compare the shape of each D-O event, we normalized the timescale that covers each D-O event and centered each record at its median. Here the term “normalizing" refers to stretching/shrinking the time over which each D-O event occurred to a consistent number of years, and “centering" to positioning each D-O event in time space by subtracting the median value of each record during each D-O event. We then narrowed down the number of D-O events (including BA/YD) by visually selecting those events that most closely resembled the pattern of NGRIP δ^{18}O during the BA/YD. This process does not apply to the statistical analysis that follows in which all 25 events were included, but as preliminary evidence for the fact that the BA/YD's shape in the context of the Greenland records is not unique in terms of the general shape of many D-O events.

In our second, arguably more important line of analysis, we investigate rigorously the shape (i.e. time evolving variability) of each of our chosen climate records (NGRIP δ^{18}O, EDML δ^{18}O, compiled Antarctic CO_2, and NGRIP CH_4) during all Dansgaard-Oeschger events (25 including the BA/YD) using a PCOut procedure by calculating (i) the magnitude of change from interstadial to stadial (peak-to-trough analysis), (ii) the rate and direction (slope) of change of each record during each stadial, and (iii) the median value of each record during each stadial. Measurements (ii) and (iii) were considered only for stadial periods due to their known volatility and clear definition in the record. When measurement (ii) was taken on the interstadial data, no significant variation was found. When measurement (iii) was taken on the interstadial data, it mirrored (iii) from the stadial periods, and was thus unnecessary. In our peak-to-trough analysis, we derived a measure of the amplitude of change from the interstadial to the stadial by calculating the difference between the mean of the warmest interstadial points and the mean of the coldest stadial points for each D-O event in the NGRIP δ^{18}O record. To ensure that the peak interstadial warmth and maximum stadial cooling are selected, the mean values are calculated using only the upper and lower 10% of the δ^{18}O values, respectively (Figure 3). We calculate this peak-to-trough measure for the other three records by taking the difference of the mean of its values within the time window of NGRIP δ^{18}O's maximum (minimum) 10% interstadial (stadial) values, acknowledging that some age uncertainty between the records may be present. However, the nature of these age uncertainties is not well known, so we use the aforementioned average of 10% maxima and minima as a robust protection against any age uncertainty. For some records, where no data exists in a given short interstadial (stadial) time window, we take the maximum (minimum) of a 300 year moving gaussian filter (250yr for CO_2, in order to give higher weight to each of the sparser points in the dataset), and while not ideal, it is the best approximation that our data limitations can offer.

We estimated the linear slope, and thus overall rate and direction of change, of each record during each of the stadials using ordinary least squares (OLS) regression. In many cases the NGRIP δ^{18}O record behavior during stadial periods is generally flat, so records with highly negative peak-to-trough measurements and stadial slopes close to zero are a good indicator of Dansgaard-Oeschger event behavior. Finally, the median of each record for each stadial in our analysis was calculated. The values of each of these metrics for each record across all 25 chosen D-O events are shown in Tables 2 and 3. It should be noted that all of the above stated measurements are robust to age uncertainties of at least 100 years. Thus, we can be fairly confident that age and delta age uncertainties will not wildly skew our results.

A robust principal component based outlier detection method, entitled PCOut, based on Filzmoser et al. (2008), was then applied to the results from our three metrics to test if the BA/YD is statistically different from other D-O events. This algorithm is proven to be efficient in high dimensions and especially effective in identifying location outliers, which is ideal for our data. We accept PCOut's slightly higher amount of false positives (i.e., higher size) than other algorithms on the basis that its extremely low level of false negatives (i.e., high power) is more important for this study since the areas in which the Younger Dryas is not unique is of particular interest. PCOut differs from typical principal component analysis schemes in two ways: 1) it robustly transforms the data before extracting principal components, and 2) it computes two measures of variance: one based on location and the other based on scatter. In short, PCOut first shifts an $n \times p$ data array by its variable-wise median and scales it by its variable-wise median absolute deviation (MAD), both of which are more robust (i.e., error resistant) estimators of location and scale (respectively) than sample mean and variance (Filzmoser et al., 2008). In our case, we let $n = 25$ correspond to the number of D-O event observations, and let $p = 12$ variables denote the result of obtaining the three aforementioned metrics on each of the four records (NGRIP δ^{18}O, CH_4, and δ^{18}O and CO_2 from Antarctica). PCOut then performs a standard principal component analysis (PCA) procedure to the transformed data that retains the first p^* components contributing 99% of the data's variance, and subsequently shifts and rescales the principal components once again by their new median and MAD. For an estimate of location exceptionality, PCOut is programmed to weight each of these resulting components z^*_{ij} by the following robust measure of kurtosis,

$$w_j = \left| \frac{1}{n} \sum_{i=1}^{n} \frac{(z^*_{ij} - \mathrm{med}(z^*_{1j}, \ldots, z^*_{nj}))^4}{\mathrm{MAD}(z^*_{1j}, \ldots, z^*_{nj})^4} - 3 \right| \text{ for } j = 1, \ldots, p^* \tag{1}$$

and then computes a robust Euclidian distance RD_i for each of the n data points using these weights, where $W = \sum_{j=1}^{p^*} w_j$, the total weight, and the z^*_{ij} are the location shifted and rescaled principal components (visualized in panel 1, Figure 4):

$$RD_i = \sqrt{\sum_{j=1}^{p^*} \left(\frac{z^*_{ij} w_j}{W} \right)^2}. \tag{2}$$

This is followed by a further transformation to acquire the final robust distances d_i, where $\chi^2_{p^*,0.5}$ is the 50th percentile of a chi-squared distribution with p^* degrees of freedom:

$$d_i = RD_i \cdot \frac{\sqrt{\chi^2_{p^*,0.5}}}{\text{med}(RD_1,\ldots,RD_n)}. \tag{3}$$

These d_i's represent the degree of separation each of the n data points (corresponding to D-O cycles) experiences from the center of the data, where each RD_i is a robust calculation of the ith data vector's distance from its variable-wise median. Dividing by the median of the RD_i's as in eq. 3 measures how much each RD_i deviates from the median of all such distances. To evaluate these distances as outliers or non-outliers, each data point is assigned a weight a_i based on its distance d_i such that higher distances receive a smaller weight so as to avoid outlier masking (visualized in panel 2, Figure 4):

$$a_i = \begin{cases} 0 & d_i \geq c \\ \left(1 - \left(\frac{d_i - M}{c - M}\right)^2\right)^2 & M < d_i < c \\ 1 & d_i \leq M \end{cases}. \tag{4}$$

For this a_i weight, the parameter M is the $\frac{1}{3}$ quantile of the distances $\{d_i\}$, and

$$c = \text{med}(d_1,\ldots,d_n) + 2.5 \cdot \text{MAD}(d_1,\ldots,d_n). \tag{5}$$

Finally, PCOut defines another metric b_i for each data point that uses the same exact procedure minus the kurtosis weighting step (i.e., unweighted euclidian distance $\sqrt{\sum_{j=1}^{p^*}\left(\frac{z^*_{ij}}{W}\right)^2}$ substitutes for eq. 2). Since the non-kurtosis weighted d_i are proven to follow $\chi^2_{p^*}$ relatively closely, $(M^2, c^2) = (\chi^*_{p^*,.25}, \chi^*_{p^*,.99})$ in eq. 4's calculation of b_i. In the final test (visualized in panel 3, Figure 4), outliers are then defined as data points where

$$\frac{(a_i + 0.25)(b_i + 0.25)}{(1.25)^2} < 0.25. \tag{6}$$

PCOut achieves much higher precision than a traditional principal component analysis scheme because of the strategic weighting mechanisms aimed to iteratively reduce the degree which outliers mask their own presence (Filzmoser et al., 2008). Further, its use of robust statistical estimators suits our constructed dataset well in that the metrics calculated are subject to high uncertainty. For a graphical representation of PCOut's data transformations spanning eq.'s 2-6, see Figure 4.

PCOut is not applicable to single variable data because principal component analysis is not a valid procedure for $p = 1$, so outliers in this case are determined using a simpler criterion: if some data point $x_i \notin [Q_1 - \text{MAD}(x_1,\ldots,x_n), Q_3 + \text{MAD}(x_1,\ldots,x_n)]$, where Q_1, Q_3 are the first and third quantiles of the data, respectively, it is considered an outlier.

3 Results

Figure 5 shows that the changes in the NGRIP δ^{18}O record during the BA/YA bear a remarkable similarity to the seven D-O events (namely events 7, 8, 11, 12, 13,16, and 19.2) visually selected. Furthermore, the overlay of mean behavior of all D-O events excluding the BA/YD (i.e. 24 as opposed to just the 7 visually selected) corroborates that the BA/YD period is strikingly similar in NGRIP δ^{18}O shape to the average D-O event. In each case, we observe the classic D-O 'sawtooth' pattern that is characterized by an abrupt warming at the onset of interstadial conditions, followed by a more gradual cooling and return to stadial conditions. These overlays are also completed for the other three records (i.e. CH_4 from Greenland, compiled CO_2 from Antarctic, and δ^{18}O from EDML). Beginning with NGRIP CH_4, Figure 5 indicates no clear overall pattern to the D-O time series, as the mean line is nearly flat. This confirms a similar lack of uniqueness in BA/YD's CH_4 record, which our PCOut analysis will later confirm as well. The BA/YD appears not to strictly follow the trend of the seven time series lines or mean line in the two Antarctic record overlays (EDML δ^{18}O and CO_2), which indicates that further study is required to determine how the BA/YD might constitute an exceptional event from the perspective of these records.

The results from our PCOut analysis allows for additional categorization of the Younger Dryas either as outlier or non-outlier in all variable subsets when equipped with our three metrics applied to four different chemical record for all 25 D-O cycles under consideration. The rationale for observing the Younger Dryas' outlier behavior in particular subsets of the 12-variable system is to understand how record subset (NGRIP δ^{18}O, NGRIP CH_4, EDML δ^{18}O, compiled Antarctic CO_2), record shape (peak-to-trough, stadial slope), and record location (median), might individually render the the data for this period unique (or not unique). Given PCOut's low level of false negatives compared to other tests of its kind, we take non-outlier results seriously as indicators that Younger Dryas is not statistically exceptional as a D-O event. Relevant results pertaining to the BA/YD are summarized in Table 4, which indicates the subsets of records and metrics for which the BA/YD is an outlier or not - "YES" ("NO") means that the BA/YD is (not) an outlier within that subset. Note we are specifically looking for subsets of records that PCOut identifies as non-outliers, and are not seeking compare the results of such subsets to one another. Thus, the temptation to tally the results should be resisted - this is not a statistically sound way of determine outlier behavior on a large scale.

Beginning with single variable results, we find that all but two cells in the median column (column 4) of Table 4 exhibit outlier behavior. This result is unsurprising given that the BA/YD occurs during a period of overall warming closer to the Holocene and thus higher percentages of all chemical records compared to other D-O events, which all occurred during the coldest stretches of the past 120 kyr. Median measurements for other D-O cycles on the edges of the last glacial period also harbor a proportionally higher level of median measurements due to their temporal proximity to warmer periods before and after the last glacial period. In fact, we find that the this same table of median-only PCOut results for D-O events 2, 20, and 23 harbor 47%, 60%, and 53% outliers, respectively, which indicates that we can consistently expect subsets of measurements including the median to be greater for D-O events near the beginning and end of the last glacial period. Thus, we attribute the a portion of the BA/YD's outlier behavior in variable subsets including the median to a known temperature increase during the time of its occurrence.

In the single variable stadial slope column (column 3, Table 4), we find particular interest in the fact that all pairs of records including NGRIP $\delta^{18}O$ (rows 6-8) do not register as outliers, while all pairs of records not including NGRIP $\delta^{18}O$ (rows 9-11) do register as outliers. This exact phenomenon is also reflected in the paired peak-to-peak and stadial slope column (column 1, Table 4), strongly indicating that the presence of NGRIP $\delta^{18}O$ within a given variable subset is associated with a lack of outlier behavior of the shape of the BA/YD. The other two pairs of metrics (columns 3-4, Table 4) exhibit no clear pattern, although it should be noted that the single and paired Greenland proxies (rows 8, 12, and 15) register as outliers in only one of their cells.

It must be noted that 80% of proxy subsets in the first (all-metric) column of Table 4 register as outliers within their distribution. While this result should be taken with skepticism due to the inclusion of the median, which has been seen to contribute significantly to outlier behavior in numerous other cases, it should not be ignored that the BA/YD is an outlier under all of our metrics and proxies combined.

Our main goal is to assess the exceptionality of the BA/YD in the Greenland record. While the single record NGRIP $\delta^{18}O$ section (row 12, Table 4) exhibits a mix of measured outliers and non-outliers, it must be taken into account that all variable subsets in this row that cause the BA/YD to become an outlier contain the median measurement, which, as previously stated, contributes significantly to the BA/YD's outlier behavior due to known warming leading up to the Holocene.

The single record NGRIP CH_4 row (row 15, Table 4) exhibits no outlier behavior whatsoever across the relevant variable subsets. This record generally follows the shape of its NGRIP $\delta^{18}O$ counterpart, yet often seems to lag or lead $\delta^{18}O$ by centennial timescales (Baumgartner et al., 2014), inevitably causing higher variance in shape metrics chosen in this study. So, a lack of outlier behavior across all NGRIP CH_4 subsets primarily indicates that Younger Dryas' lag in CH_4 is not unusual.This lack in the NGRIP CH_4 single variable median category is also somewhat surprising, and suggests that the magnitude of CH_4 amongst all D-O cycles is less closely tied to glacial-interglacial cycles than NGRIP $\delta^{18}O$.

Observing the two NGRIP ($\delta^{18}O$, CH_4) records paired across all metric subsets (row 8, Table 4) leads to further interest: namely, no outlier behavior in metrics other than the pure median exists. Since much of the ice-core based knowledge generated on the Younger Dryas relies on these two records, a lack of outlier behavior in shape is a major result, and confirms our analysis of Figure 5. Thus, the fact that the pair of behaviors of $\delta^{18}O$ and CH_4 during the BA/YD is not unique compared to the pair of behavior for these records in other D-O events is a stronger conclusion than if we were to restrict this analysis to only one record from Greenland. We observe this in the scatterplots of Figure 6, which plot the value of pairs of metrics for the Greenland shape measurements across all 25 D-O events, and clearly indicate that for each such pair, the BA/YD is within the natural scatter range of all other D-O events. In particular, notice that for the paired peak-to-trough scatterplots (third panel down from first column of Figure 6), the distribution of points roughly forms a ring of which BA/YD is a part, since there is always at least one other point in the plot that is more outlying in either direction. Similarly, in the paired slope scatterplots (fourth panel down from second column of Figure 6), the distribution of points forms a roughly straight line of which the BA/YD is also a part. In fact, these plots provide an excellent example of what an outlier would look like, namely, the point far to the far right of all others in this plot, which turns out to be D-O 23. In sum, if the shape of the BA/YD were an outlier in the Greenland record, these scatter plots would display a clear separation of the BA/YD from all other points in the scatter.

Furthermore, it should be noted that this same PCOut procedure was applied to all other D-O cycles under consideration. No clear trends were found amongst these events as a whole, but two main observations can be made. Firstly, and most importantly, it should be noted that no event exhibited non-outlying behavior isolated within the Greenland shape data as did the BA/YD. This suggests that later research may be successful in proving that the BA/YD's data from Antarctic sources is uniquely shaped as compared to other D-O events. Secondly, we find that most data subsets for D-O events in the middle of our timescale (c. 49-28 ky BP) are overwhelmingly non-outlying, whereas data subsets associated with D-O events on the tails of our timescale are more sporadically outlying and non-outlying. From this we might conclude that the period spanning D-O 3 to D-O 13 generally consisted of regular and "typical" D-O events, whereas D-O events not in this period either have average higher temperature (as previously discussed) or other inconsistencies. This observation does not, however, negate the conclusion that the BA/YD's Greenland data is non-outlying.

Note that we use the stadial/interstadial length parameters $(x, y, z) = (300, 300, 200)$ to choose 25 D-O cycles for this section, but different parameter choices that output 28-30 D-O cycles for analysis (see Table 1) yield results that are 86-93% similar across all D-O cycles. We find this by applying PCOut to all subsets of the 28 and 30 cycle versions of our algorithm output created by implementing the parameters in columns 2 and 3 of Table 1, then comparing the results to our chosen version.

4 Discussion

The aim of this study is to precisely and robustly classify the record-based qualities that would render the BA/YD a unique climate event in the context of other abrupt episodes of climate change during the last 120,000 years, known as Dansgaard-Oeschger events. If the BA/YD is to be excluded from the list of D-O events, or assigned its own particular set of triggering mechanisms there must be some statistically sound reason for doing so.

Using four chemical records commonly included in assessments of general D-O behavior - δ^{18}O and CH_4 from NGRIP, Greenland, δ^{18}O from EDML, Antarctica, and compiled CO_2 from multiple Antarctic records - we refrain from performing traditional cross correlation analysis to test for lags, and instead employ a more holistic approach that captures the shape of each D-O cycle in terms of multiple variables. Three measurements to characterize both the location (median) and shape (peak-to-trough difference, stadial slope) of each chemical record for each D-O cycle are taken, and inputted into a robust principal component analysis algorithm (PCOut) to test for outliers.

Our main result is as follows: the observed data for the BA/YD is not a unique compared to that of the other D-O events recorded in the Greenland ice core record, other than the fact that its median δ^{18}O levels are higher due to its proximity to deglacial warming into the Holocene. The increase in median δ^{18}O is also not unique to the BA/YD, as D-O events 2, 20, and 23 exhibit a similar phenomenon, which we attribute to their occurrence proximal to long term global climate fluctuations. The non-uniqueness of the BA/YD's shape is clearly indicated by the statistical indistinguishability of the changes in the Greenland ice core record with the other D-O events, especially in terms of its δ^{18}O variability, for which one-third of other D-O events appear virtually identical (Figure 5). Thus, the BA/YD's data cannot and should not be distinguished from any other D-O cycle in the last glacial period on the basis of Greenland ice core time series shape. In this context, the BA/YD could be understood as a classic example of a D-O event, and deserves further consideration as such when studying the mechanisms that triggered it. The hypothesized meltwater forcing mechanism sometimes invoked for the BA/YD is seldom considered for the other D-O events, and visa versa, the major triggering mechanisms for the D-O events are rarely used to explain the BA/YD. Our results suggest that understanding the causes of the BA/YD would benefit from examining the mechanisms used to explain D-O events, rather than relying on the meltwater hypothesis. Indeed, the role of meltwater forcing in triggering the YD has been questioned a number of times since it was first proposed by W. Broecker and others in 1989. For instance, the YD is widely viewed as a time of glacial re-advance and reduced terrestrial meltwater discharge to the ocean, such that it is likely that freshwater forcing was less during this period (Abdul et al., 2016), making it difficult to explain how the overturning circulation remained weakened for the 1000 year duration of the YD stadial (Renssen et al., 2015). In addition, the termination of the YD, and subsequent rapid warming into the Holocene coincide with a time of increasing meltwater runoff to the North Atlantic (e.g. Fairbanks (1989)) as the Laurentide Ice sheet over North America finally collapsed.

Data availability. Measurements for this project can be found in Tables 2 and 3.

Author contributions. Author 1 conducted all data analysis, figure creation, and manuscript drafting. Author 2 advised throughout the research process and edited manuscript as necessary.

Competing interests. The authors declare that they have no conflict of interest.

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References

Abdul, N. A., Mortlock, R. A., Wright, J. D., and Fairbanks, R. G.: Younger Dryas sea level and meltwater pulse 1B recorded in Barbados reef crest coral Acropora palmata, Paleoceanography, 31, 330–344, https://doi.org/10.1002/2015PA002847, 2016.

Barbante, C., Barnola, J.-M., Becagli, S., Beer, J., Bigler, M., Boutron, C., Blunier, T., Castellano, E., Cattani, O., Chappellaz, J., Dahl-Jensen, D., Debret, M., Delmonte, B., Dick, D., Falourd, S., Faria, S., Federer, U., Fischer, H., Freitag, J., Frenzel, A., Fritzsche, D., Fundel, F., Gabrielli, P., Gaspari, V., Gersonde, R., Graf, W., Grigoriev, D., Hamann, I., Hansson, M., Hoffmann, G., Hutterli, M. A., Huybrechts, P., Isaksson, E., Johnsen, S., Jouzel, J., Kaczmarska, M., Karlin, T., Kaufmann, P., Kipfstuhl, S., Kohno, M., Lambert, F., Lambrecht, A., Lambrecht, A., Landais, A., Lawer, G., Leuenberger, M., Littot, G., Loulergue, L., Lüthi, D., Maggi, V., Marino, F., Masson-Delmotte, V., Meyer, H., Miller, H., Mulvaney, R., Narcisi, B., Oerlemans, J., Oerter, H., Parrenin, F., Petit, J.-R., Raisbeck, G., Raynaud, D., Rothlisberger, R., Ruth, U., Rybak, O., Severi, M., Schmitt, J., Schwander, J., Siegenthaler, U., Siggaard-Andersen, M.-L., Spahni, R., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J.-L., Traversi, R., Udisti, R., Valero-Delgado, F., van den Broeke, M. R., van de Wal, R. S. W., Wagenbach, D., Wegner, A., Weiler, K., Wilhelms, F., Winther, J.-G., Wolff, E., and Members, E. C.: One-to-one coupling of glacial climate variability in Greenland and Antarctica, Nature, 444, 195–198, https://doi.org/10.1038/nature05301, 2006.

Baumgartner, M., Kindler, P., Eicher, O., Floch, G., Schilt, A., Schwander, J., Spahni, R., Capron, E., Chappellaz, J., Leuenberger, M., Fischer, H., and Stocker, T. F.: NGRIP CH4 concentration from 120 to 10 kyr before present and its relation to a δ^{15}N temperature reconstruction from the same ice core, Climate of the Past, 10, 903–920, https://doi.org/10.5194/cp-10-903-2014, 2014.

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and Chappellaz, J.: Revision of the EPICA Dome C CO2 record and 800 and 600 kyr before present, Geophysical Research Letters, 42, 542–549, https://doi.org/10.1002/2014GL061957, 2015.

Broecker, W. S., Peteet, D. M., and Rind, D.: Does the ocean-atmosphere system have more than one stable mode of operation?, Nature, 315, 21–26, https://doi.org/10.1038/315021a0, 1985.

Broecker, W. S., Kennett, J. P., Flower, B. P., Teller, J. T., Trumbore, S., Bonani, G., and Wolfli, W.: Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode, Nature, 341, 318–321, https://doi.org/10.1038/341318a0, 1989.

Brown, N. and Galbraith, E. D.: Hosed vs. unhosed: interruptions of the Atlantic Meridional Overturning Circulation in a global coupled model, with and without freshwater forcing, Climate of the Past, 12, 1663–1679, https://doi.org/10.5194/cp-12-1663-2016, https://cp.copernicus.org/articles/12/1663/2016/, 2016.

Clark, P. U., Marshall, S. J., Clarke, G. K. C., Hostetler, S. W., Licciardi, J. M., and Teller, J. T.: Freshwater Forcing of Abrupt Climate Change During the Last Glaciation, Science, 293, 283–287, https://doi.org/10.1126/science.1062517, 2001.

Dansgaard, W.: Greenland Ice Core Studies, Palaeogeograpy, Palaeoclimatology, Palaeoecology, 50, 185–187, 1985.

Fairbanks, R. G.: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation, Nature, 342, 637–642, 1989.

Filzmoser, P., Maronna, R., and Werner, M.: Outlier identification in high dimensions, Computational Statistics and Data Analysis, 52, 1694 – 1711, https://doi.org/10.1016/j.csda.2007.05.018, 2008.

Firestone, R. B., West, A., Kennett, J. P., Becker, L., Bunch, T. E., Revay, Z. S., Schultz, P. H., Belgya, T., Kennett, D. J., Erlandson, J. M., Dickenson, O. J., Goodyear, A. C., Harris, R. S., Howard, G. A., Kloosterman, J. B., Lechler, P., Mayewski, P. A., Montgomery, J., Poreda, R., Darrah, T., Hee, S. S. Q., Smith, A. R., Stich, A., Topping, W., Wittke, J. H., and Wolbach, W. S.: Evidence for an extraterrestrial impact

12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling, Proceedings of the National Academy of Sciences, 104, 16 016–16 021, https://doi.org/10.1073/pnas.0706977104, 2007.

Keigwin, L. D., Klotsko, S., Zhao, N., Reilly, B., Giosan, L., and Driscoll, N. W.: Deglacial floods in the Beaufort Sea preceded Younger Dryas cooling, Nature Geoscience, 11, 599–604, https://doi.org/10.1038/s41561-018-0169-6, 2018.

Li, C. and Born, A.: Coupled atmosphere-ice-ocean dynamics in Dansgaard-Oeschger events, Quaternary Science Reviews, 203, 1 – 20, https://doi.org/10.1016/j.quascirev.2018.10.031, 2019.

Lohmann, J. and Ditlevsen, P. D.: Random and externally controlled occurrences of Dansgaard–Oeschger events, Climate of the Past, 14, 609–617, https://doi.org/10.5194/cp-14-609-2018, 2018.

Lohmann, J. and Ditlevsen, P. D.: Objective extraction and analysis of statistical features of Dansgaard–Oeschger events, Climate of the Past, 15, 1771–1792, https://doi.org/10.5194/cp-15-1771-2019, 2019.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, P., Vinther, B. M., Walker, M. J., Wheatley, J. J., and Winstrup, M.: A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy, Quaternary Science Reviews, 106, 14 – 28, https://doi.org/10.1016/j.quascirev.2014.09.007, 2014.

Renssen, H., Mairesse, A., Goosse, H., Mathiot, P., Heiri, O., Roche, D., Nisancioglu, K., and Valdes, P.: Multiple causes of the Younger Dryas cold period, Nature Geoscience, https://doi.org/10.1038/ngeo2557, 2015.

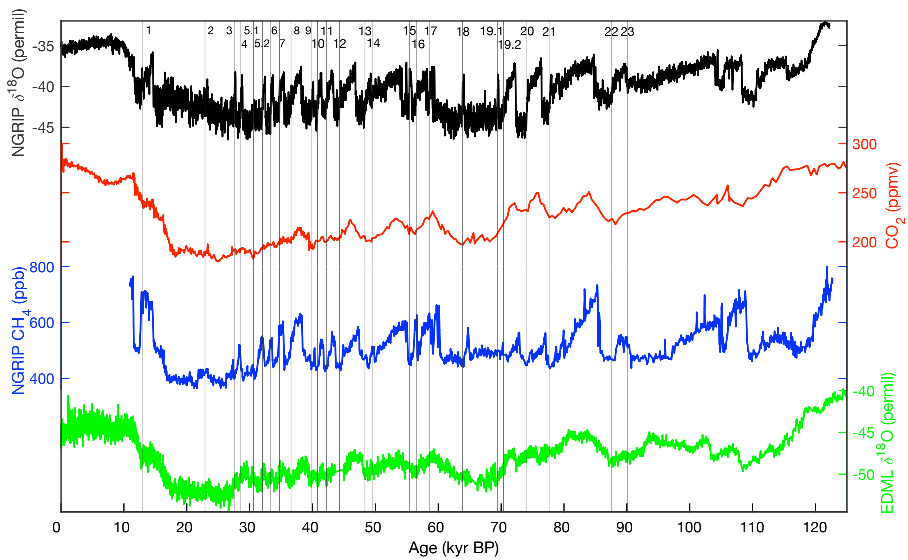

Figure 1. Full time series of all four records used. From top down: NGRIP $\delta^{18}O$, compiled CO_2 from EDML, WAIS, Siple Dome, and TALDICE, NGRIP CH_4, and EDML $\delta^{18}O$. Vertical lines indicate the main 25 interstadial-to-stadial transitions used in this study, labeled by number from Rasmussen et al. (2014).

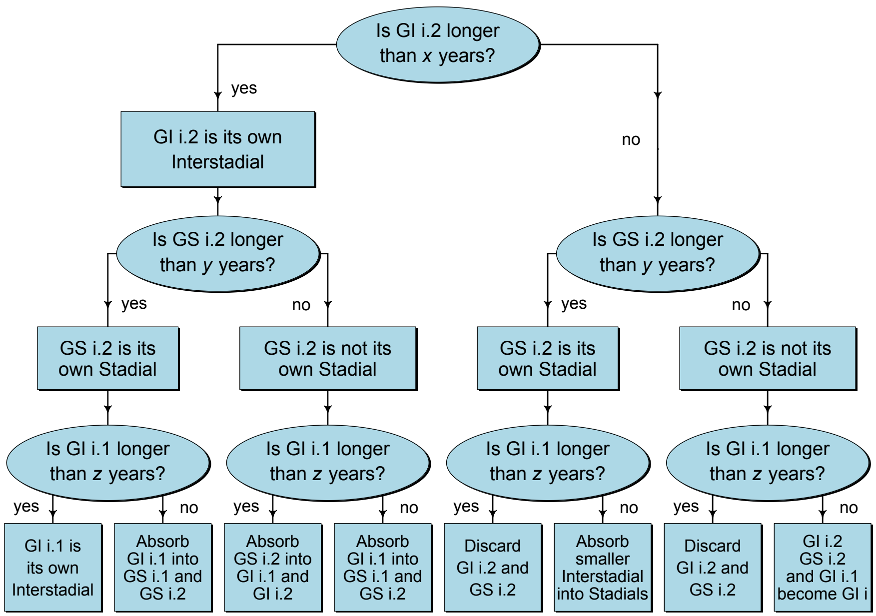

Figure 2. Duration-based scheme for including D-O cycles in analysis. Given the variety of climatic shifts present in the high-resolution INTIMATE NGRIP δ^{18}O stratigraphy, it is necessary to form a rigorous criterion for choosing D-O events to analyze. Since the duration of each D-O event in the INTIMATE stratigraphy is directly tied to the confidence that it exhibit the true characteristics of a D-O interstadial (stadial) period, we employ the above decision tree for determining which warm/cold couples split up by the INTIMATE stratigraphy can confidently be considered their own unique D-O events with flexible duration parameters (x, y, z).

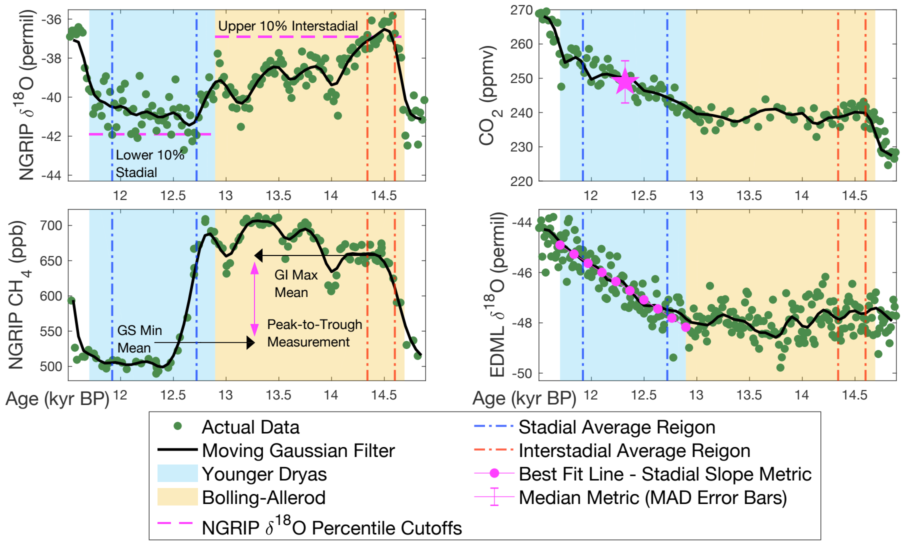

Figure 3. Three metrics for capturing the shape and location of D-O cycles across multiple paleoclimate records. In all panels, raw data is presented in green, while interpolated data using a 300yr moving gaussian filter (250yr for CO_2, given sparsity of data at points) is presented in black. Blue and orange background shading represents stadial and interstadial conditions, respectively, while pink overlays demonstrate the three measurements taken: in the NGRIP δ^{18}O panel (upper left), the extreme 10% percentiles of the δ^{18}O data are determined, and the time window into which all such data falls are extracted (blue (Stadial) and red (Interstadial) vertical average regions). The difference in means of each record's data within these time windows for any given D-O cycle constitutes our peak-to-trough (labeled peak-to-peak) measurement (shown in lower left NGRIP CH_4 panel). The OLS linear slope of the stadial data determines the stadial slope for each record in each D-O cycle (shown in the lower right EDML δ^{18}O panel). The third and final metric measured is the stadial median (shown in the upper right panel). Despite each panel only displaying one metric, all are applied to the four records examined for all D-O events.

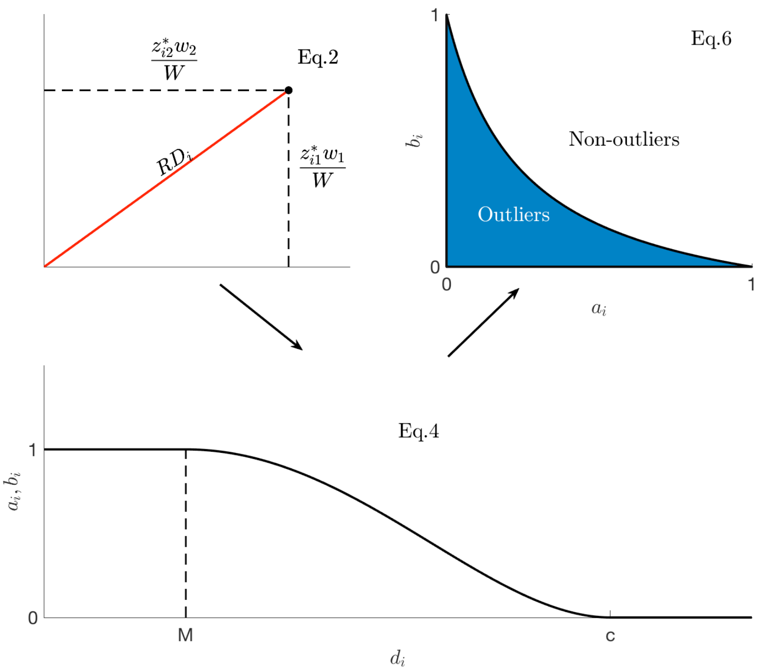

Figure 4. PCOut's main outlier decision steps. After completing PCA to produce centered and rescaled components z^*_{ij}, eq. 2 calculates the "distance" RD_i of the ith component vector from zero with sums of squares (panel 1, top left). After rescaling the RD_i's to create new "distances" d_i, we calculate quantities a_i, b_i based on the function in the bottom panel 2 (eq. 4), such that large distances d_i translate into smaller values of a_i, b_i. Finally, panel 3 (top right) illustrates the region by which PCOut classifies a_i, b_i as indicative of the ith datapoint being an outlier or not (eq. 6).

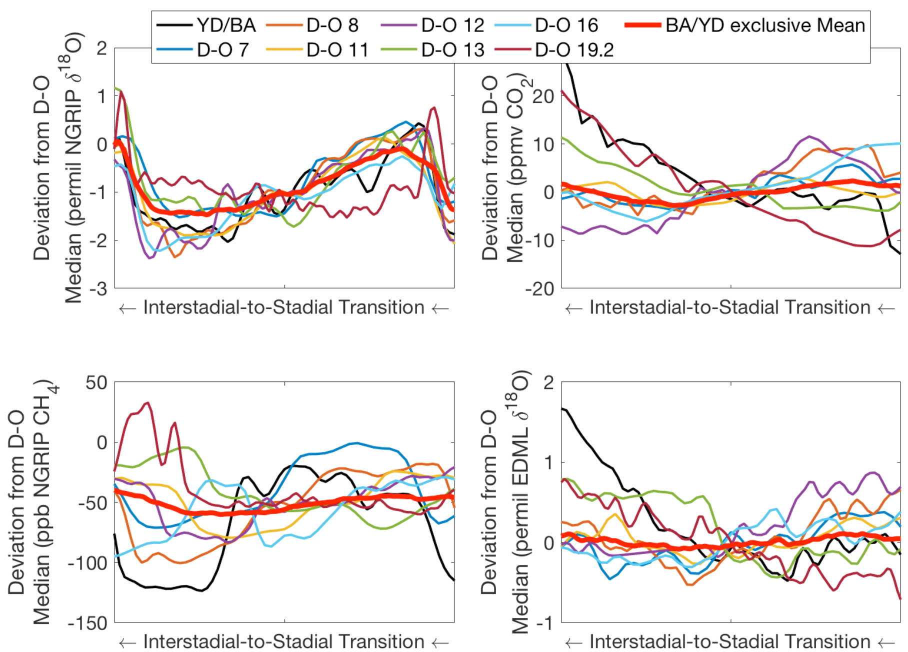

Figure 5. Shapes of eight D-O events and grand mean (excluding the BA/YD) with respect to all four records. Representing one-third of D-O events during the last glacial period, these D-O events' respective NGRIP δ^{18}O records bear remarkable similarity to that of the BA/YD, despite assumptions of its uniqueness. Additionally, the BA/YD exclusive mean of D-O events' NGRIP δ^{18}O record confirms that the shape of the BA/YD does not visibly deviate from the classic D-O shape. Further, Antarctic records (CO_2 and EDML δ^{18}O, second column) show varying trends that do not appear particularly synchronized to the D-O sawtooth shape. NGRIP CH_4 exhibits D-O-like variability, with varying leads and lags. Note: time moves right to left in this figure.

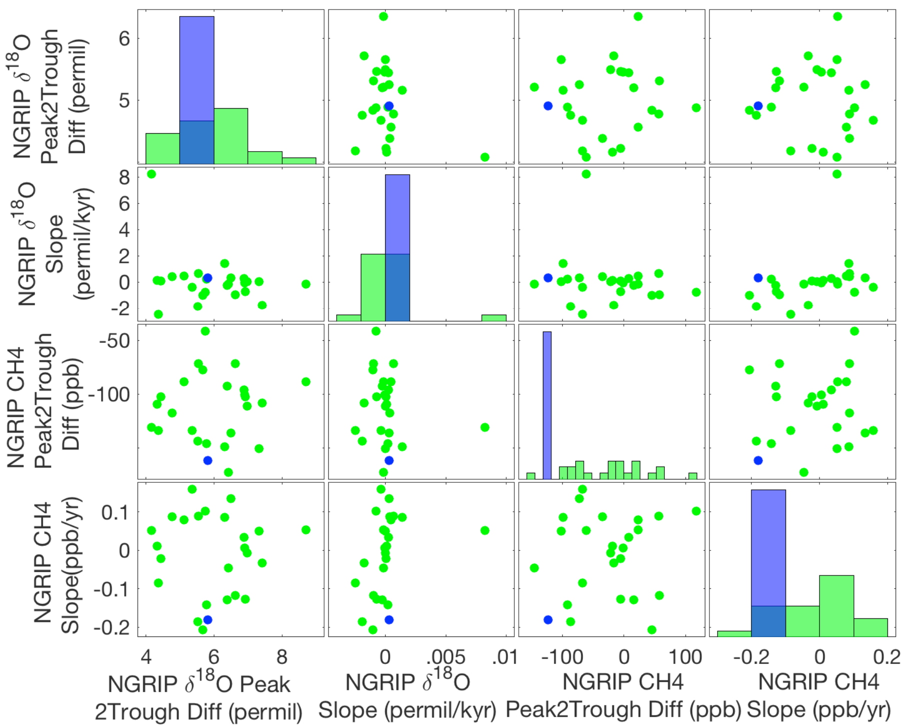

Figure 6. Greenland shape scatter grid. Of the 60 multivariate subsets analyzed for outliers, the above represents the essence of our results. Using both peak-to-trough stadial slope and measurements of NGRIP $\delta^{18}O$ and CH_4 (left), we observe minimal outlier behavior from the BA/YD in each pair of the four variable system, which indicates that the shape of the BA/YD's Greenland records is not unique in of itself. Histograms along the diagonal plot the corresponding single-variable distribution, where the horizontal location of the YD's measurement is in purple on a normalized scale (i.e., the height of the purple bar is 1).

Table 1. Three different stadial choice situations for different duration parameter choices in Figure 2. The choice results in the first column ($(x, y, z) = (300, 300, 200)$) represent our preferred choices for statistical analysis. Note that basing analysis on the stratigraphic choices represented in the second or third columns yields 86-93% similarity in results.

Decision Tree Results

	Threshold		
Cycle #	$(x, y, z) = (300, 300, 200)$	$(x, y, z) = (90, 100, 140)$	$(x, y, z) = (90, 100, 90)$
2	Join GI2.1,2.2, and GS2.2 into GI2	Absorb GI2.1 into GS2.1,2.2	Treat cycles 2.1 and 2.2 as separate
5	Treat cycles 5.1 and 5.2 as separate	Treat cycles 5.1 and 5.2 as separate	Treat cycles 5.1 and 5.2 as separate
15	Absorb GI15.1 into GS15.1,15.2	Absorb GI15.1 into GS15.1,15.2	Treat cycles 15.1 and 15.2 as separate
16	Discard cycle 16.2	Treat cycles 16.1 and 16.2 as separate	Treat cycles 16.1 and 16.2 as separate
17	Discard cycle 17.2	Treat cycles 17.1 and 17.2 as separate	Treat cycles 17.1 and 17.2 as separate
19	Treat cycles 19.1 and 19.2 as separate	Treat cycles 19.1 and 19.2 as separate	Treat cycles 19.1 and 19.2 as separate
21	Discard cycle 21.2	Treat cycles 21.1 and 21.2 as separate	Treat cycles 21.1 and 21.2 as separate
23	Discard cycle 23.2	Treat cycles 23.1 and 23.2 as separate	Treat cycles 23.1 and 23.2 as separate

Table 2. Metric measurements for Greenland records. Abbreviations for records are given by δ^{18}O=NGRIP δ^{18}O and CH_4 =NGRIP CH_4, and abbreviations for metrics are given by P2T=peak-to-trough, Slp=stadial slope, and Med=median.

D-O #	δ^{18}O P2T	δ^{18}O Slp	δ^{18}O Med	CH_4 P2T	CH_4 Slp	CH_4 Med
1	-5.82	0.000341	-40.73	-123.59	-0.181	509.80
2	-4.33	0.000126	-41.99	-18.27	0.011	404.95
3	-6.98	0.000011	-43.47	-22.04	-0.008	400.45
4	-6.63	-0.000958	-43.95	56.95	-0.118	470.40
5.1	-4.43	0.000090	-44.28	-5.33	-0.022	419.00
5.2	-6.39	-0.000228	-43.69	15.37	-0.129	475.40
6	-6.93	-0.000713	-43.81	-5.13	-0.128	467.80
7	-5.78	0.000224	-42.71	-91.68	-0.143	467.60
8	-6.42	-0.000144	-43.02	-145.68	-0.046	458.80
9	-5.12	0.000470	-43.08	22.96	0.079	481.20
10	-6.31	0.001404	-42.50	-98.50	0.086	457.80
11	-5.36	-0.000372	-42.29	-67.87	0.158	510.50
12	-6.5	0.000328	-42.68	-72.63	0.134	516.20
13	-5.55	0.000660	-42.87	56.47	0.089	532.20
14	-4.36	-0.002479	-41.52	-67.58	-0.086	486.55
15	-5.75	-0.000763	-42.52	117.16	0.102	581.90
16	-5.52	-0.001892	-42.29	-87.00	-0.185	574.70
17	-5.67	-0.001038	-42.04	45.40	-0.207	610.10
18	-6.89	0.000264	-43.65	7.79	0.034	474.00
19.1	-6.9	-0.000041	-43.87	-1.60	0.005	490.50
19.2	-7.43	-0.001761	-43.96	-16.95	-0.033	496.75
20	-8.71	-0.000154	-44.50	23.18	0.054	519.05
21	-7.32	0.000036	-42.59	-101.45	0.051	515.15
22	-4.76	0.000397	-41.20	-34.71	0.088	489.90
23	-4.16	0.008229	-39.93	-61.53	0.051	512.05

Table 3. Metric measurements for Antarctic records. Abbreviations for records are given by EDML=EDML δ^{18}O and compiled Antarctic CO_2 =CO_2, and abbreviations for metrics are given by P2T=peak-to-trough, Slp=stadial slope, and Med=median.

D-O #	EDML P2T	EDML Slp	EDML Med	CO_2 P2T	CO_2 Slp	CO_2 Med
1	1.12	0.002738	-46.46	9.12	0.0123	248.95
2	0.22	0.000534	-51.40	8.10	0.0069	202.93
3	-1.58	-0.000035	-52.22	-6.07	-0.0006	186.14
4	-0.85	-0.00087	-50.96	-3.08	-0.0032	189.65
5.1	0.65	0.000850	-50.19	5.90	0.0044	189.83
5.2	-1.17	-0.000367	-50.96	-5.08	-0.0072	191.23
6	-0.49	-0.000420	-50.50	-0.63	-0.0050	196.14
7	-1.19	-0.000516	-50.78	-7.88	-0.0040	196.07
8	-1.02	0.001384	-50.20	-11.34	0.0011	201.78
9	1.15	0.001336	-49.17	11.65	0.0072	206.09
10	-0.42	0.000794	-50.23	-3.42	-0.0202	197.90
11	-0.44	0.001256	-50.08	-3.21	0.0191	201.12
12	-1.61	-0.000310	-49.54	-15.20	-0.0003	202.59
13	0.92	0.001278	-48.25	3.75	0.0043	206.18
14	-1.02	-0.000076	-49.60	-19.76	-0.0247	202.09
15	0.31	0.000001	-48.93	1.46	0.0085	215.38
16	-0.83	0.000161	-49.64	-13.45	0.0079	208.97
17	-0.54	-0.001232	-48.54	-6.58	-0.0038	223.15
18	0.58	0.000539	-49.26	8.49	0.0060	210.57
19.1	-0.53	-0.000012	-50.66	-7.24	-0.0005	202.55
19.2	-2.28	-0.001508	-49.55	-28.21	-0.0093	213.41
20	-0.08	-0.000665	-48.16	-13.03	0.0002	232.54
21	-2.02	-0.000500	-47.44	-8.19	0.0141	231.68
22	0.23	0.000969	-47.17	-3.73	0.0083	226.07
23	-1.11	-0.000438	-47.98	-13.36	0.0000	229.33

Table 4. PCOut BA/YD Results. "YES" ("NO") indicates that the BA/YD is (not) an outlier in the subset indicated by the row/column combination in which it's located. Rows refer to the record(s) under analysis (δ^{18}O= NGRIP δ^{18}O, compiled Antarctic $CO_2 = CO_2$, EDML= EDML δ^{18}O, and CH_4 = NGRIP CH_4), and columns refers to the metric(s) applied to those records (P2T=peak-to-trough, Slp= stadial slope, and Med= median). This amounts to an $n \times p$-variate input into PCOut, where n denotes the number of records included and p denotes the metrics applied to all such records.

		1 (P2T,Slp)	2 (P2T)	3 (Slp)	4 (Med)
1	(δ^{18}O,CO_2,EDML,CH_4)	YES	**NO**	YES	**NO**
2	(δ^{18}O,CO_2,EDML)	**NO**	**NO**	**NO**	YES
3	(δ^{18}O,CO_2,CH_4)	**NO**	YES	**NO**	YES
4	(CO_2,EDML,CH_4)	YES	YES	YES	YES
5	(δ^{18}O,EDML,CH_4)	YES	YES	YES	YES
6	(δ^{18}O,CO_2)	**NO**	**NO**	**NO**	YES
7	(δ^{18}O,EDML)	**NO**	YES	**NO**	YES
8	(δ^{18}O,CH_4)	**NO**	**NO**	**NO**	YES
9	(CO_2,EDML)	YES	**NO**	YES	YES
10	(CO_2,CH_4)	YES	**NO**	YES	YES
11	(EDML,CH_4)	YES	YES	YES	YES
12	(δ^{18}O)	**NO**	**NO**	**NO**	YES
13	(CO_2)	**NO**	**NO**	**NO**	YES
14	(EDML)	YES	**NO**	YES	YES
15	(CH_4)	**NO**	**NO**	**NO**	**NO**