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Climate of the Past
Discussions

Interactive comment on "El Niño Southern Oscillation signal in a new East Antarctic ice core, Mount Brown South" *by* Camilla K. Crockart et al.

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In the study by Crockart et al, the accumulation rate records and the chloride records of 3 shallow firn cores from Mount Brown South as well as from a new shallow core from Law Dome are presented. The correlation of these records to the El Nino Southern Oscillation signal is investigated by means of Pearsons correlation coefficient and discussed. The aim of the study is to show, that a future longer record from the site will contain climate variability signatures such as the Southern Oscillation and will give different/additional information than a comparable record from Law Dome. Obtaining and analyzing ice cores from coastal Antarctica is highly valuable in order to resolve sub-annual and annual climate variability. However, the presented study aims to look at variability at larger time scales in order to evaluate the benefit of a future longer ice

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core record. This overall aim prevents a thoughtful analysis of the certainly valuable data available. The paper would benefit from a clear and consistent outline on - how the cores and records are obtained – a clear presentation of the full data set – a clear outline on which time scales are investigated and why (by which species, resolution –which processing step)

Author response: Thank you for your valuable comments and suggestions. We will revise the paper and make amendments. This is my (Camilla Crockart) first paper and is the publication from my MSc project. I will now be developing the longer MBS record in my PhD. Our aim for this manuscript is to determine whether the MBS record preserves climate signals from the lower latitudes (i.e., climate signals outside of the Antarctic region), and whether it meets the drilling requirements of Vance et al. (2016) of containing a complementary ice core record to LD. Although we present the short MBS record here, we think it is important to introduce the longer record that spans 1,000 years. The brevity and scarcity of high-resolution ice cores in Antarctica is a limitation of our understanding of climate variability (Jones et al. 2016; Stenni et al. 2017; Vance et al. 2016). Hence, both the length and location of the extended Main MBS record is what makes this ice core record unique. We would like to emphasise this point, while making it clear that the extended Main MBS ice core has not yet been fully developed. Additionally, the upper portion of the Main MBS core constitutes part of this analysis. We will add more detail on how the cores were obtained in the field and how they were transported. In terms of the chemical species, section 2.2 reads 'In order to investigate the optimal sample resolution over the satellite era for accurate dating, we cut 1.5 cm isotope samples in contrast to 3 cm chemistry samples over the upper portion of the ice cores'. And 'The Thermo-Fisher/Dionex ICS3000 ion chromatograph was used to determine the concentrations of trace ion chemistry (anions and cations), including sea salt concentrations (chloride (Cl^-), sodium (Na^+), magnesium (Mg^{2+})), calcium (Ca^{2+}) and sulphate (SO_4^{2-}), as well as methanesulfonic acid (MSA)'.

and what possible drawbacks/bias have to be considered, i.e. Example 1: comparing

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annual values of accumulation rate – by averaging the annual accumulation rates of all the three firn cores (arithmetic average?), problem: lack of high-res density – what is the influence of intrusion, single events on the overall record/correlation analysis;

Author response: Reviewer 1 has asked for additional analysis on the influence of extreme precipitation events at MBS. We propose to use the data from the Modèle Atmosphérique Régional to look at the frequency of precipitation at MBS at a monthly/seasonal timescale. Please note that detailed investigation into the extreme precipitation events at MBS will be undertaken shortly, as this is part of the first authors (Camilla Crockart) PhD project. The annual accumulation rates and sea salt concentrations from the three individual MBS ice cores (Alpha, Charlie and Main) have been compared are in agreement (please see Figure 3 and 4 table inserts).

Example 2: looking over a time period of 40 years (in comparison to ERA5 etc)- which is by no means close to centennial. What is the significance of this correlation over this time period with respect to a future millennial record?

Author response: The lack of observational data in the southern high latitudes, in particular the Indian Ocean sector, means the satellite era is the only period of time when we can intensively explore mechanisms, transport and signal preservation in the MBS record. This is standard for high latitude/Antarctic studies. That this period may not properly represent centennial climate is clear (e.g., Jones et al., 2016). However, the development of high-resolution paleoclimate records, such as MBS and LD, is an effort to extend our understanding of variability in this region. In relation to the statistical significance of the correlations with climate modes, we expect these correlations would only increase (p-value decrease) over a longer time period (i.e., with a greater n). Please note that we used effective degrees of freedom for all p-values presented in this paper to eliminate the influence of autocorrelation within any of the timeseries (L228). Future work will definitively explore the longer timeseries using longer datasets (e.g., longer ENSO and SAM indices once we have more MBS data dated and available).

Did you test for trends (affecting the correlation?) What if the correlation is (only) a result of recent changes and not due to variability itself? For variability analysis the trends have to be looked at (and removed)?

Author response: Yes, we made sure to detrend all of the time series data (including ice core data, climate mode indices, ERA5 and the HadISST data). Therefore, the correlation results are not due to trends in the time series. L254 read 'The ENSO, SAM and IOD indices were detrended (as were the corresponding accumulation and sea salts time series) to reduce the interference of any climate change signals and ensure any significance was due to inter-annual variability, rather than (for example) the pronounced shift toward the positive SAM phase during austral summer in recent decades (Marshall et al. 2003; Thompson and Wallace 2000)'.

- a better structure in distinguishing between results and discussion –

Author response: Apologies. This will be carefully edited so that there is less overlap between the results and discussion. We propose to address these issues in detail in a marked-up version of the manuscript.

a focus on the available time scale, the high-resolution data available and what one can learn from it.

Author response: We will re-write sections of the abstract, introduction and conclusion to highlight the fact that we are only looking at the upper portion of the MBS record. This period also overlaps with the satellite era, meaning that we can use reanalysis data to investigate environmental conditions associated with any climate signals preserved in the MBS record. However, we think it is important to introduce in this paper – the first MBS data paper – the extended Main MBS record, as its length combined with its location is what makes this record unique for the East Antarctic region. We appreciate that this may be somewhat frustrating to the reader, however, there is extensive work in developing long ice core records, and we still think it valuable to publish an initial study of the upper (satellite era) section of the record that has thus far been developed.

Further general remarks: 1. Terms on climate variability time scales are used inflationary and ambiguous throughout the text, for example: High-resolution ice core – long term climate variability and multi-centennial – all in one sentence/context. (Abstract, Line 21-22, Introduction Line 44), Usage of very different time scales (as relevant for the paper), for example: variability over past millennia (Intro, Line 55), sub-decadal (?) signals for climate variability (Intro, Line 126), multi-centennial (Intro, Line 86) Suggestion: There should be a clear outline of which times scales the author aim to address with their data – both in resolution (sub-annual) and coverage (30-40 years!).

Author response: This will be simplified, for example, we will change the introduction to 'Ice cores collected from the Antarctic ice sheet contain chemical signals that are used to reconstruct past climate conditions. Ice cores can be categorised as low-resolution (centennially-resolved) and high-resolution (annually-resolved) records. Low-resolution ice cores collected from low-accumulation zones of the Antarctic Plateau contain climate signals dating back hundreds of thousands of years. High-resolution ice cores contain more detailed climate signals but back date only millennia.'

It is in the nature of coastal high-res records, that they resolve-sub-annually (a benefit which is unfortunately not discussed or presented here more in-depth). Overall the (only) time scale considered here is annual mean over a period of 40 years – for both accumulation rate and sea salt concentration.

Author response: Some high-resolution ice core records can be sub-annually resolved (e.g., the LD record, McMorrow et al. 2001; Vance et al., 2013; 2015). However, here we chose to use the annual MBS accumulation and sea salt records to avoid any errors associated with assuming a uniform accumulation at the site, which has not yet been tested definitively. We fully expect to develop sub-annual records in the future, but this requires extensive analysis on the extreme precipitation events at MBS, which is too large a task for the current manuscript.

2. Talking about climate signals/climate variability at different time scales would require

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a profound analysis of the climate signal contained in the record (especially given the fact, that overall a short period of 40 years are considered. What is the common climate signal in the three cores? And what the common climate signal with the core from Law Dome? Are the 40 years long enough? What about variability vs mean/trend?

Author response: As above - all of the time series have been detrended, and therefore any climate change trends do not influence the correlation results. The three individual MBS ice cores do not have a trend over time (r = 0.122, 0.086, -0.034, p = 0.466, 0.598, 0.873 for Alpha, Charlie and Main, respectively). That this period may not properly represent centennial climate is clear (e.g., Jones et al., 2016). However, there is a lack of observational data in the southern high latitudes, meaning that the satellite era is the only period of time when we can intensively explore mechanisms, transport and signal preservation in the MBS record. The purpose of developing the MBS and LD records is to extend our understanding of variability in this region. Correlations between the LD record and climate modes can be found in Table 1 - the LD record is significantly correlated with the ENSO indices. We chose to use the MBS site average (which is in good agreement with all three of the individual MBS ice cores, please see table insert in Figures 4), because we wish to maximise the overlap time period with the satellite data as the Main MBS ice core only dates back to 2007. Moreover, using multiple records allows for improved signal to noise ratio (Jones et al. 2016). Please note that three international laboratories are working on the MBS record, with new data currently being developed (e.g., dust, stable water isotopes, volcanic signals, extreme precipitation event signals and visible stratigraphy).

3. Already in the introduction 14 different abbreviations are introduced (and used later in the text) – its hard to read and to follow your argumentation. Maybe it is possible to stick to few, relevant terms – as not all of the modes are used later or relevant for the paper (or one could stick to summarized, overarching terms of comparable modes).

Author response: Good suggestion. We propose to revise using only standard acronyms (e.g., MBS, LD, IOD, ENSO, and SAM).

4. Information to the firn cores Do you analyze the core until the surface? How do you deal with the upper meter(s). How do you cut the core in the field, transportation, cutting in the lab.

Author response: Greater detail on the drilling process of the individual ice cores will be added to the methods section. The Main MBS ice core was drilled from 4 m depth using a Danish Hans Tausen intermediate drill, while the short MBS cores were drilled from the surface using the Kovacs system.

A table of the exact coordinates, the length/logging depth etc is missing, and then the obtained coverage in time

Author response: Figure 1 will be changed to include a map with all four ice cores drilled at MBS (Alpha, Bravo, Charlie and Main). The time coverage and maximum depth for each MBS ice core will be made clearer, along with the coordinates of the individual ice cores.

There is inconsistency in the number of cores included in your analysis. In chapter 2.1 (methods) it reads, that from the three MBS firn cores, the Bravo core is not used in the study. That makes 2 shallow cores plus the upper part of the main core. i.e three cores from the MBS site. However, in line 133 it reads: The MBS record is unique in that it contains three short ice cores (20-25m) (. . .) in addition to the Main core.

Author response: There were four MBS ice cores collected (Alpha, Bravo, Charlie and Main) however, the Bravo core is not extensively analysed here, and is only used for confirmatory purposes during dating the records presented here. Section 2.1 reads 'The cores drilled include one long core, MBS1718 (hereafter termed "Main", depth 295 m), and three short cores, MBS1718-Alpha, MBS1718-Charlie, MBS1718-Bravo (hereafter "Alpha", "Bravo", and "Charlie", 20-25 m depth). The Bravo core was collected exclusively for persistent organic pollutant analysis so it will not be considered hereafter, although high resolution water stable isotope analyses from this core were considered for confirmatory purposes during dating the records presented here'. We

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will change L133 to 'The MBS record is unique in that it contains multiple short ice cores (20-25m)' to avoid confusion.

There is also unclear usage of the term: "record" – is this always meant as the stacked (averaged) record over the three (?) cores? This should be stated clearly.

Author response: This will be clarified throughout the paper, with the average accumulation and sea salt records from the three MBS ice cores referred to the 'MBS site record'.

Comments in detail: Line 21: wording in combination: high-res ice core vs long term, multi-centennial versus long-term

Author response: This will be changed to 'Ice cores collected from the Antarctic ice sheet contain chemical signals that are used to reconstruct past climate conditions. Ice cores can be categorised as low-resolution (centennially-resolved) and high-resolution (annually-resolved) records. Low-resolution ice cores collected from low-accumulation zones of the Antarctic Plateau contain climate signals dating back hundreds of thousands of years. High-resolution ice cores contain more detailed climate signals but back date only millennia'.

Line 30: occurrence of moisture and aerosol intrusions is briefly touched in the discussion but not shown in the data

Author response: Apologies, this will be changed to 'Further study on this new site may help to determine whether this inverse relationship is due to distinct moisture intrusions.' The first piece of evidence to help with this analysis is the work of Udy et al. 2021 (cited in this work), which showed that the two ice core sites have differing moisture sources at the synoptic scale, and our results support this finding. This will be made clearer in the manuscript.

Line 52: high- resolution records are required to fill spatial gaps. . . High-res records address temporal information, not spatial?

Author response: Both the brevity and sparse distribution (particularly in East Antarctica) of high-resolution ice cores limits our understanding of climate variability (Jones et al. 2016; Stenni et al. 2017; Vance et al. 2016). The only millennial length high-resolution ice cores in East Antarctica from Enderby to Wilkes land have been collected from the Law Dome region. Hence, the extended Main MBS record does fill a spatial and temporal gap in high-resolution ice cores in East Antarctica.

Line 141: please explain, what is meant by “wet deposition”?

Author response: This will be changed to ‘wet-deposition (deposition via precipitation and scavenging by blown snow, Legrand and Mayewski 1997)’.

Line 151: The MBS record: It is not explained, how you derive the “record” here – what exactly is done? The record of the single accumulation rates or the stacked/merged?

Author response: This will be clarified throughout the paper, with the average accumulation and sea salt records from the three MBS ice cores referred to the ‘MBS site record’.

Line 160-165: In the figures only 1 record for LD is shown – how did you combine the old and new records? Where they exactly the same (in the common period)? A little note on how the two records are combined is needed here

Author response: There is only one LD record presented here, which is a composite of a new short ice core (1990-2015) drilled in 2016 and the longer DSS97 ice core (1975-1989) drilled in 1997 (e.g., Zhang et al. cp-2020-124). Please note that we have written ‘The new record presented here covers the period 1989-2016’ however, the two composites were joined at 1989/1990, meaning that the new record starts at 1990, our apologies – this will be corrected. This data is an improvement on the composite of numerous short cores presented in Vance et al. (2013). At the time of writing Vance et al., 2013, the longer DSS97 record was extended into the satellite era to 2009 using four short 8-10 m ice cores drilled in the years between 1997 and 2009. The composite of two cores presented here improves on this record, principally because at a high snowfall site like Law Dome (>1.5 metres snow per year) a short ice core of less than 10 metres will not span 2009 to 1997. However, in 2016, we drilled a 30.8 m core using an eclipse drill, which enabled us to span the entire period from 1990-2016 with one complete core. The two composites were compiled using visual analysis of the raw data of overlapping seasonal cycles in 1989/1990 of key dating analytes (principally δ18O, nssSO42-, Na+ and the ratio of SO42-/Cl-).

Chapter 2.4. Deriving accumulation rates from empirical density model? Are there now bag mean densities obtained in the field/lab? As accumulation rate is one major result of the study and it is based on the empirical equation, it would be good to show the density data (modeled in comparison to bag means). In any case, different layers of density will not be consid- ered and may bias the derived ice equivalents. A more in-depth description/uncertainty analysis should be given (again, based on the fact, that this is one of major results of the paper).Line 198-199: I do not understand: You convert your profile to ice equiva- lent in order to do exactly this: to compare different layers of different depth of an ice core, no matter of the thinning (by compaction). If you refer to thinning because of flow then it reads very strange, given the fact, that you are looking at 25m depth max.

Author response: Yes, there are bag mean densities obtained in the field. These densities are essentially the same (r = 0.957, 0.956, 0.975, p = 0.000 for Alpha, Charlie and Main, respectively) as vertical thinning is negligible in the upper 20-25 m of the ice core. However, we choose to use the empirical density model to calculate accumulation so that future papers looking at the 1,000-year Main MBS record can directly compare snow accumulation rates.

Equation 1: description/ labeling of the terms is missing (i.e d = depth, what are the number standing for?)

Author response: Good suggestion. Additional detail on each of the variables will be explained in more detail. In terms of the depth, L196 reads 'The empirical density model uses the mid-point depth of the annual layer (d)'.

Line 280: The MBS record. . . Again, it is not clear to what is referred here.

Author response: This will be clarified throughout the paper, with the average accumulation and sea salt records from the three MBS ice cores referred to the 'MBS site record'.

Figure2: why do you not show the full record?

Author response: We do not show a full figure as this would be too large, and it is common to use an example section (for example Sigl et al. 2016, see Figure 4 therein). Note that we have used a portion of the record that shows not only years that were easier to discern, but also a period that was more difficult to date, in order to be upfront about the dating errors that may be incurred in the deeper record (see text in the marked-up version).

Line 302/303: wind/blown snow effect- where has this been shown? (Reference or short explanation how)

Author response: The sensitivity test indicated that the annual total snowfall derived from ERA-5 correlated most highly with ice core total precipitation when the threshold for wind saltation was set very high (i.e., the nett effect of wind distribution is close to zero at this location). This will be added to the revised manuscript.

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