Author responses to referee comment 2 - Anonymous Referee

Comments on Nilssen et al. “Evaluating the Twentieth Century Reanalysis Version 3 with synoptic typing and East Antarctic ice core accumulation” submitted to Climate of the Past

Owing to limited weather records before the satellite era, understanding long-term variability and inter-decadal pattern in synoptic systems over East Antarctica is challenging. This study evaluated the ability of the Twentieth Century Reanalysis project to reproduce the synoptic conditions associated with increased precipitation at Law Dome since 1948, using daily 500 hPa geopotential height anomalies and the annual snowfall accumulation record from the ice core. The results indicate that this Reanalysis can reliably represent the meridional weather conditions of increased precipitation at Law Dome before the satellite era, and thus extends the time span of available materials for analyzing weather conditions for this region.

I appreciate the objective of this paper, and I am interested in the results and conclusions. However, there are still several issues to be clarified in this study. I recommend that this manuscript needs a major revision before published.

Major points:

1. Since the authors used Twentieth Century Reanalysis Version 3 to perform this study, I have a major concern on the reliability of the data. Especially, the data series for this atmospheric reanalysis may have suffered a “jump” at the ice sheet scale at the beginning of the satellite era. The authors should add some works to prove that it is reliable at least on regional scales (or at Law Dome). This is very important for the analyze, as the major results and conclusions are relied on the 20CRv3 data.

Thank you for this comment. The reliability of 20CRv3 is certainly a major issue that needs to be addressed. None of the twentieth century reanalyses use satellite data, but CERA-20C does show a jump in P-E over the Antarctic ice sheet at the beginning of the satellite era, while 20CR shows a similar jump in 1950 (Wang et al., 2020). We state in lines 49-54 that we chose 20CR over ERA-20C for this study, as 20CR has been determined to be less vulnerable to inhomogeneities due to changes in observation density, as well as the different assimilation schemes. However, 20CRv3 does still have a significant increase in the number of assimilated observations over time, and therefore significant changes in error and reliability over time. We agree that determining the reliability at specific regions or points is very important, which is why we believe our study, using a well understood and accurately dated ice core record as comparison to reanalysis, contributes to this question.

We will add this sentence in the discussion (at the end of the paragraph that ends at line 230):

“However, evaporation is considered to be a minor contributor to variability at the Law Dome site, and so is unlikely to have a major effect on this study (Roberts et al., 2015).”

2. I suggest that the second part of the manuscript should be changed to “Data and Methods”, and that its content needs to undergo a substantial reorganization to make it more coherent. For instance, the headings of 2.1

and 2.3 stand for “Data” rather than “Methods”, and 2.4 includes too much information that is not relevant to the heading, such as the division of the period, and the title of 2.3 does not emphasize the classification of precipitation events. The authors should try to separate the description of the data and methods, and introduce each section specifically, such as “snowfall accumulation record from the Law Dome DSS; Twentieth Century Reanalysis version 3…”.

Thank you for this comment. We will reorganise these sections to improve coherency. The headings will be as follows:

2 Data and Methods
2.1 Data Used
2.1.1 Twentieth Century Reanalysis version 3
2.1.2 Snowfall accumulation record from Law Dome DSS ice core
2.2 Methods
2.2.1 Self-organising map inputs and evaluation
2.2.2 20CRv3 daily precipitation and synoptic types
2.2.3 Classification of precipitation events
2.2.4 Division of time period and correlation between annual precipitation and accumulation
2.2.5 Regression analysis of snowfall accumulation using synoptic types

3. The authors claim that the ice core record shows high accumulation rates and seasonality at Law Dome (L76-78), so I am concerned about the possibility of extracting seasonal climate signals (synoptic systems and accumulation) from the ice core record. This would not only enable assessing the reliability of the 20CR on a timescale with higher frequency, but also contribute to understanding the seasonal variability of synoptic patterns affecting the Law Dome.

Indeed, understanding the seasonal signals and seasonal variability at Law Dome (and by extension, other high snowfall ice core sites) is really the driving purpose of this study. We think that being able to unlock some of the seasonal variability signals from ice core records like Law Dome, either in sea salt (e.g. Vance et al., 2013; Udy et al., 2024), stratigraphy (Zhang et al., 2023) or stable water isotopes (e.g. Jackson et al., 2023) would be a hugely powerful tool in understanding how synoptic scale processes have changed in the past. However, disentangling these signals at less than annual scales in ice core records is currently still challenging, and relies on very detailed and precise dating of the annual layers. This study is another step in that direction, because it gives us evidence that we can explore the interplay between synoptic types and changes in the ice core accumulation, chemistry and stratigraphy prior to the satellite era - e.g., we now have some confidence to use 20CR to explore the seasonal cycle of snowfall at Law Dome for over 60 years. This will help us understand over the longer term when snow falls and how episodic it is - a key piece of information in then exploring any chemical or stratigraphic markers associated with seasonal snowfall. We will add some sentences to the end of the introduction and in the discussion to ensure our purpose with this study is clear to the reader.

4. Surface ablation rarely occurs over most of the Antarctic ice sheet, so snowfall accumulation is contributed mainly by precipitation. However, Law Dome is located in the Antarctic coastal region. Studies have been done to show that these areas near the coast are threatened by rainfall from extreme events such as atmospheric rivers. I would therefore suggest that you should distinguish the precipitation pattern (rainfall or snowfall, they

have almost opposite effects on accumulation) in this study, rather than comparing precipitation directly to the accumulation from ice core record. Or, another approach is to confirm that rainfall-derived melting or snow blowing is not sufficient to have a significant effect on the inter-annual variability of snow accumulation at Law Dome.

We agree that there seems to be an increasing threat of rainfall in coastal regions, and these events are increasingly being catalogued not only on the Antarctic Peninsula, but also coastal East Antarctica. However, rainfall events at Law Dome are, at this stage, still vanishingly rare, and we know this for sure because rainfall on a snowpack leaves a very clear signal of frozen liquid water that has percolated into the snowpack, as well as a disrupted oxygen isotope record. Law Dome summit is certainly a coastal location, however its elevation (1,370 metres) means its precipitation type remains only snowfall (and a small fraction of diamond dust/clear sky precipitation), because mean annual temperatures are quite low (~-22 ℃). Ensuring non-liquid precipitation only was a key aspect of the original site selection for Law Dome (and this is usually the case for the site selection of other coastal records as well). Additionally, we have no evidence from our numerous overlapping surface and deep ice core records from Dome Summit South (e.g. compiled in Jong et al., 2022) or from stratigraphic studies at the DSS site, that rainfall events occur (Zhang et al., 2023), and we know of only one instance of a melt layer (from warmer than average temperatures and high solar radiation) being observed in an ice core drilled on the eastern flank of Law Dome at a lower elevation than DSS (Pers. Comm. David Etheridge 2023). Thus, we don't think there is much point in differentiating rainfall and snowfall at the DSS site, as no rainfall has historically occurred (and we know this as we would clearly see the resulting percolated melt layers in our ice core records).

We will add a sentence to the methods and DSS site description to note the above.

5. Section 3.6 "Linear model estimates of ice core annual accumulation from synoptic typing": The description in this section is too short and the authors should have described it in more detail.

We will move some of the detail about the regression models from the discussion into section 3.6.

6. Although this paper investigated synoptic types on a regional scale, the study relied on ice core records from the Law Dome, so it is inappropriate to show "East Antarctic ice core accumulation" in the title, and I suggest changing it to the "Law Dome". East Antarctica covers a much larger spatial area not studied by this paper, and a single ice core record may not be strongly spatially representative. The authors also mention in the description of L277-279 that the accumulation record will not appear in the Law Dome DSS when the location of the blocking is slightly offset. Therefore, much of this study is not actually representative of East Antarctica.

While it is true that we use only one ice core record to 'groundtruth' our findings, we disagree that our title is inappropriate, since we are using the reanalysis to evaluate whether we can look at regional synoptic scale variability with relevance to most of East Antarctica. The synoptic variability, and the ability for 20CR to discern precipitation types (e.g. high and extreme precipitation) is the important finding, as this will allow us and others to have confidence in using a reanalysis that is longer than the satellite era for the East Antarctic region. The use of Law Dome is more to check whether the ice core accumulation record is

also representative. However, we think the results from our study are more likely to be utilised for the longer, regional synoptic typing dataset, and this implies regional rather than local applicability. We propose to change the title slightly to:

"Evaluating the Twentieth Century Reanalysis Version 3 with synoptic typing and an East Antarctic ice core accumulation record."

7. There are some technical corrections in the manuscript, such as the lack of a uniform format for the minus sign "-". In section 3.1, authors sometimes label p<..., sometimes labeled p=.... The authors need to recheck and re-edit them.

We will check these and ensure they are consistent. For the trends in section 3.1 and 3.5, we will replace the p values with 95% confidence intervals.

Minor points:
1. Please check the units of potential height in the Figures.

We have checked this, and these are correct as submitted. Figure 1 shows the mean 500 hPa geopotential height in metres, while Figure 3 shows the 500 hPa geopotential height anomaly in metres. The actual height vs the anomaly may have caused some confusion.

2. L35: please add the references, such as Zhang et al., 2018; Wang et al., 2020 (which has been presented in the references

We will add the following references:

Schneider, D. P. and Fogt, R. L.: Artifacts in Century-Length Atmospheric and Coupled Reanalyses Over Antarctica Due To Historical Data Availability, Geophysical Research Letters, 45, 964–973, https://doi.org/10.1002/2017GL076226, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2017GL076226, 2018.

Wang, Y., Hou, S., Ding, M., and Sun, W.: On the performance of twentieth century reanalysis products for Antarctic snow accumulation, Climate Dynamics, 54, 435–455, https://doi.org/10.1007/s00382-019-05008-4, 2020.

Zhang, Y., Wang, Y., Huai, B., Ding, M., Sun, W.: Skill of the two 20th century reanalyses in representing Antarctic near-surface air temperature, Int J Climatol, 38, 4225–4238, https://doi.org/10.1002/joc.5563, 2018.

3. L112: "The 90th and 99th percentile of 20CRv3 daily precipitation at Law Dome was calculated". How was the base period for defining extreme events chosen? Extreme precipitation calculated based on percentile thresholds will be very dependent on the selection of base period.

Thank you for picking this up. The base period was chosen to be 1900-2015, which we will add to the text. The 90th and 99th percentiles of daily precipitation would have been higher if we had chosen a different base period (eg 1950-2015 or 1979-2015), which would have reduced the amount of annual 20CRv3 precipitation from high and extreme days, and reduced the total number of high and extreme days. Either way, we would still see the

increase of high and extreme precipitation days from around 1950. We will add some explanation in the methods about this, and when we discuss the corresponding results.

4. Figure 2 and Section 3.1: Please plot the linear trend of the two data series in Figure 2, respectively.

We would prefer not to do this, because we think that adding trend lines to Figure 2 would make the plot busy, and importantly, would be somewhat misleading and cause some confusion. Figure 2 is to demonstrate the agreement (or lack thereof, in the first half of the 20th century) between the total annual 20CRv3 precipitation at Law Dome, and the annual snowfall accumulation at Law Dome, along with the change in 20CRv3 precipitation attributed to high/extreme precipitation days at specific points through the 20th century. The overall trends in the two data series are discussed and shown in Table 1, but the point of this figure is that linear trends would be an insuffiecient way to examine or make inferences about the variability through time, as the figure shows not only step changes at different points (e.g. 1948 and 1958) but also trend changes (e.g. 20th century Law Dome precipitation compared to satellite era Law Dome accumulation) . These changes are discussed more comprehensively in sections 3.2, 3.5 and 4.1.

5. L177-179: What are the quantitative standards for dividing the weather types? Type 2 also seems to dominate by meridional, despite the blocking high not landing on the ice sheet.

Segregating or dividing the weather types by dominant atmospheric pattern is a subjective process when using this type of analysis, in this and other studies. This means that different interpretations are possible. However, while type 2 does appear more meridional than the other mixed types, we classified it as mixed because the geopotential height anomalies are much weaker than those that are observable in the types we classified as meridional (1, 3, and 4). For this study, we are interested in meridional transport of moisture to Law Dome, and by extension other regions of East Antarctica from other synoptic types. The kinds of weather seen on type 2 days would not be strongly meridional from the perspective of additional moisture transport to the region including Law Dome. We will make this distinction in the text (section 3.4). As the reviewer mentions, the block does not extend to the ice sheet, and we know this is critical in changing the moisture transport regime to the ice sheet (e.g. Jackson et al., 2023, Pohl et al., 2021), so we think that type 2 should remain a mixed rather than meridional type.

We will add “favourable for meridional transport of moisture to East Antarctica” to line 177.

6. The discussion of the relationship between annual frequency of synoptic types and DSS accumulation is relevant and needs to be reflected in the Conclusions and Abstract.

We will further discussion of the relationship between the annual frequency of synoptic types and DSS accumulation to the conclusions and abstract.

References:

Zhang Y, Wang Y, Huai B, Ding M, Sun W. Skill of the two 20th century reanalyses in representing Antarctic near-surface air temperature. Int J Climatol. 2018; 38:4225–4238. https://doi.org/10.1002/joc.5563

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Jackson, S. L., Vance, T. R., Crockart, C., Moy, A., Plummer, C., and Abram, N. J.: Climatology of the Mount Brown South ice core site in East Antarctica: implications for the interpretation of a water isotope record, Climate of the Past, 19, 1653–1675, https://doi.org/10.5194/cp-19-1653-2023, publisher: Copernicus GmbH, 2023.

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Pohl, B., Favier, V., Wille, J., Udy, D. G., Vance, T. R., Pergaud, J., Dutrievoz, N., Blanchet, J., Kittel, C., Amory, C., Krinner, G., and Codron, F.: Relationship Between Weather Regimes and Atmospheric Rivers in East Antarctica, Journal of Geophysical Research: Atmospheres, 126, e2021JD035 294, https://doi.org/10.1029/2021JD035294, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2021JD035294, 2021.

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

Udy, D.G., Vance, T.R., Kiem, A.S., Holbrook, N.J, and Abram, N.: Australia's 2019/20 Black Summer fire weather exceptionally rare over the last 2000 years, Commun Earth Environ, 5, 317, https://doi.org/10.1038/s43247-024-01470-z, 2024.

Vance, T. R., Ommen, T. D. v., Curran, M. A. J., Plummer, C. T., and Moy, A. D.: A Millennial Proxy Record of ENSO and Eastern Australian Rainfall from the Law Dome Ice Core, East Antarctica, Journal of Climate, 26, 710–725, https://doi.org/10.1175/JCLI-D-12-00003.1, publisher: American Meteorological Society Section: Journal of Climate, 2013.

Wang, Y., Hou, S., Ding, M., and Sun, W.: On the performance of twentieth century reanalysis products for Antarctic snow accumulation, Climate Dynamics, 54, 435–455, https://doi.org/10.1007/s00382-019-05008-4, 2020.

Zhang, L., Vance, T. R., Fraser, A. D., Jong, L. M., Thompson, S. S., Criscitiello, A. S., and Abram, N. J.: Identifying atmospheric processes favouring the formation of bubble-free layers in the Law Dome ice core, East Antarctica, The Cryosphere, 17, 5155–5173, https://doi.org/10.5194/tc-17-5155-2023, publisher: Copernicus GmbH, 2023.