The influence of the Atlantic Multidecadal Variability on Storm Babet-like events

Response to reviewer 2:

The draft focuses on storm Babet and its analogs in terms of sea-level-pressure patterns. Storm Babet occurred in October 2023, bringing significant rainfall and wind speeds that affected many part of the British Isles. Analogs of storm Babet are calculated from October to November and from 1950 to 2023. It is found that the pattern of such analogs has a time evolution consistent with the influence of the Atlantic Multidecadal Variability (AMV). A warm Atlantic corresponds to a more frequent occurrence of daily sea-level-pressure patterns similar to storm Babet.

The draft is concise but remains somewhat superficial regarding methods. It lacks discussion and analysis on the role of AMV. Additionally, a discussion about the existing literature and the limitations of the analyses conducted is missing. I recommend some major revisions.

We thank the reviewer for the detailed comments. We have revised the manuscript based on the comments, and those of another reviewer, and hope the reviewer finds it improved.

We have made many changes, including further statistical testing to show the robustness of the results, and a more detailed comparison with other scientific literature on the AMV and European storms. Point-by-point responses follow, with changes to the manuscript highlighted.

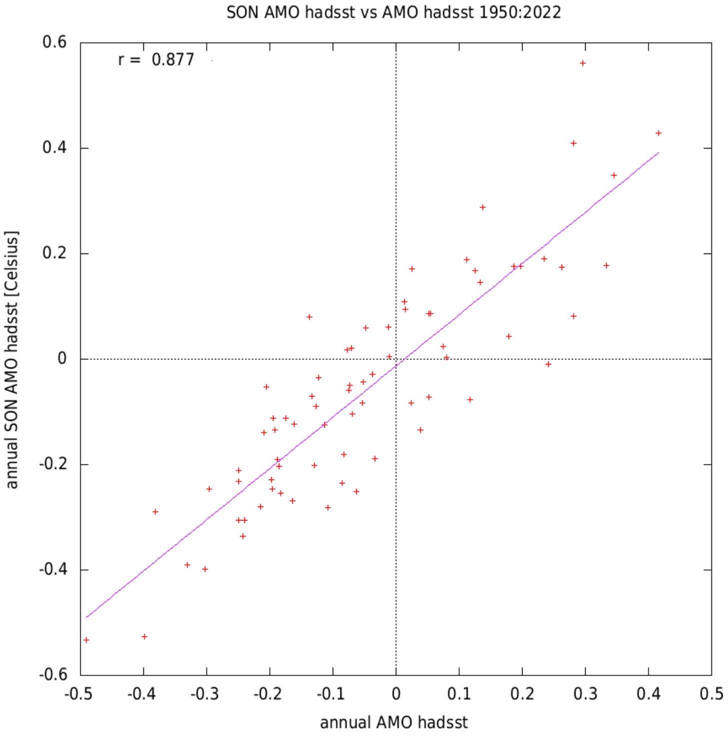
Major comments

1. The definition of the AMV (region used, smoothing applied or not) is lacking. There is a legend in Fig. 4 specifying that what is called the AMV is, in fact, the SST averaged in 25°N-60°N in September-October-November. However, what is usually called the AMV is a yearly SST average from 0° to 60°N, including the tropics from 0°N to 20°N. The dataset used to calculate the AMV is not clear (HadISST at L68, but HadSST 4.0.1.0 mentioned at L168). The smoothing applied and the dataset used for the GMST is lacking. Lastly, I suggest that the authors remove the external forcing using other methods, as the linear regression used might induce spurious connections with the Indo-Pacific (Deser and Philips, 2023). This is relevant as ENSO can be a

driver of fall European climate, which is excluded in the present draft (King et al., 2018).

There are multiple definitions of AMV in use. The definition of AMV used in this study is taken from van Oldenborgh et al (2009). By calculating AMV without including the tropics we remove some of the influence of ENSO and the Indo-Pacific. This is the version of AMV used on KNMI Climate Explorer. The dataset used is HadISST, this has been corrected in the text in the caption of Fig.4.

We used September-October-November (SON) to match the period used for analogues. Comparing the AMV timeseries for SON with the annual timeseries we find the two are highly correlated (shown below), thus changing to annual would make little difference to results. The method we have chosen allows the method to be applied to other events and other climatic indicators in a consistent manner - always taking the three months surrounding the event rather than an annual timeseries where sometimes an event could be at the start, and sometimes the end, of the period.



We have added further details of the GMST and AMV datasets used to the methods:

We use timeseries of AMV and global mean surface temperature (GMST) derived from HadISST data (Kennedy et al., 2019; Morice et al., 2021) retrieved from the KNMI Climate Explorer. The AMV index used takes only September-October-November SSTs, from 25-60°N, 7-75 °W, and is detrended by regressing against GMST (van Oldenborgh et al., 2009, Climate Explorer).- This is done to remove the effect of climate change in the AMV. By excluding the tropics the influence of ENSO and the Indo-Pacific on AMV is reduced (van Oldenborgh et al., 2009; Deser and Philips, 2023).

For all datasets a 10-year rolling mean is applied before regressing:

As AMV is a multidecadal mode of variability, a 10-year rolling mean is applied to the Sx, AMV, and GMST timeseries.

We take a smoothed GMST as a proxy for the external forcings, without removing any internal variability influences on GMST. This is common practice, as in WWA event attribution studies.

2. The links between the analogs and the AMV is not clear from the results shown. The links are presently deduced from correlations discussed at lines 155-163. However, the tests applied to deduce the p_value are not presented. The correlation of 0.53 given at line 60 is associated with a p-value of almost zero. However, given the few degrees of freedom (roughly 5, considering that there are 7 independent data points from the 7 decades), one can expect such a correlation is not significant at the 5% level. The physical process is also missing in the discussion. What is the process explaining that a warm Atlantic leads to more significant storms? This should be discussed more carefully, as such a link can be a statistical artifact.

Further statistical testing and the inclusion of p values has been added throughout the manuscript, including in the multiple regression results.

In section 3.2:

We use multiple regression to separate the potential relative roles of decadal variability AMV and GMST in forcing the decadal variability in Sx. The multiple regression model has an R^2 value of 0.45 (uncentred), with a p-value=1.3e-8, indicating a statistically significant relationship between similarity and the predictor measures, AMV and GMST. We find coefficients of 0.074 /°C (p-value = 1.3e-4) for AMV and 0.003 /°C (p-value = 2.0e-8) for GMST. AMV varies by ~0.5 °C over the past century, whereas GMST by ~1 °C - thus the GMST covariate has twice the impact, but even so, AMV dominates the variability in Sx.

In response to your next comment, we now include a map of correlation between the analogue similarity timeseries (Sx) and SST globally, on an interannual timescale. This shows significant correlation in the North Atlantic on interannual timescales, as well as the decadal scale included in the text.

We have also added more about the physical reasons we would expect causality between AMV and analogues, particularly in the introduction (exact changes highlighted in the response to your minor comments).

3. L162-163 : the other potential driver of the change in analogs are not investigated. Perhaps a regression of the sea surface temperature on the Similarity time series would help show which region is the most important: the Pacific Ocean, the subtropical Atlantic or the subpolar Atlantic. The choice of looking at the AMV time series only seems otherwise arbitrary.

In the supplementary material we now include a map of the correlation of the analogue similarity timeseries (Sx) and SST for both an annual and 10-year rolling mean timeseries. This shows statistically significant correlation in the North Atlantic, justifying our choice of assessing the AMV timeseries. This is discussed in the methods:

We assess the relationship between Sx and AMV, AMV is chosen as literature supports a physical link between it and extratropical storms, as discussed in the introduction. We tested this by assessing the correlation between Sx and SSTs, showing statistically significant correlation over the North Atlantic on both an annual and 10-year rolling timescale (Fig.A3).

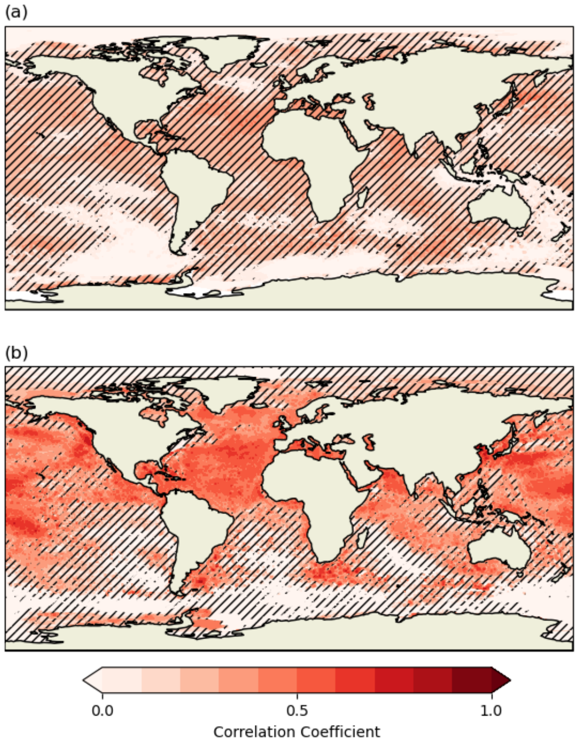


Figure A4: Correlation between similarity and SSTs. (a) Global map of the Pearson’s correlation score between annual SST timeseries and the annual maximum similarity (Sx) timeseries, hashing indicates regions where the p-value is greater than 0.05, **(b)** As in (a) with a 10-year rolling mean applied to both the SST and Sx timeseries.

We do not assess other drivers, but in the discussion section we state that the method could be extended to include other modes of internal variability or drivers of climate change – which could be particularly relevant for other event types and locations.

4. The method of adjusting a GEV with the AMV is not explained at all. Please expand the paragraph L107-112. Did the authors try to include the GMST into the estimations of the return period as well?

   We have adjusted the paragraph to clarify the method used. We do not adjust for GMST, only for AMV. Rather than assessing a factual world and counterfactual world we instead compare a ‘+AMV-only world’ to a ‘-AMV-only world’.

   Methods:

We find AMV is affecting Sx (see Results), and use extreme value theory to assess the change in return period of Sx with different AMV phase. We use the generalised extreme value distribution, as we are using annual (block) maxima (Coles, 2001; Philip et al., 2020). We assume that the trend shifts with AMV, this is factored into the GEV by allowing the location parameter to be linearly dependent on the AMV. The distribution is then evaluated at two values of AMV: +0.25 °C (positive phase) and –0.25 °C (negative phase). We make no adjustment for changes in GMST, only AMV. This is similar to how GEV can be used to assess a factual and counterfactual world, e.g. with and without climate change, but in our case we use only AMV as a covariate (van Oldenburgh et al., 2021; Philip et al., 2020).

Minor comments:

L23-25: Can the authors describe more the previous methods and results that led to the conclusion that the AMV or PDO may have an influence on events like storm Babet?

The following has been added to the text:

Their method identified analogues in two different timeslices, for Storm Babet they found these analogues occurred in statistically different phases of AMV and PDO in the past and present.

L30-32: The other potential drivers of the AMV need to be discussed as it is a controversial topic. The atmospheric forcing plays a role. The external forcing also explains a large part of the AMV (Klavans et al., 2022).

We have expanded the text to include details of evidence for external radiative forcings, and added further references:

External radiative forcings may also influence the phasing and magnitude of the AMV. For example, Undorf et al., (2018) and Watanabe and Tatebe (2019) find greenhouse gases and aerosols play a key role in the timing, yet prior to 1950 volcanic eruptions coincide with phase changes (Birkel et al., 2018), With changes to the external radiative forcings on the climate system the drivers of AMV may also be changing, Klavens et al., (2022) find a growing contribution from external drivers.

L34-36: Provide more details on how the AMV affects the NAO. The references given all presents different mechanism that can be further presented to the reader.

We have explained the mechanisms further:

The AMV can be linked to European storminess through its influence on the wintertime North Atlantic Oscillation (NAO) (Ruggieri et al., 2021; Msadek et al. 2011; Davini et al. 2015; Peings and Magnusdottir 2014, 2016). The AMV influences the spatial pattern of the NAO, influencing storm tracks across the North Atlantic (Börgel et al., 2020). Climate model experiments nudged to specified AMV states are often used to investigate the mechanisms. For example. Ruggieri et al (2021) showed that the low-level jet differs significantly between AMV states, with a positive phase leading to a more southerly jet in the eastern Atlantic. This agrees Peings and Magnusdottir (2016), who showed that temperature changes in the extratropics are required to force a shift in the NAO and storm tracks. Msadek et al. (2011) showed that, alongside the southward shift in the stormtrack there is an intensification of the subtropical jet during positive AMV.

L36-37: Provide more details on the influence of AMV on the stormtrack, and its link with the NAO. See also Varino et al. (2019)

Further details have been added:

These mechanisms, found in climate models, are also supported by reanalysis data which shows a stronger relationship between AMV and North Atlantic extratropical storms frequency, than with the accelerated polar warming seen in recent decades (Valino et al., 2019).

L42-43: "it is often inferred that the change in analogues is the effect of climate change" Please provide references.

An example has been provided:

For example, Faranda et al. (2024) test for significantly different AMO, PDO, and ENSO states between analogues phases, and in the absence of these assume the change is climate change driven.

L60: Can the authors describe Figure A1 and explain which aspects of the SLP-analogs are better than the 500 hPa-analogs.

The following description has been added:

Analogue composite identified using 500 hPa geopotential height does not show rainfall over the regions impacted by Storm Babet. The analogues do show the same wind signal as the sea level pressure analogues, but it is much weaker – and thus further from the observed event.

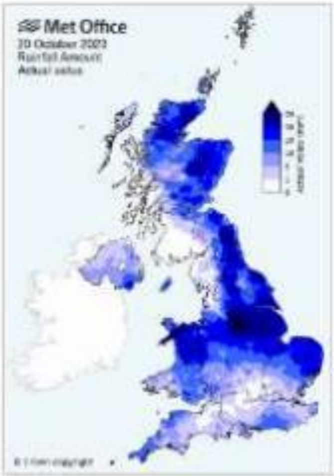
L75: Is the Euclidian distance the root mean squared error of the fields using area weighting?

Good point – it should be, but was not. We now apply an area weighting to the fields before calculating the Euclidean distance. For this event definition it did not change the analogues identified, but for other events this may not be the case. The scripts (written in python using the iris library) will be made available on publication, and a description of this is has been added to the Methods sections:

We determine similarity by calculating the area-weighted Euclidean distance of the sea level pressure field over the event domain (Faranda et al., 2022).

Fig 1 : the rainfall is strongly different in Fig. 1b and 1e. Was it expected? Can an analog built using only sea-level-pressure expected to capture high-precipitation events? Maybe part of the key dynamics of the event is missing in the analog, such an atmospheric rivers. Maybe the precipitation is not well captured in ERA5. Did the authors try other precipitation observations?

Other precipitation observations agree with the ERA5 precipitation. For example, the UK Met Office reports the daily rainfall totals for 20th October as:



It was surprising that the England / Wales rainfall is not captured by the analogues – only the Scottish rainfall. Looking into it we found that the report from Climameter on the event found similar (ClimaMeter - 2023/10/21 Storms Babet Aline). We have also been working with other groups who also find the rainfall over England and Wales is not captured so well in initialised forecast ensembles. With these groups we are carrying out further work investigating these differences and potential changes in a future climate. Atmospheric rivers are being investigated in that work – but as of yet we have no definite findings.

Interestingly, in the new Fig.5 we show that the top 1% of analogues in AMV+ years only do show some of the England/Wales rainfall pattern. We have added a comment about this in section 3.3:

For rainfall the AMV+ analogues show greater similarity to the observed event over England and Wales – a region where the analogues over the whole period failed to capture the event (Fig.1b/e).

Fig. 1: please explain in the methods the test implemented to show statistical significance. Only comparing the composite to the standard deviation of the field is too arbitrary.

The statistical testing has now been changed to instead use a one-sided t-test, with hashing indicating regions with $p>0.05$ (insignificant). The figure and caption have been updated.

Methods text has been updated:

We perform significance testing on the composites. When investigating analogues from one timeslice we assess where the signal in the composite of the analogues is statistically different to zero, using a one-sided t-test ($p<0.05$) (Fig.1).

Fig. 2: the test used for the statistical significance is not presented or explained.

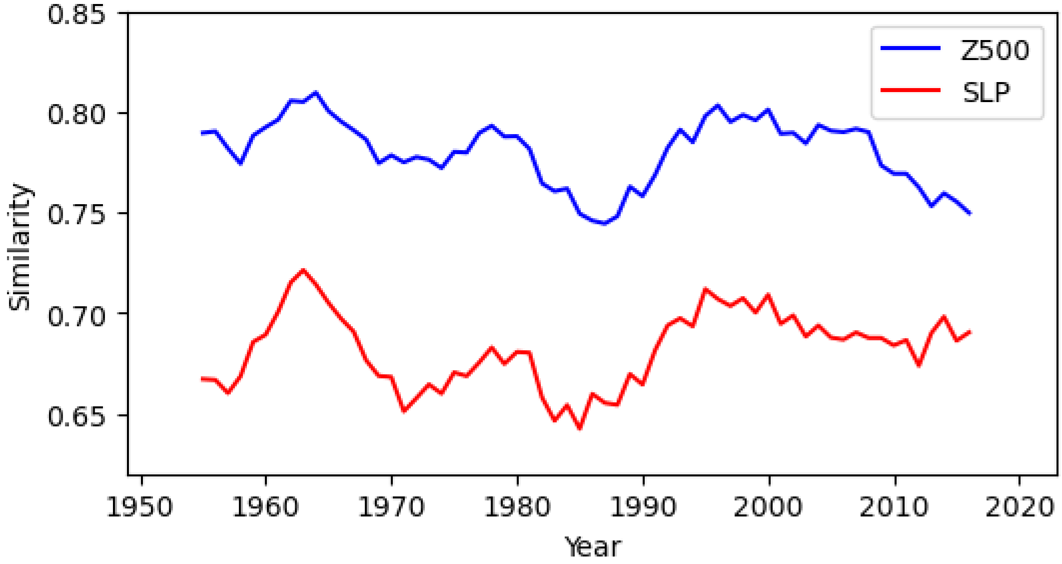
We have updated the figure caption, and added the following to the methods:

When comparing the analogues from different time periods we apply two-sided t-tests to each gridpoint, assuming equal variance, if $p<0.05$ the distributions are assumed to differ significantly (Fig.2).

L154: I am not convinced that the Sx time series based on 500-hPa would have similar results as it is correlated with the Sx time series based on sea-level-pressure. The authors should apply their analyses to the two time series (i.e. Sx based on sea-level-pressure and Sx based on 500-hPa geopotential).

We had not included applying the analysis to 500 hPa geopotential height – as in Fig.A1 we show analogues found using Z500 did not agree well with the observed event, in terms of rain or wind.

Despite of this, we have carried out the analysis – finding strong correlation between the time series of similarity from the two variables, shown below:

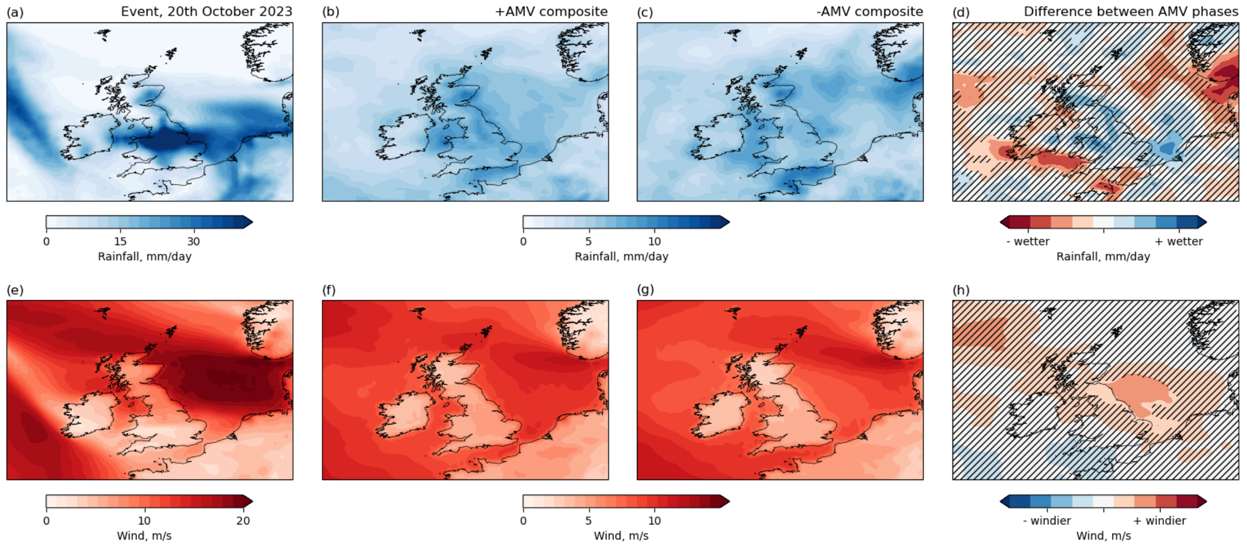


L163: "other drivers likely play a role" I do not understand why the authors did not investigate maps of SST anomalies associated with their time series. The choice of only investigating the AMV looks like cherry-picking.

See our response to major comment 3, we have now added a map as suggested and this shows the North Atlantic has greatest correlation with the analogue similarity timeseries.

L175-180 : the analysis shown in Fig. 5 is not really about the impacts of different AMV phases (see name of section 3.3); it is about the impacts of the similarity variations.

We have now changed Fig.5 to instead show maps of the top analogues in +AMO compared to –AMO, the text has also been changed:



Text in both the methods and in section 3.3 has been changed to describe the new figure:

Methods:

2.4 Analogues in different AMV phases

We assess the differences between the analogues in different AMV phases by splitting the years into three groups based on AMV. We include the lower third (AMV index below –0.14) as –AMV years and upper third (AMV index above 0.04) as +AMV years. For those years we identify the top 1 % of analogues, using the methods described in section 2.2. Composites of these analogues are calculated (Fig.5). The statistical significance is calculated using a 2-sided t-test between each gridpoint for the AMV+ and AMV- analogues, if $p<0.05$ the distributions are assumed to differ significantly.

Sec3.2:

We assess the difference between the top 1% of analogues for each AMV phase (Fig.5). For rainfall the AMV+ analogues show greater similarity to the observed event over England and Wales – a region where the analogues over the whole period failed to capture the event (Fig.1b/e). For wind, we also find the AMV+ analogues are more similar to the event than AMV- with statistically significant stronger winds in the southern North Sea during AMV+ years. In agreement with Fig.4, these results suggest events more similar to Storm Babet are more likely during AMV+ years. The spatial pattern of surface impacts – both for extreme wind and rain, are more similar to Storm Babet in AMV+ years (Fig.5).

L177: "is 3x greater" changed in text '3 times greater'

L178 : "1.2x windier" changed in text '1.2 times windier'

L188: "climameter" Can the authors explain this word?

Climameter refers to the rapid event analysis framework used on www.climameter.org. Led by Davide Faranda at IPSL, France, it produces rapid event studies.

In the text it has been replaced by two references:

> Faranda, D., Messori, G., Coppola, E., Alberti, T., Vrac, M., Pons, F., Yiou, P., Saint Lu, M., Hisi, A. N. S., Brockmann, P., Dafis, S., and Vautard, R.: ClimaMeter: Contextualising Extreme Weather in a Changing Climate, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-2643, 2023.
>
> Ginesta~~-Fernandez~~, M., and Faranda, D.: Strong winds in storms Babet & Aline likely strengthened by both human-driven climate change and natural variability, ClimaMeter. (climameter.org), 2023.

L189: "Thompson et al., in review" Can the authors make this paper available?

This paper is now published, and has been updated in the draft:

Changing dynamics of Western European summertime cut-off lows: A case study of the July 2021 flood event - Thompson - Atmospheric Science Letters - Wiley Online Library

L201-202 : "Multiple modes of variability may be considered at once, using multiple regression, but this would increase uncertainty in the results" I do not understand why investigating the role of other modes of variability through the use of multiple regression would increase the uncertainty.

This sentence has been changed:

Using multiple regression, multiple modes of variability may be considered at once~~.~~

Fig A2 (a). Can the author explain in the legend what the green and orange lines represent?

The caption has been corrected to state the 95th percentile is green and maximum orange (as in the figure legend).

References:

Deser, C., & Phillips, A. S. (2023). Spurious Indo-Pacific connections to internal Atlantic Multidecadal Variability introduced by the global temperature residual method. *Geophysical Research Letters*, 50, e2022GL100574. https://doi.org/10.1029/2022GL100574

King, M. P., Herceg-Bulić, I., Bladé, I., García-Serrano, J., Keenlyside, N., Kucharski, F., ... & Sobolowski, S. (2018). Importance of late fall ENSO teleconnection in the Euro-Atlantic sector. *Bulletin of the American Meteorological Society*, *99*(7), 1337-1343.

Klavans, J. M., A. C. Clement, M. A. Cane, and L. N. Murphy, 2022: The Evolving Role of External Forcing in North Atlantic SST Variability over the Last Millennium. *J. Climate*, **35**, 2741–2754, https://doi.org/10.1175/JCLI-D-21-0338.1.

Varino, F., Arbogast, P., Joly, B., Riviere, G., Fandeur, M. L., Bovy, H., & Granier, J. B. (2019). Northern Hemisphere extratropical winter cyclones variability over the 20th century derived from ERA-20C reanalysis. *Climate dynamics*, *52*, 1027-1048.