Dear Referee, Thank you for the time that you have spent on our manuscript. We are happy with your positive response and grateful for your comments and suggestions. These certainly contributed to improving the quality of our manuscript.

Below you will find a summary of the changes that we have made throughout the manuscript to address all your suggestions. The replies to your comments are written in blue, while your comments are reproduced in black. Please, notice that line, page, and figure numbers mentioned in our rebuttal letter refer to the new version of the manuscript.

Yours sincerely and on behalf of all the co-authors,

Guillian Van Achter

Anonymous Referee #1

GENERAL OVERVIEW

This brief communication analyses the variability of Arctic sea ice thickness in pre-industrial, historical and future climate simulations from the CESM1(CAM5) coupled model. Both temporal analysis of the timeseries of sea ice volume, and spatial analysis of the sea ice thickness are presented, and results from the two analyses are brought together in the discussion. The main findings are that this model shows two peaks of temporal variability (8 and 16 years) in the pre-industrial simulation, which persist in the historical simulation, and until the middle of the 21 st century. The first mode of spatial variability is a dynamic mode related to the AO, and corresponds to the 8 year peak in temporal variability. Both the spatial and temporal variability change significantly from the 2050s when the summer sea ice is lost.

In terms of the originality, scientific quality, significance and presentation quality I asses this communication as good. The application of wavelet analysis to the SIV timeseries is interesting, and it is really good to see the temporal and spatial analysis brought together in the same piece of work.

Overall, I feel the paper could benefit from

- More clarity in the details of the analysis, and some of the explanations.
- Some improvements to figure 1
- A better bringing together of thoughts at the end of the conclusions.

Again, we thank the referee for her/his time and the detailed revision of our manuscript. We appreciated very much her/his comments, which were all taken into account in the revised version of the paper. Below, we answer point-by-point all specific comments.

SPECIFIC COMMENTS

Lines 46-50: While the model has been well validated for the mean state of ice thickness and extent, and for the declining in ice extent, it is of course not possible to validate the variability in the ice thickness/volume, and so I think the statement that it can be assumed that the modelled time series is an adequate proxy is perhaps too strong - the assumption is a caveat of the work.
We agree with your comment. We reformulated this statement in the new manuscript version **"While it is not possible to validate the data in terms of SIT and SIV variability due to a lack of continuous observational data, the model was well validated in terms of mean state of ice thickness and extent as well as regarding the recent trends in the latter."** [pg. 2, l. 49-52].

Lines 53-54: Was the analysis done using just one of the historical and future climate ensemble members? I assume so, but it would be good to clarify this. As an aside, it would be interesting to know how robust this analysis is if it is applied to different members of the ensemble.
Since there is only member that spans from 1850 to 2005, we had decided to use only one member of the historical and future climate periods for the analysis. Thanks for your suggestion, we have now performed the multi-ensemble analysis for the study of both the temporal (wavelet) and spatial (EOF) variabilities. Please, notice that your comment agrees with one of the comments from the 2nd Referee, which also flagged the possible lack of robustness of using one member only.

We tested the robustness of our one-member EOF and wavelet analysis compared to the 30 other ensemble members. Since only one historical member is spanning the 1850-2005 time period, the historical period is now 1920-2005. For this analysis, we removed the ensemble mean from each member to obtain detrended SIT anomalies. In order to apply the EOF to the 30 members, the members were appended together over time (this method has been suggested by reviewer #2 and has already been used in the literature (Labe *et al.*, 2018)).

Figure 1 presents the first three modes of SIT variability over the historical (1920-2005) period. The modes are similar to the one of the study for the historical period (1850-2005). Figure 2 presents the first three modes of SIT variability over the future (2005-2050) time period. The first mode is similar, the second has the same pattern with small differences and the third has a different pattern of variability.

We conclude that our results for the EOF analysis over one-member are robust with the other ensemble members. The first and second modes that were described in the previous version of the manuscript are still present in the historical analysis over 30 members and the first one is still present in the future analysis. In the new manuscript, the EOF analyses for historical and future periods have been changed from a one-member to 30-member analysis.

(a) Historical, first mode **20**%　(b) Historical, second mode **11**%　(c) Historical, third mode **7**%

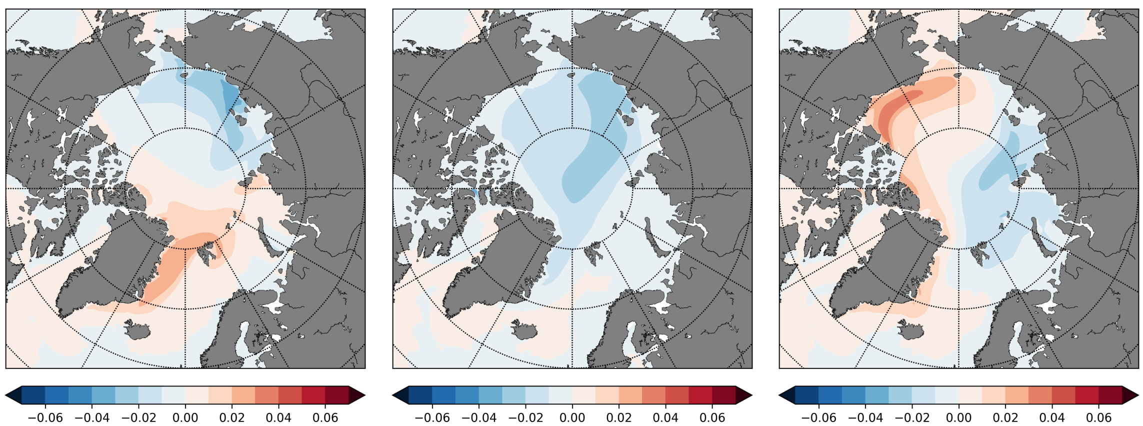


Figure 1: Modes of Arctic SIT spatial variability. First (a), second (b) and third (c) EOF of Arctic SIT over the historical period (1920-2005). EOFs are performed over 30 ensemble members by appending them over time before applying the EOF analysis.

(a) Future, first mode **20**%　(b) Future, second mode **11**%　(c) Future, third mode **7**%

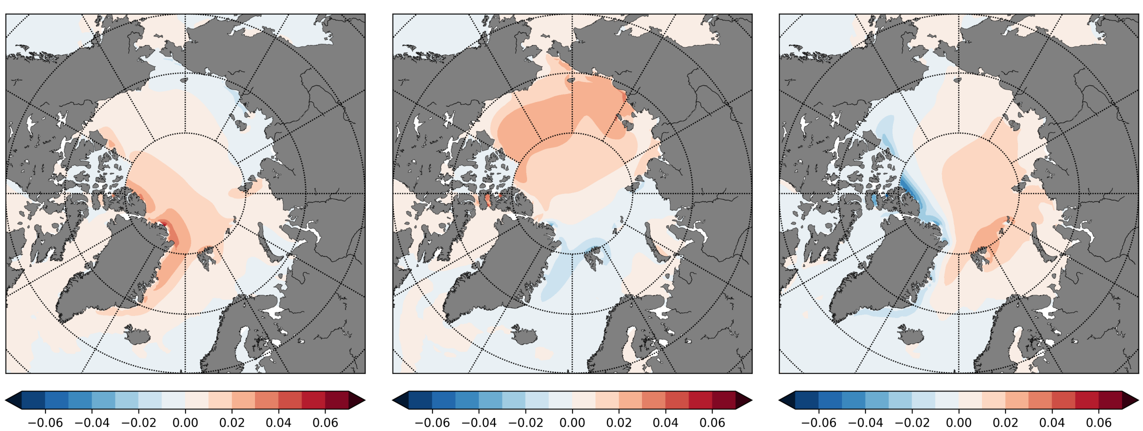


Figure 2: Modes of Arctic SIT spatial variability. First (a), second (b) and third (c) EOF of Arctic SIT over the future period (2005-2050). EOFs are performed over 30 ensemble members by appending them over time before applying the EOF analysis.

We also performed an ensemble-analysis for the temporal variability by applying the wavelet individually to each member. Afterwards, we averaged the results together (following referee #2 suggestion - Figure 3). Averaging the spectrum does not seem to be appropriate. It smoothed out any interesting information in the wavelet power spectrum (temporal-variability of the peaks), the stationarity of the SIV is not distinguishable in that form. By examining the wavelet analysis from each of the 30 members, we noticed that, for most of them (28 out of 30), 2 peaks of variability are significant and easily recognisable, one around 5-10 yrs and another around 15-25 yrs. Figure 3 presents all peaks that are significant for all ensemble members. The number of peaks (black line) shows that, for the 30 members, most of the peaks have a period of either 5-10 or 15-25 years. Because the peaks are not centered exactly at the same periods of variability, the peaks in the averaged wavelet analysis are no longer easily distinguishable.

We conclude that most of the ensemble members have two peaks of variability within the same ranges (5 to 10 and 15 to 25 years) mentioned in the paper. Because wavelet analysis over only one member has a better representation of the non-stationarity of the SIV and because the peaks are more distinguishable, we kept the one-member analysis in the study but we added a paragraph and a subfigure about results robustness with the ensemble members [pg. 6, l. 128-139].

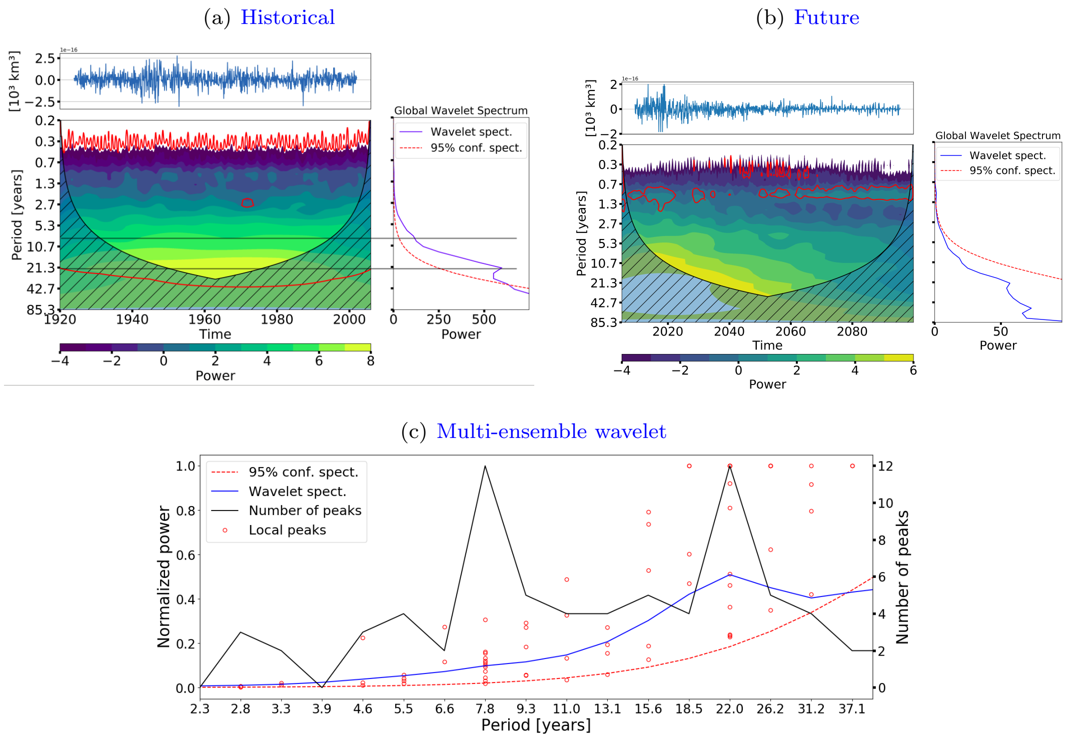


Figure 3: Wavelet analysis applied to the Arctic sea ice volume anomaly over the historical (1920-2005) (a) and future (2005-2100) (b) periods. Peaks of significant variability for 30 ensemble members (c) for the historical period. Wavelet analysis is applied to 30 ensemble members then the results are averaged together.

Lines 59-64: I found this paragraph a little confusing. The removal of the trend and seasonal cycle from monthly data for the SIV timeseries is clear, but I was less sure exactly what was done for the SIT fields before the EOF analysis. Later the analysis of Lindsay and Zhang is mentioned – they used annual mean data, so it would be good to clarify exactly what was done.
This was clarified in the text. **"For the variability analysis, the trend and seasonal cycle are removed from the time series (pan-Arctic SIV and gridded SIT) so that we focus on the interannual variability. Since the spatial variability analysis uses 30 ensemble members, the SIT anomaly fields are computed by removing the ensemble mean to each member. When only one ensemble member is used, as for the temporal analysis, the anomaly is calculated by excluding the individual trend (provided by a second-order polynomial fit) of each month."** [pg. 3, l. 67-71].

Paragraph beginning at line 67: I found this paragraph difficult to follow on first reading. I think it would help the reader to start the second sentence in a way that makes it clearer that the discussion will initially focus on the temporal analysis (the start of the following paragraph is much clearer in this regard).
We agree that some clarification is needed here. We have restructured the paragraph to that order [pg. 3, l. 74-75].

Figure 1: I have a number of suggestions that would make this figure easier to follow:

- The discussion in the text refers to the time periods in years, whereas the scale in the figure is in months – it would be easier to follow if the scale was also in years.

The y-axis labels of Fig. 1 (bottom panels) are now in years.

- Perhaps the lines marking the areas of significant variability could be a colour not used in the scale, so that they stand out more. This is especially needed in 1c, where there is more yellow on the plot itself.

  The significant levels are now highlighted in red.

- Maybe the 8 and 16 year periods could be marked by horizontal lines (on the panes representing the wavelet power spectrum).

  The horizontal lines have been added to the bottom-left panel.

- I'm not sure why the Fourier spectrum is included with the time-integrated power spectrum, as I don't think it is mentioned in the text.

  To avoid confusion, we have removed the Fourier spectrum and focused only on the wavelet analysis. [pg. 5, Figure 1].

In addition, the meaning of the hatched area is not explained anywhere.
Indeed, thanks for spotting that. The crosshatched areas indicate the cone of influence where edge effects become important. This is now clarified in the text and in the figure's caption. [pg. 4, l. 95].

Lines 110-111: It looks like the peaks discussed here are not significant? In the discussion of Fig 1a, the 42 year peak is not discussed because it is below the 95% red line. However, all the peaks in the time-integrated wavelet spectrum for Fig 1c are below the red line. Can this be clarified – is it that the integrated value is not significant because the peaks are only significant until 2050
Indeed, the peaks are significant only over the first 50 years, as it is shown in the wavelet spectrum by the red lines. In order to see the significance of the peaks in the time-integrated spectrum, it is required to apply the wavelet analysis over the 2005-2050 period, as shown in Figure 4 of this document. We decided to keep the analysis on the 2005-2100 period in the study since it is a demonstration of the loss of variability around the year 2050. But for clarification we modified the text [pg. 4, L 115-120].

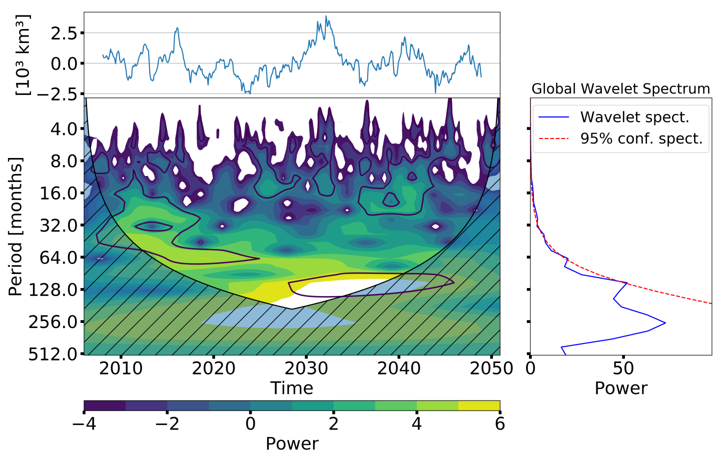


Figure 4: Wavelet analysis applied to the Arctic sea ice volume anomaly over future (2005-2050) period.

Lines 116-7: I am not sure what this last sentence means – could it be clarified please.
To make our point clearer in the text, we reformulated this sentence [pg. 5, l. 125-126].

Line 128: Could the sentence starting 'The disparities...' be tightened up a bit – I see what it means, but it sounds rather vague as written.
To make our point clearer in the text, we reformulated this sentence [pg. 6, l. 151-152].

Section 3.2: Mention here that the future period is analysed to 2050.
It is now mentioned in the text [pg. 6, l. 142] and in the caption of figure 2.

Section 3.3: I think this analysis is just done for the pre-industrial period? It would be good to make this clear – maybe even in the section title. The analysis in this section is good, but I found the text confusing in places. Were both the thermodynamic and dynamic aspects investigated for each of the first and second modes for example?

Indeed the analysis was only made over the pre-industrial period. We have decided to keep the same section's title, but we made this point clear in the first sentence of the section ([pg. 8, l. 161]). The dynamic and thermodynamic aspects were investigated for both modes (dynamic aspect in Figure 5 in this document) and this point has been clarified in the text [pg. 8, l. 170-174].

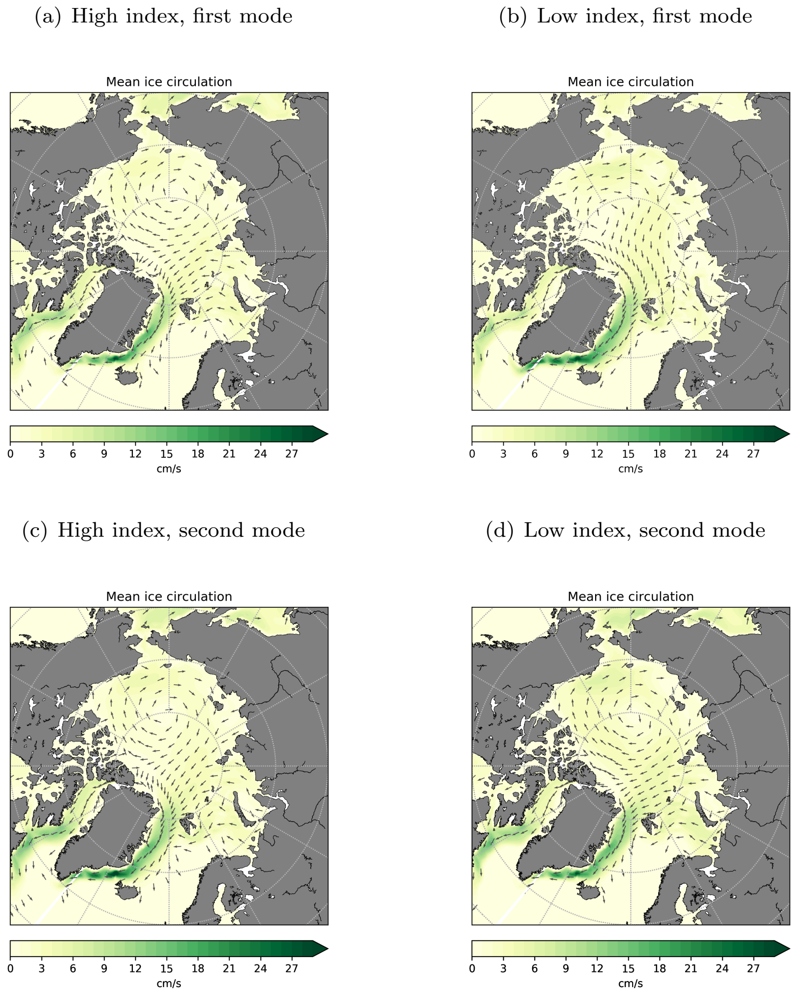


Figure 5: Mean sea ice velocity for both high and low indexes of the first and second modes of SIT spatial variability. Analysis is performed over one ensemble members.

Lines 185-186: The analysis of spatial variability presented in sect 3.2 only covers the period to 2050 – perhaps a statement can be added there about the behaviour past-2050.
We added a paragraph in the section 3.2 to address that [pg. 6, l. 159-162].

Conclusions: the first paragraphs provide a good summary of the work, but the last couple of paragraphs could be stronger. In the final paragraph do you mean the location of these devices? It would be good if this could be more explicit.
We changed the sentence to make it more explicit [pg. 11, l. 220-225]. Also, the conclusion has been changed. New information about the robustness of the result with other ensemble members and the behaviour of the sea ice variability after 2050 have been added to the text.

TECHNICAL CORRECTIONS

Line 26-27 "They enlightened..." I did not understand the first part of this sentence (relating to the historical and pre-industrial climates) – is the point that the variability for these periods is the same? It would be good if this could be re-worded to be clearer.
Yes, in Olonscheck and Notz (2017), they found the same variability for both periods. By stable, they mean that there is a remarkable similarity between the pre-industrial and the historical internal variability of Arctic sea ice volume. This point was clarified in the text [pg. 2, l. 28-30].

Line 41: It would be good to mention somewhere that this is a CMIP5 model.
This information has been added to the text [pg. 2, l. 46].

Line 70: I would suggest mentioning here (with the Torrence and Compo ref) that the Morland wavelet is used, rather than in the caption for Fig 1.
The modification has been done in the text and in the figure's caption [pg. 3, l. 76].

Line 73: It not mentioned here which 200-year period of the 1700-year control simulation is used, although it is clear from Fig 1, maybe mention that it is the 200 years preceding the historical integration.
Indeed this was not specified. We added this information in the caption of Figures 1 and 2.

Line 81: I don't think the reason for analysing the shorter period is explicitly mentioned in sect 3.1. Perhaps it can be mentioned in Section 3.2.
We thank the reviewer for spotting that gap, it is now mentioned in Sect 3.2 [pg. 6, l. 141-142].

Line 106: Sentence starting 'Those peaks and bands...' not needed - Fig 1b could instead be referenced in the first sentence of the paragraph.
It has been changed [pg. 4, l. 117].

Line 125: Ref Fig2g in this sentence.
It has been changed [pg. 6, l. 156].

Line 138: Sentence starting 'As the first mode....', rephrase to emphasise where there is and is not agreement in the behaviour of the first and second modes.
We agree with your comment and have improved this sentence in the text [pg. 6, l. 151-157].

Line 140: I don't think this sentence is needed (We looked at...)
Agreed, this sentence has been removed from the text.

Dear Referee, Thank you for the time that you have spent on our manuscript. We are happy with your positive response and grateful for your comments and suggestions. These certainly contributed to improving the quality of our manuscript.

Below you will find a summary of the changes that we have made throughout the manuscript to address all your suggestions. The replies to your comments are written in blue, while your comments are reproduced in black. Please, notice that line, page, and figure numbers mentioned in our rebuttal letter refer to the new version of the manuscript.

Yours sincerely and on behalf of all the co-authors,

Guillian Van Achter

Anonymous Referee #2

GENERAL OVERVIEW

This brief communication looks at the temporal and spatial variability of Arctic sea ice volume and thickness (respectively) using the CESM large ensemble over three multi-decadal to multi-centennial periods (pre-industrial, historical, and future). A wavelet analysis was used to explore the peak modes of variability in SIV whereas the authors used an EOF analysis to explore the spatial modes of variability in each period. The key findings of the study are that there are two peak modes of SIV variability in the pre-industrial and historical time periods centered on 8- and 16-year periods. The first of these temporal modes is shown to be related to the first spatial mode of SIT variability, which shows a strong AO signature. The relationship between the first mode of SIT and the temporal mode of SIV is made more certain by a wavelet analysis performed on the first principal component of SIT, which is found to also have a peak at 8 years. The other key finding is that both temporal modes basically vanish after 2050 when SIV reduces by 50% in winter. The results of the analysis are original in that the temporal and spatial analyses are brought together for the first time in this way. Overall, I rate the study in terms of originality, scientific quality, significance, and presentation as fair to good.
Again, we thank the referee for her/his time and the detailed revision of our manuscript. We appreciated very much her/his comments, which were all taken into account in the revised version of the paper. Below, we answer point-by-point all specific comments.

The EOF analysis is informative, but have the authors considered identifying spatial modes of variability by correlating the wavelet time series associated with the peak periods for SIV with sea ice thickness? It could be interesting to see if the SIT spatial patterns agree with the EOFs, especially since the EOFs are constrained by orthogonality.
Very interesting suggestion, we thank the reviewer for that. We computed the wavelet time series associated with the first peak of variability over the pre-industrial period. Then we correlated this time series with the spatial sea ice thickness anomalies. Figure 1a (in this document) shows the correlation coefficients with 95% of significance. The correlation is quite low, but still significant (0-0.3) and the Atlantic/Pacific dipole can be found, even if the spatial pattern has some differences with the first EOF. The Pacific part is centered in the center of the Arctic Basin and the Atlantic part is smaller, restricted to the region near the North and East coast of Greenland. Furthermore, looking at Figure 1a, we note that the highest correlation values are located in areas where sea ice drift differs the most between high and low indices of the first EOF (see Figure 3 of the manuscript). This would suggest that we are indeed showing spatial variability of the 8-yr peak that is linked to the Arctic Oscillation.

On the other hand, this method may not be the most appropriate for analysing the spatial variability. Indeed, the wavelet time series associated with the first peak captures the main part of the sea ice volume anomaly. Therefore, the wavelet associated with the first peak can be seen as an approximation of the SIV anomaly. By correlating an approximation of the sea ice volume anomaly with the sea ice thickness anomaly fields, we are not surprised to obtain a high correlation near the center of the Arctic Basin, as it is the case for the correlation map between SIV and SIT (Figure 1b).

In conclusion, the spatial pattern from the wavelet time series associated with the first peak correlation with the SIT fields does have similarities with the EOFs. But from our perspective, these spatial patterns are not comparable.

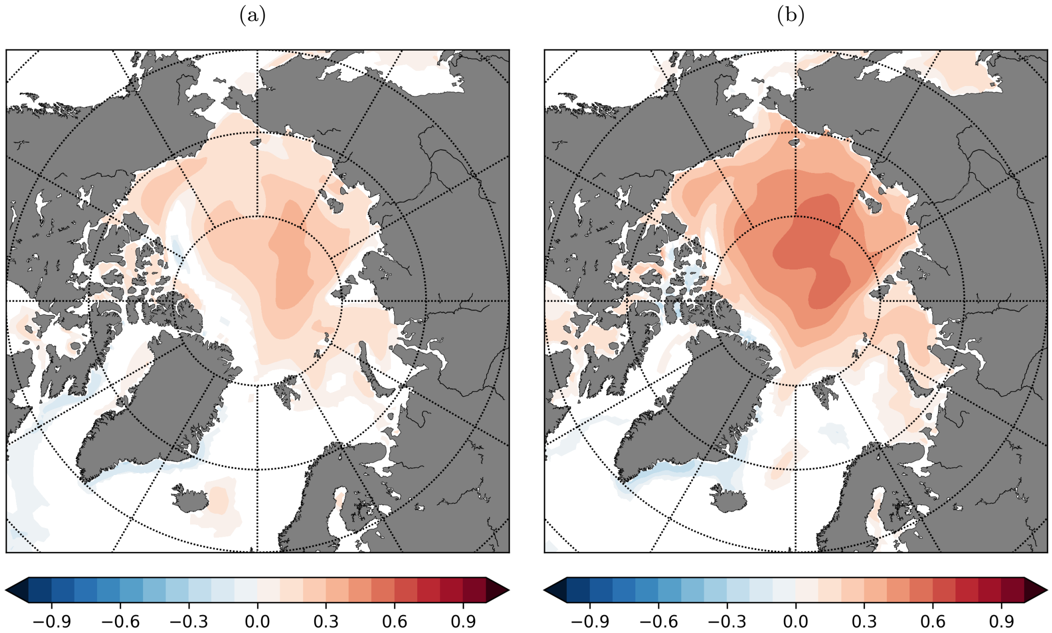


Figure 1: Correlation map between the SIT anomaly (pre-industrial period) and the wavelet time series associated with the first peak of the wavelet analysis (a). Correlation map between the SIT anomaly (pre-industrial period) and the SIV anomaly (b).

SPECIFIC COMMENTS

L20-25:

- Labe et al., 2018 did an EOF analysis comparison with PIOMAS and CESM LE monthly ice thickness that should be referenced here

  Indeed, thank you for pointing this missing reference. The paper has been added in the introduction [pg. 1, l. 21].

- The Singarayer and Bamber study didn't look at sea ice thickness, just concentration.

  Indeed, we removed it from the text.

- should state that these studies all used model-based thickness reconstructions.

  This is indeed an important information, it has been added in the text [pg. 1, l. 22].

- the EOF mode variance numbers cited were only from the Lindsay and Zhang study, so should state this. Also could note that the spatial structures of these modes and the amount of variance they explain can be sensitive to whether (and how) the SIT time series are detrended prior to performing the EOF or K-cluster analyses, the season and the time period considered, and the model.

  The paragraph has been rewritten in order to take all previous comments in account [pg. 1-2, l. 20-31].

,
L60-65:

- It needs to be clarified whether the analysis is being performed on a single ensemble member from the large ensemble or the full ensemble. If the former was done, then I would suggest at least commenting on how robust the analysis is if performed on other ensemble members. Ideally though, the full ensemble would be used. For instance, the wavelet analysis could be performed on each ensemble member and then the results of the wavelet analysis could be averaged together. It's not immediately clear to me how one would do this for EOF analysis, perhaps by appending the ensemble members to one another.

  We thank the reviewer for this comment. Since only one member spans from 1850 to 2005 we had decided to use only one historical member for the analysis.

  We tested the robustness of our one-member EOF and wavelet analysis compared to the 30 other ensemble members. Since only one historical member is spanning the 1850-2005 time period, the historical period is now 1920-2005. For this analysis, we removed the ensemble mean from each member to obtain detrended SIT anomalies. In order to apply the EOF to the 30 members, the members were appended together over time.

Figure 2 presents the first three modes of SIT variability over historical (1920-2005) period. The modes are similar to the one of the study for the historical period (1850-2005). Figure 3 presents the first three modes of SIT variability over future (2005-2050) time period. The first mode is similar, the second has the same pattern with small differences and the third has a different pattern of variability.

We conclude that our results for the EOF analysis over one-member are robust with the other ensemble members. The first and second mode that were described in the previous version of the manuscript are still present in the historical analysis over 30 members and the first one is still present in the future analysis. In the new manuscript, the EOF analyses for historical and future period has been changed from a one-member to a 30-member analysis.

(a) Historical, first mode **20%** (b) Historical, second mode **11%** (c) Historical, third mode **7%**

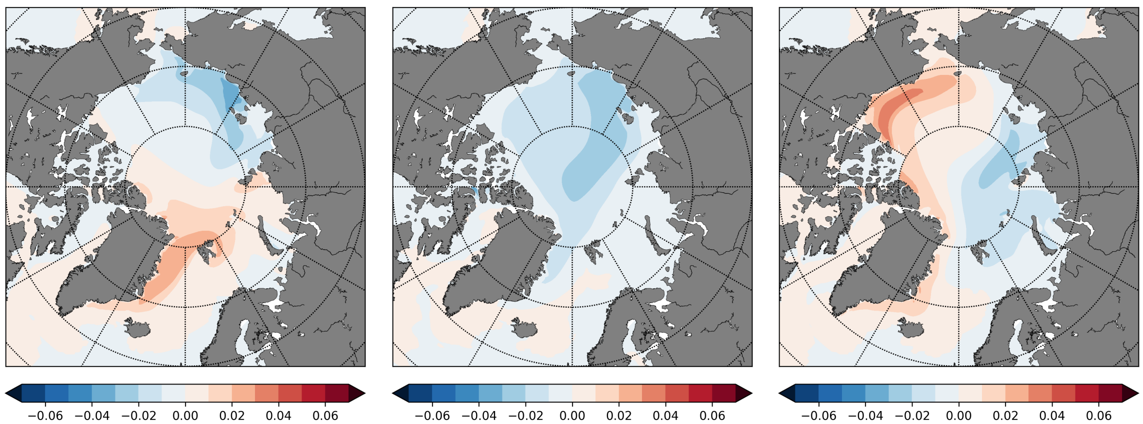


Figure 2: Modes of Arctic SIT spatial variability. First (a), second (b) and third (c) EOF of Arctic SIT over the historical period (1920-2005). EOFs are performed over 30 ensemble members by appending them over time before applying the EOF analysis.

(a) Future, first mode **20%** (b) Future, second mode **11%** (c) Future, third mode **7%**

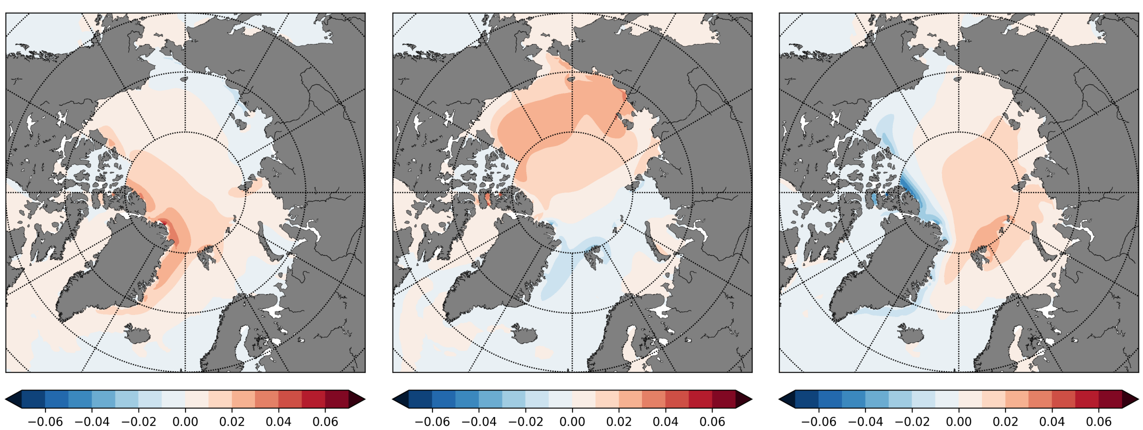
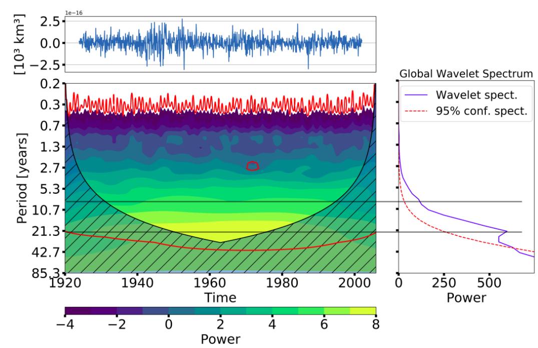


Figure 3: Modes of Arctic SIT spatial variability. First (a), second (b) and third (c) EOF of Arctic SIT over the future period (2005-2050). EOFs are performed over 30 ensemble members by appending them over time before applying the EOF analysis.

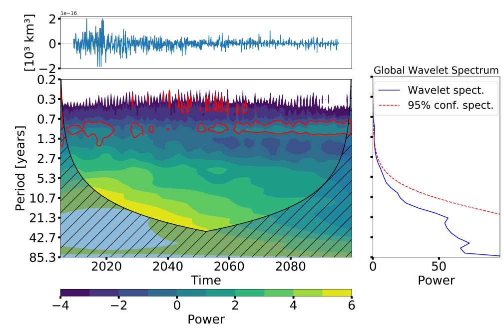
We also performed an ensemble-analysis for the temporal variability by applying the wavelet individually for each member. Afterwards, we averaged the results together (following your suggestion - Figure 4). Averaging the spectrum does not seem to be appropriate. It smoothed out any interesting information in the wavelet power spectrum (temporal-variability of the peaks), the stationarity of the SIV is not distinguishable in that form. By examining the wavelet analysis from each of the 30 members, we noticed that, for most of them (28 out of 30), 2 peaks of variability are significant and easily recognisable, one around 5-10 yrs and another around 15-25 yrs. Figure 4 presents all peaks that are significant for all ensemble members. The number of peaks (black line) shows that, for the 30 members, most of the peaks have a period of either 5-10 or 15-25 years. Because the peaks are not centered exactly at the same periods of variability, the peaks in the averaged wavelet analysis are no longer easily distinguishable.

We conclude that most of the ensemble members have two peaks of variability within the same ranges (5 to 10 and 10 to 20 years) mentioned in the paper. Because wavelet analysis over only one member has a better representation of the non-stationarity of the SIV and because the peaks are more distinguishable, we kept the one-member analysis in the study but we added a paragraph about results robustness with the ensemble members [pg. 6, l. 128-139].

(a) Historical



(b) Future



(c) Multi-ensemble wavelet

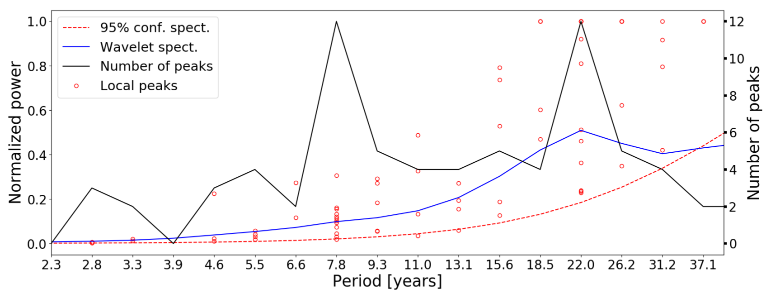


Figure 4: Wavelet analysis applied to the Arctic sea ice volume anomaly over the historical (1920-2005) (a) and future (2005-2100) (b) periods. Peaks of significant variability for 30 ensemble members (c) for the historical period. Wavelet analysis is applied to 30 ensemble members then the results are averaged together.

- One of the advantages of the large ensemble is that the externally-forced signal can be removed from the ensemble by subtracting the ensemble mean from each ensemble member. This makes detrending by fitting to a polynomial unnecessary and actually inferior since it requires an assumption about the functional form of the response to the forced signal.

  This approach is indeed better for a large number of member. We used this method when we applied the EOF and wavelet to the 30 ensemble members. It is also clarified in the manuscript [pg. 3, l. 66-70].

L70:

- Should offer some more details on how the wavelet analysis was performed [software used, wavelet function (ah I now see it says in Fig. 1 caption, but should say it here), and whether any normalization was used.]

  Details about the mother wavelet has been added in the text [pg. 3, l. 76] and the python module used to performed the wavelet analysis is now described in the Code availability Section. No normalisation is used, better description about the pre-processing of the data is given in Section 2.1 of the study.

L100:

- There is still overlap though between the occurrence of each peak so it's maybe not very accurate to say they don't occur at the same time.

  We agree with the reviewer. For more accuracy the sentence was rewritten in the text [pg. 4, l. 105].

L110:

- It might be the contouring but I'm having a hard time seeing a significant area at the 5-year period during the 2010-2025 period.

  It is more correct to say that the area is 2015-2025. We also changed the contour color [pg. 4, l. 116].

Figure 1:

- I recommend changing the units on the vertical axis from months to years since these are the units used in the text.

  We updated the figure.

- What is the yellow contour representing? Presumably it's statistical significance, but if it is then I think it would be easier to see if it were colored red as in the time integrated plots. It should also be stated.

  We changed the colour to red, and the description of the red contour has been brought to the text [pg. 4, l. 96] and in the caption of the figure.

- What are the areas of white on the contour plot representing?

  The white areas are marked by power values which are out of the range defined by the figure's color bar. For a better reading of the figure, we kept those white areas but we explained their meaning in the figure caption.

L120:

- Do the authors have any idea why the leading EOF mode over the historical period explains much less variance than that found in Labe et al., even though the spatial pattern looks the same? Could it be that it's due to the use of all ensemble members in Labe et al.?

  This is indeed an interesting question. Even after applying the EOF analysis to 30 ensemble members, we still have modes that explain much less variance than the ones of Labe *et al.* The differences are that the sea ice thickness are linearly detrended in Labe *et al*, while we use a polynomial approach to detrend the SIT. This linear detrending might not be sufficient if the forced signal is accelerating over time. This would leave too much low-frequency variability in the anomalies. Another difference, but less significant in terms of explained variability differences, is that their SIT fields are weighted by the square root of the cosine of their latitude to account for converging meridians toward the pole.

- Relatedly, I'm surprised that the variance explained by the first three modes doesn't sum to a higher number. For instance, looking at Lindsay and Zhang study, the first three modes identified in their study sum closer to 60-70%.

  In this case the greater estimation of the explained variability could come from the fact that Lindsay and Zhang applied EOF to annual mean sea ice thickness. By applying EOF analysis to yearly and not monthly gridded SIT, the first EOFs will represent more of the total variability. Also, the EOF are applied over a shorter time period (1953-2003). This could also increase the explained variability for each components.

L140:

- Why was the first mode of SIT variability only compared with ice velocity and the second mode only compared with temperature? Why not compare each mode with both ice velocity and temperature?

  Thanks to your comment, we updated this section by applying the sea ice velocity analysis to the first and second modes of SIT variability. It turned out that the first mode presents AO signature, while the second mode does not. The latter has the same sea ice velocity pattern for both high and low indices (Figure 5 in this document). Then we also applied surface air temperature analysis to the first mode, which presents also differences between indices. We kept the results in the paper but we changed our conclusion. As you suggested, the surface air temperature and the sea ice thickness variabilities are associated with each other but we can not conclude anything about its causation [pg. 8, l. 179-184].

(a) High index, first mode (b) Low index, first mode

(c) High index, second mode (d) Low index, second mode

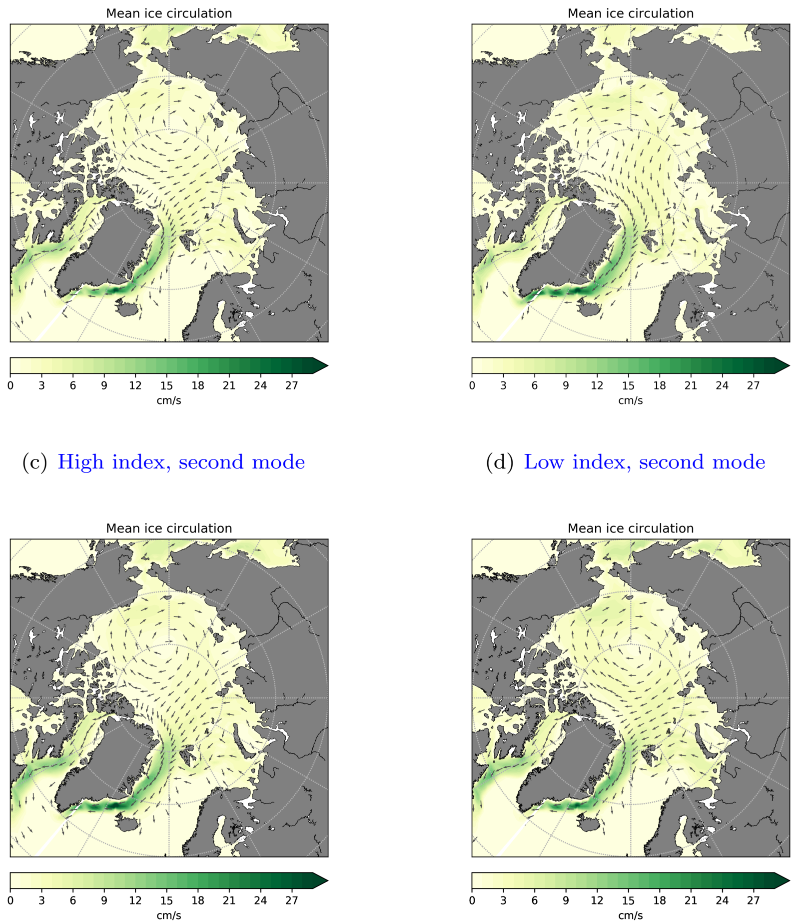


Figure 5: Mean sea ice velocity for both high and low indices of the first and second modes of SIT spatial variability. Analysis is performed over one ensemble member.

L155:

- I'm not sure it's accurate to say that the air temperatures are causing the variability in SIT from this analysis. They appear to be associated with each other, but this doesn't imply causation. For instance, a thermodynamic response from the ice thickness variability is just as plausible. Nonetheless it is at least consistent with Olonscheck et al. (as stated though, they looked at ice area not thickness).

  This has been answered in the previous point.

TECHNICAL COMMENTS

L85:

- I would suggest separating this sentence into two; it's currently a run-on (the two uses of the word "by")

  We have changed the text according to your suggestion [pg. 4, l. 89-91].

Dear Dr. Michel Tsamados,

Here are the revised manuscript and the answers to your comments.

-Mean state of sea ice thickness. Be more specific on how this validation was performed, i.e. satellite data or PIOMAS.

The validation of the Arctic sea ice extent and thickness was done using satellite observation (Jahn et al., 2016;Swart et al., 2015;Barnhart et al., 2016) and also using PIOMAS (Labe et al., 2018).

- Appending procedure seems odd as one would expect a unnatural periodicity (i.e. the duration of each ensemble member run). Was this done for the historical (1920-2005) and future scenarios? Clarify the method a little bit more.

This was done for pre-industrial, historical (1920-2005) and future (2006-2050) periods. Since the sea ice thickness fields are preprocessed by removing the ensemble mean, we do not expect to see a periodicity link to the appending procedure. The appending procedure for analysing the spatial variability for all ensemble member was proposed by Referee 2 and allready used in previous works (Labe et al., 2018). The method consists of removing the ensemble mean to each member, append the SIT fields over time all together, and then apply the PCA. The method is described in the updated paper [p. 3, l. 65-71].

-Sign on new figure 1 different. Is that an error?

This is not an error, the sign of a PCA mode does not have meaning.

- Add some comments about how you expect your result to fare with other CMIP models.

This will depend on how the CESM-LE differs from the CMIP models in terms of sea ice state. The CESM-LE sea ice mean state is well validated. Both CESM-LE and CMIP5 sea ice trends over the observational period are nearly identical (Barnhart et al., 2016). So, we expect that the main mode of Arctic sea ice spatial and temporal variability of the CMIP simulated sea ice would look similar to our results.

Brief communication: Arctic sea ice thickness internal variability and its changes under historical and anthropogenic forcing

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Abstract. We use model simulations from the CESM1-CAM5-BGC-LE dataset to characterise the Arctic sea ice thickness internal variability both spatially and temporally. These properties, and their stationarity, are investigated in three different contexts: (1) constant ~~,~~ pre-industrial, (2) historical and (3) projected conditions. Spatial modes of variability show highly stationary patterns regardless of the forcing and mean state. A temporal analysis reveals two peaks of significant variability and despite a non-stationarity on short ~~time-scales~~timescales, they remain more or less stable until the first half of the 21st century, where they start to change once summer ice-free events occur, after 2050.

1 Introduction

In the recent decades, Arctic sea ice has retreated and thinned significantly (Notz and Stroeve, 2016). The annual mean Arctic sea ice extent has decreased by $\sim 2 \times 10^6$ km^2 between 1979 and 2016 (Onarheim *et al*., 2018). An analysis combining US Navy submarine ice draft measurements and satellite altimeter data showed that the annual mean sea ice thickness (SIT) over the Arctic Ocean at the end of the melt period decreased by 2 m between the pre-1990 submarine period (1958-1976) and the Cryosat-2 period (2011-2018) (Kwok, 2018). On long timescales (~~several~~ a few decades or more), ~~these retreat~~ retreating and thinning are projected to continue as greenhouse gas emissions are expected to rise. However, on shorter timescales (1-20 yr), internal climate variability, defined as the variability of the climate system that occurs in the absence of external forcing and caused by the system's chaotic nature, limits the predictability of climate (Deser *et al*., 2014) and represents a major source of uncertainty for climate predictions (Deser *et al*., 2012). In this context, greater knowledge of Arctic ~~sea ice thickness~~ SIT internal variability and of its drivers are both essential to document the true evolution of the Arctic atmosphere–ice–ocean system and to predict its future changes.

The mean spatial distribution of the Arctic ~~sea ice thickness~~ SIT is relatively well documented (Stroeve *et al*., 2014). But there are some uncertainties around its interannual variability and its spatial modes of variability. Some studies (~~Singarayer and Bamber, 2003;~~ Lindsay and Zhang, 2006; Fuckar *et al*., 2016; Labe *et al*., 2018) already analysed the spatial distribution of Arctic sea ice variability by applying empirical orthogonal functions (EOF) (K-means cluster analysis for Fuckar *et al*., 2016) to ~~historical sea ice thickness~~ model-based historical SIT time series. ~~They reported that the first mode is~~ Lindsay and

Zhang (2006) reported a first mode nearly basinwide, while the second and third ones are orthogonal lateral modes accounting for 30, 18 and 15% of the variability, respectively. Fuckar *et al.* (2016) also found a nearly basinwide first mode, with an Atlantic-Pacific dipole as the second mode. Labe *et al.* (2018) depicted an Atlantic-Pacific dipole but as the first mode. The spatial structure and amount of explained variance of those modes are sensitive whether and how the SIT time series is detrended. It is also model-dependent and influenced by the season and analysed period. The temporal sea ice volume (SIV) variability has been studied by Olonscheck and Notz (2017). ~~They enlightened a rather stable internal variability of annual sea ice volume and area for the historical climate compared to the~~ These authors enlightened a remarkable similarity between the pre-industrial ~~one and an extremely likely~~ and historical internal variabilities of the annual Arctic SIV. They also noticed a decreased internal variability of winter and summer Arctic ~~sea ice volume~~ SIV for a future climate forced by the RCP8.5 scenario.

~~Most of~~ Apart from Olonscheck and Notz (2017), the studies cited above used data covering a few decades under historical forcing. In this work we use a long climate model control run under pre-industrial conditions from the CESM1-CAM5-BGC-LE dataset, which enables us to study only the internal variability of the Arctic ~~sea ice thickness~~SIT. We study the internal variability both temporally and spatially by applying a wavelet analysis and an EOF decomposition to the ~~Arctic sea ice volume and thickness~~ pan-Arctic SIV and gridded SIT anomaly time series, respectively. We also determine whether or not the ~~sea ice volume and thickness~~ SIV and SIT variability is stationary by analysing the model outputs under historical and future climate conditions with 30 ensemble members.

This manuscript is organised as follows. The model and its outputs are briefly described in Section 2. In Section 3, the spatial and temporal internal variability of Arctic sea ice are analysed, as well as their persistence through historical and future climate conditions. Then we explore the drivers of the main modes of internal variability. Conclusions are finally given in Section 4.

2 Data and methods

2.1 Sea ice thickness and volume datasets

We use the CESM1-CAM5-BGC-LE dataset (Kay *et al.*, 2015). The Community Earth System Model Large Ensemble (CESM-LE) was designed to both disentangle model errors from internal climate variability and enable the assessment of recent past and future climate changes in the presence of internal climate variability. The CESM1(CAM5) ~~model~~ is a CMIP5 participating-model. It consists of coupled atmosphere, ocean, land and sea ice component models. It also includes a representation of the land carbon cycle, diagnostic biogeochemistry calculations for the ocean ecosystem and a model of the atmospheric carbon dioxide cycle (Moore *et al.*, 2013; Lindsay *et al.*, 2014). While it is not possible to validate the data in terms of SIT and SIV variabilities due to the lack of continuous observational data, the model was well validated in terms of mean state of the ice thickness and extent, as well as regarding the recent trends in the latter. Jahn *et al.* (2016) showed good agreement between observations and CESM1(CAM5) simulations for mean Arctic sea ice thickness and extent in the early twenty-first century~~, and~~. Barnhart *et al.* (2016) demonstrated that CESM1(CAM5) captures the trend of declining Arctic sea ice extent over the period of satellite observations. Based on these validation studies, ~~it can be assumed~~ we consider that the CESM1-CAM5-BGC-LE time series is ~~an adequate~~ a fair proxy to study the ~~variability of Arctic sea ice thickness under different conditions. The dataset contains~~ variabilities of the Arctic SIT and SIV under different forcing conditions.

In this paper, we use the monthly averaged Arctic SIT and SIV provided over the 3 ~~main simulations. The first one is a~~ periods (pre-industrial, historical and future). The pre-industrial period is represented by a single 1700-yr control simulation with constant pre-industrial forcing. The ocean model was initialised from a state of rest (Danabasoglu *et al.*, 2012), while the atmosphere, land and sea ice models were initialised using previous CESM1(CAM5) simulations. This experimental design allows the assessment of internal climate variability in the absence of climate change. ~~The two other simulations are a historical (~~In practical terms, we will use the last 200 years of this simulation. The historical period has one ensemble member covering the 1850-2005 ~~) simulation and a future climate simulation~~ period and 30 ensemble members over 1920-2005. Also with 30 ensemble members, the future climate period (2006-2100) ~~following~~ follows the representative concentration pathway (RCP) 8.5 scenario, corresponding to a total radiative forcing of 8.5 W/m^2 in 2100 relative to pre-industrial conditions (Meinshausen *et al.*, 2011). The Canadian Archipelago region was removed from the dataset ~~due to sea ice thickness reaching~~ since SIT reaches unrealistic values in this area.

~~In this paper, we use the monthly averaged Arctic sea ice thicknesses (SIT) provided over the 3 periods (pre-industrial, historical and future). The variability analysisis applied on the SIT and sea ice volume (SIV) anomaly time series. The~~ For the variability analysis, the trend and seasonal cycle are removed ~~to focus on the long-term variability. The anomaly is calculated in three steps. For each month, we build a time series with all values of that month over the entire period. Then, we compute the second degree polynomial fitting the time series. Finally, we remove that polynomial fitting from the original time series. Repeating those steps for each month, we get the original time series without the trend and seasonal cycle.~~ from the time series (pan-Arctic SIV and gridded SIT) so that we focus on the interannual variability. Since the spatial variability analysis uses 30 ensemble members, the SIT anomaly fields are computed by removing the ensemble mean to each member. When only one ensemble member is used, as for the temporal analysis, the anomaly is calculated by excluding the individual trend (provided by a second-order polynomial fit) of each month.

2.2 Variability analysis

~~In order to~~ To characterise the internal variability of the Arctic ~~SIT~~sea ice, we aim at inspecting how ~~it evolves over time and whether there are regions marked by different variabilities. Usual spectral analyses assume stationary of the time series. Having no certainty about the stationary character of the SIV time series even over long periods, we performed the analysis of the temporal variability of the SIV time series by means of wavelet analysis~~the SIV variability evolves in time and how SIT variability is characterized in space. For addressing the temporal variability, we make use of wavelet analysis, with Morlet as wavelet mother, following the methodology proposed by Torrence and Compo (1998). The wavelet analysis ~~is appropriate for~~

~~non-stationary time series. It determines the evolution of periodicities in the time-space and provides higher resolution in the periodicity (Soon et al. 2011). The wavelet analysis is applied to the SIV anomaly time seriesunder pre-industrial (200-years),~~ has the advantage of taking into account possible non-stationarity of the time series. In this paper, we show the results for one of the historical (1850-2005) ~~and~~ members and one of the future (2006-2100) ~~conditions.~~ members, although we tested the robustness of the results over the 30 ensemble members as discussed later (Section 3.1 and 3.2).

The spatial variability is analysed by computing the EOFs on the SIT anomaly time series~~as conducted by Lindsay and Zhang (2006)~~. This decomposition reduces the large number of variables of the original data to a few variables, but without compromising much of the explained variance. Each EOF represents a mode of SIT variability that provides a simplified representation of the state of the SIT at that time along that EOF. In other words, the EOFs themselves are fixed in time but their weighting coefficients are time-varying; the associated time series (one for each mode) indicate in which state the SIT is at any time (Hannachi, 2004). The analysis is made on the gridded SIT anomaly time series ~~, over the same periodsas defined for the temporal analysis, except for the future climate period which spans from 2006 to 2050 (reasons are given in Section 3.1~~for the 3 periods. For the historical and future periods, the EOFs are computed over 30 ensemble members, all appended together over time (as done by Labe *et al.*, 2018).

By applying ~~the analysis~~ those analyses separately over the 3 periods we aim to document the internal variability in the absence of any external forcing during the pre-industrial period~~and estimate the evolution of the SIT internal variability under anthropogenic forcing, by~~. By comparing the pre-industrial results with those for the historical and future periods, we estimate the evolution of the SIT and SIV internal variability under anthropogenic forcing.

3 Results

3.1 Temporal variability

The results from the wavelet analysis are presented in Figure 1a-c, in which the ~~global wavelet~~ wavelet power spectrum is shown as a function of time (bottom-left of each subfigure). ~~The time-integrated~~ On the wavelet power spectrum, the crosshatched area denotes the "cone of influence", in which edge effects become important, and the red lines denote the 95% significance levels above a red noise background spectrum. The global wavelet spectrum is also shown (bottom-right), which is a time-integrated power of the ~~global wavelet~~ wavelet power spectrum. The significance level of the time-integrated wavelet spectrum is indicated by the dashed curve~~; it~~. It refers to the power of the red noise level at the 95% confidence level that increases with decreasing frequency.

The temporal variability of the Arctic SIV anomaly over the pre-industrial period is depicted in Figure 1a. The time-integrated power spectrum (bottom-right) shows 2 peaks of significant variability. The first peak corresponds to a period centered on 8 years but spanning from 5 to 10 years. The second one corresponds to a period of 16 years spanning from 10 to 20 years.

~~Another peak, presenting a periodicity of 42 years, is present but not taken into account since the peak is below the significance level. The~~ In the wavelet power spectrum~~is presented in the bottom-left panel of Figure 1a,~~ , the red lines enclose regions in which the ~~significant variability is highlighted by the regions enclosed by the yellow line. Two first~~ variability is significant. The two main peaks are present throughout the ~~period, but they do not appear together at the same time~~time span, but not always concomitantly. Depending on the time, ~~either~~ both the 8- ~~or 16-years peak is the dominant peak~~and 16-year periods are significant with one of them appearing stronger in the power spectrum (Figure 1a, bottom-left panel). For instance, the ~~8-years~~ 8-year peak is dominant during the 1780-1810 ~~and 1825-1840 periods, and the 16-years~~ period, the 16-year peak during the ~~1750-1790 and~~ 1750-1780 period, and both peaks are dominant during the 1830-1850 ~~periods~~period.

Over the historical period, the Arctic SIV temporal variability shows a first peak centered on 5 years and two others centered on 10 and 16 years, all with 95% ~~reliability. Regarding the~~ confidence (Figure 1b). The wavelet power spectrum ~~, it exhibits a constant line of variability at 16 years and another one, but less constant over the whole period , at 8 years. Those peaks and bands of variability are shown in Figure 1b.~~shows that the 16-year period is significant throughout the entire time span, while the 8-year period loses significance around certain periods of time (e.g., around 1925). The future climate SIV wavelet analysis in Figure 1c presents a clear loss of variability after the year 2050. This loss of variability is visible in the SIV time series and is confirmed by both the wavelet power spectrum and the time-integrated power spectrum. The 2050 sudden loss of variability coincides with the ice-free summer events occurring at that time. Apart from that loss of variability, the wavelet power spectrum exhibits one band of 5-years variability during the ~~2010-2025~~ 2015-2025 period and another band of ~~16-years~~ 10-years variability during the 2025-2050 period, both bands with 95% of confidence. In Figure 1c, the peaks are not significant on the time-integrated power spectrum because the respective variability is significant only over the the first 50 years as it is shown in the wavelet power spectrum (areas in red).

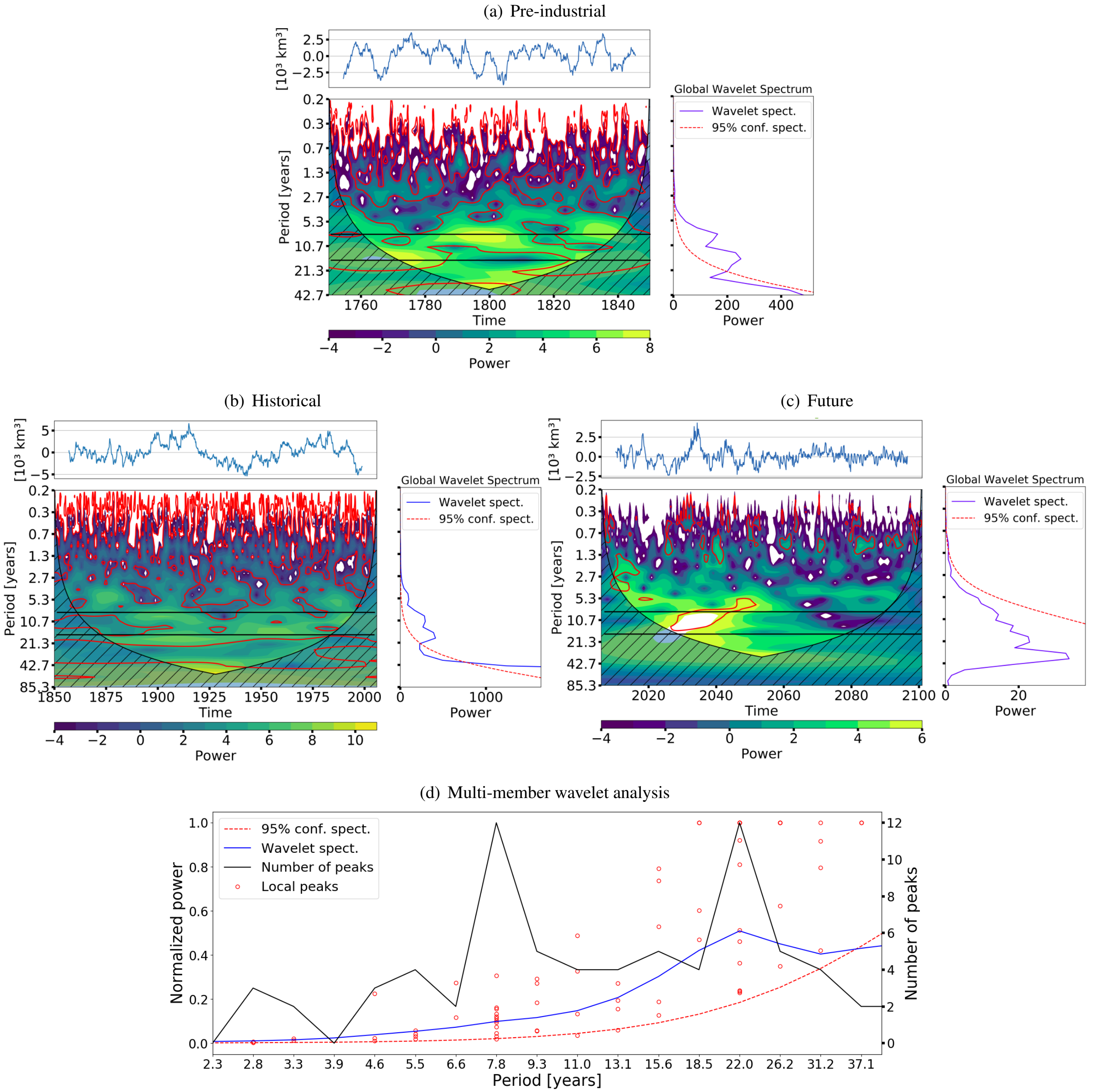

Figure 1. Wavelet analysis ~~, with Morlet as the mother wavelet,~~ applied to the Arctic sea ice volume anomaly over the pre-industrial (200 years preceding the historical integration) (a), historical (1850-2005) (b) and future (2006-2100) (c) periods. Each ~~of the~~ subfigure (a-c) presents the sea ice volume anomaly time series (top), ~~the~~ wavelet power spectrum (bottom-left), and ~~the~~ time-integrated power spectrum from the wavelet analysis (bottom-right). Morlet is used as a wavelet mother. The red lines denote the 95% significance levels above a red noise background spectrum, while the crosshatched areas indicate the cone of influence where edge effects become important. White areas in the wavelet power spectrum are representing values out of the range defined by the color bar. Horizontal black lines depict the 8 and 16-year periods. Multi-members wavelet analysis (d). The red dots depict wavelet spectrum local maxima for all members. The blue and dashed red lines show the mean normalised wavelet spectrum and 95% confidence spectrum for all members, respectively. The black line represent the number of wavelet spectrum local maxima at each period.

The main characteristics of the temporal variability of the Arctic SIV under pre-industrial conditions ~~seems~~ seem to persist under ~~anthopogenic~~ anthropogenic forcing. The two ~~main~~ major temporal peaks of variability centered on 8 ~~years~~ and 16 years, found in the pre-industrial run, are ~~present as band of variability in the power spectrum or peak of variability in the wavelet spectrum in both the historical periodand~~ also present during the historical period. For the first half of the 21st century~~.~~, the future projections are also dominated by the two main peaks but centered at 5 and 10 years in the integrated spectrum, and with relatively weaker power compared to the pre-industrial and historical runs. Furthermore, the SIV variability seems to be non-stationary ~~. Indeed, for a certain period, the main periodicity of the SIV variability can be either centered on 8 or 16 years.~~since the power is not always above the 95% significance level.

The wavelet analyses applied to the other 30 ensemble members of the historical and future simulations bring robustness to our results since, overall, each member shows a similar pattern of temporal variability. To promote such a multi-member comparison among the different spectra, we have first normalised all spectra (and the significance curve) by their respective maximum value so that the power ranges from 0 and 1. This step is required to make that the spectrum from each member has the same weight in the averaging. As shown in Figure 1d (blue line), the averaged spectrum is smoothed out across the time domain because the peaks from different spectra are not co-located exactly at the same periods. Nevertheless, it is still showing that the variability is significant over the background red noise (see dashed red line). To complement this analysis, we have counted the number of local peaks for each period and from all 30 spectra. As shown by the black line in Figure1d, there is a concentration of peaks around the 8-year and 22-year periods. This spread compared to the reference historical run is somehow expected since the internal variability between the different members is not expected to be identical, and even tends to increase with time (Blanchard-Wrigglesworth *et al.*, 2011). For members covering the 21st century, the results are close to the one-member analysis discussed above.

3.2 Spatial variability

The spatial variability of the Arctic SIT anomaly is depicted by the major modes of variability in Figure 2. Since the SIV exhibits a strong loss of variability around the year 2050, the future period for this spatial variability analysis spans from 2006 to 2050. For each period, the modes are sorted by percentage of variability explained. The first mode, which explains most of the variability, represents 22, ~~19~~ 20 and 20 % of the variability for pre-industrial, historical and future climate conditions, respectively. All periods show the same pattern of SIT spatial variability for the first mode. It corresponds to a dipole between the Fram Strait area and the East Siberian Sea (Figure 2 (a,b,c)). For both the pre-industrial and historical periods, the second mode of variability is a pole centered in the East Siberian Sea~~and~~ , but also spreading into the Arctic Basin (Figure 2 (d,e)). It accounts for 14 and ~~17~~ 11 % of the variability, respectively. The third mode of variability for the pre-industrial period corresponds to a dipole between the Laptev and Kara Seas, on the one hand, and the east coast of Greenland, the Chukchi ~~and Beaufort Seas~~ sea and Beaufort Sea, on the other hand.

The first mode of SIT is stable over time and stays the dominant mode of spatial variability in all three periods. ~~The~~ There are some disparities in percentage explained and in magnitude~~are few and some of them can be related to the length of the time series~~, which could be explained by the different lengths of the periods. As the first mode, the second mode of SIT spatial variability is persistent in ~~both the pre-industrial and historical periods, but not in~~ the historical period. For the future climate period~~. Indeed~~, the second mode of SIT variability ~~under future climate conditions presents a pole of variability centered in the Arctic Basin, but regions of highest variability are close to the Canadian Archipelago and not~~ is no longer persistent. It presents a dipole of variability as the first mode, but the Pacific part of the dipole is larger and no longer located in the East Siberian Sea~~, as it is the case for the second mode of the pre-industrial and historical periods~~. The third modes of the three periods (Figure 2 (g,h,i)) exhibit all different patterns of variability and ~~we are not going to use them in the following~~ they are not considered in further analysis.

After 2050, the SIT spatial variability is impacted by the sudden decrease in SIT. EOFs computed over the 2050-2100 period (not shown) exhibit the same pattern of the dipole as the first mode for the 2005-2050 period, but the area of high variability is not the same. The Atlantic part of the dipole is shifted toward the north coast of Greenland and the Pacific part of the dipole is also reduced near the coast.

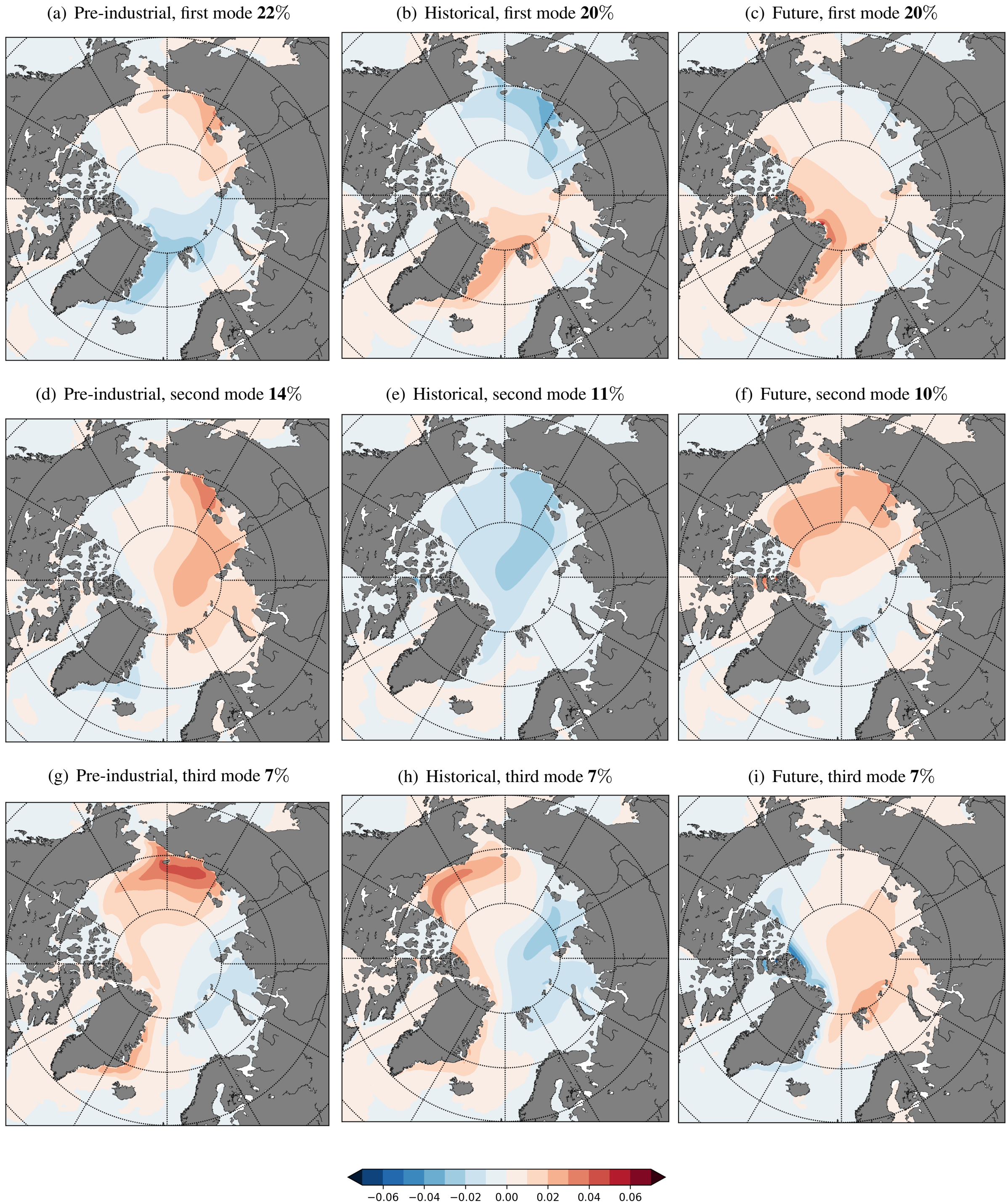

Figure 2. Modes of Arctic SIT spatial variability. From the left to the right, each row shows the three first EOF of Arctic SIT over the pre-industrial (200 years preceding the historical integration) (a,d,g), historical (1920-2005) (b,e,h) and future (2006-2050) (c,f,i) periods, respectively. EOFs for the historical and future periods are performed over 30 ensemble members.

3.3 Drivers of the major modes of SIT internal variability

By computing the temporal oscillation between phases of a certain mode of variability, we are able to characterise this mode by low and high indices. In order to find the physical drivers of the SIT modes of variability, we investigate the differences in dynamic and thermodynamic features (sea ice velocity, atmospheric surface temperature) between both phases of the modes. ~~We looked at the mean sea ice circulation for each phase. Figure 3shows the Arctic mean~~ Figure 3a,b show the mean Arctic sea ice circulation over the pre-industrial period by compositing the low (a) and high (b) indices for the first mode of SIT variability. The sea ice drift anomaly associated with the positive and negative phases of the first SIT mode share similar features with the Arctic Oscillation: a cyclonic anomaly in the Beaufort Gyre, impacting the Transpolar Drift Stream, the Laptev Sea Gyre and the East Siberian circulation, as described by Rigor *et al*., (2002).

Furthermore, applying wavelet analysis to the associated time series of the first spatial mode of variability indicates that the main periodicity of this mode is centered on 8 years and spans from 5 to 10 years (not shown). This result ~~allows us to link~~ is suggestive of a link between the first mode of temporal variability of the wavelet analysis ~~to~~ and the first mode of spatial variability, and so, to the Arctic Oscillation.

We also used the associated time series of the second mode of SIT spatial variability to characterise it by low and high indices. The same analysis over the sea ice velocity is performed for the second mode. For both indices, the sea ice velocity fields are similar. We concluded that the second mode is not dynamically driven. Following Olonscheck *et al*. (2019) results, which demonstrate that the internal variability of Arctic sea ice area and concentration are primarily caused by atmospheric temperature fluctuations, we investigated the differences in mean surface air temperature anomaly over the pre-industrial period between the low ~~(a) and high (b) indices of the second mode~~ and high indices for both the first and second modes of SIT variability~~(see Figure 3)~~. Two widely different states of surface air temperature are found ~~. When the index of the mode of variability is low, the~~ between indices for both modes (the surface air temperature ~~is about 8°C lower than on average over the eastern side of the Arctic Basin. When the index is high,~~anomaly for the second mode is depicted in Figure 3c,d). It appears that the SIT variability and the ~~center and western side of the Arctic Basin are on average colder by 8°C. Those strong discrepancies in mean~~ surface air temperature ~~, characterised by a cooling in the East Siberian, Laptev and Kara Seas in low phase or a cooling in the center and the western side of the Arctic Basin, are then causing strong variability in the SIT over the Arctic Basin through enhanced thermodynamic ice growth.~~are associated with each other.

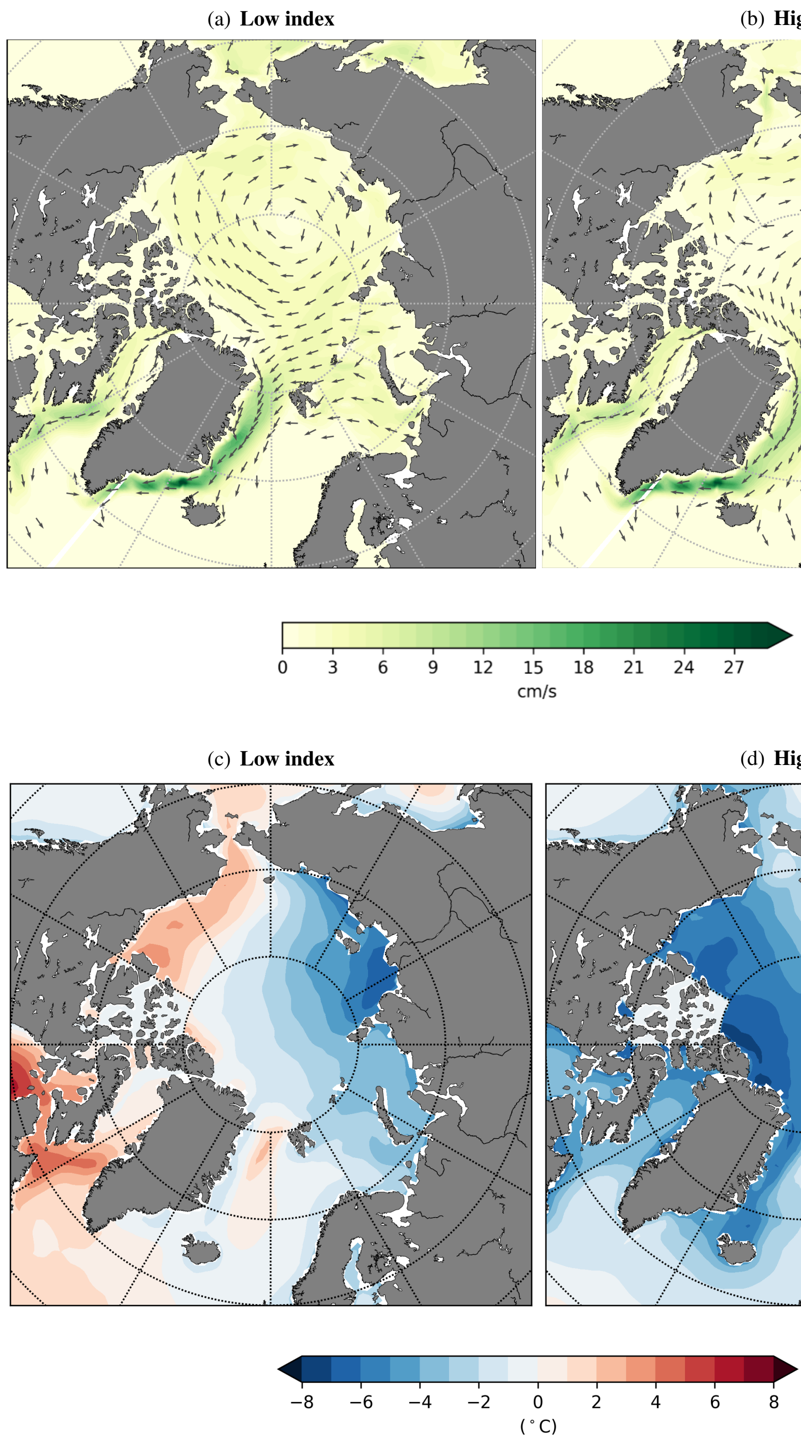

Figure 3. Arctic sea ice mean circulation during low (a) and high (b) indices of the first mode of SIT variability during the pre-industrial period. Arctic mean surface air temperature anomaly during low (c) and high (d) indices of the second mode of SIT variability.

4 Conclusions

In this work, we have analysed the internal variability of the Arctic SIT both spatially and temporally with the CESM1-CAM5-BGC-LE dataset. We conducted ~~a~~ wavelet analysis of the pan-Arctic SIV anomaly and ~~an~~ EOF decomposition of the gridded SIT anomaly, both over a 200-yr control run conducted under pre-industrial conditions. Then, to assess the persistence of the SIT anomaly internal variability under anthropogenic forcing, we performed the same analyses ~~over the 1850-2005 historical period and the future (2006-2050 for EOF and 2006-2100 for the wavelet analysis)~~with 30 ensemble members over the historical and future periods.

The temporal analysis of the SIV anomaly internal variability shows ~~2~~ two peaks of significant variability. One centered on 8 years, spanning from 5 to 10 years, and another one centered on 16 years, spanning from 10 to 20 years. These two peaks of temporal variability are present in both the pre-industrial and historical periods, as well as in the first half of the 21 century. After that, a sudden loss of variability due to ice-free summer events is found. Furthermore, despite a dominant periodicity over the three periods, the SIV anomaly has been observed to be non-stationary. Indeed, the dominant periodicity of the SIV variability can be either centered on 8 or 16 years, depending on the timescale and period. Wavelet analyses over the 30 ensemble members for the post-industrial period have shown the same behaviour of temporal variability within members, except that the peaks are not always centered in 8 and 16 years but somewhere between 5-10 and 15-26 years, depending on the member.

The spatial analysis of the SIT anomaly internal variability has been applied to the 30 ensemble members and reveals two important modes of variability. The first one is a mode with opposite signs centered in the East Siberian Sea and in the Fram Strait area, accounting for 22% of the variability in the pre-industrial period. This first mode is a dynamical one, related to the Arctic Oscillation, and persists over all pre-industrial, historical and future periods. Furthermore, this first mode of spatial variability has a temporal variability of 8 years (spanning from 5 to 10 years), corresponding to the first peak of variability found in the temporal analysis. The second mode exhibits a large pole of variation centered on the East Siberian Sea going through the Arctic Basin. It represents 14% of the variability in the pre-industrial period. ~~It is a thermodynamic mode, which is linked to a variation in surface air temperature. This second mode of spatial variability is present in both the pre-industrial and historical periods.~~

The loss of sea ice in summer starting in 2050 and the strong decrease in SIV ~~going from 15 to 10×10^3 km^3~~ in winter during the second half of the 21st century ~~modifies strongly~~ (from 15 to 10×10^3 km^3) strongly modifies the variability of the ice both spatially and temporally. The main modes of spatial variability lose their significance or just disappear after 2050, and the temporal analysis shows a total disappearance of the variability at that time.

This analysis of the Arctic SIT and SIV variability bears some limits. Indeed, our results for the temporal and spatial patterns of variability are based on only one model, and despite the use of 30 ensemble members and a reasonable validation against observations, the model is not perfect. Furthermore, the spatial modes of SIT variability are robust for all the 30 ensemble members but the temporal analysis shows some dissimilarities between members. Other studies with other model outputs are therefore needed to confirm our conclusion.

Finally, in the context of recent climate changes, predicting sea ice has never been so important. ~~Therefore, our analysis of the Arctic SIT and SIV internal variability could lead to better mooring and observing devices, able to improve our day-to-day observation of Arctic sea ice thickness andvolume data, which~~ However, to validate and improve our predictions, observational data is crucial. In this sense, our variability analysis of internal SIV and SIT variability might help the development of an optimal sampling strategy, taking into account the selection of well-placed sampling locations for monitoring the SIT and, therefore, the pan-Arctic SIV, that are not as well documented as the sea ice extent ~~or sea ice area .~~ and area (Ponsoni *et al.*, 2019).

Data availability. Data can be downloaded from the following source: https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CESM_CAM5_BGC_LE.ice.proc.monthly_ave.html. The 30 ensemble members used in this study are the first 30 members (001-030).

Code and data availability. The wavelet analysis is performed with the Waipy module on Python. https://github.com/mabelcalim/waipy

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

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