

The emergence of a dipole-like mode of Arctic atmospheric circulation conducive European heatwaves

Corresponding Author: Professor Sang-Wook Yeh

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Professor Yeh,

Your manuscript titled "The emergence of a dipole-like mode of Arctic atmospheric circulation conducive European heatwaves" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a thoroughly revised version that fully addresses these serious concerns. The revised manuscript must (1) thoroughly demonstrate the adequacy of the EOF approach used for your analysis, and (2) address the scientific basis for the design of climate model experiments and explain how and why these experiments support the interpretation of your results. Additionally, the results of this study should be put in the context of existing literature.

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Weiying Han, PhD
Editorial Board Member
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orcid.org/0000-0003-3633-9105

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This is an interesting paper which addresses of topic considerable importance. Ultimately it could be published, but significant review needs to be undertaken before I could suggest acceptance. See points below.

Lines 54-: In their review here I was surprised that the authors did not mention the recent research of Ping Chen, Xiaoyu Wang, Jinping Zhao, Tao Li, Junqiang Shi, Fangyi Zong and Lai Wei, 2023: Variability of Arctic Sea ice age and its relationship with atmospheric circulation patterns. *Frontiers in Marine Science*, 10, 1274665, doi: 10.3389/fmars.2023.1274665. Also using EOF analysis they identified THREE Arctic ice periods (namely 1984-1995, 1996-2012, and 2013-2022) rather than the TWO here. Reference this paper here, and also later compare conclusions with theirs.

Lines 62-64: In this introductory survey helpful here to also reference Rudeva et al. (2021) Midlatitude winter extreme temperature events and connections with anomalies in the Arctic and tropics. *J. Clim.* 34: 3733-3749, Li, M., & co-authors, 2021: Anchoring of atmospheric teleconnection patterns by Arctic Sea ice loss and its link to winter cold anomalies in East Asia. *Int. J. Climatol.*, 41, 547–558, and Wenqin Zhuo, Yao Yao, et al., 2023 - The key atmospheric drivers linking regional Arctic amplification with East Asian cold extremes. *Atmospheric Research*, 283, 106557.

Lines 66-67: The involvement of atmospheric 'blocking' is an interesting aspect here. Helpful here to also reference the more recent paper of Li, M., Y. Yao, et al. (2020) Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018. *Env. Res. Lett.*, 15, 114003,

Lines 71-76: I do not regard the present approach as particularly 'novel' – suggesting to delete this word here.

Lines 85-86: Of relevance to the argument here make reference to paper of Luo, B., & other authors, 2024: 'Rapid summer Russian Arctic sea-ice loss enhances the risk of recent Eastern Siberian wildfires'. *Nature Communications*, 15, 5399.

Line 94-97: I presume the SIC were detrended before the SD was calculated. Please make this clear. (If this was not done

then the SD is significantly and misleadingly inflated by the trend.)

Lines 101-104: The authors are suggesting that Supplementary Fig. 1c indicates 'a significant increase in net heat flux from the ocean to the atmosphere'. However, Supp Fig. 1c shows that the most statistically significant trends are to the north of western Russia (and colored in blue). According to the legend blue colors are positive, and the caption states that downward fluxes are positive. There seems to be a mismatch here.

Lines 107-109: To also present a much more recent paper on this, cite the work of Screen JA, et al. (2018) Polar climate change as manifest in atmospheric circulation. *Curr. Clim. Change Reps.* 4: 383-395 doi: 10.1007/s40641-018-0111-4.

Lines 109-113: Perhaps simplify this by saying that the AO is the first EOF mode in all four seasons.

Lines 114-118, and elsewhere: One of the main concerns I have with the paper is that the use of the EOFs (and their changes) have not been validated. While EOF1 in all cases presents a robust pattern, I remain to be convinced that EOF2 and EOF3 form a nondegenerate pair in all cases. In particular, Table S1 shows that in the 'POST' period these two modes explain 14.1% and 13.4% of the variance, respectively. This means that their eigenvalues are very similar, and I suspect they form a degenerate pair. If this is true, then these modes are not 'robust' and could fundamentally change their structure if more data were added or subtracted. That would mean they have no physical meaning and cannot be used to make deductions.

In many other cases here the variance explained by the two modes are very similar.

It is of fundamental importance that the authors establish whether the various EOF2 and EOF3 modes are degenerate or not, and make appropriate adjustments to the paper and its conclusions accordingly. There are a number of tests which can be applied for this. One of the simplest is that of

Gerald R. North, Thomas L. Bell, Robert F. Cahalan and Fanthune J. Moeng, 1982: Sampling errors in the estimation of Empirical Orthogonal Functions. *Monthly Weather Review*, 110, 699-706, doi: 10.1175/1520-0493(1982)110<0699:SEITEO>2.0.CO;2.

Lines 214- (Discussion): The shift in the modes discussed here bear a relationship with the LF shift in the 'Arctic dipole' discussed by Eun-Sook Heo, Mi-Kyung Sung, Soon-Il An and Young-Min Yang, 2021: Decadal phase shift of summertime Arctic dipole pattern and its nonlinear effect on sea ice extent. *International Journal of Climatology*, 41, 4732-4742, doi: 10.1002/joc.7097. Suggest referencing this paper and relate their findings to what has been uncovered here.

Lines 232-235: Important here to mention the influence of low-frequency largescale modes of atmospheric variability. As an example of these reference the analysis of Luo, B., D. Luo, et al., 2023: Increased summer European heatwaves in recent decades: Contributions from Greenhouse gases-induced warming and Atlantic Multidecadal Oscillation-like variations. *Earth's Future*, 11, e2023EF003701.

Lines 262-263: Full reference details required here.

Lines 289-290:

S. N. Rodionov, 2004: A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31, L09204, doi: 10.1029/2004gl019448.

Lines 298-300: Article number missing ...

M. C. Serreze, A. P. Barrett, A. G. Slater, M. Steele, J. L. Zhang and K. E. Trenberth, 2007: The large-scale energy budget of the Arctic. *Journal of Geophysical Research*, 112, D11122, doi: 10.1029/2006JD008230.

Line 346: Make clear what is meant by the 'relaxation time scale' – is this the 1/e e-folding time?

Figure S3: The underprediction of sea ice loss seems to become more marked with time. Comment on this and suggest reasons.

Reviewer #2 (Remarks to the Author):

The authors suggest that the reduction and increased variability of Arctic sea ice have led to changes in the dominant patterns of summer Arctic atmospheric circulation, with the dipole mode replacing the tripole mode as the second mode, and the dipole mode leading to frequent heatwaves in the Northern Hemisphere summer. The topic is interesting. The impact of sea ice reduction on summer atmospheric circulation is an important issue. However, I believe there are significant flaws in the analysis. Here are my major comments.

1. The authors conducted EOF analysis on the Northern Hemisphere SLP, and found that the dipole mode explained more variance post-2000s, thereby inferring that the dipole mode has become more frequent in recent years. However, the choice of spatial extent in the EOF method (e.g., selecting regions north of 70° N, or north of 65° N, or north of 55° N), the choice of time period (e.g., selecting time period from 2000-2015, or 2000-2018, or 2000-2023), and the processing of data (e.g., removing trends, weighting data, filtering data), can all lead to different EOF variances explained by the dipole and tripole modes. The explained variances by the EOF2 and the EOF3 are very close (Fig.2). Is the phenomenon of the dipole mode replacing the tripole mode robust? Have there been significant changes in the PC time series of the dipole mode after the year 2000? Comparing the time series changes of the dipole and tripole modes before and after the year 2000 is more

convincing.

2. The authors aim to explain that the increased dipole mode is caused by the reduction of sea ice. Why the authors not conduct AGCM experiments with different sea ice concentration forcings and climatological SST (Zhang et al., 2024)? This seems to more easily illustrate the role of sea ice. Using coupled model, the active ocean model may have complex impact on the Arctic, and nudging method further increase the complexity of the simulation. The phenomenon proposed by the author cannot be simply attributed to the reduction and increased variability of sea ice under such a complex model experimental design.
3. The author found that the dipole mode would lead to significant cold anomalies in the mid-latitude continents before the year 2000, and after the year 2000, it would lead to significant high-temperature heatwaves in the mid-latitude continents. This is an interesting finding. Why does the same circulation have exactly the opposite effect in different periods? The author's explanation for this is not sufficient. The mechanisms by which the dipole mode leads to increased surface heat flux, temperature gradients, and changes in meridional winds, soil drying and wetting, which are conducive to the increased frequency of heatwaves after the 2000s. Why did they not work before the year 2000?

Xuanwen Zhang, et al. (2024). Summer Russian Heat Waves Linked to Arctic Sea Ice Anomalies in 2010 and 2016. *Journal of Climate*. 37. 1597-1611. 10.1175/JCLI-D-23-0087.1.

Wu and Johnson (2007). A seesaw structure in SLP anomalies between the Beaufort Sea and the Barents Sea, *Geophysical Research Letters*, 34, L05811, doi:10.1029/2006GL028333.

Reviewer #3 (Remarks to the Author):

The manuscript addresses important, topical issue of Arctic forcing on European heatwaves. The manuscript is based on observational data, atmospheric reanalysis products, new climate model experiments, and statistical analyses. However, according to my evaluation, the manuscript is not written clearly enough and seems to suffer from erroneous interpretation of the results. Hence, I cannot recommendation acceptance of the manuscript.

Major comments

1. The comparison of the results between the ARCTIC_run and CLIM_run on lines 136-149 has to be clarified. The Arctic_run "is run towards the observed historical values only in the Arctic north of 65N", whereas in the CLIM_run "the climatological SST is nudged in the same Arctic region ..., where there is no sea ice decline in the Arctic region". This is confusing, and I cannot understand why calculating the difference between the two runs allows to isolate the role of Arctic sea ice reduction. Before this fundamental issue is clarified, a reader cannot be convinced about the validity of the results presented in the manuscript.
2. The message from Figure S1 seems to be interpreted wrongly. Figure S1 shows that in the regions where summer sea ice concentration has decreased most (green and blue areas in Figure S1b), the net surface heat flux has predominantly increased (blue colors in Figure S1c), with fluxes defined positive downwards. In the text, however, the interpretation is that sea ice decline has caused an increased heat loss from the sea to the atmosphere (lines 101-104, 204, and elsewhere), resulting in changes in the large-scale circulation and further on European heat waves. In summer, however, sea ice loss has occurred simultaneously with increasing net heat flux from the atmosphere to the ocean, as Figure S1 shows. This is because the summertime climate warming has been much faster in the terrestrial Arctic than over the Arctic Ocean. This is related to the facts that (a) the ice surface temperature cannot exceed 0 deg C and (b) the large heat capacity of the open ocean keeps the SST increase slow. Hence, warm air masses transported from the terrestrial Arctic to over the Arctic Ocean generate increasingly large downward net heat flux to the open and ice-covered parts of the ocean surface, enhancing ice melt. For an example of such an event, see Tjernström et al., (2015), doi:10.1002/2015GL064373.

Accordingly, while the manuscript has demonstrated summertime linkages between changes in Arctic sea ice concentration and European heatwaves, the causes and consequences seem to be something else than those presented in the manuscript.

3. Text on lines 178-186 requires clarification. Were the influences on temperature different (line 179) or not (lines 183-184)? How can these results be interpreted physically?

Minor comments

4. Lines 62-65: the European heat waves reported in previous studies were not only due to Arctic sea ice loss. Loss of terrestrial snow has been at least equally important.
5. Line 111: is stronger than that of the other atmospheric modes ...
6. Line 151: I am not sure if these can be considered similar

7. Line 192: clarify at which latitudes, as also a cooling trend is seen farther north in eastern Europe.
8. Lines 209 and 225: The structure throughout the layers shown does not appear barotropic.
9. Line 212: How can you quantify that the contribution is substantial?
10. Line 226: Increasing the ability to respond and adapt to climate change is not concretely addressed in the manuscript.

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Decision Letter:

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Dear Professor Yeh,

Your revised manuscript titled "The emergence of a dipole-like mode of Arctic atmospheric circulation conducive European heatwaves" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Alireza Bahadori, PhD
Associate Editor
Communications Earth & Environment

Weiqing Han, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0003-3633-9105

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I thank the authors for their very comprehensive response to my comments and those of my two co-reviewers. They have clarified the issues that were of concern to me. In particular, the testing for degeneracy of the EOFs was very valuable, as was the application of the Monte Carlo test (non-parametric) test procedure of Xiao-feng Li et al. (2000) (Reference 32). Incidentally, at Lines 384-386 the reference details for their paper should be Li, X.-f., L. Pietrafesa, S.-f. Lan and L.-a. Xie, 2000: Significance test for empirical orthogonal function(EOF) analysis of meteorological and oceanic data. Chinese Journal of Oceanology and Limnology, 18, 10-17, doi: 10.1007/BF02842536.

Once this is corrected I will be pleased to recommend acceptance of the paper.

Reviewer #2 (Remarks to the Author):

I have no further question and recommend acceptance for publication in the journal.

Reviewer #3 (Remarks to the Author):

The authors have done careful work in revising the manuscript on the basis of my and other reviewers' comments. I am satisfied with the response letter and revisions made, and suggest acceptance of the manuscript subject to minor linguistic revisions specified below.

Line 106: remove "on the other hand". This expression should be preceded by "on one hand".

Lines 159-160: remove "in the Arctic region".

Line 199: replace "Therefore" by "Hence"

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We thank the three reviewers for their helpful and constructive comments. We believe that the corresponding revisions have strengthened our earlier version of the manuscript. The answers to the reviewers are given after repeating the reviewer's comments.

Reply to Reviewer #1's Comments:

We are so grateful to the reviewer for the comments that helped us further improve the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #1's comments are shown in green in the revised manuscript* if indicated to be included.

Lines 54-: In their review here I was surprised that the authors did not mention the recent research of

Ping Chen, Xiaoyu Wang, Jinping Zhao, Tao Li, Junqiang Shi, Fangyi Zong and Lai Wei, 2023: Variability of Arctic Sea ice age and its relationship with atmospheric circulation patterns. Frontiers in Marine Science, 10, 1274665, doi: 10.3389/fmars.2023.1274665. Also using EOF analysis they identified THREE Arctic ice periods (namely 1984-1995, 1996-2012, and 2013-2022) rather than the TWO here. Reference this paper here, and also later compare conclusions with theirs.

Reply) Thank you for the reviewer's recommendation of relevant literature. We have added the reference suggested by the reviewer and mentioned the contents of the reference in the revised manuscript.

(Line 53)

→ atmosphere and the ocean^{1, 2, 3}.

(Line 247)

→ widely recognized as a significant impact on the sea ice decline^{3, 29, 34}

References:

3. Chen P, Wang X, Zhao J, Li T, Shi J, Zong F, et al. Variability of Arctic Sea ice age and its relationship with atmospheric circulation patterns. *Frontiers in Marine Science* 2023, 10: 1274665.

Lines 62-64: In this introductory survey helpful here to also reference Rudeva et al. (2021) Midlatitude winter extreme temperature events and connections with anomalies in the Arctic and tropics. J. Clim. 34: 3733-3749,

Li, M., & co-authors, 2021: Anchoring of atmospheric teleconnection patterns by Arctic Sea ice loss and its link to winter cold anomalies in East Asia. Int. J. Climatol., 41, 547–558, and Wenqin Zhuo, Yao Yao, et al., 2023 - The key atmospheric drivers linking regional Arctic amplification with East Asian cold extremes. Atmospheric Research, 283, 106557.

Reply) Thank you for the valuable reference recommendations. We have incorporated the reference suggested by the reviewer into the revised manuscript.

(Lines 61-62)

→ NH during summer^{9, 10, 11, 12, 13, 14}.

References:

12. Rudeva I, Simmonds I. Midlatitude winter extreme temperature events and connections with anomalies in the Arctic and tropics. *Journal of Climate* 2021, 34(10): 3733-3749.
13. Li M, Luo D, Simmonds I, Dai A, Zhong L, Yao Y. Anchoring of atmospheric teleconnection patterns by Arctic Sea ice loss and its link to winter cold anomalies in East Asia. *International Journal of Climatology* 2021, 41(1).
14. Zhuo W, Yao Y, Luo D, Simmonds I, Huang F. The key atmospheric drivers linking regional Arctic amplification with East Asian cold extremes. *Atmospheric Research* 2023, 283: 106557.

Lines 66-67: The involvement of atmospheric ‘blocking’ is an interesting aspect here. Helpful here to also reference the more recent paper of Li, M., Y. Yao, et al. (2020) Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018. Env. Res. Lett., 15, 114003

Reply) We have incorporated the reference suggested by the reviewer into the revised manuscript.

(Lines 66-67)

→ persistent blocking conditions^{19, 20}

References:

20. Li M, Yao Y, Simmonds I, Luo D, Zhong L, Chen X. Collaborative impact of the NAO and atmospheric blocking on European heatwaves, with a focus on the hot summer of 2018. *Environmental Research Letters* 2020, 15(11): 114003.

Lines 71-76: I do not regard the present approach as particularly ‘novel’ – suggesting to delete this word here.

Reply) Removed. (Line 73)

Lines 85-86: Of relevance to the argument here make reference to paper of Luo, B., & other authors, 2024: ‘Rapid summer Russian Arctic sea-ice loss enhances the risk of recent Eastern Siberian wildfires’. Nature Communications, 15, 5399.

Reply) We have added the reference in the revised manuscript.

(Lines 85-86)

→ Arctic regions with negative SIC trends are distributed across almost all longitudes, with

larger decreases observed in the Kara and Laptev Seas²¹.

References:

21. Luo B, Luo D, Dai A, Xiao C, Simmonds I, Hanna E, et al. Rapid summer Russian Arctic sea-ice loss enhances the risk of recent Eastern Siberian wildfires. *Nature Communications* 2024, 15(1): 5399.

Line 94-97: I presume the SIC was detrended before the SD was calculated. Please make this clear. (If this was not done then the SD is significantly and misleadingly inflated by the trend.)

Reply) Following the reviewer's suggestion, we detrended before the standard deviation (SD) was calculated and made a Figure R1 as follows. Although the SDs in Figure R1 during the pre- and post-2000s decreased slightly compared to those before detrending in Figure 1, the overall result—showing an increase in SD due to the intensifying decline in SIC—remained largely unchanged. Related information has been added to the revised manuscript as follows. (Lines 96-98)

➔ For reference, a comparison of SIC variability before and after detrending shows that the overall results did not change significantly.

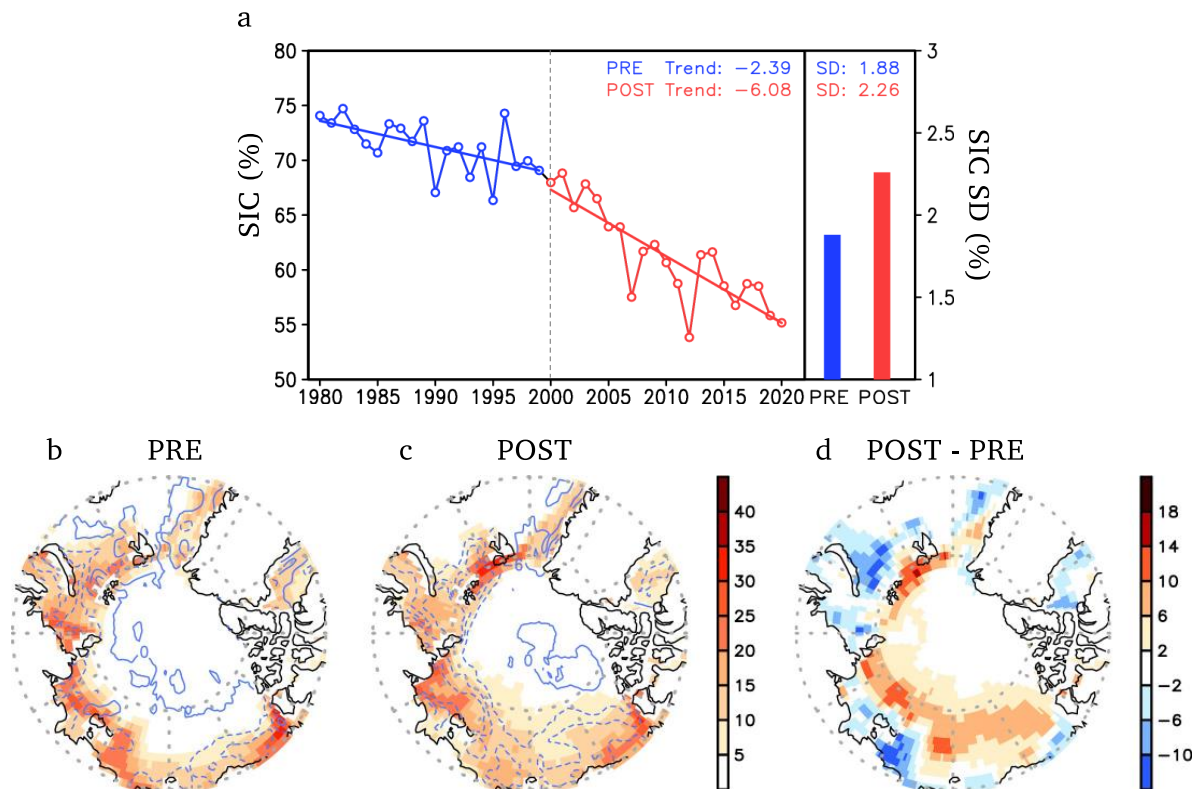


Fig. R1 | Historical change in summer Arctic sea ice for the pre-2000s (1980-1999) and post-2000s (2000-2020). a, Temporal evolution (%) and trend (% decade⁻¹) of summer (June

to August, JJA) Arctic sea ice concentration (SIC), averaged over the Arctic (70°–90° N, 0°–360° E), during the pre-2000s (1980-1999) and post-2000s (2000-2020). Both trends are statistically significant at a 95% confidence level based on a two-tailed Student's *t*-test. The blue and red bars depict the standard deviations (SD, %) of the detrended JJA SIC for the pre-2000s and post-2000s, respectively. Trend (% decade⁻¹) and SD (%) values are displayed in the upper right corner. The gray vertical dashed line indicates the year of the regime shift. **b**, Standard deviation (shaded, %) of the detrended JJA SIC and trend (blue lines, % decade⁻¹) of JJA SIC for the pre-2000s (1980-1999). The contour interval is -6. **c**, Same as (b), but for the post-2000s (2000-2020). **d**, The difference (%) in standard deviation between the post-2000s and pre-2000s.

Lines 101-104: The authors are suggesting that Supplementary Fig. 1c indicates 'a significant increase in net heat flux from the ocean to the atmosphere'. However, Supp Fig. 1c shows that the most statistically significant trends are to the north of western Russia (and colored in blue). According to the legend blue colors are positive, and the caption states that downward fluxes are positive. There seems to be a mismatch here.

Reply) Thank you for your helpful comments. Responding to the reviewer's comments, we have revised it in the manuscript as follows.

Lines (98-109)

➔ Furthermore, regions with a significant decreasing trend in SIC, particularly in the Russian Arctic (60°-150°E areas in Supplementary Fig. 1b), coincide with areas of increased SIC variability (Fig. 1b) and a notable rise in net downward heat flux from the atmosphere to the ocean (Supplementary Fig. 1c). This finding aligns with previous research²⁴, which suggests that sea ice reduction is triggered by increased downward heat flux from the atmosphere over both open water and ice-covered portions of the ocean surface, driven by the northward advection of warm air from the continent.

Despite the general understanding that the Arctic atmosphere loses heat to the ocean during summer^{7, 25, 26, 27}, there is, on the other hand, a tendency for upward heat transport into the atmosphere in the European Arctic region (0°-50°E areas in Supplementary Fig. 1c). This process is expected to influence atmospheric circulation, extending its impact beyond the Arctic to the mid- and high-latitudes of the NH.

Lines 107-109: To also present a much more recent paper on this, cite the work of Screen JA, et al. (2018) Polar climate change as manifest in atmospheric circulation. Curr. Clim. Change Reps. 4: 383-395 doi: 10.1007/s40641-018-0111-4.

Reply) We have added the reference in the revised manuscript.

(Line 114)

→ Arctic in winter and summer^{28, 29, 30}

References:

30. Screen J, Bracegirdle T, Simmonds I. Polar climate change as manifest in atmospheric circulation. *Curr. Climate Change Rep.*, 4, 383–395. 2018.

Lines 109-113: Perhaps simplify this by saying that the AO is the first EOF mode in all four seasons.

Reply) We have added the sentence as follows.

(Lines 118-119)

→ This is related to the AO or AO-like pattern consistently appearing as the first EOF mode in all seasons.

Lines 114-118, and elsewhere: One of the main concerns I have with the paper is that the use of the EOFs (and their changes) have not been validated. While EOF1 in all cases presents a robust pattern, I remain to be convinced that EOF2 and EOF3 form a nondegenerate pair in all cases. In particular, Table S1 shows that in the ‘POST’ period these two modes explain 14.1% and 13.4% of the variance, respectively. This means that their eigenvalues are very similar, and I suspect they form a degenerate pair. If this is true, then these modes are not ‘robust’ and could fundamentally change their structure if more data were added or subtracted. That would mean they have no physical meaning and cannot be used to make deductions. In many other cases here the variance explained by the two modes are very similar. It is of fundamental importance that the authors establish whether the various EOF2 and EOF3 modes are degenerate or not, and make appropriate adjustments to the paper and its conclusions accordingly. There are a number of tests which can be applied for this. One of the simplest is that of

Gerald R. North, Thomas L. Bell, Robert F. Cahalan and Fanthune J. Moeng, 1982: Sampling errors in the estimation of Empirical Orthogonal Functions. Monthly Weather Review, 110, 699-706, doi: 10.1175/1520-0493(1982)110<0699:SEITEO>[2.0.CO;2](#).

Reply) Thank you for the reviewer’s thoughtful comments. We appreciate it. As the reviewer mentioned, North’s rule is effective for distinguishing EOF modes that are close to each other in explained variance but may not be reliable for testing absolute significance, as estimating the number of degrees of freedom in geophysical time series is challenging under North’s Rule of Thumb. Responding to the reviewer’s comments, therefore, a Monte Carlo approach, regarded as one of the most reliable methods for assessing the statistical significance of EOFs in geophysical studies (Xiao-feng et al. 2000, Wilks 2016), is employed to determine whether an observed EOF mode is significantly different from what would be expected from random noise. Many surrogate datasets (here, through 1000 iterations) are generated by randomizing

the observed dataset. EOF analysis is then performed on these randomized datasets, and the eigenvalues (the explained variance is used here, λ) of the observed EOFs are compared with the distribution of eigenvalues using the 95th percentile as the cutoff (U_{95}) from the randomized datasets. A mode is considered significant if the observed eigenvalue exceeds the 95th percentile of the distribution of eigenvalues from the randomized data ($\lambda/U_{95} > 1.0$). As a result, under the randomization test, EOF2 and EOF3 appear to be significantly separated in all periods (Table R1). We have added the sentence to the revised manuscript as follows.

(Lines 130-133)

→ In addition, the significance of the separation between each mode in the observed EOF analysis was verified using a Monte Carlo approach, a highly reliable method for assessing the statistical significance of EOFs^{32, 33}, which confirmed the robustness of the separated EOF modes.

References:

32. Xiao-feng L, Pietrafesa L, Shu-Fang L, Li-an X. Significance test for empirical orthogonal function (EOF) analysis of meteorological and oceanic data. *Chinese Journal of Oceanology and Limnology* 2000, **18**: 10-17.
33. Wilks DS. Modified “rule N” procedure for principal component (EOF) truncation. *Journal of Climate* 2016, **29**(8): 3049-3056.

Table. R1 | EOF significant test using Monte Carlo approach (Randomization Test). The first four EOF eigenvalues (explained variances) from the observed SLP over the Arctic (60°–90° N) are calculated for the entire period (1980–2020), pre-2000s (1980–1999), and post-2000s (2000–2020). Randomized datasets, generated between the minimum and maximum values of the observed SLP dataset using Monte Carlo simulations, undergo EOF analysis over 1,000 iterations to obtain the 95th percentile (U^{95}) of the distribution of eigenvalues from the randomized data. EOF modes with a ratio of $\lambda/U^{95} > 1.0$ are interpreted as signals.

	Total period (1980-2020)			
<i>Eigenvalue</i> (λ)	EOF1	EOF2	EOF3	EOF4
	47.13	12.28	10.43	5.44
<i>Eigenvalue</i> (U^{95}) by Monte Carlo simulation	2.82	2.79	2.75	2.73
λ/U^{95}	16.71	4.40	3.79	1.99

	Pre-2000s (1980-1999)			
<i>Eigenvalue</i> (λ)	EOF1	EOF2	EOF3	EOF4
	51.65	13.46	9.84	6.78

<i>Eigenvalue (U^{95}) by Monte Carlo simulation</i>	5.71	5.63	5.57	5.52
λ/U^{95}	9.05	2.39	1.77	1.23

	Post-2000s (2000-2020)			
<i>Eigenvalue (λ)</i>	EOF1	EOF2	EOF3	EOF4
	47.36	14.12	13.43	6.82
<i>Eigenvalue (U^{95}) by Monte Carlo simulation</i>	5.44	5.36	5.31	5.26
λ/U^{95}	8.71	2.63	2.53	1.30

Lines 214- (Discussion): The shift in the modes discussed here bear a relationship with the LF shift in the ‘Arctic dipole’ discussed by Eun-Sook Heo, Mi-Kyung Sung, Soon-Il An and Young-Min Yang, 2021: Decadal phase shift of summertime Arctic dipole pattern and its nonlinear effect on sea ice extent. International Journal of Climatology, 41, 4732-4742, doi: 10.1002/joc.7097. Suggest referencing this paper and relate their findings to what has been uncovered here.

Reply) Thank you for the reviewer’s comment. The difference in the order of the dipole-like mode in EOF analysis between the two studies stems from methodological differences, such as the length of the data and data processing techniques (e.g., detrending, removal of zonal means). In our study, which covers the period from 1980 to 2020, the Dipole-like mode appears as the 3rd EOF mode for the entire period (though it becomes the 2nd mode for the post-2000s), whereas in Heo et al. (2021), which uses data from 1979 to 2017, it is identified as the 2nd mode. Despite this difference, both studies show notable similarities in the occurrence of a phase shift around the 2000s in the dipole-like mode and its impacts on variables such as SIC, SLP, net surface heat flux (NSHF), and temperature. This suggests that the changes in Arctic atmospheric circulations from the pre- to post-2000s, associated with the intensification of ASI loss in our study, are robust. Responding to the reviewer’s comments, we have added the sentences and references to the revised manuscript as follows:

(Line 247)

➔ widely recognized as a significant impact on the sea ice decline^{3, 29, 34}

(Lines 248-253)

➔ Despite differences in experimental designs, earlier findings^{29, 34, 35, 36} highlighting the role

of the dipole-like mode phase shift on summer sea ice decline suggest that the changes in Arctic atmospheric circulation linked to the intensified ASI loss around 2000, as seen in our study, are robust. The well-supported evidence is also provided, particularly using model simulations that focus only on the effects of ASI decline.

(Lines 255-256)

→ the emission of net surface heat flux in the European Arctic³⁴

References:

29. Wu B, Wang J, Walsh JE. Dipole anomaly in the winter Arctic atmosphere and its association with sea ice motion. *Journal of Climate* 2006, **19**(2): 210-225.
34. Heo ES, Sung MK, An SI, Yang YM. Decadal phase shift of summertime Arctic dipole pattern and its nonlinear effect on sea ice extent. *International Journal of Climatology* 2021, **41**(9): 4732-4742.
35. Wang J, Zhang J, Watanabe E, Ikeda M, Mizobata K, Walsh JE, *et al.* Is the Dipole Anomaly a major driver to record lows in Arctic summer sea ice extent? *Geophysical Research Letters* 2009, **36**(5).
36. Overland JE, Francis JA, Hanna E, Wang M. The recent shift in early summer Arctic atmospheric circulation. *Geophysical Research Letters* 2012, **39**(19).

Lines 232-235: Important here to mention the influence of low-frequency largescale modes of atmospheric variability. As an example of these reference the analysis of Luo, B., D. Luo, et al., 2023: Increased summer European heatwaves in recent decades: Contributions from Greenhouse gases-induced warming and Atlantic Multidecadal Oscillation-like variations. Earth's Future, 11, e2023EF003701.

Reply) We have added the following sentence and reference in the revised manuscript.

(Lines 268-269)

→ phase shifts in Atlantic Multidecadal Oscillation-like variations⁴⁰.

References:

40. Luo B, Luo D, Zhuo W, Xiao C, Dai A, Simmonds I, *et al.* Increased Summer European Heatwaves in Recent Decades: Contributions From Greenhouse Gases-Induced Warming and Atlantic Multidecadal Oscillation-Like Variations. *Earth's Future* 2023, **11**(8): e2023EF003701.

Lines 262-263: Full reference details required here.

Reply) We have added the full reference details in the revised manuscript.

References:

8. Masson-Delmotte V, Zhai P, Pirani S, Connors C, Péan S, Berger N, et al. IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2021: 3-32.

Lines 289-290:

S. N. Rodionov, 2004: A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters*, 31, L09204, doi: 10.1029/2004gl019448.

Reply) We have modified the reference in the revised manuscript.

References:

22. Rodionov SN. A sequential algorithm for testing climate regime shifts. *Geophysical Research Letters* 2004, 31(9): L09204.

Lines 298-300: Article number missing ...

M. C. Serreze, A. P. Barrett, A. G. Slater, M. Steele, J. L. Zhang and K. E. Trenberth, 2007: The large-scale energy budget of the Arctic. *Journal of Geophysical Research*, 112, D11122, doi: 10.1029/2006JD008230.

Reply) Corrected.

References:

26. Serreze MC, Barrett AP, Slater AG, Steele M, Zhang J, Trenberth KE. The large-scale energy budget of the Arctic. *Journal of Geophysical Research: Atmospheres* 2007, 112: D11122.

Line 346: Make clear what is mean by the 'relaxation time scale' – is this the 1/e efolding time?

Reply) The 'relaxation time scale' in a model nudging experiment refers to the characteristic time over which model variables (such as temperature, wind, or other fields) are gradually nudged or adjusted toward target values, such as observations or reanalysis data. In nudging, the model's state is adjusted gradually, with the relaxation time scale determining the speed of this adjustment. In this study, climate models can be nudged to observed SST data from NOAA ERSST v3b by relaxing the model state to reanalysis data at a time step of 5 days. The terms 'relaxation time scale' and 'e-folding time scale' often refer to the same concept, particularly in the context of nudging, damping, or relaxation processes. Both describe the rate at which variables approach their target values during a nudging (or relaxation) process. In several papers that use the nudging method, the two terms are used interchangeably. For example, Pithan et al. (2023) and Jeoung et al. (2022) use the term 'relaxation time scale,' while Sanchez-Benitez et al. (2022) and Zhang et al. (2021) use the term 'e-folding time scale.'

Responding to the reviewer's comment, we have added the sentence to the revised manuscript as follows.

(Lines 444-447)

➔ The relaxation time scale (sometimes called the e-folding time scale) in this model nudging experiment refers to the characteristic time associated with the rate at which model variables, such as SSTs in this study, approach target values (here, NOAA ERSST).

References:

- Pithan, F., Athanase, M., Dahlke, S., Sánchez-Benítez, A., Shupe, M. D., Sledd, A., Streffing, J., Svensson, G., and Jung, T. (2023) Nudging allows direct evaluation of coupled climate models with in situ observations: a case study from the MOSAiC expedition, *Geosci. Model Dev.*, 16, 1857–1873, <https://doi.org/10.5194/gmd-16-1857-2023>.

- Jeong, H., Park, H.-S., Stuecker, M. F., & Yeh, S.-W. (2022) Record low Arctic sea ice extent in 2012 linked to two-year La Niña-driven sea surface temperature pattern. *Geophysical Research Letters*, 49, e2022GL098385. <https://doi.org/10.1029/2022GL098385>

- Sánchez-Benítez, A. , Goessling, H. , Pithan, F. , Semmler, T. and Jung, T. (2022) The July 2019 European Heat Wave in a Warmer Climate: Storyline Scenarios with a Coupled Model Using Spectral Nudging , *Journal of Climate*, 35 (8), 2373-2390. <https://doi.org/10.1175/JCLI-D-21-0573.1>

- Zhang, G, Murakami, H., Yang, X., Findell, K. L., Wittenberg, A. T., and Jia, L. (2021) Dynamical Seasonal Predictions of Tropical Cyclone Activity: Roles of Sea Surface Temperature Errors and Atmosphere–Land Initialization. *Journal of Climate*, 34 (5), 1743–1766. <https://doi.org/10.1175/JCLI-D-20-0215.1>

Figure S3: The underprediction of sea ice loss seems to become more marked with time. Comment on this and suggest reasons.

Reply) Thank you for the reviewer's constructive comment. In this study, to isolate the effect of Arctic warming on Arctic Sea ice decline in the model experiments, the simulated SSTs in the high latitudes (north of 65°N) were restored to the observed historical (1951–2020) daily SST. During this process, the simulated SIC rapidly adapts to the observed SST evolution while maintaining thermodynamic balance with the restored SST in the Arctic. However, in the real world, Arctic Sea ice decline may not only be influenced by the ocean's warm SST but also by factors such as heat flux absorption from the atmosphere, surrounding wind fields, and atmospheric pressure patterns, among other weather and climate conditions. No matter how fully coupled the model is, involving the ocean, atmosphere, and sea ice, there are limitations in perfectly simulating the effects of internal variability within the climate system. The authors

believe that these factors may be among the reasons why the Arctic Sea ice decline in this study is somewhat underpredicted compared to observations. Responding to the reviewer's comment, we have added the following sentences to the revised manuscript.

(Lines 154-157)

➔ Indeed, despite limitations in perfectly simulating the effects of internal variability within the climate system, which lead to an underestimation of sea ice loss, the ARCTIC_run reasonably reproduces the observed sea ice retreat (Supplementary Fig. 3).

Reply to Reviewer #2's Comments:

We are so grateful to the reviewer for the comments that helped us further improve the earlier version of the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #2's comments are shown in red in the revised manuscript* if indicated to be included.

1. The authors conducted EOF analysis on the Northern Hemisphere SLP, and found that the dipole mode explained more variance post-2000s, thereby inferring that the dipole mode has become more frequent in recent years. However, the choice of spatial extent in the EOF method (e.g., selecting regions north of 70° N, or north of 65° N, or north of 55° N), the choice of time period (e.g., selecting time period from 2000-2015, or 2000-2018, or 2000-2023), and the processing of data (e.g., removing trends, weighting data, filtering data), can all lead to different EOF variances explained by the dipole and tripole modes. The explained variances by the EOF2 and the EOF3 are very close (Fig.2). Is the phenomenon of the dipole mode replacing the tripole mode robust?

Reply) Thank you for the reviewer's careful comments. As the reviewer mentioned, although EOF analysis can yield different results and produce varying eigenvalues depending on factors such as spatial extent, temporal length, and data processing, there is no doubt that EOF analysis is widely used as a method to distinguish specific, unique patterns in data. From this perspective, this study also identified unique patterns for the MSLP in the Arctic (60°–90° N) region using EOF and evaluated whether the EOF modes, particularly EOF2 and EOF3, are robustly separated into significant and unique spatial patterns using a Monte Carlo approach as one of the most reliable methods for assessing the statistical significance of EOFs in geophysical studies (Xiao-feng et al. 2000, Wilks 2016) (see Table R1).

First, many surrogate datasets (here, through 1000 iterations) are generated by randomizing the observed dataset. EOF analysis is then performed on these randomized datasets, and the eigenvalues (the explained variance is used here, λ) of the observed EOFs are compared with the distribution of eigenvalues using the 95th percentile as the cutoff (U^{95}) from the randomized datasets. A mode is considered significant if the observed eigenvalue exceeds the 95th percentile of the distribution of eigenvalues from the randomized data ($\lambda/U^{95} > 1.0$). As a result, under the randomization test, EOF2 and EOF3 appear to be significantly separated in all periods (Table R1). We have added the sentence to the revised manuscript as follows. (Lines 130-133)

➔ In addition, the significance of the separation between each mode in the observed EOF analysis was verified using a Monte Carlo approach, a highly reliable method for assessing the statistical significance of EOFs^{32, 33}, which confirmed the robustness of the separated EOF modes.

References:

32. Xiao-feng L, Pietrafesa L, Shu-Fang L, Li-an X. Significance test for empirical orthogonal function (EOF) analysis of meteorological and oceanic data. *Chinese Journal of Oceanology and Limnology* 2000, **18**: 10-17.
33. Wilks DS. Modified “rule N” procedure for principal component (EOF) truncation. *Journal of Climate* 2016, **29**(8): 3049-3056.

Table. R1 | EOF significant test using Monte Carlo approach (Randomization Test). The first four EOF eigenvalues (explained variances are used here) from the observed SLP over the Arctic (60°–90° N) are calculated for the entire period (1980–2020), pre-2000s (1980–1999), and post-2000s (2000–2020). Randomized datasets, generated between the minimum and maximum values of the observed SLP dataset using Monte Carlo simulations, undergo EOF analysis over 1,000 iterations to obtain the 95th percentile (U^{95}) of the distribution of eigenvalues from the randomized data. EOF modes with a ratio of $\lambda/U^{95} > 1.0$ are interpreted as signals.

	Total period (1980-2020)			
<i>Eigenvalue</i> (λ)	EOF1	EOF2	EOF3	EOF4
	47.13	12.28	10.43	5.44
<i>Eigenvalue</i> (U^{95}) by Monte Carlo simulation	2.82	2.79	2.75	2.73
λ/U^{95}	16.71	4.40	3.79	1.99

	Pre-2000s (1980-1999)			
<i>Eigenvalue</i> (λ)	EOF1	EOF2	EOF3	EOF4
	51.65	13.46	9.84	6.78
<i>Eigenvalue</i> (U^{95}) by Monte Carlo simulation	5.71	5.63	5.57	5.52
λ/U^{95}	9.05	2.39	1.77	1.23

	Post-2000s (2000-2020)			
<i>Eigenvalue</i> (λ)	EOF1	EOF2	EOF3	EOF4
	47.36	14.12	13.43	6.82

<i>Eigenvalue (U^{95}) by Monte Carlo simulation</i>	5.44	5.36	5.31	5.26
λ/U^{95}	8.71	2.63	2.53	1.30

Have there been significant changes in the PC time series of the dipole mode after the year 2000? Comparing the time series changes of the dipole and tripole modes before and after the year 2000 is more convincing.

Reply) Thank you for the reviewer’s constructive comments. To confirm the significant changes in the PC time series of the dipole and tripole modes before and after the year 2000, the temporal correlations between the PC time series for the entire analyzed period and the PC time series for the pre-2000s and post-2000s were compared. In Figure R1a, the simultaneous temporal evolution of the tripole-like mode—represented by the PC2 for the entire period, the PC2 for the pre-2000s, and the PC3 for the post-2000s—was analyzed, and the temporal correlation coefficients (TCCs) were calculated. Similarly, in Figure R1b, the dipole-like mode—represented by the PC3 for the entire period, the PC3 for the pre-2000s, and the PC2 for the post-2000s—was shown, and the TCCs were also calculated. The results showed that the TCC values for the pre- and post-2000s were statistically significant at the 99% confidence level at all times, indicating a very high correlation. This suggests that while the tripole-like and dipole-like modes were the second and third dominant modes, respectively, in the pre-2000s, a significant shift occurred in the post-2000s, with these modes switching roles. Table R2 further illustrates the TCC results. We have added the following sentence to the revised manuscript.

(Lines 133-136)

➔ The strong correlation between the PC time series of the dipole-like and tripole-like modes around the year 2000 also suggests that the interchange in atmospheric circulation modes represents a statistically significant shift in their respective roles (see Supplementary Table 2).

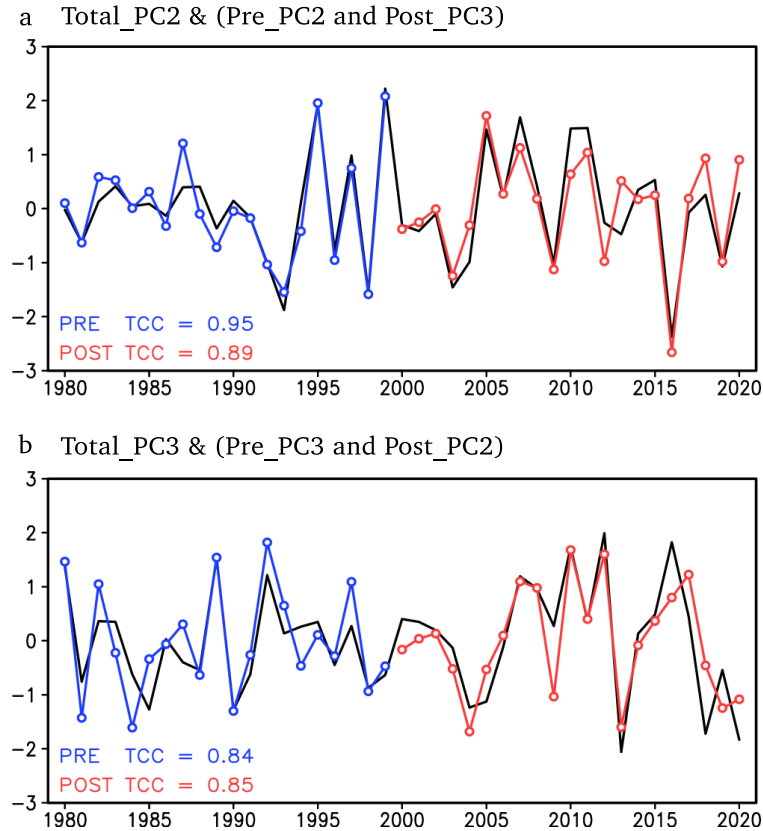


Fig. R1 | Temporal evolution of the observed main PC time series for Arctic atmospheric circulation. **a.** PC time series of the 2nd mode of the EOF analysis (PC2) of the detrended JJA SLP anomalies over the Arctic (60°–90° N) for the total period (1980–2020, black), PC2 for the pre-2000s (1980–1999, blue), and PC3 for the post-2000s (2000–2020, red). **b.** Same as **(a)**, but showing PC3 for the total period (1980–2020, black), PC3 for pre-2000s (1980–1999, blue), and PC2 for post-2000s (2000–2020, red). The TCC values are displayed in the bottom left corner of each panel.

Table. R2 | Relationship between the main PC time series of Arctic atmospheric circulation in observation. Temporal correlation coefficients (TCCs) between the PC time series of the EOF analysis over the Arctic for the total period (1980–2020) and the PC time series for the pre-2000s (1980–1999) and post-2000s (2000–2020). All TCCs are statistically significant at the 99% confidence level based on a two-tailed Student’s *t*-test.

	Total_PC2 (1980–2020, tripole-like mode)		Total_PC3 (1980–2020, dipole-like mode)	
Temporal Correlation Coefficients (TCC)	Pre_PC2 (1980–1999)	0.95	Pre_PC3 (1980–1999)	0.84
	Post_PC3 (2000–2020)	0.89	Post_PC2 (2000–2020)	0.85

2. The authors aim to explain that the increased dipole mode is caused by the reduction of sea ice. Why the authors not conduct AGCM experiments with different sea ice concentration forcings and climatological SST (Zhang et al., 2024)? This seems to more easily illustrate the role of sea ice. Using coupled model, the active ocean model may have complex impact on the Arctic, and nudging method further increase the complexity of the simulation. The phenomenon proposed by the author cannot be simply attributed to the reduction and increased variability of sea ice under such a complex model experimental design.

Xuanwen Zhang, et al. (2024). Summer Russian Heat Waves Linked to Arctic Sea Ice Anomalies in 2010 and 2016. *Journal of Climate*. 37. 1597-1611. 10.1175/JCLI-D-23-0087.1.

Reply) Thank you for your thoughtful question. We agree with the reviewer's opinion. Using AGCM experiments with varying sea ice concentrations and climatological SST, as suggested by Zhang et al. (2024), could offer more direct insights into the role of sea ice in driving changes in the dipole-like mode. However, our use of a coupled model aims to simulate realistic interactions between the atmosphere, ocean, and sea ice, which are crucial for understanding the broader complexity of Arctic climate variability. We acknowledge that coupled models, which include active ocean components, can introduce additional complexity. Despite of this notion, they also provide a more holistic understanding of the Arctic system's feedback processes. While the nudging method may increase the complexity of the simulation, it allows us to better constrain the system to observed states, thereby making the experiments more relevant to real-world conditions. Indeed, these interactions, including the potential role of ocean heat transport and its modulation of sea ice and atmospheric conditions, cannot be fully captured by AGCMs with prescribed SSTs and sea ice concentrations. Furthermore, while the complexity introduced by the coupled model and nudging may make it more difficult to attribute changes solely to sea ice reduction, we used the difference between two simulations (ARCTIC_run and CLIM_run) to remove the bias inherent in the restoration process, ensuring that the response purely reflects the observed SST anomalies related to sea ice variation in this study. For this study, our choice of a coupled model, despite its complexity, aligns with previous studies that emphasize the importance of including air-sea feedback processes when studying Arctic variability (Rinke et al. 2018; Screen et al., 2015; Deser et al., 2015). Responding to the reviewer's comment, we have added the following sentences to the revised manuscript.

(Lines 431-435)

➔ Although atmospheric model experiments⁴⁴ provide a more direct assessment of the role of sea ice in driving changes in the dipole-like mode, they lack real-world atmosphere-ocean interaction effects. Therefore, a coupled model was chosen for this study, despite its complexity, consistent with previous research^{45, 46, 47} that emphasizes the importance of incorporating

atmosphere-ocean feedback processes in studying Arctic variability.

References:

44. Zhang X, Wu B, Ding S. Summer Russian Heat Waves Linked to Arctic Sea Ice Anomalies in 2010 and 2016. *Journal of Climate* 2024, **37**(5): 1597-1611.
45. Rinke A, Handorf D, Dorn W, Dethloff K, Moore JC, Zhang X. Atmospheric feedbacks on Arctic summer sea-ice anomalies in ensemble simulations of a coupled regional climate model. *Advances in Polar Science* 2018, **29**(3): 156-164.
46. Screen JA, Deser C, Sun L. Reduced risk of North American cold extremes due to continued Arctic sea ice loss. *Bulletin of the American Meteorological Society* 2015, **96**(9): 1489-1503.
47. Deser C, Tomas RA, Sun L. The role of ocean–atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss. *Journal of Climate* 2015, **28**(6): 2168-2186.

3. The author found that the dipole mode would lead to significant cold anomalies in the mid-latitude continents before the year 2000, and after the year 2000, it would lead to significant high-temperature heatwaves in the mid-latitude continents. This is an interesting finding. Why does the same circulation have exactly the opposite effect in different periods? The author's explanation for this is not sufficient. The mechanisms by which the dipole mode leads to increased surface heat flux, temperature gradients, and changes in meridional winds, soil drying and wetting, which are conducive to the increased frequency of heatwaves after the 2000s. Why did they not work before the year 2000?

Reply) Thank you for the reviewer's constructive comments. Although the dipole mode patterns have remained structurally similar (Supplementary Table 1), their impacts have shifted due to changes in their extent and intensity after 2000 (Supplementary Fig. 6), as already mentioned in the earlier version of the manuscript. Indeed, the negative pole of dipole mode has significantly strengthened and expanded after the year 2000, while the positive pole has weakened and contracted (Figs. 2d, e). This ultimately changes the direction and intensity of meridional wind flows (Supplementary Fig. 6). Specifically, in the European region, the cold northerly winds from the negative pole of dipole mode are seen over the Barents-Kara Sea during the pre-2000s. However, in the post-2000s, the extended and intensified negative pole of dipole mode causes stronger northerly winds over the Norwegian Sea. This shift results in different meridional wind circulation patterns between the pre- and post-2000s, leading to opposing pressure patterns in Northern and Eastern Europe.

To clarify this further, in response to the reviewer's comments, we compared the effects and mechanisms driven by the dipole mode in the pre-2000s (Fig. R2) and post-2000s (Fig. 5). In contrast to the post-2000s, a significant net surface heat flux into the atmosphere driven by the dipole-like Arctic atmospheric circulation is seen over the Northern Barents Sea in the pre-2000s (Fig. R2a). This leads to a weak meridional temperature gradient change over

Eastern Europe (Fig. R2b), which affects mid-latitude circulation, weakening zonal winds at mid-latitudes and strengthening them at lower latitudes (Fig. R2c). This pattern fosters cyclonic circulation over Eastern Europe (Fig. R2d). In terms of thermodynamic influence, this atmospheric circulation keeps the soil moist and induces strong downward sensible heat flux into the soil (Figs. R2e,f). These factors clearly demonstrate that heat waves were less likely in the pre-2000s over Eastern Europe.

In addition to differences in the characteristics (intensity and extent) of Arctic atmospheric circulation, another possible explanation for the relatively lower frequency of heatwave occurrences in the pre-2000s compared to the post-2000s could be differences in the mean state conditions of heatwave-related climate variables in Eastern Europe (20°–70° E, 40°–55° N) between the two periods. Specifically, assuming no major changes in Arctic atmospheric circulation, differences in the mean states of these variables between the two periods could lead to different effects. For instance, as shown in Figure R3, during the pre-2000s period, geopotential height and upward sensible heat flux into the atmosphere are lower, while soil moisture exhibits higher mean states compared to the post-2000s. This is ultimately consistent with the relative decrease in heatwave frequency in the pre-2000s of Figure 4d.

Responding to the reviewer's comment, we have added the following sentences to the revised manuscript and Figure R2 to the revised supplementary materials.

(Lines 235-241)

➔ In contrast, the mechanism driven by the dipole-like mode in Eastern Europe before the 2000s exhibits a vulnerability to the formation and development of heatwaves. This is characterized by a weakened meridional temperature gradient, the development of cyclonic circulation, wet soil conditions, and a strong downward sensible heat flux into the soil (Supplementary Fig. 10). Additionally, the unfavorable mean state conditions of climate variables related to heatwave occurrences in Eastern Europe can be considered a contributing factor.

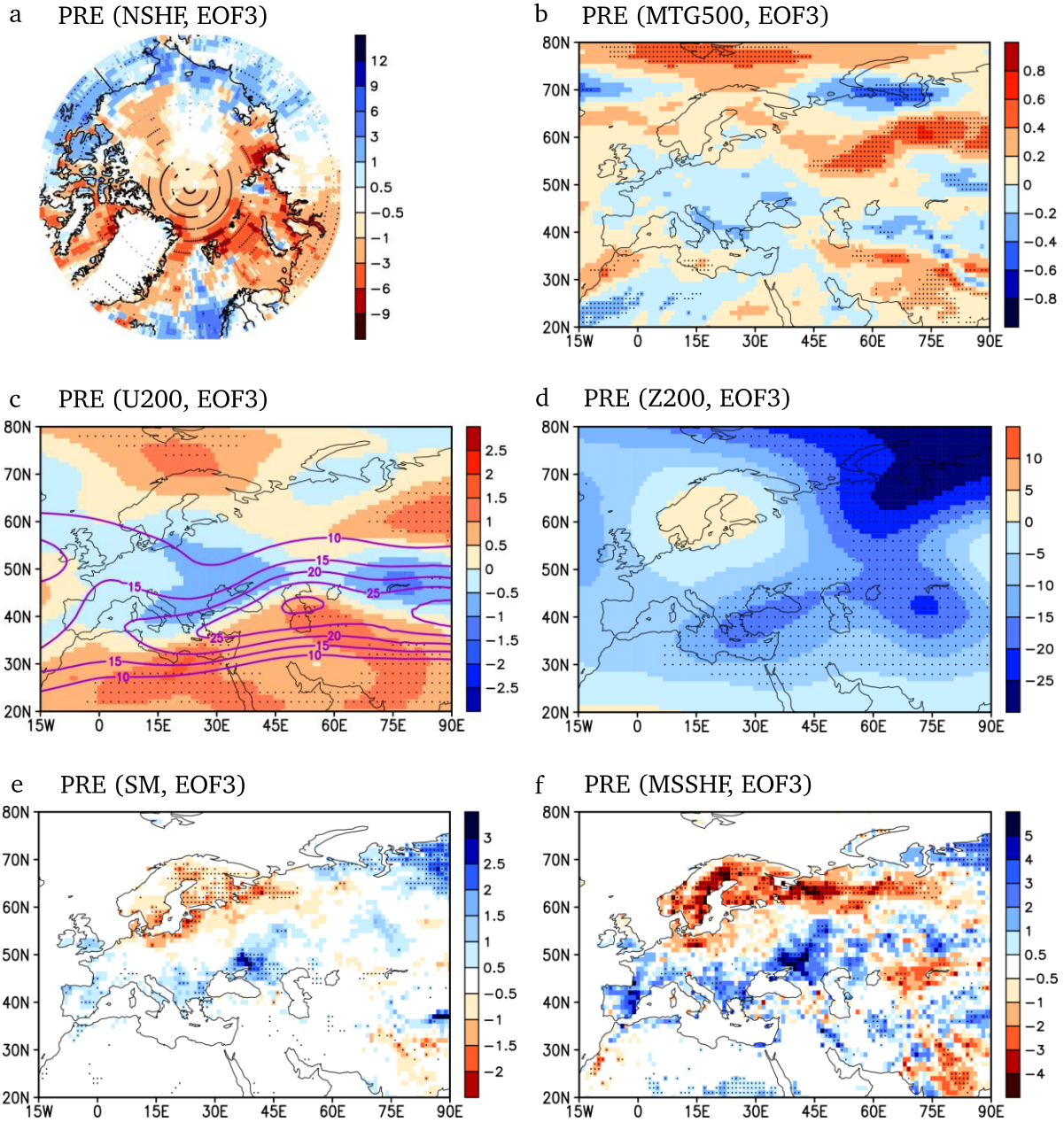


Fig. R2 | Responses related to Arctic atmospheric mode in the pre-2000s (1980-1999). **a**, Regression pattern of the detrended JJA mean net surface heat flux (NSHF, W m^{-2}) anomalies onto the standardized time series of the 3rd mode of the EOF analysis of the detrended JJA SLP anomalies weighted by cosine latitude over the domain of 60° – 90° N in the pre-2000s (1980-1999). Upward (surface to atmosphere) fluxes are negative. **b**, Same as **(a)**, but for meridional temperature gradient at 500 hPa (MTG500, $\times 10^{-6}$, $^{\circ}\text{C m}^{-1}$). **c**, Same as **(a)**, but for zonal wind at 200 hPa (U200, m s^{-1}). The purple contour is the climatological mean (m s^{-1}). **d**, Same as **(a)**, but for geopotential height at 200 hPa (Z200, m). **e**, Same as **(a)**, but for soil moisture (SM, $\times 10^{-2}$, $\text{m}^3 \text{m}^{-3}$). **f**, Same as **(a)**, but for mean surface sensible heat flux (MSSHf, W m^{-2}). Upward (surface to atmosphere) fluxes are negative. The stippled areas are statistically significant at a 90% confidence level for a two-tailed Student's *t*-test.

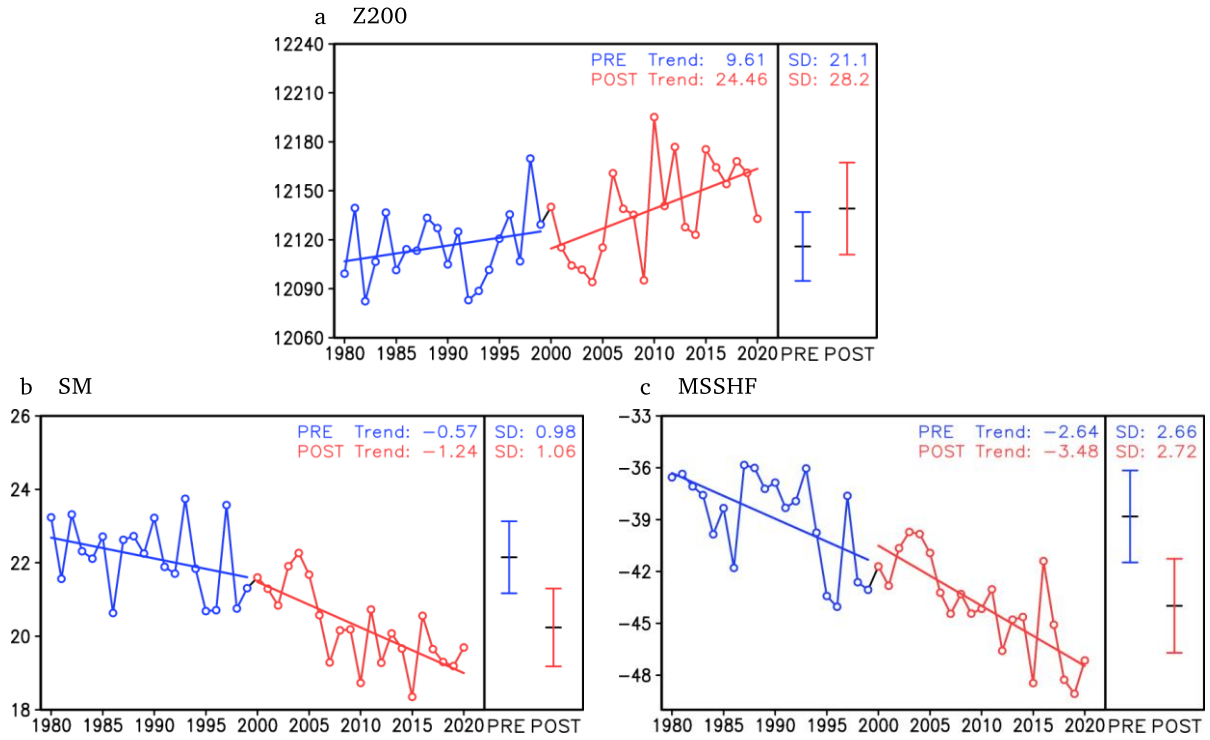


Fig. R3 | Temporal evolution for geopotential height (Z200), soil moisture (SM), and mean surface sensible heat flux (MSSHf). **a.** Time series and trend (decade⁻¹) of JJA geopotential height at 200 hPa (Z200, m) area-averaged over Eastern Europe (20°–70° E, 40°–55° N) in the total period (1980–2020). The blue and red error bars depict the standard deviations (SD), and the black center dashed marks represent the averages for the pre-2000s and post-2000s, respectively. Trend and SD values are displayed in the upper right corner. **b.** Same as **(a)**, but for soil moisture (SM, 10⁻² m³ m⁻³). **c.** Same as **(a)**, but for mean surface sensible heat flux (MSSHf, W m⁻²).

Reply to Reviewer #3's Comments:

We are grateful to the reviewer for the comments that helped us further improve the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #3's comments are shown in violet in the revised manuscript* if indicated to be included.

Major comments

1. *The comparison of the results between the ARCTIC_run and CLIM_run on lines 136-149 has to be clarified. The Arctic_run "is run towards the observed historical values only in the Arctic north of 65N", whereas in the CLIM_run "the climatological SST is nudged in the same Arctic region ..., where there is no sea ice decline in the Arctic region". This is confusing,*

Reply) We would like to thank you for your comments. Responding to the reviewer's comment, the above sentences have been revised as follows.

Lines (158-160)

→ the observed climatological SST is nudged in the same Arctic region (see Methods) (CLIM_run, hereafter), where sea ice responds to the climatological SST in the Arctic region.

and I cannot understand why calculating the difference between the two runs allows to isolate the role of Arctic sea ice reduction. Before this fundamental issue is clarified, a reader cannot be convinced about the validity of the results presented in the manuscript.

Reply) In this study, we performed SST nudging simulations (ARCTIC_run) that restore the simulated SSTs in the model to observed SSTs (observed climatological SSTs + observed anomalous SSTs) in the region north of 65°N. Additionally, we conducted another SST nudging simulation (CLIM_run) under the same conditions as the ARCTIC_run, but using observed climatological SSTs for the high-latitude region. The only influence of observed anomalous SSTs in the Arctic on the global climate can be identified by the difference between the ARCTIC_run and CLIM_run simulations. Responding to the reviewer's comments, we have added the following sentences to the revised manuscript.

(Lines 160-162)

→ By calculating the difference between the two runs (ARCTIC_run minus CLIM_run), we isolate the role of ASI reduction as the sole influence of observed anomalous SSTs in the Arctic on the global climate (Methods).

2. The message from Figure S1 seems to be interpreted wrongly. Figure S1 shows that in the regions where summer sea ice concentration has decreased most (green and blue areas in Figure S1b), the net surface heat flux has predominantly increased (blue colors in Figure S1c), with fluxes defined positive downwards. In the text, however, the interpretation is that sea ice decline has caused an increased heat loss from the sea to the atmosphere (lines 101-104, 204, and elsewhere), resulting in changes in the large-scale circulation and further on European heat waves. In summer, however, sea ice loss has occurred simultaneously with increasing net heat flux from the atmosphere to the ocean, as Figure S1 shows. This is because the summertime climate warming has been much faster in the terrestrial Arctic than over the Arctic Ocean. This is related to the facts that (a) the ice surface temperature cannot exceed 0 deg C and (b) the large heat capacity of the open ocean keeps the SST increase slow. Hence, warm air masses transported from the terrestrial Arctic to over the Arctic Ocean generate increasingly large downward net heat flux to the open and ice-covered parts of the ocean surface, enhancing ice melt. For an example of such an event, see Tjernström et al., (2015), doi:10.1002/2015GL064373. Accordingly, while the manuscript has demonstrated summertime linkages between changes in Arctic sea ice concentration and European heatwaves, the causes and consequences seem to be something else than those presented in the manuscript.

Reply) Thank you for your helpful comments. We appreciate it. The reviewer is right. We referred to the above literature (Tjernstrom et al. 2015). Following the reviewer's comment, we have revised it in the manuscript as follows.

Lines (98-109)

➔ Furthermore, regions with a significant decreasing trend in SIC, particularly in the Russian Arctic (60°-150°E areas in Supplementary Fig. 1b), coincide with areas of increased SIC variability (Fig. 1b) and a notable rise in net downward heat flux from the atmosphere to the ocean (Supplementary Fig. 1c). This finding aligns with previous research²⁴, which suggests that sea ice reduction is triggered by increased downward heat flux from the atmosphere over both open water and ice-covered portions of the ocean surface, driven by the northward advection of warm air from the continent.

Despite the general understanding that the Arctic atmosphere loses heat to the ocean during summer^{7, 25, 26, 27}, there is, on the other hand, a tendency for upward heat transport into the atmosphere in the European Arctic region (0°-50°E areas in Supplementary Fig. 1c). This process is expected to influence atmospheric circulation, extending its impact beyond the Arctic to the mid- and high-latitudes of the NH.

References:

24. Tjernström M, Shupe MD, Brooks IM, Persson POG, Prytherch J, Salisbury DJ, *et al.* Warm-air advection, air mass transformation and fog causes rapid ice melt. *Geophysical Research Letters* 2015, **42**(13): 5594-5602.

3. Text on lines 178-186 requires clarification. Were the influences on temperature different (line 179) or not (lines 183-184)? How can these results be interpreted physically?

Reply) We compared the temperature responses of the same modes between the pre-2000s and post-2000s. Specifically, as shown in Figures 4a and 4b (in the revised manuscript), the dipole-like modes indicate distinctly different impacts on temperature. This difference can be clearly explained by the variation in the meridional wind patterns in the mid- and high-latitudes of the Northern Hemisphere (Figure S6 in the revised manuscript). On the other hand, the impacts of the tripole-like modes on temperature, as seen in Figures S7a and S7b, show very similar temperature patterns. Therefore, in terms of the increase in summer heat waves in Europe (Figures 4c, d), the dipole-like mode, which shows significant temperature changes, particularly a marked rise in temperatures over Europe, seems more relevant than the tripole-like mode, which shows little change in temperature between the pre- and post-2000s.

Responding to the reviewer's comments, the sentences are revised as follows:

(Lines 192-203)

➔ Despite the similarity in the dipole-like mode of atmospheric circulation between the pre-2000s and the post-2000s, its influence on temperature differs markedly between the two periods. This difference arises primarily from variations in the extent and intensity of the dipole-like mode (Fig. 2d,e), which lead to changes in the meridional wind patterns across the mid- and high-latitudes of the NH (Supplementary Fig. 6). In contrast, the temperature influence associated with the tripole-like mode of atmospheric circulation—the second EOF in the pre-2000s and the third EOF in the post-2000s—shows little variation between the two periods (Supplementary Fig. 7). Therefore, regarding the increase in summer heatwaves in Europe (Fig. 4c,d), the dipole-like mode—which displays significant temperature changes, particularly a marked rise over Europe in the post-2000s—appears more relevant than the tripole-like mode, which shows minimal temperature change between the pre- and post-2000s.

Minor comments

4. Lines 62-65: the European heat waves reported in previous studies were not only due to Arctic sea ice loss. Loss of terrestrial snow has been at least equally important.

Reply) Thank you for the reviewer's careful comments. We have added relevant literature and statements regarding the impact of terrestrial snow decline on European heatwaves to the revised manuscript.

(Lines 63-65)



The accelerating loss of Eurasian terrestrial snow has also been identified as a contributing factor to heatwaves in the Europe/Russia region^{9, 10, 16}.

References:

9. Zhang R, Sun C, Zhu J, Zhang R, Li W. Increased European heat waves in recent decades in response to shrinking Arctic sea ice and Eurasian snow cover. *NPJ Climate and Atmospheric Science* 2020, **3**(1): 7.
10. Coumou D, Di Capua G, Vavrus S, Wang L, Wang S. The influence of Arctic amplification on mid-latitude summer circulation. *Nat. Commun.*, 9, 2959. 2018.
16. Ji L, Fan K. Extreme heat waves in June 2021 over Europe regulated by shrinking Eurasian snow cover in mid–high latitudes. *Atmospheric Research* 2023, **295**: 107049.

5. Line 111: *is stronger than that of the other atmospheric modes ...*

Reply) The sentence has been modified in the revised manuscript as follows.

Lines (115-116)

→ its explained variance is greater than that of other atmospheric modes obtained from EOF analysis

6. Line 151: *I am not sure if these can be considered similar*

Reply) To validate that the main modes of observed Arctic atmospheric circulation are similarly captured in model experiments, the pattern correlation for each major EOF mode (First to Third modes) in the Arctic region (60°–90° N) between observations and model simulations was calculated, as shown in Table R1. The analysis was conducted for three periods: the entire study period (1980–2020), pre-2000s (1980–1999), and post-2000s (2000–2020). The results demonstrate that the observed key features of atmospheric circulation are similarly represented in model simulations.

Table. R1 | Relationship between the main modes of Arctic atmospheric circulation in observations and simulations. Pattern correlation coefficients (60°–90° N) between the main modes of the EOF analysis for observations and simulations over the Arctic for three periods.

Pattern Correlation (60°–90° N)		OBS Total Period (1980-2020, Reg. SLP)		
		EOF 1 st	EOF 2 nd	EOF 3 rd
Model Total Period	EOF 1 st	0.96	-	-

(1980-2020, Reg. SLP)	EOF 2 nd	-	0.75	-
	EOF 3 rd	-	-	0.73

Pattern Correlation (60°–90° N)		OBS Pre-2000s (1980-1999, Reg. SLP)		
		EOF 1 st	EOF 2 nd	EOF 3 rd
Model Pre-2000s (1980-1999, Reg. SLP)	EOF 1 st	0.86	-	-
	EOF 2 nd	-	0.82	-
	EOF 3 rd	-	-	0.51

Pattern Correlation (60°–90° N)		OBS Post-2000s (2000-2020, Reg. SLP)		
		EOF 1 st	EOF 2 nd	EOF 3 rd
Model Post-2000s (2000-2020, Reg. SLP)	EOF 1 st	0.69	-	-
	EOF 2 nd	-	0.81	-
	EOF 3 rd	-	-	0.63

7. Line 192: clarify at which latitudes, as also a cooling trend is seen farther north in eastern Europe.

Reply) The sentence has been modified in the revised manuscript as follows.

Lines (210-214)

➔ In particular, a notably strong warming trend in the post-2000s over Eastern Europe (40°–55° N, 20°–70° E) (Supplementary Fig. 9) is very similar to the temperature pattern associated with the dipole-like mode of atmospheric circulations emerging dominantly after the 2000s (Fig. 4b).

8. Lines 209 and 225: The structure throughout the layers shown does not appear barotropic.

Reply) The sentences have been modified in the revised manuscript as follows.

Line (227)

➔ quasi-barotropic anticyclonic circulation

Lines (257-258)

➔ quasi-barotropic circulation

9. Line 212: *How can you quantify that the contribution is substantial?*

Reply) Thank you for the reviewer's careful comment. To quantify the substantial contribution of soil moisture (SM) decline and the release of mean surface sensible heat flux (MSSHf) to the atmosphere to the increase in heat wave frequency (HWF) over Eastern Europe (40°–55° N, 20°–70° E) during the summer (JJA) in the post-2000s, the temporal evolution of SM and MSSHf is shown in Figure R1 and compared with the temporal changes in HWF in Figure 4d. Unlike the increasing trend in HWF seen in Figure 4d, SM and MSSHf in Figure R1 show a gradual decreasing trend. In particular, the steeper decline in both variables in the post-2000s compared to the pre-2000s (Fig. R1) aligns well with the strong increasing trend in HWF (Fig. 4d). Additionally, the increase in the variance of each variable (HWF, SM, MSSHf) since the 2000s is clearly evident, and the impact of the decrease in the mean values of SM and MSSHf also demonstrates their contribution to the increase in HWF.

To confirm this more explicitly, the temporal correlation between HWF, SM, and MSSHf in the post-2000s is calculated and quantified (Table R2). The results show that the correlation coefficients of SM and MSSHf with HWF are -0.71 and -0.44, respectively, with over 95% statistical confidence. Responding to the reviewer's comment, we have added the following sentences to the revised manuscript.

(Lines 228-235)

➔ In addition to the effects of changes in the mean state conditions of soil moisture and sensible heat flux, this mechanism can exert a thermodynamic influence on atmospheric circulation by drying the soil and inducing a strong upward sensible heat flux from the soil to the atmosphere (Fig. 5e, f). This process significantly contributes to the increase in heatwave frequency observed after the 2000s, as evidenced by the temporal correlation coefficients of soil moisture (-0.71) and sensible heat flux (-0.44) with heatwave frequency, both statistically significant at over 95% confidence (Supplementary Table 6).

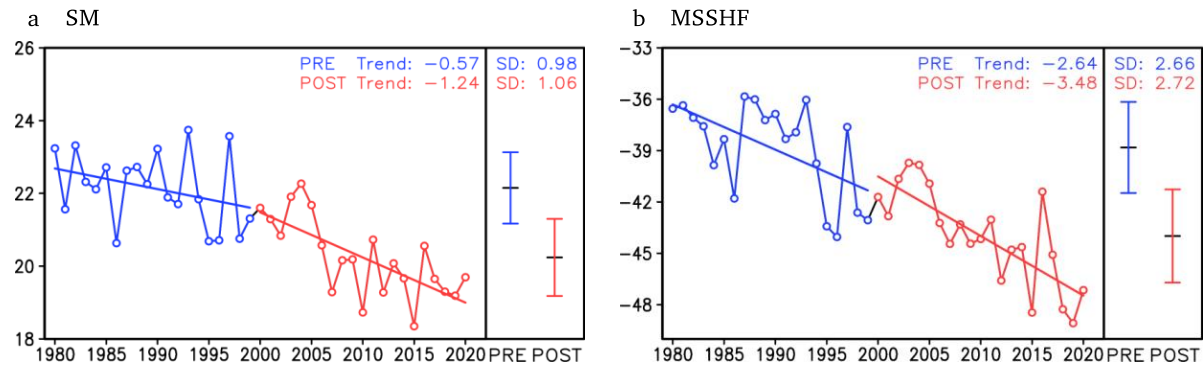


Fig. R1 | Temporal evolution for soil moisture (SM) and mean surface sensible heat flux (MSSHF). **a.** Time series and trend (decade⁻¹) of JJA soil moisture (SM, 10⁻² m³ m⁻³) area-averaged over Eastern Europe (20°–70° E, 40°–55° N) in the total period (1980–2020). The blue and red error bars depict the standard deviations (SD), and the black center dashed marks represent the averages for the pre-2000s and post-2000s, respectively. Trend and SD values are displayed in the upper right corner. **b.** Same as **(a)**, but for mean surface sensible heat flux (MSSHF, W m⁻²).

Table. R2 | Relationship between the temporal evolution of summer (JJA) heat wave frequency (HWF), soil moisture (SM), and mean surface sensible heat flux (MSSHF) in the post-2000s. Temporal correlation coefficients (TCC) between the observed JJA HWF in Figure 4d and SM (MSSHF) in Figure R1 area-averaged over Eastern Europe (20°–70° E, 40°–55° N) during the post-2000s (2000–2020). Asterisks (*) and (**) denote statistical significance at the 95% and 99% confidence levels, respectively, based on a two-tailed Student's *t*-test.

Temporal Correlation Coefficients (TCC) for Eastern Europe (20°–70° E, 40°–55° N)	HWF & SM	HWF & MSSHF	SM & MSSHF
Post-2000s 2000–2020 (21yrs)	-0.71**	-0.44*	0.85**

10. Line 226: Increasing the ability to respond and adapt to climate change is not concretely addressed in the manuscript.

Reply) Thank you for helping enhance the natural flow of the manuscript. We have revised it as follows in the manuscript.

Lines (258–259)

➔ These results are expected to improve our ability to anticipate and forecast extreme climate events by predicting Arctic atmospheric circulation patterns.

We thank the three reviewers for their helpful and constructive comments. We believe that the corresponding revisions have strengthened our earlier version of the manuscript. The answers to the reviewers are given after repeating the reviewer's comments.

Reply to Reviewer #1's Comments:

We are so grateful to the reviewer for the comments that helped us further improve the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #1's comments are shown in green in the revised manuscript* if indicated to be included.

I thank the authors for their very comprehensive response to my comments and those of my two co-reviewers. They have clarified the issues that were of concern to me. In particular, the testing for degeneracy of the EOFs was very valuable, as was the application of the Monte Carlo test (non-parametric) test procedure of Xiao-feng Li et al. (2000) (Reference 32). Incidentally, at Lines 384-386 the reference details for their paper should be Li, X.-f., L. Pietrafesa, S.-f. Lan and L.-a. Xie, 2000: Significance test for empirical orthogonal function(EOF) analysis of meteorological and oceanic data. Chinese Journal of Oceanology and Limnology, 18, 10-17, doi: 10.1007/BF02842536.

Reply) Thank you for the reviewer's comments. The reference has been modified in the revised manuscript as follows.

Lines (384-386)



32. Li X.-f., Pietrafesa L., Lan S.-f. and Xie L.-a. Significance test for empirical orthogonal function (EOF) analysis of meteorological and oceanic data. *Chinese Journal of Oceanology and Limnology* 2000, **18**: 10-17. doi: 10.1007/BF02842536.

Reply to Reviewer #2's Comments:

We are so grateful to the reviewer for the comments that helped us further improve the earlier version of the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #2's comments are shown in red in the revised manuscript* if indicated to be included.

I have no further question and recommend acceptance for publication in the journal.

Reply) Thank you for the reviewer's *acceptance of our manuscript*.

Reply to Reviewer #3's Comments:

We are grateful to the reviewer for the comments that helped us further improve the manuscript. We appreciate the reviewer's thorough advice and comments and the precious time. The responses to the reviewer's line-specific comments are provided in blue below. Note that *the responses to reviewer #3's comments are shown in violet in the revised manuscript* if indicated to be included.

The authors have done careful work in revising the manuscript on the basis of my and other reviewers' comments. I am satisfied with the response letter and revisions made, and suggest acceptance of the manuscript subject to minor linguistic revisions specified below.

Line 106: remove "on the other hand". This expression should be preceded by "on one hand".

Reply) The phrase has been modified in the revised manuscript according to the reviewer's comment. Line (106)

Lines 159-160: remove "in the Arctic region".

Reply) The phrase has been removed from the sentence. Line (159)

Line 199: replace "Therefore" by "Hence"

Reply) The word has been replaced in the revised manuscript. Line (199)