

Water sources and land capacitor effects stimulate observed summer Arctic moistening and warming

Corresponding Author: Dr Ian Baxter

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

Version 0:

Decision Letter:

**** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors ****

Dear Dr Baxter,

Your manuscript titled "Water sources and land capacitor effects driving observed summer Arctic moistening and warming" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. Specifically, we ask you to clarify mechanisms of moisture supply and ensure your methods are fully described and justified and limitations of your approach acknowledged.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point 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.

We are committed to providing a fair and constructive peer-review process. Please don't 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 referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:

Link Redacted

**** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first ****

We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still 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.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Sylvia Sullivan, PhD
Editorial Board Member
Communications Earth & Environment

Aliénor Lavergne, PhD
Senior Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability
ORCID: 0000-0002-4591-1217

EDITORIAL POLICIES AND FORMATTING

We ask that you ensure your manuscript complies with our editorial policies. Please ensure that the following formatting requirements are met, and any checklist relevant to your research is completed and uploaded as a Related Manuscript file type with the revised article.

Editorial Policy: [Policy requirements](https://www.nature.com/documents/nr-editorial-policy-checklist.pdf) (Download the link to your computer as a PDF.)

For Manuscripts that fall into the following fields:

- Behavioural and social science
- Ecological, evolutionary & environmental sciences
- Life sciences

An updated and completed version of our Reporting Summary must be uploaded with the revised manuscript

You can download the form here:

<https://www.nature.com/documents/nr-reporting-summary.zip>

Furthermore, please align your manuscript with our format requirements, which are summarized on the following checklist: [Communications Earth & Environment formatting checklist](https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf)

and also in our style and formatting guide [Communications Earth & Environment formatting guide](https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

*** DATA: Communications Earth & Environment endorses the principles of the Enabling FAIR data project (<http://www.copdess.org/enabling-fair-data-project/>). We ask authors to make the data that support their conclusions available in permanent, publically accessible data repositories. (Please contact the editor if you are unable to make your data available).

All Communications Earth & Environment manuscripts must include a section titled "Data Availability" at the end of the Methods section or main text (if no Methods). More information on this policy, is available at <http://www.nature.com/authors/policies/data/data-availability-statements-data-citations.pdf>.

In particular, the Data availability statement should include:

- Unique identifiers (such as DOIs and hyperlinks for datasets in public repositories)
- Accession codes where appropriate
- If applicable, a statement regarding data available with restrictions
- If a dataset has a Digital Object Identifier (DOI) as its unique identifier, we strongly encourage including this in the Reference list and citing the dataset in the Data Availability Statement.

DATA SOURCES: All new data associated with the paper should be placed in a persistent repository where they can be freely and enduringly accessed. We recommend submitting the data to discipline-specific, community-recognized repositories, where possible and a list of recommended repositories is provided at <http://www.nature.com/sdata/policies/repositories>.

If a community resource is unavailable, data can be submitted to generalist repositories such as [figshare](https://figshare.com/) or [Dryad Digital Repository](http://datadryad.org/). Please provide a unique identifier for the data (for example a DOI or a permanent URL) in the data availability statement, if possible. If the repository does not provide identifiers, we encourage authors to supply the search terms that will return the data. For data that have been obtained from publically available sources, please provide a URL and the specific data product name in the data availability statement. Data with a DOI should be further cited in the methods reference section.

Please refer to our data policies at <http://www.nature.com/authors/policies/availability.html>.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript investigates the pathways of moisture transport into the Arctic during summer, with a particular emphasis on the mediating role of land processes in facilitating long distance moisture transport from lower to high latitudes. While the

main concept of land-mediated moisture pathways is not entirely new, this study re-visits the topic using water tagging and wind nudging techniques. The results are generally consistent with previous studies that highlight the Europe as a significant land source of Arctic moisture, but this work also emphasizes North America as an additional major contributor. This work also demonstrate the water tagging technique can be a valuable tool for studying transpiration processes. The manuscript is well written in general, but includes a few statements where the physical mechanisms require clarification.

One of the major concerns is about the understanding of physical processes involved in the moisture supply from region 43 and 44 (Europe and Siberia). The manuscript suggests that the spring precipitation (in the manuscript) could contribute to summer evaporation. Although the authors did not formally discussed, the attached Fig.S5 indicates the enhancement of summer evaporation through soil and vegetation (Fig.4d) might be from the melting of snow cover in summer. Meanwhile, soil moisture (Fig.S5e) is declining. I cannot follow the storyline here. If snow cover is the source of increased evaporation in summer, we would expect it to first moisten the soil before supporting vegetation transpiration. In addition, this modeled decline in soil moisture contradicts satellite observation (Fig.S6a), which show no trend, possibly indicating that increased evaporation offsets any increase in soil moisture. The authors should reconsider or clarify their interpretation of the land moisture processes in region 43 and 44.

Some specific comments:

Line 21-23: the second part of this sentence seems incomplete.

Fig.1c,e: the significance test for the vectors (moisture transport) is also needed.

Line 157-158: this sentence seems unnecessary.

Line 298: "a south asian high pattern" should be revised. South Asian High only exists in summer month.

Fig4 a,c: the caption of the subplots indicate these panels show the source of moisture, while the colorbar describes precipitation trends. Please clarify the actual quantity being shown and ensure that the terminology is consistent between the captions, colorbars, and figure description in the main text.

Reviewer #2 (Remarks to the Author):

This paper aims to identify the sources of recent Arctic moistening trends, attribute Arctic warming through radiative effects, and analyze the influence of moisture transport from the tropics, particularly via land surface processes, on sea ice loss and surface heat absorption. Data used include reanalysis data from ERA5, output from the Community Earth System Model versions 1 and 2 (iCESM1 and CESM2), and observation-based precipitation products.

The study employs a combination of water tagging and circulation nudging techniques to identify the sources of recent summer Arctic moistening trends. It uses iCESM and radiative kernels built using ERA5 and the CAM5. To analyze atmospheric river (AR) events, the Guan and Waliser (2015, 2019) tracking algorithm is used however limited details of this method are offered in the manuscript. The contribution to Arctic moisture changes from individual regions is determined by computing an Arctic mean of total precipitable water evaporated from the 55 tagging regions.

The study focuses on the summer season, and finds increased moisture transport from the tropics and mid-latitudes, particularly via increased evapotranspiration from land, which significantly contributes to Arctic moistening and warming. This increased moisture amplifies warming through in-season radiative effects and contributes to sea ice loss, highlighting the importance of land surface processes in driving Arctic change. Additionally, the study suggests that current climate models may underestimate the influence of land-sourced moisture on Arctic moistening.

Aspects of the manuscript I find unique to the best of my knowledge include the use of the "land capacitor effect", which the authors describe as the tendency of high-latitude land to store and recycle lower-latitude moisture to the Arctic, contributing to Arctic moistening. The paper highlights the crucial role of plant evapotranspiration and the tropical Atlantic/Caribbean as key sources in this land-driven moisture transport to the Arctic, in addition to highlighting the role of remote land-based moisture transport in Arctic water vapor radiative feedback, which potentially has a more important role than local ocean evaporation.

Limitations of the current study include the heavy reliance on model simulations, despite observational nudging using ERA5 data. Results are still subject to model biases that most likely impact the results presented. The water tagging technique is also subject to limitations of model physics and parameterization as pointed out by the authors themselves. Finally, some of the conclusions are based on correlations and statistical relationships. While these suggest strong connections between the identified processes, they do not definitively prove causation.

Overall, I found the paper to be well written, results are presented clearly and framed within the context of the current literature. I was not familiar with the "land capacitor" effect prior to this, in addition to water tagging, and perhaps a small criticism would be the authors to offer even a brief summary of the methodologies of such techniques in the current manuscript. I found the results associate with the percent attribution of precipitation trends to different regions difficult to follow. A minor comment is to revise some of the figure captions for clarity, specifically figure 4, which I find difficult to follow after multiple reads.

I would recommend for publication subject to these minor comments.

Reviewer #3 (Remarks to the Author):

Review of Baxter et al "Water sources and land capacitor effects driving observed summer Arctic moistening and warming"

Overall recommendation: Reject

This manuscript examines seasonal atmospheric moisture transport from the tropics to the Arctic and attempts to identify the underlying land surface source regions which supply water vapor to the atmosphere through processes of evaporation and evapotranspiration. The authors employed several datasets, including ERA5 reanalysis and a host of gridded soil and precipitation products, along with a host of numerical simulations and experiments conducted with the Community Earth System Model CESM. Several CESM simulations incorporated nudging and included a water tagging capability for tracking atmospheric water vapor and identifying moisture source regions. Results are presented primarily in form linear trends for gridded regional source region zones. Moisture trends in each zone are also partitioned in terms of their radiative percent contribution to warming in the Arctic. While I find the topic of land surface moisture source regions in relation poleward moisture transport quite interesting, I do have major concerns with the manuscript in its current form, in particular (1) quality of the writing and (2) descriptive clarity of the data/models and analysis as presented. I also believe additional analysis would better support the authors claims regarding moisture source regions. With the following comments, I provide some examples of these concerns. I do think the authors could improve the manuscript, but it would require extensive revisions. My overall recommendation is to reject the manuscript at this time.

Major Comments:

1. Abstract.

Line 21: First sentence after "uncertain," is not coherent.

Line 24: "land capacitor processes", what are land capacitor processes? The word capacitor is awkward in this context, rephrase throughout or explain clearly what is meant by land or ocean capacitor effect when the phrase is first introduced.

Line 26: "traveling from the tropics to the Arctic by passing through the high latitude land surface", passing through? The air is moving above or across the land surface.

In general, when one reads the abstract, it should give a clear and concise description of the overarching theme of the manuscript, analysis performed, and key results. In its current form, it is too scattered and unclear.

2. Introduction. The writing is better in this section.

Line 47: "this phenomena". Plural form used but the reference is singular. Phenomenon? See Line 54: "However these phenomena"

Line 57: "such as water vapor", water vapor is parameter not a process. Rephrase.

Line 100: "The conclusions that terrestrial sources are the dominant contributing regions in summer..."

Is the above statement accurate when referencing the studies cited, i.e., terrestrial sources are the dominant contributors? Perhaps terrestrial sources are amplified in summer but not dominant, at least in terms of moisture?

Line 102: "we explore the transport of moisture from the tropics to the Arctic via the land surface – which we refer to as a land capacitor effect

"via the land surface", rephrase

This is the first description of the land capacitor effect. A clearer description is needed, and it should come earlier on. Does land capacitor effect represent the transfer of heat and moisture from the land surface to the atmosphere and vice versa? If so, perhaps the authors should explore the land surface latent and sensible heat fluxes in addition to the evaporation.

3. Results

As I start reading the results, interpretation is problematic, and the writing is hard to follow. I believe this is because the writing in the Materials and Methods section lacks clarity and lacks sequential structure. The results and Methods are not well connected.

4. Material and Methods

The explanation of the ERA5 dataset starts off well, however, atmospheric rivers are mentioned on Line 402. I know ARs were mentioned in the abstract, but not in the introduction. So, moisture transport is examined by itself or in the form of atmospheric river events or both?

Line 411: "For AR detection we use daily output from the iCESM1..."

iCESM1 data has not been described yet. This miss-order of writing and description occurs throughout the methods section

(and in several other instances throughout the manuscript) and this makes the writing extremely difficult to follow. Perhaps a flow diagram figure could be included that explicitly provides a roadmap of the analysis, datasets, experiments etc.. Then, results could be presented in reference to this roadmap figure.

I wish I could be more positive. On a positive note, the figures are high quality.

** Visit Nature Research's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Communications Earth & Environment is committed to improving transparency in authorship. As part of our efforts in this direction, we are now requesting that all authors identified as 'corresponding author' create and link their Open Researcher and Contributor Identifier (ORCID) with their account on the Manuscript Tracking System prior to acceptance. ORCID helps the scientific community achieve unambiguous attribution of all scholarly contributions. You can create and link your ORCID from the home page of the Manuscript Tracking System by clicking on 'Modify my Springer Nature account' and following the instructions in the link below. Please also inform all co-authors that they can add their ORCIDs to their accounts and that they must do so prior to acceptance.

<https://www.springernature.com/gp/researchers/orcid/orcid-for-nature-research>

For more information please visit <http://www.springernature.com/orcid>

If you experience problems in linking your ORCID, please contact the [Platform Support Helpdesk](http://platformsupport.nature.com/).

Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Baxter,

Your manuscript titled "Water sources and land capacitor effects driving observed summer Arctic moistening and warming" 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, which pertain to improving clarity of the descriptions of your simulations. 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.

EDITORIAL REQUESTS:

Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

SUBMISSION INFORMATION:

In order to accept your paper, we require the files listed at the end of the Editorial Requests Table; the list of required files is also available at <https://www.nature.com/documents/commsj-file-checklist.pdf>.

OPEN ACCESS:

Communications Earth & Environment is a fully open access journal. Articles are made freely accessible on publication. For further information about article processing charges, open access funding, and advice and support from Nature Portfolio, please visit <https://www.nature.com/commsenv/open-access>

At acceptance, you will be provided with instructions for completing the open access licence agreement on behalf of all authors. This grants us the necessary permissions to publish your paper. Additionally, you will be asked to declare that all required third party permissions have been obtained, and to provide billing information in order to pay the article-processing charge (APC).

Please use the following link to submit the above items:

Link Redacted

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Alice Drinkwater, PhD
Associate Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have carefully reviewed the revised manuscript and am satisfied with the authors' responses to the previous comments. The revisions have adequately addressed the concerns raised, and I have no further suggestions. I recommend the manuscript for publication in its current form.

Reviewer #3 (Remarks to the Author):

Second review of Baxter et al "Water sources and land capacitor effects driving observed summer Arctic moistening and warming"

I thank the authors for addressing my comments. I do think, in general, the manuscript is improved. The abstract and introduction read well. The significance statement reads with some phrasing that a non-expert might struggle with which could be improved with minor edits. However, despite the manuscript improvements, I still struggle with the methods description, in particular the lack of explanation of the model simulations and experiments performed with iCESM1. This lack of explanation carries into the results and the discussion and makes interpretation problematic.

Comments:

Significance statement:

Line: 36-38:

Suggest rephrasing:

"By combining nudging and water isotope tagging approaches to explicitly track water vapor we are now able to directly track transport trends over the reanalysis period."

To:

"By utilizing numerical techniques such as nudging to observations and isotope tagging for water vapor, moisture transport trends can be directly evaluated over space and time."

Line 39-40:

Suggest removing the phrase:

"via a land capacitor effect"

Introduction:

Line 123:

Revise phrase: "pathways simulated this nudging simulation"

Line 124:

Suggest rephrasing: "the two primary source regions"

To:

"primary source regions" as the existent of two is a result of your analysis.

Model simulations

Nudged, water isotope enabled simulations: This section reads fine until Line 475. The CAM5.3 is introduced early on, but POP2 and CICE4 are not. I can examine the references cited [e.g., 60, 38, 39] which provide detailed information. However, there should be some small explanation of the POP2 and CICE4 sub models provided here.

Line 477, "these experiments". No details of the experiments are discussed. Again, do I revisit the references to understand what experiments were done? Which experiments are used in this study? There should be some explanation of "these experiments" and what they represent. Connecting this lack of explanation to the results, Line 129 "The iCESM1 simulations with atmospheric nudging...". Which simulations or experiments are shown here? In Figure 1a, does the black curve (iCESM1) represent one experiment or is it a mean of several? This lack of explanation translates throughout the results and makes interpretation problematic because there is no clear description of the iCESM1 experiments used in this study.

iCESM1 Experimental Design, As I read Lines 487-492, I get the sense that there's one iCESM1 simulation (nudged to ERA5 for u, v, and T) to be used after evaluating the sensitivity of the lowest model specific humidity; is this accurate?

Line 501 "these runs". Are multiple runs or experiments used? A mean?

Line 503-504 implies multiple iCESM1 simulations?

Results

Line 133:

"relative to iCESM1, with the nudged simulations", is iCESM1 a mean of multiple simulations?

Line 145, Figure 1a caption

"from CESM2-LE (blue, grey shading),"

Add text or revise the legend to clarify that the blue curve represents the ensemble mean and the grey shading represents the ensemble spread in Fig. 1a. In Fig 1b, the legend appropriately identifies the mean and spread.

In general, I believe the results and discussion read well. I think if the authors clarify in detail their explanation of iCESM1 simulations and experiments, it would go a long way to improving the manuscript and interpretation of the results.

** Visit Nature Portfolio's author and referees' website at www.nature.com/authors for information about policies, services and author benefits**

Open Access This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

Your manuscript titled "Water sources and land capacitor effects driving observed summer Arctic moistening and warming" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. Specifically, we ask you to clarify mechanisms of moisture supply and ensure your methods are fully described and justified and limitations of your approach acknowledged.

Thank you for your consideration and reviews of our manuscript. The reviewer comments are shown here in bold, black font and our responses and revisions to the main text are detailed in blue font. In response to the comments made by the reviewers we have:

1. Clarified the mechanisms of moisture supply facilitating the transport of moisture from low to high latitudes and the land capacitor effect.
 - a. The land moisture processes in regions 43 and 44 (Eurasia).
 - i. The role of declines in snow cover and soil moisture
 - b. The fidelity of the isotope enabled Community Earth System Model (iCESM) simulations to represent soil moisture changes expected from the reanalysis
2. Added more thorough and clear descriptions of the datasets and methods used.
 - a. Reorganization of the Data and Methods section
 - i. Sequential structuring of the Data and Methods section
 - ii. Sequential consistency in the main text
 1. Comparison of reanalysis and iCESM simulations
 - b. The Figure 4 titles, caption, and text have been revised to provide a clearer description of the information being shown and our interpretation of the mechanism.
 - c. Expanded discussion of the land capacitor effect, especially earlier in the abstract and introduction.
3. Added further acknowledgement of the limitations of our study
 - a. While we have included comparisons between observation-based products (satellite and rain gauge), our study is ultimately a modeling study. Both the reanalysis and the models are subject to their own unique biases when it comes to each component of the Earth system and the coupling between them.
 - b. We have added additional description of the limitations of this modeling approach and its relationship with observational products in the discussion.
 - c. Acknowledgement that the correlations are not necessarily evidence of causation.

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript investigates the pathways of moisture transport into the Arctic during summer, with a particular emphases on the mediating role of land processes in facilitating long distance moisture transport from lower to high latitudes. While the main concept of

land-mediated moisture pathways is not entirely new, this study re-visits the topic using water tagging and wind nudging techniques. The results are generally consistent with previous studies that highlight the Europe as a significant land source of Arctic moisture, but this work also emphasizes North America as an additional major contributor. This work also demonstrate the water tagging technique can be a valuable tool for studying transpiration processes. The manuscript is well written in general, but includes a few statements where the physucial mechanisms require clarification.

One of the major concerns is about the understanding of physical processes involved in the moisture supply from region 43 and 44 (Europe and Siberia). The manuscript suggests that the spring precipitation (in the manuscript) could contribute to summer evaporation. Although the authors did not formally discussed, the attached Fig.S5 indicates the enhancement of summer evaporation through soil and vegetation (Fig.4d) might be from the melting of snow cover in summer. Meanwhile, soil moisture (Fig.S5e) is declining. I cannot follow the storyline here. If snow cover is the source of increased evaporation in summer, we would expect it to first moisten the soil before supporting vegetation transpiration. In addition, this modeled decline in soil moisture contradicts satellite observation (Fig.S6a), which show no trend, possibly indicating that increased evaporation offsets any increase in soil moisture. The authors should reconsider or clarify their interpretation of the land moisture processes in region 43 and 44.

Thank you for the careful review of our manuscript. We have added clarification about the mechanisms mentioned in your comments as well as the ones mentioned by other reviewers.

1. Cleaned up storyline regarding the role of snow cover/melt contributing to evaporation. We have rewritten the corresponding section to make the reasoning of the land capacitor effect over Eurasia easier to follow. Snow melt is potentially an indirect source of evaporation i ncreases.
2. We have added additional discussion to include the role of snow cover change in the story and interpretation of land moisture processes in region 43+44

We have added a supplementary figure showing the spatial trends and interannual time series in annual snowmelt, computed as the difference between August (annual minimum) and March (annual maximum), with stronger negative values indicating enhanced melting each year, in Fig. R1. There are significant declines in annual snow melt in the northwest and southeast corners of region 43 where we see strong declines in summertime soil moisture. We then check changes in snow melt across regions 43+44 (Eurasia) to understand if melting of snow cover can aid in supplying the increasing evaporation seen in summer (Fig. R1b). There is a decreasing trend in total snow melt (Fig. R1), due to decreasing snowfall and warmer temperatures. This could suggest that melting snow cover may have contributed to recharging summertime soil moisture and evapotranspiration. In addition to snow cover, increased evapotranspiration may occur due to increases in temperature or downwelling shortwave radiation associated with anticyclonic circulation trends over the region.

Additional text (Line 337-339):

“Statistically significant enhancement of snow melt also coincides with regions of soil moisture decrease over Eastern Europe and may have contributed to soil moisture recharge that could supply increasing evapotranspiration (Sup. Fig. 5d)”

Though we find good agreement in the spatial patterns between modeled trends in annual snow cover and soil moisture change (Fig. R1, Supplementary Fig. 6), we also note that there is large uncertainty in model generated (reanalysis and iCESM) snow cover and melt. This caveat is discussed further in the main text. We also add the new figure to the Supplementary Information.

Revised text (Lines 339-342):

“This decrease in snow cover, particularly in spring, could impart some memory into the trends in moisture transport via summertime soil moisture changes over Eurasia (Supplementary Fig. 7). However, there are still large uncertainties in measurements and model simulated snow cover, its seasonality and its interactions with summertime soil moisture and atmosphere circulations.”

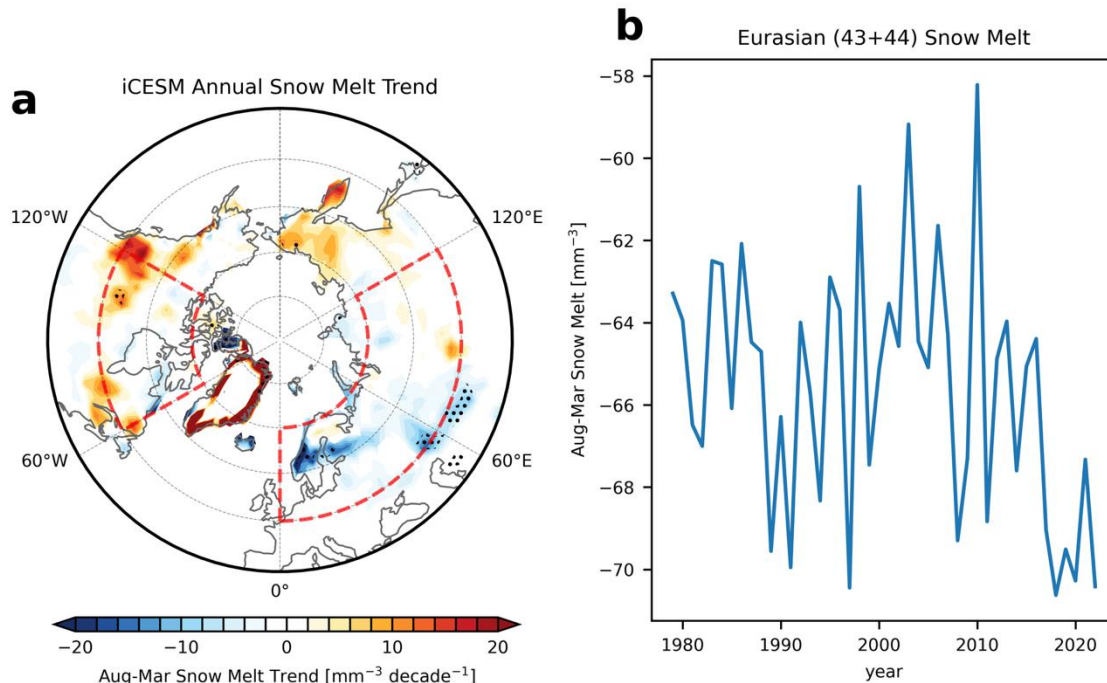


Figure R1 (now Supplementary Fig. 7): Trends in annual snow melt. a, Linear trends (1981-2022) in August minus March snow cover (representative of the total snow cover melt each year) in the iCESM nudged simulation (a). Black hatching in panel a indicates statistically significant trends at the 95% confidence level according to a two-sided student t-test. b, Time series of annual snow melt (August minus March snow cover) over the Eurasian region (43+44, shown by dashed red line in a).

3. Comparison between iCESM simulated and SMAP soil moisture trends

We agree that there are large uncertainties in land surface processes and soil moisture between the iCESM model and satellite-based measurements. The SMAP satellite-based product does show a statistically significant decline in soil moisture in both regions 43 and 44 (Eurasia), and

the magnitude and pattern is consistent with iCESM simulations. We have modified Supplementary Figure 6 (Fig. R2 below) to better show this consistency and clarified that the SMAP product shows the soil moisture only in the upper 10 cm.

The following section in the Methods describing SMAP and the comparison with the iCESM soil moisture has been moved to provide a clearer roadmap of the data and methods (also see R3 Major comment 4):

Original text (Lines 566-567):

“Simulated soil moisture trends are compared with trends from SSMV-PASSIVE soil moisture product, which combines measurements from 15 different satellite products from 1981 to 2022.”

Revised text (Line 463-466):

“Simulated soil moisture trends are compared with trends from SSMV-PASSIVE (SMAP) surface soil moisture product, which combines measurements from 15 different satellite products from 1981 to 2022. This product measures moisture within the upper 10 cm of the soil column. While we compare total column soil moisture from the model with this surface soil moisture product.”

We also added more discussion about these results and how they motivated the exploration of a land capacitor effect supplying long-term trends in moisture transported into the Arctic.

Additional text (Lines 158-168):

“Prior water tagging studies have highlighted the role of high latitude surfaces, therefore we also evaluate trends in a key reservoir for water vapor transport into the Arctic, represented by soil moisture (Supplementary Fig. 2). Fearon et al. (2023) showed that soil moisture accounted for more than 30% of this moisture flux into the Arctic. We also find reasonable agreement between the iCESM1’s simulated soil moisture trends and those from the satellite measurement derived Soil Moisture Active Passive product (SMAP, Supplementary Fig. 2a,b). SMAP shows a decrease in soil moisture across most of the high latitude land surface, again consistent with the nudged model simulation. This could be interpreted as a redistribution of moisture from the land to the Arctic, however there must be some recharge mechanism capable of sustaining a long-term decrease in soil moisture coinciding with an increasing trend in moisture sourced from these regions being transported to the Arctic. This “paradox” motivates the subsequent analysis and the proposition of a land capacitor effect to explain sustained moisture facilitating water vapor transport from low to high latitudes discussed in the following sections.”

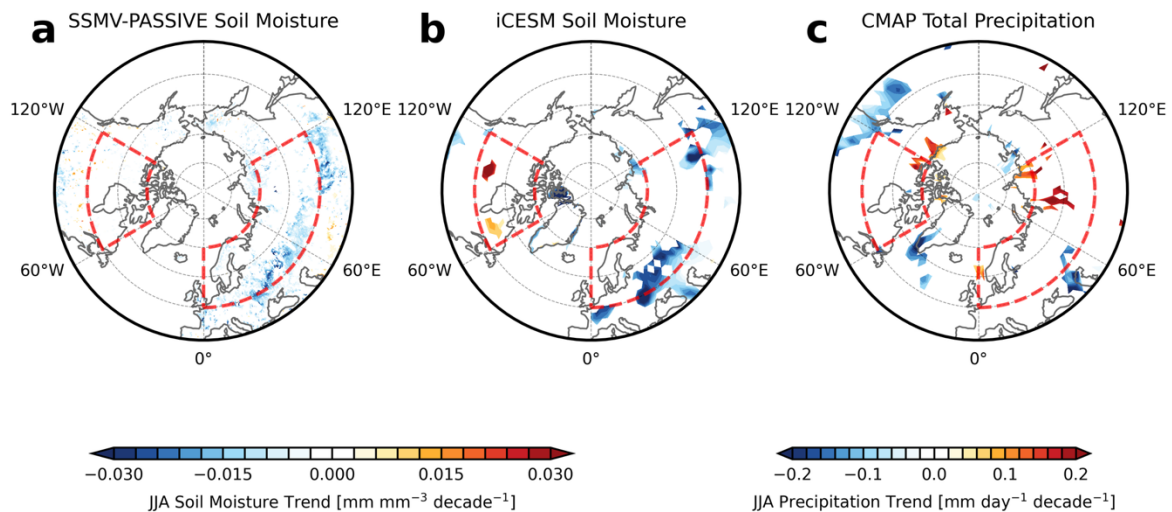


Figure R2 (Supplementary Fig. 2 in the text): Trends in soil moisture and precipitation. **a-b**, Linear trends (1981-2022) in June-July-August soil moisture in the upper 10 cm (representative of the total snow cover melt each year) from SMAP (**a**) and the iCESM nudged simulation (**b**). **c**, Linear trends (1981-2022) in CMAP total precipitation. Shading only shown for trends significant at the 95% confidence level according to a two-sided student t-test.

Some specific comments:

Line 21-23: the second part of this sentence seems incomplete.

Thank you for catching this. We have updated the sentence to complete the point that we were trying to make.

Original sentence (Lines 21-23):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, which represents a substantial research gap hindering attribution and detection of observed Arctic warming via in-season radiative effects and delayed impacts of moistening on sea ice loss and surface heat absorption.”

Revised text (Lines 21-23):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, which represents a substantial research gap hindering attribution and detection of observed Arctic warming via in-season radiative effects and delayed impacts of moistening on sea ice loss and surface heat absorption.”

Fig.1c,e: the significance test for the vectors (moisture transport) is also needed.

We have conducted a significance test for the vectors in Fig. 1c,e so that now the only vectors being shown are significant at the 95% confidence level following a two-sided student t-test. The updated figure and figure caption is included below:

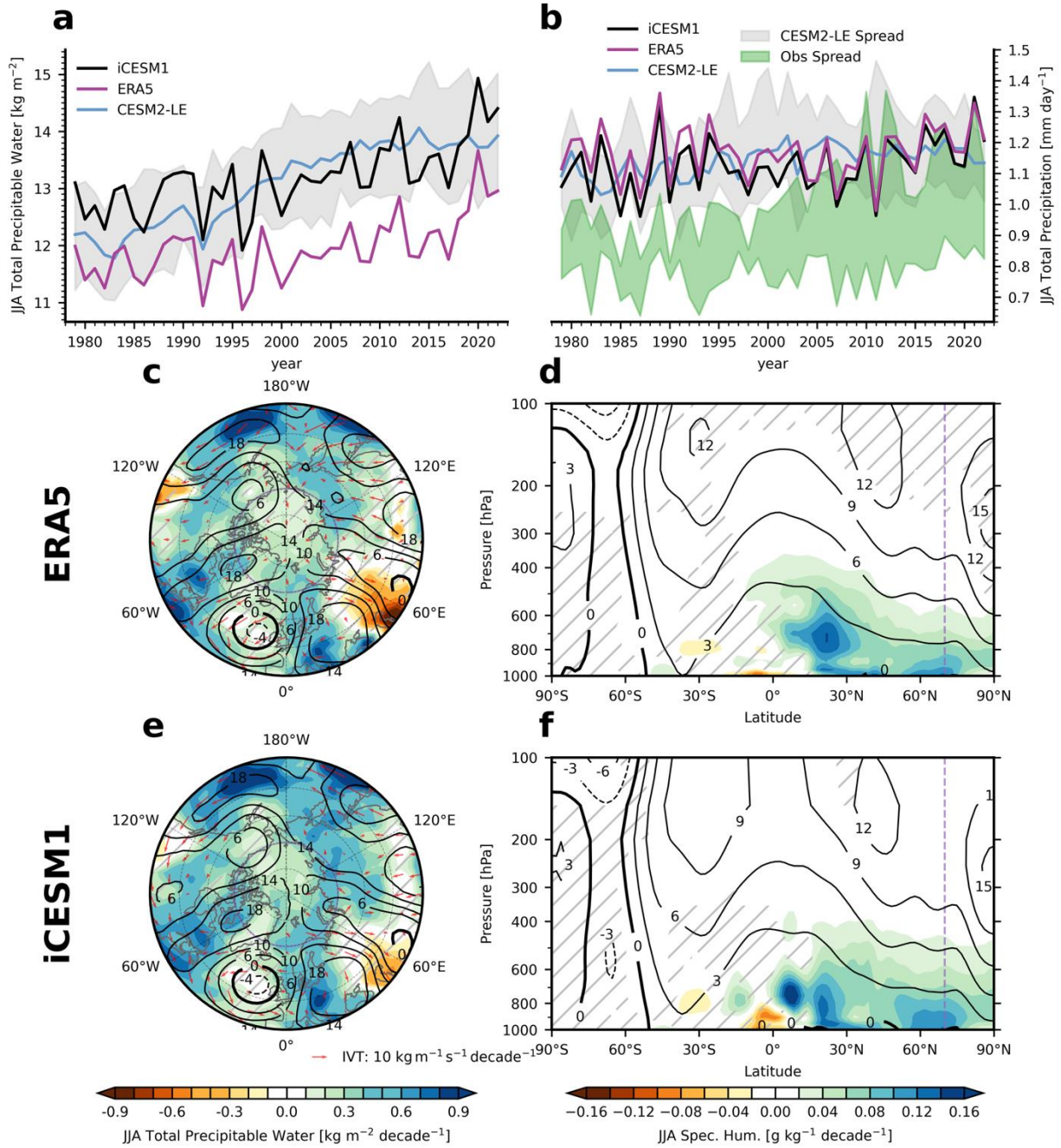


Figure 1. Variability and trends in moisture transport from nudged iCESM1 simulations and observation-based datasets. **a**, JJA total column precipitable water (i.e., vertically integrated specific humidity) (kg m^{-2}) within the Arctic ($70\text{--}90^\circ \text{N}$) from CESM2-LE (blue, grey shading), iCESM1 (black) and ERA5 (magenta) (**a**). **b**, JJA total precipitation (snow+rain, large-scale+convective) within the Arctic ($70\text{--}90^\circ \text{N}$) from the spread across observation-based precipitation products (green shading), iCESM1 (black), ERA5 (magenta), and the CESM2-LE (blue, grey shading) (**b**). **c,e**, 1981–2022 linear trends in total precipitable water (shading, $\text{kg m}^{-2} \text{decade}^{-1}$), 200 hPa geopotential height (contour, m decade^{-1}), and IVT (red vectors, $\text{kg m}^{-1} \text{s}^{-1} \text{decade}^{-1}$) from ERA5 (**c**) and iCESM1 (**e**). IVT vectors in panels **c,e** only shown where trends in total IVT are statistically significant at the 95% confidence level according to a two-sided student

t-test. **d,f**, 1979-2022 linear trends (calculated by linear regression) in zonal mean specific humidity (shading, $\text{g kg}^{-1} \text{ decade}^{-1}$) and geopotential height (contour, m decade^{-1}) from ERA5 (**d**) and iCESM1 (**f**). Vertical dashed line in panels (**d**) and (**f**) shows the 70° N line which we use as the southern boundary of the local Arctic region. Gray stippling in panels (**c-f**) indicates insignificant trends ($<95\%$ confidence level according to a two-side *t*-test) in total precipitable water or zonal mean specific humidity. Vectors are only shown if they are significant at the 95% confidence level following a two-sided student *t*-test.

Line 157-158: this sentence seems unnecessary.

We agree that the sentence was not necessary and have removed it.

Line 298: “a south asian high pattern” should be revised. South Asian High only exists in summer month.

Thank you for this comment. We have revised this phrasing, changing “South Asian High” to “upper-level high pressure pattern” because the South Asian High only exists during summer as pointed out.

Original text (Line 298-300):

“Between February and May, South Asian high pattern over low latitude Eurasia contributes to this rainfall trend over northern central Eurasia, diverting moisture from the Mediterranean poleward into northern central Eurasia (Supplementary Fig. 5d).”

Revised text (Line 298-300):

“Between February and May, an upper-level high pressure pattern over low latitude Eurasia contributes to this rainfall trend over northern central Eurasia, diverting moisture from the Mediterranean poleward into northern central Eurasia (Supplementary Fig. 5d).”

Fig4 a,c: the caption of the subplots indicate these panels show the source of moisture, while the colorbar describes precipitation trends. Please clarify the actual quantity being shown and ensure that the terminology is consistent between the captions, colorbars, and figure description in the main text.

We apologize for the confusion, as the phrasing between the figure and caption were unclear. To clarify this, we have adjusted figure titles in panels a,c. The titles now say, “Source of N. American/Eurasian precipitation”. We also show the same time periods (Winter-Spring) for both regions. The maps show the sources of precipitation into regions 47 (top row) and regions 43+44 (bottom row). The first blue bar in panels b and d, are the summation across all source regions shown in the maps (left column).

In order for the land surface to supply 40-yr trends of evapotranspiration and water vapor transport into the Arctic, it requires input from ocean sourced precipitation. In addition, the model is not currently able to track moisture through the land surface, therefore we are only able to quantify remote contributions to land moisture changes in the form of precipitation. Thus, the maps in this figure show the source regions where precipitation over NE North America (region 47) and western/central Eurasia (regions 43+44) originate from.

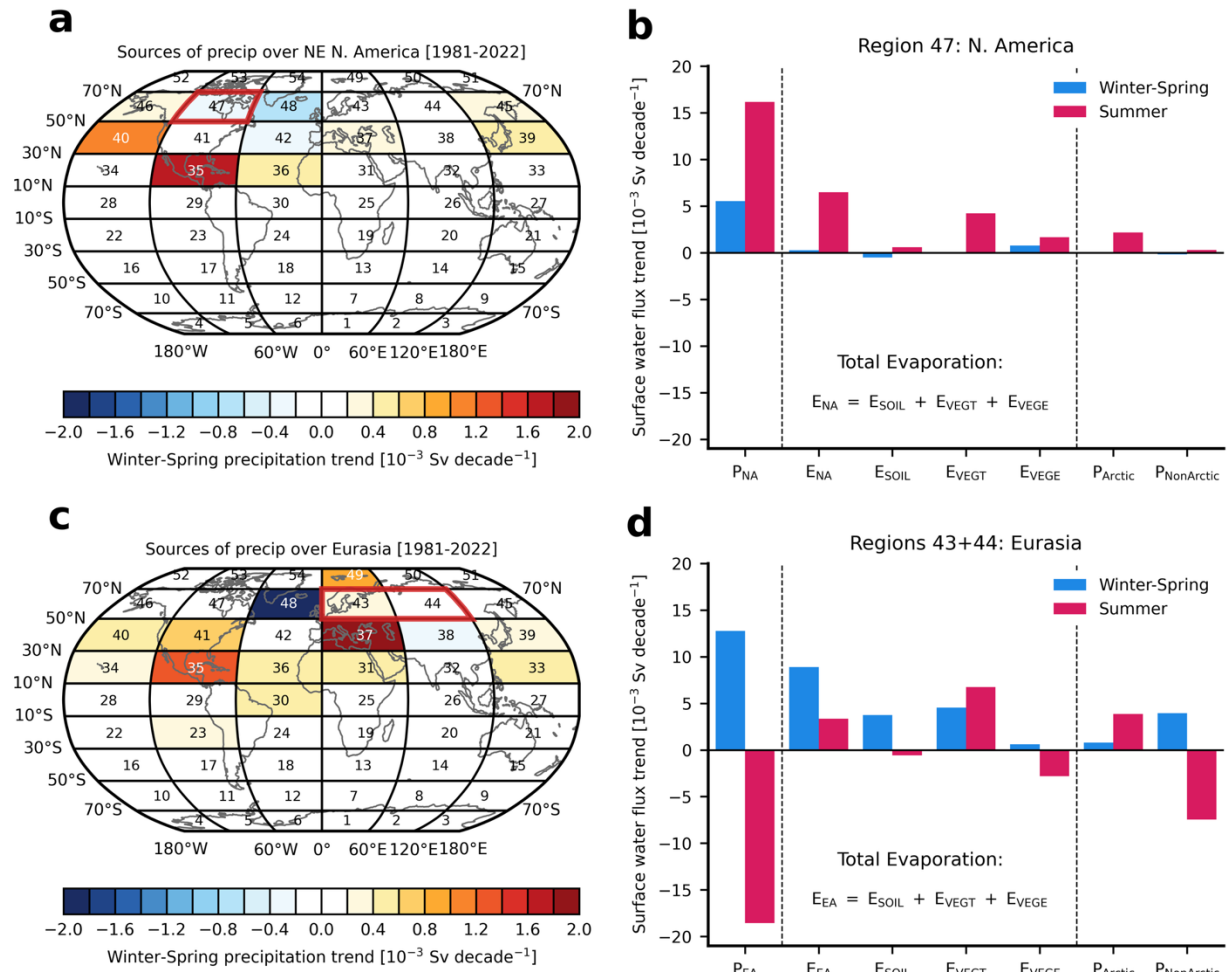


Figure 4. A land capacitor effect driven by tropical-midlatitude transport in spring and transpiration in summer. **a**, Linear trends (1981-2022, 10^{-3} Sv decade $^{-1}$) in precipitation accumulated between January-May that falls northeastern North America (region 47, red outlined box). Each grid cell shows the region from where each portion of the precipitation trend originated (**a**). **b**, Linear trends (1981-2022, 10^{-3} Sv decade $^{-1}$) in total precipitation (P_{NA}), total evaporation (E_{TOT}), soil evaporation (E_{SOIL}), vegetation transpiration (E_{VEGT}), and vegetation evaporation (E_{VEGE}) accumulated over January-May (winter-spring, blue bars) and June-August (summer, red bars) integrated over northeastern North America (50-70° N, 240-300° E, region 47, 10^{-3} Sv decade $^{-1}$), as well as precipitation originating from northeastern North America and falling over the Arctic (P_{Arctic}, 70-90° N) or all non-Arctic regions (P_{NonArctic}, 90° S-70° N). These trends show the moisture convergence (P_{NA} – E_{TOT}) over region 47 and the proportion of moisture evaporated from region 47 that is transported into the Arctic (P_{Arctic} vs. P_{NonArctic}) (**b**). **c-d**, Same as panels **a-b** but for the western and central European region (region 43+44). Shading in (**a**) and (**c**) only shows statistically significant trends at the 95% confidence level using a two-side t-test. Positive trend values in (**b**) and (**d**) indicate increasing precipitation and increasing evaporative fluxes.

Reviewer #2 (Remarks to the Author):

This paper aims to identify the sources of recent Arctic moistening trends, attribute Arctic warming through radiative effects, and analyze the influence of moisture transport from the tropics, particularly via land surface processes, on sea ice loss and surface heat absorption. Data used include reanalysis data from ERA5, output from the Community Earth System Model versions 1 and 2 (iCESM1 and CESM2), and observation-based precipitation products.

The study employs a combination of water tagging and circulation nudging techniques to identify the sources of recent summer Arctic moistening trends. It uses iCESM and radiative kernels built using ERA5 and the CAM5. To analyze atmospheric river (AR) events, the Guan and Waliser (2015, 2019) tracking algorithm is used however limited details of this method are offered in the manuscript. The contribution to Arctic moisture changes from individual regions is determined by computing an Arctic mean of total precipitable water evaporated from the 55 tagging regions.

The study focuses on the summer season, and finds increased moisture transport from the tropics and mid-latitudes, particularly via increased evapotranspiration from land, which significantly contributes to Arctic moistening and warming. This increased moisture amplifies warming through in-season radiative effects and contributes to sea ice loss, highlighting the importance of land surface processes in driving Arctic change. Additionally, the study suggests that current climate models may underestimate the influence of land-sourced moisture on Arctic moistening.

Aspects of the manuscript I find unique to the best of my knowledge include the use of the "land capacitor effect", which the authors describe as the tendency of high-latitude land to store and recycle lower-latitude moisture to the Arctic, contributing to Arctic moistening. The paper highlights the crucial role of plant evapotranspiration and the tropical Atlantic/Caribbean as key sources in this land-driven moisture transport to the Arctic, in addition to highlighting the role of remote land-based moisture transport in Arctic water vapor radiative feedback, which potentially has a more important role than local ocean evaporation.

Limitations of the current study include the heavy reliance on model simulations, despite observational nudging using ERA5 data. Results are still subject to model biases that most likely impact the results presented. The water tagging technique is also subject to limitations of model physics and parameterization as pointed out by the authors themselves. Finally, some of the conclusions are based on correlations and statistical relationships. While these suggest strong connections between the identified processes, they do not definitively prove causation.

Overall, I found the paper to be well written, results are presented clearly and framed within the context of the current literature. I was not familiar with the "land capacitor"

effect prior to this, in addition to water tagging, and perhaps a small criticism would be the authors to offer even a brief summary of the methodologies of such techniques in the current manuscript. I found the results associate with the percent attribution of precipitation trends to different regions difficult to follow. A minor comment is to revise some of the figure captions for clarity, specifically figure 4, which I find difficult to follow after multiple reads.

I would recommend for publication subject to these minor comments.

Thank you for your thorough comments. Below are the modifications and responses to the comments.

1. Additional discussion of the limitations of our experimental setup, particularly the heavy reliance on the model simulations has been added. This focus on the model simulations is due to the large uncertainty in observational products and substantial biases in both reanalysis and global climate model simulations. While with wind and temperature nudging in the iCESM we find generally good agreement between the two products in terms of year-to-year variability and long-term trends of total column water vapor and moisture transport, the results are still very susceptible to biases in cloud physics, land surface, plant physiological processes and ocean components.

Revised text (Lines 417-420):

“However, much of the analysis here is focused on the nudged simulations, and studies that build on this framework by further integrating model simulations and observations is necessary to better account for model biases (i.e., cloud physics, land surface, plant physiological processes and ocean components).”

2. We have added a brief summary of the methodologies in the introduction. This has focused on a more in depth discussion of the tagging and how we use it to show the land capacitor effect. This addition complements nicely changes made following the comments by Reviewer #3, where we have added a description of the land capacitor effect and the context upon which we decided this naming. We have also added some more detail in the introduction broadly discussing the water tagging approach.

Revised text (Lines 179-182):

“As poleward transport trends are concentrated along narrow pathways over Eurasia and Greenland (Fig. 1c,e)⁴⁷, we calculate the amount of simulated Arctic moistening resulting from atmospheric river (AR) events, defined using the Guan and Waliser (2015, 2019)^{48,49} tracking algorithm, which utilizes a threshold detection approach based on seasonally dependent extreme (>85th percentile) total integrated vapor transport^{48,49} (See Methods).”

Revised text (Lines 101-103):

“Water tagging enabled models address these previous limitations by directly tracking water vapor parcels from evaporation and following them through all atmospheric processes to when they are precipitated out at the land or ocean surface.”

3. Added additional details about the Guan & Waliser (2019) AR detection algorithm

Revised text (Lines 179-182):

“As poleward transport trends are concentrated along narrow pathways over Eurasia and Greenland (Fig. 1c,e)⁴⁸, we calculate the amount of simulated Arctic moistening resulting from atmospheric river (AR) events, defined using the Guan and Waliser (2015, 2019)^{49,50} tracking algorithm, which utilizes a threshold detection approach based on seasonally dependent extreme (>85th percentile) total integrated vapor transport^{49,50} (See Methods).”

4. Modifications made to clarify the percent contributions from individual regions (1-54) to changes in NE. North American (region 47) and Eurasian (regions 43+4) precipitation. The figure has also been rotated to place the regions of interest towards the center

Original text (Line 186-200):

“To understand the contribution of each source region, we focus on the source contributions to both mean and trends in JJA Arctic averaged (70-90°N) total precipitable water. Consistent with previous water tagging studies, we find a leading contribution being sourced from a narrow band between 50-70°N for both the mean (7.50 g m⁻², 46.6%) and in the long-term trends (1981-2022, 1.63 g m⁻² decade⁻¹, 41% when normalized by area) (Fig. 2)^{29,35}. This 50-70°N band includes a large contribution from the North American land mass, contributing 7.67% (7.40% normalized) to the mean and 0.329 g m⁻² decade⁻¹ or 16.1% (9.73% normalized) to the 1981-2022 trends. This strong influence of North America has not been identified in previous simulations examining poleward moisture transport without nudging, which are only forced by various external radiative forcing.

The 44-yr trends in source-region contributions to Arctic WV show some similar relationships as their mean contribution, with the strongest contributions coming from Northern Hemisphere land masses, particularly northern Europe, central Eurasia, and northeastern North America (Fig. 2b). Remote sources account for 84.2% (62% of total from land) of the moistening trend over the Arctic in the last 4 decades. These trends show less emphasis on Siberia and Alaska, as well as a decreased importance of the midlatitude oceans, especially northern extensions of these regions. Locally, there is a strong normalized increase in moisture coming from the Kara Sea and Canadian Arctic Archipelago regions.”

Revised text (Line 208-221):

“To understand the contribution of each source region, we focus on the source contributions to both mean and trends in JJA Arctic averaged (70-90° N) total precipitable water. Consistent with previous water tagging studies, we find a leading contribution being sourced from a narrow band between 50-70°N for both the mean (7.50 g m⁻², 46.6%) and in the long-term trends (1981-2022, 1.63 g m⁻² decade⁻¹, 41%) (Fig. 2)^{29,35}. This 50-70°N band includes a large contribution from the North American land mass, contributing 7.40% to the mean and 0.329 g m⁻² decade⁻¹ or 9.73% to the 1981-2022 trends. This strong influence of North America has not been identified in previous simulations examining poleward moisture transport without nudging, which are only forced by various external radiative forcing.

The 44-yr trends in source-region contributions to Arctic WV show some similar relationships as their mean contribution, with the strongest contributions coming from Northern Hemisphere land masses, particularly northern Europe, central Eurasia, and northeastern North America (Fig. 2b). Remote sources outside the Arctic (south of 70° N) account for 84.2% (62% of total from land) of the moistening trend over the Arctic in the last 4 decades. These trends show less emphasis on Siberia and Alaska, as well as a decreased importance of the midlatitude oceans, especially northern extensions of these regions. Locally, there is a strong normalized increase in moisture coming from the Kara Sea and Canadian Arctic Archipelago regions.”

5. We have added more description to the precipitation trends section to help guide the reader through the figure.

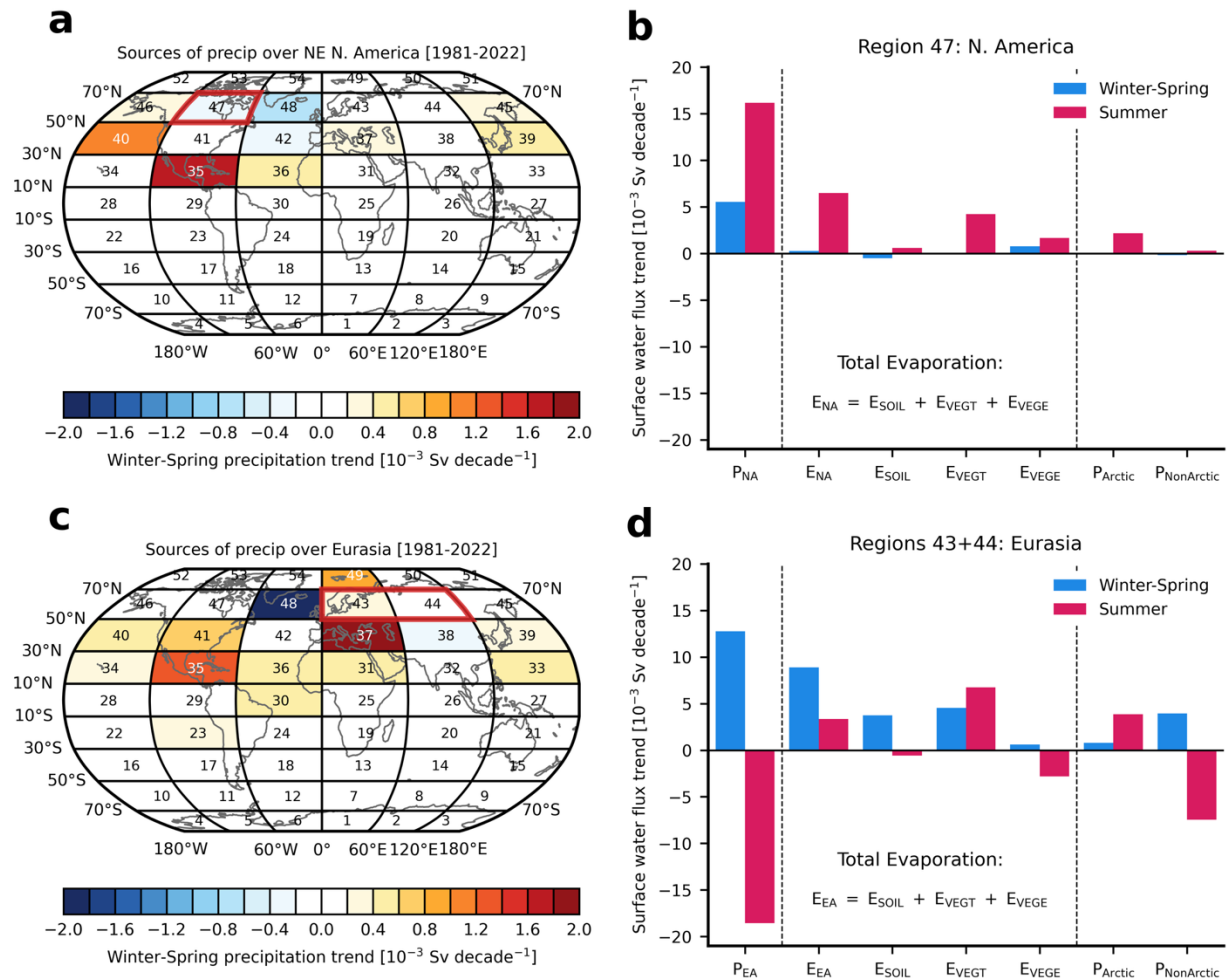


Figure 4. A land capacitor effect driven by tropical-midlatitude transport in spring and transpiration in summer. a, Linear trends (1981-2022, 10^{-3} Sv decade $^{-1}$) in precipitation accumulated between January-May that falls northeastern North America (region 47, red outlined box). Each grid cell shows the region from where each portion of the precipitation trend originated (a). **b,** Linear trends (1981-2022, 10^{-3} Sv decade $^{-1}$) in total precipitation (P_{NA}), total evaporation

(E_{TOT}), soil evaporation (E_{SOIL}), vegetation transpiration (E_{VEGT}), and vegetation evaporation (E_{VEGE}) accumulated over January-May (winter-spring, blue bars) and June-August (summer, red bars) integrated over northeastern North America (50-70° N, 240-300° E, region 47, 10^{-3} Sv decade⁻¹), as well as precipitation originating from northeastern North America and falling over the Arctic (P_{Arctic} , 70-90° N) or all non-Arctic regions ($P_{NonArctic}$, 90° S-70° N). These trends show the moisture convergence ($P_{NA} - E_{TOT}$) over region 47 and the proportion of moisture evaporated from region 47 that is transported into the Arctic (P_{Arctic} vs. $P_{NonArctic}$) (**b**). **c-d**, Same as a-b but for the western and central European region (region 43+44). Shading in (**a**) and (**c**) only shows statistically significant trends at the 95% confidence level using a two-side t-test. Positive trend values in (**b**) and (**d**) indicate increasing precipitation and increasing evaporative fluxes.

Reviewer #3 (Remarks to the Author):

Review of Baxter et al “Water sources and land capacitor effects driving observed summer Arctic moistening and warming”

Overall recommendation: Reject

This manuscript examines seasonal atmospheric moisture transport from the tropics to the Arctic and attempts to identify the underlying land surface source regions which supply water vapor to the atmosphere through processes of evaporation and evapotranspiration. The authors employed several datasets, including ERA5 reanalysis and a host of gridded soil and precipitation products, along with a host of numerical simulations and experiments conducted with the Community Earth System Model CESM. Several CESM simulations incorporated nudging and included a water tagging capability for tracking atmospheric water vapor and identifying moisture source regions. Results are presented primarily in form linear trends for gridded regional source region zones. Moisture trends in each zone are also partitioned in terms of their radiative percent contribution to warming in the Arctic. While I find the topic of land surface moisture source regions in relation poleward moisture transport quite interesting, I do have major concerns with the manuscript in its current form, in particular (1) quality of the writing and (2) descriptive clarity of the data/models and analysis as presented. I also believe additional analysis would better support the authors claims regarding moisture source regions. With the following comments, I provide some examples of these concerns. I do think the authors could improve the manuscript, but it would require extensive revisions. My overall recommendation is to reject the manuscript at this time.

We appreciate your suggestions in regard to improving the quality and clarity of the writing in our manuscript. To address these concerns, we have thoroughly reorganized and rewritten the “Data and Methods” sections. This has entailed:

1. Reordering the sections and clarifying the discussion of each dataset and method to reflect that in the main body text.
2. Ensuring that datasets or models are not referred to prior to being fully introduced and defined.

3. We have provided a roadmap below to organize and summarize our presentation of the data and methods. A concise roadmap summarizing the structure of the manuscript has been added to the end of the introduction:

Additional text (Lines 123-126):

“In the following sections, we first present our analysis of the moistening trends and the corresponding pathways simulated this nudging simulation, then assess the role of land processes across the two primary source regions in contributing to the moistening. Finally, we conduct a kernel analysis of the radiative impacts of this moistening that can be attributed to each source region.”

Major Comments:

1. Abstract.

Line 21: First sentence after “uncertain,” is not coherent.

Thank you for mentioning this. This was also noted by Reviewer #1 and the revision is detailed below.

Original sentence (Lines 21-23):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, which represents a substantial research gap hindering attribution and detection of observed Arctic warming via in-season radiative effects and delayed impacts of moistening on sea ice loss and surface heat absorption.”

Revised text (Lines 21-23):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, hindering attribution of observed Arctic warming due to radiative effects from water vapor changes.”

Line 24: “land capacitor processes”, what are land capacitor processes? The word capacitor is awkward in this context, rephrase throughout or explain clearly what is meant by land or ocean capacitor effect when the phrase is first introduced.

Thank you for this comment. We had not previously defined what we refer to as the “land capacitor” or “land capacitor effect”, until the following sentence. The phrase in question has been modified:

Original text (Line 24):

“land capacitor processes”

Revised text (Line 24):

“land surface processes”

Line 26: “traveling from the tropics to the Arctic by passing through the high latitude land

surface”, passing through? The air is moving above or across the land surface.

We agree that this phrasing does not appropriately describe the actual process. This phrase has been revised to suggest that moisture is transported poleward through the atmosphere and recycled along this path through the land surface.

Original text (Line 26):

“... traveling from the tropics to the Arctic by passing through the high latitude land surface”

Revised text (Line 26):

“... traveling from the tropics to the Arctic, with their moisture being recycled along the way through the high latitude land surface”

In general, when one reads the abstract, it should give a clear and concise description of the overarching theme of the manuscript, analysis performed, and key results. In its current form, it is too scattered and unclear.

We appreciate this comment. Revisions to the abstract structure have been made to highlight the organization and key points of the manuscript.

Original text (Lines 21-34):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, which represents a substantial research gap hindering attribution and detection of observed Arctic warming via in-season radiative effects and delayed impacts of moistening on sea ice loss and surface heat absorption. Using combined water tagging and circulation nudging techniques, we find that trends in Northern Hemisphere summertime large-scale circulation and land capacitor processes drive moistening over recent decades. Trends in circulation direct atmospheric rivers (ARs) poleward, traveling from the tropics to the Arctic by passing through the high latitude land surface, referred to as a land capacitor effect. This transport has a large impact on the Arctic radiative budget, accounting for 94% of the increasing water vapor radiative feedback. A North American pathway originates from the tropical Atlantic, transported poleward by anticyclones over the subtropics and Greenland, released through summertime evapotranspiration over northeastern North America. In contrast, overlying anticyclonic circulation over central Eurasia enhances evapotranspiration and redistributes moisture previously deposited during the preceding winter and spring. Thus, the impacts of large-scale circulation changes on ARs and diverse land-atmosphere interactions over high latitudes represent the underlying mechanisms of the recent moistening and warming in the Arctic and sub-Arctic regions.”

Revised text (Lines 21-32):

“The primary sources of recent summer Arctic moistening trends in reanalysis are uncertain, hindering attribution of observed Arctic warming due to radiative effects from water vapor changes. Here we use a combined online numerical water tracer and circulation nudging approach in the Community Earth System Model to track the sources of water vapor beyond its initial sources. Trends in boreal summer large-scale circulation have driven moistening of the Arctic over recent decades, having a large impact on the Arctic radiative budget, accounting for 94% of the strengthening water vapor radiative feedback. We identify two key regions supplying

the Arctic water vapor feedback: Northeast North America and western/central Eurasia. In both regions, anticyclonic circulations over the southwest Atlantic and eastern Europe move moisture from the tropical oceans poleward to high latitude land through precipitation in winter and spring. During summer, evapotranspiration over land releases this water vapor and it is transported by winds into the Arctic. We refer to this sequence of terrestrial moisture storage and release as the land capacitor effect. Thus, the impacts of circulation changes on poleward moisture transport and land-atmosphere interactions over high latitudes represent the underlying mechanisms of the recent moistening and warming in the Arctic.”

2. Introduction. The writing is better in this section.

Line 47: “this phenomena”. Plural form used but the reference is singular. Phenomenon?
See Line 54: “However these phenomena”

Thank you. This has been corrected.

Original text (Line 48):
“phenomena”

Revised text (Line 48):
“phenomenon”

Line 57: “such as water vapor”, water vapor is parameter not a process. Rephrase.

Thank you, part of this sentence was lost at some point. It has been corrected to be a process not a parameter.

Original text (Line 57-58):
“thus it can be argued that to make systematic progress in constraining the future rate of Arctic Amplification we should focus on specific processes that lead to sea ice decline and surface warming, such as water vapor”

Revised text (Line 57-58):
“thus it can be argued that to make systematic progress in constraining the future rate of Arctic Amplification we should focus on specific processes that lead to sea ice decline and surface warming, such as the water vapor feedback”

Line 100: “The conclusions that terrestrial sources are the dominant contributing regions in summer...”

Is the above statement accurate when referencing the studies cited, i.e., terrestrial sources are the dominant contributors? Perhaps terrestrial sources are amplified in summer but not dominant, at least in terms of moisture?

In the most comparable model simulation to ours (i.e., Harrington et al. 2021 with the same base isotope-enabled CESM1), they find that in summer 56% of the moisture in the Arctic is sourced from terrestrial sources, especially those close to the Arctic. This study used the free-running iCESM and evaluated equilibrium climate changes. The model will have its inherent biases in

moisture sources and transport, therefore there is no certainty that the contributions from terrestrial or ocean sources to Arctic water vapor are indicative of that in reality.

Line 102: “we explore the transport of moisture from the tropics to the Arctic via the land surface – which we refer to as a land capacitor effect

“via the land surface”, rephrase

Original text (Line 102):

“via the land surface”

Revised text (Line 102):

“In this study, we explore the transport of moisture from the tropics to the Arctic and its recycling through the land surface as it is transported poleward – which we refer to as a land capacitor effect – to reconcile results from water tagging studies with meridional heat and energy transport in radiative frameworks”

This is the first description of the land capacitor effect. A clearer description is needed, and it should come earlier on. Does land capacitor effect represent the transfer of heat and moisture from the land surface to the atmosphere and vice versa? If so, perhaps the authors should explore the land surface latent and sensible heat fluxes in addition to the evaporation.

Thank you for these suggestions. We have expanded our description of the land capacitor effect in the introduction and moved it to earlier in the section:

Original text (Lines 93-104):

“The key finding in these studies is generally that the local changes in atmospheric water vapor and precipitation associated with decreased sea ice cover and increased evaporation only explain a limited fraction of the simulated changes ^{31–36}. Rather, they highlight the contributions from remote terrestrial sources as playing a leading role in increasing Arctic water vapor during boreal summer, though these conclusions are based on idealized frameworks derived from climate model simulations ²². Differences in the sources of moisture transport are known to have a wide range of impacts on humidity, clouds, and radiation upon entering the Arctic ³⁵, however it is still uncertain how these sources have contributed to trends in Arctic water vapor and their radiative impacts over the reanalysis era. The conclusions that terrestrial sources are the dominant contributing regions in summer do not necessarily reconcile themselves with studies of meridional heat and energy transport that implicate warming and moistening in the tropics for increased poleward moisture transport.

In this study, we explore the transport of moisture from the tropics to the Arctic via the land surface – which we refer to as a land capacitor effect – to reconcile results from water tagging studies with meridional heat and energy transport in radiative frameworks.”

Revised text (Lines 79-90):

“A key result of these tracking studies is that local changes in atmospheric water vapor and precipitation are not associated with decreased sea ice cover and increased evaporation^{27–32}. Rather, these studies tend to highlight the contributions from remote terrestrial sources as playing a leading role in increasing summer Arctic water vapor, though these conclusions are based on idealized frameworks derived from climate model simulations^{22,31,33}. Due to limitations related with internal variability in free-running model simulations, these previous studies have not been able to diagnose the terrestrial contribution to a continually increasing long-term trend in Arctic water vapor over the historical period³⁴. For these terrestrial moisture sources to be capable of fueling the observed wetting trend of the Arctic would require a reduction in the bias associated with internal variability in climate models and a mechanism by which the land surface could maintain transport of moisture into the Arctic over four decades. In this study, we explore the transport of moisture from the tropics to the Arctic and its recycling through the land surface as it is transported poleward, or the land capacitor effect, to reconcile results from water tagging studies with meridional heat and energy transport in radiative frameworks.”

We appreciate the suggestion to examine latent heat fluxes. We had previously presented evaporation in Sverdrup units. This was to facilitate direct comparison with previous water tagging studies that had reported their findings in Sverdrups.

While examining sensible heat fluxes would also be very interesting in the context of poleward heat transport, this is somewhat outside the scope of this study, despite potentially being important contributors to Arctic warming. The tool that we are focused on is the water tagging capability in the isotope-enabled Community Earth System Model (iCESM). Therefore, we prefer to focus latent heat fluxes in the form of evaporation and quantify their contribution through the water vapor feedback.

3. Results

As I start reading the results, interpretation is problematic, and the writing is hard to follow. I believe this is because the writing in the Materials and Methods section lacks clarity and lacks sequential structure. The results and Methods are not well connected. Thank you for your suggestion on improving the clarity of our presentation. We have restructured some aspects of the Results section following comments from other reviewers.

4. Material and Methods

The explanation of the ERA5 dataset starts off well, however, atmospheric rivers are mentioned on Line 402. I know ARs were mentioned in the abstract, but not in the introduction. So, moisture transport is examined by itself or in the form of atmospheric river events or both?

We have reorganized the description of AR detection and tracking so that it is now in the Methods subsection. We have also more thoroughly clarified in the main text when we are examining moisture transport (in the form of integrated vapor transport) or in ARs.

Revised text (Lines 159-168):

“As poleward transport trends are concentrated along narrow pathways over Eurasia and Greenland (Fig. 1c,e) ⁴⁸, we calculate the amount of simulated Arctic moistening resulting from atmospheric river (AR) events, defined using the Guan and Waliser (2015, 2019) ^{49,50} tracking algorithm, which utilizes a threshold detection approach based on seasonally dependent extreme (>85th percentile) total integrated vapor transport^{49,50} (See Methods). The JJA total precipitable water trends in the Arctic associated with ARs is consistent with poleward IVT along the aforementioned pathways, contributing 2.56 g m⁻² decade⁻¹ or 77.4% of the total trend (See Methods). Using JJA troposphere mean specific humidity or poleward zonally integrated IVT at 70° N yields contributions of 0.047 g kg⁻¹ decade⁻¹ (80.0%) and 9.22 million kg m⁻¹ s⁻¹ (66.8%), respectively. Contributions of ARs to total poleward IVT along 70° N over western Greenland, northern Europe, and central Eurasia is 3.16 million kg m⁻¹ s⁻¹ decade⁻¹ (65.2%), 0.67 million kg m⁻¹ s⁻¹ decade⁻¹ (73.0%), and 3.08 million kg m⁻¹ s⁻¹ decade⁻¹ (95.5%), respectively (magenta boxes in Fig. 2a).“

Line 411: “For AR detection we use daily output from the iCESM1...”

iCESM1 data has not been described yet. This miss-order of writing and description occurs throughout the methods section (and in several other instances throughout the manuscript) and this makes the writing extremely difficult to follow. Perhaps a flow diagram figure could be included that explicitly provides a roadmap of the analysis, datasets, experiments etc.. Then, results could be presented in reference to this roadmap figure.

We have addressed this specific miss-ordering of references and its related sequence in the main text by moving the AR detection description to a Methods subsection on its own. Now it is after the descriptions of the datasets or products and model simulations. A flow chart reflecting this is included below.

Revised text (Lines 491-512):

“Methods

Atmospheric River Detection

While 6-hourly data is ideal for examining atmospheric rivers (ARs), the highest frequency the iCESM1 output were archived at was daily mean timesteps. We find the overall pathways and trends in frequency on seasonal mean timescales are consistent between the 6-hourly ERA5 and daily mean iCESM1 data.

ARs are detected and tracked using the Guan and Waliser (2019) ⁵⁰ tARget v3 AR detection and tracking algorithm. It is an updated version of Guan and Waliser (2015) ⁴⁹, one of the earliest and most widely used AR detection tools. The tARget algorithm has been recommended by the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) as a scheme suitable for both global and regional studies, particularly regions with climatologically low IVT such as the high latitudes ⁵⁴, due to the season- and location-dependent AR thresholds used in this algorithm.

For AR detection we use daily output from the iCESM1 simulations and 6-hourly outputs from the CESM2-LE and ERA5. The contributions and magnitudes of AR frequency and poleward IVT between ERA5 and iCESM1 are nearly identical, even despite using daily output from iCESM1 for AR detection and tracking. We calculate the AR contribution to Arctic (70-90° N) TMQ (Equation 1), 300-1000 hPa mean specific humidity or poleward IVT at 70° N using the AR mask determined by the Guan and Waliser (2019) ARDT algorithm. The AR mask is

expanded by 6 degrees in all directions to account for the potential spatial influence of the events. Since water vapor and precipitation impacts associated with ARs can precede or lag an event by a day, we also extend the grid points flagged as an AR by one day before formation and one day after termination. All grid points that fall within these expanded AR shapes or masks are considered to be associated with an AR event. We then compute JJA means using total, AR only, and non-AR TMQ, specific humidity and 70° N poleward IVT. The differences using TMQ or specific humidity are small. The AR contribution to Arctic moistening is then determined by the ratio of AR associated TMQ/specific humidity/IVT trends divided by the total trend over 1981-2022.”

We have also included below a flow chart, detailing the structure of our manuscript for reference. The flow chart reflects the reorganized structure of the main text and methods sections. The Methods section is organized based on the flow of the main text as well into sections based on the type of product or methodology, with each individual dataset or methodology labeled in its own subsection.

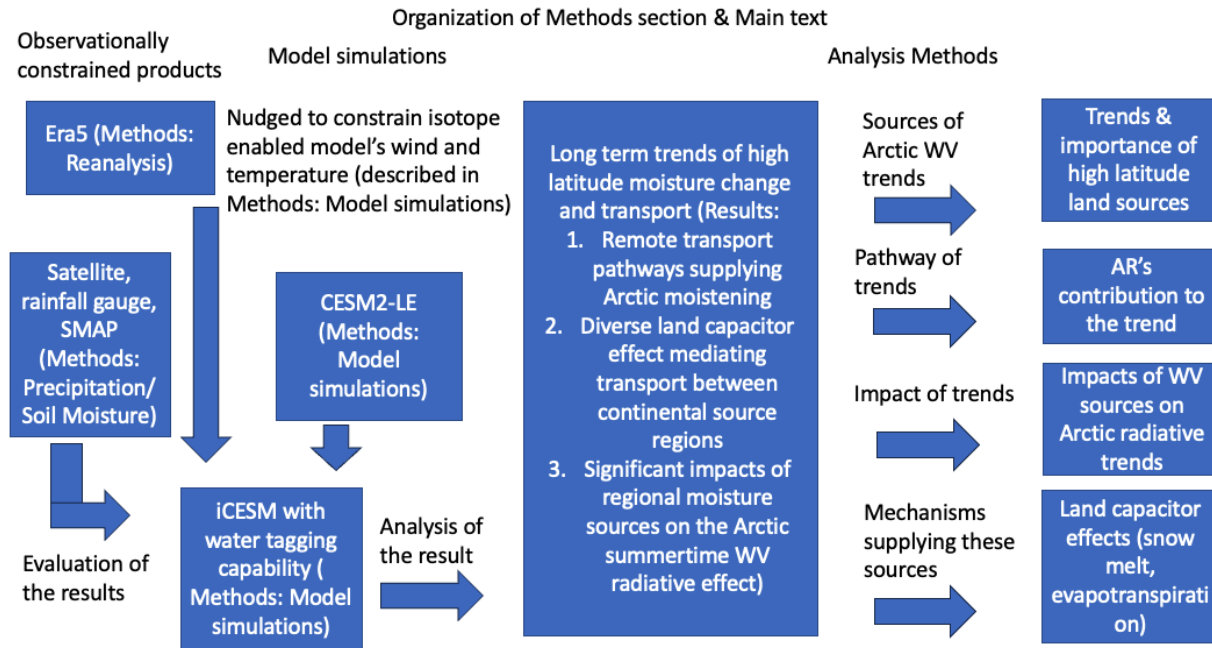


Figure R2. Flowchart organizing structure of Main text and Methods section.

I wish I could be more positive. On a positive note, the figures are high quality.

We appreciate your efforts and those of the other reviewers. We hope that the revisions made in accordance with your comments have addressed your concerns.

REVIEWERS' COMMENTS:

Thank you to the reviewers for their efforts. We have revised the text to clearly describe the iCESM1 experiment setup (number of realizations) and clarified this point in the phrasing throughout the text. Below the reviewer comments are in bold blue and the responses/revisions to each comment are in black.

Reviewer #1 (Remarks to the Author):

I have carefully reviewed the revised manuscript and am satisfied with the authors' responses to the previous comments. The revisions have adequately addressed the concerns raised, and I have no further suggestions. I recommend the manuscript for publication in its current form.

Thank you for your efforts in helping to improve the clarity and presentation of our manuscript. We hope that you are satisfied with our additional revisions.

Reviewer #3 (Remarks to the Author):

Second review of Baxter et al "Water sources and land capacitor effects driving observed summer Arctic moistening and warming"

I thank the authors for addressing my comments. I do think, in general, the manuscript is improved. The abstract and introduction read well. The significance statement reads with some phrasing that a non-expert might struggle with which could be improved with minor edits. However, despite the manuscript improvements, I still struggle with the methods description, in particular the lack of explanation of the model simulations and experiments performed with iCESM1. This lack of explanation carries into the results and the discussion and makes interpretation problematic.

We are very appreciative of the suggestions to improve the readability and organization of the manuscript. Additional revisions have been made to better describe the iCESM1 model experiment setup. Namely we have rephrased the text to clearly state that we have only run a single realization with the tagging and nudging implemented. Justification for the use of a single member has been added to the Methods section where discuss the iCESM1 setup. Previous studies have shown that internal variability in the climate system mainly arises from a wide range of atmospheric circulation variations across multiple time scales. (Deser et al. 2020). Therefore, to reflect the ensemble spread resulting from such variability, multiple realizations (also called ensemble members) are typically required, regardless of how the external forcing is prescribed. However, in our model configuration, model's wind and temperature fields are closely constrained by ERA5 (surface to top of atmosphere)), leaving no room for member to member spread to develop. Thus, no matter how many realizations we could generate, all these simulations would be close to identical and produce very similar tagging results.

Below we provide the updated text for the Methods section:

Updated text:

Lines 489-493: “A single simulation is run from 1979 to 2022 (with 2 years of spinup), with the model nudged to ERA5 horizontal winds (u, v) and temperature throughout the atmosphere, and specific humidity in the lowest model level nearest the surface. In previous studies, such as Ding et al. (2022)³⁷, the constraints imposed by the nudging (u, v, and T) result in very little member to member spread. For this reason, we only examine only this single iCESM1 realization.”

Comments:

Significance statement:

Line: 36-38:

Suggest rephrasing:

“By combining nudging and water isotope tagging approaches to explicitly track water vapor we are now able to directly track transport trends over the reanalysis period.”

To:

“By utilizing numerical techniques such as nudging to observations and isotope tagging for water vapor, moisture transport trends can be directly evaluated over space and time.”

Updated to suggested phrase.

Updated text:

Lines 36-38: “By utilizing numerical techniques such as nudging to observations and isotope tagging for water vapor, moisture transport trends can be directly evaluated over space and time.”

Line 39-40:

Suggest removing the phrase:

“via a land capacitor effect”

Updated text:

We have removed this phrase.

Introduction:

Line 123:

Revise phrase: “pathways simulated this nudging simulation”

Updated text:

Lines 121-122: “we first present our analysis of the moistening trends and the corresponding pathways the contribute to Arctic moistening in this nudging simulation”

Line 124:

Suggest rephrasing: “the two primary source regions”

To:

“primary source regions” as the existent of two

is a result of your analysis.

Updated text as suggested.

Original text:

Lines 121-124: “In the following sections, we first present our analysis of the moistening trends and the corresponding pathways the contribute to Arctic moistening in this nudging simulation, then assess the role of land processes across *the two primary source regions* in contributing to the moistening, and finally conduct a kernel analysis of the radiative impacts of this moistening that can be attributed to each source.”

Updated text:

Lines 121-124: “In the following sections, we first present our analysis of the moistening trends and the corresponding pathways the contribute to Arctic moistening in this nudging simulation, then assess the role of land processes across *two primary source regions* in contributing to the moistening, and finally conduct a kernel analysis of the radiative impacts of this moistening that can be attributed to each source.”

Model simulations

Nudged, water isotope enabled simulations: This section reads fine until Line 475. The CAM5.3 is introduced early on, but POP2 and CICE4 are not. I can examine the references cited [e.g., 60, 38, 39] which provide detailed information. However, there should be some small explanation of the POP2 and CICE4 sub models provided here.

Additional detail of the model components has been added so that one can interpret any discussion of these components as comparable to the CESM1 Large Ensemble.

Updated text:

Lines 475-478: “The same ocean (POP2) and sea ice model (CICE4) components used in the CESM1-LE ⁶⁶ are also run on the nominal 1° resolution grid with displaced poles over Greenland and Antarctica. However, the iCESM experiment is run in an “atmosphere-land only configuration” with prescribed monthly sea surface temperatures and sea ice concentrations taken from ERA5 that are remapped to the iCESM1 ocean model grid.”

Line 477, “these experiments”. No details of the experiments are discussed. Again, do I revisit the references to understand what experiments were done? Which experiments are

used in this study? There should be some explanation of “these experiments” and what they represent. Connecting this lack of explanation to the results, Line 129 “The iCESM1 simulations with atmospheric nudging...”. Which simulations or experiments are shown here? In Figure 1a, does the black curve (iCESM1) represent one experiment or is it a mean of several? This lack of explanation translates throughout the results and makes interpretation problematic because there is no clear description of the iCESM1 experiments used in this study.

iCESM1 Experimental Design, As I read Lines 487-492, I get the sense that there’s one iCESM1 simulation (nudged to ERA5 for u, v, and T) to be used after evaluating the sensitivity of the lowest model specific humidity; is this accurate?

The Methods section has been updated to better detail the iCESM1 experiment to aid with interpretation of the results. We run a single iCESM1 realization, this is because with full atmospheric nudging (surface to top of atmosphere) to ERA5 reanalysis and a nudging parameter strength of 1 (from 0 to 1), there is very little influence of internal variability (Ding et al. 2022).

Updated text:

Lines 489-493: “A single simulation is run from 1979 to 2022 (with 2 years of spinup), with the model nudged to ERA5 horizontal winds (u, v) and temperature throughout the atmosphere, and specific humidity in the lowest model level nearest the surface. In previous studies, such as Ding et al. (2022)³⁷, the constraints imposed by the nudging (u, v, and T) result in very little member to member difference resulting from initial states. For this reason, we only examine only this single iCESM1 realization.”

Line 501 “these runs”. Are multiple runs or experiments used? A mean?

Updated to reflect a single iCESM1 realization.

Line 503-504 implies multiple iCESM1simulations?

Updated to reflect a single iCESM1 realization.

Results

Line 133:
“relative to iCESM1, with the nudged simulations”, is iCESM1 a mean of multiple simulations?

Updated to reflect a single iCESM1 realization.

Previous text:

Lines 132-133: “with the nudged simulations largely falling within the envelope from the CESM2-LE members”

Updated text:

Line 132-133: “with the nudged simulation largely falling within the envelope from the CESM2-LE members”

Previous text:

Line 136-137: “the iCESM1 simulations generally agree well with the observed year-to-year variability and trends of most products examined here”

Updated text:

Lines 136-137: “the iCESM1 simulation generally agrees well with the observed year-to-year variability and trends of most products examined here”

Line 145, Figure 1a caption
“from CESM2-LE (blue, grey shading),”

Add text or revise the legend to clarify that the blue curve represents the ensemble mean and the grey shading represents the ensemble spread in Fig. 1a. In Fig 1b, the legend appropriately identifies the mean and spread.

Updated the caption to denote the ensemble is the blue line and the ensemble spread is the grey shading.

Updated text:

Line 144: “from CESM2-LE (ensemble mean: blue, ensemble spread: grey shading)”

In general, I believe the results and discussion read well. I think if the authors clarify in detail their explanation of iCESM1 simulations and experiments, it would go a long way to improving the manuscript and interpretation of the results.

Thank you for your thorough revision and suggestions to improve the interpretability. We’ve clarified the model experiment design and revised the text to reflect the use of a single realization and the justification for this.

References:

Ding, Q., Schweiger, A. & Baxter, I. Nudging Observed Winds in the Arctic to Quantify Associated Sea Ice Loss from 1979 to 2020. *J. Clim.* **35**, 6797–6813 (2022).

Deser, C., and Coauthors, 2020: Insights from Earth system model initial-condition large ensembles and future prospects. *Nat. Clim. Chang.*, **10**, 277–286, <https://doi.org/10.1038/s41558-020-0731-2>.