**North American land capacitor effect on summer Arctic moistening and water vapor feedback**

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Key Points:

* Land-based moisture sources play leading role in historical summertime Arctic moistening and related WV positive feedback
* Atmospheric rivers are the primary mechanism transporting this moisture into the Arctic
* Remote moisture transport determines the Arctic summertime water vapor feedback contributing to 92% over the satellite era

Abstract

The primary sources and drivers of recent observed summer Arctic moistening trends are still unclear, which represents a significant research gap hindering attribution and detection analyses of observed arctic warming. Here, using the water tagging and circulation nudging capabilities enabled in CESM, we find that the summertime circulation trend pattern over recent decades, which is in part internally driven, play a key role in moistening the Arctic through directing more ARs into the Arctic along three narrow pathways. The circulation trend pattern is characterized by a high-pressure anomaly over Greenland and a low-pressure center over Eurasia, favoring the primary pathways of enhanced poleward moisture transport from North America along western Greenland and from Eurasia into the Central Arctic. This enhanced moisture transport induces more precipitation and moisture changes across the Arctic which have likely contributed to changes in GrIS SMB and sea ice via the water vapor feedback, contributing as much as 92% of the total effect. On the other hand, the circulation trend pattern resulting in recent Artic moistening acts to shift originally prevailing moisture transport and AR propagations in the extratropcis, rather than induce a net overall increase of moisture in the mid and high latitudes as simulated by forced model response to global warming. Thus, the role of large scale circulation on ARs and both anthropogenic and internal variability should be taken into account to explain the underlying mechanism of recent moistening of the Arctic.

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1 Main

Over the last four decades, the Arctic has warmed at a rate more than 2-3 times that of global mean surface temperature [ref]. The warming has led to a rapid decline of Arctic sea ice and Greenland Ice Sheet (GrIS) surface mass balance (SMB) [ref; Topal 2023]. Following the temperature rise, moisture in the Arctic has increased, leading to greater cloud cover and precipitation [ref; Bintanja and Selton, 2014; Kopec et al., 2016]. Understanding moisture changes in the Arctic is important for constraining water vapor feedbacks, which are the second strongest contributor to summertime Arctic warming following the sea ice albedo feedback [ref; Pithan and Mauritsen 2014] and a leading source of model uncertainties in projecting the future climate response in the Arctic.

Under increasing anthropogenic warming, humidity in the atmosphere would be expected to increase at a rate of 7% per K, constrained by the Clausis-Clapeyron (CC) relation, leading to increases in downwelling longwave radiation, changes in cloud and precipitation characteristics, and many other alterations to the hydrological cycle. This constraint has led to one possible response of the hydrological cycle in the tropics and subtropics to global warming: “the wet gets wetter, and the dry gets drier” [ref; Held and Soden, 2006; Trenberth, 2011] due to the forced response of large scale circulation including the walker circulation, the Hadley cell and the Ferrel cell. The Arctic is unique in this regard, because Arctic circulation appear to be less sensitive to global warming since it is located at the far end of the thermally and dynamically driven global circulation. Furthermore, the circulation response at high latitudes usually exhibits very diverse patterns from model to model [ref; Wills & Schneider 2016]. In the tropics and midlatitudes, the moistening scenario across models to global warming is still thermodynamically determined, but modulated by dynamical changes. However, in regions not directly over the tropical oceans, such as over land or in the Arctic, it remains unclear how global warming has shaped the moistening pattern there [ref; Simpson et al. 2023].

Despite being relatively dry, the Arctic is expected to become wetter as sea ice retreats, exposing more open ocean and increasing local evaporation and precipitation as well as resulting from phase changes in cloud moisture roughly following temperature. Additionally, preferential moistening at lower latitudes is expected to strengthen faster than that in the Arctic, resulting in equator-to-pole moist static energy (MSE) gradients that enhance transport towards higher latitudes [Hahn et al. 2021; Chung & Feldl 2023]. However, prior studies have found that the local changes in precipitation associated with decreased sea ice cover and increased evaporation only explain a fraction of the simulated changes [ref; Singh et al. 2016, 2017, Harrington et al. 2021]. Contributions from remote land and ocean sources also play leading roles during different seasons in these studies, despite studies centering on MSE focusing on equator-to-pole gradients that might not be the major determining factor in determining moisture transport into the Arctic [Hahn et al. 2021]. These theories focusing on the forced response of local moisture source and MSE-gradient driven moisture transport often do not fully account for land-sea differences and have to make important assumptions, such as fixed relative humidity [ref; Lague et al. 2023; Feldl & Merlis 2023]. Differences in the sources of moisture transport can have a wide range of impacts on humidity, clouds, and radiation upon entering the Arctic [ref; Harrington et al. 2021], however it is still unknown how these sources have contributed to observed changes. These lines of analyses also focus on annual mean changes, despite extreme events, such as polar lows and atmospheric rivers (ARs) that reach into the Arctic, being known to contribute varying degrees of high latitude transport in different seasons.

The focus on moisture transport has focused on its impacts on sea ice, driving melting or preconditioning in colder months, but there has been very little exploration of the relationships between moisture and the Arctic surface during summer [Yang & Magnusdottir 2017; Zheng et al. 2023]. Therefore, where the main moisture source that has acted to moisten the Arctic in recent decades sources from, how moisture is transported into the Arctic in summer, and how important it contributes to the summertime radiative forcing in the Arctic remain elusive. This knowledge gap hinders our ability to assess the models’ skill in projecting moisture, precipitation and radiation changes and resultant summer sea ice variability in the future. Analysis of the simulation in models has highlighted a slim chance of models being able to reproduce observed circulation trend pattern, suggesting that imposing observed winds in the models serves as a plausible approach to estimate how the observed circulation trend pattern drive moisture transport into the Arctic. In particular, the recently available water tagging capability in iCESM and radiative kernels built using ERA5 and atmospheric climate models (CAM5) enables us to further trace the source and sink of moisture transport and its related radiative impact. With these new tool kits that have been added in iCESM and available for in the community, it has recently become possible to archive a full understanding of a number of key processes that collectively induce the recent moistening trends and enhanced radiative forcing, including local and remote evaporation, transport into the Arctic, the change of specific humidity, precipitation and radiative forcing within the Arctic.

2. Historical and model simulated trends.

The iCESM1 simulations with nudging yield nearly identical replays of anomalous JJA atmospheric water vapor within the Arctic from ERA5 (Figure 1, blue and orange lines). The moistening trends are xx kg m-2 decade-1 in iCESM1 and xx kg m-2 decade-1 in ERA5. The 10-member ensemble mean from CESM1-GOGA (or CESM1-len) exhibits a comparable magnitude trend over 1979-2012, but a slightly higher trend when including 2013-2015, when reanalysis shows a brief cooling period and no increase in atmospheric moisture. It is over this later period where iCESM1 and ERA5 fall outside the 10-member envelope from CESM1-GOGA for multiple consecutive years. While, there is an increasing trend over the satellite era in both atmospheric water vapor and precipitation, total precipitation in iCESM1 and ERA5 does not increase as strongly as water vapor in the Arctic over the historical period. It is only around 2015 that there is a rapid increase in precipitation, contributing to the overall increasing trend. CESM1-LE and CESM2-LE fail to capture the key features of mid- to high latitude atmospheric circulation (i.e., anticyclonic circulation over Greenland and the Arctic), indicating it is necessary to consider the role of circulation in shaping moisture variability [Baxter & Ding 2022].

During boreal summer there is significant moistening throughout most of the Northern Hemisphere and at most vertical levels (Figure 1c-d). The Arctic experiences moistening of the atmospheric column throughout most of the basin, except for a small patch over the Beaufort Sea (Figure 1c). Wetting trends follow circulation, occurring where there is geopotential height increases and poleward IVT. There has been an increasing geopotential height trend extending from the North Atlantic, over Greenland and into the Arctic that has transported water vapor poleward to the west of Greenland. Poleward vapor transport has also occurred between a low pressure center over the Northeast Atlantic and high pressure center over Europe, as a well as east of a low pressure center over central Eurasia. Zonal mean trends show an increase in specific humidity focused ~800 hPa and throughout the entire Northern Hemisphere. The only non-significant trends occur near the surface in the tropics and Arctic and at middle levels of the tropical troposphere. Geopotential height trends show the strongest increases at upper levels in the troposphere that extend downward closer to the pole. The results from the nudged iCESM1 simulations highlight the importance of capturing the appropriate circulation patterns for moisture transport, in addition to the correct sources.

Previous studies have examined summertime water vapor transport in the iCESM1 and its impact on Arctic water vapor [Singh et al. 2016, 2017, Harrington et al. 2021], however no study has carried out this analysis using observed circulation in the iCESM1. By nudging to ERA5 winds, we are able to capture the observed year-to-year and long-term changes in circulation patterns that create the major vapor transport pathways into the Arctic. Eurasia is a commonly highlighted region contributing to Arctic vapor changes in previous experiments due to its close proximity. We find a consistent leading contribution being sourced from a narrow band between 50-70° N. This band expands to the North American land mass with comparable magnitudes, though there has not as strong an influence of North America in previous free-running simulations. Summertime blocking over Greenland is a pattern that the CESM model struggles to capture, therefore previous experiments without nudging generally do not find the North American pathway or source region playing an important role. The western boundary current regions in both the Pacific and Atlantic also contribute to Arctic moisture changes on interannual timescales (Figure 2a), but this contribution is weaker than that from land-based sources.

3. Role of ARs in increasing Arctic moisture trend.

Trends in AR frequency from an ensemble mean for the CESM2-LE (Figure 3a) show a relatively uniform increase in AR occurrence across most of the Northern Hemisphere. GCMs tend to show moistening throughout the atmosphere

Trends in AR frequency (Figure 3) show similar pathways to the IVT trends in Figure 1. There are three primary pathways that transport large amounts of moisture: 1.) North American pathway west of Greenland, 2.) Siberian pathway, and 3.) central Eurasian pathway. Each coincides with areas that have poleward trends in winds driven by the large-scale circulation seen in Figure 1c. The transport pathways from North America and central Eurasia coincide with large-scale patterns suggesting increased occurrence of cyclonic wave breaking that is responsible for carrying this moisture poleward in extreme events [Liu & Barnes 2016].

ARs contribute 80-90% to poleward moisture transport trends in the iCESM1 simulations. In the region near northeastern Canada and western Greenland, ARs account for > 92% of poleward moisture transport – the most of any region around the Arctic. In the Eurasian pathways, ARs are responsible for 85-86% of moisture transport. The contributions and magnitudes between ERA5 and iCESM1 are nearly identical, even despite using daily output from iCESM1 for AR detection and tracking, showing that capturing large-scale circulation in the model can alleviate computational and storage burdens on future AR studies.

4. Water tagging runs

44-yr trends in source-region contributions to Arctic water vapor show similar relationships as year-to-year timescales, with the strongest contributions coming from Northern Hemisphere land masses, particularly northern Europe, central Eurasia, and northeastern North America (Figure 2). These trends show less emphasis on Siberia and Alaska, as well as a decreased importance of the western boundary currents -- especially the more northern extensions of these regions. Locally, there a small increases in moistening coming from the Kara Sea and Canadaian archipelago regions.

Since the 54 tagging regions are evenly distributed based on latitude and longitude, they have much larger areas closer to the equator. Therefore, we scale each region by its total area, giving weighting to the smaller, high latitude regions. This shifts relative contributions to regions that are closer to or within our target region in the Arctic.

5. Significance of land-based moisture in warming the Arctic.

We quantify the radiative impacts of moisture transport on the Arctic surface using radiative kernels derived from ERA5 and CAM5 (Figure 4). Examining the zonal mean patterns of the summertime water vapor feedback, we find good agreement when using either ERA5 or CAM5 surface radiative kernels. Both show a negative feedback in the tropics due to cooling SSTs in the eastern equatorial Pacific and a strong positive feedback in the midlatitudes. The primary differences in the pattern (not magnitude) occur within the central Arctic. Specifically, the radiative kernels computed using a single-year simulation with CAM5 show a much stronger positive magnitude from 850 to 600 hPa, north of 75 N (Figure 4c). In contrast, the ERA5 kernels use the average of 5 years (2011-2015), that provides a relatively broad sampling of the variability in the Arctic, with 2011-2012, 2015 being dominated by strong anticyclones and 2013-2014 being dominated by strong cyclonic patterns. Therefore, the differences between ERA5 and CAM5 are likely the result of a combination of internal atmospheric processes (subsidence over the central Arctic) and model physics. Ultimately, we find small differences between the two products and in the following focus on results using the CAM5 kernels.

Radiative feedbacks are typically examined using a column integrated or surface perspective, however this can overlook the impacts of vertical changes in moisture and temperature that modulate radiative fluxes. We find that the water vapor feedback within the column can be vertically uniform or unevenly distributed. The strongest water vapor feedback occurs in the middle troposphere, between 300 and 800 hPa (Figure 4a). Moisture sourced from eastern Eurasia, northwestern Pacific, and the Bering/Beaufort Seas produce the strongest positive water vapor feedback, with the more remote source regions affecting higher altitudes (300-600 hPa) and the local sources affecting lower altitudes (600-900 hPa). The moisture transport from central Eurasia (regions 42 and 43) is the exception. Both have contributed to enhanced moistening on year-to-year and long-term timescales (Figure 2). However, this transport contributes unevenly to the vertical structure of the water vapor feedback, being positive at mid- to upper levels, but negative at lower levels. Central Eurasia, for example, contributes the largest amount of total moisture for both year-to-year variability and trends, but this transport occurs primarily at upper levels, and there is a slight negative feedback that occurs near the surface that results in a dampened water vapor feedback. In contrast, northeastern North America has slightly weaker trends in IVT and total column water vapor, but the uniform warming throughout the middle and lower levels of the column creates the strongest contribution to the positive Arctic water vapor feedback.

The total summertime Arctic water vapor feedback determined from the trends in the nudged iCESM1 simulations is 1.67 W m-2 K-1. Northeastern North America contributes 0.32 W m-2 K-1 (22.9%) to the Arctic water vapor feedback in terms of the long-term change over the satellite era. 0.32 W m-2 K-1 (19.0%) and 0.26 W m-2 K-1 (15.7%), respectively. Locally, moisture sourced through evaporation from the Arctic Ocean only contributes to 8% (0.13 W m-2 K-1) of the water vapor feedback computed over the historical period and remote sources account for the remaining 92%. This local contribution primarily results from a positive feedback originating from the Canadian archipelagos (0.10 W m-2 K-1).

High pressure over Greenland, in the form of Greenland blocking or a negative North Atlantic Oscillation (NAO), is the primary contributor to strong influence of North America and a decreased influence of the North Atlantic and Europe (Figure 1c). On higher frequency timescales, these modes manifest as increased cyclonic wave breaking events that push moisture and ARs to the west of Greenland [Liu & Barnes 2016]. Anticyclonic winds promote transport from northeastern North America, west of Greenland and over the Canadian archipelagos, while decreasing transport from the North Atlantic to the east of Greenland.

6 Land capacitor effect

Moisture sourced from the leading regions contributing to Arctic moistening generally leaves behind drying trends both globally and over midlatitude land masses (Figure 7). The one exception being over northeastern Canada, over region 47, where there is a weak moistening signal in soil moisture (red box in Figure 7). This suggests that, even though the region is a leading contributor redistributing moisture from the midlatitudes to the Arctic, there is a local recycling of moisture between the land and atmosphere. The importance of land and soil processes enhancing sources of moisture that can then be transported to the Arctic are also likely important for region 47 having such a strong influence on summertime Arctic moistening and radiative feedbacks.

The soil creates a land capacitor effect by storing incoming precipitation from remote, equatorward regions. During spring, much of the moisture is evaporated from the Caribbean and tropical Atlantic (regions 35 & 36), accounting for 54% of the precipitation over northeastern North America. The strongest increasing precipitation trend occurs near the southern part of region 47, where soil moisture increases the most (Figure 6a,c). Both MAM and JJA soil moisture in the southern parts of region 47 are shown to have increased in response to more precipitation (Figure 6c). During summer, the source of this moisture shifts to the Caribbean and continental United States (regions 35 & 41, 35.6%). Local recycling in both spring and summer can only explain 18% of the increase in soil moisture, with most of the locally evaporated water vapor being transported and precipitated northward in the Arctic (Figure 6d). Despite our tagging and those prior suggesting that land-sourced moisture is most important for summertime Arctic water vapor increases and their radiative impacts, this moisture originally comes from the Caribbean Sea and tropical Atlantic before passing through the land surface in northeastern North America and ultimately terminating in the Arctic. This highlights the importance of accurately capturing land surface processes because they mediate the interactions between the Arctic and lower latitudes.

7 Discussion

Moisture transport into the Arctic is dominated by the eddy transport () such as ARs’ impact from 40 to 60, over the region governed by the upward branch of the Ferrel Cell. However, ARs are sensitive to circulation changes that are also driven by internal variability of the climate system. This indicates a possible scenario by which internal variability interacts with anthropogenic forcing. This is also the mechanism that needs more attention in future model evaluations. Given that the water vapor feedback is a key component of Polar Amplification, more efforts should be spent to understand its significance.

In addition, tropical moistening does not since the moisture source moving toward the Arctic is near to the pole (50-70°s N). This indicates that sub-Arctic is a critical region shaping moisture variability within the Arctic. The pole-to-equator MSE gradient concept may oversimply issues of sources and pathways of transport. For example, the upward branch of the Ferrel cell (around 60-70° N) may play a key role in determining moistening trend in the Arctic. The large-scale zonal mean circulation cells, like the Ferrel cell, are likely very important for determining poleward moisture transport. However, transport along these systems show a muted response to anthropogenic forcing, suggesting that other factors, such as internal variability, are needed to understand changes over the historical record and into the future [Wills & Schneider 2016]. Models tend to be biased in their representations of large-scale SST trends [Wills et al. 2022]. This is particularly evident in the negative tropical WV feedback from the iCESM1 simulations that use observed SSTs (Figure 4). When comparing observed trends from the satellite record it is important to consider large biases in simulated SSTs and their influence on atmospheric circulation.

Contrary to expectations, local open water and evaporation plays an insignificant role in moistening the Arctic atmosphere and the subsequent radiative impacts. Locally sourced moisture contributes to 7% of total column water vapor trends and 8% of the water vapor feedback across the satellite era. Weak air-sea gradients in the Arctic limit the surface’s ability to influence the atmosphere through evaporation or latent heat fluxes during summer [Kay et al. 2011].

Within region 47, moisture recycling appears to be critical (Figure 6). Previous studies have emphasized the role of moisture from the ocean or the tropics in moistening the Arctic, however results from the iCSEM1 simulations suggest that land processes are equally important, especially in boreal summer. Soil moisture trends over the satellite record show drying trends across most of the Earth, except over northeastern Canada, labelled as region 47 (Figure 6). Region 47 shows increasing water vapor directly above the region that likely helps to retain soil moisture, while region 41 shows drying throughout the local atmosphere and soil (Figure 5 & 6).

It is important to note that the CESM1 has well documented biases in clouds and precipitation. The model lacks super-cooled cloud liquid and therefore its clouds are optically thin. Meaning these clouds do not reflect as much shortwave radiation back into space or emit as much longwave radiation down to the surface [ref; McIlhattan et al., 2022]. Therefore, polar cloud feedbacks in this version of the model play a minimal role in terms of their radiative impacts [ref; Middlemas et al., 2020]. However, despite very strong agreement between the iCSEM1 and ERA5, biases in cloud processes can alter precipitation and moisture that may lead to discrepancies between the model simulations and in situ or satellite observations.

In addition, we use both atmosphere-only or AMIP-style and fully-coupled approaches. Prescribing sea surface temperatures and sea ice concentrations may not accurately reflect important atmosphere-ocean-sea ice coupling processes that contribute to evaporation or stability of the lower Arctic troposphere. We see relatively large differences in the colder seasons between the atmosphere-only and fully coupled simulations during the colder seasons, when large air-sea gradients promote evaporation. However, in this study we focus on boreal summer, finding that the conclusions are not sensitive to ocean-atmosphere coupling. Future examination of the interactions between seasons is necessary, though this is outside the scope of this study.

8 Conclusions

In this study, we determine the leading sources and transport pathways driving increases in Arctic moisture and precipitation during summer. We use a novel nudging and moisture tagging approach in iCESM1 to quantify year-to-year variability and long-term trends in transport driven by observed circulation. We also quantify the contributions from ARs to moisture transport sourced from over land.

The main findings in the study are:

* Increased moisture transport into the Arctic is associated with land sources (central Eurasia and North America) and AR events during summer determines the boreal summer water vapor feedback in the Arctic
* Northeastern Canada (region 47) plays a leading role in this summertime Arctic WV radiative effect (22.9%)
* Internal large-scale circulation variability has likely contributed to increased moistening and precipitation in the Arctic over the last 4 decades, and therefore could change sign in the future. Thus, future Polar Amplification may be susceptible to the future changes in the circulation and its associated moisture transport in the coming decades.
* Land processes are critical to capturing poleward moisture transport. Soil moisture and local recycling over land in region 47 plays an important role.

How moisture transport interacts with the much stronger moistening in the tropics and the subsequent changes in meridional moist static energy gradients, with realistic atmospheric circulation is still yet to be determined. It has been theorized that changes in the equator-to-pole temperature and moisture gradients could modify large-scale circulation patterns and storm tracks. It should be noted that during boreal summer these gradients are relatively small and the anthropogenically forced response from climate models induces very weak regional changes, especially in atmospheric circulation. Therefore, with the importance of wind-driven changes for moisture transport highlighted in this study, we emphasize the importance of understanding atmospheric variability and the pattern effect – which can simultaneously drive evaporation and transport – while simultaneously modulating meridional gradients and global temperature imbalances that are the foundation for simplified feedback frameworks.

In the future, better constraints on the interaction of forced response and internal variability can help us to better project changes in Arctic moisture and precipitation under increasing greenhouse gas concentrations. This understanding will also help us to better simulate the forced response in global climate models and reduce the uncerntainty of models’ cimate sensitivity due to moisture variability.

**Methods**

**Acknowledgments**

**Open Research**

**References**