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

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Key Points:

* Remote land sources account for 62% (81% remote) of the moistening over the Arctic in the last 4 decades
* Remote moisture transport determines the Arctic summertime water vapor feedback contributing to 92% over the satellite era
* A North American land capacitor effect supplies diverted ARs west of Greenland creating the largest contribution to summer water vapor feedback

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 combined water tagging and circulation nudging techniques, we find that the summertime circulation trend pattern over recent decades, plays a key role in moistening the Arctic through directing more ARs into the Arctic along four narrow pathways. We quantify the radiative impact of these transport pathways using the traditional kernel approach, finding a dominant contribution from mid- to high latitude land sources (65%). We focus on the strongest radiative pathway associated with an anticyclonic trend pattern over Greenland, favoring enhanced poleward moisture transport from North America along western Greenland. 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 summertime water vapor feedback, contributing as much as 24% of the total effect. The long-term trend in poleward moisture transport is consistently supplied by a land capacitor effect through early summer rainfall originating from the Caribbean Sea. Thus, the role of large scale circulation on ARs and both anthropogenic and internal variability should be taken into account to explain the underlying mechanisms of recent moistening of the Arctic.

Main

Over the last four decades, the Arctic has warmed at a rate more than 2-3 times that of global mean surface temperature1,2. The warming has led to a rapid decline of Arctic sea ice and Greenland Ice Sheet (GrIS) surface mass balance (SMB)3. Following the temperature rise, sea ice cover has retreated, which is expected to increase moisture in the Arctic, leading to greater cloud cover and precipitation4,5. 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 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 Clausius-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”6,7 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 model8. 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 there9.

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 latitudes10,11. 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, comprehensive understanding of where the main moisture sources that have moistened the Arctic in recent decades originate, how moisture is transported into the Arctic in summer, and how important it contributes to 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 model simulations has highlighted important questions of the ability of models to reproduce observed circulation trend patterns, 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 [Baxter & Ding 2022]. In particular, the recently available water tagging capability in the isotope-enabled Community Earth System Model (iCESM) and radiative kernels built using ERA5 and atmospheric climate models (CAM5) enables us to further trace the sources and sinks of moisture transport and their related radiative impact. With these new tools that have been added in iCESM and are available for 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.

Results

a. Historical and model simulated trends.

The iCESM1 simulations with atmospheric 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.

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.

b. 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, resulting in the uniform trend pattern [Simpson et al. 2023]. Previously, it was shown that the CESM struggles to capture the anticyclonic circulation over Greenland, necessary to divert ARs to the west of Greenland [Eade et al. 2014; Baxter & Ding 2022]. Typically, these systems enter into the Arctic through the North Atlantic, however, Greenland blocking or a negative North Atlantic Oscillation (NAO), is likely the primary contributor to a strengthening 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. Despite its rarity, the CESM2-LE is able to capture sustained diversion of ARs west of Greenland over 4 decades in a single member. This highlights the need to consider internal variability when constructing water tagging experiments in the free-running configuration.

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.) Siberian pathway, and 2.) central Eurasian pathway, 3.) Alaskan pathway, and 4.) North American pathway west of Greenland. Each coincides with areas that have poleward trends in winds driven by the large-scale circulation seen in Figure 1c.

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.

d. 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 (Supplementary Figure 2). 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).

e. Land capacitor effect

Because region 47 appears to be particularly effective in inducing the summertime WV feedback, we run an additional simulation with 9 smaller regions within the area of interest (Figure 5). The vertical structure of trends originated from region 47 suggest this radiative efficiency is likely because of increased transport at lower levels (Figure 5a). Other regions (i.e., 41, 43) have much weaker radiative impacts, because over recent decades their transport has been pushed to higher elevations, reducing their capability to travel farther distances into the Arctic and influence surface radiative fluxes.

The strongest source regions within region 47 are from the southern and southwestern areas, just south of Hudson Bay (Figure 5b). These regions coincide with the strongest positive soil moisture trend (Figure 5c). Moisture sourced from the leading regions contributing to Arctic moistening generally leaves behind drying trends both globally and over midlatitude land masses (Figure 5c). The one exception being over northeastern Canada, over region 47, where there is a weak moistening signal in soil moisture (red box in Figure 5c). This suggests that, even though the region is a leading contributor redistributing moisture from the midlatitudes to the Arctic, there is a capacitor effect, where the buildup of moisture supplies transport into the Arctic over several decades. 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 5c). Both MAM and JJA soil moisture in the southern parts of region 47 are shown to have increased in response to more precipitation (Supplementary Figure 4c). During summer, the source of this moisture shifts to the Caribbean and continental United States (regions 35 & 41, 35.6%). The Carribean and tropical Atlantic are the key source regions supplying this increase in soil moisture over northeastern Canada via precipitation in June (Figure 6a). Much of the transport originating from these tropical sources continue on into the Arctic, though precipitation along the way feeds land-sourced moisture towards the end of the summer season. 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. These results also highlight the need for caution when interpreting tagging and backtracking approaches to understanding the sources of Arctic moisture change.

Discussion

Moisture transport into the Arctic is dominated by the eddy transport () as indicated by the impact of ARs 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 a 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.

These results still need to be further reconciled with conceptual frameworks built on the importance of the tropics for determining polar moistening, as 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 the 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 (Supplementary Figure 2). 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 sourced from the tropical Atlantic 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 in mediating this poleward transport, especially in boreal summer. Soil moisture trends over the satellite record show drying trends across most of the Earth, except over northeastern Canada, (Figure 5c). 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 (Supplementary Figure 1).

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 thanks to weak air-sea gradients. Future examination of the interactions between seasons is necessary, though this is outside the scope of this study.

5 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 ocean that passes through the land surface via a North American land capacitor effect.

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%) with 92% of that transport occurring in ARs.
* 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. Serving as a mediator or capacitor for poleward transport.

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 impacts 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 the 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 uncertainty of models’ climate sensitivity due to moisture variability.

Methods

2.1 Nudged, water isotope enabled CESM1 simulations

We use the isotope-enabled Community Earth System Model version 1 (iCESM1). iCESM1 uses as its base the CESM1.2, which has the Community Atmosphere Model version 5.3 [CAM5.3; Neale et al., 2010], Community Land Model version 4 [CLM4; Oleson et al., 2010], Parellel Ocean Program version 2 [POP2; Smith et al., 2010], and Los Alamos Sea Ice Model version 4 [CICE4; Hunke, 2010]. The atmosphere and land components have the nominal 1° (0.9° x 1.5° finite volume grid) and 2° (1.9° x 2.5° finite volume grid) resolution and finite-volume dynamical core (CESM1-FV2). Previously, iCESM1 has only been run with the nominal 2° resolution grid, therefore we examine both to gauge the impacts of horizontal resolution on moisture transport and precipitation. Granted in the future, higher resolutions with regional-refinement or global cloud resolving models would be more ideal to address issues of resolution. CAM5.3 has 30 active atmospheric levels in hybrid-sigma coordinates. POP2 and CICE4 are on the nominal 1° resolution grid with a displaced poles over Greenland and Antarctica. In these experiments we run the model with prescribed monthly sea surface temperatures and sea ice concentrations taken from ERA5 that are remapped to the iCESM1 ocean model grid.

2.2 Experiment Design

iCESM1 uses numerical water tracers [Nusbaumer et al. 2017] to follow movement and phase changes beginning from evaporation, when moisture is tagged based on its region, to when it is precipitated out of the atmosphere. The model is nudged to ERA5 horizontal winds (u, v), temperature, and specific humidity in the lowest model level nearest the surface. A number of sensitivity experiments are conducted and the nudging simulation does not appear to be sensitive to whether observed specific humidity is constrained at the lowest model level. Sea surface temperatures and sea ice concentration from ERA5 are prescribed. Greenhouse gas concentrations are fixed at year 2000 levels, so as not to double count the effects from greenhouse gas driven warming and thereby introduce artificial heating. The goal of setting the model in this manner is to replay observed atmospheric conditions (derived from ERA5 ) in iCESM1 so that the simulated hydrological cycle (i.e., evaporation, transport, precipitation) can be decomposed into its observed sources and pathways.

We construct 54 evenly dispersed regions (in terms of latitude and longitude, rather than area) around the globe without consideration for land or ocean surfaces. A second simulation is conducted with 7 regions for which these tracers are tagged. Two regions consist of land from North America and Eurasia, separately. The other regions include the North Pacific, Subtropical North Pacific, North Atlantic, Subtropical North Atlantic, and a local region over the Arctic Ocean. Everything south of 20 N is not explicitly tagged but can be considered its own regional tag. We focus on our analysis on the simulations using the 54 regions. To ensure that these runs correctly simulate the climatological patterns of humidity and rainfall, we check the annual cycles in the iCESM1 simulations against reanalysis, finding that the two products agree and the results from the iCESM1 simulations are representative of the changes over the satellite era (Supplementary Figure).

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.

3.1 Reanalysis

Gridded winds (u,v), temperature, precipitation rate, and specific/relative humidity from the ERA5 atmospheric reanalysis are used to derive year-to-year variability and trends in the Arctic hydrological cycle over the satellite era (1979-2022) [ref]. ERA5 has been shown to capture precipitation relatively well in the Arctic region compared with other major reanalysis products [ref; Graham et al. 2019; Wang et al. 2019; Barrett et al 2020]. We focus on total column-integrated water vapor (TMQ) as vertically integrated total specific humidity at each grid cell and integrated vapor transport (IVT) to evaluate changes in moisture and transport, respectively.

3.3 Models

To evaluate the differences of using the model’s inherent circulation and quantify the role of anthropogenic forcing (which we do not directly quantify in the nudged iCESM1 simulations), we examine a suite of available output from CESM1 and CESM2 simulations. We first use CESM1-GOGA as a comparison with the fully-coupled and AMIP-style tagging simulations to verify that there small differences between the iCESM1 configurations.

3.2 Radiative feedback analysis

To better understand how increasing Arctic moisture contributes to a change in radaitve forcing, we follow the classical radiative kernel approach using the ERA5 and CAM5 surface, all-sky radiative kernels from Huang and Huang (2023) and Pendergrass et al. (2018), respectively. The moisture kernel quantifies the radiative response to the moistening caused by 1 K warming, assuming constant relative humidity. The water vapor feedback is integrated through the tropospheric column (below ~300 hPa) and we use the local feedback, which considers the surface temperature response at each latitude or an area-weighted average over the Arctic region (70-90° N). The contribution of each moisture source region to the Arctic water vapor feedback is computed by subtracting the water vapor tagged from each region individually from the total water vapor at each level and gridpoint then computing the feedback parameter. All analysis focuses on June-July-August (JJA) means to examine the summertime Arctic water vapor feedback and its associated moisture transport.

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**Figure 1. Trends:** (a) JJA total column precipitable water (kg m-2) within the Arctic (70-90° N) from iCESM1 (blue) and ERA5 (orange). (b) JJA total precipitation (snow+rain, large-scale+convective) within the Arctic (70-90° N) from iCESM1 (blue) and ERA5 (orange). (c) 1979-2022 linear trends in total precipitable water (shading, kg m-2 decade-1), 200 hPa geopotential height (contour, m decade-1), and IVT (kg m-1 s-1 decade-1). (d) 1979-2022 linear trends in zonal mean specific humidity (shading, kg kg-1 decade-1) and geopotential height (contour, m decade-1).

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**Figure 2. Regional contribution to Arctic water vapor:** (a) Root mean square error (kg kg-1) when each region is removed from the Arctic total column water vapor and (b) linear decadal trends (1979-2022, 10-4 kg kg-1 decade-1) in Arctic (70-90° N) total column water vapor sourced from each of the 54 tagged source regions. Numbers indicated the source region number.

A map of the earth

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**Figure 3. Atmospheric Rivers:** Linear trends in (a) a 10-member mean from the CESM2-LE and (b) iCESM1 JJA atmospheric river (AR) frequency from 1981-2022. (c) Area-weighted average of JJA AR frequency within the Arctic (70-90° N) from the iCESM1 (black) and ERA5 (purple).

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**Figure 4. Regional contribution to the Arctic summertime water vapor feedback:** (a) Vertical structure of Arctic (70-90° N) water vapor feedback (W m-2 K-1), computed by removing water vapor from each tagged source region (x-axis). (b) Total column integrated water vapor feedback (W m-2) computed by removing water vapor sourced from each region. Region numbers in (a) are shown in panel (b).

A diagram of soil moisture trend

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**Figure 5. Source and pathway for key region in northeastern Canada.**

(a) Vertical structure of moistening (kg kg-1 decade-1) associated with 9 smaller tagging regions within region 47. (b) The linear trends (1981-2022) in Arctic total column WV (kg m-2 decade-1) originating from the 9 smaller regions within northeastern Canada. (c) The linear trends (1981-2022) in soil moisture (cm3 mm-3 decade-1).

**A graph of different colored lines

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**Figure 6. A North American land capacitor effect.**

(a) Linear trends (1981-2022) in total precipitation (mm day-1 decade-1) over region 41 from regions in the Northern Hemisphere (regions 25-54). (b) Linear trends (1981-2022) in precipitation (mm day-1 decade-1) over the Arctic from regions in the Northern Hemisphere (regions 25-54). Shading only shows significant trends at the 95% confidence level. Dashed blue lines denote region 35 (Caribbean Sea) and region 47 (northeastern Canada).

**Supplementary Figures:**

Diagram

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**Supplementary Figure 1. Major moisture transport pathways:** (a) Trends in zonal mean (180-320° W) water vapor transport from North American land-based sources (shading, kg m-1 s-1 decade-1) and equivalent potential temperature (red contours, K decade-1). Green shading indicates poleward (right) transport. Black contours show 1979-2022 mean isotherms. (b) Trends in zonal mean (340-160° W) water vapor transport (shading) and equivalent potential temperature (red contours). Black contours show mean isotherms. (b) Trends in zonal mean (180-320° E) water vapor transport from Eurasian land-based sources (shading, kg m-1 s-1 decade-1) and equivalent potential temperature (red contours, K decade-1). Black contours show 1979-2022 mean isotherms.

A group of graphs showing different types of data

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**Supplementary Figure 2. Zonal mean water vapor feedback:** The zonal mean water vapor feedback (W m-2) in iCESM1 using the (a) ERA5 or (b) CAM5 radiative kernels and (c) the difference between the two approaches.

**A graph of a number of red and blue lines

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**Supplementary Figure 3.**

A group of maps with numbers

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**Supplementary Figure 4. A North American land capacitor effect:** 1981-2022 trends in (a) MAM and (b) JJA total precipitation (mm day-1 decade-1) from outside of region 47 (remote). (c) 1981-2022 trends in total column soil moisture (mm3 mm-3 decade-1) from the iCESM1 nudged simulations. (d) 1981-2022 trends in JJA total precipitation (mm day-1 decade-1) from region 47 outlined in red. Note the scale in panel (d) is 1/3 of those in panels (a) and (b). The red box indicates region 47 from Figure 2 and 5.