Seasonal Changes in Poleward Atmospheric Heat Transport Under Increased CO2

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Seasonal Changes in Poleward Atmospheric Heat Transport Under Increased CO_2

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Key Points:

- Sea-ice loss reduces dry heat transport to the Arctic in winter; sub-Arctic warming increases latent heat transport to the Arctic in summer.
- Intermodel spread in Arctic warming controls intermodel spread in seasonal heat transport changes.
- The seasonal pattern of poleward heat transport change is well-captured by down-gradient diffusion of temperature and moisture anomalies.

Abstract

Arctic warming under increased CO_2 peaks in winter, but is influenced by summer forcing via seasonal ocean heat storage. Yet changes in atmospheric heat transport into the Arctic have mainly been investigated in the annual mean or winter, with limited focus on other seasons. We investigate the full seasonal cycle of poleward heat transport modelled with increased CO_2 or with individually applied Arctic sea-ice loss and global sea-surface warming. We find that a winter reduction in dry heat transport is driven by Arctic sea-ice loss and warming, while a summer increase in moist heat transport is driven by sub-Arctic warming and moistening. Intermodel spread in Arctic warming controls spread in seasonal poleward heat transport. These seasonal changes and their intermodel spread are well-captured by down-gradient diffusive heat transport. While changes in moist and dry heat transport compensate in the annual-mean, their opposite seasonality may support non-compensating effects on Arctic warming.

Plain Language Summary

The Arctic is warming much faster than the rest of the planet in response to rising greenhouse gas concentrations. Because Arctic warming peaks in winter, many studies have focused on the wintertime processes amplifying Arctic warming. However, others have found that summer atmospheric heating also contributes to winter warming by melting sea ice and storing heat in the ocean until it is released to the atmosphere in winter. Here we study changes in all seasons for one source of atmospheric heating in the Arctic—atmospheric heat transport from lower latitudes. Using climate model simulations, we find that heat and moisture are transported away from the regions that warm and moisten the most in response to rising greenhouse gas concentrations. The Arctic warms more than lower latitudes in winter, which reduces heat transport to the Arctic in winter. Atmospheric moisture increases most in late summer at lower latitudes, driving increased moisture transport in late summer from lower latitudes to the Arctic. We suggest that changes in heat and moisture transport may impact Arctic warming differently due to their opposite seasonality: by producing a larger change in surface solar reflectivity, summer changes in moisture transport may outweigh winter changes in heat transport.

1 Introduction

The Arctic has warmed as much as four times faster than the global mean in recent decades (Chylek et al., 2022; Hahn et al., 2021; Rantanen et al., 2022), motivating research to understand what produces this Arctic-amplified warming pattern. Local climate forcing and feedbacks associated with sea-ice loss are thought to contribute most to Arctic-amplified warming (Hwang et al., 2011; Kay et al., 2012; Stuecker et al, 2018). In contrast, annual-mean atmospheric heat transport (AHT) from lower latitudes to the Arctic changes little under CO_2 forcing in comprehensive climate models, suggesting that it makes a small contribution to Arctic warming (Goosse et al., 2018; Pithan and Mauritsen, 2014). However, this small change in total poleward AHT reflects compensation between larger changes in decreased dry heat transport and increased latent heat transport, which itself has been highlighted as a major contributor to Arctic warming (e.g., Alexeev et al., 2005; Armour et al., 2019; Feldl and Merlis, 2021; Graversen and Wang, 2009; Merlis and Henry, 2018; Woods and Caballero, 2016). By separating each of these components in the latest generation of climate models, Hahn et al. (2021) find that increased latent heat transport is the third largest contributor to Arctic-amplified warming, after local albedo and lapse-rate feedbacks. Others suggest that increased latent heat transport will outweigh decreased dry heat transport by contributing a larger greenhouse effect, yielding a net warming effect of projected heat transport changes into the Arctic (Graversen and Burtu, 2016; Graversen and Langen, 2019).

Changes in poleward AHT under increased CO_2 forcing have been investigated in the annual-mean from a diffusive perspective, in which AHT is proportional to meridional gradients in temperature and moisture (e.g., Armour et al., 2019; Roe et al., 2015). In this perspective, increased latent heat transport to the Arctic with increased CO_2 results from greater moistening at warmer, lower latitudes than at the poles, following the Clausius-Clapeyron relation. This amplifies the meridional gradient in moisture and therefore the poleward latent heat transport (Armour et al., 2019; Held and Soden, 2006; Siler et al., 2018). In contrast, stronger warming at the poles than at lower latitudes weakens the meridional temperature gradient and reduces dry AHT to the Arctic (Armour et al., 2019; Feldl et al., 2017; Henry et al., 2021). Consistent with this perspective, dry heat transport decreases most in models with larger Arctic feedbacks and warming, suggesting that poleward dry AHT weakens in response to Arctic warming (Hahn et al., 2021; Hwang et al., 2011; Pithan and Mauritsen, 2014).

While heat transport changes have been studied in the annual mean or in specific seasons, the full seasonal cycle of heat transport and its drivers have received less attention. Some studies highlight the role of latent heat transport in winter as a key contributor to winter-amplified Arctic warming (Doyle et al., 2011; Gong et al., 2017; Luo et al., 2017; Woods et al., 2013; Woods and Caballero, 2016), while others emphasize the importance of springtime latent heat transport for preconditioning extreme summer sea-ice melt (Kapsch et al., 2013; Mortin et al., 2016). Under rising CO_2, climate models project that latent heat transport to the Arctic will increase most in summer, while dry heat transport will decrease most in winter (Kaufman and Feldl, 2022; McCrystall et al., 2021). However, these changes have not been studied across the full range of climate models, and the causes and impacts of this seasonality have not been fully explored.

Based on previous studies, we expect that the winter peak in Arctic warming will be directly damped by decreased dry AHT in winter, but indirectly amplified by increased latent AHT in summer, which will enhance the summer ice-albedo feedback, seasonal ocean heat storage, and its winter release to the atmosphere (Chung et al., 2020; Dai et al., 2019; Deser et al., 2010; Manabe and Stouffer, 1980; Screen and Simmonds, 2010b). Moreover, others have found that summer radiative forcing causes a larger annual-mean Arctic warming than the same amount of winter radiative forcing (Bintanja and Krikken, 2016). This suggests that despite its winter amplification, Arctic warming is impacted by year-round changes in poleward AHT. Given the disproportionate impact of atmospheric forcing in different seasons, understanding the seasonality of poleward heat transport will be essential for understanding observed Arctic changes and accurately predicting future Arctic warming.

In this study, we explore the seasonal cycle of latent and dry heat transport in climate model simulations with abrupt CO_2 quadrupling and with individually applied sea-surface warming and Arctic sea-ice loss from a 2˚C global warming scenario. These experiments allow us to explore how the Arctic and lower latitudes contribute to seasonal heat transport changes and their intermodel spread. To understand these changes, we investigate the utility of a diffusive perspective for predicting the seasonal evolution of poleward heat transport. We conclude by considering how seasonality in latent and dry heat transports may mediate their impacts on Arctic warming.

2 Results

2.1 Seasonal Changes in Poleward Heat Transport in CMIP6 Models

We analyze seasonality in heat transport using output from 41 fully-coupled climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6; Supplementary Table S1; Eyring et al., 2016). We calculate anomalies using abrupt CO_2 quadrupling simulations (*abrupt4xCO2*) in comparison with pre-industrial control (*piControl*) simulations. As in previous studies (e.g., Hahn et al., 2021), we apply a 21-year running mean to the *piControl* simulations to account for model drift before calculating anomalies between corresponding periods in the *abrupt4xCO2* and *piControl* simulations. We take 31-year averages centered on year-100 after CO_2 quadrupling to compute monthly anomalies.

We calculate the seasonal cycle of AHT convergence using the difference between the net top-of-atmosphere radiation (TOA) and net surface heat flux (SHF), accounting for atmospheric energy and moisture storage terms following Donohoe et al. (2020). We calculate the latent component of the total heat transport ($\mathrm{AHT_{latent}}$) using the difference between evaporation (E) and precipitation (P) multiplied by the latent heat of vaporization (L), and calculate the dry component ($\mathrm{AHT_{dry}}$) as the residual between the total and latent heat transports:

$$\mathrm{AHT}(\theta) = -2\pi a^2 \int_{\theta}^{90} cos(\Theta) \left[TOA(\Theta) - SHF(\Theta) - \frac{1}{g}\int_0^{p_s} \frac{d}{dt}\left(c_p T(\Theta) + Lq(\Theta)\right)dp\right] d\Theta\ ; \quad (1a)$$

$$\mathrm{AHT_{latent}}(\theta) = -2\pi a^2 \int_{\theta}^{90} L\, cos(\Theta) \left[E(\Theta) - P(\Theta) - \frac{1}{g}\int_0^{p_s} \frac{d}{dt} q(\Theta)dp\right] d\Theta\ ; \quad (1b)$$

$$\mathrm{AHT_{dry}}(\theta) = \mathrm{AHT}(\theta) - \mathrm{AHT_{latent}}(\theta)\ , \quad (1c)$$

where a is the radius of Earth, θ is latitude, g is the acceleration due to gravity, c_p is the specific heat of air, p_s is the surface pressure, T is the atmospheric temperature, q is the specific humidity, and $\frac{d}{dt}$ is calculated using centered finite differences of monthly-mean data. The atmospheric energy storage does not include a geopotential term because this changes only by thermal expansion, which is accounted for by using the specific heat at constant pressure, c_p (Donohoe et al., 2020; Trenberth and Stepaniak, 2004). To assess heat transport changes into the Arctic, we focus on AHT at 70˚N, and define the Arctic as 70-90˚N.

In CMIP6 models under abrupt CO_2 quadrupling, changes in latent and dry heat transports exhibit opposite sign and seasonality (Figures 1a, b). Latent heat transport into the Arctic increases year-round, with a maximum increase in summer and fall; dry heat transport into the Arctic decreases year-round, with a maximum decrease in winter. As a result, the total poleward heat transport increases in summer and decreases in winter. These results are consistent with the seasonal pattern of heat transport change found in a single large-ensemble model (Kaufman and Feldl, 2022) and with a summer maximum in vertically-integrated moisture flux at 70˚N found across CMIP6 models (McCrystall et al., 2021). In the annual- and ensemble-mean at 70˚N, the reduction in dry heat transport (-0.17 PW) overcompensates the increase in latent heat transport (0.09 PW) to produce a net negative change (-0.08 PW). Large intermodel spread in the total heat transport change is dominated by intermodel spread in dry heat transport

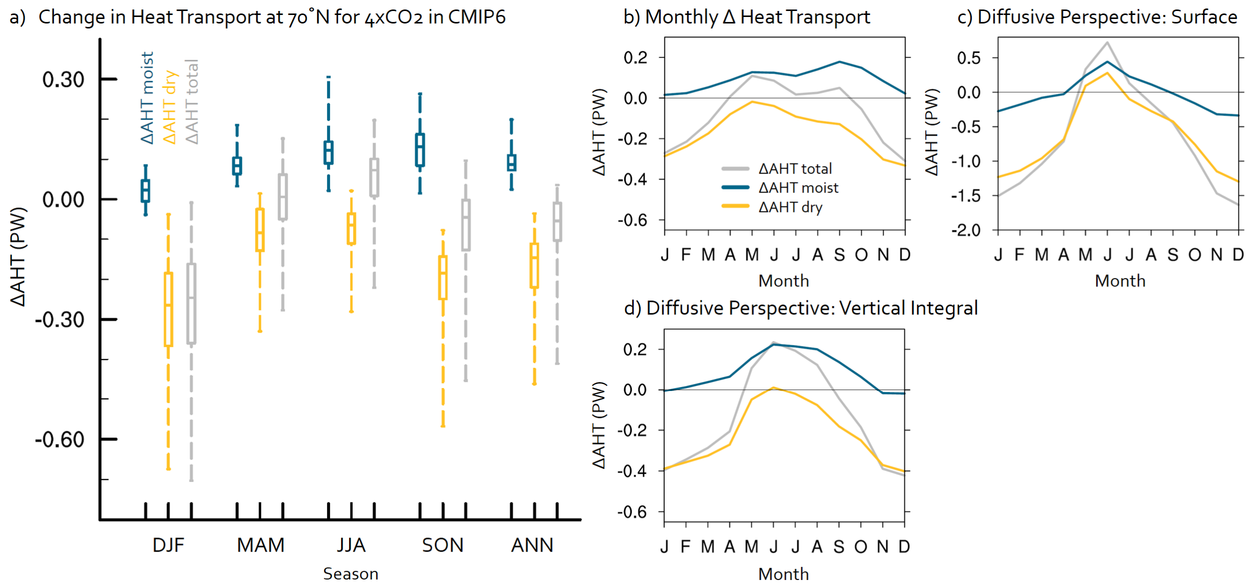

Figure 1. (a) Seasonal and (b) monthly-mean changes in moist (blue), dry (yellow), and total (grey) atmospheric heat transport (AHT; PW) at 70˚N, averaged over 31 years centered on year-100 after CO_2 quadrupling in CMIP6. (c,d) Monthly-mean change in AHT calculated from down-gradient diffusion of (c) surface (d) and vertically-integrated anomalies in moist and dry static energy in the same simulations. Line plots (b-d) show the ensemble-mean change in AHT, and box plots (a) show the minimum, 25th percentile, median, 75th percentile, and maximum change in AHT across CMIP6 models.

as a result of larger climatological values; when normalized by the climatology, intermodel spread is larger for the relative change in moist heat transport (Figure S1a). Large intermodel spread persists when heat transport changes are normalized by global-mean near-surface warming in each model (Figure S1b).

2.2 A Diffusive Perspective on Seasonal Changes in Poleward Heat Transport

We next explore what causes this seasonal pattern of heat transport change from a diffusive perspective. Down-gradient diffusion of near-surface temperature and specific humidity has previously been used to explain heat transport changes in the annual mean (e.g., Armour et al., 2019; Flannery, 1984; Frierson et al., 2007; Hwang et al., 2011; Roe et al., 2015). Can diffusive transport also explain the seasonality of heat transport changes?

In a diffusive perspective, atmospheric heat transport is assumed to be proportional to the meridional gradient of moist static energy (MSE); this gradient can be calculated separately for the latent energy (Lq) and dry static energy ($c_pT + gZ$; Z is geopotential height) components of

MSE to partition latent and dry heat transports (e.g., Armour et al., 2019; Bonan et al., 2023; Siler et al., 2018). Down-gradient diffusion is typically applied to the near-surface MSE, eliminating the geopotential term and resulting in:

$$\mathrm{AHT_{dry}}(x) = -2\pi a^2 D(1-x^2)c_p\frac{dT_s}{dx}, \quad (2a) \qquad \mathrm{AHT_{latent}}(x) = -2\pi a^2 D(1-x^2)L\frac{dq_s}{dx}, \quad (2b)$$

where x is the sine of latitude, D is a diffusivity constant, T_s is the near-surface temperature, and q_s is the near-surface specific humidity. This diffusive perpective can also be applied to MSE integrated throughout the Arctic troposphere:

$$\mathrm{AHT_{dry}}(x) = -2\pi a^2 D(1-x^2)\frac{d}{dx}\frac{1}{p_{trop}}\int_{300\ hPa}^{p_s} c_pT + gZ\,dp, \tag{3a}$$

$$\mathrm{AHT_{latent}}(x) = -2\pi a^2 D(1-x^2)\frac{d}{dx}\frac{1}{p_{trop}}\int_{300\ hPa}^{p_s} Lq\,dp, \tag{3b}$$

where we take 300 hPa to be representative of the Arctic tropopause, and $p_{trop} = \int_{300\ hPa}^{p_s} dp$ is the pressure thickness of the troposphere.

We use an annual-mean diffusivity D calculated from the ensemble mean of *piControl* simulations by setting the total diffusive heat transport equal to the total heat transport from Eq. (1). This yields a diffusivity of 0.3 W m^{-2} K^{-1} at 70°N for surface diffusion, similar to values of D diagnosed in previous studies (e.g., Hwang and Frierson, 2010), and a diffusivity of 0.6 W m^{-2} K^{-1} at 70°N for vertically-integrated diffusion. We find the same values of diffusivity when using MSE gradients and total heat transport averaged more broadly from 65 to 75°N. We use these values of diffusivity for the CO_2 forcing simulations as well, with the assumption that diffusivity changes are relatively small in these simulations (Armour et al., 2019; Roe et al., 2015).

When applied to near-surface anomalies in temperature and humidity from CMIP6 models (Eq. 2), down-gradient diffusion does not fully capture the seasonal pattern of heat transport change. In line with actual changes (Figure 1b), a diffusive perspective predicts increased moisture transport in summer and decreased dry heat transport in winter (Figure 1c). However, near-surface diffusion also predicts decreased moisture transport in winter, and overestimates dry heat transport changes by an order of magnitude. This large decrease in diffusive dry heat transport results from Arctic-amplified near-surface warming that peaks in winter (Figure S2d). Meanwhile, increased poleward moisture transport in summer results from warmer preindustrial temperatures at lower latitudes, which moisten more than the Arctic under CO_2 forcing following the Clausius-Clapeyron relation (Figures S2a, e-f). In winter, this initial-temperature effect is overcome by Arctic-amplified winter warming, which produces a larger moistening at higher latitudes (Figures S2d-f) and decreases the diffusive moisture transport to the Arctic.

With near-surface diffusion failing to capture the full seasonal pattern of poleward heat transport changes, we consider diffusion of anomalies in moist static energy integrated throughout the troposphere (Eq. 3). This vertically-integrated diffusion is motivated by the expectation that transient eddies respond to meridional temperature gradients throughout the troposphere, not just at the surface. We expect vertically-integrated diffusion to better predict heat transport particularly in the Arctic, where the full tropospheric temperature response is decoupled from the surface response as a result of stable surface inversions in winter (Cronin and Jansen, 2015; Payne et al., 2015). We note that the value of diffusivity we use for the vertically-averaged MSE diffusion is approximately twice the magnitude of that used for near-surface diffusion as the meridional MSE gradients are generally weaker higher in the atmosphere.

Arctic stability supports peak warming and moistening near the surface in winter under CO_2 forcing, with weaker changes aloft (Figure S3). As a result, vertically-integrated warming is less Arctic-amplified than near-surface warming. This yields a weaker reduction in diffusive dry heat transport that more closely resembles the actual heat transport change (Figure 1d). Also in line with actual heat transport changes, larger vertically-integrated moistening at lower latitudes than in the Arctic produces an almost year-round increase in diffusive latent heat transport that peaks during summer (Figure 1d). This yields smaller differences between the actual heat transport diffusive transport of vertically-integrated anomalies than for surface diffusion (Table S2). We find similar results when diffusive transport is applied exclusively to the lower troposphere (integrated from 1000 to 600 hPa; not shown), where eddy poleward heat flux is projected to change most under CO_2 forcing (Audette et al., 2021; Kaufman and Feldl, 2022).

In summary, vertically-integrated diffusion captures the magnitude and sign of seasonal heat transport changes better than near-surface diffusion due to a dropoff in Arctic warming with height. The fit between the diffusive and actual heat transports could be improved by allowing for seasonal variations in diffusivity, but even with annually constant diffusivity, seasonality in temperature and humidity anomalies broadly predicts seasonality in heat transport changes. We find that a diffusive perspective is useful for understanding the seasonal pattern of poleward heat transport: initially warmer conditions generate greater moistening at lower latitudes, particularly in summer, and support a summer-amplified increase in poleward latent heat transport, while winter-peaking Arctic amplification supports a winter-amplified decrease in poleward dry heat transport.

2.3 Relative Roles of Arctic and Lower Latitudes for Seasonal Heat Transport Changes

In Section 2.2, we showed that seasonal changes in moist and dry static energy gradients predict seasonal changes in poleward heat transport, following a diffusive perspective. Lower-latitude moistening appears to primarily control changes in the moisture gradient and therefore latent heat transport, while Arctic warming appears to primarily control changes in the temperature gradient and therefore dry heat transport. To better isolate the contributions of the Arctic and lower latitudes to seasonality in heat transport anomalies, we next analyze atmosphere-only simulations from the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al., 2019), which separately prescribe changes in Arctic sea-ice concentration (SIC) and global sea-surface temperature (SST).

In a control PAMIP simulation, year-2000 SIC and SST are applied. In a sea-ice loss simulation (*ΔSIC*), Arctic SIC anomalies from a 2˚C global warming scenario are applied, while the year-2000 SST is held fixed. In a sea-surface warming simulation (*ΔSST*), global SSTs from the same 2˚C warming scenario are applied while the year-2000 SIC is held fixed. This future warming scenario is a snapshot of the high-emissions RCP8.5 pathway at 2˚C of global warming relative to preindustrial control conditions. The *ΔSIC* simulation also applies SSTs from the 2˚C warming scenario in grid points that transition from sea-ice cover to open ocean. We use five PAMIP models with sufficient data to compute seasonal atmospheric heat transport (Supplementary Table S1), and calculate anomalies for the *ΔSST* and *ΔSIC* simulations relative to the control simulation. For each model, we take the average of 100 ensemble members with different initial conditions, and analyze the last 12 months of these 14-month simulations.

The sum of heat transport changes in the individual PAMIP simulations (*ΔSST* + *ΔSIC*) broadly reproduces the seasonal pattern of heat transport change in the CMIP6 *abrupt4xCO2* simulations: decreased dry heat transport that peaks in winter, and increased latent heat transport that peaks in summer (compare Figures 2a and 2d). The heat transport changes in the PAMIP simulations are smaller than those in the *abrupt4xCO2* simulation, which is expected given the weaker global warming in PAMIP (2˚C) compared to *abrupt4xCO2* (5.5˚C): a smaller global warming

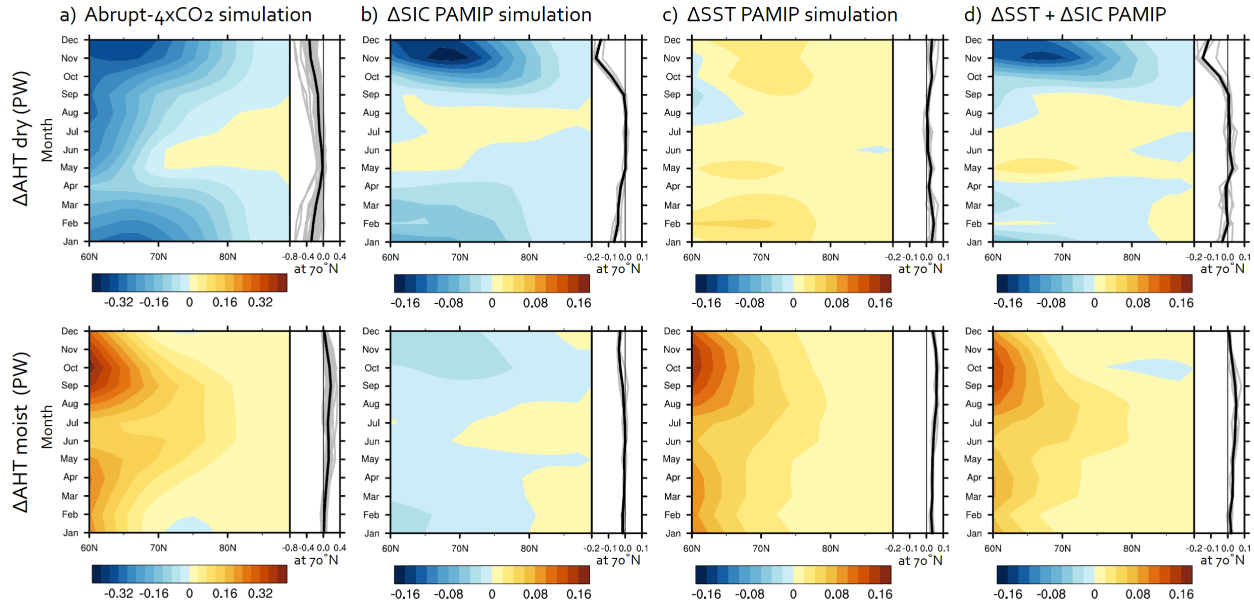

Figure 2. Change in dry (top) and moist (bottom) atmospheric heat transport (AHT; PW) in (a) CO_2 quadrupling simulations in CMIP6 and (b, c) PAMIP simulations that individually apply anomalies in (b) sea-ice concentration (ΔSIC) and (c) sea surface temperature (ΔSST) from a 2°C global warming scenario. The sum of the ΔSIC and ΔSST simulations is shown in d). Line plots show ΔAHT at 70˚N for individual models (grey) and the ensemble mean (black), and contour plots show ensemble-mean ΔAHT.

produces smaller Arctic warming and mid-latitude moistening, weaker changes in meridional temperature and moisture gradients, and therefore weaker changes in poleward heat transport from a diffusive perspective. In addition, the *abrupt4xCO2* simulation shows a larger decrease in dry heat transport in late winter (January-March) than the combined PAMIP simulations. This difference is also predicted by diffusive transport: with greater warming in the Arctic, the seasonal warming maximum shifts from early to late winter (Hahn et al., 2022; Holland and Landrum, 2021; Liang et al., 2022), reducing the meridional temperature gradient and shifting the reduction of dry heat transport into late winter.

With the PAMIP simulations reproducing the key seasonal features of heat transport anomalies found in CMIP6 simulations, we next investigate what controls these features—the Arctic or lower latitudes? For dry heat transport, Arctic sea ice changes produce a winter-peaking decrease

(Figures 2a,b) by promoting Arctic-amplified warming in winter (Figures S4b,f). The *ΔSST* simulation produces a more meridionally uniform warming (Figures S4c,g), causing little change in dry heat transport (Figure 2c). In contrast, lower-latitude moistening due to sea-surface warming (Figures S3k,o) largely explains the increase in poleward latent heat transport found in CMIP6 (Figures 2a,c). While sea-surface warming increases poleward latent heat transport in late summer and fall (Figure 2c), Arctic sea-ice loss contributes to a lesser degree by reducing latent heat transport in early winter (Figure 2b), producing a summer peak in the net latent heat transport increase (Figure 2d).

Consistent with previous analysis of how the Arctic and lower latitudes contribute to heat transport in the annual-mean (Audette et al., 2021), we find that Arctic sea-ice loss primarily controls dry heat transport change while lower-latitude moistening primarily controls latent heat transport change. When considering the seasonality of heat transport change, we find that Arctic sea-ice loss also plays a role for latent heat transport by reducing it in early winter to support a summer peak, in combination with lower-latitude moistening. These PAMIP simulations again suggest that heat transport changes are broadly consistent with down-gradient diffusion of moist and dry static energy anomalies, which produces similar results for these simulations (Figure S5).

2.4 Intermodel Spread in Seasonal Heat Transport Changes

We next consider the sources of intermodel spread in seasonal heat transport. A diffusive perspective again provides physical insight: CMIP6 models with larger changes in the meridional gradients of winter temperature and summer moisture tend to show larger changes in dry and latent heat transports, respectively (Figures 3e,g). To investigate what regions control intermodel spread in these gradients and in seasonal heat transport, we examine the meridional structure of

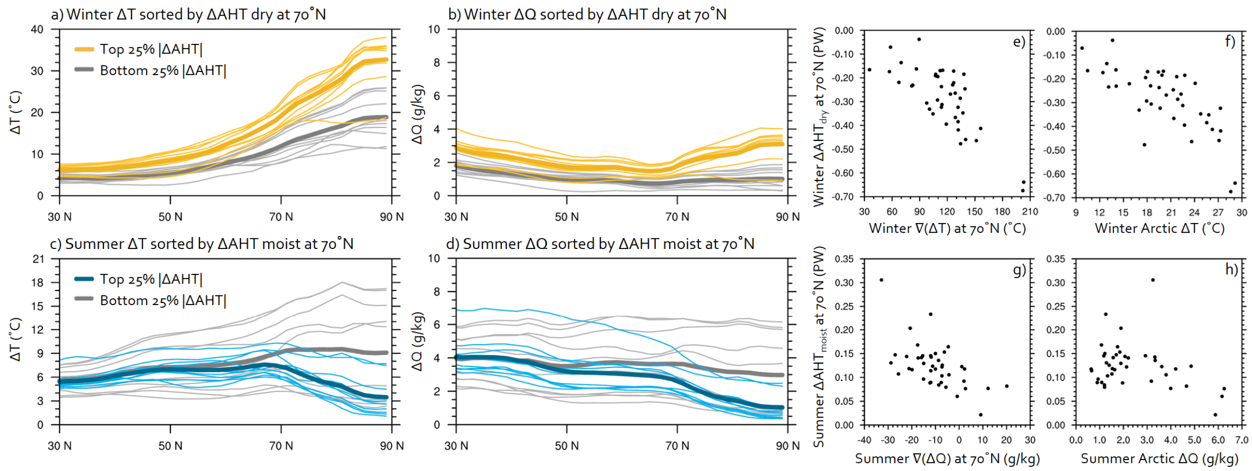

Figure 3. Anomalies in (a, c) near-surface temperature (ΔT; °C) and (b, d) specific humidity (ΔQ; g/kg) in CO_2 quadrupling simulations in CMIP6 for the top and bottom 25% of models sorted by their change in (a, b) winter dry and (c, d) summer moist atmospheric heat transport (AHT) for individual models (thin lines) and their ensemble means (thick lines). Change in winter dry AHT (PW) versus (e) the gradient in ΔT at 70˚N (˚C/sinθ; $r^2 = 0.59$) and (f) Arctic ΔT (˚C; $r^2 = 0.54$), and change in summer moist AHT (PW) versus (g) the gradient in ΔQ at 70˚N (g/kg/sinθ; $r^2 = 0.35$) and (h) Arctic ΔQ (g/kg; $r^2 = 0.09$) for CO_2 quadrupling simulations in 41 CMIP6 models.

temperature and moisture anomalies for models in the top and bottom quartiles of winter dry (Figures 3a,b) and summer latent (Figures 3c,d) heat transport changes. Intermodel differences in Arctic warming contribute more than lower latitudes to intermodel spread in both latent and dry heat transport change. Models with the largest reduction in winter dry heat transport have more Arctic warming than other models (weakening the meridional temperature gradient; Figure 3a); models with the largest increase in summer latent heat transport have similar midlatitude warming but less Arctic warming than other models (steepening the meridional moisture gradient; Figures 3c,d).

Negative correlations exist across CMIP6 models between Arctic warming and dry heat transport in winter, and to a lesser extent between Arctic moistening and latent heat transport in summer (Figures 3f,h). Correlations are much weaker between heat transport changes and midlatitude temperature and moisture. This indicates that while poleward latent heat transport increases due to lower-latitude moistening, its intermodel spread at 70˚N is more strongly controlled by the Arctic than lower latitudes. Using near-surface anomalies in temperature and moisture produces stronger intermodel correlations with heat transport than vertically-integrated anomalies (Figure S6), likely because intermodel spread in heat transport is dominated by considerable intermodel spread in Arctic warming, which is surface-trapped. Our results again support a diffusive understanding of seasonal changes in poleward heat transport, and suggest a key role for the Arctic in generating intermodel spread, particularly for dry heat transport.

3 Conclusions

We investigate the seasonal cycle of poleward atmospheric heat transport change in CMIP6 models, the relative roles of Arctic sea-ice loss and sub-Arctic warming in driving those changes, and the extent to which heat transport changes can be understood from a diffusive transport perspective. We find a summer maximum in increased latent heat transport and a winter maximum in decreased dry heat transport under CO_2 forcing. While down-gradient diffusion of near-surface anomalies in moist static energy overestimates the extent to which heat transport is reduced in winter, diffusion of vertically-integrated anomalies more accurately predicts the seasonal pattern and magnitude of heat transport changes. PAMIP simulations that isolate the role of Arctic sea-ice loss versus global sea-surface warming also demonstrate that a diffusive perspective can be used to understand seasonality in heat transport. While Arctic sea-ice loss is responsible for the winter-amplified reduction in dry heat transport, the summer-amplified increase in latent heat transport is primarily controlled by sub-Arctic warming and moistening, with a smaller contribution from Arctic sea-ice loss damping latent heat transport in early winter. Lastly, we find that Arctic warming differences between models are the dominant contributor to intermodel spread in poleward heat transport in CMIP6 models under CO_2 quadrupling, again in line with a diffusive perspective.

Our results suggest that a diffusive transport model is an effective way to understand changes in poleward heat transport seasonally, in addition to the annual mean. Diffusive transport offers intuition into how poleward heat transport will evolve over time based on future temperature and moisture gradients: for example, we expect that the migration of the seasonal maximum in Arctic warming from early to late winter (Hahn et al., 2022; Holland and Landrum, 2021; Liang et al., 2022) will also shift the reduction in poleward heat transport from early to late winter. A diffusive perspective also indicates that heat transport acts to dampen intermodel spread in Arctic warming, as models with weaker Arctic warming exhibit more poleward heat transport.

While past literature has focused on the contribution of latent heat transport in winter to the winter peak in Arctic warming (Doyle et al., 2011; Gong et al., 2017; Luo et al., 2017; Woods et al., 2013; Woods and Caballero, 2016), we find that CMIP6 models predict the largest increases in latent heat transport in summer. As these summer changes will be translated into winter warming via seasonal ocean heat storage and sea-ice thinning (Chung et al., 2020; Dai et al., 2019; Deser et al., 2010; Manabe and Stouffer, 1980; Screen and Simmonds, 2010b), future research should investigate the impact of heat transport changes in summer as well as winter. Graversen and Langen (2019) posit that Arctic warming from increased latent heat transport will outweigh cooling from decreased dry heat transport by producing a larger greenhouse effect and a larger sea-ice albedo change for a positive versus negative forcing. We hypothesize that opposite seasonality in latent and dry heat transports is another reason to expect non-compensating effects of changes in atmospheric heat transport on Arctic warming. Specifically, we expect the summer amplification of a given increase in latent heat transport to cause greater Arctic warming than the cooling caused by the same magnitude of decreased dry heat transport in winter. This intuition is built on past findings that summer forcing produces more annual-mean warming in the Arctic by supporting a larger albedo feedback than winter forcing (Bintanja and Krikken, 2016). Our results underscore the importance of studying poleward heat transport in all seasons, rather than only the season of peak Arctic warming. Future efforts to understand and predict Arctic climate change should investigate how seasonality in heat transports, as well as other Arctic feedbacks, mediates their effect on Arctic climate change.

Acknowledgments

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Data Availability Statement

All CMIP and PAMIP data analyzed in this study can be found in the Earth System Grid Federation (ESGF) repository at https://esgf-node.llnl.gov/projects/esgf-llnl/. The CMIP and PAMIP models used in this analysis are listed in Supplementary Table S1.

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