Section 1. Introduction

The combined poleward meridional heat transport (MHT) by the ocean and atmosphere plays a fundamental role in moderating temperatures on Earth. In the absence of MHT, the equator-to-pole temperature gradient would be approximately three times greater than observed (Piererehumbert, 2010). Therefore, future and past changes in MHT exert a primary control on the spatial pattern of temperature change with increased MHT resulting in a weakening of the equator-to-pole temperature gradient equivalent to the polar amplification of warming (Holland and Bitz, 2003). The spatial pattern of warming, in turn, impacts the sensitivity of global mean temperature to climate forcing by way the spatial pattern of climate feedbacks – the so-called pattern effect (Armour et al., 2013).

Coupled climate models simulate almost no change (approximately 1%) in MHT in response to anthropogenic and paleoclimate forcing ranging from the Last Glacial Maximum to CO_2 quadrupling (Donohoe et al., 2020). The lack of significant changes in MHT is due in part to compensation between increases in atmospheric heat transport (AHT) and decreases in (implied) ocean heat transport (OHT) under warming. This compensation is also found in idealized model simulations (Enderton and Marshall, 2008). Models that have greater increases in AHT in the Arctic simulate less polar amplification of warming (Hwang et al., 2011) suggesting that AHT responds to patterns of warming as opposed to AHT causing the pattern of warming (Feldl and Roe, 2013 and Armour et al., 2020). In contrast, OHT is generally thought to force patterns of surface temperature including the climatological hemispheric asymmetry (Kang and Seager, 2014) and the response of the high-latitudes to future changes (Rose et al., 2014) with future changes in Arctic sea ice being particular sensitive to OHT changes (Bitz et al. 2005, Liu et al., 2020).

On shorter timescales (e,g, days), AHT is the primary driver of heating in the climate system which suggests that model biases and future changes in temperature variance may be a consequence of the natural variability of simulated AHT. Yet almost no work exists on identifying model biases in AHT variability that likely impact future predictions of heat wave occurrence.

Should we expect that future changes in observed AHT and OHT will compensate for one another such that MHT changes are small in magnitude as seen in the models? Is it possible that MHT changes will be larger than seen in climate models and the resultant changes in the spatial pattern of temperature (and hydrology) will diverge from the range of model projections? Given that the majority of insights into the connection (or lack thereof) between MHT changes and changes in the spatial pattern of temperature have come from model simulations – both comprehensive and idealized – it is imperative to ask if models adequately represent MHT, its partitioning between the AHT and OHT and its temporal variance. While the most societally impactful question to address is how long-term changes in MHT will affect surface climate, this question is scientifically untenable absent long-term records of observed MHT, which are not discernible outside of the satellite era. Instead, we propose to analyze potential model biases in MHT by comparing models and observations at timescales that are well constrained by the observational record. Specifically, we will analyze model biases in:

1) *The climatological partitioning of total poleward heat transport (MHT) between atmospheric heat transport (AHT) and ocean heat transport (OHT*

2) *Trends in atmospheric heat transport (AHT) over the historical record*

3) *The sub-seasonal variability of atmospheric heat transport and its connection to atmospheric heating events, including heat waves.*

Our goal is to use these observationally constrained problems to identify potential model biases in the (atmospheric and oceanic) processes contributing to MHT and to provide insights into whether model simulations of past and future changes in MHT should be trusted. We emphasize that the co-PIs have been developing diagnostic tools for over a decade that make the comparison of model and observations of MHT and its partitioning across the three time scales identified above possible for the first time.

This proposal is organized as follows. We cover the three timescales of potential model biases in MHT sequentially. Section 2 discusses annual mean climatological partitioning of MHT between AHT and OHT. Section 3 discusses trends in AHT over the historical record. Section 4 discusses AHT variability at sub-seasonal timescales. Within each section we introduce the problem conceptually and give a summary of the existing literature on each subject. We then discuss the methods we will use to address the problem and some initial results. We end each section with the proposed work to be performed on each problem.

Section 2. Identifying model biases in the climatological partitioning of poleward heat transport between the atmosphere and ocean.

Observational studies dating back 50 years found that poleward heat transport by the ocean (OHT) exceeds but is comparable in magnitude to that in the atmosphere (AHT) in the tropics (equatorward of 20, Figure 1) whereas AHT comprises the vast majority of total MHT in the extratropics (Vonderhaar and Oort, 1973 and Oort, 1976). More modern analysis has refined the quantitative estimates of MHT partitioning but paints the same qualitative picture of OHT dominance in the tropics and AHT dominance in the extratropics (Trenberth and Caron, 2006 and Mayer et al., 2021). Coupled climate models qualitatively reproduce the spatial structure of MHT partitioning (Donohoe et al. 2020). However, a quantitative observational-model comparison in MHT partitioning is lacking in the literature, in part because the methods used to diagnose AHT and OHT in the observations and models differ (as we document below). The PIs have developed a method to overcome these differences and make a meaningful comparison between MHT partitioning in models and observations.

The partitioning of MHT between AHT and OHT has impacts on mean state climate and likely will impact forced climate changes and variability for the following reason: the convergence of OHT in the extratropics is inherently linked to the surface energy budget and thus demands a surface temperature response whereas the convergence of the same quantity of AHT in the upper atmosphere can be radiated to space with minimal impact on surface climate. Thus, AHT and OHT have disproportionate impacts on surface climate and its changes by way of their control on the vertical structure of atmospheric temperature. AHT is argued to fundamentally control the extratropical lapse rate (Hahn et al. 2020) and its change (Feldl, 2020). High latitude surface climate is particularly sensitive to the partitioning of MHT between OHT and AHT due to the substantial (order 20%) contribution of the stratospheric circulation to AHT (Overland, 94) that make a negligible contribution to the surface energy budget (Cardinale et al., 2021). Therefore, model biases in MHT partitioning between the AHT and OHT will likely affect not only mean state climate but also may be indicative of model biases in the thermodynamic coupling between the atmosphere and ocean which will have downstream impacts on forced climate change and variability.

Conceptual approach and initial results:

MHT in climate models and observations is calculated as the poleward heat transport through a given latitude circle needed to balance the net radiative deficit at the top of atmosphere (TOA) integrated over the polar cap bounded by that latitude:

$$MHT(\theta) = 2\pi a^2 \int_{\theta}^{90} -TOA^{!} \cos\theta \, d\theta \quad , \tag{1}$$

where a is the Earth's radius and the ($^{!}$) indicates an anomaly from the global mean which ensures MHT goes to zero at the south pole even if global mean TOA is non-zero. Similarly, OHT in climate models is calculated from heat transport needed to balance the net surface heat flux (SHF) out of the ocean surface:

$$OHT(\theta) = 2\pi a^2 \int_{\theta}^{90} SHF^{!} \cos\theta \, d\theta \quad . \tag{2}$$

AHT in climate models is then diagnosed as the difference in MHT and OHT. Observational estimates of SHF are sparse and feature unrealistically large global mean imbalances (Stephens et al., 2012) which renders the calculation of OHT from Eq. 2 unreliable. Instead, AHT is calculated from the vertical integral the product of meridional velocity and moist static energy (MSE) using high frequency atmospheric reanalysis:

$$AHT(\theta) = \frac{2\pi a^2 \cos\theta}{g} \int_{0}^{Ps} V * MSE \, dP \quad . \tag{3}$$

The mass balance of the atmosphere must be balanced prior to the AHT calculation in Eq. 3 which is achieved by removing the zonal and vertical average MSE at each latitude as was done in Donohoe and Battisti (2013), Liang et. al. (2018) and Donohoe et al. (2020). The observational estimate of OHT is then calculated as the difference between MHT and AHT. ***The methods we use to calculate AHT and OHT in models (Eq. 2) and observations (Eq. 3) produce nearly identical results when applied to a single model in which the high frequency atmospheric field need to apply Eq. 3 are saved (Fig. 1).*** This result suggests that specific methods used to calculate model and observational AHT and OHT are self-consistent (e.g. balance the energy budget of the climate system) which enables comparison of observational and model MHT partitioning for the first time.

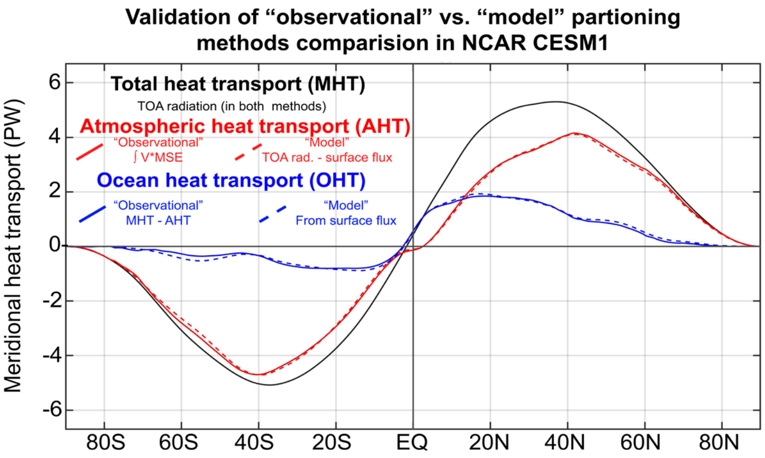


Figure (1). Comparison of the observational and model approach to MHT partitioning in an NCAR CESM1 simulation. AHT (red) is calculated from the vertical and zonal integral of the product of moist static energy and winds in the observational approach (solid) and from TOA radiation minus the surface heat flux in the model approach (dashed). OHT (blue) is calculated from the residual of MHT and AHT in the observational methodology (solid) and from the spatial integral over the polar cap of the surface heat flux in the model methodology (dashed).

The observational partitioning of MHT into AHT and OHT derived from CERES EBAF satellite TOA radiation (Loeb et al., 2018) and ERA 5 atmospheric reanalysis (Hersback et al., 2020) is compared to that in the ensemble of coupled climate models using model output from CMIP3, CMIP5 and CMIP6 in Fig. 2. OHT is biased low in the subtropics and extratropics of both hemispheres and AHT is biased high in the Northern Hemisphere (NH). These biases are independent of the CMIP model generation, observational satellite radiation and atmospheric reanalysis used (not shown).

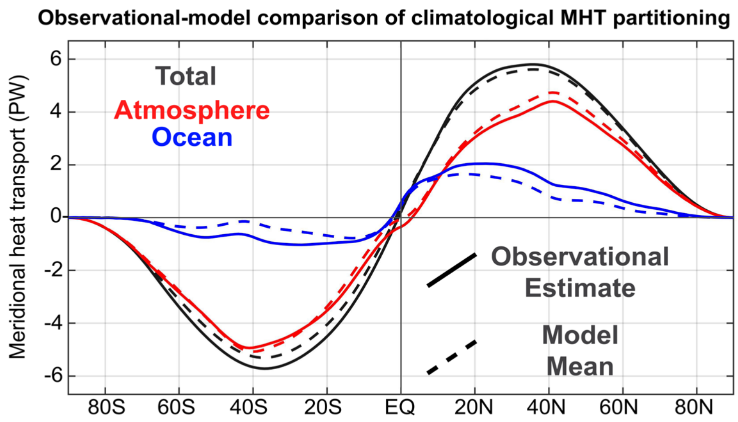


Figure 2. Comparison of annual mean MHT partitioning in observations (solid lines) and the ensemble mean of models (CMIP3,5, and 6 --dashed line). The black line shows the combined northward heat transport by the ocean and atmosphere (MHT). Atmospheric heat transport (AHT) is shown in red. Ocean heat transport (OHT) is shown in blue.

Proposed work: *Understanding the physical mechanisms responsible for model biases in AHT and OHT*. This proposed work will be pursued from two complimentary perspectives: i) *Dynamics perspective:* AHT and OHT biases result from biases in the atmospheric and oceanic circulation and/or the energy contrast between equatorward and poleward moving air/water; ii) *Energy perspective:* Model biases in AHT and OHT result from biases in the energy input into the atmosphere/ocean at the equator-to-pole scale due to radiative processes and turbulent energy exchange between the atmosphere and ocean. We will diagnose the causes of model biases in AHT/OHT from the dynamic and energetic perspectives to diagnose the root cause of model biases in MHT partitioning.

Dynamics perspective: The atmospheric circulations responsible for AHT will be diagnosed by decomposing the meridional velocity and MSE into time means (denoted by $overbars$) and zonal means (denoted by $[brackets]$), zonal anomalies (denoted by *), temporal anomalies (denoted by ′s) at each pressure level and anomalies from the vertical average (denoted by †):

$$AHT(\theta) = \frac{2\pi a^2 \cos\theta}{g} \int_0^{Ps} \underbrace{\overline{[V'MSE']}}_{\substack{Transient\\ eddy}} + \underbrace{[\overline{V^*}\ \overline{MSE^*}]}_{\substack{Stationary\\ eddy}} + \underbrace{\overline{[V]}^\dagger\ \overline{[MSE]}^\dagger}_{\substack{Overturning\\ Circulation}} dP \qquad . \qquad (4)$$

Because only the product of like quantities give non-zero time and zonal means (Lorenz, 1953), there a 3 contributions to AHT: 1) transient eddies (TE) associated with baroclinic eddies at synoptic timescales; 2) stationary eddies (SE) associated with planetary scale waves due to orography and land-ocean thermal contrast and; 3) the meridional overturning circulation (MOC) associated with the tropical thermally direct Hadley cells and extratropical thermally indirect Ferrel cells. Donohoe et al. (2020) developed a method to calculate AHT by transient eddies in CMIP5 models without high frequency data by way of the residual of the total AHT calculated from Eq. 1 and 2 and the MOC and SE calculated from time mean 3-dimensional atmospheric fields. They found that the primary model bias in AHT was due to transient eddies but that models had a large spread and substantial bias in SE and MOC as well.

In the proposed work we will decompose AHT in CMIP6 models into TE, SE and MOC contributions and compare to AHT in observations to identify which circulations contribute to AHT biases following Donohoe et al. (2020). We will further decompose the MSE into moist and dry components, do the calculations season by season and analyze potential model biases in the vertical and longitudinal structure of each contribution. Model biases in the vertical structure of AHT would likely contribute to model biases in the mean state lapse rate and lapse rate feedback (Hahn et al., 2020, Feldl et al. 2020). We will additionally use high frequency model output to understand why models are biased in the TE heat transport. We will perform a spatial-temporal spectral analysis of the TE AHT to identify if models are biased in the dominant spatial scale or temporal frequency of the TE AHT.

Energy perspective: Here we wish to diagnose which energetic processes cause model biases toward too much poleward AHT and too little OHT. Model biases in the partitioning of MHT (Fig. 2) suggest that models add too much energy to the tropical atmosphere at the expense of removing energy from the tropical ocean. Fajber et al. (2022) demonstrated that AHT can be decomposed into the processes contributing to spatial gradients in energy input to the atmosphere, specifically:

$$AHT(\theta) = -2\pi a^2 \int_{\theta}^{90} \left(LE' + SENS' + RAD_{ATMOS}{}'\right) \cos\theta \, d\theta \quad , \tag{5}$$

where E is the evaporation, L is the latent heat of evaporation, SENS is the sensible heat flux and RAD_{ATMOS} is the net radiative flux into the atmospheric column and, as before, ($'$) indicates an anomaly from the global mean. Eq. 5 says that the AHT is set by energetic processes that add energy to the tropical atmosphere or, equivalently, remove energy from the extratropical atmosphere relative to the global mean atmospheric heating. Fajber et al. (2022) demonstrated that AHT is primarily determined by E' due to the large contrast in evaporation between the tropics/subtropics and extratropics whereas sensible heat fluxes are smaller in magnitude and the radiative heating of the atmosphere is fairly spatially homogenous. Spatial gradients in evaporation (E') add energy to the low-latitude atmosphere at the expense of removing energy from the ocean and, thus, have compensating impacts on AHT and OHT. Therefore, our initial hypothesis is that *models are biased toward too much AHT and too little OHT due to stronger than observed evaporation in the low latitudes*. Initial analysis (not shown) shows that models are indeed biased toward too much low latitude evaporation relative to observational estimate from WHOI OA flux (Yu et al., 2004) and SEAFLUX (Curry et al. 2004) and the implied AHT due to evaporation biases (diagnosed from Eq. 5) is quantitatively consistent with the ensemble mean AHT bias.

In the proposed work, we will analyze the energetic processes that contribute to model biases in AHT via Eq. 5 by additionally analyzing model biases in atmospheric radiation (relative to satellite observations) and sensible heat fluxes to evaluate whether they are consistent with the AHT bias identified in Fig. 2. We will check for consistency of these results against different observational estimates of turbulent energy fluxes and radiation including atmospheric reanalysis and additional satellite derived estimates. We will analyze the regions and seasons that contribute to energetic biases and evaluate if models with larger seasonal biases in energetics also have larger seasonal biases in AHT/OHT partitioning.

We will also perform some idealized climate model simulations to evaluate the proposed mechanism of evaporation strength determining the partitioning of MHT between AHT and OHT. Specifically, we will use a coupled version of the GFDL MOM6-AM2 model with idealized ocean basin geometry which has realistic partitioning of AHT/OHT in the mean state (Ragen et al., 2022). We will change the strength of evaporation by multiplying the coefficient that determines evaporation in the model (via the bulk formula) by a pre-factor varying from 25% to 400%. Our hypothesis is that simulations with a smaller evaporation pre-factor (less evaporation) will have more poleward OHT and models with a larger pre-factor (more evaporation) will have more poleward AHT. We will analyze the sensitivity of these results to different ocean basin geometries which exhibit different character of mean state ocean circulation including a cross equatorial AMOC. We will additionally change the evaporation pre-factor in single ocean basins to analyze if the AHT/OHT partitioning is more sensitive to surface energy exchanges in the Atlantic-like or Pacific-like basin. These experiments will illuminate how large model biases in the parametrization of the bulk formula of evaporation would have to be to be responsible for the AHT/OHT biases seen in Fig. 2. Guided by these results, we will analyze if models with similar formulations of the bulk formula have similar biases in AHT/OHT partitioning or if other complicating factors (e.g. surface wind and radiation biases) come into play.

OHT biases by ocean basin: We will analyze which ocean basin is responsible for the biases in OHT by applying Eq. 2 ocean basin by ocean basin which requires the SHF as a function of longitude. The observational SHF will be calculated by way of the difference between the TOA radiation and local AHT convergence (Trenberth, 1997) which will also require that the zonal structure of AHT to be calculated. We will apply the 2-dimensional (lat-lon) AHT methodology of Donohoe and Battisti (2012) which expresses the atmospheric heat flux in advective form and closes the mass budget via removal of the vertical average MSE at each gridpoint (akin to the approach used in Eq. 4):

$$\nabla \cdot AHT(\theta,\varphi) = \frac{1}{g}\int_0^{Ps}(U,V)\nabla MSE + MSE^{\dagger}\nabla \cdot (U,V)dP \quad . \qquad (6)$$

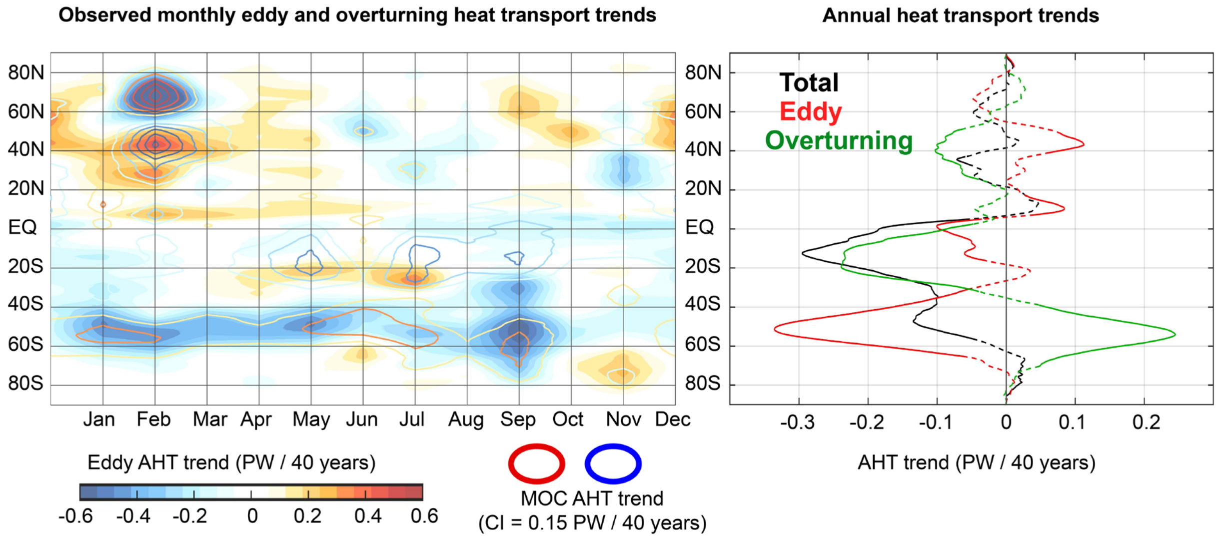
We have used this approach on ERA-interim data at monthly timescales (Donohoe and Battisti, 2012) and found that the climatological AHT was in good agreement with that calculated using more standard conservation of mass adjustments (Trenberth and Stepaniak, 2004). The first task will be to verify that this method of calculating inferred SHF by way of the difference between TOA radiation and two-dimensional vertically integrated AHT convergence reproduces the SHF in climate models. We will do the two-dimensional equivalent of the calculation shown in Fig. 1 working with CESM model to make sure our method of calculating two-dimensional AHT is consistent with the energy conservation in the model. We will then decompose the observed OHT basin by basin and analyze which ocean basin is responsible for model biases in OHT and which regions and seasons contribute to the SHF biases.

Section 3. Trends in atmospheric heat transport over the historical record

Conceptual approach and initial results: Long-term increases in AHT have the potential to warm the extratropics but may also be a response to ocean heat uptake and/or radiative feedbacks in the high latitudes (e.g., Armour et al. 2019). Hwang et. al (2011) demonstrated that models with larger increases in poleward AHT in the equilibrium response to CO_2 forcing had less polar amplified warming which suggests that AHT *responds* to radiative feedbacks instead of forcing high latitude warming. This anti-correlation has been explained, in idealized models, as a mediation of the AHT by decreases in dry static energy transport in response to the ice albedo feedback (Feldl et al. 2017, Henry et al. 2021). It is, however, unclear if the simulated changes in AHT are consistent with the observed changes over the historical period and if the sensitivity of AHT to radiative feedbacks and long-term warming are adequately represented in the models.

Preliminary analysis of trends in observed AHT calculated from Eq. 4 using (6-hourly) ERA5 data over the historical (1980-2020) record are shown in Fig. 3. For ease of presentation, we have combined the transient and stationary eddies into a single “eddy” AHT to more clearly see the connection between trends in AHT by eddies and overturning circulation (MOC). Poleward AHT has increased significantly in the tropics, subtropics and extratropics of the Southern Hemisphere (SH) whereas changes in AHT in the NH are smaller in magnitude and only significant in the subtropics (as indicated by the solid black line in Fig. 3B). The increased poleward AHT in the SH is consistent with the downgradient response to increasing equator-to-pole temperature gradient in the SH associated with delayed Southern Ocean warming (Armour et al., 2016).

The changes in total AHT in the extratropics are smaller in magnitude than the changes in AHT partitioned into component circulations due to the strong but imperfect compensation between AHT by the eddies (red) and MOC (green). These changes are in the sense of an amplification of the climatological fluxes (which are poleward by the eddies and equatorward or thermally indirect by the Ferrel cell) and are significant in both hemispheres (as indicated by the solid lines). The compensation between trends in eddy and MOC AHT is also seen in the trends broken down by season (left panel of Fig. 3) where NH trends are most pronounced in late winter whereas SH trends are more seasonally invariant with only a modest enhancement in late winter. These results suggest that trends in total AHT are strongly muted by the near compensation between AHT by eddies and MOC which are spatially co-located and concurrent in time (including inter-annual variations – not shown). Importantly, the total AHT change is approximately one third of the eddy AHT change in the SH and near zero in the NH suggesting that total AHT changes are strongly muted by eddy and MOC AHT compensation and, thus, AHT changes have had a minimal impact on climate as compared to the eddy AHT acting alone.


Observed monthly eddy and overturning heat transport trends

Annual heat transport trends

Figure 3. Trends in AHT over the historical (1980-2020) period. The right panel shows the trends in total AHT (black) which are subdivided into eddy heat transport (red) and heat transport by the atmospheric meridional overturning circulation (green). Solid lines indicate trends that are significant at the 95% confidence interval. The left panel shows the trends within each month with colors showing the eddy AHT trend and contours showing the trend in AHT by the overturning circulation.

Should we expect future changes in eddy and MOC AHT to counter-balance one another resulting is small total AHT changes (and small climate impacts)? Alternatively, is the compensation noted in the historical record coincidental over the limited length record or a consequence of the transient response to anthropogenic forcing? Is the compensation between eddy and MOC AHT fundamental and represented in coupled climate models? The compensation between AHT changes by eddies and the Ferrel cell is expected based on the transformed Eulerian-mean equations and/or the thermodynamic forcing of vertical motion by the eddy heat flux convergence. However, the degree of compensation and its implication for climate change and variability has received less attention in the literature and has important implications for climate variability and trends. Our working hypothesis is that changes in eddy heat transport cause changes in the Ferrel cell AHT through the following mechanism: the intensified eddy AHT results in anomalous heat flux convergence which can either be balanced by radiative (and surface heat flux) feedbacks or by upward vertical motion with the latter manifested as an intensified thermally indirect Ferrel cell (due to mass continuity). Under this mechanism, the degree of compensation between eddy and MOC AHT is set by radiative (and surface heat flux) feedbacks of the eddy heat flux anomalies with strong feedback resulting in no compensation and no feedbacks resulting in perfect compensation.

Proposed work: We will analyze the consistency of the trends in AHT identified in Fig. 3 between different observational data sets including the ERA interim , NCEP, NASA MERRA-2 (Gelaro et al., 2017) and JRA 55 (Kobayashi et al., 2015) reanalysis. This will determine if the total AHT trends and compensation between eddy and MOC AHT is unique to the ERA5 data set. Specifically, we will ask if the eddy-MOC compensation depends on knowledge of the stratospheric circulation which is known to impact the MOC AHT (Marshall et al., 2012) and is less observationally constrained. Our calculations of AHT via Eqn. 4 have already been run on NCEP and ERA-interim reanalysis through 2015 and we will update these calculations through to the present day. We have yet to calculate AHT using MERRA data but anticipate that the methodology we have used on other reanalysis products can be extended to standard MERAA output. We will also compare our ERA5 AHT calculations with those performed by Mayer et al (2021) which use a different methodology to calculate AHT (in regard to the mass balance) and do not decompose the AHT into eddy and MOC but can be used to check the dependence of total AHT on methodology.

Our next task will be to compare the observed historical trends in AHT with those in climate models. We will analyze trends in AHT and its partitioning into eddy and MOC contributions in: (i) coupled climate models under historical forcing and (ii) atmosphere-only models (AMIP) forced by historical sea surface temperatures (SSTs). We will also analyze large ensembles of historical forcing simulations to diagnose the role of natural variability versus external forcing in AHT trends. In the coupled historical simulations, we will analyze if models that better match the observed trends in surface temperature and sea ice also have trends in AHT and its partitioning that better match those observed. In the AMIP simulations, we will ask if the AHT trends differ from those in the same model under historical forcing to diagnose the degree to which AHT is responding to observed temperature changes. We will additionally consider the inter-model spread of the spatial pattern of radiative feedback to further diagnose how much the inter-model spread in the radiative response to SST patterns impacts the inter-model diversity in the AHT trends over the historical record. The seasonality and partitioning of AHT into moist and dry components will be used as additional factors to discern the degree to which AHT is forcing versus responding to observed temperature and sea ice changes. Lastly, we will consider the degree of compensation between extratropical changes in eddy and MOC AHT to understand if our hypothesized mechanism of eddy AHT forcing MOC AHT changes is well represented in models. We will compare the degree of compensation seen in the transient (historical forcing and AMIP) with that seen at near equilibrium timescales under 4XCO_2 to understand if the eddy/MOC compensation is partially a result of the spatial pattern of transient heat uptake by the ocean or persists to equilibrium timescales. The Ferrel cell AHT changes will be decomposed into dynamical changes associated with the strength, meridional location, vertical extent and meridional width of the Ferrel cell and thermodynamic changes associated with changes in the gross moist stability of the atmosphere.

Idealized aquaplanet simulations with and without radiative feedbacks will be performed to test the mechanism of compensation between the eddy and MOC AHT. Specifically, we will run the GFDL AM2 atmospheric model coupled to a stagnant aquaplanet ocean of uniform depth under CO_2 ranging from half to quadruple pre-industrial values. We expect that under global warming, the equator-to-pole gradient in MSE will be increased, leading to more AHT primarily by the eddies with some degree of compensation by the MOC. We will then "lock" the radiation the atmosphere feels to its pre-industrial control state following the method we used in Cox et. al (2020), which demands that AHT is unchanged but that the atmospheric and surface temperatures can adjust to come into “dynamical equilibrium” with the forcing. Our theory predicts that radiative locking will require near perfect compensation between the eddy and MOC AHT and that the increased AHT by the eddies under global warming will result in an equal magnitude equatorward AHT by the Ferrel cell.

Section 4. Sub seasonal variability of atmospheric heat transport forces temperature variability

Conceptual approach and initial results: This component of the proposed work will analyze the processes responsible for atmospheric heating events at daily timescales and evaluate if the relevant processes are well represented in climate models. Initial results (expanded on below) demonstrate that AHT variability at daily timescales is responsible for the vast majority of the heating of the atmospheric column, which is tightly coupled to surface warming over most of the globe. Our initial results suggest that temperature variability is fundamentality set by AHT and the goal of the proposed work is to understand if AHT variability and the resultant surface temperature variability at daily timescales is well represented in state-of-the-art coupled climate models.

We recently developed a novel methodology for computing observational zonal mean AHT at six-hourly timescales (Cox et al., 2022) from ERA5 reanalysis. Conceptually, this approach subdivides the AHT into two contributions: i. the MOC acting on the vertical anomalies of MSE relative to the atmospheric column average MSE at each latitude and; ii. the eddies acting on zonal anomalies in MSE at a given pressure level:

$$AHT(\theta,t) = \frac{2\pi a^2 \cos\theta}{g} \int_0^{Ps} \underbrace{[V(t)^* MSE(t)^*]}_{EDDY} + \underbrace{[V(t)]^\dagger\,[MSE(t)]^\dagger}_{MOC}\,dP \quad . \quad (7)$$

Importantly, the time mean of this approach identically matches that of the more standard calculation of the AHT via Eq. 4 but has some important differences from existing work on high frequency AHT. Firstly, our calculation relies on meridional velocity and MSE data at each instant only (with no reference to the climatological values) and thus allows temporal anomalies in winds to advect the climatological MSE, which enhances the temporal variance of eddy AHT relative to other approaches that consider the transient eddy anomalies only (Messori et al, 2014). Secondly, our approach calculates the AHT with respect to a fixed mass of atmosphere (via implicitly balancing the mass budget through removal of the vertical average MSE) and, thus, removes temporal variations in AHT associated with changes in mass of the atmosphere averaged over the polar cap (equivalent to temporal tendencies in surface pressure). The latter contribution to AHT variability has been shown to be both large in magnitude and not a contributor to heating the atmosphere and surface (Liang et al., 2018). This point is demonstrated in Fig. 4 which shows the vertical (left panel) and latitudinal structure of (zonal mean) temperature anomalies associated with anomalous AHT at 50N using our 6-hourly calculation of AHT from ERA5 reanalysis. There is a clear heating (and moistening as shown by the contours) of the lower and middle troposphere which is most pronounced in the day following the AHT anomaly but persists for almost a week (Fig. 4A). AHT at 50N heats a latitude swath from 50N to 75N and cools the region equatorward of the AHT anomaly from 30N to 50N (Fig. 4B). Our definition of AHT shows a clear connection to heating of the atmospheric column. In contrast, the AHT associated with the atmospheric mass flux which is included in the standard definition of AHT shows a weak connection to atmospheric *cooling* over the polar cap (Fig. 4C and D) which is unexpected on physical grounds.

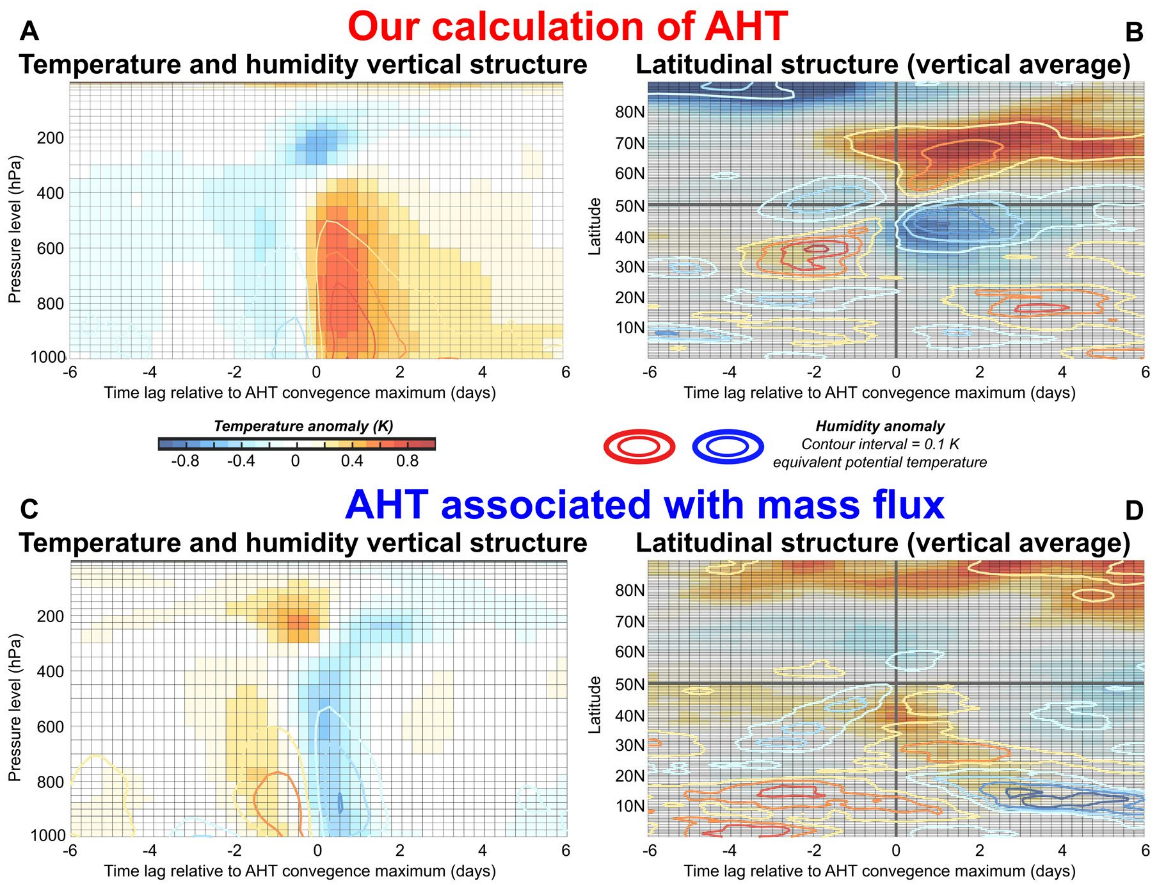


Figure (4). Temperature and humidity anomalies associated with a 1σ AHT anomaly. The upper panels show composites defined from the definition of AHT used in the proposed work. The lower panels show composites defined from AHT associated with the poleward mass flux only. Left panels show the vertical structure of lagged regressions against normalized AHT convergence at 50N. The right panels show lagged regressions of the atmospheric vertical average against normalized AHT at 50N. Temperature composites are shown in colors and humidity composites are shown by the contours (interval of 0.1 K equivalent moist potential temperature).

In summary, we have created an AHT metric that is more clearly connected to the thermal budget of the atmosphere as compared to the standard definition which combines mass and thermal fluxes. These relationships are encapsulated in the temporal correlation between AHT convergence and column integrated atmospheric tendency Fig. 5 which demonstrates that our novel definition of AHT convergence is more strongly correlated with atmospheric column heating than the standard definition (c.f. the red and blue curves in Fig. 5) with the latter being compromised by the unphysical relationship between mass fluxes and temperature anomalies. Importantly, our calculation of AHT is correlated with the atmospheric heating at values of greater than 0.6 and as high as 0.8 with the exception of the deep tropics. This result suggests that AHT is responsible for the vast majority of atmospheric heating on sub-monthly timescales with atmospheric radiation and surface processes playing a substantially smaller role. We note that the same compensation between eddy AHT and MOC AHT that we see in the long-term trends is present in our 6-hourly calculations, but it is much weaker (approximately 20%) which we interpret as follows: AHT anomalies are primarily driven by eddies and balanced by atmospheric heating with only a small residual available to force the upward motion which results in eddy/MOC AHT compensation. In a model setting (not shown), AHT and atmospheric heating are correlated at values of order 0.8 throughout the domain, which suggest that the lower values we see in our observational result at some latitudes is a consequence either of the consistency of the energy budget in the reanalysis or a limitation of our methodology. None the less, we see this result as incredibly important as it suggest that we can link atmospheric heating – which is strongly coupled to the surface (Fig. 4A) -- to AHT. This result will enable an understanding of historical warm and cold events and projections of changes in temperature variability through the lens of AHT variability.

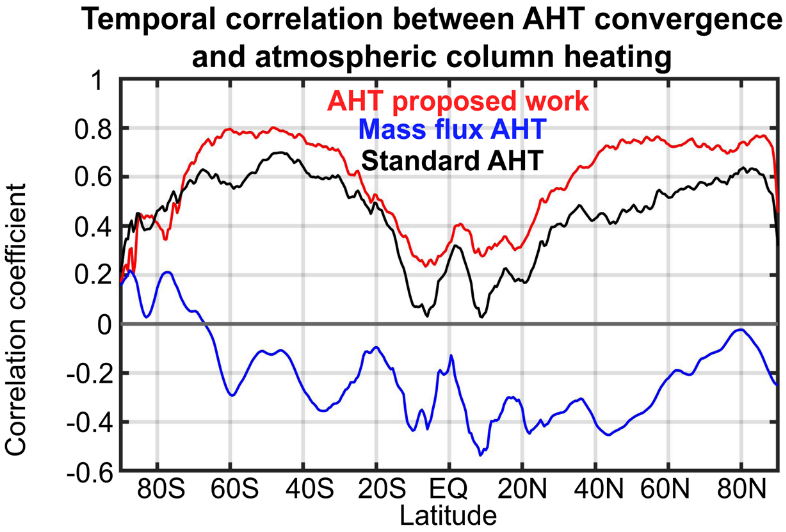


Figure 5. Temporal correlation between AHT convergence and heating of the atmospheric column in observations (ERA5). The red line shows results from the AHT to be used in the proposed work. The black line shows results from the standard definition of AHT and the blue line shows correlation with the mass flux component of AHT that is included in the standard definition of AHT.

Proposed work: ***Model representation of high frequency zonal mean AHT:*** We showed that observed AHT variability is the primary cause of (zonal mean) atmospheric heating. We will ask: (i) do coupled models simulate the right amount of AHT variability at daily timescales? And (ii) can the inter-model spread and (potential) bias in AHT variability explain the spread and biases in natural variability of surface temperature? We will calculate AHT at daily timescales in historical model simulations. We will begin by doing this calculation in two different ways in the NCAR CESM2 model: using the same methodology to calculate AHT in observations (Eq. 7) from the instantaneous three-dimensional atmospheric fields and diagnosing AHT simply from the difference of TOA radiation, surface heat fluxes and atmospheric column energy tendency. This procedure will validate the closure of the energy budget on daily timescales (akin to the validation procedure shown in Fig. 1.) and will determine if we can evaluate daily AHT in the CMIP models using the simpler calculation.

Next, we will analyze the temporal variability of daily AHT in all CMIP models (with the required daily output fields). We will ask: are models biased in their high frequency natural variability of AHT and can these biases be related to biases in the magnitude of natural variability in atmospheric and surface temperature? To our knowledge, there is no existing work on identifying model biases in temperature variability at daily timescales, and it is important to understand if models adequately simulate natural temperature variability for the right physical reasons in order to determine if future predictions of changes in temperature variability are trustworthy. Model biases in temperature variance may be impacted by both surface processes and the amplitude of natural variability in AHT, and by separating these two impacts in the mean state we seek to glean an understanding of robust regional predictions on future changes in temperature variance. We will further analyze changes in temperature variance under historical and future (4XCO_2) forcing to understand the roles of AHT variance and surface/atmospheric stability changes in shaping the modeled response of temperature variance to future warming. The simulated historical trends in AHT and temperature variance will be compared to those seen in the observational record.

The connection between regional heating events and AHT: Our final proposed task is to extend the daily AHT calculations to two dimensions, which will allow an analysis of the longitudinal variations in AHT convergence that impact regional climate variability. Similar to the previous sections of proposed work, observational AHT will be calculated from the tedious calculation of the vertical integral of atmospheric MSE flux and modeled AHT will be calculated from energy budget constraints after first validating the closure of the energy budget in a model setting. Specifically, observational iinstantaneous two-dimensional AHT will be calculated via the same approach used for monthly timescales (Eq. 6) following Donohoe and Battisti (2012). Our first task in the proposed work will be to validate, in a model setting, that the technique used to calculate two-dimensional (lat,lon) AHT convergence at daily timescales via Eq. 6 balances the energy budget of the atmosphere:

$$\nabla \cdot AHT(\theta,\varphi) = RAD_{TOA} + SHF + \underbrace{\frac{d}{dt}\left(\frac{1}{g}\int_0^{Ps} CpT + LQ\; dP\right)}_{Atmospheric\ Heating} \quad . \qquad (8)$$

Because all the terms on the right-hand side of Eq. 8 are diagnosable from model output, we can evaluate if the AHT convergence calculated by Eq. 6 is consistent with the (daily) energy budget of the model. If our calculations balance the energy budget, we can then evaluate daily AHT convergence in all models using the (slightly) more computationally compact calculation on the right-hand side of Eq. 8 and compare the relationship between AHT convergence and climate variability in models with ERA5 observationally based calculations.

The analysis presented in Figs. 4 and 5 demonstrate that observed ***zonal mean*** atmospheric and surface heating is controlled by **zonal mean** AHT; the work in this section will ask if the same relationship holds for regional heating events. Initial results in a single climate model (CESM2) suggest that (daily) surface heating at each gridpoint is strongly temporally correlated with AHT convergence (R >0.7) throughout the extratropical domain, but the magnitude of surface heating per unit of AHT convergence varies spatially due to atmospheric stability and soil moisture. This result suggests that AHT convergence is the primary cause of regional heating events – with radiation and surface processes playing a much smaller energetic role – and surface properties and atmospheric stability set the degree of coupling between the atmosphere and surface. This emerging insight into the dynamics of regional heating events will be used to analyze two different broad questions: 1. How can observationally derived AHT convergence be used to understand observed historical heating events? and 2. Do models adequately represent the magnitude of variability in regional AHT convergence and daily temperature variance, and can model biases be used to inform the robustness of future predictions of temperature variability?

Specific question that we will ask in the observational record include: are historical extreme heating events such as the Dome C Antarctica warm anomaly in March 2022 and the Pacific Northwest heat wave of June 2021 -- both order of five standard anomaly temperature events (Overland, 2021) – associated with comparable magnitude anomalies in AHT convergence? Our hypothesis is that atmospheric column heating is tightly constrained by AHT convergence and, thus, extreme surface events are either caused by extreme AHT events or anomalous coupling between the atmosphere and surface due to soil moisture anomalies. We will decompose the role the AHT variations and surface coupling on surface heating events over the globe and additionally consider winter cooling events.

Specific questions we will ask in the model representation of temporal variations in regional AHT convergence include: are models biased in the magnitude and spatial pattern of AHT variability and do these biases coincide with model biases in surface temperature variability? Initial results in a single model (CESM2, not shown) suggest that the model is biased low by a factor of 2 (relative to observations) in magnitude of daily surface temperature variability with a significantly different spatial pattern. In the model, the spatial pattern of surface temperature variance is significantly (spatial correlation of 0.7 over the global land masses) but imperfectly correlated with the spatial pattern of AHT convergence variability. This result suggests that AHT variability and surface properties both set the magnitude of surface temperature variability, and our analysis will use this novel perspective to analyze the relative importance of AHT biases and simulated surface coupling (e.g. soil moisture, boundary layer biases) in model biases in surface temperature variability.

Lastly, we will analyze the robustness across models of predicted change in surface temperature variability and the relative importance of changes in AHT variability and surface properties across different regions. Previous work has demonstrated that future increases in **monthly** temperature variance are greatest in regions where the soil dries in the models (Muller and Seneviratne, 2014) and, thus, are potentially biased by mean state soil moisture biases (Vargas Zepetello and Battisti, 2020). Our work will extend this analysis to changes in daily temperature variability (which has not been analyzed in models) and will analyze the relative importance of mean state biases and changes in both AHT variability and surface properties. This analysis will address the question of whether projected changes in daily temperature variance will exacerbate (or ameliorate) future heat wave intensity and how robust these model projections are considering mean state biases.

Broader impacts

The broader impacts are threefold: (i) educational, (ii) process level improvement of biases in comprehensive climate models and (iii) advancing our understanding of a natural system of significant scientific and societal importance.

This project will fund one graduate student at the University of Washington. Additionally, the PI is serving on the PhD committee of USCS graduate student advised by the Co-I. As PIs at state institutions, we believe that our scientific practice must be open and inclusive and that our outreach must reflect the diverse stakeholders that have an interest in our work. The lead-PI has advised students of diverse racial and gender backgrounds through his work at the University of Washington. The co-PI has demonstrated her commitment to fostering a supportive and inclusive learning environment through implementing anti-racist practices in teaching across the university curriculum to enrollments of ~150 students per year, improving equity in graduate student recruitment at the department level, supporting paid undergraduate research opportunities, and adopting a community-centered approach to graduate professional development designed to help students build mentoring networks and navigate barriers to success. We plan to accept a graduate student researcher to work with us on this project. We will additionally entrain undergraduates interested in research projects at both the University of Washington and UC Santa Cruz, a designated Hispanic Serving Institution (HSI; since 2012). We will strongly encourage applications from underrepresented groups in the sciences, and consider diversity positively in our hiring to the extent that we are able. UC Santa Cruz is one of only two universities (members of the American Association of Universities) nationally that holds designations as a Hispanic Serving Institution (HSI; since 2012), and as a Asian American Native American Pacific Islander Serving Institution (AANAPISI). The large and diverse undergraduate population will permit us to entrain outstanding undergraduates interested in research projects.UC Santa Cruz is one of only two universities (members of the American Association of Universities) nationally that holds designations as a Hispanic Serving Institution (HSI; since 2012), and as a Asian American Native American Pacific Islander Serving

Institution (AANAPISI). The large and diverse undergraduate population will permit us to entrain outstanding undergraduates interested in research projects.

Our research will identify systematic climate model biases in the way that energy moves through the climate system and its temporally variability. These novel metrics will provide a process level understanding of model mean state biases and potentially provide new insights into poorly represented model physics and how they can be improved in future model generations (or otherwise find ways to bias correct future projections). The long-term goal of this work is to provide more robust predictions of societally relevant climate fields such as heat wave intensity and spatial patterns of temperature and precipitation changes. Our work will also develop methodologies and data sets that will be of general use to the climate research community – most notably the observational atmospheric heat transport and methodologies for energy budget closure across timescales in climate models. We will release source code and observational calculations to the research community via distribution on publicly accessible institutional websites and the pangeo.io data catalog (see data archiving plan).

Lastly, we think the problems we've identified are really cool from a pure science perspective and our potential to make fundamental progress on basic understanding is exciting. We hope that our enthusiasm and emerging understanding of energy flow through climate system will be impact the way our colleagues teach climate science, engender a new generation of scientist and inspire wonder from the general public of how the climate system works. Our understanding will be conveyed to the public through the various outreach activities the PI and Co-I are involved in including "Curiosity days: Climate change" museum exhibits, the UW Program on Climate Change Outreach and "Science on Tap".

Section 6. Results from prior research:

Here we list only the most relevant recent NSF funded project for the PI and Co-I

Donohoe: OPP Award 1643436; $387,742: "What Processes Drive Southern Ocean Sea Ice Variability and Trends? Insights from the Energy Budget of the Coupled Cryosphere-ocean-atmosphere System" (5/2017-5/2022). *Intellectual Merit:* Analyzed the relative role of radiation, atmospheric dynamics and ocean processes for Southern Ocean sea ice loss events in climate models and observations. *Broader Impacts:* Developed public outreach exhibits for annual Polar Science Weekend. Advised undergraduate research resulting in a peer reviewed publication. Provided climate research community scripts and datasets for calculating high latitude radiative feedbacks and atmospheric heat transport. *Publications:* Zeppetello et al. (2019, Doi:10.1029/2019GL082220), Donohoe et al. (2020, Doi: 10.1175/JCLI-D-19-0329.1), Donohoe et al. (2020, Doi: 10.1175/JCLI-D-19-0674.1), Hahn et al. (2020, Doi: 10.1029/2020GL088965), Blanchard et al. (2021, Doi: 10.1175/JCLI-D-20-0386.1), Hahn et al. (2021, Doi: 10.3389/feart.2021.710036), Cardinale et al. (2021, 10.1175/JCLI-D-20-0722.1), Blanchard et al. (2021, Doi: 10.1029/2020GL092356). Data archiving: Source code for radiative feedback calculations are archived in the Department of Atmospheric Sciences at the University of Washington.

Feldl: AGS Award 1753034; $798,235: "CAREER: The Lapse Rate Feedback and Other Mechanisms of High-Latitude Climate Change" (9/2018-8/2023). *Intellectual Merit:* Using a hierarchy of climate models, quantified the role of dry and moist atmospheric dynamics, clouds, sea ice, and coupled ocean-atmosphere processes on the lapse rate feedback and polar amplification. *Broader Impacts:* Designed and produced a digital game, in collaboration with a team of undergraduate researchers, for teaching middle and high school students about the feedbacks and forcings that govern global climate change. *Publications:* 8, including Kaufman and Feldl (2022, Doi: 10.1175/JCLI-D-21-0298.1), Taylor et al. (2022, Doi: 10.3389/feart.2021.758361), Feldl et al. (2021, Doi: 10.1029/2021GL094130), Feldl et al. (2020, Doi: 10.1038/s41612-020-00146-7). Code and data are available on GitHub and Zenodo repositories.

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