

CAREER: Understanding the flow of energy through the climate system

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1 Research Component: Background and Introduction

Conservation of energy provides a powerful tool for understanding the governing mechanisms of climate change and climate variability at global to regional scales. Globally, energy conservation demands a balance of the radiative budget at the top of atmosphere (TOA) at equilibrium such that the temperature response achieves a balance between the radiative forcing and the radiative response (which is governed by radiative feedbacks). At regional scales, non-zero net TOA radiative fluxes are balanced by dynamic transport of energy by the oceanic and atmospheric circulations; for example, at the equator-to-pole scale, the meridional heat transport (MHT) by the atmosphere and ocean is equal to the net TOA radiative imbalance spatially integrated over the polar cap. Therefore, MHT can be viewed through two complementary perspectives: **from a dynamic perspective** MHT is equal to the (zonally and vertically integrated) energy contrast between poleward and equatorward moving air/water and; **from a radiative perspective** MHT is equal to the (spatially integrated) difference between absorbed solar radiation and outgoing longwave radiation. These complementary perspectives on the flow of energy through the climate system – hereafter the energetic framework – highlight the mutual interactions between dynamical and radiative changes in the climate system; radiative changes in a given region result in changes in the dynamical transport of energy into the region and changes in the energy transport into a region result in changes in temperature and humidity that change TOA radiation via radiative feedbacks. The interplay between radiative feedbacks and dynamical energy fluxes thus provide insight into the drivers of regional temperature, hydrological, and circulation changes under both climate change and internal climate variability.

The energetic framework has been used extensively to study many aspects of climate including: (i) the spatial structure of tropical precipitation (*Frierson et al., 2013; Marshall et al., 2013*) including model mean state biases (*Hwang and Frierson, 2013; Kim et al., 2020*), future/past changes (*Kang et al., 2008; Donohoe et al., 2013c; Frierson and Hwang, 2012; Schneider et al., 2014*) and zonal inhomogeneous changes (*Boos and Koorty, 2016*); (ii) the location and strength of mid-latitude jets (*Ceppi et al., 2012; Donohoe et al., 2013a*) and storm tracks (*Shaw et al., 2018*); (iii) the impact of the spatial structure in radiative feedbacks on atmospheric circulation (*Roe et al., 2015; Hwang and Frierson, 2010; Armour et al., 2019*) and hydrological changes (*Siler et al., 2018*); and (iv) analyzing the causes of Arctic amplification (*Pithan and Mauritsen, 2014*) and its inter-model spread (*Hwang et al., 2011a*).

The overarching theme of the proposed work is to use the energetic framework to evaluate and improve climate model simulations by comparison to observable climate properties across a wide range of spatial-temporal scales. As a concrete example (elaborated on in Section 3), my previous work has demonstrated that the observed seasonal migration of the intertropical convergence zone (ITCZ) off the equator is governed by the same quantitative relationship between the ITCZ location and energetic fluxes that governs future and past ITCZ responses to external forcing (*Donohoe et al., 2013c*). This observationally-derived energetic constraint mandates that future ITCZ shifts will be small in magnitude given the spatial structure of radiative forcing and feedbacks (*Donohoe and Voigt, 2015*). The energetic framework permits an evaluation of simulations of climate and its changes using observational climate data.

A consistent methodology for model-observational comparison of energy fluxes is paramount to this task and my work to date (expanded on in Section 4) has led the field in innovative methods for observational-model comparison of energy fluxes. An online repository of observational calculations and code for performing these calculations will be developed as part of the proposed outreach work. Fig. 1 shows an overview of annual mean total (atmosphere plus ocean) meridional heat transport (MHT) and its decomposition into oceanic (OHT) and atmospheric (AHT) contributions in climate models compared to that derived from ob-

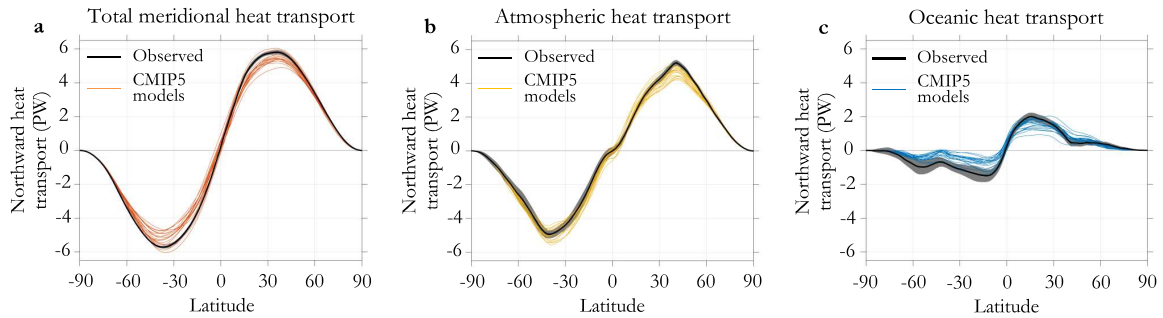


Figure 1: Comparison of annual and zonal mean MHT (a), AHT (b) and OHT (c) in an ensemble (CMIP5) of climate models (colored lines) and observations (black line with shading to indicate observational uncertainty) using the techniques outlined in Section 4. Figure was prepared for IPCC AR6 Chapter 7.

servational fields. Climate models differ substantially (20% at the location of peak values) in the magnitude of MHT primarily due to the inter-model spread in AHT. Moreover, model simulated OHT is biased low relative to observational estimates especially in the southern ocean. This motivates my first research question:

Research Question 1 (Section 2A): What is the underlying cause of inter-model spread and biases in MHT? How is the spread and bias partitioned into AHT, OHT and circulation components/thermodynamic components as viewed from dynamics and radiative perspectives?

Despite the substantial inter-model spread in climatological MHT, the simulated MHT *within a given model* is nearly unchanged in response to external forcing ranging from CO₂ quadrupling to Last Glacial Maximum (Fig. 2A here *Donohoe et al., 2020a*) with the exception of very cold climates (*Shaw and Tan, 2019*). The underlying atmospheric and oceanic dynamics and thermodynamics responsible for MHT differ remarkably with climate state yet their sum is (spatially smooth) and nearly unchanged suggesting that large-scale net TOA radiation is relatively inflexible to external forcing. This result motivates my second research question:

Research Question 2 (Section 2B): How are radiative constraints communicated to atmospheric and oceanic circulations to maintain near invariance of total poleward energy transport in response to external forcing?

Much of the climate insights on spatial patterns and forced changes in precipitation, temperature and circulation gleaned from the energetic framework have focused on zonal and annual mean MHT, AHT and OHT. The extension of the energetic framework to zonal heterogeneities (*Boos and Koorty, 2016; Adam et al., 2016b*) and seasonal time-scales (*Donohoe et al., 2019; Shaw et al., 2018; Donohoe et al., 2020b; Donohoe and Battisti, 2013*) has received less attention and potentially will transform the community’s understanding of climate processes ranging from tropical precipitation, mid-latitude temperature variability and high-latitude sea-ice changes and variability. My work on extending observationally-based and model calculations of MHT, AHT and OHT to seasonal and regional scale (Section 4) will help to address research question 3:

Research Question 3: How can regional and seasonal diagnostics of energy transport inform our understanding of mechanisms of model biases, variability and future changes in climate phenomena? Specifically, what is the signature of energy transport in the spatial pattern of tropical precipitation (Section 3A) and sea-ice variability and changes (Section 3B)?

This document is organized as follows. Sections 2 covers the first two primary research questions organized of diagnosing model spread and biases in MHT (Q1) and radiative controls of MHT invariance (Q2). Section 3 covers the connection between regional and seasonal energy transport and climate processes in the tropics and high-latitudes in Section 3. Background information on each topic and the proposed research

questions and tasks are organized within each section. The detailed methodology for observational/model comparison of MHT, AHT and OHT is withheld until Section 4 even though the work in the previous sections relies on these methods. These methods directly tie into the primary outreach activity of creating an online repository of energy transport calculations for the climate science community. A description of the educational activities follows (Section 5).

2 Research Component: Controls on energy transport from the equator to pole

In the absence of poleward energy transport by the atmosphere and ocean (MHT), the equator-to-pole surface temperature contrast would be approximately 120K as mandated by local radiative equilibrium between absorbed solar radiation (ASR) and outgoing longwave radiation (OLR) at each latitude. The observed equator-to-pole temperature contrast of approximately 40K suggests that dynamics ameliorate the spatial structure of insolation that drives the equator-to-pole contrast by approximately $\frac{2}{3}$. In this regard, the peak magnitude of MHT could achieve values between 0 and 9PW (*Donohoe and Battisti, 2012; Czaja and Marshall, 2006; Stone, 1978*) with a corresponding equator-to-pole temperature contrasts ranging from the local radiative equilibrium (120K) to zero. However, MHT is nearly invariant, with a peak value of approximately 6 PW, across a wide range of simulated perturbations to Earth's climate simulations including mechanically altered ocean circulations (*Enderton and Marshall, 2009; Vallis and Farnetti, 2009*), inclusion of moisture in the atmosphere (*Frierson et al., 2007*), and under paleoclimatic and anthropogenic forcings (Fig. 2A-D *Yang et al., 2015; Donohoe et al., 2020a*).

The meridional smoothness of net radiation at the TOA mandates that MHT be meridional smooth and singly peaked in each hemisphere whereas the mix of OHT and AHT and transport by overturning circulation, eddies and moist and dry components is highly spatially heterogeneous (*Trenberth and Caron, 2001*). The abundant literature on MHT suggests that net TOA radiation is more inflexible to climate forcing and climate state than are the details of the atmospheric and oceanic circulation. It remains unclear: (i) why MHT is nearly climate state invariant in response to forcing but can vary between models (and observationally derived calculations), and (ii) how the large-scale radiative constraints are communicated to atmospheric and oceanic circulations to maintain spatial smoothness and near invariance of total MHT. An essential ingredient to these questions – and common to all a posteriori energy flux analysis– is that energy balance requires that changes in AHT and OHT be balanced by net radiative changes and thus prohibits a determination of whether radiative processes are causing changes (or lack thereof) in dynamics or vice-versa. I propose several analyses and idealized experiments to separate the dynamical and radiative controls of MHT.

2.1 Model biases in MHT and its partitioning.

MHT in unforced (i.e., pre-industrial) coupled climate models differs by 20% at its peak and is generally biased low relative to observations in both hemispheres (Fig. 1A). Inter-model differences in AHT contribute most to MHT spread and Northern Hemisphere (NH) bias in the mid-latitudes (Fig. 1b) whereas the inter-model spread in the sub-tropics and biases throughout the Southern Hemisphere (SH - Fig. 4C). The first proposed project will diagnose the inter-model spread and bias in MHT and its partitioning from the radiative and dynamic perspectives. *Donohoe and Battisti (2012)* found similar inter-model MHT spread and SH biases in CMIP3 models to those shown in Fig. 1 (with CMIP5 models). Those biases resulted from model differences in the equator-to-pole gradient of ASR due to simulated cloud radiative effects (*Donohoe and Battisti, 2011*) that were uncompensated by model differences in OLR. These results suggest MHT is primarily determined by the spatial gradients of heating in the climate system set up by the radiative impact of clouds.

Proposed work: I will repeat the above radiative analysis of MHT biase and spread in CMIP5 and CMIP6 models which have substantially improved mean-state cloud properties (*Zelinka et al., 2020*). I will

evaluate if the improved simulation of clouds in CMIP6 models reduces the bias and spread in MHT and diagnose the cloud type, regions and seasons that are contributing to shortwave cloud radiative effect biases and spread. Since inter-model differences in TOA radiation are primarily due to ASR and highly correlated with surface shortwave fluxes (*Kato et al., 2013*), I will analyze if model biases in SH OHT can be explained by biases in surface radiation relative to satellite derived observations.

My methodology for comparing MHT/AHT/OHT in observations and models using standard climate model output (details in Section 4) allows an unprecedented model-observation comparison of the dynamical partitioning of MHT between OHT and AHT across large suite of climate models. These methods also allow further decomposition of OHT by ocean basin and AHT into overturning, stationary and transient eddies and moist dry components. I will analyze which dynamical components give rise to the inter-model spread and biases in MHT and how consistent these results are between different observational estimates (using different atmospheric re-analysis) and across CMIP3, CMIP5 and CMIP6. Outstanding questions include: (i) is the inter-model differences in one component of MHT compensated for by inter-model differences in a different component – for example, do models with more OHT tend to have less AHT suggesting that total MHT is more constrained than the component contributions; (ii) do some models have the right (i.e., matching observations) total MHT but the wrong partitioning; (iii) is the moist or dry component of AHT responsible for the inter-model spread or bias.

Additionally, I will analyze the vertical structure and spectral characteristics of AHT. Recent work has demonstrated that observed climatological AHT and its variability into the high-latitudes is composed of comparable magnitude contributions from the lower troposphere and stratosphere (*Cardinale et al., 2020*) and that only the tropospheric component is connected to surface climate variability. Therefore, I will analyze whether models are biased in their vertical structure of AHT and if these biases are linked to model biases in high latitude sea-ice and temperature.

Atmospheric transient eddies dominate the mid-latitude MHT and can be decomposed into the variability in meridional winds and MSE and the temporal correlation between components. AHT by transient eddies will be decomposed into space/time spectral variance and coherence (*Donohoe and Battisti, 2009*) to ask if models are biased in the structure of circulations that give rise to AHT even if the total AHT is nearly radiatively constrained. This analysis addresses compensation of AHT components in the spectral domain and has implications for model biases in the spatial scales and persistence of climate variability.

2.2 How are large-scale radiative constraints on the climate state invariance of MHT communicated to the atmosphere?

Together with a UW graduate student and several collaborators, I have recently developed a modeling framework (*Cox et al., 2020*) whereby the interaction between dynamic and radiative changes can be turned on and off in an idealized modeling framework with a simplified gray radiation scheme (*Frierson et al., 2006*). For example, we are able to perform slab ocean aquaplanet simulations in which Earth's rotation rate is altered with radiative feedbacks either enabled or disabled. In one set of experiments radiation is freely evolving and responds to the rotation rate induced temperature changes. This results in factor of two increase in MHT at slower rotation rate as atmospheric circulations become more meridionally elongated and efficiently mix MSE gradients (Fig. 2E-H solid lines). In the other set of experiments the meridional and vertical structure of radiative heating in the atmosphere and surface is fixed to that in the control (regular rotation rate) simulation. In these "fixed radiation" simulations, the temperatures and atmospheric circulations can freely evolve with altered rotation rate but there is no radiative response to these changes and, thus, MHT does not change with rotation rate (Fig. 2E dashed lines). Comparison of these two sets of simulations for like rotation rates allows the circulation response to be decomposed into purely dynamically induced changes (i.e. rotation rate) and the circulation response to radiative feedbacks. These simulations allow us to explore how radiative constraints are communicated to the atmospheric circulations underlying AHT. Additionally, because

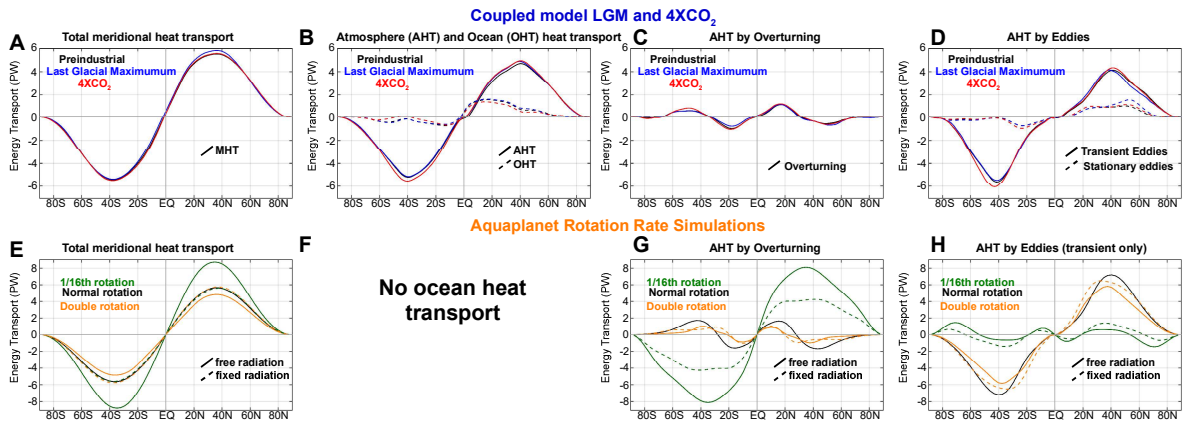


Figure 2: (A-D) CMIP5 ensemble mean energy transports in simulations of the Last Glacial Maximum (blue), pre-industrial (black) and $4XCO_2$ (red). Panel A shows total Meridional heat transport (MHT). Panel B shows the partitioning between atmosphere (AHT, solid) and ocean (OHT, dashed) heat transports. Panel C and D decomposes AHT into contributions from meridional overturning circulation (C, solid) and transient eddies (D, solid) and stationary eddies (D, dotted). (E-H) As in the upper panels but for the aquaplanet rotation rate experiments. Solid lines show the freely evolving radiation simulations and dashed lines show the fixed radiation in which the total MHT is constrained to match the control simulation with regular rotation rate.

the circulations responsible for MHT vary across the suite of experiments— with MHT being dominated by overturning circulation in the limit of lower rotation rate (Fig. 2G) and eddies in the limit of fast rotation rate— we can analyze how radiative constraints are conveyed to different circulation regimes to better address the meridionally smoothness of total heat transport across different regions (i.e., tropics, mid-latitudes) in the observed climate system.

Proposed work: I will perform additional radiation enabled/disabled simulations including: (i) introducing idealized (Gaussian, and water-covered) mid-latitude topography and (ii) changing the latent heat of evaporation of water. Because the total AHT is radiatively constrained to be unchanged in the simulations with disabled radiative feedbacks, I hypothesize that there will be perfect compensation between the component changes in AHT (relative to the control aquaplanet simulation): (i) the increased poleward AHT by stationary eddies (*Kaspi and Schneider, 2013*) will be compensated for by reduced transient eddy AHT (and possibly changes overturning circulation) and (ii) the changes in moist AHT will be compensated by changes in dry AHT. I can then compare the circulation response between the radiation enabled and disabled (with the same prescribed topography, latent heat) to probe how radiative constraints impact the compensation between AHT by stationary/transients/overturning and moist/dry components. The analysis will focus on both the zonal mean and longitudinally structure of radiative constraints on AHT. Specifically, I anticipate that storm tracks will be intensified downstream of the imposed topography due to enhanced baroclinity in this region and comparison of the radiation enabled and disabled circulation changes will probe the role of radiative feedbacks in the localized response. Additionally, in the suite of perturbed latent heat of evaporation simulations, it is unclear if the moist/dry compensation in AHT will be seen within each component circulation (e.g., overturning and transient eddies) and if the radiative feedbacks will alter this result as the vertical distribution of atmospheric heating changes with differing strengths of condensational heating.

The preliminary simulations highlighted in Fig. 2E-H were performed using a gray radiation scheme with no cloud feedback in the GFDL model. I will also perform the same suite of simulations using an atmospheric model with a full radiative transfer scheme coupled to a slab ocean aquaplanet in the GFDL AM4 model to evaluate the role of cloud feedbacks in the changes in MHT and their coupling the atmospheric circulation (*Liu et al., 2017*).

3 Research Component: Extension of the energetic framework to seasonal and regional scales to understand hydrological and cryospheric climate variability and changes.

3.1 Controls on tropical precipitation: moving beyond the ITCZ shift paradigm

The displacement of the intertropical convergence zone (ITCZ) off the equator and the AHT between the two hemispheres are mutually dependent on the Hadley cell location (*Kang et al.*, 2008). Thus, the ITCZ location and shifts under forcing are proportional to the climatological (*Marshall et al.*, 2013; *Frierson et al.*, 2013) and anomalous (*Frierson and Hwang*, 2012; *Donohoe and Voigt*, 2015) hemispheric contrast of energy input to the atmosphere. This energetic theory of ITCZ shifts has been used to connect ITCZ shifts across seasonal (*Donohoe et al.*, 2013c; *Chiang and Friedman*, 2012), interannual (*Donohoe et al.*, 2013b; *Adam et al.*, 2016a) and paleoclimatic (*Schneider et al.*, 2014; *McGee et al.*, 2014) time-scales.

Despite the ubiquity of the ITCZ shift paradigm in the literature, little attention has been spent on how well ITCZ shifts describe tropical precipitation changes in model simulations, observations and paleoproxy data. My colleagues and I recently developed a framework for diagnosing this question using a novel methodology that shifts, contracts, and intensifies the climatological precipitation to optimally describe forced precipitation changes and variability in tropical precipitation (*Donohoe et al.*, 2020c). This framework asks how the changes are best described in terms of manipulations of the climatological precipitation in each model and has the advantage of accounting for how mean state biases in models impact the spatial distribution of precipitation changes. Our initial results demonstrate that the ITCZ shift paradigm is of very limited use for describing tropical precipitation changes (ΔP) across a large suite of model simulations under anthropogenic and paleoclimatic forcings: (i) meridional translations of the ITCZ explain a small fraction (<7%) of zonal mean tropical precipitation changes across a large ensemble of simulated responses to a myriad of paleoclimate and anthropogenic forcing (Fig. 3A) and (ii) even the direction of the shift is not robust in response to most forcings with the exception of freshwater hosing and hemispherically isolated volcanoes (Fig. 3B). In contrast, tropical precipitation robustly and nearly unanimously contracts and intensifies in warming climates and expands and reduces in colder climates with a nearly fixed ratio of contraction and intensification (Fig. 3C). The combined contraction and intensification of tropical precipitation is robust mode of ΔP (hereafter the CI mode) explains a much larger (>40%) fraction of ΔP across all forcings than ITCZ shifts. Additionally, our work indicates that ΔP is dominated by zonally-inhomogeneous response with robust (i.e., consistent between different models) regional signatures within each type of forcing (i.e., the tropical Atlantic responds most strongly to freshwater hosing and the Central Pacific responds to Mid-Holocene forcing; *Atwood et al.*, 2020). My proposed work will focus on understanding the dynamics of the CI mode and the zonally inhomogeneous tropical precipitation changes using the energetic framework.

Proposed work: Understanding the contracting and intensifying (CI) mode of tropical precipitation. Previous work has argued that the width of the tropical precipitation is set by the amplitude of the seasonal migration of the ITCZ with smaller amplitude seasonal cycle corresponding to precipitation that is more meridionally confined near the equator. This paradigm explains the contraction of tropical precipitation under global warming (*Donohoe et al.*, 2019) and model “double ITCZ” biases (*Kim et al.*, 2020). What then controls the seasonal range of the ITCZ? Just as the annual mean ITCZ and Hadley cell location are dictated by the hemispheric contrast of energy input to the atmosphere the seasonal range of ITCZ migration off the equator is governed by the seasonal cycle of energy input into the atmosphere. Additionally, the ITCZ displacement off the equator is inversely proportional to the efficiency of atmospheric energy transport per unit of Hadley cell migration which was found to increase in warmer world due to enhanced gross moist stability of the tropical atmosphere with warming (*Donohoe et al.*, 2019; *Inoue and Back*, 2017; *Wu and Tan*, 2013). This provides a mechanistic explanation of the CI mode that I will further test using model output and idealized simulations.

The optimal shifting/contracting/intensifying decomposition of ΔP (*Donohoe et al.*, 2020c) will be ap-

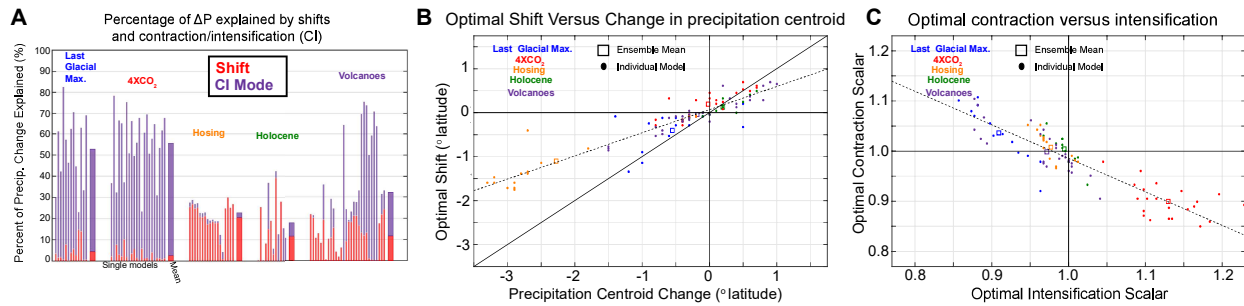


Figure 3: Optimal description of forced (anthropogenic and paleoclimate) zonal mean precipitation changes (ΔP) in terms of shifts, contractions and intensifications of the climatological precipitation. (A) Percent ΔP explained arranged by forcing type. (B) Optimal shift (abscissa) versus the change in precipitation centroid (ordinate) that is commonly used to quantify ITCZ shifts. (C) Contraction scalar (abscissa) versus intensification scalar (ordinate). The response to forcings are color coded as follows: LGM (blue), $4XCO_2$ (red), Mid-Holocene (green), freshwater hosing (orange) and volcanic forcing (purple).

plied on seasonal time-scales. This analysis will be performed across the large suite of CMIP/PMIP simulations included in Fig. 3 expanded to include historical forcing and RCP scenarios and additional paleoclimate simulations. I will ask whether annual mean ITCZ contractions are best described as a modification of the seasonal range of the ITCZ (seen as an amplified seasonal cycle of ITCZ shifts) or as a meridional contraction of precipitation within each season. This analysis will evaluate the hypothesis that the amplitude of the seasonal cycle of ITCZ migrations sets the width of the tropical precipitation. I will apply the same seasonal decomposition to the observational trends and internal variability to place observed trends in the context of long-term forced responses. The energy fluxes (cross-equatorial AHT and tropical heating by radiation and surface fluxes) will be analyzed to understand the root cause of the CI mode. Additionally, I will use the model constrained modes of tropical precipitation variability to optimally interpret the existing records from the NCDC/NCEI and PANGAEA paleoclimate data repositories over several target periods including: (i) Last Glacial Maximum, (ii) Mid-Holocene, (iii) Heinrich events and (iv) last millennium. Key questions are: given the dominate modes of tropical precipitation changes in models (i.e., the scaling between contraction and intensification in the CI mode), is the sparse network of paleoclimate observations sufficient to constrain past precipitation changes, and what combination of shifts and CI mode changes is most consistent with the proxy records?

I will also analyze the dynamics of the CI mode using idealized modeling studies. Starting from the hypothesis that the CI mode is dictated by the amplitude of the the seasonal cycle of atmospheric heating and the tropical temperature (via the efficiency of tropical AHT) I will explore this parameter space in gray radiation aquaplanet simulations. The amplitude of the seasonal cycle will be modified by changing the ocean mixed layer depth (*Donohoe et al., 2013a*) and the temperature of the tropics will be changed by modifying the prescribed longwave optical depths. Additionally, to evaluate the role of mean state tropical precipitation biases in more comprehensive models, I will also perform paleoclimate and anthropogenic forcing simulation in models with mean state bias correction of tropical SSTs and including more realistic tropical topography following the technique of my colleagues and I as discussed in *Atwood et al. (2020)*.

Proposed work: Zonally inhomogeneous modes of tropical precipitation. The robust zonally localized tropical precipitation response to external forcing (*Atwood et al., 2020*) will be characterized using the shifting/contracting and intensifying mode framework and the underlying dynamics will be analyzed.

Simulated ΔP in the CMIP/PMIP simulations will be decomposed into shifting, contracting and intensifying modes by optimally manipulating the climatological (model/observations specific) precipitation in the 2-dimensional (lat/lon) space. I will define five different modes of ΔP : (1) meridional shift, (2) zonal shift, (3) meridional contraction, (4) zonal contraction and (5) intensification. These modes will be defined independently within the Pacific, Atlantic and Indian Ocean basins. All modes are optimized simultaneously.

I will first focus on annual mean ΔP . The methodology is generalizable to seasonal changes and observed inter-annual variability. These results will provide a physically interpretable optimal description of ΔP in response to forcing, evaluate the robustness of precipitation response to paleoclimate forcing across models and provide a basis set to optimally describe proxy reconstructions of past tropical precipitation changes.

I will additionally analyze the dynamics responsible for zonally-inhomogeneous ΔP in the suite of anthropogenic/paleoclimatic forced simulations discussed above. East-west differences in tropical precipitation are associated with the zonal mass overturning circulation of the atmosphere (i.e., the Walker cell) with intense precipitation co-located with the ascending branch of the circulation in each ocean basin. Just as the Hadley cell exports energy away from the region of ascent, the zonal overturning cells transport energy away from the regions of ascent to the region of subsidence and thus mandate a zonal contrast of energy input to the atmosphere. This zonal contrast in atmospheric heating is associated primarily with turbulent surface heat fluxes set by zonal SST gradients (due to ocean circulation) and secondarily by radiative processes. Shifts, contractions and intensifications of the zonal circulation (and associated changes in precipitation) must be accompanied by changes in the spatial pattern of atmospheric heating. This paradigm has the potential to quantitatively connect changes in surface processes (e.g., ocean circulation, vegetative changes) and radiative processes to their resultant ΔP . *Boos and Koorty* (2016) recently demonstrated that zonal shifts in energy fluxes and precipitation patterns co-vary over the observed El-Nino and the model response to mid-Holocene forcing. There is much work to do in order to make this theory more generalizable and extend the analysis to additional paleoclimate states. Our novel methodology for decomposing energy fluxes into divergent and advective components (*Donohoe and Battisti*, 2013; *Marshall et al.*, 2013) and diagnosing the 2-dimensional AHT in large ensembles of models from standardized output (Section 4) provide an unprecedented opportunity to analyze the inter-model robustness of the energetic theory of tropical precipitation in response to a myriad of external forcings.

3.2 Identifying atmospheric drivers of sea-ice variability and long-term changes.

Sea-ice variability varies drastically between climate models and is biased low substantially relative to observations (*Blanchard-Wrigglesworth et al.*, 2020) at synoptic time-scales (2-20 days) in both the Arctic and Southern Ocean but is too persistent at sub-seasonal timescales (*Blanchard-Wrigglesworth et al.*, 2011). Low frequency variability has drawn much attention in the literature (*Kwok*, 2011; *Ding et al.*, 2017; *Mahlstein and Knutti*, 2012) but identification of model biases at these time-scales is statistically limited by the number of degrees of freedom over the observational record and conflation of internal variability and forced trends (*Polvani and Smith*, 2013). I propose an observational-model comparison of the drivers of high-frequency sea-ice variability which is well resolved in the limited length observational record and is made possible by the recent availability of daily sea-ice output in CMIP6 models (*Notz et al.*, 2016). It is unclear if model biases (and spread) in sea-ice variability result from atmospheric/oceanic drivers or the physical coupling of the cryosphere/atmosphere/ocean. Understanding the root cause of sea-ice variability biases at high-frequencies potentially informs and improves model predictions of inter-annual variability and long-term trends – which have widespread socioeconomic impacts – due to the commonality of the coupling physics across timescales.

Proposed work: The proposed work will focus on high frequency atmospheric drivers of sea-ice loss events and I turn to preliminary results from a control NCAR CESM2-CAM6 simulation (Fig. 4) to demonstrate the proposed analysis technique for evaluating the atmospheric energy transport anomalies associated with sea-ice loss events. Sea-ice loss events are defined independently within each sector of the Arctic (demarcated by the dashed meridians) from the time series of high-pass filtered (cutoff period of 20 days) daily sea-ice concentration (SIC) at the location of maximum (spatially smoothed) SIC concentration variability in each sector. I then performed a lead-lag regression analysis between normalized SIC anomalies in each sector and climate fields to produce maps of a “typical” (one standard deviation) atmospheric energy transport and SIC preceding, during and after a sea-ice loss event (Fig. 4). “Typical” events are defined

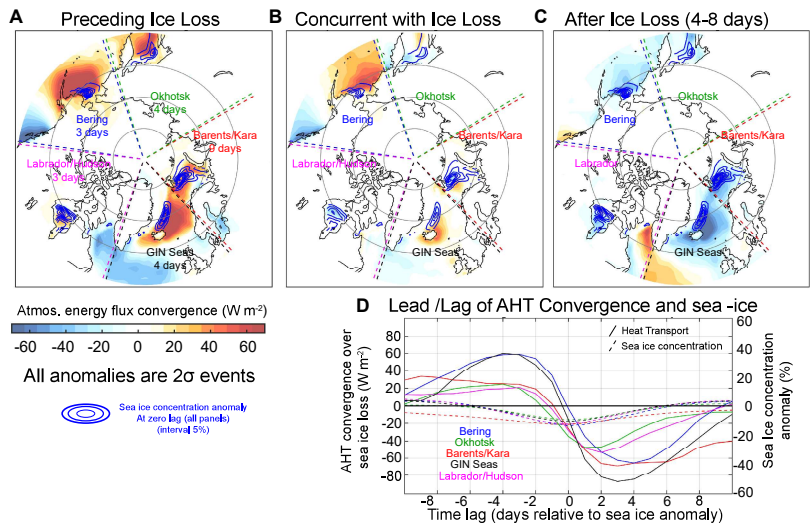


Figure 4: Composites of atmospheric energy flux convergence (shading) preceding (A), concurrent with (B) and after (C) high frequency winter time (DJF) sea-ice loss events in a CESM control simulation. Sea-ice loss events are defined independently in each sector indicated by the dashed line and the sea-ice anomaly is shown by the blue contour. Panel D shows the time series of lagged composites of the spatially averaged atmospheric energy flux convergence over the region of sea-ice loss for each sector.

independently in each sector, are nearly temporally orthogonal between sectors, and maps in each sector are merged in Fig. 4 for visual purposes. In CESM2-CAM6, sea-ice loss events are preceded by anomalous atmospheric energy flux convergence over and equatorward of the sea-ice loss region that peak 3 to 9 days prior to the sea-ice loss. This atmospheric energy transport primarily acts to heat the atmospheric column (not shown) in the days preceding the sea-ice loss and the warmed and moistened atmosphere subsequently melts sea-ice via downwelling longwave radiation and turbulent energy fluxes (as seen in *Woods and Caballero, 2016*). Interestingly, at the time of maximum sea-ice loss, the atmospheric energy flux anomaly over the region of sea-ice has dissipated (Fig. 4B) and thereafter the atmosphere removes energy from the region of sea-ice loss (Fig. 4C). Spatially averaged over the region of sea-ice loss, the atmospheric energy transport is in quadrature phase with the ice loss (Fig. 4D).

This analysis supports the hypothesis that high frequency winter sea-ice loss events are initiated by atmospheric heat input to the region but further suggests that the relevant sea-ice/atmosphere interactions would not be seen at the monthly timescale (*Yang et al., 2015*) and in the zonally integrated (*Graversen et al., 2007; Baggett and Lee, 2015; Graversen et al., 2008*) energy flux. Additionally, a significant portion (23%) of the variability in the atmospheric energy flux into the Arctic is in the stratosphere and decoupled from the surface climate (*Cardinale et al., 2020*). In the proposed work, I will analyze the 3-dimensional (latitude, longitude, vertical) of atmospheric energy fluxes associated with sea-ice loss events across all the CMIP models (control and forced) that output daily SIC. The co-variability of observed high frequency SIC (from NSIDC) and atmospheric energy fluxes derived from reanalysis (using the techniques detailed in Section 4) will be compared between the models and observations. I will ask: are models biased in their simulation of the high frequency variability of atmospheric energy transport events into the polar regions and/or the spatial structure (i.e. length scale and vertical extent) of these events?

4 Research Component: Methodology for observational-model comparison of energy fluxes

The calculation of zonal and annual mean MHT/OHT/AHT from standard model output is fairly well established in the climate research community but some technical aspects are unresolved and present ambiguity when comparing and interpreting results across different modeling studies including the lack of global energy conservation (*Lucarini and Ragone, 2011*) and the treatment of phase transitions of precipitation (*Hwang et al., 2011b; Mayer et al., 2017*). More significantly, the standard approach for calculating energy fluxes differs between models and observations (see summary in Table 1) due to model-observational differences in the availability and reliability of climate fields (*Donohoe et al., 2020a*):

Table 1: Summary of methodology for calculating global flow of energy via radiative, atmospheric and oceanic processes in observations and models. V is meridional velocity and MSE is moist static energy.

Diagnostics of large scale energy flow		
Climate Field	Observations	Models
TOA Radiation	Satellites (CERES)	direct model output
Atmospheric heat transport (AHT)	Vertical and time integral of instantaneous $V \times \text{MSE}$ (reanalysis)	Spatial integral of TOA radiation minus surface heat flux
AHT by stationary circulation	Vertical integral of time average $V \times \text{MSE}$	Vertical integral of time average $V \times \text{MSE}$
AHT by transient eddies	Vertical integral of eddy covariance instantaneous V and MSE	residual of total AHT and AHT by stationary circulation
AHT – moist component	Vertical integral of time average $V \times \text{specific humidity}$	spatial integral of evaporation minus precipitation
Surface heat flux (SHF)	residual of TOA and AHT	direct model output
Ocean heat transport (OHT)	Spatial integral of SHF minus ocean heat content change	Spatial integral of SHF minus ocean heat content change

Coupled Climate Models: surface heat fluxes (SHF) can be diagnosed from standard model output which, in conjunction with the TOA radiation, allows the net (radiative plus turbulent) heating of the atmospheric and oceanic columns to be calculated at each latitude from *time-averaged* (i.e. monthly-mean) model output. The spatial integral of the atmospheric heating over the polar cap equals the AHT at the bounding latitude whereas the spatial integral of the SHF equals the OHT.

Observations: the geographic sparsity of reliable observational SHF products prohibits evaluation of the meridional structure in net heating of the atmospheric and oceanic columns. However, satellite observations of TOA radiation constrain the total MHT (=AHT+OHT). AHT can be calculated dynamically from the vertical and time integral of the meridional flux of moist static energy ($\text{MSE} = C_p T + LQ + gZ$) using instantaneous 3-dimensional (lat-lon-height) velocity, temperature, humidity and geopotential reanalysis data. The AHT divergence then constrains the SHF by energy conservation of the atmospheric column which can then be used to calculate the OHT (*Trenberth and Caron, 2001*).

Similar contrasting model/observational approaches are typically taken to evaluate the moist component (LQ) of AHT ($\text{AHT}_{\text{MOIST}}$) as : (i) in models, the spatial integral of precipitation minus evaporation over the polar cap and (ii) in observations the vertical and time integral of meridional velocity times latent energy ($V \times Q$ – Table 1). Given the contrasting data-sets and methodologies used to calculate MHT/AHT/OHT in model versus observations, evaluation of model biases in the global flow of energy in the climates system is computationally and methodologically cumbersome and lacking in many studies.

In addition to observational uncertainty in satellite derived TOA radiation and reanalysis fields, there is an ongoing debate in the literature regarding how to consistently treat the mass and moisture budgets of the atmosphere that are not closed in reanalysis products. There are 4 primary approaches: (i) using a barotropic wind correction to mandate poleward mass and moisture fluxes balance polar cap surface pressure tendency and precipitation minus evaporation (*Trenberth, 1997; Trenberth and Stepaniak, 2004*), (ii) scalar adjustment of the poleward and equatorward winds to ensure zero mass flux (*Hill et al., 2015; Rencurrell and Rose, 2018*), (iii) careful accounting of the phase transitions so that the (necessarily) opposing poleward moisture flux in the atmosphere and ocean are treated consistently (*Mayer et al., 2017*) and (iv) calculation of energy fluxes with regard to column average MSE over an unchanging mass of atmosphere (*Donohoe and Battisti, 2013; Donohoe et al., 2013b; Liang et al., 2018; Donohoe et al., 2020a*). While the work proposed above will focus on method iv, it is worth noting that the other methods could prove valid provided all energy fluxes (i.e.

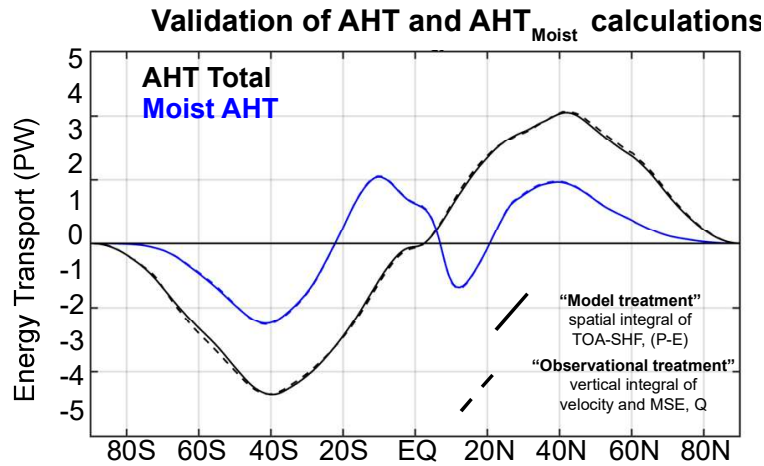


Figure 5: Demonstration of the near-equivalence of (zonal and annual mean) AHT and AHT_{MOIST} calculated using the radiative (“model treatment”) and dynamical (“observation treatment”) approaches in a CESM control simulation. The solid lines show the **model approach** of calculating polar cap spatial integrals of TOA radiation minus SHF to evaluate AHT and precipitation minus evaporation to evaluate AHT_{MOIST} . The dashed lines show the **observational approach** of calculating the vertical and time average of the instantaneous fields to determine AHT from velocity and MSE and AHT_{MOIST} from velocity and latent energy.

SHF, AHT, storage) are treated consistently. I will evaluate how methodological differences would impact the evaluation and interpretation of model/observational comparison.

Here, I demonstrate the ability of method iv (*Donohoe et al., 2020a; Donohoe and Battisti, 2013*) to be used for model-observation comparison by using “perfect model” experiment. Instantaneous 3-dimensional model velocity, temperatures, geopotential and humidity is output (onto pressure levels) in a CESM control simulation and AHT is calculated as if the model output was reanalysis data – from the vertical integral of $V \times MSE$. I then compare the resultant AHT to that found using the typical model based calculation as the spatial integral of TOA radiation and SHF (Fig. 3). The AHT and AHT_{MOIST} calculated by these two methods match incredibly well indicating that the energy budget at each latitude has been closed and that my method for balancing the mass and moisture budgets are self-consistent. Because AHT and OHT in models is calculated from standard model monthly mean output, global energy flows across large suites of coupled models participating in the Coupled Model Inter-comparison project (*Eyring et al., 2016; Taylor et al., 2012*) can be compared to observational MHT/AHT/OHT to give an unprecedented understanding of model biases and spread in global scale energy flows (Fig. 1). Additionally, the AHT can be partitioned into components associated with the mass overturning circulation of the atmosphere (e.g. Hadley and Ferrel cells), stationary eddies (e.g. monsoon and standing mid-latitude mountain waves) and transient eddies (e.g. storms) where the latter are evaluated from the residual of total AHT and that associated with the stationary circulation (Fig. 2 *Donohoe et al., 2020a*). The accompanying observational calculations will be performed using data from three sets of reanalysis: (i) NCEP (*Kalnay et al., 1996*) – completed; (ii) ERA5 (*Hersbach et al., 2020*) – existing calculations used ERA interim; and (iii) MERRA (*Rienecker et al., 2011*) – not started.

In the proposed work I will extend the methodology for model-observation comparison of energy flux calculations to seasonal and inter-annual time-scales and zonally inhomogenous spatial scales.

Proposed work: Seasonal and inter-annual time-scales. Evaluation of energy fluxes at non-equilibrium time-scales requires the additional accounting for energy and moisture storage in the atmospheric and oceanic columns. My work to date has contributed several novel techniques to evaluating AHT/OHT at non-equilibrium time-scales (*Donohoe et al., 2020a, 2013b*) and show good (but imperfect) agreement in the dynamical and radiative based calculations (not-shown). We propose to use similar perfect model experiments to evaluate how well the alternative treatments of the mass and moisture budgets perform and to extend the non-equilibrium evaluation of energy fluxes to different models. This work will establish which framework for dynamical calculation of AHT and OHT provide self consistent treatments of the energy, mass and moisture budgets (they possibly all do) and how the interpretation of AHT and OHT differs between these frameworks.

Proposed work: Zonally heterogeneous energy transport. Climate energetics are inherently non-

zonally homogenous ranging from the mid-latitude land-ocean contrast (*Fasullo and Trenberth, 2008; Donohoe and Battisti, 2013*), the regional nature of tropical precipitation (*Atwood et al., 2020*) and sea-ice (*Kay et al., 2011*) trends and variability. Extension of the energetic framework to regional scales requires similar methods to those used in the zonal mean calculations to consistently treat the mass and moisture budgets so that observationally based (*Liu et al., 2015; Trenberth and Stepaniak, 2004*) calculations can be compared model derived energy fluxes. My work has developed a computationally efficient method for doing these calculations in models and observations that calculates two dimensional energy fluxes relative to the atmospheric-column average MSE and dividing the atmospheric winds into advective and divergent components (*Donohoe and Battisti, 2013*). The proposed work will evaluate the reliability of these calculations – and those using different techniques (*Trenberth, 1997; Liu et al., 2015*)– in perfect model experiments to evaluate the fidelity of the dynamical based calculations in capturing the lateral energy flux convergence constrained by TOA radiation and SHF. I will also develop a catalog of observational based atmospheric energy fluxes –from ERA5 (*Hersbach et al., 2020*), NCEP (*Kalnay et al., 1996*) and MERRA (*Gelaro et al., 2017*) reanalysis – and the implied SHF from the residual of CERES radiation, AHT and atmospheric column energy storage (Table 1). Finally, the SHF in conjunction ocean heat content changes from ARGO (*Johnson et al., 2009*) will allow an estimation of OHT as the residual of SHF and ocean heat content change.

Outreach activity: development of online community resource for model-observation comparison of MHT/AHT/OHT calculations. The use of atmospheric (AHT) and oceanic (OHT) heat transport for analyzing a myriad of climate problems across spatio-temporal scales has become ubiquitous in the climate research community. Model-observational comparison of energy fluxes is useful for evaluation of model biases in mean-state and variability and the fidelity of modeled trends over the observational period.

The code for all zonal mean and zonally-inhomogeneous model based calculations and observational calculations will be integrated into a PANGEO gallery – an organizational of coding notebooks into a geoscience analysis themes – for open access use by the climate research community. This online repository will provide source code for global energy flux calculations as python notebooks linked to cloud based CMIP6 model output and the observational based calculations I will develop as part of the proposed work (Section 4). The PANGEO online community has already made use of CMIP6 model output and I will work with Ryan Abernathey (see letter of support) to integrate our analysis techniques and calculations into this existing community.

5 Education activities

The primary educational component of the proposed work will develop hands-on interactives that illustrate climate science for K-12 and adult audiences. These interactives will be used in three different settings: (i) as part of the Curiosity Expo: Climate Science events hosted by the Pacific Science Center in Seattle Washington – an event attended by over 5,000 unique visitors each year, (ii) as a module for the Pacific Science Center’s Science on Wheels program – a traveling classroom throughout Washington state in which Pacific Science Center staff run classroom and after school K-8 programs and (iii) as part of the University of Washington Program on Climate Change outreach program that provides classroom and general public presentations on climate science and impacts of climate change. These demos will be co-developed by the PI and graduate students at the University of Washington under the guidance of the staff at Pacific Science Center as part of the graduate student’s capstone project for the graduate certificate from the Program in Climate Change. The proposed interactive activities will develop novel demonstrations of the cutting edge research my students and I are doing about the fundamentals of energy flows in the climate system tailored toward engendering enthusiasm for scientific inquiry amongst young students. The proposed activities will make use of the existing infrastructure at the University of Washington and the Pacific Science Center to both multiply the number of climate science experts giving outreach presentations and the inertia of existing outreach networks to reach wide audience.

The strategy for developing the climate science demos will be to enlist a cohort of graduate students (along with the PI) to first attend the multi-week Science Communication Fellowship at the Pacific Science Center in Seattle, WA (budget justification item 5d). The content of this internationally recognized course is based around the Portal to the Public concept of science communication (NSF grant DRL-0639021) and is designed to help scientist refine key messaging and develop techniques for discussing and delivering complex topics to public audiences. This fellowship also supports the development of hands-on activities related to the Fellow's field of expertise. The PI and 2-3 graduate students will participate in the Fellowship in year one of the proposed work (Fig. 5 – target Fall 2021). After the Fellowship the students and PI will work with Science on Wheels team at the Pacific Science Center to develop climate and climate change related hands-on interactives. A second cohort (2-3) of graduate students will participate in the Science Communication Fellowship in Year 3 (target Fall of 2023) and then take over the module development. This will allow continuity to the outreach activities after the initial group of students finish their capstone projects. The work the graduate students devote to developing these hands-on interactives will constitute their capstone projects– a final project for the graduate certificate from the UW Program on Climate Change (UW PCC). The UW PCC is a cross disciplinary collaboration across natural sciences, engineering, social and health sciences that was founded in 2001 from UW initiative for cross- disciplinary research and education. The UW PCC's primary goals are to train the next generation of climate researches and communication leaders to research and educate across (as opposed to within) traditional academic perspectives. I have been involved in the UW PCC since 2004 when, as a graduate student fellow, I co-founded the PCC-funded Graduate Climate Conference, an all graduate student cross-disciplinary annual conference that has been successfully run between MIT and UW for 14 years and is now funded by NSF. I currently serve on the UW PCC board of directors, have organized summer institutes and frequently guest lecture in UW PCC classes. UW PCC Capstone projects are targeted to be 120 hours of work per student across multiple academic quarters devoted to communicating climate science expertise to the general public and build connections between the University of Washington and broader community.

The contents of the hands-on interactives will be developed during the Science Communication Fellowship, informed by lessons learned on how to message key scientific concepts and communicate complex ideas to the general public. These interactive will be developed with the help of Jim Johnson, a Field Engineer at the UW Applied Physics Lab (see budget justification for details) who runs his own machine shop and has extensive experience designing custom research and outreach components. Two of each interactive will be developed, one for use in UW PCC outreach events and one for the SOW program. I provide here some initial ideas on possible hands-on modules that could be developed.

Example of proposed educational interactive: The seasonal cycle of temperature throughout the world. This module would be focused on understanding how the shape (i.e. amplitude and phase) of the seasonal cycle of temperature differs between geographic regions of the world and the underlying physics responsible for these geographic variations. There would be both an interactive software and hands-on activity components.

Interactive software: This component would allow participants to select various locations throughout the world and compare the shape of the seasonal cycle of temperature. For example, a student could start by finding their home town and comparing the seasonal cycle of temperature to someplace they have visited. The software would allow the students to calculate the amplitude (peak to trough temperature difference) and phase (dates of maximum and minimum temperature) at each location. We would then ask students to search for locations where they think the seasonal cycle of temperature will be largest (e.g. high latitude interior of the continents such as Siberia) and smallest (e.g. low latitude oceans) and where they think the seasonal cycle will be most and least delayed (land versus ocean). The goal of these exercises is to first and foremost emphasize how drastically the seasonal cycle differs with geographic location but also to emphasize that proximity to land versus ocean impacts both the amplitude and phase of the seasonal cycle with terrestrial locations having large amplitude and less delayed seasonal cycles than their maritime

counterparts at comparable latitudes.

Hands-on interactive demo: This component would probe the key physics controlling the seasonal cycle of temperature in a tank setting. Two side by side insulated tanks of air would each be illuminated by (visible spectrum) lights that oscillate in intensity (akin to the seasonal cycle of insolation). The temperature and light intensity at the surface would be measured in each tank and output as a time series on a screen. This allows visualization of the amplitude and phase of the temperature oscillations relative to intensity of light. We would then ask the students to make changes to one of the tanks that they think will change the amplitude and phase of the temperature response. For instance, the students could add water to the surface of one tank resulting in a decreased amplitude (and delayed phase) of the temperature variations to emphasize the concept that the heat capacity of the surface moderates the amplitude (and phase) of temperature changes. We could ask the students to calculate how much water would be needed to double the heat capacity of the tank (1 meter of air = 0.25 mm of water) and half the temperature response and emphasize the enormity of the heat capacity of water (and the role of the oceans in climate and climate change). Alternatively, the students could change the color of the surface from black (default) to white. This would change the amount of light absorbed at the surface with the black surface resulting in a larger temperature variations as compared to the white surface. This would get at the impact of surface albedo on absorbed solar radiation.

Other possible demos to develop include: (i) greenhouse effect of carbon dioxide, water vapor or methane in the same lighted tank environment discussed above– to our knowledge, no classroom demonstration of the greenhouse effect has really gotten the physics right, (ii) ocean acidification, (iii) ocean water mass transformation. In the event that COVID-19 related social distancing prohibits in person outreach events, the hand-on activities will be replaced with virtual presentations.

The interactives developed will ultimately form sub-components of a module for the Pacific Science Center's Science on Wheels program (SOW). SOW was developed by and is run by Pacific Science Center's outreach education program and travels to schools and summer camps throughout the Pacific Northwest to bring science to life through content-rich, hands-on experiences. SOW programs are designed to supplement traditional classroom curriculum. The Pacific Science Center staff tailors the SOW program to the needs of the students and content is provided through school assemblies, inquiry-based workshops and interactive Exhibit Sets. SOW provides unique, hands-on programs aimed at creating opportunities to build, experiment, think critically and aims to foster curiosity in science and math that extends beyond the classroom. Programs are aligned with Washington State Science Learning Standards (Next Generation Science Standards). Depending on the exact nature of the demos the graduate students and I develop, our modules will form sub components of one of either the "Physics on Wheels" or "Mathfinder" existing Science on Wheels themes. Pacific Science Center staff have been contracted (as a consultant service in years 1 and 3, see budget justification item 3 under other costs) to serve as educational consultants to ensure the interactives developed for the SOW program are grade level appropriate and meet the technical specifications of the existing program.

The interactives I develop with the UW PCC graduate students will also be displayed (staffed by me and others from the UW community) during outreach events at the Pacific Science Center including "Meet a Scientist" events and the annual 4-day Curiosity Expo: Climate Change. The latter event evolved from the Polar Science Weekend that was developed by my colleague Harry Stern at the UW Polar Science Center in collaboration with the Pacific Science Center and has drawn 5,000-10,000 visitors per year since 2005. This event aimed to bring students, teachers, and families face-to-face with active scientists who work in some of the most remote and challenging places on Earth to learn first-hand about polar research in a fun and informal setting event. The event is free of charge and grants to subsidize transportation to the event from financially challenged communities aimed to bring enthusiasm for scientific inquiry to underrepresented groups in the natural sciences. In 2018, the scope of this event was expanded from polar regions to encompass the global climate system (with the name changed to Curiosity Expo:Climate Change), building on the strong inertia of the annual events and the collaboration between UW and the Pacific Science Center. A key component of the proposed educational activities is to develop hands-on interactives and other climate relevant material

to engage the UW PCC climate science expertise with the public outreach expertise of the Pacific Science Center through the SOW and Curiosity Expo activities.

Additionally, the hands-on interactives will supplement the existing outreach activities of the UW Program on Climate Change. These outreach presentations are coordinated by the UW PCC and bring graduate students, faculty and scientist to classrooms and public events (including civic groups, retirement communities) free of charge. These presentations include basic climate science, climate impacts and policy presentations and build off the presentation resources (primarily a slide bank) developed by the UW PCC community. The hands-on interactives that we develop would complement and expand the UW PCC outreach capabilities.

6 Timeline for research and Education/Outreach activities

Project timeline by year	1	2	3	4	5
Project 1: Controls on the energy transport from equator-to-pole (Section 2)					
Analyzing climate model biases in MHT and its partitioning	X	X			
Idealized rotation rate and topography experiments -- gray and full radiation		X	X		
Writing and publication			X	X	
Project 2: Controls on the tropical precipitation (Section 3.1)					
Analysis of the zonal mean contracting/intensifying mode -- seasonal analysis	X	X			
Characterizing and understanding mechanisms of zonal inhomogenities			X	X	
Reintpreting the paleo record with model constraints on patterns of variability				X	X
Writing and publication		X		X	X
Project 3: Armospheric drivers of high frequency sea-ice variability (Section 3.1)					
Analyzing co-variability of atmospheric energy transport and sea ice loss in models	X	X			
Observational analysis and impact on long-term trends			X	X	
Writing and publication		X			X
Project 4: Developing an online repository for model/observational comparison of energy transport (section 4)					
Zonal mean observational calculations and comparison to models	X	X			
Development and testing of 2-dimensional AHT calculations		X	X	X	
Outreach Project: Software implementation on PANGEO			X	X	X
Educational and outreach activities					
Science Communication Fellowship (Cohort I and Cohort II)	X		X		
Development of hands on climate interactives (with Jim Johnson, APL)		X	X		
Pacific Science center and UW PCC outreach events		X	X	X	X
Science on wheels program			X	X	X

7 Prior NSF Results

Donohoe: AGS Award 1702827; \$269,534: "Expansion/Contraction of the Intertropical Convergence Zone; An Emerging Mechanism of Tropical Precipitation Changes for Reinterpreting Paleoclimate" (8/2017-8/2020). Intellectual Merit: Analyzed modes of tropical precipitation variability in models and observations, developed theory, applied knowledge to paleoclimate records. Broader Impacts: Tropical precipitation variability changes have widespread agricultural impacts especially in semi-arid regions. Funding support aided 1 early career female scientist (Atwood). Publications: Donohoe, Atwood, Byrne (2019) Atwood et al. (2020) Donohoe et al. (2020). Data archiving: Observed atmospheric energy heat transport calculations are archived in the Department of Atmospheric Sciences at the University of Washington.