1 Introduction

Meridional shifts in the inter-tropical convergence zone (ITCZ) are ubiquitous for explaining past changes in tropical precipitation deduced from paleoclimate records. Collectively, paleoclimate data suggest that the ITCZ may have shifted north or south by of order several degrees latitude in response to paleoclimate forcing. For example, compilations of paleoclimate records have been interpreted as a 7° southward ITCZ shift during the Last Glacial Maximum (LGM) in the Atlantic sector (*Arbuszewski et al.*, 2013) and abrupt Pacific ITCZ migrations of order 4° associated with Northern Hemisphere iceberg discharges (Heinrich events, *Wang et al.*, 2001; *Jacobel et al.*, 2016). In addition, a northward ITCZ displacement has been inferred during the early to mid-Holocene (e.g. *Haug et al.*, 2001) – when boreal summer insolation was more intense– although the zonal homogeneity and magnitude of the ITCZ shift is unclear. During the Little Ice Age (LIA, 1400-1850 CE), a 5° southward ITCZ shift has been inferred from proxy records in tropical Pacific lake sediment (*Sachs et al.*, 2009; *Newton et al.*, 2006).

The notion of a meridional translation of the ITCZ under paleoclimatic forcing is attractive in part because of the prominence of seasonal migrations of the ITCZ in contemporary climate which are visually evident from satellite data. The climatological seasonal migration of the ITCZ sets the meridional extent of the tropics – regions within the seasonal meridional range of the ITCZ are wet and bio-diverse (*Koppen*, 1936) and those outside the range are dry and barren. The essential role that seasonal migrations of the ITCZ play in the observed climate system presents a visually compelling analog for how tropical hydroclimate may have adjusted in past climate states by meridionally translating the ITCZ in response to global scale forcing. Meridional shifts in the ITCZ have also been commonly invoked to describe modeled precipitation changes due to idealized (*Kang et al.*, 2008), historical (*Hwang et al.*, 2013) and future (*Frierson and Hwang*, 2012) forcings using an energetic framework that links hemispheric scale energy budget to the ITCZ location. Because the atmospheric energy transport across the equator is dominated by the Hadley Cell (*Trenberth and Caron*, 2001) and the ITCZ is co-located with the ascending branch of the Hadley cell (*Held*, 1980), the displacement of the ITCZ off the equator is proportional to the hemispheric contrast of energy input into the atmosphere (Fig. 1A). This theory quantitatively unifies the seasonal migration of the ITCZ in contemporary climate – namely the ITCZ moves toward the solar heating of the atmosphere (*Chiang and Friedman*, 2012; *Donohoe et al.*, 2013b) – with the ITCZ shift due to hemispherically asymmetric forcing (*Chiang and Bitz*, 2005; *Donohoe and Voigt*, 2015) and response surface heat fluxes associated with ocean heat transport (*Marshall et al.*, 2013; *Frierson et al.*, 2013). Specifically, observational and modeling constraints suggest that in order to meridionally translate the ITCZ northward by 3° latitude, 1 PW of energy must be added (removed) from the Northern (Southern) Hemisphere. This amount of energy is equivalent to a simultaneous CO_2 doubling in one hemisphere and halving in the other hemisphere. This magnitude of hemispheric contrast in energy input to the atmopshere is unrealizable in models, even under extreme forcing, and not seen in observations (*Stephens et al.*, 2016).

This emerging theoretical understanding suggests that the magnitude of ITCZ shifts deduced from paleoclimate records are incompatible with the theory and modeling of ITCZ shifts in response to paleoclimate forcing. Furthermore, paleoclimate reconstructions of past sea surface temperature (SST) changes are inconsistent with ITCZ shifts that are $> 1°$ in magnitude during the last glacial and in response to Heinrich events (*McGee et al.*, 2014). Yet, is is undeniable from paleoclimate hydrological records that large magnitude tropical precipitation changes which are regional in

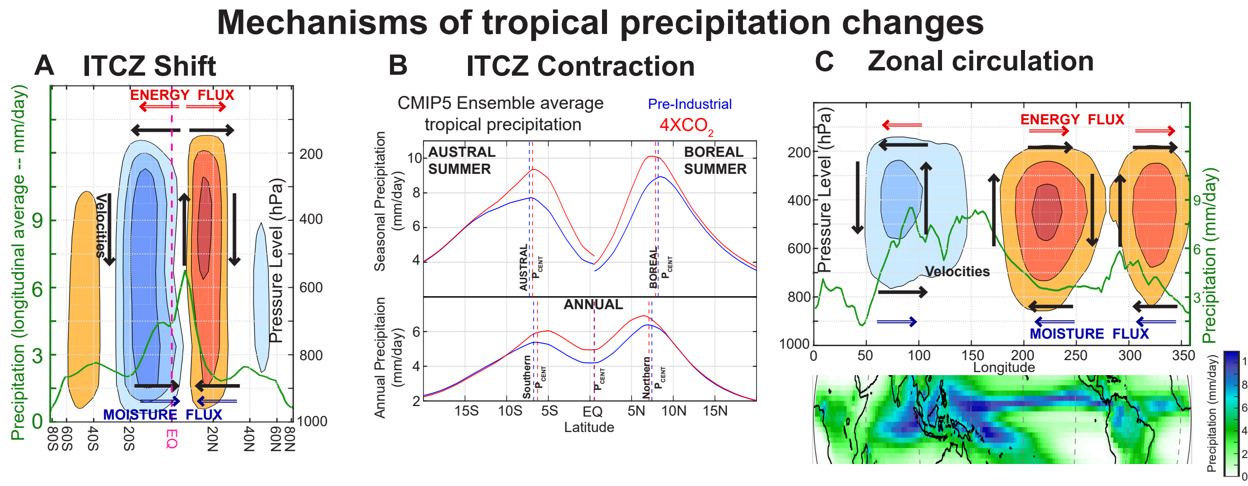

Figure 1: Mechanisms of tropical precipitation changes considered in the proposed work. (A) The ITCZ shift responds to the hemispheric asymmetry of energy input into the atmosphere that causes the Hadley Cell (colored contours with interval 20 Sverdrups) to shift into the more strongly heated hemisphere such that the atmosphere exports energy (red arrows) away from the heated hemisphere. The precipitation (green) is co-located with the ascending branch and shifts alongside the Hadley cell. (B) The ITCZ contraction is governed by the seasonal range of the ITCZ. During the Boreal (upper right) and Austral (upper left) summers, the (CMIP5 ensemble mean) ITCZ is closer to the equator under 4XCO$_2$ (red) as compared to in the pre-industrial (blue). As a result, the annual mean (bottom) tropical precipitation is meridionally contracted. (C) Zonal asymmetries in tropical precipitation respond to zonal asymmetries in atmospheric heating via shifting, contracting and intensifying the zonal overturning circulation (i.e Walker circulation) and associated zonal atmospheric energy transport. As in (A), the overturning streamfunction is shown in colored contours, the precipitation in green, the moisture fluxes in blue and the energy fluxes in red.

nature did occur. The goal of the ongoing and proposed work is to provide alternative mechanisms of past tropical precipitation changes and analyze the ability of these novel mechanisms to describe the spatiotemporal structure of paleoclimate reconstructions of tropical precipitation changes and variability. Our ongoing work indicates that, despite the ubiquity of the paradigm of meridional ITCZ shifts in both the paleoclimate and modeling literature, ITCZ shifts explain very little of the tropical precipitation changes seen in paleoclimate modeling studies in response to myriad of different forcings (*Atwood et al.*, 2019).

Here, we propose two alternative mechanism of regional scale tropical precipitation changes (hereafter ΔP) in response to external forcing:

> **Meridional contraction of the ITCZ**: This mode is characterized by the meridional expansion/contraction of the region of intense convective precipitation near the equator. We demonstrate below that, in both modeling studies and modern-day observations, meridional contractions (expansions) of the ITCZ are robustly accompanied by intensification (reductions) of tropical precipitation. Furthermore, the scaling between the degree of contraction and intensification is consistent across a myriad of climate states ranging from the LGM to the response to CO$_2$ quadrupling. As a result, free and forced variations of the zonal average tropical precipitation (ITCZ) are best characterized by simultaneous changes in the width and intensity of the precipitation and not (as is widely assumed) by meridional shifts in the ITCZ.
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> **Shifts and intensifications of the zonal atmospheric circulation**: Much of the modeled ΔP in response to external forcing is zonally inhomogeneous but still regional in nature with

robust changes within specific ocean basins. The degree of zonal inhomogeneity and localization of ΔP depends on the nature of the forcing with high-latitude forcing generally producing more zonally uniform tropical precipitation changes and low-latitude forcing (and ocean circulation changes) resulting in zonally localized responses (*Atwood et al.*, 2019).

We demonstrate here that these modes of tropical precipitation changes explain a much larger fraction of simulated tropical precipitation changes than the commonly invoked ITCZ shift. Understanding the relative importance and dynamics of these additional modes of tropical precipitation changes in climate models will advance our understanding of the characterization and causes of tropical hydroclimate changes deduced from the paleoclimatic record and this task is central to the proposed work.

The proposed work is threefold:

Characterizing the tropical precipitation response to climate forcing in models: The goal of this component is to optimally describe ΔP using conceptually intuitive modes tropical circulation changes. We will decompose ΔP into zonally homogenous and zonally inhomogeneous responses and further decompose each into shifting/contracting and intensifying modes of ΔP.

Understanding the dynamics of the modes of tropical precipitation changes: ITCZ shifts have been linked to the hemispheric contrast of energy input to the atmosphere in recent literature. Our work has developed a similar theory linking the contraction of the ITCZ to the seasonal cycle of hemispheric scale atmospheric heating. Additionally, the zonally localized precipitation changes will be related to the shifts and contractions of zonal atmospheric circulation demanded by inhomogeneities of atmospheric heating as pioneered by *Boos and Koorty* (2016).

Reinterpretation of existing paleoclimate data: The dominant modes of ΔP simulated in response to external forcing will be used to inform the spatial structure of ΔP deduced from paleoclimate records of the Last Glacial Maximum, Mid-Holocene, Heinrich events and the last millennium. These results will also inform whether the relevant physical processes, feedbacks and large scale forcings are well represented in coupled climate models and accounted for in paleoclimate forcing scenarios.

The proposed work will primarily analyze existing model simulations and paleoclimate data composites using the novel and transformative framework of tropical precipitation modes developed by the PI.

2 Scientific framework and results to date

Here we describe the methodology for characterizing modes of tropical precipitation changes (ΔP) and the dynamical processes responsible for these modes. We also share some results from work to date which demonstrate the utility of these novel paradigms for diagnosing robust precipitation changes in response to forcing and the underlying mechanisms of these changes.

2.1 Zonal mean precipitation changes

We begin by characterizing the zonal mean precipitation changes (hereafter $|\Delta P|$, where vertical bars denote zonal means). $|\Delta P|$ is analyzed in a suite of paleo and future climate simulations in-

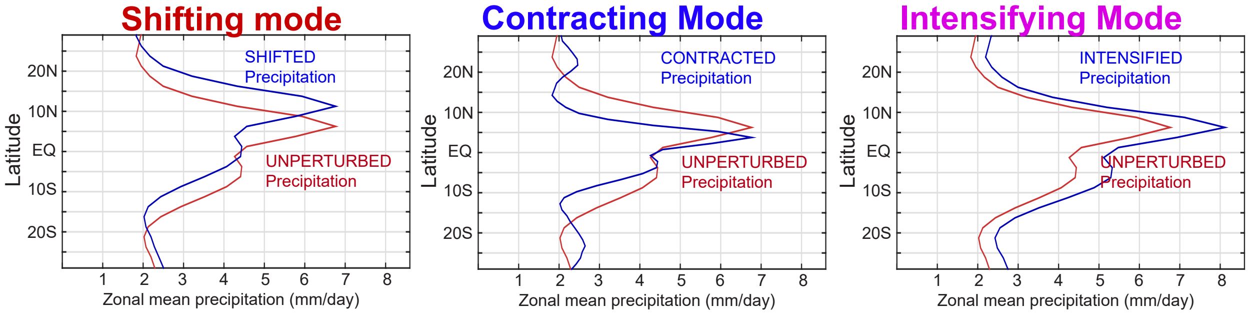

Figure 2: Cartoon of the modes of zonal mean tropical precipitation changes considered in this work. The red lines show the observed climatological zonal mean precipitation. The left panel shows the shifting mode of precipitation in blue produced by meridionally translating the climatological precipitation by θ degrees latitude ($P_{SHIFT}(\theta) = P_{CLIM}(\theta+\theta_{SHIFT})$). The middle panel shows the contracting mode in blue which is produced by mapping the climatological precipitation (red) onto the latitude multiplied by a scalar, C ($P_{CON}(\theta) = P_{CLIM}(C\theta)$). The right panel shows the intensifying mode in blue which is produced by multiplying the climatological precipitation by a scalar, I ($P_{INTENS} = I\, P_{CLIM}(\theta)$.

cluding the LGM (*Braconnot et al.*, 2007), the mid-Holocene (*Braconnot et al.*, 2012), the response to an abrupt quadrupling of CO_2 (*Taylor et al.*, 2012), volcanic forcing and the response to North Atlantic freshwater hosing experiments to simulate the impact of iceberg discharge on ocean circulation (*Chiang and Bitz*, 2005; *Atwood*, 2015). We wish to explicitly ask: what fraction of $|\Delta P|$ can be explained by ITCZ shifts versus other modes of variability? This question is motivated by the fact that, in the presence of strong climatological spatial gradients of precipitation, precipitation anomalies often show dipole features that are often interpreted as a shift in the ITCZ even if the $|\Delta P|$ changes are poorly described by a shift. In addition to the ITCZ shift mode, we consider two additional modes of $|\Delta P|$: i) the intensification of the tropical precipitation without a change in shape and ii) the meridional expansion/contraction of the region of intense precipitation. The shifting, contracting and intensifying modes are demonstrated schematically in Fig. 2. We characterize $|\Delta P|$ by optimally manipulating the climatological precipitation via these three modes – the mathematical formalism is given in the Fig. 2 caption – to best match (in the least squares fit sense) the perturbed precipitation. We optimize all three modes in conjunction and then can ask what combination of shifting, intensifying and contracting best describes $|\Delta P|$ in each simulation and how much each mode contributes to the fractional change $|\Delta P|$.

Across all models and forcing scenarios, ITCZ shifts explain very little of $|\Delta P|$ ($< 15\%$, Fig. 3B) and models differ on the direction of the ITCZ shift with no robust ensemble mean shift (not significantly different from zero at the 95% confidence interval) in response to $4XCO_2$ and LGM forcing. There is a robust (statistically significant) but modest (0.2°) northward shift in simulations of the mid-Holocene (*Liu et al.*, 2018) and robust ($\approx 1^\circ$) southward shift in response to freshwater hosing. These results demonstrate that ITCZ shifts explain very little of $|\Delta P|$, do not respond robustly to external forcing and are much smaller in magnitude than the changes deduced from the synthesis of paleoclimate records.

In contrast, there is a robust meridional expansion and reduction of precipitation in simulations of the LGM and a contraction and intensification of precipitation in simulations of $4XCO_2$ (Fig. 3A). Furthermore, ITCZ intensifications and contractions are tightly coupled to each other; models with larger magnitude contraction/expansion in response to forcing show larger magnitude intensifications/reductions. Therefore, we define a joint mode of ITCZ contraction and intensification

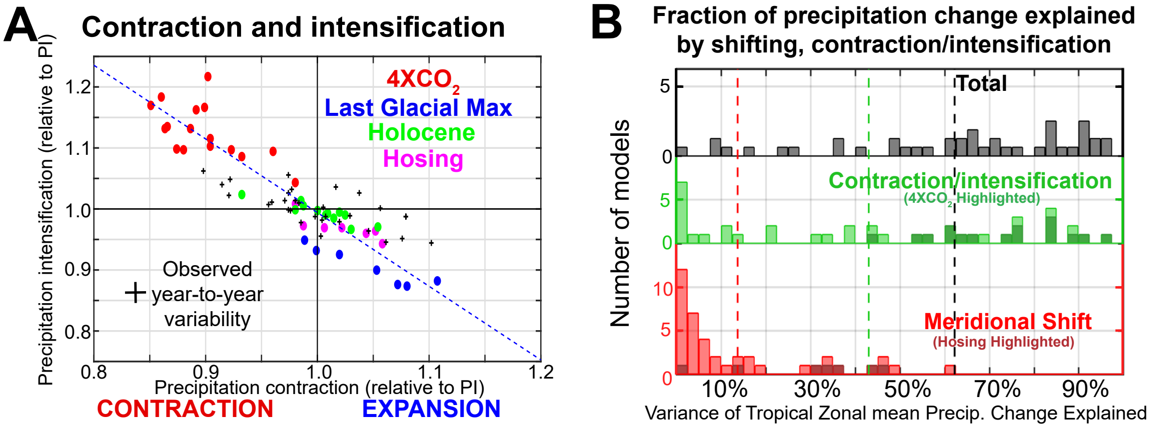

Figure 3: (A) Scatter plot of contraction scalar (ordinate) versus intensification scalar found by optimally shifting-contracting-intensifying the climatological precipitation to best match that in the Last Glacial Maximum (blue dots), 4×CO_2 (red dots), freshwater hosing (magenta dots) and mid-Holocene (green dots) simulations. The black crosses show the same values for the year-to-year anomalies in observations. (B) Histogram of fraction of $|\Delta P|$ explained by each mode. The intensification and contraction scalars are treated as a single variable constrained by the statistical relationship from the linear best fit in (A).

(CI mode) by using the empirical linear best fit relationship between contraction and intensification scalars (dashed blue line). The CI mode explains more than 60% of $|\Delta P|$ with a single metric. The CI mode is a far more powerful mode than the ITCZ shift in explaining $|\Delta P|$ in response to external forcing. Additionally, models robustly simulate the CI mode in response to warming and cooling climate. The CI mode has the potential to transform our understanding of past tropical precipitation changes and their underlying mechanisms.

Dynamics of ITCZ contractions: Our recent work (*Donohoe et al.*, 2019b) demonstrated that the meridional contraction of tropical precipitation under 4XCO_2 results from reduced seasonal range of ITCZ migration off the equator; the ITCZ migration into the summer hemisphere is reduced under CO_2 forcing resulting in a more meridionally confined annual and zonal mean precipitation (Fig. 1B). Model mean-state biases in the meridional width of tropical precipitation are also explained by biases in the seasonal range of the ITCZ (*Kim et al.*, 2019). 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 (Fig. 1A), the seasonal range of ITCZ migration off the equator is governed by the seasonal cycle of energy input into the atmosphere; during the solstice seasons, the magnitude of the energy input (loss) in the summer (winter) hemisphere demands how much the Hadley cell and ITCZ must migrate off the equator to balance the same hemispheric contrast of seasonal atmospheric heating. Additionally, the ITCZ displacement off the equator is inversely proportional to the efficiency of atmospheric energy transport per unit of Hadley cell migration. If the atmosphere can move more energy across the equator for a given Hadley cell shift, the ITCZ will move less off the equator seasonally to balance the hemispheric contrast of solar heating. Our work (*Donohoe et al.*, 2019b) found that the seasonal cycle of atmospheric heating is relatively climate state invariant (dictated primarily by Earth-Sun geometry) whereas the efficiency of atmospheric heat transport in the tropics increases in a warming climate. We speculated that the latter results from enhanced gross moist stability of the tropical atmosphere whereby a warmer and moister tropical atmosphere has more energy aloft and, thus, can export more energy from the upper branch of the Hadley circulation per unit of mass transport (*Inoue and*

Back, 2017; *Wu and Tan*, 2013). This result is speculative, and our explanation here shortcuts some detailed tropical processes such as the depth and vertical structure of the circulation (*Wu and Tan*, 2013) and the potential role of eddy moisture fluxes (*Hill et al.*, 2015) which we hope to address in this proposed work. Nonetheless, this mechanism provides a potential explanation for the CI mode whereby the moisture content of the tropical atmosphere dictates the tropical precipitation intensity (via moisture convergence) and the meridional extent of the precipitation by way of moderating the atmospheric stability and energy transport in the Hadley circulation.

Observational constraints on the contraction/intensification (CI) mode: The consistent scaling between ITCZ contraction and intensification seen in climate models (Fig. 3A) has strong implications for paleoclimate interpretations because it suggests that the dominant spatial pattern and intensity of tropical precipitation change in concert thus reducing the degrees of freedom of $|\Delta P|$. A central question moving forward is: do models adequately represent the scaling between contraction and intensification and can observational constraints on the CI mode inform model behavior? The observed inter-annual variability of the CI mode (black crosses in Fig. 3A) demonstrates that ITCZ contractions and intensifications occur together in nature at the inter-annual time scale but the relative scaling features more contraction per unit of intensification than that in the model response to long-term external forcing (c.f. the slope of black crosses to the dashed blue line). This observed inter-annual variability is primarily associated with El Nino which features strong heating of the atmosphere in tropical Pacific and may not elicit the same CI mode response as climate time-scale temperature changes that are more spatially uniform. Therefore, it is essential to see if the inter-annual variability of the CI mode in modern day climate model simulations follow the same scaling seen in observed inter-annual variability or, otherwise, in response to long-term external forcing. This analysis will provide like-for-like comparison with the observational data and potentially will provide an emergent constraint on the CI mode scaling

2.2 Zonally localized precipitation changes

In response to paleoclimate forcing, particularly the mid-Holocene, the tropical precipitation change is zonally inhomogeneous (*Liu et al.*, 2018) and is qualitatively consistent with an intensification of the Northern Hemisphere monsoonal systems (*Braconnot et al.*, 2007). The zonal inhomogeneity of the precipitation response can be visualized by defining an ITCZ shift at each longitude (see Fig. 1 of *Atwood et al.*, 2019). In response to forcing such anthropogenic CO_2 and LGM, the ITCZ shift in each model is zonally localized and the zonal location of the ITCZ shifts differ between models. In response to volcanic forcing and freshwater hosing, the zonal location of the ITCZ shift is more consistent between models and is basin wide in scale. Overall, the zonally inhomogeneous precipitation response explains far more (>80%) of the precipitation changes across models and forcing scenarios than does the zonally homogenous response (<20%). Thus, it is paramount to develop a quantitative method for characterizing the zonal structure of ΔP and understanding the underlying dynamics.

We wish to formalize the characterization and robustness (i.e. consistency between models) of zonally inhomogeneous precipitation changes in response to paleoclimatic and anthropogenic forcing by decomposing ΔP into shifting, contracting and intensifying modes in the 2-dimensional space. The proposed approach is similar to the optimal shifting, contracting and intensification of the climatological zonal mean precipitation schematized in Fig. 2 but operating in 2-dimensions. We define five different modes of ΔP all operating on the climatological two dimensional pattern of tropical (equatorward of 20°) precipitation: (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 (demarcated by black lines in Fig. 4). All modes are optimized simultaneously. We will focus on annual mean ΔP but the methodology is generalizable to seasonal changes and inter-annual variability (including observations). These results will provide a physically interpretable optimal description of tropical precipitation changes 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.

One advantage of our novel approach is that, because all the modes are defined starting from the model specific pre-industrial climatology precipitation, *our modal decomposition takes into account biases in the tropical precipitation within each model*. For example, consider two models with different zonal locations of the climatological Western Pacific warm pool (and associated intense tropical precipitation). If the intense precipitation and warm pool shifted eastward in both models in response to LGM forcing, our methodology would identify the robustness of this precipitation change, whereas simply analyzing the differences in precipitation within each model would suggest that ΔP was inconsistent between the two models. We will also define zonal and meridional shifts of the zonal and meridional mass overturning circulations by optimally shifting the climatological Walker and Hadley cells. This exercise will evaluate if the precipitation changes are indeed linked to shifts in the overlying atmospheric overturning circulation as one would expect for large-scale convective precipitation or are, alternatively, linked to shallow convective or eddy processes.

Dynamics of zonally inhomogeneous tropical precipitation changes: 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 (Fig. 1C). 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.

The interpretation of zonal energy fluxes is severely limited by the lack of mass conservation in the zonal flow (*Kiehl and Trenberth*, 1997); since upward moving air in convective systems can diverge mass meridionally as well as zonally, there is no constraint that the zonal mass flux divergence spatially integrates to zero across a given ocean-basin or region and this limits the interpretation of the zonal atmospheric energy fluxes which are conventionally defined starting from a closed mass budget. *Boos and Koorty* (2016) circumvented this issue by defining the divergent energy flux from the (inverse Laplacian) of the atmospheric energy budget. Two conceptual developments by our research group (lead by PI AD) uniquely position us to improve on the methodology of

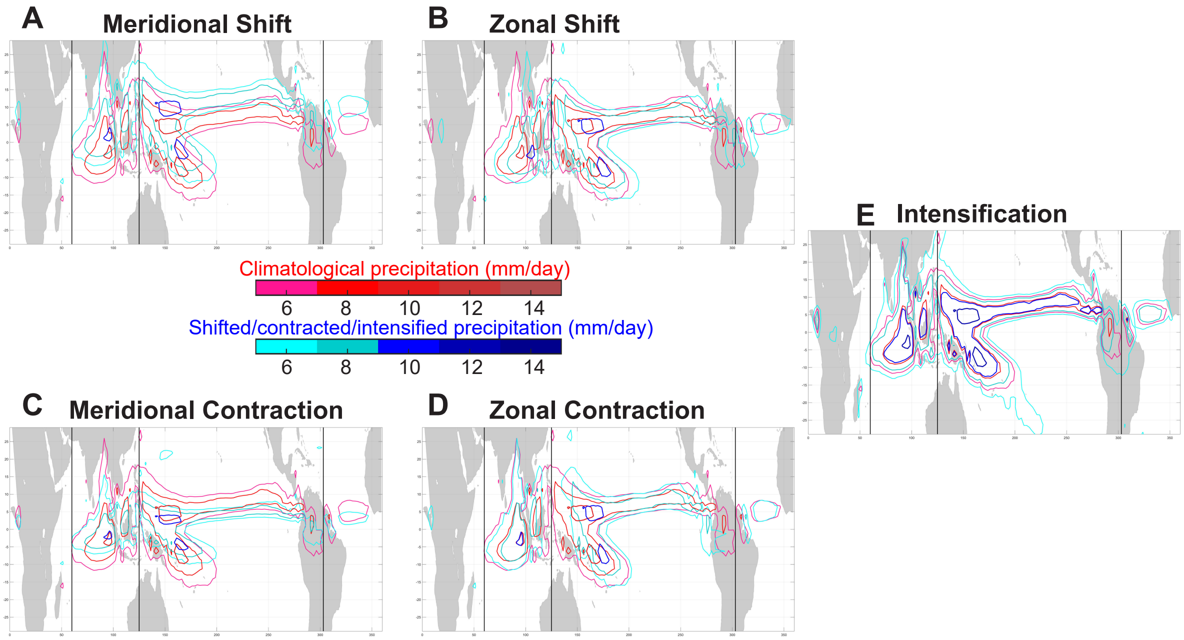

Figure 4: Schematic representing the different modes of 2-dimensional tropical precipitation changes. Red contours show the climatological precipitation and blue contours show the resultant precipitation pattern after manipulation by the mode. The black lines indicate boundaries between the ocean basins. (A) 5° south meridional shift, (B) 10° eastward zonal shift, (C) meridional contraction by 0.6 scalar multiplication (D) zonal contraction by 0.8 scalar multiplication and (E) Intensification by 20%.

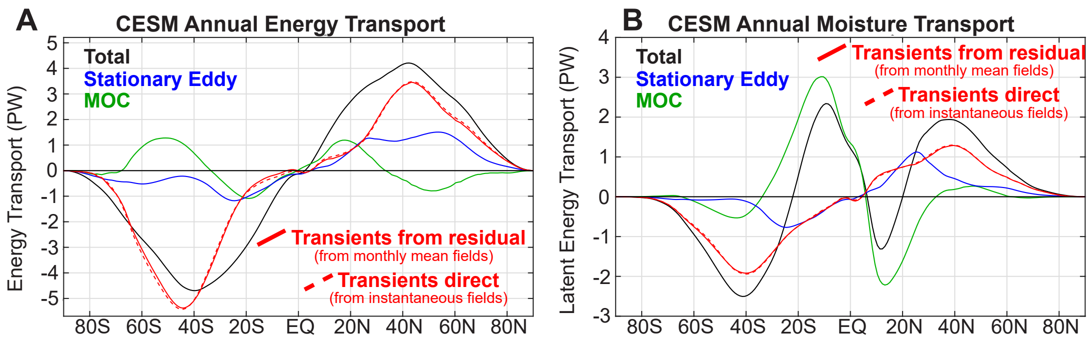

Figure 5: Validation of atmospheric heat transport calculation from standard model output that will be used in the proposed work. (A) Comparison of the zonally and vertically integrated transient eddy energy transport in CESM calculated from two different methods: a. **Residual method** (solid red lines) – calculated as that required by the atmospheric energy budget from standard monthly-mean model output and b. **Direct method** (dashed red lines)– calculated directly from instantaneous data. The black line shows the total AHT, the green line shows the MOC energy transport and, the green line shows the stationary eddy energy transport. (B) As in (A) but for the atmospheric moisture (latent energy) transports.

calculating zonal atmospheric energy fluxes. First, *Donohoe and Battisti* (2013); *Marshall et al.* (2013) developed an alternative method for calculating atmospheric energy fluxes by decomposing the winds into divergent and advective components and evaluating the associated 2-dimensional energy fluxes relative to the column averaged atmospheric energy content (an approach that was extended by *Liang et al.*, 2018). Second, these calculations which would normally require high temporal frequency observations or model output to calculate the transient eddy energy fluxes were replicated using standard (monthly-mean) model output (Fig. 5) by calculating the transient eddy energy transport as a residual of the atmospheric energy budget (*Donohoe et al.*, 2019a) and the energy transport by the stationary circulation. These methodological advancements give us an unprecedented database of how the atmosphere moves energy and moisture across a large suite of model simulations that will provide insights into the energetic controls of large scale atmospheric circulations.

We provide an example of a simulated zonal contraction of the tropical precipitation from a single coupled climate model as a proof of concept of the connection between changes in the zonal structure of tropical precipitation and the zonal energy fluxes by the zonal overturning circulation of the atmosphere (Fig. 6). The precipitation in the tropical Pacific clearly contracts zonally from the LGM to the PI to the 4XCO_2 simulation and is most evident in the South Pacific Convergence Zone. The changes in the overlying Walker circulation are characterized by a contraction of the ascending branch of the circulation and a modest westward shift with warming (Fig. 6B). The steepened zonal gradient in precipitation is associated with an enhanced magnitude and stronger zonal gradient in zonal energy fluxes (Fig. 6C). This strengthened atmospheric zonal energy flux must be accompanied by a enhanced zonal anomalies in atmospheric heating provided by either surface fluxes (associated with SST) or radiative processes. This framework thus links the zonal structure of tropical precipitation to the underlying structure of energy input of the atmosphere just as the zonal mean energetic theory links the ITCZ location to the hemispheric scale energy budget.

3 Proposed work

We emphasize that most of the proposed work involves applying our novel framework of characterizing tropical precipitation changes and diagnosing the underlying dynamics to existing paleoclimate simulations and applying this understanding with compilations of existing proxy data. Some additional idealized modeling experiment are proposed to elucidate the underlying dynamical processes. We emphasize our unique position to make progress on the dynamics of ITCZ contractions and the energetic theory of the zonal structure of ΔP due to the PI's expertise in atmospheric energy flux partitioning in both observations and in large ensembles of models from standard model output (*Donohoe et al.*, 2019a). We know of no other group that can do such calculations and strongly believe this approach will allow rapid progress in understanding the dynamics of tropical precipitation changes under paleoclimate forcing.

3.1 Dynamical analysis

3.1.1 Contraction/intensification (CI) mode

Our work has already optimally decomposed zonal mean changes in tropical precipitation between shifting contracting and intensifying modes in CMIP5 (*Taylor et al.*, 2012), PMIP2 (*Braconnot*

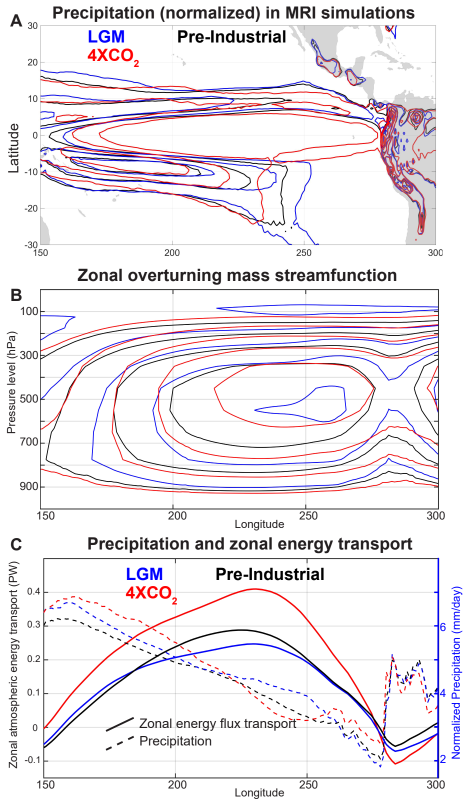

Figure 6: Example of a zonal contraction in the spatial pattern of tropical precipitation and associated changes in atmospheric circulation/energy fluxes from the MRI CGCM3 coupled model. (A) Normalized precipitation – defined such that the tropical averaged precipitation is equal to that in the pre-industrial in all simulations– for the LGM (blue), PI (black) and 4XCO$_2$ (red) with 2 mm/day contour interval. (B) Zonal overturning streamfunction with 20 Sv contour interval. (C) Zonal structure of normalized precipitation (dashed lines) and zonal energy fluxes (solid lines)

et al., 2007) and PMIP3 (*Braconnot et al.*, 2012) models to identify the prominence of the CI mode in explaining ΔP and the robustness of the CI mode response to paleoclimate forcing. We will extend this analysis to PMIP4 (*Kageyama et al.*, 2018) and CMIP6 (*Eyring et al.*, 2016) simulations.

Observational constraint on the CI mode scaling: The degree of contraction per unit of intensification is fairly robust across models and external forcing scenarios (Fig. 3A). Our working hypothesis is that *the contraction and intensification of tropical precipitation are linked by a mutual dependence on tropical surface temperature via the Clausius Clapeyron relationship and the dependence of atmospheric energy transport efficiency on the gross moist stability of the tropical atmosphere* (*Donohoe et al.*, 2019b), receptively. We will assess if this relationship is well represented in climate models to evaluate if the CI scaling identified in the model ensemble should be expected to apply to paleoclimate records (and future changes) by using the observed inter-annual variability as an analog. An essential question is if the inter-annual variability of ITCZ contractions and intensifications scales as the long-term response. Top answer this question, we will evaluate whether the inter-annual variability of the CI modes scale as the long term response of the CI mode to external forcing in the same model. This exercise will evaluate if the observed CI mode scaling can be used as an emergent constraint on the CI mode response to external forcing. The atmospheric energy transport in observations and coupled climate model simulations has already been decomposed (including seasonally) into overturning and eddy components in the novel framework developed by the PI and this will allow rapid progress in this component of the proposal.

Idealized simulations: Our previous work identified that the ITCZ width is determined by the seasonal cycle of energy input into the atmosphere and the efficiency of cross equatorial energy transport which we hypothesize is controlled by tropical surface temperature. We will analyze this parameter space in aquaplanet simulations with simplified (gray) radiation (*Frierson et al.*,

2006) atmospheric circulation models coupled to slab oceans. This model framework with the GFDL AM3 model is currently being run in collaborative research efforts with the PI locally in the Department of Atmospheric Sciences at the University of Washington. We will control the seasonal cycle of atmospheric heating by altering the slab ocean depth (as in *Donohoe et al.*, 2013a) and the global mean temperature by introducing a greenhouse forcing like radiative perturbation via altered longwave optical depth (*Frierson et al.*, 2006). This will identify the dependence of the ITCZ width within the seasonal amplitude of heating/surface temperature parameter space. Additional experiments will be run with an active shortwave atmospheric absorption which damps the ITCZ contraction with global warming due to the enhancement of seasonal atmospheric heating provided by this feedback.

3.1.2 Zonal modes of tropical precipitation

Characterization of zonally inhomogeneous tropical precipitation response to paleoclimate forcing: The tropical precipitation response will be optimally partitioned into shifting, contracting and intensifying modes allowing for both zonal and meridional manipulations of the climatological 2-dimensional precipitation field (Fig. 4). We will test the robustness of the partitioning to formulations of the manipulations (i.e. where the contractions are centered) and division of ocean basins. We will also pursue a formulation of precipitation changes in terms of a modified seasonal cycle of the climatological patterns. The end result will be a description of the dominant modes of the tropical precipitation changes including the robustness of the response to external forcing across models and the fraction of precipitation changes described by each mode. The same methodology will be applied to both the observed and simulated inter-annual variability to diagnose if the observational record provides a constraint to model biases in the preferred modes of tropical precipitation variability and changes.

Dynamical analysis in climate models: An energetic theory of the zonally inhomogeneous tropical precipitation will be pursued linking the response of the atmospheric circulation to zonal inhomogeneities in the energy input to the atmosphere. We will calculate the changes in two-dimensional atmospheric energy transport using two methodologies: 1. inverting the atmospheric energy transport demanded by the atmospheric energy budget by way of defining a energy potential as pursued by *Boos and Koorty* (2016), 2. decomposing the winds and associated energy transport into divergent and advective components as pursued by *Donohoe et al.* (2019a); *Donohoe and Battisti* (2013). We will use these complementary perspectives to analyze how the atmospheric overturning circulations respond to different spatial patterns of energy input and how the changes in atmospheric energy transport are decomposed between overturning and eddy components. These results will be compared to changes in the atmospheric mass overturning circulation to diagnose changes in the atmospheric energy transport efficient (i.e. gross moist stability) that we hypothesize govern the contraction of tropical circulations with under global warming. These changes in atmospheric circulation will be compared to the shifting, contracting and intensifying modes of precipitation variability where we expect the precipitation changes to mirror the changes in the atmospheric circulation. This theoretical development is useful because the changes in energy input to the atmosphere result from SST changes and surface processes. Thus, the precipitation response to paleoproxy constraints on SST changes and ecological changes can potential be quantified with this emergent theory allowing for an assessment of the consistency between paleoproxy precipitation responses and paleoproxy SST and vegetative reconstructions.

The proposed work primarily pursues the atmospheric response to altered SST patterns (and radiative processes) as a first step to understanding controls on the zonal atmospheric circulation changes. SST changes are inherently linked to ocean dynamics and future work will need to directly address the underlying and essential role that changes in ocean dynamics play in shaping SST patterns under paleoclimate forcing in addition to the role that atmosphere ocean coupling plays in moderating tropical precipitation changes (*Green et al.*, 2019). We see isolating the atmospheric response as a vital first step to understanding past hydrological changes.

Observational constraints on zonal precipitation changes: The same diagnostics of the coupling between zonal anomalies in atmospheric energetics, circulation and precipitation will be performed on the observed inter-annual variability. We will diagnose the atmospheric circulation and energy transport anomalies associated with the dominant modes of inter-annual variability of the 2-dimensional tropical precipitation. We will then compare the observed variability with the inter-annual variability in climate models to determine if models are biased in their representation and underlying mechanisms of tropical precipitation variability. This analysis will potentially provide an emergent constraint on which models adequately represent past and future changes in the long-term tropical precipitation response to external forcing.

Idealized simulations of zonally inhomogeneous tropical precipitation responses: These simulations will diagnose the relative importance of changes in tropical mean temperature versus changes in the spatial pattern of SST and energy input to the atmosphere in the atmospheric circulation response to paleoclimate forcing. The central hypothesis is that, if the zonal asymmetries in atmospheric heating are unchanged, the ascending branch of the atmospheric circulation contracts under warming due to more efficient atmospheric energy transport (*Byrne and Schneider*, 2016). These ideas will be tested in the same slab ocean aquaplanet framework with idealized (gray) atmospheric radiation described earlier with a zonally inhomogeneous energy flux provided to the ocean. This will result in zonal overturning circulation in the atmosphere and associated zonally localized convective precipitation akin to the Walker circulation. Tropical temperature will be altered by applying a greenhouse gas like perturbation to the longwave optical depths. We will then analyze the contraction, shifting and intensifying of the zonal cells and precipitation. Additional simulations will be run in a novel framework in the same model configuration whereby the atmospheric energy transport is held fixed by way of fixing the longwave heating of the atmospheric column but allowing atmospheric and surface temperature to adjust (*Cox et al.*, 2019). In this framework, global mean temperature can be altered by imposing a spatially uniform surface flux. We can then ask, how the atmosphere and precipitation respond to tropical warming subject to the constraint of fixed atmospheric energy transport to isolate the role of surface temperature on the atmospheric circulation changes.

3.2 Paleoclimate evidence of past tropical precipitation mode changes

We now describe the target paleoclimate states we will focus our dynamical analysis and paleo-proxy hydroclimate synthesis on.

3.2.1 Last Glacial Maximum

The LGM represents a high-priority target for comparing tropical hydroclimate changes between model simulations and proxy reconstructions, as the models demonstrate a pronounced signature of

ITCZ expansion and reduced intensity during this time period (Fig. 3A). However, interpretations of tropical precipitation patterns from proxy records during the LGM diverge. Compilations of sedimentary, cave and glacier records from the eastern Pacific, Cariaco Basin, and South America have been interpreted in terms of a weakened East Asian Summer Monsoon (*Wang et al.*, 2005), strengthened South Asian Summer Monsoon (*Auler and Smart*, 2001; *Baker et al.*, 2001; *Koutavas and Lynch-Stieglitz*, 2004; *Thompson et al.*, 1998) and arid conditions in central America and northern South America (*Peterson et al.*, 2000; *Koutavas and Lynch-Stieglitz*, 2004). These records have typically been invoked to infer a southward migration of the mean annual ITCZ during the LGM (*Koutavas and Lynch-Stieglitz*, 2004). Planktonic foraminifera records spread across the tropical Atlantic provide further support for a southward migration of the Atlantic ITCZ during the LGM (*Arbuszewski et al.*, 2013). In contrast, organic sedimentary biomarkers from marine sediment cores off the western coast of tropical Africa instead provide evidence for a contracted African rainbelt during LGM (*Collins et al.*, 2006).

3.2.2 Early to mid-Holocene

The early to mid-Holocene presents an additional target for this work, due to the existence of large but conflicting hydroclimate reconstructions from this period. NH summer insolation increased from the LGM to the mid-Holocene with a corresponding retreat of the large NH ice sheets (*Paillard*, 342) to near modern-day size around 8kyrs ago. From 8kyr to present, precessional phasing has decreased insolation intensity during boreal summer and decreasing obliquity has decreased high latitude insolation which has been argued to result in a thermal optimum from 6-8kyr ago followed by cooling until pre-industrial times (*Marcott et al.*, 2013). A progressive southward migration of the ITCZ over this time period has been inferred from a number of proxy records, including sediment records from the Cariaco Basin (off the north coast of Venezuela; Haug et al., 2001), sediment records across the tropical Atlantic (*Arbuszewski et al.*, 2013), δ18O values in cave stalagmites from Oman (*Fleitmann et al.*, 2003), and from lacustrine, ice core and speleothem records throughout South America (*Bird et al.*, 2011). However, an alternate hypothesis, based on organic biomarkers in marine sediment off the coast of tropical Africa, suggests that the tropical rainband was instead expanded during the early to mid-Holocene (*Collins et al.*, 2006).

3.2.3 Last millennium

Substantial tropical precipitation changes have been inferred from the paleoclimate record over the last millennium despite the absence of large-scale orbital and boundary condition (i.e. ice sheet) changes. Specifically, during the LIA, proxy records from tropical Pacific (see discussion in Sec. 3.2.3) have been interpreted to represent a southward ITCZ by as much as 5°. A recent compilation of sediment, cave and coral records from the western Pacific has instead invoked a meridional contraction of the ITCZ (*Yan et al.*, 2015). While an ITCZ contraction during the global cooling of the LIA (*PAGES 2k Consortium*, 2013) seems at odds with the relationship between contraction/expansion and global mean temperature change seen in the LGM and 4×CO_2 simulations (i.e. the ITCZ expands in colder climates and contracts in warmer climates; Fig. 3B), we note that that dynamics responsible for the CI mode and its response to different paleoclimate forcings (such as those during the LIA) is currently unknown and is precisely the focus of this proposal. In particular, *Yan et al.* (2015) argue that a reduction of the solar constant during the LIA was responsible for the ITCZ contraction. This result is consistent with our proposed mechanism; we would expect a reduced solar constant to decrease the seasonal amplitude of atmospheric heating resulting in a contracted region of tropical precipitation. The consistency of tropical hydroclimate changes deduced from paleo records and modeled in the ensemble of PMIP4 last millenium simulations (*Kageyama et al.*, 2018) will be analyzed through the novel framework developed in the proposed work.

3.2.4 Proposed synthesis of proxy data

To reconcile these competing interpretations of large-scale changes in tropical rainfall, we propose to re-evaluate the proxy evidence for tropical hydroclimate changes during each of these time periods, bringing together all available tropical hydroclimate proxy records to compare with the GCM simulations. Invoking the novel paradigm of tropical hydroclimate changes outlined in this proposal, we will ask: given the sparse collection of paleo hydroclimate records during each target period, what is the most likely interpretation of large scale tropical precipitation changes consistent with the dominant modes of ΔP identified in model simulations (and constrained by contemporary observations)? We will utilize the extensive network of proxy reconstructions available on the NCDC/NCEI and PANGAEA paleoclimate data repositories for this synthesis. Each proxy record will be categorized as representing “wetter", “drier"' or “no change" conditions during the time period of interest (relative to modern times) based on a 2-sample t-test for difference in means of the corresponding Z-scores. We will then use a Monte-Carlo simulation of random realizations of all possible modes of tropical precipitation changes (zonal and meridional shifts, contractions and intendsifications)– guided by our model analysis– and rank how well each randomly generated mode matches the paleoproxy evidence (weighted by the confidence in each proxy record). This exercise will provide a probabilistic most likely modal characterization of tropical precipitation constrained by both model behaivor and compilations of paleoproxy evidence.

Proxy records will be selected based on the following criteria: proxy locations lie within the tropics (20°N to 20°S, with the exception of the EASM region, where records as far north as 30°N will be included to resolve changes in the EASM), records cover the period of interest (19-23 kyr BP for the LGM, 6-8 kyr BP for the early- to mid-Holocene, and 0-1 kyr BP for the last millennium) with a minimum temporal resolution of 1000 yr for the LGM, 500 yr for the Holocene, and 100 years for the last millennium. Proxy records must either include the modern period, or modern values of the reconstructed variable of interest (e.g. $\delta 18O_{seawater}$) must be constrained.

4 Intellectual merit

This work directly addresses 3 of the 4 core P2C2 intellectual objectives:

1. *“document the past temporal and spatial variability of Earth’s climate system":* The emerging understanding that ITCZ contractions and intensification are tightly coupled and are the leading mode of tropical precipitation changes will allow us to reinterpret paleoclimate records within the context of this mode of variability.
2. *“determine the sensitivity of the Earth’s climate system to variations in climate-forcing factors":* Understanding the dynamics that underlie the robust CI mode response to cooling and warming climates allows past climate reconstructions to serve as an analog to expected future changes in tropical hydroclimate. Specifically, constraining past CI mode variability with observational and paleoclimate data will allow an assessment of whether and which models

have the appropriate tropical hydroclimate sensitivity to climate forcing and, therefore, can provide reliable forecast of the response to anthropogenic forcing.

3. *“provide a test environment for simulation predictions from numerical models":* Comparison of the dominant modes of tropical hydroclimate changes in paleoclimate simulations and paleoclimate data provide a test environment for whether the dynamical processes controlling ΔP and their sensitivity to external forcing are adequately represented.

5 Broader Impacts

Tropical hydroclimate variability and long-term (forced) changes have widespread socioeconomic and biological impacts. The proposed work will use a combination of paleoclimate data and dynamical models to evaluate and improve model forecasts of future changes (and variability) in topical precipitation. Conveying to the public how past knowledge of the climate system informs our understanding of future climate change and its impacts is a powerful tool for garnering appreciation of the importance of climate research. The robust connection between past and future changes in the width and intensity of the ITCZ outlined in this proposal is a clear example of the link between past and future climate change. This project will support one graduate student and one summer undergraduate summer intern via leveraged funds from the Washington NASA Space Grant Consortium. As part of a long-standing commitment to public education and outreach efforts, Aaron Donohoe will continue to actively integrate education and outreach into his research programs. Such activities will include developing age-appropriate curricular materials, guest lecturing in local schools (from the elementary to college level) and volunteering in community education programs through the University of Washington Program on Climate Change. Aaron Donohoe will develop lecture material and a museum module to communicate the results of this work and its broader impacts as part of the Polar Science Weekends at the Pacific Science Center in Seattle. This proposal will support the career growth of an early career scientists (Aaron Donohoe) and his first graduate student under his newly appointed affiliate faculty position.

6 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 carrier female scientist (Atwood). Publications: Donohoe, Atwood, Byrne (2019) Atwood et al. (2019) Donohoe et al. (2019)

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" (5/2017-5/2020). 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. Publications: Zeppetello, Donohoe and Battisti (2019), Donohoe, Wrigglesworth, Schweiger, Rasch (2019)