1 Introduction

The hydrological contrast between the abundant rainfall in the moist and bio-diverse deep tropics (*Koppen*, 1936) and the deficit of precipitation in the dry and barren subtropics is an essential feature of Earth's climate system. Intense tropical rainfall is associated with atmospheric convection in the region where low level winds converge known as the intertropical convergence zone (ITCZ). In contrast, the dry subtropics are associated with the subsiding dry air from the upper atmosphere. In broad terms, the mass overturning circulation of the tropical atmosphere – the Hadley cell– consists of air rising in the ITCZ region, subsequently diverging into northern and southern branches which descends in the subtropical desert regions of the northern and southern hemispheres. The surface flow, from the subtropics back to the ITCZ, supplies moisture to the ITCZ whereas the flow aloft transports energy away from the ITCZ (Fig. 1, *Frierson et al.*, 2013). The ITCZ migrates seasonally by approximately 8° latitude (*Donohoe et al.*, 2013c) north and south toward the summer hemisphere (*Chiang and Friedman*, 2012) with a mean position that is slightly ($\approx 2°$) but distinctly north of the equator (*Philander et al.*, 1995). As a result: i) at a given tropical location there is strong seasonality of tropical rainfall as the ITCZ migrates into and out of a region, ii) in the annual average, the distribution of tropical rainfall is meridionally broadened over the latitudes encompassing the seasonal march of the ITCZ and iii) there is more tropical rainfall in the northern hemisphere (NH) as compared to that in the southern hemisphere (SH, *Philander et al.*, 1995).

There is widespread (direct observational and paleoclimatic) evidence that the distribution of tropical rainfall has varied substantially on timescales ranging from years to millennia with consequential socio-economic and biological impacts. This hydrologic variability is most commonly described as a meridional shift in the ITCZ (e.g. a latitudinal translation of the climatological precipitation). 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 (*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).

It is tempting to interpret regional (i.e. ocean basin-wide) hydrological changes in terms of meridional shifts in the Hadley cell connected to the global scale atmospheric circulation (*Chiang and Bitz*, 2005). However, recent work in the dynamics community has demonstrated that zonal mean ITCZ shifts of more than 1° latitude are highly unlikely due to energetic constraints (*Donohoe and Voigt*, 2016) and are not realized in climate model simulations even when forced with extreme forcing such as glacial boundary conditions and unrealistically large freshwater forcing (*Donohoe et al.*, 2013c). Specifically, a 3° latitude shift of the ITCZ and Hadley cell demands an energy flow between the NH and SH equivalent to a simultaneous doubling of CO_2 in one hemisphere and halving in the other hemisphere. Such a hemispheric contrast in energy input is unrealizable in models and not seen in observations (*Stephens et al.*, 2016).

In the observational record, the dominant and most impactful mode of tropical precipitation is completely unrelated to meridional ITCZ shifts. The dominant mode of tropical precipitation variability is the El Niño/Southern Oscillation (ENSO) mode of coupled atmospheric-oceanic variability which is predominated by an east-west shift in precipitation in the Pacific (*Rasmusson and*

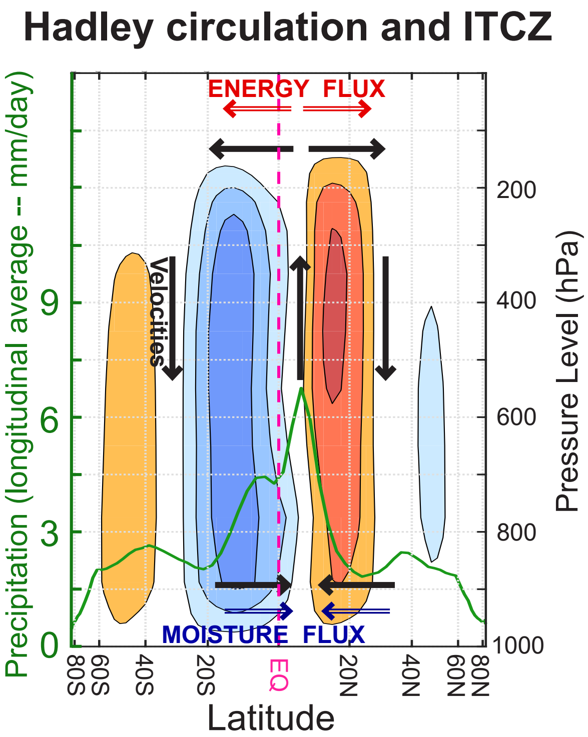

Figure 1: Diagram of the relationship between the mass overturning circulation of the atmosphere (Hadley cell) and the spatial distribution of tropical precipitation. The colored contours show the mass overturning streamfunction (contour interval 20 Sv) with motion in the sense shown by the black arrows. The green line is the zonal mean precipitation. The red arrows indicate the direction of atmospheric energy fluxes and the blue arrows show the direction of moisture fluxes.

Wallace, 1983). ENSO variability has a dramatic impact on fisheries globally, agricultural production particularly in climatologically semi-arid regions where production is water limited and has even been suggested to impact civil unrest (*Hsiang et al.*, 2011). There is a meridional *contraction* of the ITCZ during El Niño events both in the Pacific domain and in the zonal mean (*Adam et al.*, 2016; *Rasmusson and Wallace*, 1983) but no meridional *translation* of the precipitation. The ITCZ has shifted meridionally from year-to-year over the satellite record with zonal mean displacements of less than 1° (*Waliser and Gautier*, 1993; *Adam et al.*, 2016). However, ENSO and zonal mean ITCZ shifts have no significant correlation (*Donohoe et al.*, 2013b). Thus, the most commonly invoked mechanism of tropical hydroclimate variability in past climates– ITCZ shifts– is completely orthogonal to the mode of greatest tropical precipitation variability and societal impacts in the current climate state. While the dominant mode and mechanism of year-to-year tropical hydroclimate variability need not be the same as those that influence long-term tropical precipitation changes, this disconnect motivates the question: what mechanisms are responsible for the large-scale tropical precipitation changes due to past and future forcings such as orbital changes, volcanic forcings, ice sheet topography changes and greenhouse gas concentrations?

The large ($> 5°$ latitude) ITCZ shifts inferred from paleoclimate records and the implausibility of such large ITCZ shifts (due to theoretical energetic arguments and supported by modeling results) advocate for an alternative mechanism of past and future changes in the spatial distribution of precipitation in the tropics. An alternative explanation is that proxy records are responding to *local* (i.e. zonally inhomogeneous) precipitation changes that result from changes in the zonal mass overturning circulation (Walker cell) that may appear to be nearly basin wide (*Donohoe*, 2016). This paradigm is likely apt for the hydroclimate changes during periods such as the mid-Holocene (*Boos and Koorty*, 2016), which are characterized primarily by the contrast of precipitation falling between the land and ocean domains associated with a strengthening of the summer monsoons

(*Braconnot et al.*, 2007a). However, a changing Walker circulation is unlikely to explain the more globally synchronous hydroclimate changes in response to volcanic eruptions (*Colose et al.*, 2016) or those associated with abrupt NH cooling events during the last deglaciation (*Peteet*, 1995; *Benson et al.*, 1997) where evidence suggests concurrent and zonally homogenous changes in the tropical precipitation (*Wang et al.*, 2001; *Peterson et al.*, 2000) linked between the tropics and both poles (*Porter and Zhisheng*, 1995; *Steig et al.*, 1998).

Here, we propose an alternative mechanism of large scale (e.g. zonally homogenous) changes in the distribution of tropical precipitation: the expansion/contraction of the region of intense convective precipitation. 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 described as a simultaneous variations in the width and intensity of the precipitation and not (as is widely assumed) by meridional shifts in the ITCZ. This new paradigm will be used to reexamine how proxy records of tropical precipitation can be used to infer past changes in the large scale circulation of the climate system. Furthermore, isolating and understanding the underlying mechanisms that have governed past changes in the spatial distribution of tropical precipitation will help shed light on how it is likely to change in the future.

2 Framework and results: modes of tropical precipitation changes

2.1 Scientific framework

The paradigm of meridional shifts of the climatological ITCZ has been invoked to explain a vast array of tropical precipitation changes deduced from compilations of paleoclimate records that span time periods from the LIA (e.g. *Atwood and Sachs*, 2014; *Newton et al.*, 2006; *Sachs et al.*, 2009), to the early Holocene (*Haug et al.*, 2001), to abrupt climate change events during the last deglaciation (*Wang et al.*, 2001). ITCZ shifts have also been used to describe modeled precipitation changes due to idealized (*Kang et al.*, 2008), historical (*Hwang et al.*, 2013) and future (*Frierson and Hwang*, 2012) forcings. Here, we consider the shifting mode of tropical precipitation variability alongside two additional modes of tropical precipitation changes: i) the intensification of the tropical precipitation without a change in shape and ii) the meridional expansion/contraction of the region of intense precipitation without a meridional shift. Employing a suite of paleo and future climate simulations, we ask: what fraction of the tropical precipitation changes is explained by ITCZ shifts, intensification and contractions? We demonstrate that ITCZ shifts explain very little of tropical precipitation changes ($< 15\%$) compared to contractions and intensifications. Furthermore, ITCZ intensifications and contractions are tightly coupled to each other such that we can consider a joint mode of ITCZ contraction and intensification (CI mode) which explains a large fraction ($> 60\%$) of tropical precipitation changes with a single metric. The details of this mode of variability and the underlying dynamics will be pursued as part of the proposed work. The main overarching goal of this proposal is to use this new framework to reinterpret existing paleoclimate records in order to constrain the dynamics responsible for past hydroclimate variability and future changes.

We begin by defining the shift, contraction and intensification modes of tropical precipita-

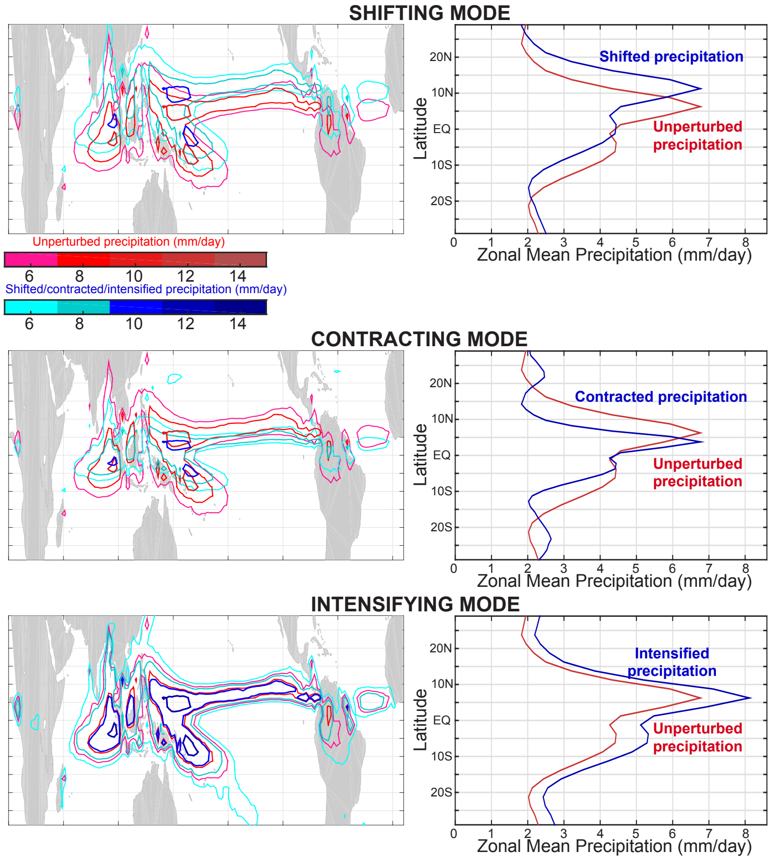

Figure 2: Cartoon of the modes of tropical precipitation variability and change considered in this work. The red contours and lines show the climatological (left panels) lat/lon structure and (right panels) zonal mean distribution of precipitation. The blue contours and lines show the meridionally shifting mode (top panels). In the contracting mode (middle panels), the climatological precipitation (red) is mapped onto a compressed/expanded latitude (blue). In the intensifying mode (bottom panels), the climatological precipitation (red) distribution is multiplied by a constant (blue).

tion changes (see Fig. 2). The premise is to manipulate the climatological precipitation pattern ($P_{CLIM}(\theta)$– where P is a function of latitude, θ) via these three mechanisms to best match the perturbed precipitation pattern ($P_{PERTURB}$) resulting from external forcing or year-to-year variability. In this proposal, we focus on the zonally averaged precipitation for the purposes of simplifying the discussion. However, all three modes can be applied to the lat/lon structure precipitation changes by optimally manipulating the climatological lat/lon precipitation pattern (left panels of Fig. 2) and will be explored as a part of the proposed work. We define the three modes of tropical precipitation variability as follows:

Shift	The climatological precipitation pattern is translated north/south by adding a constant (θ_{SHIFT}) to the latitude: $P_{SHIFT}(\theta) = P_{CLIM}(\theta+\theta_{SHIFT})$.
Contraction	The climatological precipitation pattern is contracted/expanded by multiplying the latitude by a constant (C) where values of $C<1$ ($C>1$) correspond to contraction (expansion): $P_{CON}(\theta) = P_{CLIM}(C\theta)$.
Intensification	The climatological precipitation pattern is intensified/reduced by multiplying the precipitation by a constant (I) with no changes to underlying spatial structure: $P_{INT}(\theta) = I\,P_{CLIM}(C\theta)$.

The shift, contraction and intensification (θ_{SHIFT}, C and I parameters) of precipitation for a given climate state is determined as follows: parameters are swept over a broad range of possible values and the resulting precipitation structures (P_{SHIFT}, P_{CON} and P_{INT}) that best match $P_{PERTURB}$ (in the least squares sense) is chosen as the optimal manipulation. We consider each of the above manipulations acting on P_{CLIM} in isolation to determine how much of the precipitation changes from P_{CLIM} to $P_{PERTURB}$ are explained by each manipulation (Lower 3 panels of Fig. 3A). We determine the total fraction of ΔP explained by the combination of the modes by optimizing all three manipulations acting together: $P_{ALL}(\theta) = I\,P_{CLIM}(C\,[\theta+\theta_{SHIFT}]\,)$.

The above framework can be used to interpret the mechanisms underlying any perturbation to tropical precipitation, be it year-to-year variability or the long term response to forcing. Here, we focus on broadly characterizing the precipitation response to both anthropogenic and paleoclimatic forcing in a large ensemble of coupled climate models from different modeling centers. We include 4 different forcing experiments encompassing a total of 42 simulations: i) CO_2 quadrupling (*Taylor et al.*, 2012); ii) LGM boundary conditions, greenhouse gas concentrations and orbital parameters representative of 21,000 years ago (*Braconnot et al.*, 2007b); iii) mid-Holocene orbital parameters (*Braconnot et al.*, 2012); and iv) North Atlantic freshwater hosing experiments to simulate the impact of iceberg discharge on ocean circulation (*Chiang and Bitz*, 2005; *Atwood*, 2015). In each simulation, we optimize C, I and θ_{SHIFT} to best describe $P_{PERTURB}$ by manipulating P_{CLIM}– the long term average tropical precipitation in a pre-industrial (PI) control simulation within the same climate model. We also briefly consider the observed year-to-year tropical precipitation variability over the satellite era (*Xie and Arkin*, 1996) where long term averages are used as P_{CLIM} and low-pass (annual) precipitation distributions are treated as $P_{PERTRUB}$.

2.2 Results: emergence of the contraction-intensification (CI) mode

We begin by discussing how much of the tropical (equatorward of 20°) zonal mean precipitation changes ($\Delta P = P_{PERTURB} - P_{CLIM}$) in the various forcing experiments can be explained by the shifting, contracting and intensifying modes acting (optimally) in isolation and with all three modes optimized simultaneously to best fit the $P_{PERTURB}$. Optimally shifting the climatological precipitation in isolation (P_{SHIFT}) explains 13% of ΔP averaged over all the different forcing experiments and models (red histogram in Fig. 3A). The shifting mode explains a substantially greater fraction of ΔP in the freshwater hosing simulations (highlighted by the dark red histogram in Fig. 3A) with an inter-model average of 30%. In contrast, the shifting mode explains very little of ΔP in both the LGM simulations (ensemble average of 5%) and $4\times CO_2$ simulations (6%). Averaged over all simulations, the contraction mode explains a similar fraction of the ensemble average ΔP (11%) as the ITCZ shift whereas the intensifying mode explains a greater fraction of ΔP (19%) than either of the other two modes acting in isolation. We note that, optimizing all three modes simultaneously (P_{ALL}) explains a remarkable fraction (66%) of ΔP that substantially exceeds the sum of ΔP explained by the three modes acting in isolation (11% + 13% + 19% = 43 %). This result suggests that the modes of tropical precipitation variability considered here are tightly coupled to each other such that the combined manipulation of modes has far greater explanatory power than the sum of the individual manipulations. We expand on the cause of this result below.

The fraction of ΔP explained by the shifting, contracting and intensifying modes acting in isolation obscure the robust coupling between the contracting and intensifying modes of tropical precipitation changes and the power of a combined mode of contracting and intensifying the precipitation. The optimal intensification (I) and contraction (C) coefficients are strongly ($R = 0.93$) correlated across all forcing experiments (Fig. 3B). In contrast, the shifting mode is not significantly correlated with either the contracting or intensifying mode. An increase in intensity ($I>1$) is accompanied by a contraction ($C<1$) with a linear best fit relationship implying one unit decrease in the C (contraction) is accompanied by a 1.2 unit increase in I (e.g. a 20% increase in the peak precipitation amplitude). Intriguingly, the different forcing experiments (indicated by the colors of the dots in Fig. 3B) are neatly sorted into discrete regions within the C-I plane; in the 4×CO_2 simulations (red circles) there is a robust contraction and intensification of the tropical precipitation whereas, in the LGM models simulations (blue), there is a robust expansion and reduction of tropical precipitation. The mid-Holocene(green) and hosing (purple) simulations fall somewhere in between the LGM and 4×CO_2 results in the C-I plane. Most importantly, the scaling between C and I is consistent between all experiments which suggest that *knowing either the intensification or contraction of tropical precipitation constrains the other*.

The observed year-to-year variability of tropical precipitation over the satellite era is co-plotted (black crosses) with results from the modeled long-term forced changes in the C-I plane (Fig. 3B). We see that there is also a robust connection between contraction and intensification in the observational record (R = 0.73) with a slightly different scaling between C and I. Though the dynamics of the long-term response in tropical precipitation and internal variability need not be the same, this preliminary result suggests that studying the dynamics of observed variability could elucidate the mechanism connecting precipitation intensity and ITCZ width.

The above result allows us to define a combined contraction and intensification mode – hereafter the CI mode – by constraining the C and I changes to lie along the linear best fit line in Fig. 3B. In this formulation, C and I are no longer independent variables and specifying either one constrains the other. We previously optimized three independent parameters (C, I and θ_{SHIFT}) to optimize the fit of P_{ALL} to $P_{PERTURB}$ to explain an average of 66% of ΔP. We now optimize 2 independent variables (the combined CI and θ_{SHIFT}) to explain an average ΔP of 63%. The CI mode acting in isolation explains 47% of ΔP averaged over all forcing experiments (Fig. 3C) and a remarkable 74% and 63% of ΔP in the ensemble of 4×CO_2 and LGM simulations respectfully. Thus, *the CI mode is a remarkably efficient mode for explaining future and past changes and present day variability in tropical precipitation; the CI mode explains 4 times more of the tropical precipitation changes than the commonly invoked meridional ITCZ shift*. The goal of the proposed work is to ask how paleoclimate records inform the behavior of the CI mode in past climates and how knowledge of the past state of the CI mode will inform future projections of tropical hydroclimate change.

3 Proposed work

We demonstrated that the combined contraction and intensification (CI) mode of tropical precipitation changes is an efficient representation of tropical precipitation changes that relies on the robust coupling of ITCZ contraction and intensification. This mode explains far more of modeled and observed tropical precipitation changes than the commonly invoked shifting mode. The primary task of the proposed work is twofold: i) investigate the dynamics which underlie the robust coupling between ITCZ contraction and intensification seen in observations and models and evaluate how this mode responds to external forcing; ii) use the robust contraction/intensification scaling seen in the models to reinterpret the paleoclimate data in terms of ITCZ shifts versus CI changes. As our analyses suggest that the ITCZ contracts and intensifies in response to CO_2 forcing (Fig. 3B), these insights will help us understand how tropical precipitation may change in the future.

We emphasize that our team of collaborators are in a unique position to make progress on the dynamics of ITCZ contractions and use the paleoclimate record to deduce past changes in ITCZ width; our team has lead past advances on knowledge of the dynamics and paleo reconstructions of

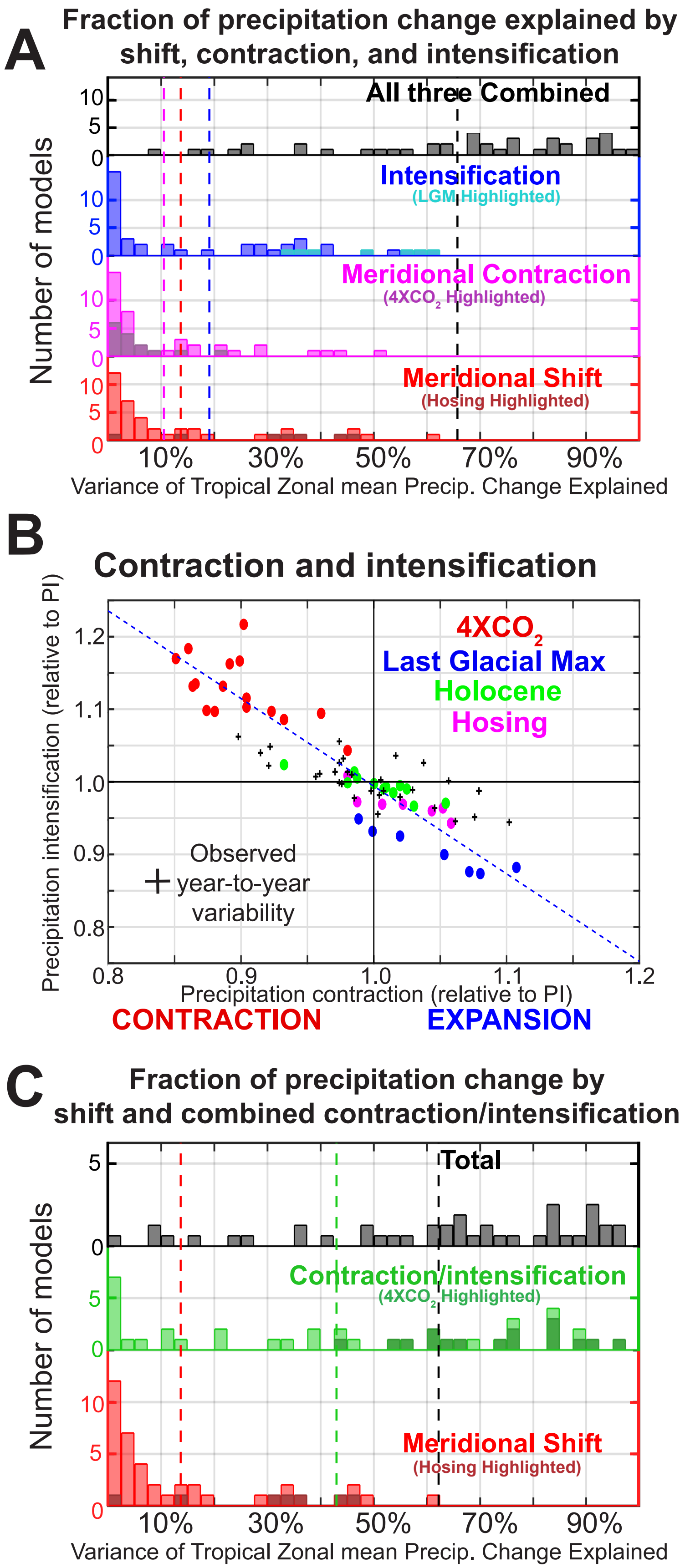

Figure 3: (A) Histogram of fractional variance of zonal mean tropical precipitation changes explained by the shifting, contracting and intensifying modes of variability across the ensemble of anthropogenic and paleoclimate forcing experiments. The ensemble average of the fractional change explained by each mode is shown by the dashed vertical lines. The darker shading in each histogram highlights the results of just the freshwater hosing simulations for the shifting mode, the $4\times CO_2$ simulations for the contracting mode and the LGM simulations for the intensifying mode. (B) 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), $4\times CO_2$ (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. (C) As in (A) except the intensification and contraction scalars are treated as a single variable constrained by the statistical relationship from the linear best fit in (B).

the ITCZ and has the computational resources and data compilations needed to make rapid progress on this problem. Aaron Donohoe has made fundamental contributions to energetic theory of ITCZ location using both idealized and state-of-the-art climate models and observations and the proposed work is a novel extension of his previous research. Alyssa Atwood has compiled a myriad of paleo proxy data which only needs to be applied to the emerging understanding of the CI mode. Since this data is already available, her efforts will be front loaded into the first two years of the proposed work. John Chiang and David Battisti pioneered work on ocean-atmosphere tropical variability including the concept that high latitude climate changes can induce shifts in the ITCZ location and will play an invaluable role in thinking about how the seasonal cycle in polar climate can alter the width of the ITCZ.

3.1 Contraction/intensification mode dynamics

Beyond the remarkable fraction of ΔP explained by the CI mode, it is equally remarkable that all 16 of the $4\times CO_2$ simulations show a contraction and intensification of the tropical precipitation and 6 of 7 LGM simulations show a expansion and reduction of tropical precipitation (Fig. 3B). These results suggest a robust mechanism controls the CI mode which may be linked to global mean temperature. Recent literature (*Byrne and Schneider*, 2016) has recognized the robust ITCZ contraction in response to global warming but a mechanistic understanding of the processes that link the precipitation changes between the glacial climate, present day and future warming is currently lacking. We propose one leading and several alternative mechanisms underlying the behavior and its link to global climate. The primary argument is that the width of the tropics is determined by the amplitude of the seasonal migration of the ITCZ off the equator. The latter is controlled by the seasonal input of energy into the atmosphere in the polar regions and will be impacted by sea and land ice extent. This mechanism links the tropical precipitation to the polar climate and global mean temperature.

3.1.1 A possible mechanism for the CI mode

The region of intense tropical precipitation (ITCZ) migrates meridionally from season to season by approximately 16° latitude. As such, the annual mean precipitation does not represent a physical state that is realized in the climate system but, rather, represents the seasonal smearing out and smoothing of the seasonal march of the ITCZ (*Donohoe and Voigt*, 2016). To demonstrate this point, we turn to an idealized climate model simulation whereby we modulate the amplitude of the seasonal migration of the ITCZ off the equator. We do so by coupling an atmospheric model to a stagnant ocean (slab-ocean aquaplanet) and we vary the depth of the ocean between simulations – between 2.4 and 50m (*Donohoe et al.*, 2013a). When the ocean is shallow, the seasonal migration of the sun into the summer hemisphere rapidly heats up the sea surface temperatures (SST) and pulls the ITCZ off the equator. In contrast, in the simulations where the ocean is deep, the seasonal modulation of insolation mostly gets stored within the (high heat capacity) ocean and SSTs are nearly seasonally invariant; the ITCZ stays near the equator year round. The resulting meridional structure of the annual mean tropical precipitation is profoundly different (Fig. 4A) between the simulations with deep (orange and pink lines) and shallow (blue lines) ocean with precipitation intensity varying by an order of magnitude and the width of the tropical precipitation varying between 5° and 30° latitude. These simulations demonstrate that the width of the tropics in the annual

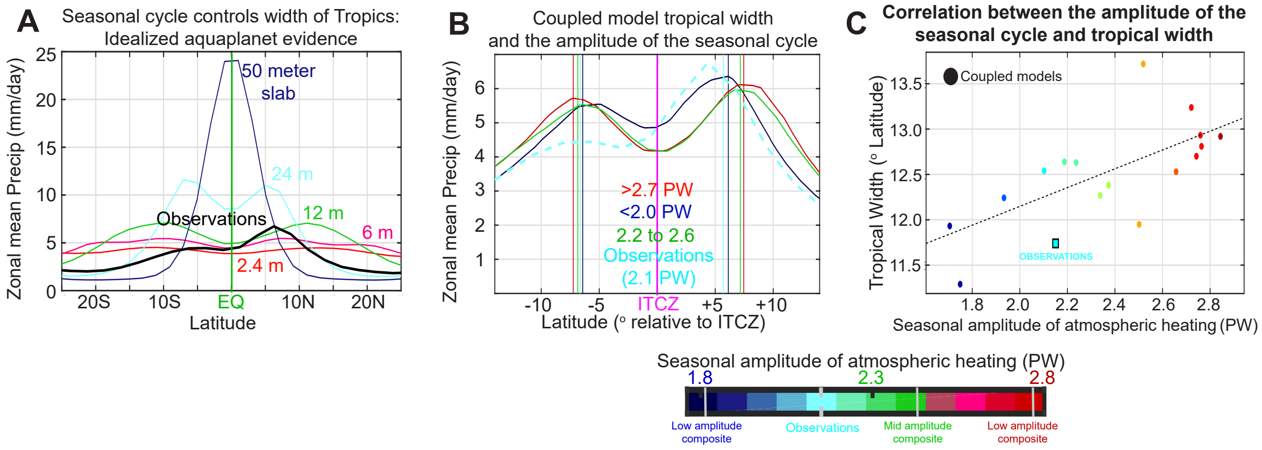

Figure 4: (A) Zonal (and annual) mean precipitation in idealized aquaplanet simulations with varying mixed layer depth. Each color is a different mixed layer depth and observations are shown in black. (B) Zonal mean precipitation in CMIP5 PI models sorted in composites by the magnitude of the seasonal cycle of atmospheric heating – equivalent to the seasonal amplitude atmospheric heat transport across the equator ($|\mathrm{AHT}_{EQ}|$). The red line is the average of models with the largest magnitude seasonal cycle ($|\mathrm{AHT}_{EQ}| > 2.8$PW), and the blue line is the composite of models with the smallest magnitude seasonal cycle ($|\mathrm{AHT}_{EQ}| < 2.0$PW). The observations are shown in light blue and the color coding indicates $|\mathrm{AHT}_{EQ}|$ as shown in the color bar. Vertical lines show the location of the NH and SH tropical precipitation centroids used to define the tropical width. (C) Scatter plot of tropical width (latitude between precipitation centroids) and $|\mathrm{AHT}_{EQ}|$. Coupled models are shown with circles shaded by the value of $|\mathrm{AHT}_{EQ}|$ and the observations are shown by the cyan square.

mean is controlled by the seasonal amplitude of the ITCZ migration off the equator. The latter has been argued to be controlled by the seasonal amplitude of energy input to the atmosphere (*Donohoe et al.*, 2013c) in the mid and high latitudes.

The same mechanism is apparent in state-of-the art coupled model simulations where we demonstrate that the inter-model differences in the ITCZ width is dictated by the magnitude of the seasonal migration of ITCZ off the equator by way of the seasonal amplitude of energy input to the atmosphere. As the sun migrates into the summer hemisphere, the atmosphere is heated locally and the energy input to the atmosphere (less the piece that is stored in the column or radiated to space) is fluxed across the equator into the winter hemisphere. This cross equatorial atmospheric energy transport across the equator (AHT_{EQ}) is accomplished by shifting the Hadley cell and ITCZ off the equator (*Kang et al.*, 2008; *Adam et al.*, 2016; *Schneider et al.*, 2014; *Donohoe et al.*, 2013c). Thus, the more energy that is input into the atmosphere seasonally, the farther the ITCZ must move off the equator (*Donohoe and Voigt*, 2016). The seasonal input of energy into the atmosphere in the summer hemisphere differs substantially (≈30%) between unforced coupled climate models for unknown reasons. If we sort models according to the amplitude of seasonal heating of the atmosphere in the summer hemisphere (equivalent to the seasonal amplitude of AHT_{EQ}) we see that the annual mean tropical precipitation is meridionally broader in the models with a large seasonal cycle in the high latitudes (red lines in Fig. 4C) as compared to those with a small seasonal cycle in the high latitudes (dark blue lines). Indeed, the width of tropics – defined as the distance between the tropical precipitation centroid (*Frierson and Hwang*, 2012) in the NH and that in the SH (shown in the vertical lines in Fig. 4B)– is highly correlated with the seasonal amplitude of AHT_{EQ} (R=0.64, Fig. 4C).

Previous work has suggested that the hemispheric contrast of energy input into the atmosphere determines the annual mean ITCZ location (*Frierson et al.*, 2013; *Marshall et al.*, 2013) and that models systematically place the ITCZ too far south because cloud biases in the southern ocean put too much energy into the SH (*Hwang and Frierson*, 2013). The present result suggests that the width of the tropical precipitation is determined by seasonal amplitude of energy input into the atmosphere and the ITCZ is broader in climate models than observations because models put too much energy into the high latitude atmosphere of each hemisphere during the summer. Indeed, selecting models that adequately simulate the observed amplitude of extratropical atmospheric heating more realistically simulates the ITCZ width (c.f. the dark blue and observed dashed blue curves in Fig. 4B and the position of the observations indicated by the blue square in 4C).

This mechanism offers a possible explanation for the connection between tropical width and global mean temperature noted prominently in Fig. 3B when comparing the LGM and 4×CO_2 simulations. If we take as a given that warm climates have less sea (and land) ice than cold climates, more of the high latitude ocean will be exposed to the atmosphere in warm climates. As a result, the warmer climates have a higher effective heat capacity of the climate system and a smaller seasonal amplitude of atmospheric heating and temperature (*Donohoe and Battisti*, 2013; *Dwyer et al.*, 2012) resulting in a smaller seasonal migration of the ITCZ off the equator and a narrower region of intense precipitation in the annual mean. In addition, we expect the intensity of tropical precipitation to increase in warmer climates due to the increase in saturation vapor pressure of water (*Held and Soden*, 2006). Therefore, *the simultaneous contraction and intensification of the ITCZ noted from the LGM to a 4×CO_2 climate states may reflect the impact of global temperature on both the intensity (directly) and width (via the seasonal amplitude changes caused by ice extent) of the ITCZ.*

3.1.2 Proposed dynamical analysis

We have demonstrated that the ITCZ contraction and intensification is tightly coupled (with fixed scaling) in the model response to a myriad of different external forcings and postulated that the underlying mechanism is via the modulation of the amplitude of the seasonal cycle by global mean temperature (and sea ice extent). Here, we test this and other mechanisms of the ITCZ contractions. We ask: how robust is the mechanism of ITCZ contraction across models, what processes are essential for getting the sensitivity of contraction to external forcing and how can we use observational data to constrain which models best represent future ITCZ contractions?

Coupled model response to paleoclimate and anthropogenic forcing: The ensemble of coupled paleoclimate and anthropogenic forcing simulations analyzed in Fig. 3 will be expanded to include results from all the relevant PMIP2, PMIP3, CMIP3 and CMIP5 experiments. The paleoclimate simulations will focus on the climate of the LGM, mid-Holocene and the last millennium. We wish to combine results from PMIP2 and PMIP3 to analyze how robust the changes in the width and intensity of ITCZ is across models in response to the paleoclimatic forcing and understand the mechanism that leads to inter-model differences. We will also extend our analysis of future changes to include forcing agents other than CO_2 (i.e. ozone and aerosols) as well as the transient response to forcing. The most intriguing preliminary finding in this study is that the ITCZ contraction and intensification is tightly coupled across models and across forcing experiments and that the ensemble of simulations within each forcing experiment robustly cluster into distinct regions of the C-I plane (Fig. 3B). We hope to further document both the robustness and limitations of this conclusion and probe what determines the magnitude and direction of CI mode changes. We will evaluate whether any cases can be identified in which the precipitation changes do not follow the robust relationship between contraction and intensification and if so, evaluate the reasons for the departure and the relevancy for past and future climate states.

Last millennium simulations 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. Further, *Griffiths et al.* (2016) recently argued that tropical paleoclimate data over the last millennium in the Pacific is consistent with successive expansions and contractions of the ITCZ. This conclusion seems consistent with our finding that the CI mode is the dominant mode of tropical precipitation in response to a wide variety of different forcings.

In the proposed work, we will explicitly evaluate modeled and inferred hydroclimate variability over the last millennium by utilizing two data sets: i) the publicly available PMIP3 last millennium simulations (*Braconnot et al.*, 2012; *Atwood et al.*, 2016) and ii) output from the NSF P2C2 funded project “Paleoclimate Data Assimilation" (co-I David Battisti). These runs will allow us to asses how tightly coupled ITCZ contractions and intensifications are in response to climate forcing over the last millennium including volcanic forcings at different latitudes, internal variability and the transient response to accumulating greenhouse gases. In addition, we will compare the model results to proxy records (Sec. 3.2.4) and the data assimilation products, which will allow us to assess the consistency of the observed, assimilated and modeled changes in tropical width over the last millennium.

Observational analysis The observed year-to-year variability of the CI mode need not match that seen in response to long-term forcing (c.f. the colored dots and crosses in Fig. 3B) due to both the transient nature of the former as well as to differences in the spatial structure and mechanisms of the forcings. However, we expect the dominant mechanism of ITCZ contractions to be evident in the observations. Specifically, if we find that the meridional extent of the tropical rainbelt is a consequence of high latitude seasonal atmospheric heating (as was speculated in Sec. 3.1.1) we should expect years with anomalous high latitude energy input to the atmosphere to coincide with more expansive tropics. To analyze these connections, we will use a combination of satellite and atmospheric reanalysis data. *Donohoe and Battisti* (2013) recently developed a novel methodology for closing the atmospheric energy budget using satellite radiation from the Clouds and Earth’s Radiant Energy System (CERES, *Wielicki et al.*, 1996) project alongside atmospheric energy fluxes and storage calculated from atmospheric reanalysis data (*Kalnay et al.*, 1996; *Dee et al.*, 2011) to deduce the surface energy fluxes as a residual. We will use these calculations alongside observational estimates of tropical precipitation (*Xie and Arkin*, 1996) to calculate the year-to-year and seasonal anomalies of atmospheric heating, energy transport and Hadley cell shifts that accompany changes in ITCZ width.

3.1.3 Zonally and seasonally inhomogeneous tropical precipitation changes

We have emphasized the interpretation of zonal and annual mean tropical precipitation changes for the simplicity of discussion in this proposal. However, the methodology for decomposing tropical precipitation changes into optimally shifted, contracted and intensified modes can be applied to the longitudinally varying precipitation changes by assuming that the zonally varying (lat/lon) climatological precipitation structure is meridionally contracted, shifted and intensified by the same amount at all longitudes (left panels of Fig. 2). Preliminary results indicate that the contraction and intensification of the local precipitation are tightly coupled as was seen in the zonal mean. As a result, one can define a localized CI mode which is a much better description of the longitudinally varying precipitation changes than a local shift of the ITCZ. Additionally, we are pursuing an alternative framework for interpreting annual mean tropical precipitation changes in terms of a amplification of the intensity and/or duration of the climatological precipitation during a given season. This framework will be pursued alongside the CI mode analysis in the proposed work.

We will extend the analysis of the paleoclimate simulations outlined in the previous subsection to analyze how much of the lat/lon structure of tropical precipitation changes can be explained by the shifting, contracting and intensifying modes. By decomposing the local precipitation changes into these three modes, we can then ask how much the local precipitation changes are controlled by the large scale modes of ITCZ variability versus more localized changes such as changes in the contrast of precipitation between land and ocean (*Boos and Koorty*, 2016). This will allow us to pinpoint regions where paleoclimate proxies are most likely to provide information about large-scale changes in the Hadley circulation and, thus, potentially provide insight into high-latitude climate processes.

3.2 Paleoclimate evidence of past ITCZ contraction-intensification mode behavior

Modeling and observational work suggest that ITCZ contractions and intensifications are coupled to each other with a scaling between the contraction and intensification that is climate state invariant (i.e. the data from all forcing experiments fall close to the straight line in Fig. 3B). The underlying mechanism and consistency of this result between modeling experiments will be explored as part of this proposal. This work will provide an incredibly powerful constraint to interpreting paleoclimate data: *if we know either the contraction or intensification of the ITCZ the other is constrained by the CI mode dynamics*. Stated otherwise, if we take the relationship between contraction and intensification in the CI mode as (an empirical) given, the sparse network of paleoclimate data should provide enough information to optimally constrain the state of the CI mode (a single unknown parameter) and the ITCZ shift to provide the most efficient representation of tropical precipitation changes. In this way, we aim to improve reconstructions of tropical hydroclimate changes during three paleoclimate time periods: the LGM, the early to mid-Holocene, and the Little Ice Age. We emphasize that the current interpretation of an order 5° latitude zonal mean ITCZ shift during the

Little Ice Age is untenable given energetic constraints on the required climate forcing and feedbacks. This work will provide an alternative explanation of such paleoclimate data, characterizing tropical hydroclimate changes in terms of combinations of an ITCZ shift and CI mode variability.

Our approach is to compile and analyze hydroclimate changes during each paleoclimate time period by utilizing the extensive network of proxy reconstructions that are publicly available. We outline existing proxy evidence and intepretations of tropical precipitation changes during each the LGM, mid-Holocene and LIA below.

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. 3B). 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), from sediment records across the tropical Atlantic (*Arbuszewski et al.*, 2013), from 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

The last millennium represents our third and final target for evaluating tropical hydroclimate changes in model simulations and proxy reconstructions, as ample evidence exists for substantial changes in tropical rainfall patterns over this period. For example, persistently arid conditions were recorded in central China ca. 1350-1850 CE (Zhang et al., 2008). Extreme droughts were recorded in India and southern Thailand ca. 1300-1450 CE (Buckley et al., 2010; Sinha et al., 2011), in southern China ca. 1400-1600 CE (Wang et al., 2005), and the Arabian Sea off the coast of Oman ca. 1350-1650 CE (Anderson et al., 2002). Inferred changes in monsoonal rains are thought to have played a major role in driving societal changes around this time (Sinha et al., 2011; Zhang et al., 2008). In addition, oxygen isotopes in cave deposits, lake sediments, and tropical glacier records in Peru and Brazil suggest that the South American summer monsoon intensified beginning ca. 1300-1500 CE and continuing through 1800 CE (Vuille et al., 2012). Records from tropical Pacific island lake sediments and the Cariaco Basin provide evidence for a southward shifted ITCZ in the Pacific and western Atlantic ca. 1400-1800 CE (Haug et al., 2001; Newton et al., 2006; Sachs et al., 2009). In contrast, a recent compilation of lacustrine, marine, cave and coral records from the western Pacific and northern Australia has instead provided evidence for a contracted ITCZ in the western Pacific during the LIA (Yan et al., 2015).

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: what combination of meridional ITCZ shift and CI mode change best explains the compilation of paleoclimate data? Initial analyses of the PMIP2 and PMIP3 simulations indicate that the CI mode dominates the ITCZ response during the LGM (21 kyr BP) and mid-Holocene (6 kyr BP). Through the proposed work, we will extend this analysis to the PMIP3 last millennium simulations as well as to output from a data assimilation project of last millennium (NSF P2C2 funded project “Paleoclimate Data Assimilation", co-I David Battisti). 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 bin these reconstructions into different geographical zones as they relate to the modern spatial pattern of mean annual tropical rainfall (e.g.“core rainband", “rainband edges" and “outside rainband"). Finally, we will look for coherency in the records within each zone- at both regional and global scales. 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 Broader Impacts

Scientific: 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. This framework will give a more comprehensive picture of how tropical precipitation varied in past climate and the underlying causes and implication of those changes, especially the connection to polar climate processes.
2. *“determine the sensitivity of the Earth’s climate system to variations in climate-forcing factors":* Understanding the dynamics that underlie the robust direction of CI mode changes between the cold LGM to present day to the warm future in models will improve future forecast of tropical hydroclimate change. Specifically, constraining past CI mode variability with 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":* The comparison of paleoclimate simulations of the CI mode of the ITCZ with paleoclimate data provide a test environment for whether the dynamical processes controlling the CI mode and their sensitivity to external forcing are adequately represented.

Education and outreach: 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. As part of a long-standing commitment to public education and outreach efforts, Alyssa Atwood and Aaron Donohoe will continue to actively integrate education and outreach into their 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, Bay Area Scientists in Schools and the educational nonprofit organization Educurious. 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. Alyssa Atwood will continue to empower and support women in pursuit of higher education in STEM fields through the Women in Science and Engineering program at UC Berkeley. This proposal will support the career growth of two early career scientists (Aaron Donohoe and Alyssa Atwood).

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