Optimal description of forced zonal mean tropical precipitation changes.

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Key Points:

- The simulated response of the zonal mean tropical precipitation (ΔP) to paleoclimate, anthropogenic and volcanic forcing is analzyed in terms of optimal shifts, contractions and intensifications of the climatological unperturbed precipitation .
- ITCZ shifts are small in magnitude and describe a small fraction ΔP whereas intensification and contractions are tightly anti-correlated and describe a large portion of the ΔP.
- The annual mean response is best characterized as a modification of the climatological seasonal cycle; annual shifts correspond to an intensification during on solstice and contractions to reduced seasonal migration of the ITCZ.

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Abstract

Place Holder.

1 Introduction

Meridional shifts in the region of intense tropical precipitation – the intertropical convergence zone (ITCZ) – are often invoked to explain paleoclimate proxy records of precipitation at single and/composites of sites in the tropics and subtropics. Here, we examine how useful the concept of a meridional shift of the climatological precipitation pattern is for explaining precipitation changes in response to external forcings (e.g. anthropogenic, paleoclimatic boundary conditions and freshwater hosing) in comprehensive climate model simulations. We also explore how the shift in the location of simulated tropical precipitation varies by longitude (i.e. between the different ocean basins). We demonstrate the meridional ITCZ shift– defined as the north-south translation of the unperturbed annual mean precipitation – explains a very small portion of the local ($< 1\%$) and zonal mean ($< 9\%$) precipitation changes in the ensemble average response to a myriad of external forcings. We further consider two additional modes of ITCZ variability: the meridional contraction/expansion of the tropical precipitation and the amplification/reduction of the tropical precipitation with the same spatial structure as the climatology. The amplifying mode explains the greatest fraction of local (8%) and zonal mean (35%) precipitation changes over the ensemble of forcing experiments. The contracting mode explains a smaller fraction of tropical precipitation changes than the amplifying mode (3% locally and 20% in the zonal average) but is a more useful theoretical construct for thinking about large scale patterns of precipitation change than the idea of a meridional ITCZ shift. These results demonstrate that tropical precipitation changes seen in paleoclimate records and anticipated in the future are influenced by the following processes listed in order of decreasing importance: 1.) localized circulation changes leading to zonal inhomogeneities in precipitation anomalies, 2.) tropics wide (spatially invariant) amplification/reduction of the hydrological cycle, 3.) meridional contraction/expansion of the region of intense pre-

cipitation and 4.) the meridional shift of the climatological precipitation. We emphasize that ITCZ shift is the least influential mode of tropical precipitation changes and speculate that the often invoked ITCZ shift deduced invoked in paleoclimate studies reflect localized changes as opposed to large scale modes of climate variability.

2 Model simulations analyzed and methodology

We analyze tropical precipitation changes in coupled model simulations under paleoclimatic (e.g. glacial boundary conditions, freshwater hosing and mid-Holocene orbital forcing) and anthropogenic (increased atmospheric CO_2) forcings. We ask how much of these precipitation changes are explained by each: 1.meridional shifts (translation), 2. meridional contraction and 3. domain wide intensification of the climatological pattern on tropical precipitation. Here, we outline the model simulations and methodology used for answering this question.

2.1 Model simulations

We examine precipitation changes in 4 different sets of forcing experiments, each in an ensemble of coupled climate models. A total of 42 simulations are analyzed.

1. **Last Glacial Maximum (LGM)**. We use model output from the Paleoclimate Modeling Intercomparison Project phase 2 (PMIP2) project, an ensemble of state of the art coupled (ocean-atmosphere-cryosphere) model simulations run under prescribed forcing and boundary condition scenarios that represent different paleoclimatic epochs. The Last Glacial Maximum (LGM) simulations are forced by solar insolation from 21,000 years before present, greenhouse gas and aerosol concentrations deduced from ice core data (CO_2 is set to 185 ppm) which amounts to a radiative forcing of approximately -2.8 W m^{-2} [*Braconnot et al.*, 2007], coastlines consistent with a 120m decrease in sea level, and the prescribed land ice topography of *Peltier* [2004] which includes the expansive Laurentide ice sheet over North

America. We use the LGM simulations with fixed vegetation (PMIP2 OA runs). All comparisons are made to the pre-industrial simulations in the same model and resolution. 12 simulations are analyzed.

2. **Mid-Holocene**. Mid Holocene runs are taken from the PMIP3 [*Braconnot et al.*, 2012] simulations of the climate system approximately 6,000 years ago. Coastlines, vegetation, and ice sheets are identical to the PI simulations. CO_2 and aerosols are also identical to the PI while there is a modest reduction in methane concentration [*Taylor et al.*, 2012]– from 760 ppbv to 650 ppbv. Orbital parameters representative of 6,000 years before present are taken from *Berger* [1978]. Most significantly, orbital precession causes the seasonal cycle of insolation in the Northern Hemisphere to amplify, while the duration of summer is reduced. We note that the sum of all mid-Holocene forcing agents are symmetric about the equator in the annual average. Seven different model simulations are analyzed.
3. **Hosing experiments**. Placeholder for description. 7 models with Axel's.
4. **4XCO$_2$**. We analyze the CMIP5 instantaneous CO_2 quadrupling [*Taylor et al.*, 2012]. Each model is initialized from the equilibrated pre-industrial (PI). Atmospheric carbon dioxide is instantaneously quadrupled and is then held fixed thereafter. We calculate the climatology of each model over the last 20 years of simulations and then take differences relative to the climatology in the PI (or PD) run. Sixteen different models are analyzed.

2.2 Methodology

Paleoclimatic and modeled precipitation changes are commonly interpreted in terms of an ITCZ shift defined as a meridional translation of the climatological pattern of precipitation in the tropics. Such shifts are often invoked to explain the zonal mean and two-dimensional (latitudinal-longitudinal) structure of precipitation changes – hereafter refereed to as local. In both the local and zonal mean cases, a northward ITCZ shift results

in an increase in precipitation at tropical locations [1] North of the climatological precipitation maximum and a concurrent decreases in precipitation at locations on or South of the tropical precipitation maximum. To test how well this theoretical construct of tropical precipitation variability works in explaining the precipitation changes, we take the climatological pattern of tropical precipitation – defined as equatorward of 20°– from the PI simulation in each model and shift it North and South (hereafter referred to as the shifted precipitation) until we achieve an optimal fit to the perturbed precipitation pattern under the forcing. We optimize the shift for both the local pattern of precipitation changes– whereby the latitudinal/longitudinal structure of precipitation is shifted North and South by the same amount at each longitude (upper left panel of Figure 1 shows a 5° northward shift) – and zonal mean precipitation change – whereby the PI zonal mean precipitation is simply shifted North and South to best match the perturbed zonal mean (upper right panel of Figure 1). To achieve the shifted precipitation, we interpolate the PI precipitation to a 0.5 degree grid with the shift added to the input latitude and compare to the perturbed precipitation interpolated to the same 0.5 degree grid. Grid resolution was found to have a minimal impact on the results. We define the optimal shift as that which minimizes the root mean squared difference between the shifted precipitation and the precipitation in the forced simulation spatially averaged over the tropics. We note that the optimal shift for the local and zonal mean cases need not be (and often are not) the same as the local shift will be optimized when precipitation increases North/South of regions (longitudes) of climatologically intense precipitations where as the zonal mean optimization does not account for whether the longitudinal structure of the climatological and perturbed precipitation match each other.

[1] For the purposes of this study, we define the tropics as equatorward of 20]° although, for the discussion here, the region equatorward of the subtropical precipitation minimum would be expected to follow juxtaposing precipitation changes North and South of the tropical precipitation maximum

Additionally, we consider two more modes if ITCZ variability: a meridional contraction and a domain wide intensification. The contraction mode is defined by multiplying the input latitude by a scalar prior to interpolating to the 0.5 degree grid. The scalar of 1 would redefine the PI precipitation, scalars > 1 correspond to expansion of the tropical precipitation and scalars < 1 correspond to contraction (middle panel of Figure 1). The intensification mode is defined by taking the spatial pattern of precipitation in the PI simulation and simply multiplying it by a scalar; it represents an intensification of the precipitation with no changes in the underlying spatial structure (lower panel of Figure 1).

All three modes of variability are considered simultaneously to optimize the fit to the perturbed tropical precipitation; starting from the PI precipitation, the pattern of combined shifted, contracted and intensified precipitation that minimizes the RMS difference with the GCM precipitation from the perturbed simulation is considered the best answer. To achieve this answer, we start by optimizing the fit to the perturbed precipitation for each mode (shift/contraction/intensification) separately, starting from the PI precipitation as a first iteration. We then repeat the optimization of each mode starting from the optimal answers provided by the other modes in the previous iteration. For example, in iteration number 2, we optimize the shifting mode by starting from the contracted and intensified PI precipitation defined by the optimal contraction and intensification in iteration 1 and then finding the shift in that starting precipitation pattern that minimizes the RMS difference from the perturbed precipitation spatially averaged over the tropics. This process is equivalent to considering all possible modes of variability simultaneously but is computationally less demanding. 10 iterations are sufficient to converge on the optimal answer.

The optimal mode of shifting/contraction/intensification found by the above consideration of combined modes of variability agrees reasonable well with the optimal shift/contraction/intensification that is found when considering a mode of variability in isolation (e.g. optimizing from the PI precipitation). However, in some cases it differs substantially, including a reversal of directionality and does so in fairly systematic ways for a given forcing experiment. For

example, the global warming in the $4XCO_2$ simulations results in increased tropical precipitation which intuitively should be captured by the intensification mode. However, an expansion of the tropical precipitation also results in a domain average increase in precipitation since the precipitation closer to the equator exceeds that on the edge of our tropical domain (20°) in all PI models. Therefore, when considered in isolation, the contraction mode can capture the domain average precipitation increase even the spatial structure of the precipitation is unchanged and, thus, can confuse an a scalar intensification with a genuine contraction of the precipitation; the shifting, contraction and intensification modes of precipitation changes are not orthogonal over the tropical domain. In the specific example above, when the contraction mode is considered in isolation, the ensemble average contraction to optimize the fit to precipitation under $4XCO_2$ is not significantly different from unity ($0.99 \pm 0.03 - 1\ \sigma$) where as a robust contraction (0.91 ± 0.03) is found when all modes are allowed to operate simultaneously.

The fraction of precipitation change explained by the best answer, $F_{S,C,I}$ (where the subscripts denote Shifted, Contracted and Intensified) is given by

$$F_{S,C,I} = 1 - \frac{\sqrt{\overline{\left(P_{perturbed} - P_{S,C,I}\right)^2}}}{\sqrt{\overline{\left(P_{pert}\right)^2}}} \tag{1}$$

where $P_{S,C,I}$ is the optimally shifted, contracted and intensified PI precipitation, P_{pert} is the simulated precipitation under forcing in the same model and $\overline{overbars}$ denote the spatial average over the tropical domain. We define the fraction of precipitation change explained by a single mode as the reduction in the fraction of precipitation explained when that mode of variability is eliminated from the best answer. For example, the fraction of precipitation change explained by the shifting mode is

$$F = F_{S,C,I} - F_{C,I} = \frac{\sqrt{\overline{\left(P_{perturbed} - P_{C,I}\right)^2}} - \sqrt{\overline{\left(P_{perturbed} - P_{S,C,I}\right)^2}}}{\sqrt{\overline{\left(P_{pert}\right)^2}}} \tag{2}$$

where the $P_{C,I}$ is the contracted and intensified precipitation without the shift and the shift/intensification are taken from the optimization in the best (combined) answer. Qualitatively similar results are found if the fraction of explained precipitation is defined as the fraction of precipitation explained if the PI is shifted by the best answer shift or if the PI precipitation is optimally shifted although both cases lead to the sum of the fractional precipitation changes explained by all three modes exceeding the $F_{S,C,I}$ due to the non-orthogonality of the modes.

3 Results

We discuss the tropical precipitation shifts, contractions and intensifications that best match the ensemble of perturbed forcing experiments and how well those modes of precipitation variability describe the tropical precipitation changes. The overarching conclusion of this analysis is that the shifting mode explains a very small percentage of the precipitation changes, the contraction and intensification modes are more useful modes for thinking about precipitation changes but still fail to capture much of the tropical precipitation changes in the zonal mean but especially in the local structure.

3.1 Shifting mode

The meridional shift that optimizes the fit to the perturbed precipitation is small in magnitude ($< 1°$) and differs drastically between models even within the same experiment type; the optimal shift – for both the zonal mean and 2D structure– is not significantly different from zero in the LGM and $4XCO_2$ experiments, shows a small (0.2°) northward shift of marginal (90% confidence interval) significance in the mid-Holocene and is robustly southward (average of 1°) in the heavily forced hosing experiments (Table 1). Overall, the optimal zonal mean precipitation shift is well correlated with other metrics of ITCZ shifts that have been used in the literature such as the centroid of the zonal mean precipitation equator-ward of 20° [*Frierson and Hwang*, 2012; *Donohoe et al.*, 2013] with a correlation coefficient of 0.9 (Figure **??**A). However, the magnitude of the optimal

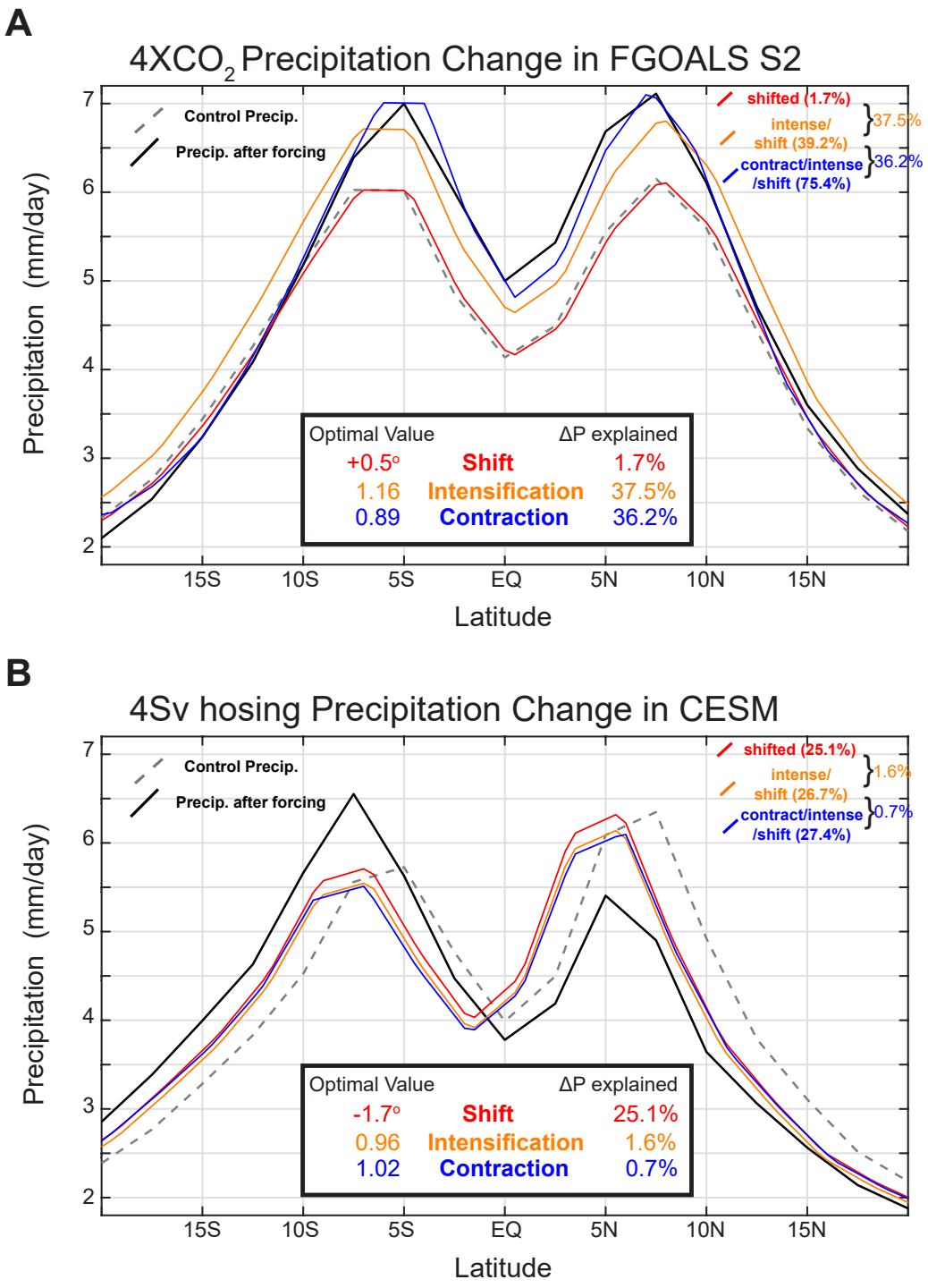


Figure 1. Illustration of optimal fitting to shifted/contracted/intensified modes of tropical precipitation and the procedure used to define the percent of the precipitation change explained by each mode. The dashed gray line shows the climatoligcal (zonal and annual mean) precipitation in the control (preindustrial) simulations and the black line shows the precipitation after external forcing. First the precipitation is optimally shifted (red line). Next the precipitation is optimally intensified and shifted together (orange line). Finally, the precipitation is optimally contracted, intensidifed and shifted together (blue). The percentage of ΔP explained by each mode is defined as the additional reduction in RMS ΔP by succesiively introducing the mode and all optimal

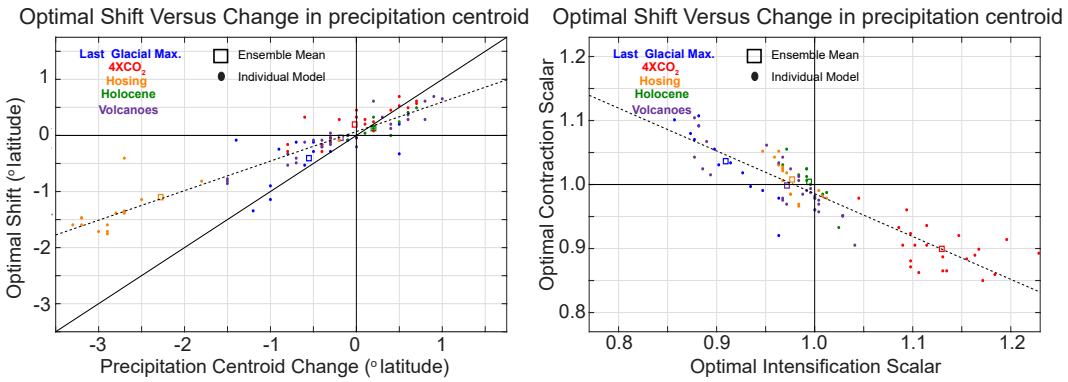


Figure 2. Optimal shift, contraction and intensification parameters for the zonal and annual mean precipitation changes in response to LGM (blue), $4XCO_2$ (red), Mid-Holocene (green), freshwater hosing (orange) and volcanic (purple) forcing. (A) Optimal shift (abscissa) versus the change in precipitation centroid (ordinate) that is commonly used to quantify ITCZ shifts. (B) Contraction scalar (abscissa) versus intensification scalar (ordinate). The 1:1 line is shown by the solid black line and the linear best fit is shown by the dashed black line. Dots represent individual models and the square shows the ensemble mean of simulations for each forcing experiment.

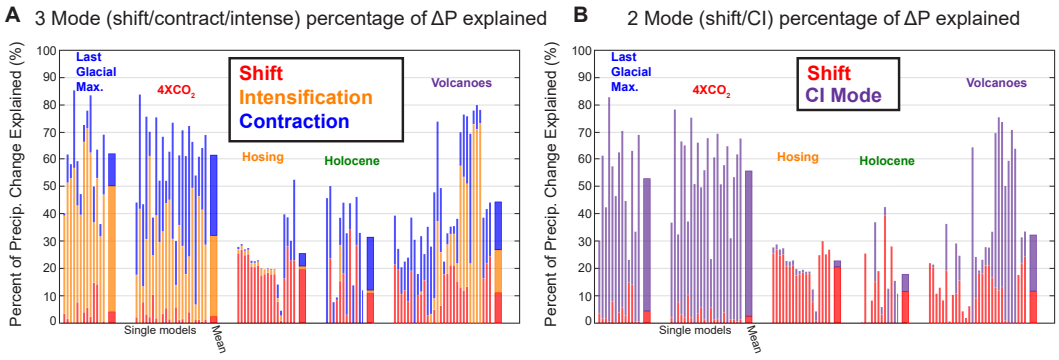


Figure 3. The percentage of ΔP explained by each mode of tropical precipitation changes in the ensemble of forced simulations. Results are grouped by forcing type with individual models shown by thin bars and the ensemble average shown in the thick bar to the right. (A) Three mode optimization with percentages defined starting from the shifting mode only (red) then adding the intensification mode (orange) and the adding the contraction (blue). (B) Two mode optimization with percentages defined starting from the shifting mode (red) then adding the combined contraction-intensification mode (CI – purple) with the ratio of the contraction to intensification defined from the linear best fit across all simulations shown in Fig. 1B. The loss of percentage explained going from 3 to 2 modes is: total (7.4) LGM(8.7) $4XCO_2$ (5.4) Hosing(2.0) Holocene(8.3) Volcanic(11.2)

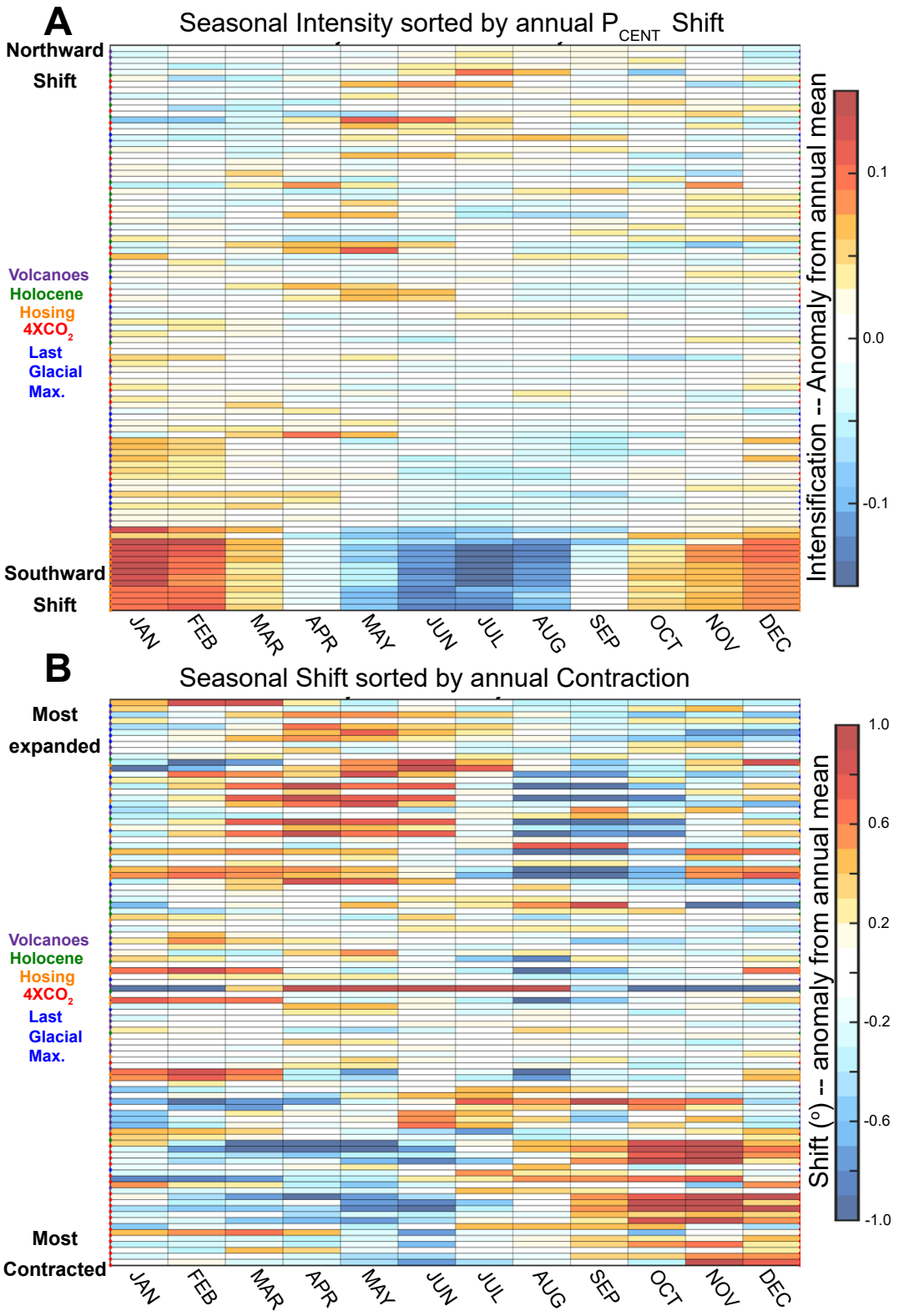
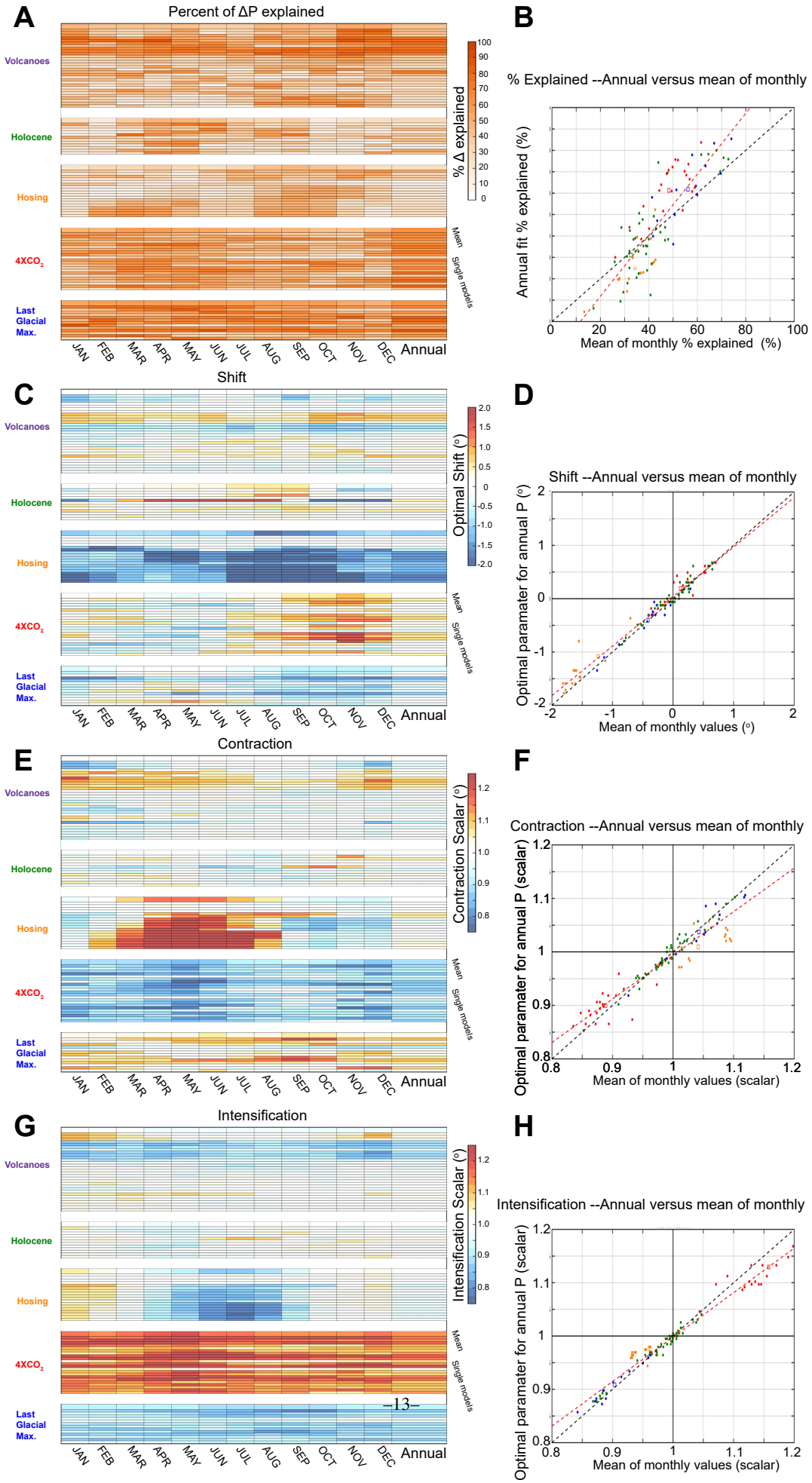


Figure 4. Analysis of the how the seasonal cycle of changes one tropical precipitation mode manifests in the annual mean change of a different mode. (A) The seasonal anomaly of the optimal intensification sorted by the annual precipitation centroid (P_{CENT}). Models with the the most southward annual P_{CENT} shift are on the bottom of the plot and models with the most northward annual shift are on the top. (B) The seasonal anomaly of the optimal shift sorted by the annual mean contraction. Models with the largest annnual mean expansion of the tropical precipitation are on the top of the plotP and models with the most contracted


A
Percent of ΔP explained
Volcanoes
Holocene
Hosing
4XCO2
Last Glacial Max.
Mean
Single models
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC Annual
% Δ explained
100 90 80 70 60 50 40 30 20 10 0
B
% Explained --Annual versus mean of monthly
Annual fit % explained (%)
Mean of monthly % explained (%)
0 20 40 60 80 100
C
Shift
Optimal Shift (°)
2.0 1.5 1.0 0.5 0 -0.5 -1.0 -1.5 -2.0
D
Shift --Annual versus mean of monthly
Optimal paramater for annual P (°)
Mean of monthly values (°)
E
Contraction
Contraction Scalar (°)
1.2 1.1 1.0 0.9 0.8
F
Contraction --Annual versus mean of monthly
Optimal paramater for annual P (scalar)
Mean of monthly values (scalar)
G
Intensification
Intensification Scalar (°)
H
Intensification --Annual versus mean of monthly

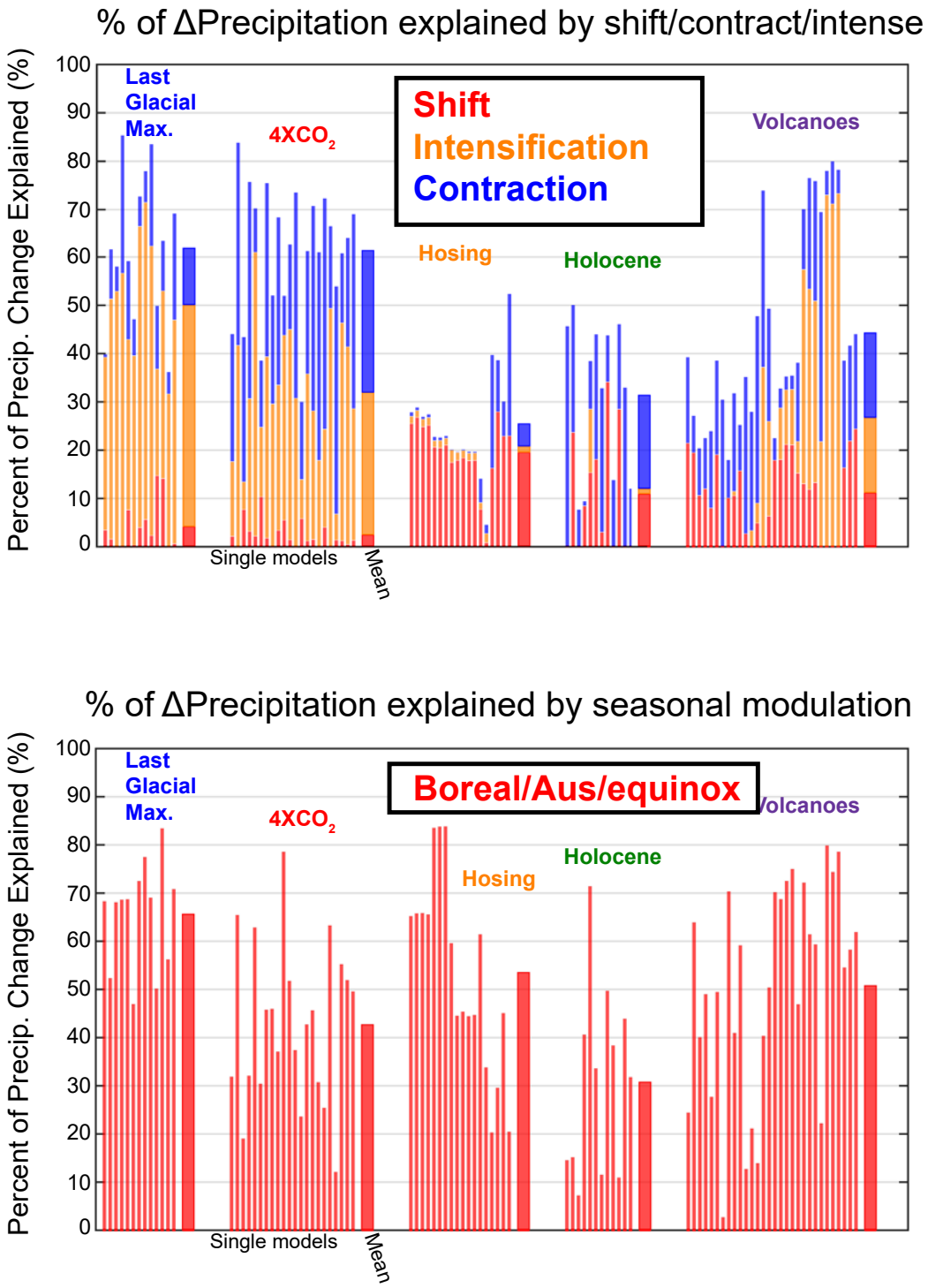


Figure 6. Percentage of annual ΔP explained by (A) optimal shift/contraction/intensification and (B) modulation of seasonal intentsities using 3 modes (Boreal/Austral/Equinox).

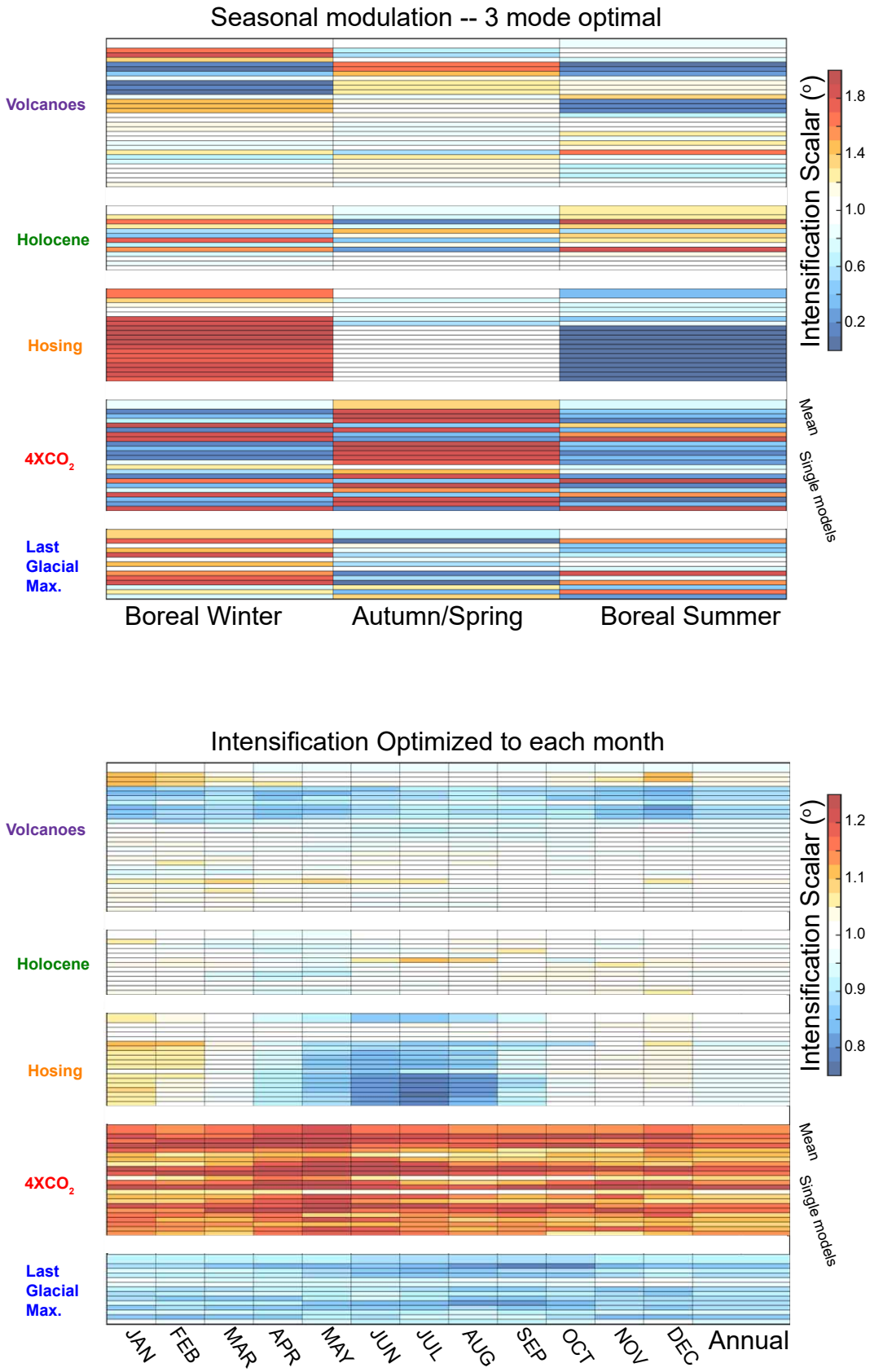


Figure 7. (A) Weighting factors for the 3-mode seasonal modulation clustered by forcing type. The total P is = to .25*Boreal Winter + 0.25*Boreal Summer + 0.5 Spring/Fall such that the unperturbed annual mean would have a value of 1,1,1. (B) The intensification scalar optimized to fit the monthly precipitation for

precipitation shift is approximately half of that in the precipitation centroid (regression coefficient of 0.45) and the optimal shift of the 2D precipitation is even smaller (regression coefficient = 0.16 – Figure **??**B). These results suggest that the metric of the zonal mean precipitation centroid may overemphasize the magnitude of ITCZ shifts in comprehensive modes where zonal inhomogeneities and seasonal variations in the tropical precipitation complicate the meaning of a zonal mean ITCZ. More importantly these results and those presented below question whether the concept of an ITCZ shift is useful for thinking about precipitation changes; while the location of the ITCZ in zonally symmetric (i.e aquaplanet) annual mean simulations where the precipitation is singly peaked at a given latitude is un-ambiguous, defining the same ITCZ in a system with zonally and seasonally varying precipitation is very ambiguous with different metrics of the ITCZ location giving both quantitatively and even qualitatively different results in terms of the direction of the ITCZ shift results (note the points on quadrants II and IV in Figure **??**). Here, we are not concerned of what metric is the best for the ITCZ location but rather, whether defining an ITCZ shift by any metric is useful for thinking about precipitation changes in the complex system or whether such an exercise is simply trying to fit a square peg in a circular hole.

The optimal shifting mode explains 9% of the zonal mean precipitation changes in the ensemble of all experiments considered here and only 1% of the local changes in the tropical precipitation (Table 1). In the majority of models, the shifting mode explains less then 2% of the precipitation change even in the zonal mean (Figure **??**) . In a minority of models, the shifting mode explains a much larger fraction (up to 45%) of the zonal mean precipitation changes explains (note the long tail in red histogram in Figure **??**A). The shifting mode is better than average at explaining the zonal mean precipitation change in the hosing simulations (highlighted by dark red bars in Figure **??**A – ensemble average of 13.2%) and in the mid-Holocene simulations (average of 12.2% and including the two outliers on the far right of the distribution). It's unclear whether the increased utility of the shifting mode in the minority of models is due to differences in the mean state precipitation in the models (i.e. zonal and seasonal homogeneity) or the response to the forcing.

Here we emphasize that, in the majority of models, the shifting mode does rather poorly at explaining precipitation changes in both the zonal mean and especially in the 2D structure.

3.2 Contraction mode

The tropical precipitation contracts robustly (significantly different than unity) in the ensemble average zonal mean response to $4XCO_2$ (average contraction scalar = 0.91± 0.03) and expands with marginal statistical significance (1.03±0.04) in response to LGM boundary conditions. The optimal 2D contraction in the LGM and $4XCO_2$ shows the same directionality with reduced amplitude and statistical significance (Table 1). In all other experiments, the contraction/expansion differs between ensemble members with no robust ensemble average directionality.

The contraction of the tropical precipitation found by the optimal fit to the altered precipitation under $4XCO_2$ appears at odds with the tropical expansion found concurrent with global warming in observations over the recent decades [*Johanson and Fu*, 2009] and in the modeled response to historical forcing [*Lu et al.*, 2007]. We further analyze the changes in the width of the tropical precipitation under $4XCO_2$using the following methodology:

1. **A)**.The central latitude of the tropical precipitation (i.e. ITCZ location) is defined as the latitude that delineates an equal area-average precipitation between 20°N and 20°S – hereafter referred as the tropical precipitation centroid (P_{CENT} – most equatorward solid vertical lines in Figure **??**)
2. **B)**.The central latitude of the tropical precipitation on either side of P_{CENT} is defined as the latitude that delineates an equal area-average precipitation between P_{CENT} and 15° poleward of P_{CENT} (the dashed vertical lines in Figure **??**). Hereafter we define this metric as the northern and souther precipitation P_{CENT}. This metric measures how far off the ITCZ the precipitation extends meridionally; be-

cause the zonal mean precipitation distribution is bi-modal in most climate models, this metric roughly coincides with the location of the maximum precipitation in each of the modes but also takes into account if the precipitation distribution is asymmetric about the peak as well.

3. **C**). The width of the tropical precipitation is defined as the distance between the northern and southern precipitaion centroids.

In the $4XCO_2$ ensemble average, the precipitation increases equatoward of the two precipitation peaks and is nearly unchanged on the poleward sides of the precipitation maxima with a concurrent modest equatorward shift in both precipitation maxima (upper left panel of Figure **??**). As a result, the width of the tropical precipitation contracts from and average of 14.2° in the PI simulations to 13.4° in the $4XCO_2$ simulations. In fact, the width of tropical precipitation decreases in every one of the 16 $4XCO_2$ ensemble members.

The contraction mode explains 20.2% of the zonal mean 2.4% of the local structure of precipitation changes over the ensemble of simulations. The contraction mode exceeds the utility of the shifting mode by more than a factor of 2 (9.0% and 1.0% respectively – Table 1). The contraction mode is most useful for describing zonal mean precipitation changes under $4XCO_2$ (33.0%) where there was a robust ensemble average precipitation contraction and in the Holocene (17.7%) where the ensemble members differ substantially on the contraction/expansion of the tropical precipitation with no consensus. With the exception of the hosing experiments, the contraction mode is more useful for describing precipitation changes than the shifting mode.

3.3 Intensification mode

The optimal fit to the perturbed precipitation features robust tropical precipitation intensification in response to $4XCO_2$ (the intensification scalar averages of 1.11 and 1.07 for zonal mean and local cases respectively) and precipitation reduction during the LGM

(0.91 and 0.91) as would be expected from the cahnges in global mean temperature. There is modest precipitation reduction in the ensemble of hosing experiments (0.97 and 0.95) and no significant changes in the intensification mode in the Holocene simulations (1.00±0.01 and 0.98±0.01 – Table 1).

The intensification mode explains 35% of the zonal mean and 5.4% of the zonal mean and 2D pattern of precipitation changes in the ensemble of experiments, exceeding the combined utility of the shifting and contraction modes in both cases. Not surprisingly, the intensification mode explains the largest fraction of precipitation changes in the LGM (57.7% in the zonal mean and 10.1% in the 2D case) and $4XCO_2$ (56.6% and 7.0%) . In contrast, the zonal mean intensification mode is less useful than both the shifting and contraction modes in the ensemble of hosing and mid-Holocene simulations (Table 1) but still explains the largest fraction of the local precipitation change in those experiments. The lack of utility of the intensification mode in explaining zonal mean precipitation changes in the Holocene experiments is explained as follows: the optimal intensification scalar was found to be unity in several (3) members resulting in 0% of the precipitation changes explained by the intensification mode. We emphasize that, for the most part, the intensification of climatological pattern of precipitation is the most likely explanation of a given (zonal mean or local) tropical precipitation change, especially when changes in global mean temperature are present; the intensification mode is far more useful than even the combined effect of the shifting and contraction modes.

Acknowledgments

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