Can energy fluxes be used to interpret glacial/interglacial precipitation changes in the Tropics?

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Key Points:
- The relationship between the zonal mean ITCZ and heat transport over the seasonal cycle and in response to glacial forcing is different
- Over the seasonal cycle the Hadley Circulation dominates heat transport: in response to forcing it does not
- Local rainfall is very different for the same position of the ITCZ; it is hard to place a single record into a global, zonal mean, context

Supporting Information:
- Supporting Information S1

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Can energy fluxes be used to interpret glacial/interglacial precipitation changes in the tropics?

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Abstract Recent theoretical advances in the relationship between heat transport and the position of the Intertropical Convergence Zone (ITCZ) present an elegant framework through which to interpret past changes in tropical precipitation patterns. Using a very large ensemble of climate model simulations, we investigate whether it is possible to use this framework to interpret changes in the position of the ITCZ in response to glacial and interglacial boundary conditions. We find that the centroid of tropical precipitation, which represents the evolution of precipitation in the whole tropics, is best correlated with heat transport changes. We find that the response of the annual mean ITCZ to glacial and interglacial boundary conditions is quite different to the response of the climatological annual cycle of the ITCZ to the seasonal cycle of insolation. We show that the reason for this is that while the Hadley Circulation plays a dominant role in transporting heat over the seasonal cycle, in the annual mean response to forcing, the Hadley Circulation is not dominant. When we look regionally, rather than at the zonal mean, we find that local precipitation is poorly related either to the zonal mean ITCZ or to meridional heat transport. We demonstrate that precipitation is spatially highly variable even when the zonal mean ITCZ is in the same location. This suggests only limited use for heat transport in explaining local precipitation records; thus, there is limited scope for using heat transport changes to explain individual paleoprecipitation records.

Plain Language Summary How energy is moved across the equator is important in determining how the temperature of the Northern and Southern Hemispheres differ. Recent theory has suggested that this energy transport can be related to the rainfall in the tropics. Understanding how the global temperature and the rainfall are related is an important question for understanding the climate of the past and the future. To understand the relationship between rainfall and heat transport in the past and future, it had been assumed that it was possible to use the relationship between them over the seasonal cycle in the modern day as a template. In this paper we show that this is not the case. To understand how rainfall and energy are related in the past and future will require additional theory. One implication of this is that we must be very careful when assessing records of rainfall from the past, not to use our intuition from how rainfall varies over the course of the year in the present. This unfortunately makes the interpretation of these records markedly more difficult!

1. Introduction

Recent advances in the theory for how the position of the zonal mean Intertropical Convergence Zone (ITCZ) is determined have provided a useful framework within which to interpret its movements [e.g., *Schneider et al.*, 2014]. In particular the idea that the ITCZ's position is either related to or determined by the transport of heat between the hemispheres, the energetic framework, provides an elegant way to relate changes in the tropical climate to much larger-scale global changes in the energy budget [*Marshall et al.*, 2013]. It is frequently argued that this framework could be useful for explaining changes in the tropics in the past [*Donohoe et al.*, 2014].

There is evidence from numerous paleorecords for changes in local precipitation in many areas of the tropics over many thousands of years [e.g., *Haug et al.*, 2001; *Konecky et al.*, 2011; *Russell et al.*, 2014]. These have frequently been linked to changes in the much larger-scale tropical circulation and to movements in the global ITCZ, often in the context of zonally uniform northward and southward "shifts" [e.g., *Wang et al.*, 2006]. Through the energetic framework these shifts can potentially be linked to even larger-scale phenomena such as Northern Hemisphere warming during Dansgaard/Oeschger events or changes in insolation. One might even use paleorecords to infer the size of the changes in the heat fluxes [*McGee et al.*, 2014].

However, to use the energetic framework to interpret paleorecords, we must first understand how the ITCZ responds to forcing that is typical of these paleorecords: forcings such as greenhouse gases or ice sheets. Much of the theory that underpins the energetic framework arises from an analysis of the seasonal cycle; however, it is not clear if, or indeed why, the climate should respond to glacial and interglacial forcings in the same way as it does to the seasonal cycle. For example, an ice sheet evolves over thousand of years and has a large amount of zonal asymmetry: the insolation forcing over the seasonal cycle is zonally symmetric and quickly varying. Studies using idealized forcing [*Shaw et al.*, 2015] or elevated greenhouse gases [*Hill et al.*, 2015] have shown that the ITCZ does not necessarily respond to forcing as it does the seasonal cycle. The energetic framework assumes that the mean meridional circulation in the tropics (the Hadley Circulation) is responsible for the majority of the heat transport across the equator. While this is true on a month by month basis, in the annual mean it is not [*Marshall et al.*, 2013; *Heaviside and Czaja*, 2013]. It is thus an open question whether analyzing changes in the annual mean Hadley Circulation in response to glacial forcing will yield insights into the changes in the total heat transport.

The energetic framework is based on an assessment of the zonal mean ITCZ. Over the seasonal cycle there is a remarkable zonal symmetry to movements in the precipitation; it is not obvious that this is the case in response to glacial forcings [*DiNezio and Tierney*, 2013]. Furthermore, even over the seasonal cycle it has been shown that the across-equator heat transport is not the only term that determines the location of the ITCZ [*Bischoff and Schneider*, 2014]. If there is no zonal symmetry in the response of the climate to the glacial forcing or if other terms are important, it is not clear how to then relate the local changes in precipitation to the zonal mean ITCZ and thus place the local precipitation into the global context.

We shall investigate these questions in this paper by examining the response of the zonal mean ITCZ in a climate model to the seasonal cycle and many different glacial/interglacial forcings.

2. Simulations and Metrics

We analyze output from the fully coupled atmosphere-ocean model HadCM3 [*Gordon et al.*, 2000; *Valdes et al.*, 2017]. The model is forced with a variety of glacial and interglacial boundary conditions; for convenience we henceforth refer to these as “glacial” boundary conditions. In all we have 363 such simulations. One hundred twenty-two of these simulations simulate the evolution of the climate over the last 120 thousand years in a series of snapshots [*Singarayer and Valdes*, 2010]; 240 investigate the sensitivity of the climate to individual glacial forcings such as orbital forcing, greenhouse gases, or the configuration and sea level impacts of the continental ice sheets [*Roberts and Valdes*, 2017]. There is one preindustrial control experiment about which we compute anomalies. To assess the robustness of the results, we also use some “hosing simulations.” Such hosing simulations are argued to represent the effects of abrupt climate changes in glacial times [*Singarayer and Valdes*, 2010]. There are eight hosing simulations each of which imposes the hosing to different glacial boundary conditions. These simulations are not used in any of the regressions or correlations presented; they are thus an independent test.

All simulations are run for at least 500 years with averages of the final 100 years of simulation analyzed. Data shown in analysis of the seasonal cycle (Figures 1a, 1c, 1e, and 1g) are monthly averages over the final 100 years of each simulation. Data shown in analysis of the glacial forcing (Figures 1b, 1d, 1f, and 1h) are annual averages of the final 100 years of each simulation. From this ensemble of models we also show results from four members that are run for an extra 50 years over which we calculate the complete moist static energy budget.

A host of different metrics for the ITCZ location exists. The energy flux equator (δ and δ_{lin}) [*Bischoff and Schneider*, 2014] frames the ITCZ in terms of moist static energy transports across the equator. The centroid of tropical precipitation (p_{cent}) [*Donohoe et al.*, 2013] and the maximum of tropical precipitation ($p_{\max}$) [*Adam et al.*, 2016] are the most conventional views of the ITCZ assessing the precipitation, with an emphasis on the peak precipitation ($p_{\max}$) or the tropic-wide distribution (p_{cent}). The location at which the atmospheric meridional stream function is zero (Ψ_0) [*Donohoe et al.*, 2013] views the ITCZ as the boundary between the Northern and Southern Hemispheres Hadley Cells, emphasizing the transport of dry static energy. In this study we calculate all of these metrics to establish whether any one is particularly good at explaining movements in the ITCZ in response to glacial forcing. We do, however, emphasize those metrics that could potentially be used for interpreting paleoclimate records, which are generally some sort of proxy for rainfall.

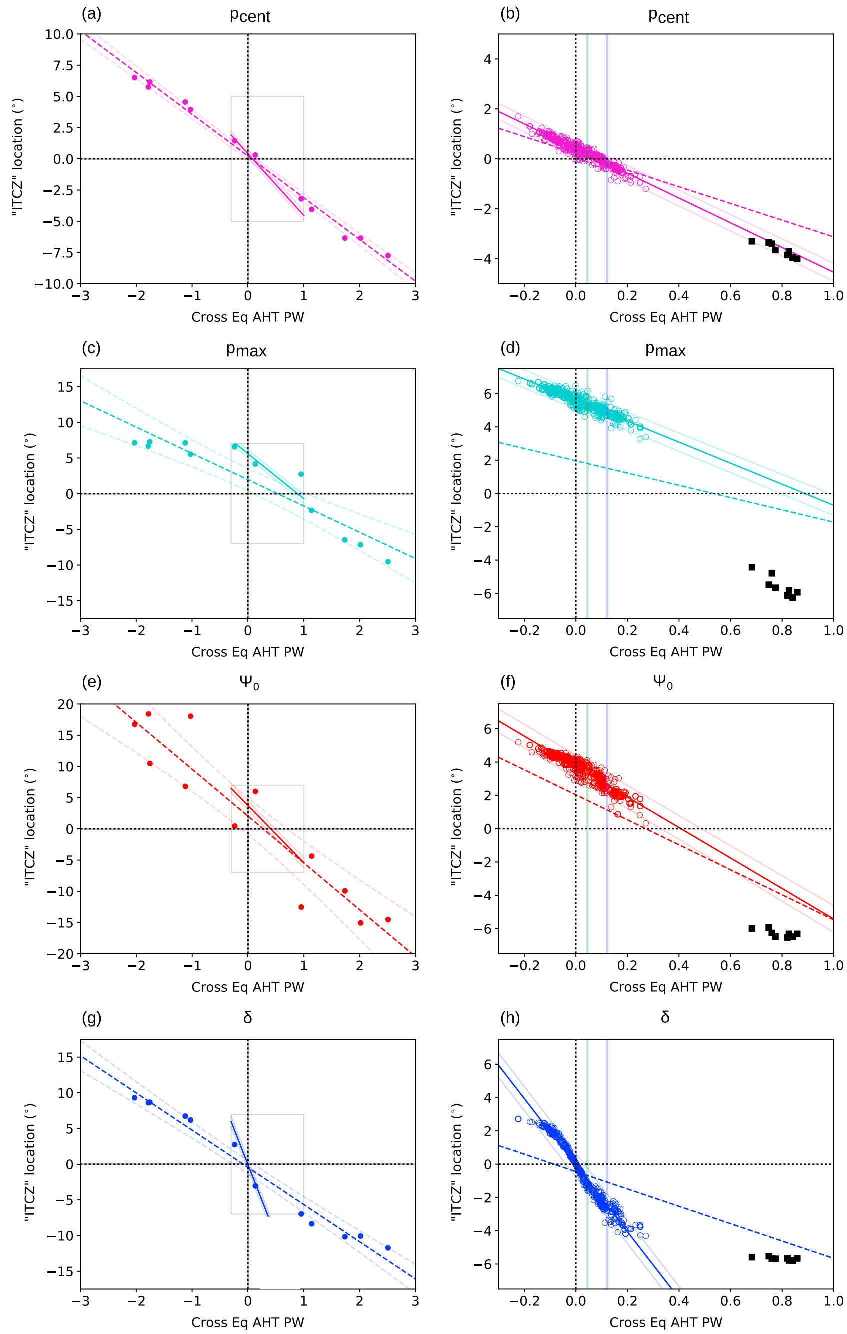

Figure 1. Metrics of ITCZ location plotted against atmospheric heat transport across the equator over the course of the (a, c, e, g) seasonal cycle and in response to (b, d, f, h) glacial forcing. Over the seasonal cycle each point represents the average of 100 years of each month in a preindustrial simulation; in response to glacial forcing each point represents a 100 year average. Solid lines show regression for the glacial forcing simulations; dashed lines show regression over the seasonal cycle. Dashed lines show the best fit to the data with faint lines indicating the 95% confidence interval on these fits. The grey central rectangle in Figures 1a, 1c, 1e, and 1g indicates the range of the axes used in the corresponding plots (Figures 1b, 1d, 1f, and 1h). The black squares (Figures 1b, 1d, 1f, and 1h) indicate the results from the hosing simulations. Note that the scale of the y axes (ITCZ location) in each panel is different. The x axes (AHT) in Figures 1a, 1c, 1e, and 1are the same; the x axes in Figures 1b, 1d, 1f, and 1h are the same. Green vertical lines in Figures 1b, 1d, 1f, and 1h indicate the AHT at the preindustrial; blue vertical lines indicate the AHT at the LGM.

In the simulations in which the moist static energy budget is calculated, we decompose the meridional transports into its mean meridional, stationary, and transient eddy components. Full details of this decomposition are contained in the supporting information. The mean meridional circulation component represents heat transported by the time mean Hadley Circulation; the heat transported by this circulation is primarily due to the contrast in moist static energy between the upper and lower level flows. The stationary eddy term represents heat transported by the zonally asymmetric flow; heat transports by this circulation are predominantly a result of horizontal contrasts in the column-integrated moist static energy. The transient eddy term represents heat transported on timescales shorter than the time averaging used.

3. ITCZ Response to the Seasonal Cycle

Over the course of the year the position of the ITCZ moves north and south of both the equator and its mean position slightly north of the equator. The heat transport mirrors this migration going from negative (southward) when the ITCZ is farthest north to positive (northward) when it is farthest south. By relating the ITCZ location to the heat transport over this seasonal march we can derive a relationship which we might apply to other climate states. This was the procedure followed by *McGee et al.* [2014] and *Donohoe et al.* [2013]. This assumes that the dynamics that control the transport of heat and moisture over the seasonal cycle are the same as those that control these transports in the annual mean [see *Donohoe et al.*, 2013, Figure 11]. This is by no means assured. For example, *Hill et al.* [2015] show that although over the seasonal cycle the largest contributor to the northward heat transport is the Hadley Circulation, with small roles for the stationary and transient eddies, in response to either an aerosol or greenhouse gas forcing, the changes in the heat transport are similarly large in the Hadley Circulation or the eddy terms. We cannot therefore assume that because the Hadley Circulation dominates heat transports over the course of the seasonal cycle, its changes are also the dominant cause of heat transport changes in response to some external forcing. We shall return to this point in section 6.

In Figures 1a, 1c, 1e, and 1g we show the relationship between the ITCZ and heat transport over the seasonal cycle from a preindustrial simulation. For all of the metrics shown there is a strong correlation with the heat transport: for all metrics the correlation coefficient is greater than 0.9 (supporting information Table S1). The gradients of the slopes are however rather different. The circulation ITCZ, Ψ_0, has the greatest slope ($-7.5 \pm 1.9°$ PW^{-1}) and the precipitation centroid, p_{cent}, the least ($-3.3 \pm 0.2°$ PW^{-1}). These model-derived relationships agree well with those derived from the National Centers for Environmental Prediction reanalysis (reported by *Donohoe et al.* [2013]) of $-8.9°$ PW^{-1} for Ψ_0 and $-2.7 \pm 0.6°$ PW^{-1} for p_{cent}.

We find that the weakest correlation between the ITCZ and heat transport is for p_{max} and Ψ_0. This is because, while the seasonal change in atmospheric heat transport is nearly sinusoidal [see, e.g., *Adam et al.*, 2016], the movements in the precipitation distribution are far less smooth, with the ITCZ spending relatively more time at its seasonal extremes [*Chiang and Friedman*, 2012]. *Hu et al.* [2007] showed that it is only in a number of distinct domains and seasons that the precipitation associated with the ITCZ does not vary smoothly over the seasonal cycle. These are still large enough, however, to affect the seasonality in the zonal mean. The position of δ, the energy flux equator, is, unsurprisingly, well correlated with the seasonal cycle in heat transport. The high correlation between p_{cent} and atmospheric heat transport is rather more surprising since, as was just discussed, the maximum rainfall in the ITCZ spends much of its time at its seasonal extremes. However, since p_{cent} represents the total rainfall across the whole tropics, it includes changes that are not exclusively related to the peak rainfall bands. It has been shown that, when considered over the whole of the tropics, the circulation of the Hadley Circulation does vary smoothly over the seasonal cycle [*Dima and Wallace*, 2003; *Hu et al.*, 2007]. We therefore suggest that over the seasonal cycle, p_{cent} represents the precipitation associated with Hadley Circulation and the circulation of the Tropics more generally, whereas p_{max} represents the precipitation associated exclusively with the strongest rainfall in the ITCZ. The difference between p_{cent} and Ψ_0, both of which are associated with the Hadley Circulation, is that p_{cent} mostly represents moisture convergence at the surface whereas Ψ_0 is more representative of the three dimensional circulation and dry static energy. Furthermore, since p_{cent} encapsulates changes over a large latitudinal band, it can represent changes associated with more than just the ITCZ: changes in the monsoons, for example. Monsoon circulations are crucially important in determining the heat transport across the equator and are not zonally symmetric [*Heaviside and Czaja*, 2013].

4. ITCZ Response to Glacial/Interglacial Forcing

We turn now to the relationship between the ITCZ and the heat transport in response to glacial forcing (Figures 1b, 1d, 1f, and 1h). We first note that the changes in the annual mean location of the ITCZ in response to glacial forcing are considerably smaller than those in response to the seasonal cycle. Typical movements in the zonal mean ITCZ over the seasonal cycle are on the order of 5–10°, whereas in response to glacial forcing typical movements are on the order of 1–2°. The response to "hosing" simulations is larger, although again it is smaller than that from the seasonal cycle. To detect such small changes presents a challenge: the measurement of the zonal mean ITCZ position must be precise enough to resolve movements on the order of 100 km. We also find that the changes in the atmospheric heat transport (AHT) in response to glacial forcing are smaller than those in response to the seasonal cycle.

Many of the simulations show a northward shift in the ITCZ. This northward shift occurs in a number of runs in which there is an ice sheet in the Northern Hemisphere, which is counter to our intuition that a cooler Northern Hemisphere would move the ITCZ south. In these simulations the changes in the greenhouse gas (GHG) and orbital forcing both act to move the ITCZ north counteracting the effect of the ice sheet.

If we analyze the relationships between ITCZ location and AHT, we find that, as was the case for the seasonal cycle, the slope between p_{cent} and AHT is the shallowest, $-5.0 \pm 0.2°$ PW^{-1}. However, with glacial forcing the steepest gradient is seen in δ $-20.0 \pm 0.4°$ PW^{-1} rather than in Ψ_0. Most notably, we find that for all the ITCZ metrics, their relationships with AHT are significantly different to those over the seasonal cycle and all are significantly steeper—the ITCZ shifts more for a change in the heat transport with glacial forcing than it does over the seasonal cycle. This is a different conclusion to previous studies.

Donohoe et al. [2013] report that the gradient between both the observed and simulated seasonal cycles of p_{cent} and AHT is, within error, the same as the gradient between the annual mean change in p_{cent} and AHT calculated for each model in the Paleoclimate Modelling Intercomparison Project (PMIP) simulations forced by either Last Glacial Maximum (LGM) or mid-Holocene forcing (the relationship is not the same for the $2\times CO_2$ forcing). They also report that the gradient between both the observed and simulated seasonal cycles of p_{cent} and AHT is the same as the gradient between the annual mean p_{cent} and AHT calculated for the preindustrial simulation of each of the 15 PMIP models. This is a statement that the relationship between AHT and p_{cent} among the different models is the same as that seen over the seasonal cycle. Thus, the observation that in each of the forcing experiments the gradient remains the same is a statement that the model to model relationship between p_{cent} and AHT that is seen in the preindustrial is robust to forcings such as the LGM and mid-Holocene. The PMIP simulations can be used to examine the relationship between AHT and p_{cent} in response to forcing, the question we address, only if all three different forcing scenarios are considered together. However, with only 3 different forcing scenarios and 15 different models this comparison will still be heavily biased toward analyzing the model to model relationship rather than the forcing relationship. By contrast, our simulations use one single model but 363 different sets of glacial boundary conditions; thus, our results show only the response of the climate to glacial forcing.

To further examine the robustness of the relationship between AHT and the ITCZ, we also examine hosing simulations. Such simulations are proposed to represent rapid climate changes during glacial periods such as Heinrich or Dansgaard/Oeschger events. These simulations dramatically perturb the ocean circulation and cool the Northern North Atlantic by more than 15°C [*Singarayer and Valdes*, 2010]. Both of these responses can act to change the climate's energy transports and thus may move the ITCZ. In common with other simulations of this kind we see a large change in the rainfall patterns [*Cheng et al.*, 2007; *Stouffer et al.*, 2006]. We note that the regressions that we present above, and are plotted in the figures, exclude these simulations and thus use an independent test of the relationship of the ITCZ to forcing.

We find that for all ITCZ metrics, except p_{cent}, the relationships between AHT and ITCZ location derived from either the seasonal cycle (dashed lines) or from glacial boundary conditions (solid lines) fail to capture the changes in the ITCZ during the hosing simulations. The ITCZ shifts measured by Ψ_0 and p_{max} during the hosing simulations are larger than those seen with changes in the glacial boundary conditions; however, they remain much smaller than the movements seen over the seasonal cycle. The changes in δ, by contrast, are far smaller than those suggested by a linear relationship derived from the glacial boundary condition simulations.

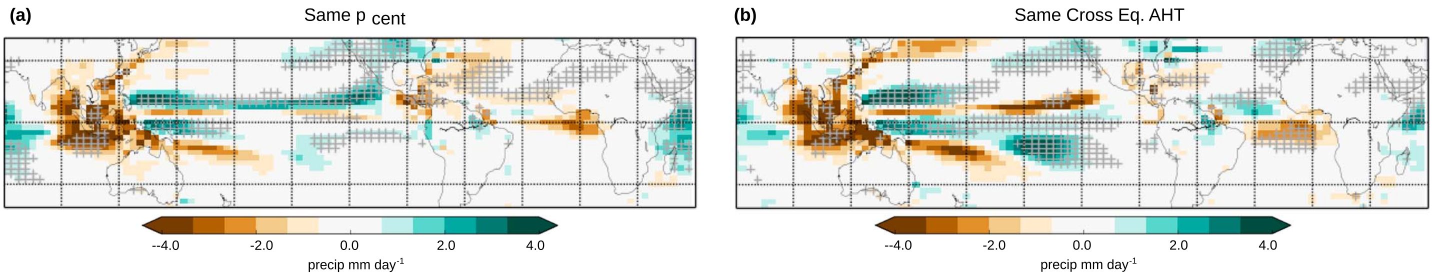

Figure 2. Difference maps of annual average precipitation between two simulations with the same (a) p_{cent} and (b) AHT. The regions marked with crosses indicate that the precipitation differs by more than 50% between the two simulations.

Interestingly, they lie close to the location predicted by the linear approximation of *Bischoff and Schneider* [2014] (supporting information). This suggests that the effect of any change in the net incoming radiation at the top of the atmosphere in the tropics is negligible in the hosing simulations.

The relationship derived from p_{cent} using glacial boundary conditions is a remarkably good predictor of the AHT and ITCZ location during the hosing simulation. We note, though, that the relationship derived from the seasonal cycle is, once again, a poor predictor of forced changes in the annual mean location: this relationship predicts a shift in the ITCZ location that is roughly half that seen in the model.

5. Precipitation Patterns Associated With ITCZ Shifts

In the derivation of p_{cent}, we must be able to quantify the mean rainfall across the whole tropics: we must quantify the rainfall at all longitudes to compute the zonal mean, and we must quantify the rainfall across all latitudes to compute the distribution. Knowing how the peak rainfall varies is insufficient. With modern satellite-derived rainfall products it is relatively easy to compute p_{cent}. Before satellites, however, our understanding of the global rainfall distribution is far less well known. It is important therefore to understand how local precipitation is related to the zonal mean, so that we might be able to place point records of precipitation, typical of paleorecords, into the energetic framework.

To demonstrate how different the spatial patterns of the precipitation can be for the same value of a zonal mean ITCZ metric, we plot maps of the difference between the global rainfall for two simulations with glacial forcing whose annual mean p_{cent} is the same (Figure 2a) and two simulations where the annual mean AHT is the same (Figure 2b). If local precipitation reflects either the zonal mean ITCZ or AHT, we would expect the difference between these maps to be zero or at least small, everywhere. However, in both case we find that there are large changes in the tropical precipitation patterns. Rainfall in many locations changes by more than 50% (as shown by the crosses). Furthermore, we also find that in these simulations although p_{cent} (AHT) is effectively the same, the AHT (p_{cent}) is quite different. For the two simulations in which p_{cent} is the same, the AHT differs by 0.05 PW, which compares to the standard deviation of 0.09 PW over all glacial forcings. Similarly for the simulations in which the AHT is the same, p_{cent} differs by 0.40° compared to the standard deviation of 0.47° over all the glacial forcings. The region that accounts for much of the spread in these simulations which have the same p_{cent} and AHT, and more generally to all glacial forcing, is the West Pacific (supporting information Figure S4). HadCM3 has been shown to well simulate the changes in precipitation in this region at the LGM, suggesting that it is a robust response to glacial forcing [*DiNezio and Tierney*, 2013]. In this region the response to glacial forcing has little in the way of symmetry either zonally or across the equator; this is in contrast to the response to the seasonal cycle where there is a generally zonally symmetric response (supporting information Figure S3) [*Adler et al.*, 2003].

6. Why is the Seasonal Cycle and Glacial Forcing Response Different?

We have shown that there are statistically significant relationships between the ITCZ and heat transport in response to both the seasonal cycle and glacial forcing, but that the nature of these relationships is rather different. We now seek to explain these differences.

In Figure 3 we decompose the zonal mean cross-equatorial moist static energy transport into its Hadley Circulation component (the mean meridional circulation) and its stationary and transient eddy components for

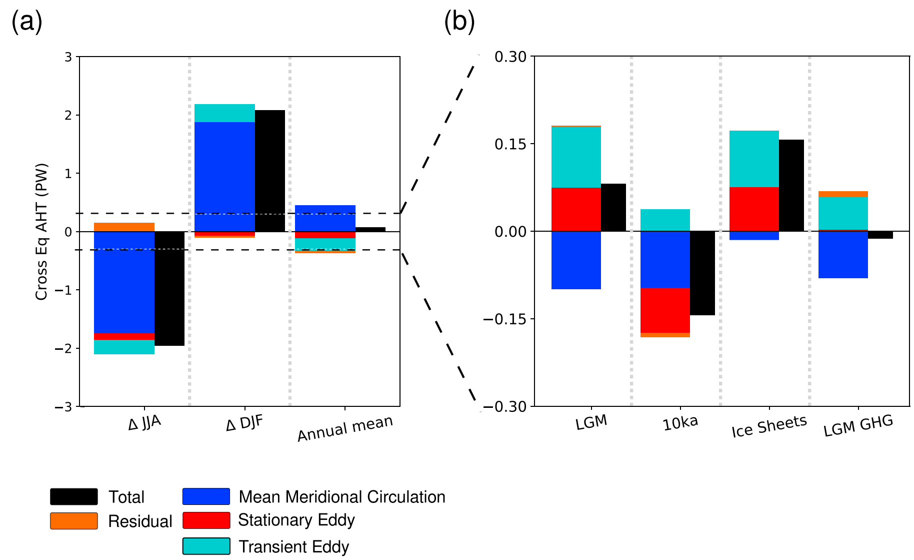

Figure 3. Decomposition of zonal mean meridional heat transport. (a) Preindustrial seasonal cycle: JJA and DJF average as anomalies about the annual mean which is shown in the rightmost bar. (b) Forced runs shown as annual mean differences to the preindustrial annual cycle, which is shown in the rightmost bar of Figure 3a. Forced simulations, from left to right: full LGM forcing (orbit/GHG/ice sheets); 10ka forcing (GHG/orbit); LGM ice sheets (all other forcings for preindustrial); LGM GHG forcing (all other forcings for preindustrial). Scale on seasonal cycle extends from ± 3 PW, forced simulation ± 0.3 PW, with this range shown by dashed lines in Figure 3a.

four different experiments with glacial forcing (see supporting information for details of the decomposition). Consistent with reanalysis data, we find that in the annual mean there is an important contribution from all components of the heat transport [*Marshall et al.*, 2013, Figure 3a and Table 1]. Looking at the two seasons, December, January, February (DJF) and June, July, August (JJA), we see that the dominant component of the meridional heat transport is the Hadley Circulation; this observation forms the basis of the energetic framework (the Hadley Circulation is also dominant on interannual timescales [*Donohoe et al.*, 2014]). In the glacially forced simulations, however, we do not find that the Hadley Circulation is the dominant cause of the change in the heat transport. This component can be of opposite sign to the total change in the heat flux (LGM) or so small as to be negligible (ice sheets only).

We therefore find that the mechanism that drives changes in heat transport over the seasonal cycle, a change in the Hadley Circulation, is not the same mechanism that drives heat transport changes in response to different glacial forcings, which includes changes in the stationary and transient eddies. *Hill et al.* [2015] show a similar result. In their simulation with elevated greenhouse gas concentrations, the change in the total meridional heat transport is due to changes in the eddy and mean meridional circulations, with the mean meridional circulation change opposing that in the eddies. This is a similar result to that seen in our LGM greenhouse gas experiment. The heat transport response to the imposition of LGM ice sheets shows negligible change in the Hadley Circulation yet large changes in both eddy components. The LGM ice sheets impose a large albedo anomaly in the Northern Hemisphere which would imply a reduction in the top of the atmosphere radiation in the Northern Hemisphere and a related increase in the northward heat flux across the equator [*Chiang and Bitz*, 2005; *Yoshimori and Broccoli*, 2008; *Roberts and Valdes*, 2017]. Our model shows this increase in the heat transport across the equator; however, it is not manifested in the Hadley Circulation. The Full LGM response is a linear combination of the effect of ice sheets and greenhouse gases. The response to 10 ka forcing shows changes to the Hadley Circulation and the eddies. At 10 ka there is a large change in the seasonality of insolation which has a large impact on the monsoon circulations [*Braconnot et al.*, 2007]. Because the monsoon circulations are responsible for much of the heat transport across the equator [*Heaviside and Czaja*, 2013], any change in the monsoons will result in a change in heat transport. Furthermore, since the monsoon circulations lack zonal symmetry this change will not be seen in the mean meridional circulation. At 10 ka the climate is forced by changes in the insolation: over the seasonal cycle the climate is also forced by insolation. Therefore, although insolation forces the changes in heat transport in both cases, this change in heat transport is caused by two different mechanisms.

This decomposition shows why the response of the heat transport to seasonal forcing is not the same as the response to glacial forcing. It does not, however, explain why we see the strong relationships between heat transport and the ITCZ in response to glacial forcing. Given the very different mechanisms that combine to give the changes in the total heat transport in the four experiments that we show, it is rather surprising that there is any relationship between the zonal mean ITCZ and the across-equator heat transport.

7. Conclusions

By comparing 363 climate model simulations using the same climate model but forced with different glacial and interglacial boundary conditions we have investigated the relationship between the location of the ITCZ and the transport of heat across the equator by the atmosphere. We have shown that, although there are relatively robust relationships between the AHT and various metrics of the ITCZ over both the seasonal cycle and in response to forcing, the strength of these relationships (i.e., the regression between them) is not the same. We cannot therefore make inferences about past changes in the annual mean location of the ITCZ from analyzing changes in the present-day seasonal cycle. Furthermore, our results suggest that the relationship between the ITCZ and AHT is different in response to abrupt climate changes such as might be simulated by hosing experiments.

We have demonstrated that the energetic framework is a robust way to interpret changes in the zonal mean circulation, in model configurations that are far more complex than those in which it has previously been demonstrated [e.g., *Kang et al.*, 2008; *Yoshimori and Broccoli*, 2008; *Cvijanovic and Chiang*, 2012; *Maroon et al.*, 2016]. We caution, however, that in order to understand the change in AHT that arises from a particular forcing, one must carefully consider the mechanisms by which the climate responds to the forcing. We have shown that in response to glacial forcings, the Hadley Circulation is not necessarily the dominant cause of any changes in the heat transport. At the heart of the energetic framework lies the assumption that the Hadley Circulation is the reason for the relationship between rainfall and AHT; it is, therefore, somewhat surprising that there was any relationship in these simulations. We found that in response to glacial forcing the strongest correlations were between heat transport and p_{cent}. Since the calculation of p_{cent} requires the full tropical precipitation distribution, this metric can reflect more moist processes than just those involved in the Hadley Circulation. We suggest that this is the reason for the closer relationship between AHT and p_{cent}. By contrast, metrics such as p_{max} and Ψ_0 more closely reflect only the Hadley Circulation and are thus less able to reflect changes in the circulation due to the eddies. These changes in the eddies were shown to be important in response to glacial forcing.

We have demonstrated that the energetic framework only works when considering changes in the *zonal mean* ITCZ. There are some regions where the local rainfall does seem to correlate well with some metrics of the zonal mean ITCZ, such as the Atlantic, South America, and Africa, but equally, there are large areas where the local rainfall is uncorrelated with the zonal mean ITCZ, such as the East and West Pacific. It is thus unsurprising that dramatically different patterns of rainfall are possible for the same value of an ITCZ metric. In the context of the decomposition of the meridional circulation, this may be understood as reflecting the importance of the stationary and transient eddy components of the flow. As a way to encapsulate these zonal inhomogeneities it has been suggested that an energetic framework for the zonal circulation may exist [*Boos and Korty*, 2016]. We caution that, given the complexity of the response in the meridional circulation, attempts to frame the far less understood zonal flow in a similar context may be premature. Separating the zonal and meridional circulations will be confounded by the important zonally inhomogeneous stationary wave component of the heat transport.

We motivated this study by seeking to make more explicit how we might apply a theoretical framework for understanding tropical rainfall to observations of the past. We have shown that it is not possible to try to extend an understanding of the precipitation at one single point to the global zonal mean; furthermore, it is also not possible to place one single rainfall record in the context of changes in the global energy budget. Networks of records, however, might be placed into a global context—especially those that have significant latitudinal extent. We have shown that p_{cent} has skill at explaining changes in the heat transport in both response to glacial forcing and the hosing. However, to correctly estimate p_{cent}, the precipitation distribution must be known throughout the tropics. There are hints that in some regions, such as the Atlantic, South America, and Africa, movements in the rainfall are rather well correlated with p_{cent} (supporting information Figure S3) and thus might be placed into a global context. However, we caution that when calculating p_{cent}

on a basin scale, as might be done with a network of precipitation proxies in the Atlantic, although we find statistically robust relationships between local precipitation and global energy fluxes, these relationships are not the same as those between global precipitation and global energy fluxes (supporting information Figures S5 and S6). Further study is needed to understand this.

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References

Adam, O., T. Bischoff, and T. Schneider (2016), Seasonal and interannual variations of the energy flux equator and ITCZ. Part I: Zonally averaged ITCZ position, *J. Clim.*, *29*(9), 3219–3230, doi:10.1175/JCLI-D-15-0512.1.

Adler, R., et al. (2003), The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979-present), *J. Hydrometeorol.*, 1147–1167.

Bischoff, T., and T. Schneider (2014), Energetic constraints on the position of the Intertropical Convergence Zone, *J. Clim.*, *27*(13), 4937–4951, doi:10.1175/JCLI-D-13-00650.1.

Boos, W. R., and R. L. Korty (2016), Regional energy budget control of the intertropical convergence zone and application to mid-Holocene rainfall, *Nat. Geosci.*, *9*(12), 892–897, doi:10.1038/ngeo2833.

Braconnot, P., et al. (2007), Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum—Part 1: Experiments and large-scale features, *Clim. Past*, *3*(2), 261–277, doi:10.5194/cp-3-261-2007.

Cheng, W., C. M. Bitz, and J. C. H. Chiang (2007), Adjustment of the global climate to an abrupt slowdown of the Atlantic meridional overturning circulation, in *Ocean Circulation: Mechanisms and Impacts—Past and Future Changes of Meridional Overturning, Geophys. Monogr. Ser.*, vol. 173, edited by A. Schmittner, J. C. H. Chiang, and S. R. Hemming, pp. 295–313, AGU, Washington, D. C., doi:10.1029/173GM19.

Chiang, J. C., and A. R. Friedman (2012), Extratropical cooling, interhemispheric thermal gradients, and tropical climate change, *Annu. Rev. Earth Planet. Sci.*, *40*(1), 383–412, doi:10.1146/annurev-earth-042711-105545.

Chiang, J. C. H., and C. M. Bitz (2005), Influence of high latitude ice cover on the marine Intertropical Convergence Zone, *Clim. Dyn.*, *25*(5), 477–496, doi:10.1007/s00382-005-0040-5.

Cvijanovic, I., and J. C. H. Chiang (2012), Global energy budget changes to high latitude North Atlantic cooling and the tropical ITCZ response, *Clim. Dyn.*, *40*(5–6), 1435–1452, doi:10.1007/s00382-012-1482-1.

Dima, I. M., and J. M. Wallace (2003), On the seasonality of the Hadley Cell, *J. Atmos. Sci.*, *60*(12), 1522–1527, doi:10.1175/1520-0469(2003)060.

DiNezio, P. N., and J. E. Tierney (2013), The effect of sea level on glacial Indo-Pacific climate, *Nat. Geosci.*, *6*(6), 485–491, doi:10.1038/ngeo1823.

Donohoe, A., J. Marshall, D. Ferreira, and D. Mcgee (2013), The relationship between ITCZ location and cross-equatorial atmospheric heat transport: From the seasonal cycle to the Last Glacial Maximum, *J. Clim.*, *26*(11), 3597–3618, doi:10.1175/JCLI-D-12-00467.1.

Donohoe, A., J. Marshall, D. Ferreira, K. Armour, and D. Mcgee (2014), The interannual variability of tropical precipitation and interhemispheric energy transport, *J. Clim.*, *27*(9), 3377–3392, doi:10.1175/JCLI-D-13-00499.1.

Gordon, C., C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood (2000), The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, *16*(2–3), 147–168, doi:10.1007/s003820050010.

Haug, G. H., et al. (2001), Southward migration of the intertropical convergence zone through the Holocene, *Science*, *293*(5533), 1304–1308, doi:10.1126/science.1059725.

Heaviside, C., and A. Czaja (2013), Deconstructing the Hadley cell heat transport, *Q. J. R. Meteorol. Soc.*, *139*(677), 2181–2189, doi:10.1002/qj.2085.

Hill, S. A., Y. Ming, and I. M. Held (2015), Mechanisms of forced tropical meridional energy flux change, *J. Clim.*, *28*(5), 1725–1742, doi:10.1175/JCLI-D-14-00165.1.

Hu, Y., D. Li, and J. Liu (2007), Abrupt seasonal variation of the ITCZ and the Hadley circulation, *Geophys. Res. Lett.*, *34*(18), 1–5, doi:10.1029/2007GL030950.

Kang, S. M., I. M. Held, D. M. W. Frierson, and M. Zhao (2008), The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM, *J. Clim.*, *21*(14), 3521–3532, doi:10.1175/2007JCLI2146.1.

Konecky, B. L., J. M. Russell, T. C. Johnson, E. T. Brown, M. A. Berke, J. P. Werne, and Y. Huang (2011), Atmospheric circulation patterns during late Pleistocene climate changes at Lake Malawi, Africa, *Earth Planet. Sci. Lett.*, *312*(3–4), 318–326, doi:10.1016/j.epsl.2011.10.020.

Maroon, E. A., D. M. W. Frierson, S. M. Kang, and J. Scheff (2016), The precipitation response to an idealized subtropical continent, *J. Clim.*, *29*(12), 4543–4564, doi:10.1175/JCLI-D-15-0616.1.

Marshall, J., A. Donohoe, D. Ferreira, and D. McGee (2013), The ocean's role in setting the mean position of the Inter-Tropical Convergence Zone, *Clim. Dyn.*, *42*(7–8), 1967–1979, doi:10.1007/s00382-013-1767-z.

McGee, D., A. Donohoe, J. Marshall, and D. Ferreira (2014), Changes in ITCZ location and cross-equatorial heat transport at the Last Glacial Maximum, Heinrich Stadial 1, and the mid-Holocene, *Earth Planet. Sci. Lett.*, *390*, 69–79, doi:10.1016/j.epsl.2013.12.043.

Roberts, W. H. G., and P. J. Valdes (2017), Green mountains and white plains: The effect of northern hemisphere ice sheets on the global energy budget, *J. Clim.*, *30*(10), 3887–3905, doi:10.1175/JCLI-D-15-0846.1.

Russell, J. M., H. Vogel, B. L. Konecky, S. Bijaksana, Y. Huang, M. Melles, N. Wattrus, K. Costa, and J. W. King (2014), Glacial forcing of central Indonesian hydroclimate since 60,000 y B.P., *PNAS*, *111*(14), 5100–5105, doi:10.1073/pnas.1402373111.

Schneider, T., T. Bischoff, and G. H. Haug (2014), Migrations and dynamics of the intertropical convergence zone, *Nature*, *513*(7516), 45–53, doi:10.1038/nature13636.

Shaw, T. A., A. Voigt, S. M. Kang, and J. Seo (2015), Response of the intertropical convergence zone to zonally asymmetric subtropical surface forcings, *Geophys. Res. Lett.*, *42*(22), 9961–9969, doi:10.1002/2015GL066027.

Singarayer, J. S., and P. J. Valdes (2010), High-latitude climate sensitivity to ice-sheet forcing over the last 120 kyr, *Quat. Sci. Rev.*, *29*(1–2), 43–55, doi:10.1016/j.quascirev.2009.10.011.

Stouffer, R. J., et al. (2006), Investigating the causes of the response of the thermohaline circulation to past and future climate changes, *J. Clim.*, *19*(8), 1365–1387, doi:10.1175/JCLI3689.1.

Valdes, P. J., et al. (2017), The bridge hadcm3 family of climate models: HadCM3@bristol v1.0, *Geosci. Model Dev. Discuss.*, *2017*, 1–42, doi:10.5194/gmd-2017-16.

Wang, X., A. S. Auler, R. L. Edwards, H. Cheng, E. Ito, and M. Solheid (2006), Interhemispheric anti-phasing of rainfall during the last glacial period, *Quat. Sci. Rev.*, *25*(23–24), 3391–3403, doi:10.1016/j.quascirev.2006.02.009.

Yoshimori, M., and A. J. Broccoli (2008), Equilibrium response of an atmosphere-mixed layer ocean model to different radiative forcing agents: Global and zonal mean response, *J. Clim.*, *21*(17), 4399–4423, doi:10.1175/2008JCLI2172.1.