Global energy constraints on the ITCZ location and mid-latitude jet in paleo climate states

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1. Introduction

This is a proposal to build a rigorous understanding of the response of the mid-latitude jets and the Intertropical Convergence Zone (ITCZ) to changing forcings and boundary conditions. Changes in the position of the mid-latitude jets and the ITCZ play a key role in determining the hydrological impact of climate change at the regional scale. In addition, surface winds and buoyancy fluxes related to the jets have the potential to alter ocean circulation and the ocean carbon cycle, representing an important potential climate feedback that has been hypothesized to be involved in glacial terminations and millennial-scale climate variability.

Much effort has gone into reconstructing past changes in the position and intensity of the ITCZ and mid-latitude storm tracks using proxy data thought to reflect changes in hydrology or wind strength. These include records of vegetation, lake water balance, precipitation 18O and D, river sediment discharge, surface ocean 18O, and marine primary productivity. Together, these records have pointed to prominent changes in atmospheric circulation that have accompanied the climate changes of the last 25,000 years.

During the last glacial maximum (LGM), there is substantial proxy evidence that the Northern Hemisphere (NH) mid-latitude storm tracks were displaced south, including large expansions of closed-basin lakes in the U.S. Great Basin (Antevs, 1952; Oviatt et al., 1992; Benson et al., 1990). In the Southern Hemisphere, several proxy studies have been interpreted as indicating an equatorward shift or intensification of the mid-latitude storm track at the LGM (see recent review by Kohfeld et al., 2013). Models consistently find a similar response in the NH and point to the topographic effect of the Laurentide and other ice sheets as the dominant contributor to the southward shift of the storm track (COHMAP, 1988). In the SH, however, models do not agree as to changes in the position or intensity of the storm track under LGM boundary conditions (Rojas et al., 2009), and Sime et al. (2013) have demonstrated that precipitation proxy records can be matched without an equatorward shift of the westerlies.

During the deglaciation and Holocene, when changes in the Atlantic Meridional Overturning Circulation (AMOC) and the seasonal distribution of insolation are thought to have changed interhemispheric temperature gradients, proxy records provide widespread evidence for changes in tropical precipitation and winds interpreted as representing shifts of the Intertropical Convergence Zone (ITCZ) toward the warmer hemisphere (Fig. 1) (e.g., CITES). A growing number of proxy data have pointed to synchronous changes in the position and/or intensity of mid-latitude storm tracks in both hemispheres, with most attention focused on Heinrich Events, periods of reduced AMOC and especially negative (colder NH) interhemispheric temperature gradients when the ITCZ appears to be displaced south. In the NH, dust records in the Japan Sea (Nagashima et al., 2007) and cave and lake records in the western U.S. (Asmerom et al., 2010; McGee et al., 2012; Wagner et al., 2010) point to southward shifts of mid-latitude storm tracks during Heinrich Events. In the SH, records of primary productivity thought to reflect wind-driven upwelling (Anderson et al., 2009), as well as proxy data thought to reflect the position of the subtropical front (de Deckker et al., 2012; Putnam et al., 2010), have similarly been interpreted to indicate southward shifts of the SH westerly storm track during Heinrich Events (Fig. 1).

The synchronous meridional shifts of the ITCZ and storm tracks during Heinrich Events implied by paleo-records suggest a mechanistic relationship between low- and mid-latitude circulations. Such a relationship is important to understand, both in terms of understanding the sensitivity of mid-latitude precipitation patterns to changes in the interhemispheric temperature gradient and in light of hypotheses linking shifts in westerly storm tracks to changes in ocean circulation and the partitioning of carbon between the ocean and the atmosphere (Anderson et al., 2009; Denton et al., 2010; Eisenman et al., 2009; Toggweiler et al., 2006). Importantly, models do not consistently reproduce the ITCZ-storm track relationships inferred from paleo-data; for instance, a simulation involving cooling of the high-latitude North Atlantic using CCM3 and a simplified ocean model finds links between ITCZ and storm track shifts (Lee et al., 2011), while the recently completed transient simulation of the last 22,000 years by the fully coupled CCSM3 (TraCE) does not show significant changes in either hemisphere's storm track during prominent ITCZ shifts associated with Heinrich Event 1 and the Younger Dryas (Fig. 2) (He CITE).

Are the shifts in atmospheric circulation that are inferred from proxy data physically realistic, or are proxy data being misinterpreted? Why do state-of-the-art models disagree as to the response of mid-latitude storm tracks to past climate changes? This proposal seeks to address these questions through a rigorous examination of the fundamental drivers of changes in the globally averaged positions of ITCZ and storm tracks. Our proposed work builds on recent work that has used hemispheric energy budgets to offer important scaling relationships governing the magnitude of present and past ITCZ shifts (Donohoe et al. 2013c; Marshall et al. 2013; McGee et al. 2013). Moving further, we seek to apply this framework to the relationship between ITCZ shifts, storm track changes and global energy budgets, with a focus on the LGM, Heinrich Event 1, and the Mid-Holocene. In so doing, we aim to provide a set of constraints on past storm track changes that will serve as a useful framework for interpreting paleoclimate data, offering an important complement to the substantial efforts being put into developing new records and conducting new model simulations of past atmospheric circulation.

2. Past work

The Authors have developed a theoretical framework that relates the location of the intertropical convergence zone (ITCZ) to the hemispheric contrast of energy input into the atmosphere at all latitudes. More specifically, the Authors have demonstrated that a 3° northward ITCZ shift requires an anomalous 1 PW of energy to enter the Northern Hemisphere (NH) atmosphere, resulting in southward atmospheric heat transport across the equator (AHT_{EQ}). This relationship was found to apply to the annual mean climatology (Marshall et al. 2013; Frierson et al. 2013), the seasonal cycle (Donohoe et al. 2013c,a), the inter-annual variability (Donohoe et al. 2013b), and the changes in paleoclimate states (McGee et al. 2013; Donohoe et al. 2013c). Conceptually, the relationship between the ITCZ location and AHT_{EQ} is a consequence of the mutual dependence of the ITCZ location and AHT_{EQ} on the Hadley cell location as follows: 1. the ITCZ is co-located with the ascending branch of the Hadley Cell and 2. the atmospheric energy transport in the deep tropics is dominated by the mean overturning circulation (MOC), is in the sense of motion in the upper branch of the Hadley cell and, thus, is away from the ITCZ (Figure 3A). In the annual mean, the ITCZ is north of the equator, resulting in southward AHT_{EQ} that is energetically balanced by energy import into the NH by the large scale ocean circulation in the Atlantic Meridional Overturning Circulation (AMOC–Marshall et al. 2013; Frierson et al. 2013). Shifting the ITCZ farther northward would result in more energy export from NH and thus demands a source of atmospheric heating in the NH either by enhanced northward ocean heat transport or radiative input at the top of atmosphere (TOA).

We previously found that, in both observations and an ensemble of coupled climate models, seasonal variations in ITCZ location and AHT_{EQ} are highly correlated with a 3° northward ITCZ shift corresponding to a 1 PW of southward AHT_{EQ} (Donohoe et al. 2013c, see Figure 3B). On the seasonal timescale, changes in AHT_{EQ} are of order 2 PW and is a consequence of the hemispheric asymmetry of insolation. We also found that the inter-annual variability of ITCZ location and AHT_{EQ} over the satellite era are highly correlated (Figure 3C) with a statistically identical relationship to that found over the seasonal cycle (Donohoe et al. 2013b). Lastly, we demonstrated that the same quantitative relationship between ITCZ location and AHT_{EQ} applied to the annual mean change due to external climate forcing independent of whether the forcing was anthropogenic or a result of paleoclimate boundary conditions (see Figure 3D here, Donohoe et al. 2013c); in these models, the simulated AHT_{EQ} change is a much better predictor of the ITCZ shift than is the external forcing.

The relationship between ITCZ location and AHT_{EQ} has been demonstrated to be robust across observations, idealized models and coupled climate models and is consistent (quantitatively) across a myriad of timescales. Placing this theory within the context of paleoclimate proxy records will provide additional insights into both the relevant dynamics and the interpretation of past climate states. We have made an initial effort to compare the ITCZ shifts noted in the PMIP2 simulations of the mid-Holocene and LGM with those deduced from the paleoclimate records of tropical SSTs. This work made use of the statistical relationships between the inter-hemispheric SST gradient in the tropics, the ITCZ location, and AHT_{EQ} (Donohoe et al. 2013c) and paleothermometry of marine sediment cores (Shakun et al. 2012; McGee et al. 2013). Estimates of the change in ITCZ location and AHT_{EQ} during the mid-Holocene and LGM are indicated by the filled circles (dashed lines are error bars) in Figure 3D and compare very well with the PMIP2 ensemble mean changes (solid boxes). This work demonstrates that energy flux theoretical framework for ITCZ shifts provides constraints on ITCZ shifts and the global scale energy budget that can be placed in the context of paleoclimate proxy records.

3. Conceptual framework; the relationship between energy fluxes and paleoclimate proxies

The atmospheric energy budget demands that energy be transported from regions of atmospheric heating to regions of atmospheric cooling. On the equator-to-pole scale, the atmosphere transports energy out of the tropics where there is a surplus of insolation at the top of the atmosphere (TOA) toward the poles where the emitted radiation at the TOA (OLR) exceeds the insolation (North 1975). On the inter-hemispheric scale, the atmosphere moves energy away from the hemisphere in which the atmosphere is heated more strongly (Frierson et al. 2013; Marshall et al. 2013). The spatial pattern of atmospheric heating is, in turn, a consequence of radiative forcing at the TOA (i.e. Milankovitch and atmospheric composition) and the surface energy fluxes that result from oceanic energy transport. Thus, one can quantitatively predict the change in atmospheric energy transports given estimates of forcing and feedbacks at the TOA and changes in oceanic circulation (i.e. the AMOC).

The atmospheric energy transport is a smooth function of latitude because the net heating of the atmosphere is a continuous function of latitude (Stone 1978). However the component circulations that lead to the seamless transport of energy in the atmosphere differ by latitude: the atmospheric energy flux is dominated by the mean overturning circulation of the atmosphere in the tropics (i.e. the Hadley cell Held 2001) whereas storms (transient eddies) dominate the energy transport in the mid-latitudes (Czaja and Marshall 2006). As a result, atmospheric energy fluxes and their changes under paleoclimatic forcing can be related to observable climate variables in the both the tropics and mid-latitudes. In the tropics, the atmospheric energy transport at the equator is proportional the magnitude of the mass overturning streamfunction at the equator, which itself is a consequence of the displacement of the rising branch of the Hadley circulation off the equator (Donohoe et al. 2013c). The latter dictates the region of intense tropical precipitation (the intertropical convergence zone – ITCZ). Thus, estimates of previous ITCZ shifts imply concurrent changes in AHT_{EQ} and, thus, the hemispheric asymmetry of atmospheric heating that can be quantified as in McGee et al. (2013). In the mid-latitudes, the surface westerlies are driven by the low level eddy heat fluxes (Edmon et al. 1980) which achieve a maximum where the eddies are most vigorous. Thus, the surface westerly maximum is co-located with the eddy energy flux maximum. Therefore, paleo-proxy estimates of the shift in storm tracks (i.e. mid-latitude precipitation or wind variance) and/or the position of the surface wind stress maximum imply concurrent changes in the mid-latitude atmospheric energy fluxes which are quantifiable.

In recap, changes in the net heating of the atmosphere induced by either orbital forcing at the TOA or changes in the global scale oceanic circulation demand changes in the atmospheric energy fluxes that are smooth in latitude; changes in the atmospheric energy transport in the Tropics are concurrent with changes in the atmospheric energy transport at mid-latitudes. Proxy evidence allows for estimation of changes in the atmospheric energy transport in 1) the deep tropics by way of ITCZ shifts and 2) in the mid-latitudes by way of shifts in the storm tracks or surface wind stress. This conceptual framework allows one to quantitatively link changes seen in the tropics with those seen in the extratropics by way of the common metric of atmospheric energy fluxes and how the energy fluxes project onto the surface observables of ITCZ and storm track/surface westerly shifts. The combined estimates of atmospheric energy flux changes in the mid-latitudes of both hemispheres and at the equator also provide quantitative constraints on the changes in atmospheric energy heating and, thus, an estimate of regional changes in TOA radiation and/or oceanic circulation changes. These estimates of atmospheric heating changes can then be compared to the representation of climate forcing and feedbacks and ocean circulation changes in model simulations of paleoclimate states to see if the proxy data is consistent with the physical processes in the models.

The perspective taken here is inherently global in scope and will rely on a synthesis of proxy data to understand the global response of the atmospheric circulation to past forcing (orbital and atmospheric composition) and boundary conditions. The dynamical framework also requires further validation in the context of both idealized and complex climate models. Our research group has firmly established the connection between ITCZ location, atmospheric energy transport at the equator and the hemispheric contrast of energy input into the atmosphere. However, more work needs to be done on the connection between mid-latitude atmospheric energy fluxes and the location of the surface westerlies; while the initial foundations of this concept have been demonstrated in idealized climate models (Donohoe et al. 2013a) further work needs to be done to include stationary eddies in the theory.

This section is organized as follows. In subsection a we introduce the framework for relating ITCZ shifts to the hemispheric asymmetry of energy input into the atmosphere and the relevant physical mechanisms on paleoclimate timescales. In subsection b we describe the theoretical framework that connects the mid-latitude jet location with atmospheric energy fluxes and discuss the mechanisms that can lead to jet shifts within this framework. We then discuss the insights that can gained from applying the energy flux framework (of ITCZ location and mid-latitude jets) to the interpretation/synthesis of paleoclimate proxy records (subsection c).

a. Atmospheric energy transport at the equator and ITCZ location

1. The relationship between AHT$_{EQ}$ and ITCZ location

The ITCZ locations and the atmospheric energy transport in the deep tropics are both a consequence of the mean overturning circulation of the Hadley cell; the precipitation occurs in the upwelling branch of the Hadley circulation and the atmospheric heat transport is in the sense and proportional to the magnitude of the mass flux in the upper branch of the cell. As a result, a northward shift in the ITCZ requires energy export from the NH (southward AHT$_{EQ}$). The latter demands the NH atmosphere be heated by either a hemispheric asymmetry of surface heat fluxes – by way of the ocean energy transport across the equator – or radiation at the TOA (Figure 5A). We emphasize that this framework suggests that the ITCZ responds to the hemispheric contrast of atmospheric heating at all latitudes and, thus, connects the ITCZ location to hemispheric scale energy fluxes including extratropical processes. This energetic framework for ITCZ shifts has been used in the literature to explain the ITCZ response to external forcing in idealized simulations (Yoshimori and Broccoli 2008, 2009; Kang et al. 2008), anthropogenic forcing (Frierson and Hwang 2012), and freshwater forcing (Chiang and Bitz 2005).

More recently, Donohoe et al. (2013c) argued that a 3° ITCZ shift requires 1 PW of AHT$_{EQ}$ and that this relationship holds across timescale and climate state. They argued that the annual mean ITCZ location is the small residual of large seasonal migrations of the ITCZ resulting from an insolation driven hemispheric contrast of atmospheric heating of order 2 PW. Because the seasonal variations in AHT$_{EQ}$ are substantially larger than those implied by external forcing scenarios, the quantitative relationship between ITCZ location and AHT$_{EQ}$ over the seasonal cycle encapsulates the response to external forcing. Furthermore, the seasonal relationship between ITCZ location and AHT$_{EQ}$ was found to be consistent between climate models and observational estimates alike suggesting that the physics underlying this relationship (i.e. the strength and extent of the Hadley cell and the atmospheric static stability) are robust and well understood. Additionally, the 3° latitude ITCZ per PW AHT_{EQ} relationship was demonstrated to apply to inter-annual variability (Donohoe et al. 2013b), the inter-model spread of the climatology (Hwang and Frierson 2013), and the annual mean shift due to external forcing (Donohoe et al. 2013c; Frierson and Hwang 2012). These results collectively demonstrate that the relationship between ITCZ location and AHT_{EQ} is robust and quantitatively consistent across a multitude of timescales in both models and observations and is a consequence of the mutual dependence on the Hadley cell location.

2. The cause of variability in $\mathbf{AHT}_{EQ}$

The quantitative relationship between ITCZ location and AHT_{EQ} is timescale independent and demands that an ITCZ shift be accompanied by a hemispheric asymmetry of atmospheric heating. The source of the latter varies with timescale, with ocean circulation playing a vital role at longer timescales, and radiative processes in the atmosphere dominating the variability at shorter timescales. Stated simply, at short timescales, variations in the large scale ocean energy transport are stored locally in the oceanic column and never enter the atmosphere. In contrast, on long timescales, ocean heat storage become negligible and the anomalous ocean energy transport is fluxed upward to the atmosphere. Specifically, the inter-annual and decadal variations of the energy transport in the ocean's Atlantic Meridional Overturning Circulation (AMOC) are comparable to those in AHT_{EQ} but the former does not influence the latter because the vast majority (95%) of the ocean energy transport is stored in the subsurface ocean (Donohoe et al. 2013b). In contrast, in the annual mean climatology– akin to the infinite timescale– surface energy balance requires that the OHT_{EQ} be balanced by a hemispheric contrast in surface heat fluxes to the atmosphere (green arrows Figure 5A) and this is the dominant contribution to the hemispheric contrast in atmospheric heating (Marshall et al. 2013; Frierson et al. 2013); the large scale ocean heat transport in the AMOC fundamentally sets the mean position of the ITCZ in the NH, and so changes in the mean ITCZ position should be linearly related to changes in AMOC strength.

What processes drive changes in AHT_{EQ} and, therefore, ITCZ location over the paleoclimate record? The hemispheric contrast in radiative forcing associated with Milankovitch cycles and the Laurentide ice sheet is comparable in magnitude to that associated with fluctuations in the ocean's AMOC (Braconnot et al. 2007; Donohoe et al. 2013c). Preliminary results in the TraCE experiment suggest that the albedo of the Laurentide ice sheet removed 0.4 PW of energy fro NH whereas the expansion of sea ice during Heinrich Stadial 1 (HS1) removed 0.2 PW from the NH and the OHT_{EQ} associated with the AMOC varied by 0.4 PW between HS1 and the Bolling Allerod (orange line Figure 2).

The quantitative relationship between ITCZ location and AHT_{EQ} allows one to assess how individual climate forcings and feedbacks would have impacted the ITCZ location under various limited assumptions. For example, the 0.4 PW of radiation reflected at the TOA of the NH by the Laurentide ice sheet would lead to a 1.2° southward ITCZ shift in the absence of cloud and Planck feedbacks (likely an upper bound). Similarly, a complete shutdown of the AMOC (of order 0.6 PW) would lead to a 1.8° southward ITCZ shift in the absence of ice albedo, cloud and Planck feedbacks. Thus, the energy flux framework allows proxy estimates of ITCZ shifts, climate forcing mechanisms and the representation of forcing and feedbacks in global climate models to be reconciled within a simple, quantitative framework.

b. Mid-latitude atmospheric energy transport and the position of surface westerlies/storm tracks

We previously demonstrated the relationship between the atmospheric energy transport at the equator and the ITCZ location based on the mutual dependence on the Hadley cell location. We now describe a emerging theory on the relationship between the mid-latitude atmospheric energy fluxes and the jet position. In the mid-latitudes, three classes of atmospheric circulations contribute to the poleward energy transport: 1. the mean overturning circulation of the Ferrel cell is in the opposite sense of the Hadley cell and, therefore, transport energy equatorward, 2. transient eddies (i.e. storms) do the lionshare of the poleward energy transport moving heat and moisture poleward, primarily in the lower atmosphere and 3. stationary eddies (i.e. meanders in the jet stream) transport warm air poleward and cold air equatorward in the upper atmosphere resulting in a net poleward energy transport. We argue that the surface westerlies and storm track are co-located with the transient eddy energy flux maximum. The total energy transport in the climate system is primarily controlled by the Earth-Sun geometry (Stone 1978; Czaja and Marshall 2006) and is nearly climate state invariant. Therefore, the transient eddy energy flux can shift meridionally if the stationary eddies amplify or the mean overturning circulation shifts (i.e. an ITCZ shift). This energy flux theory of the mid-latitude jet provides constraints to past shifts in the mid-latitude jet similar to those provided on ITCZ migrations in the previous subsection. Here, we begin with a discussion of the theoretical underpinnings and evidence for the relationship between jet location and transient eddy energy fluxes. We then discuss candidate mechanisms for jet shifts in paleoclimate states and preliminary evidence for their realization in the TRACE simulation.

1. The relationship between mid-latitude energy fluxes and surface westerlies

The acceleration of the surface westerlies in the atmosphere is approximately equal to the eddy energy flux in the lower atmosphere by way of Eliassen-Palm flux theory (Edmon et al. 1980). Stationary eddies in the atmosphere transport energy primarily around the tropopause level wheres the transient eddy energy transport is primarily in the mid and lower troposphere and maximizes just above the surface (below 850 hPa Trenberth and Smith 2010). Therefore, the surface westerlies will be located where storms are strongest, i.e. at the vertically integrated transient eddy energy flux maximum. This approximate relationship is realized over the observed seasonal cycle in both hemispheres (Figure 6A) and in idealized climate models where large modifications of planetary albedo induce simultaneous jet and transient eddy energy fluxes of greater than 15° latitude (Donohoe et al. 2013a). The inter-model spread of the location of the SH surface westerlies in an ensemble of pre-industrial simulations is also well correlated with shortwave cloud forcing biases in the Southern Ocean (Ceppi et al. 2012a). The latter result in a large inter-model differences in total meridional energy transport demanded by the TOA radiation budget (Donohoe and Battisti 2012) which is accomplished by shifting the magnitude and location of the transient eddy energy flux. Thus, there is widespread evidence for the co-location of transient eddy energy fluxes and surface westerlies across observations, idealized models and coupled climate models.

2. The cause of changes in the mid-latitude eddy energy flux

Given the relationship between transient eddy energy fluxes and surface westerlies highlighted above, we now discuss possible mechanisms for shifting the location of the transient eddy energy flux maximum in the context of paleoclimate states. The maximum poleward energy transport in the climate system is equal to the TOA net radiative deficit over the extratropics and occurs at the latitude where the net shortwave radiation at the TOA equals the OLR. Although both the magnitude and location of the maximum total poleward energy transport can differ with climate state due to planetary albedo albedo differences (Donohoe and Battisti 2012; Donohoe et al. 2013a), the changes in total energy transport are very small (Czaja and Marshall 2006; Ferreira et al. 2011) even in simulations of the glacial climate state (Li and Battisti 2008; Donohoe and Battisti 2009); the total poleward energy transport in the climate system is primarily a consequence of the Earth-Sun geometry and is nearly climate state invariant. As a consequence, the total poleward energy transport always maximizes around 40° in each hemisphere (Stone 1978).

The near invariance of the total poleward energy transport into the extratropics requires that any shift or intensification in the transient eddy energy flux be accompanied by changes in either A.) the mid-latitude ocean energy transport, B.) the stationary eddy energy transport in the atmosphere C.) or the strength and/or location of the Ferrel cell. A schematic of the relevant energy fluxes between the tropics and extratropics – defined as the regions equatorward and poleward of the poleward energy flux maximum – is shown in Figure 5B. The ocean energy transport into the extratropics is less than 0.1 PW in each hemisphere (Trenberth and Caron 2001) and thus makes a negligible contribution to the total energy transport which is of order 6.0 PW. Therefore, we pursue two leading hypotheses on how the location of maximum transient eddy energy flux, and therefore the surface westerlies, can vary over paleoclimate states: 1.) the amplification of stationary waves, which peak poleward of the surface westerlies, causes a equatorward shift in the transient eddy energy transport maximum and 2.) a meridional shift of the mean overturning cells in the atmosphere (i.e. Hadley and Ferrel cells and ITCZ) leads to a jet shift in the same direction as the ITCZ shift.

The atmospheric stationary wave amplitude in the NH was most likely enhanced during the glacial when large ice sheets occupied the NH (Peltier 2004). The meridional energy transport associated with the stationary waves and the constraint that total energy transport is nearly unchanged due to the TOA radiation budget requires that the transient eddy energy flux decreases in magnitude and shifts equatorward at the LGM (Li and Battisti 2008). This expectation is realized in the TraCE simulation when comparing the partitioning of total energy transport for the LGM (20-21 ka before present–solid lines in Figure 6C) with that for the modern (1-0 ka before present – dashed lines in Figure 6C) in the NH; the total meridional energy transport in the atmosphere is nearly unchanged (black lines) whereas the stationary eddy energy transport is amplified in the LGM (bluie lines) and achieves a maximum poleward of the heat transport maximum. As a result, the transient eddy energy flux is reduced in magnitude and shifted equatorward in the LGM (c.f. the solid red and dashed red lines in the NH in Figure 6C). The surface westerlies are co-located with the eddy energy flux maximum (the red and black lines peak at the same latitude in Figure 6B) in both hemispheres in both the LGM and modern states. As a result, the LGM surface westerlies follow the equatorward shifted eddy energy flux maximum in the LGM which results in a 3° equatorward jet shift (c.f. the vertical red line for the modern jet location with the vertical blue line for the LGM jet in Figure 6B). We note that the westerlies in the SH do not migrate between the LGM and modern simulation (Figure 6B) because the total heat transport is nearly unchanged, stationary eddies are negligible in the SH and, thus, the transient eddy energy flux is unchanged (Figure 6C).

An alternative mechanism for shifting the location of the transient eddy energy flux is to change the Ferrel cell energy transport into the extratropics by meridionally shifting the Ferrel cell. The former can be accomplished by shifting the Hadley cell, the associated subtropical jet, and thus the waveguide for eddy momentum fluxes (Thorncroft et al. 1995). This mechanism would result in the concurrent shift of the Hadley and Ferrel cells, ITCZ and surface westerlies. In this scenario, the surface westerlies shift less than the cells because the jet follows the transient eddy energy flux which is the residual of the total energy transport and Ferrel cell energy transport. Recently, Ceppi et al. (2012b) invoked a similar mechanism to explain the teleconnections between anomalous atmospheric heating in the NH and jet shifts in the SH. The connection between ITCZ shifts and the location of the mid-latitude jet has also been invoked to explain shifts in the SH wind stress during the last deglaciation (Anderson et al. 2009; Toggweiler and Lea 2010; Denton et al. 2010). We note that, in the TRACE simulations, the shift in surface westerlies does not mirror the ITCZ shift (Figure 2) which suggests that ITCZ and jet shifts are not 1:1, as is expected from the energy flux framework, and that other processes (i.e. changes in the stationary eddies in the NH) also influence the mid-latitude westerlies. The energy flux framework for jet shifts could provide a quantitative scaling for the expected relationship between a given ITCZ shift and the shift in the SH surface westerlies; this framework casts changes in the tropical and extratropical circulation into the common metric of atmospheric energy fluxes.

c. Key questions addressable with paleoclimate proxies

Paleoclimate data provide broad constraints on the response of the ITCZ and storm tracks to changes in energy budgets over the last 25,000 years. Key time slices in this interval include: 1) The LGM, a time of enhanced albedo, steeper meridional temperature gradients and reduced surface temperatures in both hemispheres when paleodata suggest an equatorward movement or intensification of both hemispheres' storm tracks (Kohfeld et al., 2013; XXXX) with little change in ITCZ mean position (McGee et al., submitted);

2) Heinrich Stadial 1, a time of reduction or cessation of northward heat transport by AMOC, when several paleodata studies have suggested correlated shifts in ITCZ position and the position of mid-latitude storm tracks toward the south (Fig. 1); and

3) The mid-Holocene, a period of maximum NH summer insolation when the mean position of the ITCZ appears to have shifted northward (CITE), but there is no broad consensus on the position of storm tracks at this time (CITES).

These time slices provide insights into the impact of changes in albedo, meridional temperature gradients, AMOC and orbital changes on the positions of the ITCZ and storm tracks. The changes inferred from paleodata also raise important questions: How far can storm tracks and the ITCZ plausibly move in response to these forcings? Should we expect consistent relationships between storm track location and global temperature? Should we expect mean ITCZ shifts to be linked to storm track shifts? Efforts that incorporate data, model results and theory are required to make progress in answering these questions. Though paleodata are insufficient to provide precise constraints on the magnitude or zonal heterogeneity of a shift, they provide an important opportunity for consistency checks that can demonstrate certain changes to be less likely (Braconnot et al., 2007; Dinezio and Tierney, 2013; Kohfeld et al., 2013). In turn, models can provide insights into paleodata interpretation; for example, a recent data-model synthesis for the LGM SH storm track found that paleo-precipitation data interpreted as requiring an equatorward shift of the storm track could be matched even by models that did not move the storm track or moved it poleward (Sime et al., 2013). Incorporation of theory can then assist in making sense of inter-model differences. As an example, we have recently demonstrated that even though fully-coupled models produce divergent changes in ITCZ position in response to common forcings, these models demonstrate constant relationships between ITCZ position, cross-equatorial heat transport and tropical SST gradients (Donohoe et al., 2013). This consistent signal hidden within noisy model results is supported by theory (Donohoe et al., 2013; Marshall et al., 2013) and places important constraints on past changes in ITCZ position (McGee et al., submitted).

In this project, we will utilize paleodata from the three time slices above to test the spatial coherence of changes inferred from individual records. Recent syntheses have provided good coverage of the LGM and mid-Holocene (e.g., Farrera et al., 1999; Bartlein et al., 2011; Kohfeld et al., 2013), so our efforts will be concentrated on bringing together data that summarize the atmosphere's response during Heinrich Stadial 1 (HS1). Hydrological changes in parts of the tropics during HS1 have been summarized by Stager et al. (2011); we will add additional tropical sites as well as records reflecting mid-latitude precipitation and winds. Records from all three time slices will then be used to test the consistency of model simulations with observed changes in precipitation and ocean surface properties. These comparisons will identify models that appear to be best matching the data and will lead us to explore the dynamics involved in producing good data-model agreement in these models.

4. Broader Impacts

The preparation of a postdoctoral researcher for an independent career in teaching and research is a central goal of this project. This project will offer the researcher the opportunity to build expertise at the intersection of climate dynamics and paleoclimate. We hope to contribute to training a next generation of researchers whose facility with models, theory and proxy data helps to bridge historical divides between the climate dynamics community and the empirical paleoclimate community. Optional: Both McGee and Marshall are actively involved in outreach and teaching. Marshall's group is involved in informal science outreach through the MIT Museum and the Cambridge Science Festival, demonstrating principles of ocean and atmospheric circulation with the "Weather in a Tank" program that Marshall has spearheaded. This program has also been the basis of a textbook and curriculum development led by Marshall. McGee's group is becoming active in the "There's a Scientist in my Classroom!" outreach program that involves researchers in classroom visits and informal science outreach. McGee and Marshall also co-teach a course that merges climate dynamics, the carbon cycle and paleoclimate reconstructions into a unified introduction to Earth's climate system. Findings from this project will be incorporated into both classroom teaching and outreach by the PIs.

5. Relationship to P2C2 goals

This proposal focuses on building a fundamental understanding of the coupled response of the ITCZ and the mid-latitude jets to changing forcings and boundary conditions. It is thus closely tied to Area of Research Interest 1 of the P2C2 program, which is focused on determining "the regional response of coupled climate systems such as ENSO, the monsoons, NAM and the MOC during past climate changes." The P2C2 program description seeks contributions "to improve understanding [of] the large-scale hydrological variability of tropical and extra-tropical regions andto understand variability in ENSO, monsoons, Inter Tropical Convergence Zone (ITCZ) position" It also highlights a need for proposals that synthesize existing data to understand what forced hydrological variability observed in the geological record and determine how realistically the full range of climate variability can be simulated in current climate models.

By bringing model results, theory and proxy data to bear on linkages between low- and mid-latitude atmospheric circulation during past changes in the MOC, global temperature, and orbital configurations, this project is poised to make significant progress toward goals central to the P2C2 program.

6. Results of prior NSF support

a. D. McGee

OCE-1030784/1265343, 347,769 (9/1/10-8/31/13), Co-PIs: P.B. deMenocal, G. Winckler. Mapping Saharan dust fluxes through the onset and termination of the African Humid Period in a transect of African margin cores.

Intellectual Merit: This ongoing project builds on recent advances in determining fluxes of windblown dust to produce quantitative reconstructions of Saharan dust deposition in the north tropical Atlantic in a spatial array of cores. Our records from multiple cores provide improved estimates for the timing and magnitude of dust flux changes over the last 20 kyr, including an increased amplitude of dust flux changes associated with the beginning and end of the African Humid Period and a new, more precise estimate for the age of the end-AHP transition. The results highlight systematic relationships between African climate and meridional temperature gradients and provide a basis for estimates of the radiative impact of past dust emission changes.

Broader Impacts: This project has involved three undergraduate interns and two graduate students. Results have been included in informal outreach talks and have been featured in stories on national news websites (e.g. NBC News).

Publications: McGee et al. (2013; submitted); Donohoe et al. (2013); 4 additional in preparation. Data: All published data have been archived at the NOAA National Climate Data Center website.

b. J. Marshall

Intellectual Merit:

Broader Impacts:

Publications:

Data or other products:

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List of Figures

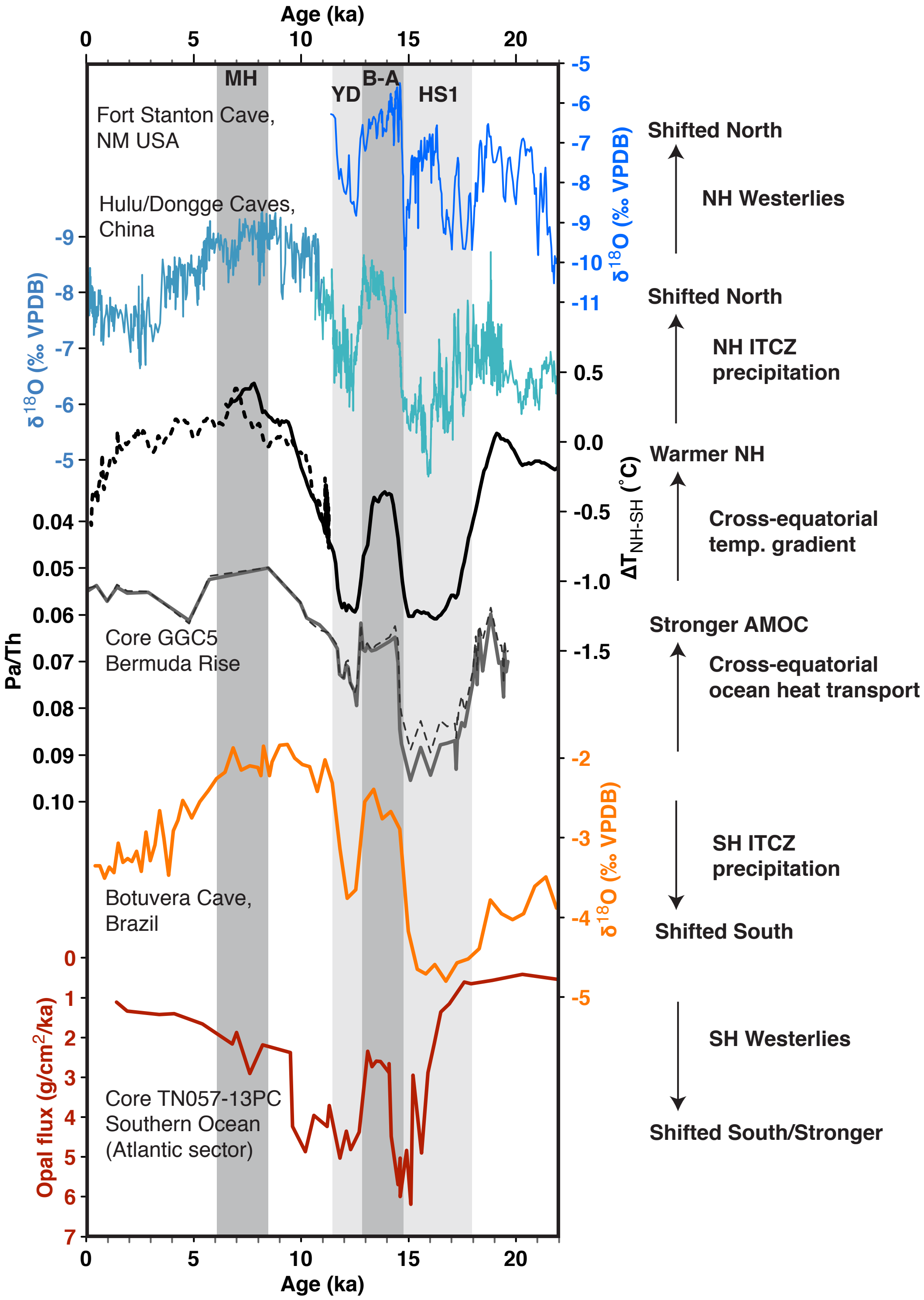

Figure 1: Proxy records of ITCZ and surface westerly position. XXXXXX.

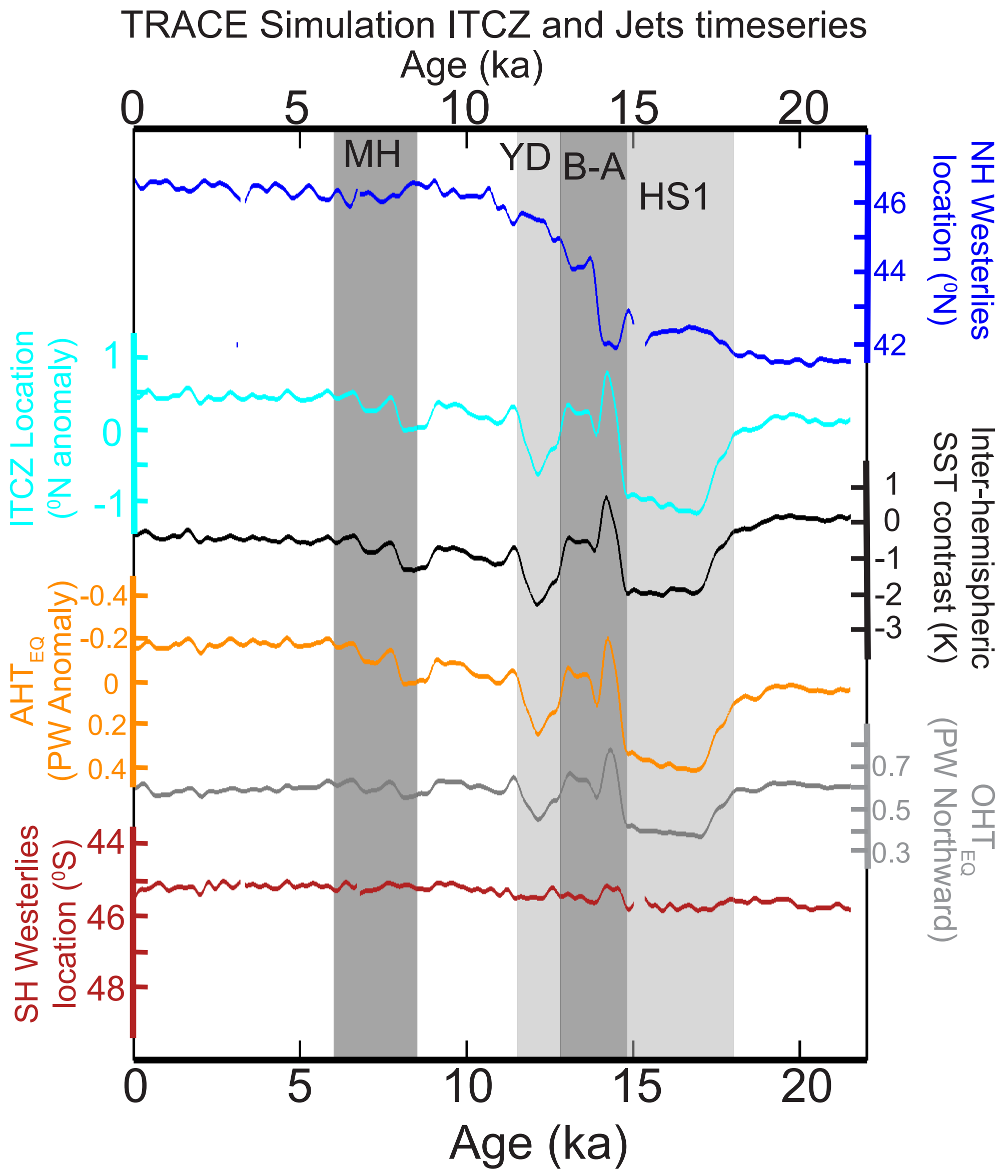

Figure 2: Time series of climate parameters over the 22,000 year transient paleoclimate simulation in the TraCE simulation. The blue and red lines are the location of the NH and SH surface westerlies respectively as defined by the zonal wind speed weighted latitude over the region of surface weterlies. The light blue line is the ITCZ location as measured by the median of precipitation equatorward of 20° (P_{CENT}. The black line is the hemispheric contrast in tropical SST defined as the average SST from 0 to 20N minus that from 0 to 20S. The orange is the atmospheric energy transport at the equator (AHT_{EQ}– positive Northward with an inverted y-axis). The gray line is the ocean heat transport at the equator, calculated from the spatially integrated surface energy flux (assuming no ocean storage). All values are low pass filtered using a cutoff period of 400 years.

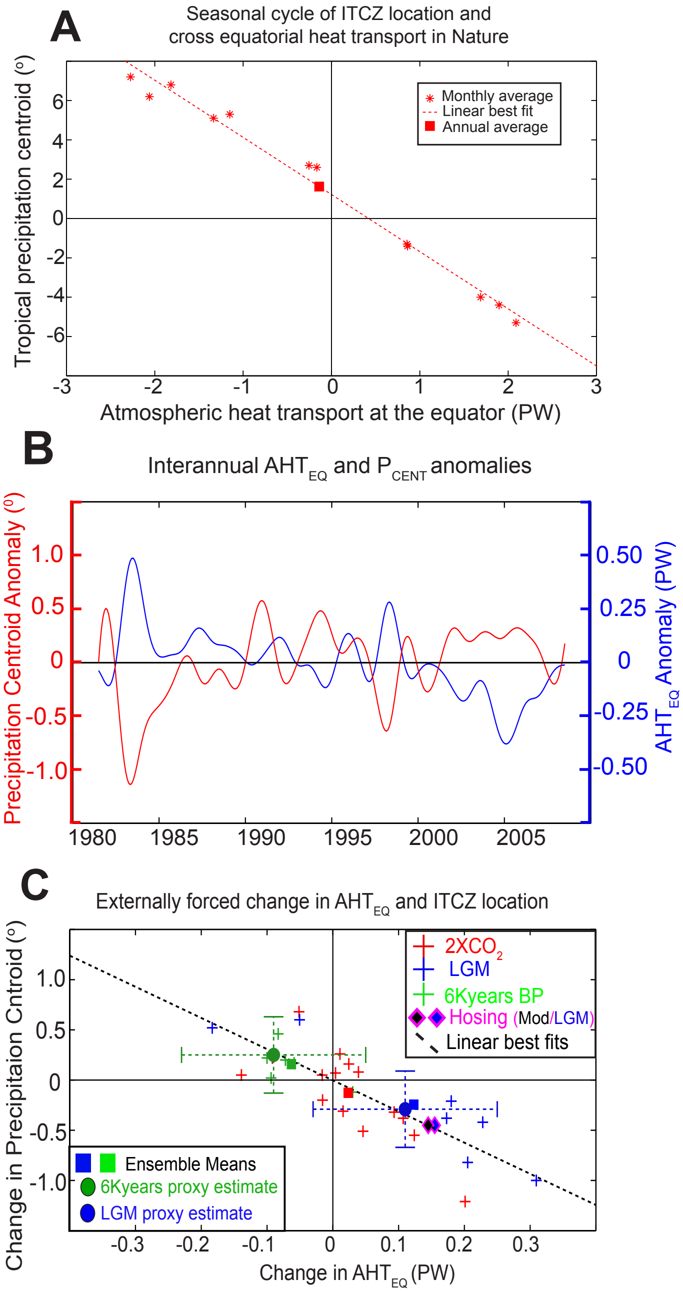

Figure 3: Previous work demonstrating the relationship ITCZ position and inter-hemispheric energy transport in the climate system across different timescales. (A) The correlation between ITCZ location as measured by precipitation centroid (P_{CENT}) – defined as the median of precipitation equatorward of 20°– and AHT_{EQ} over the observed seasonal cycle from Donohoe et al. (2013c). Each asterisk is a monthly mean. The dashed line is the linear best fit and the solid box is the annual mean. (B) The inter-annual variability of ITCZ location (P_{CENT} – red lines with axis to the left) and AHT_{EQ} (blue lines with axis to the right) over the satellite record (Donohoe et al. 2013b). The monthly mean values have been low pass filtered using with a 2 year cutoff period. (C) The change in annual mean ITCZ location and AHT_{EQ} in an ensemble of different perturbation experiments (Donohoe et al. 2013c; McGee et al. 2013). Each cross is a different climate model. Red crosses are CO_2 doubling experiments in the CMIP3 simulations, blue crosses are the LGM simulations in the PMIP2 simulations, green crosses are the mid-Holocene simulations in the PMIP2 experiment and diamonds are the freshwater housing experiments of Chiang and Bitz (2005). The circles and dashed lines are the estimates from proxy records (McGee et al. 2013) of the mid-Holocene and LGM.

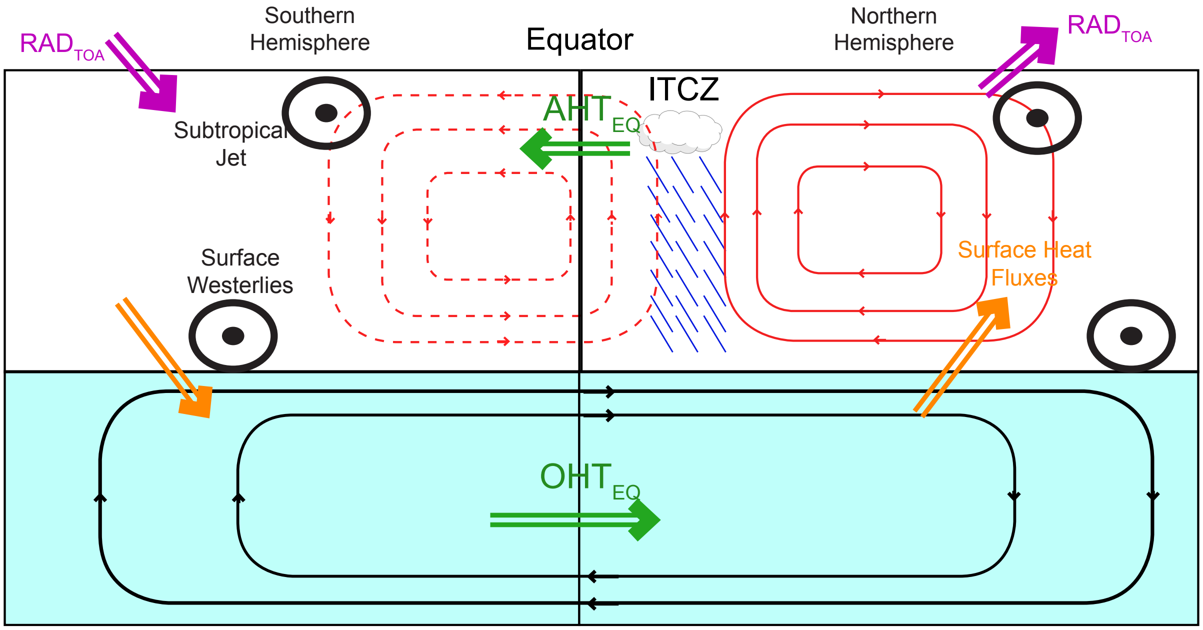

Figure 4: Schematic of the relationship between atmospheric energy transport, the location of the ITCZ and the jet location. The ITCZ location and atmospheric energy transport across the equator (AHT$_{EQ}$) have a mutual dependence on the Hadley cell location. The atmospheric energy transport across the equator is balanced by the hemispheric asymmetry of radiation at the TOA (RAD$_{TOA}$ and surface energy fluxes by way of ocean energy energy transport across the equator (OHT$_{EQ}$). The subtropical jet is located on the poleward flank of the upper branch of the Hadley cell and steers the surface westerlies by way of its influence on eddy momentum fluxes.

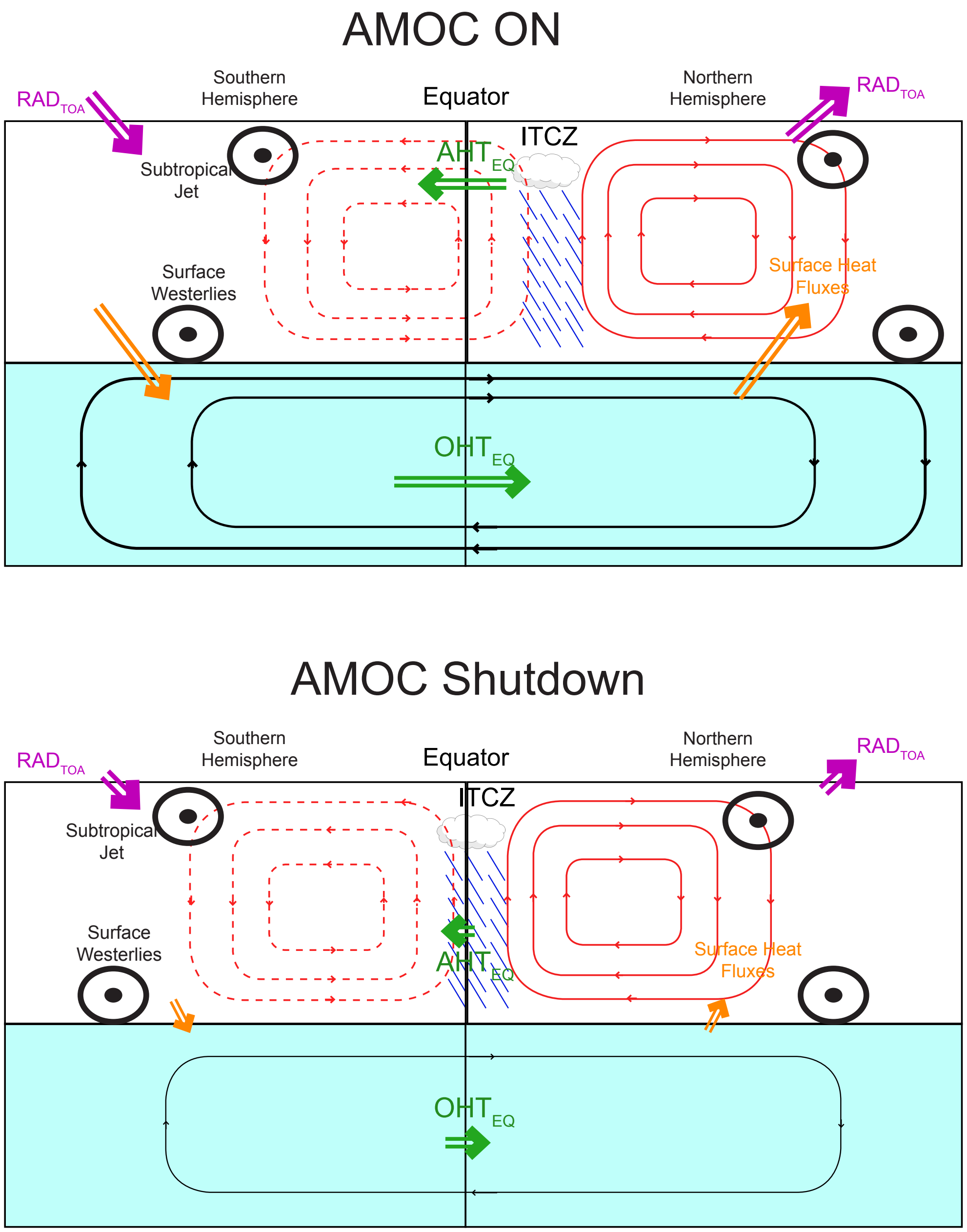

Figure 5: OPTIONAL REPLACEMENT: STRAW MAN ARGUEMNT FOR ROLE OF AMOC IN ITCZ AND JET SHIFTS.

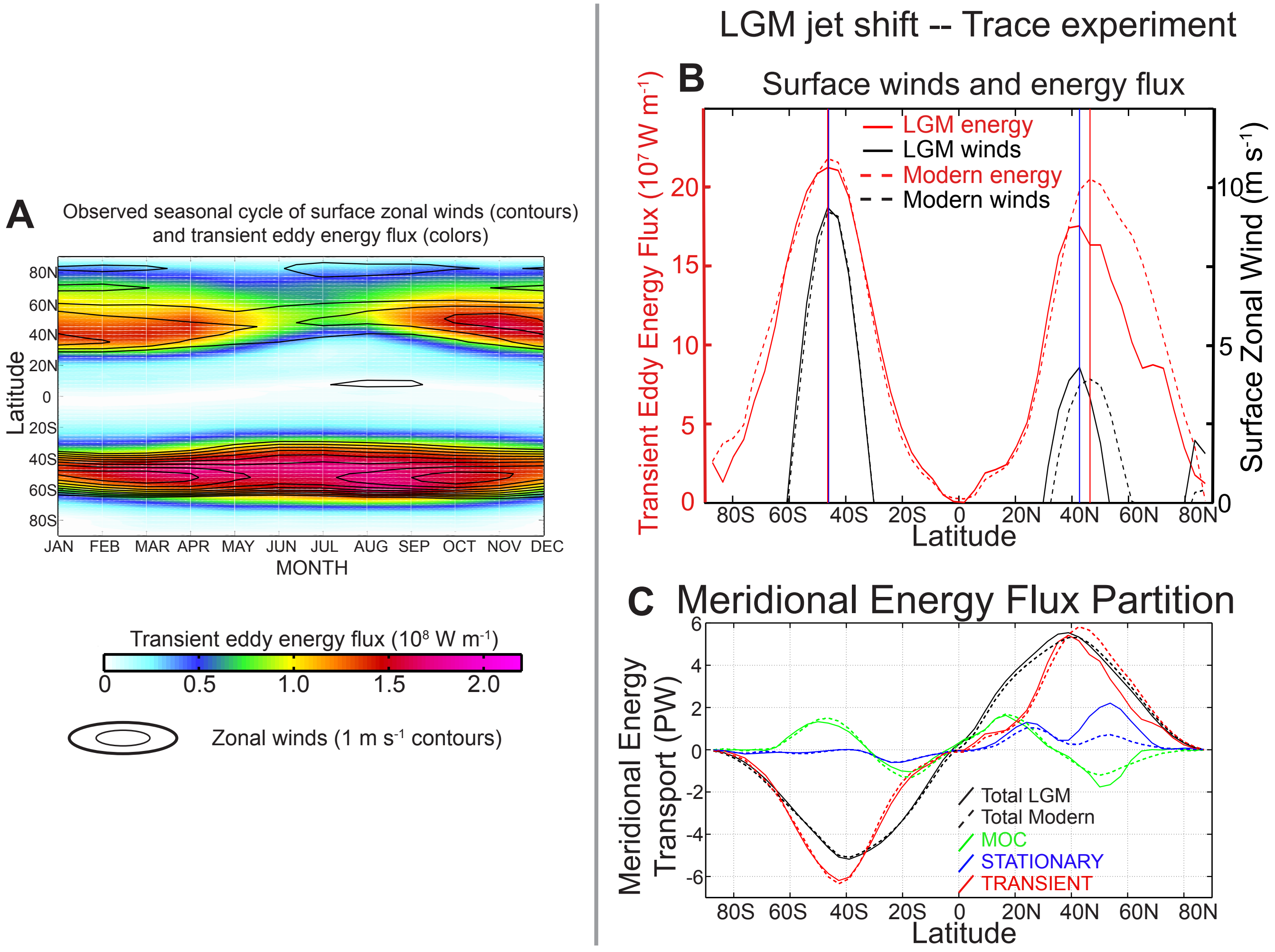

Figure 6: (A) The seasonal cycle of transient eddy energy flux (Colors) and zonal mean surface zonal winds (contours - interval 1 m s^{-1}) in Nature. Only the Westerly winds are shown. (B) The zonal mean transient eddy heat flux (red lines) and surface zonal winds (black lines) in the CCSM3 Trace simulation of the Last Glacial Maximum (solid lines) and modern climate system (dashed lines). The surface wind values are indicated on the left axis and the eddy energy flux values are indicated on the right axis. The vertical red lines shows the location of the wind maximum in each hemisphere for the modern climate simulation and the blue shows that in the LGM simulation. (C) The partitioning of the meridional energy transport in the atmosphere between the mean overturning circulation (green – MOC), stationary eddies (blue), transient eddies (red) and total energy transport (black). The solid lines are for the LGM simulation and the dashed lines are for the modern climate simulation.