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The Interhemispheric Pattern and Long-Term Variations in the Tropical Climate over the 20th and 21st Centuries

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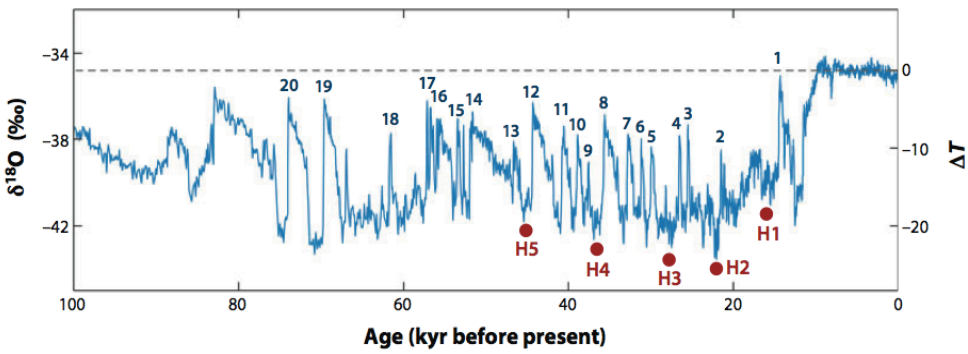
Several lines of evidence – paleoclimate observations, model simulations, and theory - suggest that thermal forcing originating from the extratropics have a profound effect on tropical rainfall. Cold thermal forcing located in the Northern extratropics cools air and surface temperatures over the entire hemisphere, generating an interhemispheric temperature asymmetry that shifts the latitudinal position of the Intertropical Convergence Zone southwards and weaken rainfall over Northern Hemisphere summer monsoon regions. This change is associated with a northward anomalous cross-equatorial atmospheric energy transport induced by differences in the energy flux entering each hemisphere. I summarize how this 'interhemispheric pattern' could be usefully applied to understanding multidecadal and longer-timescale forced changes in tropical rainfall over the 20th and 21st centuries, focusing on three specific causes: anthropogenic aerosols, the late 1960's climate shift, and hemispheric asymmetric feedbacks to greenhouse warming.

1. Introduction

Paleoclimate evidence examining the worldwide occurrence of millennial events during the last deglacial reveals a systematic global reorganization of climate. These millennial events – the Dansgaard/Oeschger (D/O) and Heinrich events – punctuated climate throughout the last glacial and into the deglacial period. They are most strongly expressed in proxy temperature records from Greenland ice core measurements (figure 1a). Figure 1b shows a schematic of a typical D/O cycle as recorded by Greenland cores: starting from a cold ('stadial') phase, Greenland temperatures undergo a rapid warming to a warm ('interstadial') phase, where they stay (with a small drift to cooler temperatures) for several hundred years before shifting back down to a colder stadial phase (Ganopolski and Rahmstorf 2001). These events are remarkable for two reasons: (i) the rapidity with which the temperature changes from cold to warm phases, typically on the order of a few decades; and (ii) the magnitude of the temperature change is on the order of 10°C, comparable to the difference in annual mean temperatures between Moscow and Madrid (Alley 2004). Heinrich events in particular are associated with some of the coldest millennial events in the Greenland ice core record (figure 1a, red dots).

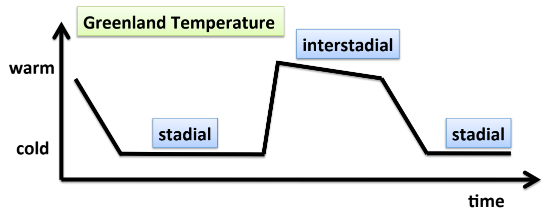
These events are associated with global climate changes, in particular impacting Northern Hemisphere temperatures and tropical rainfall. Northern Hemisphere temperatures are cooler during cold D/O stadials (Voelker 2002), the tropical Atlantic Intertropical Convergence Zone (ITCZ) shifted southwards (Peterson et al. 2000), and the northern hemisphere monsoons were



(a)

Figure 1. **(a)** Greenland temperatures during the last glacial period, as recorded by stable oxygen isotopes in the Greenland Ice Core Project (GRIP) core (Grootes et al. 1993). The Dansgaard-Oeschger (D/O) events are numbered, and the timing of the Heinrich events (H1-5) are marked by dots. Figure taken from Chiang (2009). **(b)** Schematic of a typical D/O cycle. Starting from a cold phase (stadial), Greenland temperatures abruptly warm typically over a few decades to a warm (interstadial) phase. It will stay in the interstadial for a few hundred years (and with a slight drift to cooler conditions), before returning to stadial conditions. A typical temperature difference between a stadial and interstadial is ~10°C.

(b)

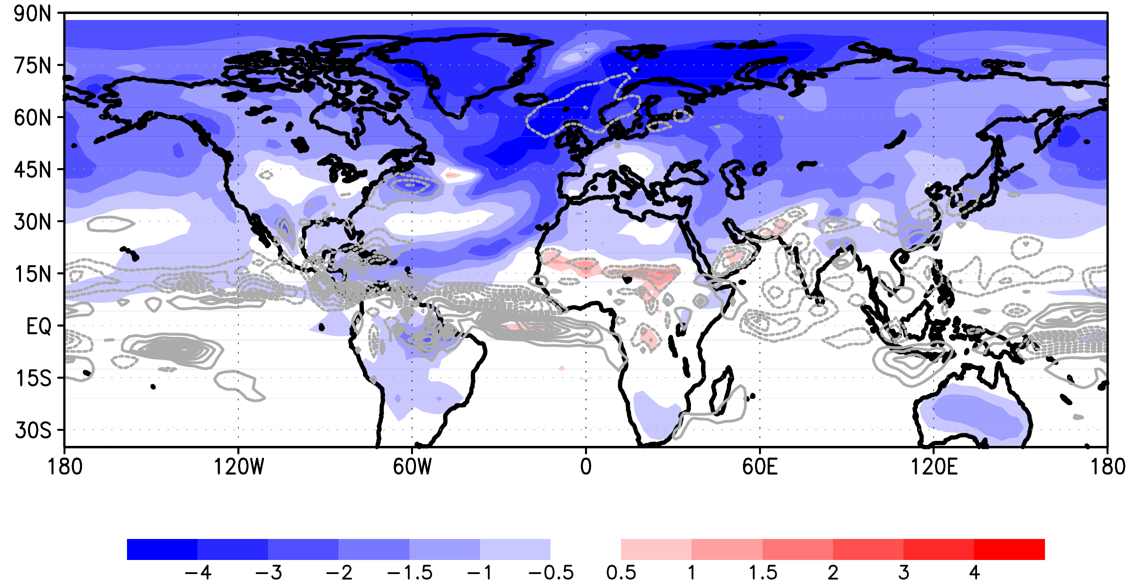


weaker (Wang et al. 2001). There is also proxy evidence for changes to the Southern Hemisphere climate, in particular warming (cooling) over Antarctica during stadials (interstadials) (Barbante et al. 2006); and a shift in the Southern Hemisphere westerlies during Heinrich events (Anderson et al. 2009). Taken together, the proxies show strong evidence for a global rearrangement of climate during these abrupt climate changes.

The dominant hypothesis for the driver of these millennial events is a weakening of the Atlantic Meridional Overturning Circulation (AMOC), as first proposed by Broecker et al. (1985). Since then, a wealth of proxy and modeling evidence has accumulated in support of this hypothesis (Alley 2007). Most significantly, coupled model simulations whereby the AMOC is artificially slowed down (commonly through input of freshwater in the North Atlantic) show a global rearrangement of climate with a colder Northern Hemisphere, southward-shifted ITCZ, and weakens northern hemisphere monsoon rainfall, in agreement with paleoclimate proxies (figure 2). Thus, an abrupt slowdown of the AMOC appears to drive a global reorganization of climate (Cheng et al. 2007; Vellinga and Wood 2002; Zhang and Delworth 2005).

The purpose of this paper is to summarize an emerging hypothesis for extratropical thermal influence on the tropical rainfall climate via a global teleconnection pattern – the so-called ***interhermispheric pattern*** - mediated by the atmosphere. We focus here on the specific applicability of this hypothesis to multidecadal and longer-term variations in tropical rainfall changes over the 20th and 21st centuries.

(a)



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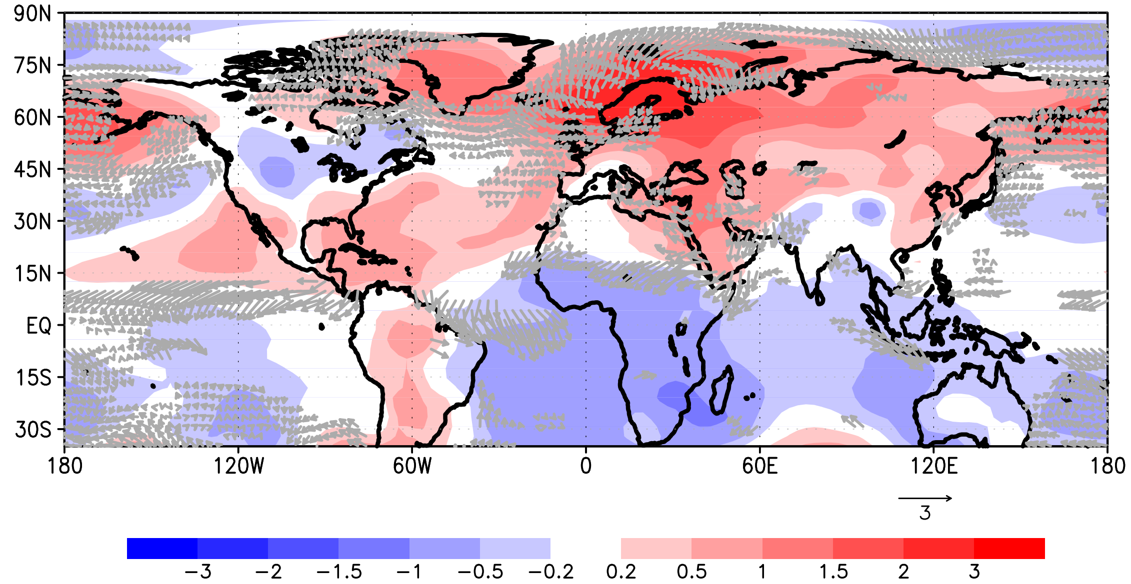

2. Modeling and Theory

So, what is the essential dynamics of this teleconnection? The pattern of global changes seen in the AMOC shutdown appear to largely result from atmospheric teleconnections of high-latitude North Atlantic cooling (Cheng et al. 2007; Chiang and Bitz 2005): simulations with an atmospheric general circulation model (AGCM) coupled to a slab ocean with a cooling artificially applied in the extratropical North Atlantic show climate anomalies that are similar to the AMOC shutdown (cf. figure 2). We point specifically to these gross features of the climate response: a hemispheric-wide cooling/warming in the same hemisphere as the extratropical forcing and little temperature response in the opposite hemisphere, producing an interhemispheric temperature asymmetry; a hemispheric asymmetric response in sea level pressure, with anomalously high pressure in the colder hemisphere; and a shift of tropical rainfall away from the cooler hemisphere. We will refer to this response as the 'interhemispheric pattern' or 'interhemispheric response'.

This gross global pattern of changes is not just a consequence of North Atlantic cooling, but also occurs in many other situations of extratropical thermal forcing. For example, Chiang and Bitz (2005) applied extratropical cooling in an AGCM-slab ocean framework separately to the North Atlantic and North Pacific (using an alteration to the q-flux), and also to Northern Hemisphere land regions (by applying a last glacial maximum land ice-sheet boundary condition, but with zero thickness) – all showed an interhemispheric pattern of climate response. Rotstayn and Lohmann (2002) examined the global climate response to the direct and indirect effects of 20th century anthropogenic aerosols – largely occurring over the extratropical northern hemisphere – in an AGCM-slab ocean framework, also finding an interhemispheric response. Kang (2009) applied a localized extratropical thermal forcing in an AGCM-slab ocean in an aquaplanet configuration, also finding that the climate response to be approximately zonally symmetric, and exhibiting an interhemispheric temperature asymmetry and ITCZ shifted away from the anomalously colder hemisphere.

These observations lead us to propose a hypothesis: ***that extratropical thermal forcing (localized or otherwise) can drive a global climate response characterized by the interhemispheric pattern, mediated through the atmosphere and aided by thermodynamic interactions with the surface ocean.*** This hypothesis is conceptually analogous to atmospheric teleconnections resulting from the other great global teleconnection of Earth's climate, those occurring during El Nino-Southern Oscillation (ENSO) events. Pursuit in our understanding of the ENSO teleconnection advanced our understanding of tropical-to-extratropical teleconnections, including the development of a theory for the teleconnection through stationary Rossby wave dynamics (Hoskins and Karoly 1981), and a greater understanding of the role of the tropics in driving extratropical circulation and climate changes (Trenberth et al. 1998).

Development of this extratropical-to-tropical teleconnection from extratropical thermal forcing is still in its infancy, with most of our knowledge coming from modeling studies – primarily those using an AGCM-slab ocean configuration, where the effect on the tropical circulation and rainfall is quite apparent and pronounced. A plausible mechanistic theory, akin to Hoskins and Karoly (1981) for the ENSO teleconnection, remains to be developed. However, a recent trend has been to interpret the teleconnection from an energy flux framework (Yoshimori and Broccoli 2008; Kang et al. 2009). The idea is that there is an interhemispheric contrast in energy flux between the hemispheres that lead to a compensation by the cross-equatorial heat transport in moving energy from one hemisphere to the other. This, in turn, is tied to the Hadley circulation response, as that

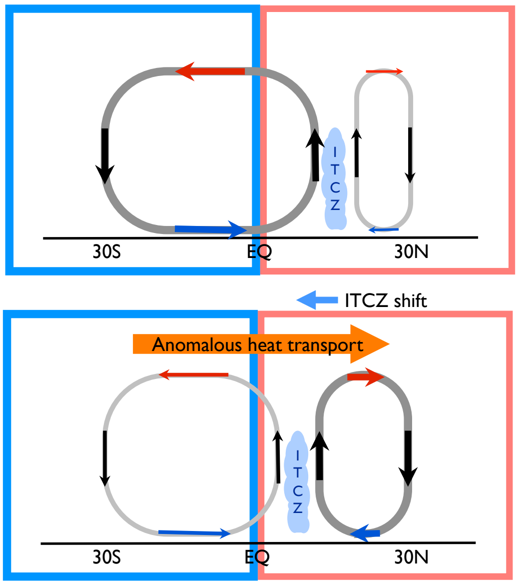

Figure 3. Schematic of energy transports by the Hadley circulation. **Top panel:** Hadley circulation as depicted for northern hemisphere summer. Energy transport by the Hadley circulation is in the direction of the upper branch of the Hadley cells (red arrows). In this case, the southern (winter) Hadley cell is stronger, and transports energy from the northern (summer) hemisphere to the southern (winter) hemisphere. **Bottom panel:** with a southward displacement of the ITCZ, the southern cell becomes weaker and the northern cell becomes stronger, with commensurate changes to the energy transported by each. The net change in the energy transport is northward, so that a southward shift in the ITCZ leads to an anomalous northward cross-equatorial heat transport (orange arrow). Figure courtesy of Yen-Ting Hwang

circulation is responsible for meridional energy transports in the tropics. Specifically, meridional atmospheric energy transports are in the same direction as the upper branch of the Hadley circulation, with a magnitude approximately proportional to the mass flux; so in the northern summer (for example), the winter Hadley cell straddles the equator, and the energy flux is directed to the Southern Hemisphere (figure 3). This cross-equatorial energy flux is reduced if the winter cell weakens; this is achieved readily by an equatorial shift in the latitude of the uplift (Lindzen and Hou 1988). Given the change in cross-equatorial atmospheric heat transport, and climatological values of the gross moist stability and gross moisture stratification, the change in zonal mean tropical rainfall can be quantified (Kang et al. 2009).

While hemispheric asymmetric forcings drive the cross-equatorial flux changes, there are radiative feedbacks (positive and negative) that modify the cross-equatorial flux requirements and thus the magnitude of the tropical response. We illustrate this with a study by Cvijanovic and Chiang (2013) who examined the energy flux changes for the specific case of a surface extratropical North Atlantic cooling, in an AGCM-slab ocean simulation. In this case, cooling was applied to the slab ocean over the North Atlantic north of 50°N as a modification to the Q-flux (and with no compensating warming). The forcing drives an interhemispheric pattern of response, and a new energy balance configuration with altered top-of-atmosphere and horizontal energy fluxes are achieved by the model climate in equilibrium (figure 4). If the surface flux changes over the northern extratropics are normalized to 1, then around 1/3 of the cooling is locally compensated for by TOA radiative changes in the northern extratropics, whereas the other 2/3 is obtained from increased northward energy transports from the northern tropics. The local compensation is driven largely by negative temperature- outgoing longwave radiation (OLR) feedbacks.

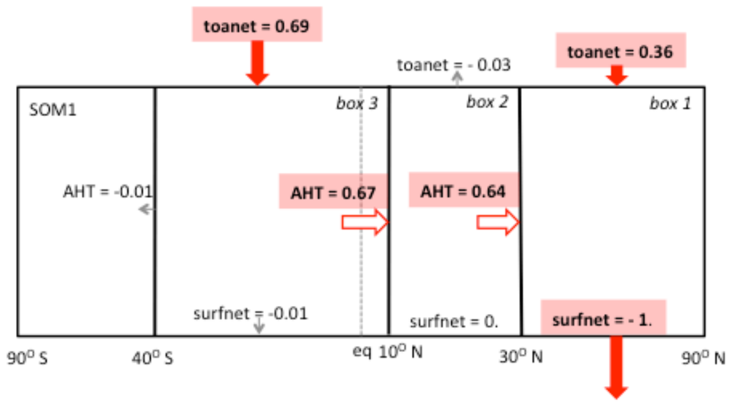

Figure 4. Box diagram of (normalized) energy flux changes into the atmosphere in an AGCM-SOM simulation given extratropical North Atlantic cooling. The cooling is applied as a q-flux anomaly in the North Atlantic north of 50N (see Cvijanovic and Chiang 2013 for details). Shown is the summary of the equilibrated energy flux changes divided into latitudinal boxes, chosen to reflect the gross changes in the response. TOA and surface net energy budget anomalies are given at the top and bottom of each box respectively, and anomalous atmospheric heat transports are shown at the borders between the boxes. The arrows indicate the directions of the anomalous fluxes, and flux values are normalized relative to the surface flux anomaly in box 1 (which comes mostly from the applied North Atlantic cooling). The major flux changes are emphasized in boldface and in red. Adapted from Cvijanovic and Chiang (2013).

Interestingly, the energy derived to supply the increased northward atmospheric heat transport to the northern extratropics comes not from TOA changes in the northern tropics (there, cloud longwave feedbacks are almost perfectly compensated for the cloud shortwave feedbacks), but from the *southern* tropics (this was also noted in Chiang and Bitz (2005)). The TOA flux changes in the southern tropics comes largely from cloud longwave feedbacks – the southward ITCZ shift leads to more deep convective clouds there the replace shallow cumulus, resulting in a decrease to the outgoing longwave radiation (OLR). This anomalous increase in the southern tropics TOA flux gets fed into the northern tropics via cross-equatorial atmosphere energy transports; this cross-equatorial transport is tied to the southward ITCZ shift. Note that the southern extratropics do not play a role in the energy flux changes, though this does not preclude circulation changes there (e.g. Lee et al. 2011 found significant changes to the Southern Hemisphere westerlies in a model simulation with applied North Atlantic cooling).

The radiative feedbacks associated with this extratropical cooling and ITCZ shift is generally quite varied and complex, and no simple story emerges from it. However, it does indicate that radiative feedbacks play an important role in determining the character of the teleconnection, specifically the sensitivity of the tropical response to extratropical forcing. For example, a number of relatively small but positive radiative feedbacks occur in the northern extratropics; if the strength of (say) the cloud shortwave feedback increased, then it could lead to a larger poleward energy flux requirement and hence larger tropical response. (Kang et al. 2009) showed that cloud radiative feedbacks modulate the strength of the tropical response to extratropical forcing.

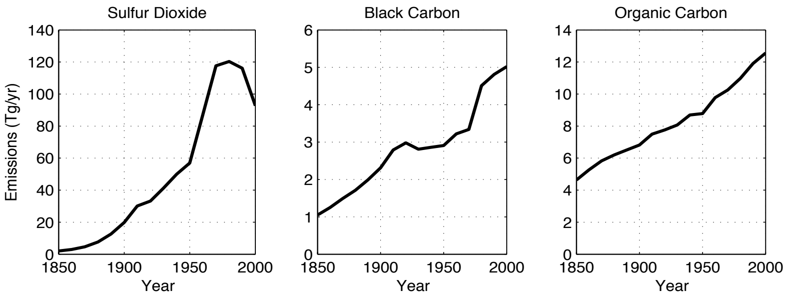

Figure 5. Timeseries of global anthropogenic aerosol emissions, from L to R: Sulfur Dioxide, Black Carbon, and Organic carbon. Data from Lamarque et al. (2010).

On the other hand, changes to the ocean heat transport (not considered in the AGM-slab ocean framework) could act to reduce the sensitivity of the tropical response to extratropical cooling. For example, were the ocean allowed to also move heat, then part of the cross-equatorial energy flux demand could be taken up by the ocean heat transport. For example, Cai et al. (2006) found that the northward ocean heat transport increased in a coupled model simulation in response to anthropogenic aerosol forcing, largely from changes to the AMOC. The actual sensitivity of the tropical ITCZ climate to extratropical thermal forcing is an outstanding question that needs to be addressed.

3. Drivers of 20thC and future interhemispheric gradients

Our purpose is to explore whether the hypothesis presented - extratropical thermal forcing leading to tropical rainfall changes via the interhemispheric pattern - can be usefully applied to interpreting and understand decadal and longer-term changes in 20th century and future tropical climate. Two questions are addressed here:

(i) What are the extratropical thermal forcings in historical and future climate that can drive an interhemispheric response?

(ii) Is there evidence that such forcings impact tropical climate through an interhemipsheric pattern of response?

We address the latter question in sections 4 and 5. For the first question, we highlight three forcings – anthropogenic aerosols, North Atlantic SST, and feedbacks to anthropogenic greenhouse warming – that appear to be relevant to our hypothesis for analyzing 20th century and future climate changes.

Anthropogenic Aerosols: Anthropogenic aerosol emissions, in particular sulfates, increased dramatically since the 1960's (Boucher and Pham 2002; Lamarque et al. 2010) (figure 5). The emissions occur largely over the northern extratropics where the industrialized nations are located, and because of the relatively short lifetime the aerosols remain largely in the northern hemisphere. Aerosol emissions are dominated by sulfates that have a direct cooling influence, but black carbon (a warming influence) has become relatively more important towards the end of the 20th century. A plateauing of sulfate emissions occurred in the 1970's with introduction of legislation in North America and Europe to combat air pollution; as we will show later, this plateau apparently has a marked effect on the tropical changes to anthropogenic aerosols. Unlike sulfates however, black carbon emissions have steadily increased throughout the 20th century.

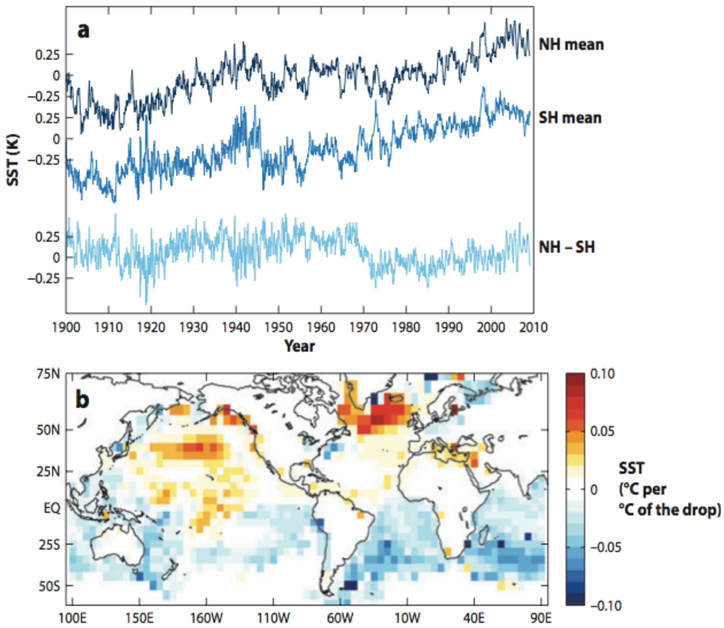

Figure 6. Figure from Thompson et al. (2010). (*a*) Northern Hemisphere (NH) mean sea-surface temperatures (SSTs) (*top curve*), Southern Hemisphere (SH) mean SSTs (*middle curve*), and NH mean SST minus SH mean SST (*bottom curve*). (*b*) Spatial regression formed by regressing SST data that have been weighted by a triangular function centered about 1970, with end points in 1940 and 2000, onto a time series of the drop. The time series of the drop was generated by fitting a third-order polynomial fit to the NH-minus-SH time series from panel *a* for the period 1968–1972 and then by extending the resulting fitted time series backward and forward over various time intervals centered about 1970 using fixed pre- and postdrop values for years before 1968 and after 1972. Units for the regressed SST are °C per degree of the drop.

Anthropogenic aerosols generally provide a cooling influence over the Northern Hemisphere. Several idealized studies imposing direct and indirect effects of late 20th century aerosol emissions in AGCMs coupled to slab ocean models reveal a global climate response similar to the interhemispheric pattern (e.g. Rotstayn and Lohmann 2002; Williams et al. 2001). The potential range in magnitude of these effects are however large because of uncertainty in the representation of indirect effects.

Abrupt North Atlantic SST changes in the late 1960's. Thompson et al. (2010) showed that the interhemispheric SST difference (the difference in SST averaged over the each hemisphere) underwent a significant and abrupt shift in the late 1960's with the north cooling relative to the south by around 0.5K (figure 6). The interhemispheric SST difference stayed this way until the late 1990's before partially recovering. While the source of the shift remains unknown, the spatial pattern reveals high loadings over the northern North Atlantic, reminiscent of changes associated with a weakening of the AMOC.

This late 1960's shift is also associated with multidecadal SST variations over the entire North Atlantic, as measured by the Atlantic Multidecadal Oscillation (AMO – a detrended and temporally-smoothed measure of SST averaged over the North Atlantic basin). The AMO also exhibits a decline in the late-1960's to colder conditions. Detection and attribution studies have generally indicated that while the 20th century warming trend over the North Atlantic is due to external forcing, no definitive consensus has emerged on the origins of the multidecadal swings. Several studies have argued that the AMO is largely due to internal variations (Terray 2012; Ting et al. 2009), while others have argued that it is largely anthropogenically forced (e.g. Mann amd Emanuel 2006). On the other hand, coupled modeling studies of natural variations in the AMOC have shown that the surface temperature anomalies associated with such changes resemble those of the AMO, suggesting a link between the two (e.g. Knight et al. 2005; Latif et al. 2004).

Hemispheric asymmetric responses to greenhouse warming. Radiative forcing by long-lived greenhouse gases is generally symmetric about the equator. However, the hemispheric asymmetry of earth leads to an uneven response to anthropogenic greenhouse warming. Unlike oceans, land has negligible heat capacity, so ocean heat uptake from greenhouse warming is larger in the South. There is an interhemispheric contrast in surface fluxes resulting from this; and the North is expected to warm faster than the south. Second, summertime Arctic sea ice extent started decreasing since around the 1960 (Stroeve et al. 2007), leading to more solar absorption in the Northern Hemisphere; on the other hand, Antarctic sea ice extent has increased slightly over 1979-2006 (Cavalieri and Parkinson 2008). Finally, wind-driven upwelling and mixing over the southern ocean means that the ocean there is thermally connected to greater depths, thus warms up slower under transient warming. In all these cases, they lead to greater warming in the North over the South. However, a slowdown of the AMOC in response to greenhouse warming could lead to the opposite effect of greater warming in the South than North (e.g. Feulner et al. 2013).

4. Regional Tropical climate changes over the 20th century

I now address the second question posed in section 3, whether interhemispheric forcings affect tropical climate. I focus on 20th century changes in two regions with particularly strong connections to Greenland during abrupt climate changes – the tropical Atlantic, and the Asian monsoon region.

4.1. *Tropical Atlantic*

Chang et al. (2011) investigated long-term trends of the Atlantic ITCZ over the 20th century, using a measure of the difference in SST between the north and south tropical Atlantic (south minus north; the Atlantic Interhemispheric SST gradient, or AITG) as a proxy. The AITG (figure 7) shows multidecadal behavior associated with the AMO, on top of an upward trend indicating that the south tropical Atlantic has been warming up relatively faster than the North. Given the strong coupling between the Atlantic ITCZ and the AITG (e.g. Chiang et al. 2002), this trend indicates a progressive southward displacement in the Atlantic ITCZ.

Chang et al. (2011) analyzed coupled model simulations of the AITG in the Coupled Model Intercomparison Project (CMIP) phase 3 multimodel simulations of the 20th century. They extracted the common behavior of the model AITG indices through an empirical orthogonal function analysis (Barnett 1977), finding that a majority of the models exhibit a common upward AITG trend until around 1980, followed by a reversal. The ensemble-mean AITG upward trend from 1900-1982 was found to be statistically significant, but significantly smaller in magnitude than the observed. It meant that either there is a strong unforced component to the actual trend (which was entirely possible, as indicated by the AITG behavior in CMIP3 preindustrial simulations), but also that the models could be systematically underestimating the forced trend. Finally, an attribution analysis using a small set of single forcing runs indicated that the forced trend was predominantly due to anthropogenic sulfate aerosols.

Recently, Chiang et al. (2013) repeated the same Chang et al. (2011) analysis on the AITG with the CMIP5 multimodel ensemble, essentially confirming the broad conclusions of the CMIP3 study – namely, that there is a forced component to the trend, and primarily by anthropogenic aerosols. The attribution analysis in Chiang et al. (2013) was significantly more robust than Chang et al. (2011) because of the inclusion of many more single forcing runs in the analysis. Like the CMIP3, the CMIP5 also simulated a reversal of the trend around 1980, confirming that this reversal is also forced. The attributed causes of the reversal arises from two sources: (i) from the leveling of anthropogenic aerosol emissions in the 1970s with the introduction of legislation limiting atmospheric pollution; and (ii) to the increasing influence of anthropogenic greenhouse gases that warmed the northern hemisphere faster than the southern hemisphere.

The influence of anthropogenic aerosols may also have weakened the Atlantic cold tongue, via its influence on the AITG. Tokinaga and Xie (2011) examined observations of SST and surface winds over the past six decades in the equatorial Atlantic, showing a warming of the equatorial cold tongue relative to the SST around it, combined with a weakening of the easterly trades. Their analysis of CMIP3 historical simulations over the same time period showed a similar change to the equatorial cold tongue and trades, and correlated to changes in the interhemispheric SST gradient (figure 8). The link between the interhemispheric and equatorial zonal SST gradients are dynamically linked: a colder North/warmer South pattern leads to a weakening of the southeasterly trades, the latter which have a zonal component at the equator. The resulting weakening of surface equatorial easterlies reduces the east-west equatorial thermocline gradient and thus the equatorial zonal SST contrast.

4.2. *Monsoons*

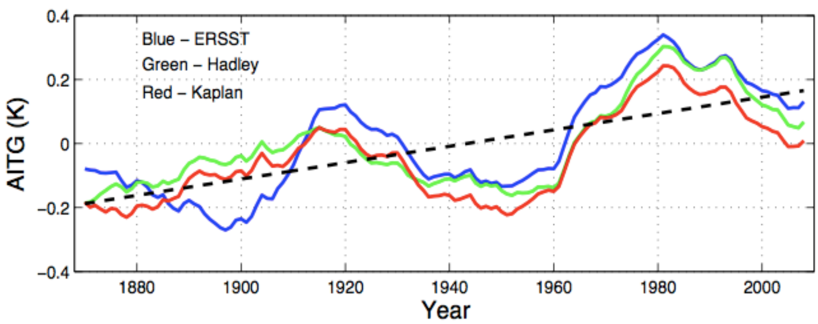

Figure 7. The observed Atlantic Interhemispheric Gradient Index, defined as the SST difference between the North Tropical Atlantic (5°N-35°N, 0°W-80°W, northern box in top panel) and the South Tropical Atlantic (5°S-35°S, 60°W-20°E, southern box in top panel), South minus North. Each line is from an observational SST dataset as denoted: ERSST v3b (Smith *et al.,* 2008), Hadley Centre SST (Rayner *et al.,* 2003), and Kaplan Extended SST v2 (Kaplan *et al.,* 1998). The black dashed line is the linear least-square best-fit line to the average of the three curves. Figure from Chiang et al. (2013).

Several recent papers have argued for the role of the interhemispheric thermal gradient in driving late 20th century weakening of to the North African and South Asian summer monsoons, in particular associated with aerosol forcing. The earliest suggestions came from AGCM-slab ocean simulations with imposed aerosol concentrations (Rotstayn et al. 2000; Williams et al. 2001). In particular, Rotstayn and Lohmann (2002) explored the effect of anthropogenic aerosols on the global climate in an AGCM-slab ocean model simulation with prescribed late 20th century aerosol concentrations and a parameterization for indirect effects. They noted a complex pattern of rainfall changes in the tropics, but grossly reflecting a southward shift in the tropical rainbands. They showed that the observed tropical rainfall trends resembled the modeled changes, albeit with smaller amplitudes. In particular, they focused on the Sahel drying which was prominent both in the model simulations and observational records. They concluded that the spatially-varying aerosol forcing can substantially alter tropical rainfall and low latitude circulations, and specifically proposed it as a mechanism for the observed Sahel drought in the latter half of the 20th century.

More recently, the Sahel hypothesis proposed by Rotstayn and Lohmann (2002) gained support from more comprehensive modeling study. Kawase et al. (2010) analyzed a fully coupled model simulation of the 20th century that showed a drying of the summer rainfall over North Africa. Their attribution analysis using single-forcing runs showed that the drying trend was primarly due to anthropogenic aerosols. Through a moisture-budget analysis, they inferred that aerosols reduced West African rainfall both through a thermodynamic effect of tropospheric cooling brought about by the aerosol forcing; and a dynamic effect through altering the local atmospheric circulation from changing the meridional SST gradient in the tropical Atlantic. The analysis of Kawase et al. (2010) thus showed the possible influence of anthropogenic aerosols on Sahel drought in a comprehensive coupled climate model, and furthermore pointed to specific mechanisms of how remote anthropogenic aerosol forcing alters tropical rainfall.

Anthropogenic aerosols have also been

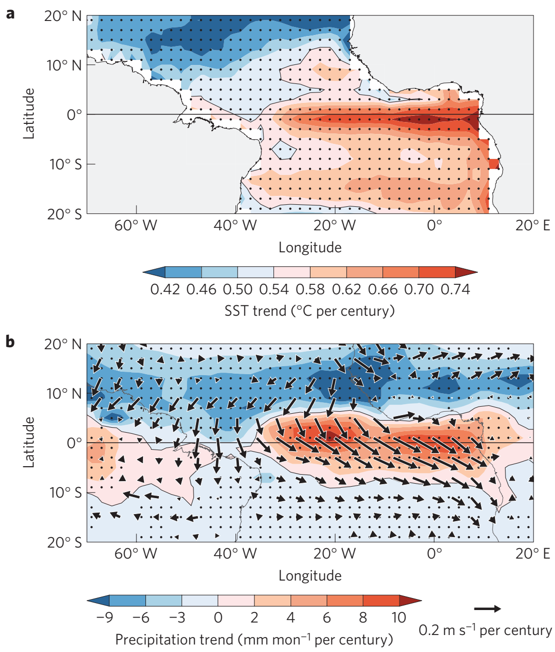

Figure 8: From Tokinaga and Xie (2011), figure 4. As quoted from their figure caption: "Patterns of simulated climate for 1900-1999. **a**,**b**, SST (colour) (**a**), surface wind (vector) and precipitation (colour) (**b**) for June–August, based on the ensemble mean of the climate of the twentieth-century experiments from 19 CMIP3 models. For SST and precipitation trends, grid points marked with filled circles exceed the 95% confidence level based on the Mann–Kendall test. For surface wind trend, only vectors exceeding the 95% confidence level are plotted"

implicated in the weakening of the South

Asian monsoon rainfall over the latter half of the 20th century. Using a coupled modeling approach similar to Kawase et al. (2010), Bollasina et al. (2011) showed that the all-forcing simulations was able to reproduce the downward trend in the South Asian monsoon rainfall over the latter half of the 20th century, and with comparable magnitude. Their attribution using single-forcing runs showed anthropogenic aerosols to be the cause of the simulated drying. Bollasina et al. (2011) explained the drying effect by aerosols to be a consequence of a slowdown in the tropical meridional overturning circulation, compensating for the aerosol-induced energy imbalance between the hemispheres; by this interpretation, they highlight the potential contribution of remote aerosols to the drying (although their analysis did not explicitly show this). In this sense, their interpretation bear resemblance to energy flux interpretation of Kang et al. (2009) for extratropical thermal forcing on tropical rainfall. Interestingly, a modeling study by Cowan and Cai (2011) found a similar Asian monsoon response to anthropogenic aerosols in the CSIRO coupled model, but they also tested the relative roles of Asian and non-Asian roles in this drying. They show that Asian (i.e. local) aerosols only drive a weak drying of rainfall, with a larger contribution by remote aerosols.

While anthropogenic aerosols have been shown to drive a weakening of the monsoons over the latter half of the 20th century, its influence is gradual (a trend), reflecting the temporal history of anthropogenic aerosol emissions. This is in direct contrast to changes in the Sahel rainfall that abruptly weakened in the late 1960's, suggesting that the cause of this abrupt shift was not due to aerosols. Folland et al. (1986) showed in 1986 that the Sahel drought was linked to global SST temperature changes resembling an interhemispheric pattern. Given that the interhemispheric SST gradient underwent an abrupt shift in the late 1960's towards anomalously cooler conditions in the North (Thompson et al. 2010), the suggestion is that the SST changes drove the Sahel drought.

Liu and Chiang (2012) explored this idea from observations and model simulations. They attempted to extract the signatures of a North Atlantic influence on the Sahel and Asian monsoon by focusing on surface temperature and pressure anomalies over Eurasia and North Africa – AGCM-slab ocean model simulations of extratropical North Atlantic cooling showed that Eurasian and North African temperatures cooled, and sea-level pressure increased (similar to the pattern seen in the AMOC shutdown simulation of figure 2). Using a combined EOF method on surface temperature, pressure, and rainfall over Eurasia and North Africa, they extracted a leading mode that spatially resembled the impact of North Atlantic cooling, and with a temporal signature of a late 1960's shift. They were able to achieve a similar result with analyzing an ensemble of AMIP-type runs where the observed SST was prescribed; this indicated that the information of the 1960's shift resided in the surface ocean temperature. Liu and Chiang (2012) concluded that the observed climate changes associated with Sahel drought were consistent with the influence of North Atlantic cooling, though they did not establish a causal relationship.

There are observational suggestions of a global climate shift in the late 1960's, not just with Sahel rainfall. Baines and Folland (2007) found evidence for a rapid shift in atmospheric

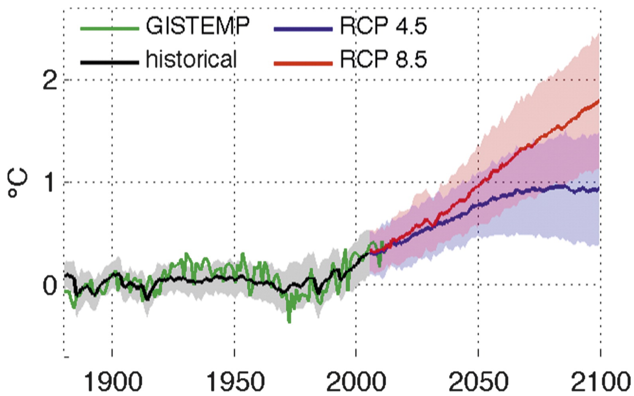

Figure 9: Interhemispheric Temperature Asymmetry (ITA), defined as the surface air temperature averaged over the northern hemisphere, minus that for the southern hemisphere. The observed ITA is shown in green (derived from GISTEMP), and CMIP5 multimodel ensemble mean in black. The multimodel ensemble mean for the future scenarios RCP 4.5 and 8.5 are in blue and red, respectively. Shading represents one ensemble standard deviation. The simulated ITA remains relatively flat throughout most of the 20th century, then trends upward from around 1980, extending into the future scenarios. From Friedman et al. (2013).

circulation around that time associated with changes to the interhemispheric SST difference, and largely in tropical regions like rainfall Amazon basin and Northeast Brazil; and sea level pressure and SST changes over the tropical North Atlantic and west and central Pacific. They also find changes to the Southern Hemisphere midlatitude circulation - subtropical jet and storm track – and possible changes to the Antarctic sea ice boundary. Interestingly, the global climate changes described in Baines and Folland (2007) are reminiscent of those seen during the abrupt events of the last glacial; it suggests a common origin with global teleconnections resulting from North Atlantic cooling.

5. Global interhemispheric changes in the 20th century and future

Future forced changes to the interhemispheric pattern will dominated by anthropogenic greenhouse gas and aerosol emissions, as highlighted in section 3. However, unlike the 20th century forced changes to the interhemispheric pattern where the two influences acted in opposition, in the future they will likely both act in the same direction as anthropogenic aerosol emissions are projected to decrease in the 21st century (Lamarque et al. 2011).

Friedman et al. (2013) examined simulations of an index in the global interhemspheric surface temperature (land+ocean) difference – the Northern Hemisphere minus Southern Hemisphere mean surface air temperature, which Friedman et al. (2013) coined the 'Interhemispheric Temperature Asymmetry' (ITA) index - in the Coupled Model Intercomparison Project (CMIP) phase 3 and phase 5 simulations of historical and future climates. Over the 20th century, the observed ITA stayed relatively flat with no significant trend; the most pronounced feature was an abrupt shift in the late 1960's, similar to what Thompson et al. (2010) found in the interhemispheric SST gradient. However, around 1980 a significant upward trend towards more positive ITA started to emerge (figure 8, green line), with the North warming significantly faster than the South.

The CMIP3 and 5 multimodel simulations of the ITA was able to reproduce the observed relative lack of trend in the 20th century, and the emergence of a significant positive trend starting around 1980; this trend continues upward in all future simulations examined (figure 9), reaching values that well exceed the 20th century range by the end of the 21st century. Interestingly, the late 1960's shift in the ITA is not simulated, suggesting that the shift was not a response to climate forcing.

Attribution studies using single-forcing runs showed that prior to 1980, a positive trend induced by increasing greenhouse gases was essentially negated by anthropogenic aerosol emissions that drove the ITA trend in the opposite direction; it was only after the leveling-off of sulfate aerosol emissions in the mid-1970's and its subsequent decline, that the greenhouse-gas induced ITA trend could finally manifest itself (Chiang et al. (2013) came to a similar interpretation for the reversal in the AITG trend after the late 1970's). While Friedman et al. (2013) did not extend their attribution study to future projections, anthropogenic greenhouse gas and aerosols are both likely to contribute significantly to the projected ITA trend, and in the same direction, as anthropogenic aerosol emissions are projected to decrease in the 21st century. As an indication of the relative importance of aerosols, Levy et al. (2103) show that the reduction to anthropogenic aerosol emission in the RCP 4.5 scenario contributes around 0.9K global warming in the new GFDL coupled chemistry-climate model CM3 by the end of the 21st century. Since this warming is concentrated largely in the Northern Hemisphere (see their figure 6), it indicates a ~1K contribution to the interhemispheric difference.

What does the positive future trend in the ITA mean for tropical rainfall? Naively, one would expect a more northern position of the mean tropical rainfall position; and indeed Friedman et al. (2013) shows that the CMIP5 simulated rainfall indeed shift progressively more northwards into the 21st century. However, from energy flux arguments the tropical rainfall should more strictly follow the interhemispheric contrast in energy fluxes and not temperature; predicting the latter, however, is nontrivial. A study by Frierson and Hwang (2012) is instructive in this regard: they examined nine AGCM-SOM simulations of doubled CO2 simulations from several modeling groups, finding a range of latitudinal ITCZ shifts in these simulations, and in both directions. They attributed the range in the simulated ITCZ responses to modeled differences in the cloud and ice responses in the extratropics of both hemispheres, which in turn altered the nature of the interhemispheric energy flux contrast.

The variety in the AGCM-slab ocean ITCZ responses to global warming as found by Frierson and Hwang (2012) are likely to carry over into fully coupled model simulations of future warming, since similar radiative feedbacks operate in both. Another factor to consider in future projections is the anthropogenic aerosol influence, both in the nature of the future decrease, as well as the strength of the influence especially with regards to the indirect effect (Levy et al. 2013). Moreover, changes to the cross-equatorial ocean heat transports, in particular the response of the AMOC to global warming, is likely to factor into the future projections: most CMIP5 coupled model simulations of future scenarios show weakening of the AMOC (Cheng et al. 2013), and which would drive a *southward* shift in the ITCZ. Finally, other non-atmospheric effects such as land use change may also be able to alter the interhemispheric contrast in forcing due to changes in albedo (Swann et al. 2012), though this effect still has to be quantified.

6. Discussion

This paper outlines an emerging hypothesis for the influence of extratropical thermal forcing on the tropical climate through a global atmospheric teleconnection, one characterized by an interhemispheric pattern in temperature and surface pressure and a shift in the tropical rainband to the anomalously warmer hemisphere. I specifically focus on the potential applicability of this hypothesis to interpreting multidecadal changes to 20th century and future projected changes to tropical rainfall, in particular over the Atlantic ITCZ and North African and Asian monsoons. The plausibility for this hypothesis rests of several lines of evidence:

1. Empirical evidence from paleoproxies that such a global rearrangement of climate indeed occurred during abrupt climate changes during the last glacial, and tied specifically to pronounced cooling events over Greenland.
2. Consistent modeling evidence from various models (especially in the AGCM-slab ocean configuration) and various forcing types for an interhemispheric pattern of response to extratropical thermal forcing.
3. A quantitative and consistent interpretation for the influence of extratropical thermal forcing on the tropical climate from energy flux constraints, specifically tying tropical circulation changes to cross-equatorial heat transport changes to compensate for hemispheric differences the TOA and surface energy flux.

Further advancement of this hypothesis rests on two separate lines of development. First, there is a need to put this teleconnection on a more secure mechanistic footing. The energy flux constraint, whilst able to provide quantitative interpretation for the tropical rainfall change, is still essentially a diagnostic analysis, and applicable only to zonal means. The development of a mechanistic theory – akin to Hoskins and Karoly (1981) for the ENSO teleconnection – will be important in expanding the acceptance and applicability of this hypothesis. In particular, the theory will have to reconcile the energy flux interpretation of tropical rainfall changes on the one hand, with the more traditional viewpoint of tropical SST control of the structure of tropical rainfall (e.g. Xie et al. 2010).

Advancement will also rest on how well the hypothesis is able to lend insight into the dynamics of the real tropical rainfall – both the mean state structure and its change with time. There has been some success already in interpreting 20th century tropical rainfall changes – as highlighted in this review – but further advances in this regard may be limited by the lack of reliable observational rainfall data over the long-term. A more likely avenue for advancement would be from applying the hypothesis to climate model simulations of the tropical climate and its changes. For example, a recent and interesting result by Hwang and Frierson (2013) showed that coupled model simulations with more energy flux into the southern hemisphere atmosphere have stronger double-ITCZ bias. They specifically find that cloud biases over the Southern Ocean explain the most model-to-model differences in the excess precipitation in the southern Tropics. The hypothesis presented here offers a potential explanation for this in that the ITCZ is drawn towards the southern hemisphere extratropical heating. Thus in this view, the tropical ITCZ bias problem rests not with tropical ocean-atmosphere processes, but with the Southern hemisphere midlatitude processes! Should this prove to be correct, it would provide an important breakthrough to a longstanding problem in climate simulation.

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