

Mechanisms controlling the hemispheric asymmetry in the climate response to global warming
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1. Background

During my Ph.D. studies with David Battisti at UW, I have been viewing climate dynamics from the perspective of the radiation budget and its interaction with atmospheric dynamics (see, for example, Donohoe and Battisti 2011a). In particular I have been interested in the processes that control global scale energy fluxes into and out of the atmosphere (on both annual and seasonal time scales) including the air-sea flux of energy, the meridional energy flux, the energy flux from the ocean-to-land, and the radiative fluxes (Donohoe and Battisti 2011b). I am applying to join John Marshall and his group at MIT as a NOAA postdoctoral fellow. They have also has been thinking about the same large scale energy fluxes, but from the perspective of the global ocean circulation (Enderton and Marshall 2009, Rose and Marshall 2009) and its coupling to the atmosphere. We believe our individual expertise (including our modeling capabilities and toolboxes of analytical techniques) and differing perspectives, put us in a unique position to make progress in studying mechanisms that control the hemispheric asymmetry in the climate response to global warming. This is a hugely important problem because the response of the climate system to greenhouse forcing is not spatially uniform but exhibits pronounced meridional, and particularly hemispheric, asymmetries.

My proposal is set out as follows. In Section 2 I review the questions I plan to address in my postdoc, including a brief review of prior studies. In section 3 I outline my proposed plan of work.

2. The research problem: Hemispheric Asymmetry in the Climate Response to Global Warming.

The projected climate response to anthropogenic greenhouse gas emissions shows a marked hemispheric asymmetry that is robust across the suite of state of the art coupled climate models (Meehl et al. 2007 -- Figure 1A). The surface temperature increase in the Northern Hemisphere (NH) extra-tropics is projected to exceed the global average temperature increase by a factor of approximately two (IPCC, 2007): a phenomenon known as polar amplification (Holland and Bitz 2003; Serreze and Francis, 2006). In contrast, the surface temperature change in the Southern Hemisphere (SH) extra-tropics is projected to be significantly smaller than the global average temperature change, especially in the vicinity of the Drake passage. The observational record of surface temperature trends over the last century also feature enhanced warming in the NH extratropics (especially over land) and more neutral or even negative trends in the Southern Ocean (Smith and Reynolds 2005).

The cause of the inter-hemispheric asymmetry in the climate response to anthropogenic radiative forcing is an unresolved problem in coupled (atmosphere-ocean-cryosphere) climate dynamics. The inter-hemispheric differences in land area, the geography of the continental boundaries and topography, and the resulting basic state oceanic and atmospheric circulations could all contribute to the asymmetric response. Several mechanisms for the hemispheric asymmetry of the climate response have been discussed in the literature including transient heat storage in the Southern Ocean, changes in the atmospheric energy transport, and hemispheric differences in the cryospheric

response imposed by continental geography. We now briefly critically discuss the proposed mechanisms below.

A. Southern ocean heat storage

Stouffer et al. (1989) postulated that ocean heat storage in the region equatorward of the Antarctic Circumpolar Current was responsible for the reduced warming in the southern extratropics as compared to the northern extratropics. The same mechanism is referred to in the IPCC's third report where it is stated that the projected surface temperature change features "a maximum warming in the high latitudes of the Northern Hemisphere and a minimum in the Southern Ocean (due to ocean heat uptake)" (IPCC 2001). The enhanced ocean heat uptake in the Southern Ocean is realized in the simulated response to CO₂ doubling with the CMIP3 ensemble (FIG 1B). However, the magnitude and meridional structure of the ocean heat uptake are highly variable between models, and the hemispheric asymmetry in the ocean heat storage is much less pronounced than the surface temperature response (c.f. FIG 1A and 1B). The lack of correspondence between the inter-hemispheric asymmetry and meridional structures of temperature response and ocean heat storage suggests that additional mechanisms may be important. Even if ocean heat storage in the Southern Ocean is the root cause of the hemispheric asymmetry in the temperature response, the response is highly non-local and is communicated via unresolved changes in atmospheric and/or oceanic dynamics.

Furthermore, the root cause of the hemispheric asymmetry in transient ocean storage is an interesting and unresolved coupled climate dynamics problem in itself. The burying of energy in the Southern Ocean is a twofold process: A.) energy must first be fluxed from the atmosphere to the ocean mixed layer and then B.) removed from the ocean mixed layer into the ocean interior and away from interaction with the atmosphere. Process A occurs preferentially in the Southern Ocean due to the upwelling of cold mid-depth (2-3km) water poleward of the Antarctic Circumpolar current; no where else in the world is water of this depth upwelled directly to the surface (Russell et al. 2006). The cold water extracts energy from the atmosphere as it flows equatorward in the Ekman surface layer. The annual average flux of energy from the atmosphere to the ocean in the SH extratropics (poleward of 40N) has no counterpart in the NH (Czaja and Marshall, 2011) and is thought to be a consequence of coupled ocean-atmosphere dynamics. Process B also occurs preferentially in the Southern Ocean where the outcropping of isopycnal surfaces provides a conduit for energy to flow from the ocean surface to the ocean interior (Sabine et al. 2004). Thus, the basic state oceanic circulation of the Southern Ocean allows energy to be extracted from the atmosphere to the ocean interior.

However, it is unclear if the transient heat storage seen in the simulated response to greenhouse gas emissions is a consequence of the basic state oceanic circulation interacting with a warmer atmosphere or if changes in oceanic and/or atmospheric circulation under global warming also contribute to the energy storage. The storage of heat and carbon in the Southern Ocean is sensitive to the surface winds (*Sallée et al. 2010 and Mignone et al. 2006*) which are projected to change due to both greenhouse and ozone forcing (Thompson and Solomon 2005). Thus, the transient heat storage in the Southern Ocean is a coupled climate dynamics problem that results from both the atmospheric and ocean circulation in the basic state and their changes under global warming.

B. Change in heat transports

Alexeev et al. (2005) found that the climate response to spatially uniform positive radiative forcing exhibits polar amplification due to increased equator-to-pole energy transport associated with the moistening of the atmosphere. Increased energy transport over the observational period has also been linked to polar amplification (Graverson et al. 2008 and Yang et al. 2010). Although enhanced moisture transport should lead to polar amplification in both hemispheres, the land-ocean contrast and topography in the NH could lead to a response that is hemispherically asymmetric because the mean atmospheric circulation is very different in the two hemispheres (the NH circulation features stationary waves and zonally localized storm tracks that are largely absent from the SH).

Furthermore, moisture transport also contributes to moderating the land-ocean temperature contrast on both seasonal time scales and in the annual average (Fasullo and Trenberth 2008). The projected and observed spatial pattern of anthropogenic climate change shows the most warming over the NH continents during the winter, suggesting that polar amplification is itself a manifestation of moderated wintertime temperatures over the continents. The seasonal cycle of temperature over the NH continents is driven by the seasonal cycle of solar radiation but is highly damped by the import of moist static energy from the adjacent oceans (Donohoe and Battisti 2011b); winter-time cooling of the atmosphere above the continents is limited by *zonal* energy import (of approximately 6 PW – the same magnitude as *the meridional* heat transport in the climate system) primarily in the form of latent heat fluxes. *Ceteris paribus*, one would expect a warmer and moister climate to lead to an enhanced wintertime ocean-to-land energy flux and thus warmer winter-time continents. During the summer, the reverse flux of energy from the land domain to the ocean domain is impeded by moisture gradients because the ocean domain is moister than the warm land and thus the zonal advection of latent heat opposes the larger zonal advection of sensible heat from the land to the ocean. Thus, in a moister world we would expect the continents to warm more than the global average during the winter and approximately on par with the global average during the summer due to enhanced zonal moisture advection alone. This mechanism of polar amplification is largely absent from the SH due to lack of continents and could explain the inter-hemispheric asymmetry of the temperature response to anthropogenic forcing. This mechanism would be further amplified by reductions in sea ice (independent of the ice-albedo feedback) because a larger area of the ocean mixed layer becomes accessible for seasonal energy storage.

C. Ice albedo feedback

The differing continental geographies of the North and South poles also have large implications for the polar amplification of climate change due to the ice albedo feedback. The Arctic is projected to see large decreases in summertime ice extent due to anthropogenic climate change (IPCC, 2007) because the retreat of the sea ice from the summertime ice edge in the unperturbed climate is unimpeded by coastlines in the Arctic ocean. In contrast, the Antarctic summertime ice extent is projected to undergo half the reduction seen in the Arctic (Eisenman et al. 2011) because the retreat of summer ice is impeded by the coastline (and topography) of the Antarctica continent (Manabe and Stouffer 1980). This causes an enhanced positive radiative feedback in the NH as compared to the SH which could also explain the hemispheric asymmetry of the climate response.

3. Proposed work

The hemispheric asymmetry of the transient climate response to anthropogenic forcing is the consequence of the mechanisms discussed above working in conjunction as well as additional processes. Our future predictions of climate change are contingent on understanding the dominant mechanisms leading to the response and the uncertainties in those processes. Furthermore, the climate change problem is embedded in more fundamental questions of coupled climate dynamics such as: is the climate response to a globally uniform radiative forcing spatially uniform or does it exhibit a meridional structure? Is the meridional structure the same in the transient and equilibrium case? Are these answers contingent on the basic state circulation or are the conclusions applicable on paleoclimate time scales with altered continental geographies and orbital parameters? We propose approaching these problems primarily through the use of idealized models. We will extend our conclusions and analysis to the suite of climate simulations used in the IPCC's fourth assessment and the observational records.

A. Idealized model experiments

We will use a hierarchy of model experiments in both the sense that we will limit the number of radiative/dynamical processes represented in the model and we will change the complexity of the continental/topographical geography. In each experiment we will compare the equilibrium climate state under the pre-industrial CO₂ concentration (the control climate) with a 1% CO₂ ramping to doubling experiment (then run for an additional 150 years) in order to look at both the transient and equilibrium response to doubling CO₂. All simulations will include a seasonal cycle of solar forcing. The series of experiments is listed below.

I. AQUAPLANET COUPLED TO A SLAB OCEAN – NO ICE ALBEDO FEEDBACK

In this experiment, sea ice will be prohibited from forming even if the temperature drops below freezing. This experiment will exclude the role of ocean circulation, continental geography, and the ice-albedo feedback from the climate response and will be hemispherically symmetric by definition. It will primarily be used as a basis for comparison for later experiments. Alexeev et al. (2005) performed a similar set of experiments without a seasonal cycle and focused their attention on the equilibrium response only. Our analysis will evaluate the relative importance of heat transport changes, local ocean heat storage, and the spatial structure of shortwave and longwave radiative forcing (see Donohoe 2009 for an analysis of the spatial structure of clear sky shortwave forcing under global warming) for polar amplification.

II. AQUAPLANET COUPLED TO A SLAB OCEAN – WITH ICE ALBEDO FEEDBACK

This experiment will be identical to (I) except it will allow sea-ice formation in both the control (pre-industrial CO₂) and perturbed (ramped CO₂) experiments. It will allow us to assess the role of the ice albedo feedback in polar amplification.

III. SLAB OCEAN WITH A STRIP OF MID-LATITUDE LAND IN THE NH

We will introduce a land mass (no topography) over half the zonal circumference of the NH extra-tropics. This experiment will allow us to explore if the enhanced moisture transport from the ocean domain to the land domain in a warmer planet can explain the magnitude and seasonality of polar amplification in the NH (see section 2B above).

IV. SLAB OCEAN WITH A SOUTH POLE ISLAND

This experiment will place a disc of land over the south pole, extending to the latitude of the summer ice edge in the control climate. The continental boundary will impede the

summer retreat of the ice edge in the perturbed climate (see Section 2C above). We will assess the role of the hemispheric asymmetry in the ice-albedo feedback on the climate response.

V. COUPLED SIMULATION WITH IDEALIZED DRAKE PASSAGE GEOMETRY

This experiment will examine the coupled (atmosphere-ocean) response of the climate system to global warming using an idealized continental configuration. Enderton (2009) has demonstrated that the gross features of the global oceanic circulation, including the hemispheric asymmetry of the deep overturning circulation, can be captured in a coupled aquaplanet model with a thin ocean boundary running from the North Pole to 40S as to mimic the Drake Passage. We will explore the spatial pattern of transient heat storage and its impact on the hemispheric asymmetry of the surface temperature response. We will perform an additional run with the same continental configuration but with the surface wind stress fixed at the climatology of the control run. Analysis of this run will allow us to assess the impact of the surface wind stress change on the transient heat storage by comparison with the fully coupled perturbed run.

B. Additional analysis

The mechanism(s) that were found to contribute most to the hemispheric asymmetry of the climate state will be further analyzed in the CMIP3 suite of simulations. We will compare the pre industrial simulations with the 1%to2X runs (the identical forcing as prescribed in the idealized runs). We will also explore the relevant mechanisms in the observational record.

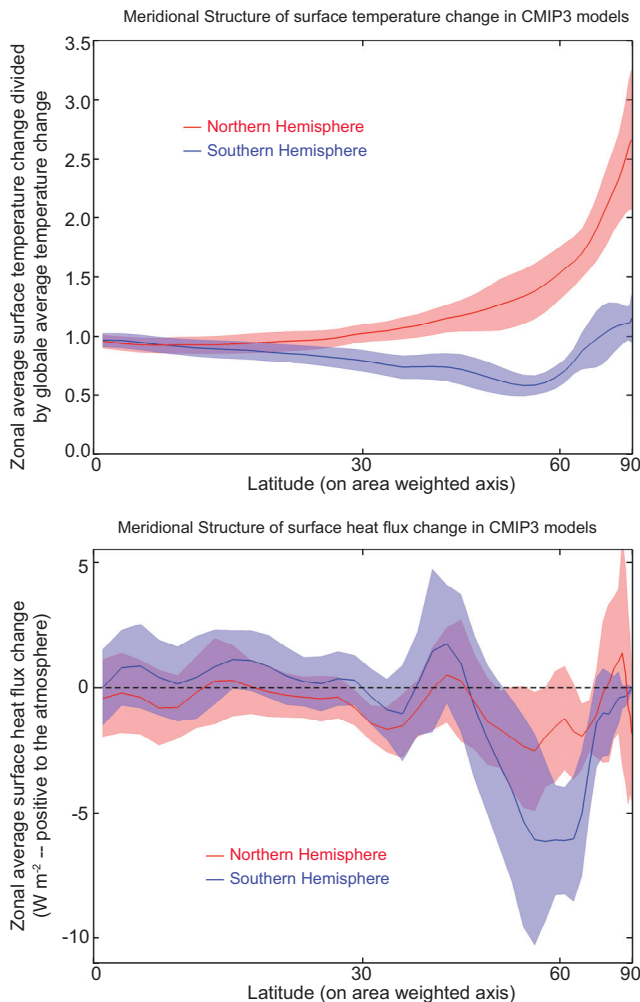


FIG 1. (Top Panel) The CMIP3 ensemble and zonal average surface temperature change due to doubling CO₂ (solid lines). The temperature difference between years 170-220 of the 1% CO₂ and the pre-industrial runs is divided by the global average temperature change and then averaged over the 15 different climate models; the 90% confidence interval is given by the shaded lines. The Southern Hemisphere curve (blue) is mirrored about the equator for ease of comparison with the Northern Hemisphere curve (red). (Bottom panel) As in the top panel except for the net surface energy flux.

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