Influence of the extratropical ocean circulation on the intertropical convergence zone in an idealized coupled general circulation model

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We investigate elements of the extratropical ocean dynamics that can control interhemispheric asymmetry of the meridional overturning circulation (MOC) and the intertropical convergence zone (ITCZ). We use a coarse-resolution coupled general circulation model (CGCM) with simplified atmospheric physics and idealized land-sea distribution. In an equatorially symmetric setting, unforced climate asymmetry develops due to the advective circulation-salinity feedback that amplifies asymmetry of the deep MOC cell and the upper-ocean meridional salinity transport. It eventually confines the deep-water production and the dominant extratropical ocean heat release to a randomly selected hemisphere. The resultant cross-equatorial ocean heat transport (OHT) toward the hemisphere with the deep-water source is partially compensated by the atmospheric heat transport across the equator in the opposite direction by asymmetric Hadley circulation. It places the ITCZ in the hemisphere warmed by the ocean. When a circumpolar channel is open at subpolar latitudes, the circumpolar current disrupts the poleward transport of the upper-ocean saline water from the subtropics and suppresses deep-water formation poleward of the channel. The MOC adjusts by shifting the deep-water production into the opposite hemisphere from the channel and the ITCZ follows due to Hadley circulation adjustment to forced cross-equatorial OHT. The climate response is sensitive to the sill depth of a circumpolar channel, but becomes saturated when the sill is deeper than the main pycnocline depth. In our model with a circumpolar channel, the ITCZ is in the Northern Hemisphere (NH) due to the southern hemisphere (SH) circumpolar flow that forces northward OHT.
1. Introduction

The developing line of research investigates the influence of various extratropical perturbations on the mean global climate through the interhemispheric thermal gradient and, specifically, on the tropical circulation and precipitation. Early motivation can be traced to the goal to understand the nature of abrupt climate changes during glacial periods in the late Quaternary (Dansgaard et al. 1993; Alley et al. 2003). The rapid warming and cooling over the North Atlantic, recorded in Greenland ice cores (Grootes and Stuiver 1997), are reflected in the tropical Atlantic (Peterson et al. 2000; Wang et al. 2004) and the east Pacific (Koutavas and Lynch-Stieglitz 2004). The tropical rainfall in the examined regions shifts southward (northward) during rapid cooling (warming) in the North Atlantic that is typically hypothesized to stems from weakening (strengthening) of the Atlantic MOC (e.g., Broecker et al. 1985).

Proxy records and observations will always contain gaps, hence their combination with models provide a more complete understanding. Changes in high-latitude land and sea ice cover in AGCM-slab ocean models generate an interhemispheric thermal difference that shifts the global tropical precipitation away from the cooled hemisphere (Broccoli 2000; Chiang and Bitz 2005). In a series of CGCM experiments, AMOC disruption, due to additional freshwater input in the northern Atlantic, manifests various degrees of NH cooling and southward displacement of the ITCZ (Manabe et al. 1995; Zhang and Delworth 2005; Timmermann et al. 2007). Modeling studies of industrial aerosol emissions, primarily originating in the NH, show that these tend to increase the reflectivity of the atmosphere (due to higher scattering and cloud albedo) and induce NH-wide cooling that shifts the ITCZ south and weakens the NH summer monsoons (Broccoli et al. 2006; Yoshimori and Broccoli 2008).
Realistic model geometries can sometimes entangle or mask the key processes and pathways from being distinctly revealed. Thus, an idealized geometry under hypothetical conditions can enrich our understanding at a more fundamental level. The influence of prescribed extratropical surface heating perturbations, representing the OHT, on the tropical mean state in a set of AGCM-slab ocean models without land confirms the sensitivity of the ITCZ position to the interhemispheric thermal gradient (Kang et al. 2008; Kang et al. 2009). Atmospheric physics with different levels of complexity show that the amplitude of the tropical response can significantly vary with different representations of radiative, cloud and surface feedbacks, but the basic dynamical response is robust: the zonal average maximum precipitation in the tropics moves away from (toward) the cooled (warmed) hemisphere.

These findings about the remote influence of the extratropics on the global interhemispheric asymmetry and therefore on the tropical ocean-atmosphere domain enrich our understanding of the dynamics of the Hadley circulation and the ITCZ (e.g., Held and Huo 1980; Xie and Philander 1994; Philander et al. 1996). The specific configurations of the eastern coastline and the air-sea feedbacks are the key local controlling factors in the tropics (Xie 2004). We aim to contribute to the formulation of a more encompassing dynamical picture as the superposition of local and remote processes governing the tropical circulation and precipitation. Our focus is on the crucial elements of the ocean dynamics connecting upper-ocean horizontal circulation with the MOC as the source of extratropical climate perturbation. The Southern Ocean circumpolar flow is the key interhemispheric difference throughout the world oceans with crucial effects on the Earth’s cli-
mate. Various geometries of the Drake Passage\(^1\) in OGCM-atmosphere energy balance setups
(Toggweiler and Bjornsson 2000; Sijp and England 2004; Sijp and England 2005) lead to sub-
stantially different MOC, OHT and interhemispheric thermal gradient. Our paper builds on the
above-mentioned modeling studies and goes forward by employing both a dynamically resolved
ocean and atmosphere in an idealized geometry.

We examine the influence of extratropical ocean circulation on the mean coupled climate
and, specifically, on the tropical circulation and precipitation in a coupled numerical setup. Sec-
tion 2 describes our simplified CGCM, outlines a series of experiments, and presents the control
cases. Section 3 focuses on unforced interhemispheric symmetry breaking in a closed-basin
symmetric configuration. Section 4 studies the consequences of opening a circumpolar channel
with different sill depths in different hemispheres, i.e., examines the effects of tectonically forced
symmetry breaking. Section 5 summarizes results that contribute to our understanding of remote
processes controlling the tropical circulation and precipitation, and discusses possible future di-
rections.

2. Numerical setup and the control experiments

A comprehensive understanding of global and regional climate processes has the potential to
benefit society with, among other things, improved climate predictions and projections. Develop-
ing insight into such a complex system as the planetary climate (Pierrehumbert 2010) requires
analysis and modeling of various domains at different levels of complexity (Held 2005). We em-

\(^1\) The narrow body of water between Patagonia and the Antarctic Peninsula.
ploy a fully dynamical intermediate complexity climate model (ICCM) unburdened by realistic land distribution and complex atmospheric physics. Our ICCM setup is derived from the Geophysical Fluid Dynamics Laboratory (GFDL) CM2.0 (Delworth et al. 2006) in a modular way through a set of parameterization and geographic simplifications (Farneti and Vallis 2009; Vallis and Farneti 2009). ICCM is publically available from GFDL as a part of CM2 distribution (https://fms.gfdl.noaa.gov/gf).

a. Elements of idealized climate system

This CGCM solves the three-dimensional primitive equations for the atmosphere and ocean with dynamically-consistent surface exchange of momentum, heat and freshwater fluxes, but it uses rather simplified atmospheric physics. We select an idealized coarse-resolution configuration with a sector atmosphere over land without mountains and a single-basin flat-bottom ocean. The goal is to expose crucial elements of coupled dynamics in a more revealing geometrical setting, and to make the model computationally less demanding. Sector geometry with cyclic zonal boundary conditions is a conceptual heritage of the very first CGCM developed at GFDL (Manabe 1969).

The atmospheric component, with 7 vertical levels and 3.75°x3° horizontal resolution, has a sector geometry that is 120° long and spans from 84°S to 84°N. This AGCM is based on a moist B-grid dynamical core, but it uses a grey radiation scheme with the long-wave flux independent of water vapor and cloudiness (Frierson et al. 2006). The model is forced with a time-independent, zonally uniform top-of-atmosphere solar radiation that analytically mimics the observed mean profile. Solar absorption in the atmosphere is neglected. A large-scale condensation scheme is applied along with a simplified Betts-Miller convection scheme (Betts 1986, Frierson 2007); thus, humidity and temperature are adjusted when saturation occurs and precipitation falls
out immediately (there is no liquid water or clouds in the atmosphere). Eliminating water vapor and cloud feedbacks enables us to focus on a purely dynamical response of the coupled climate system to the ocean state changes.

The ocean component is the Modular Ocean Model (MOM) version 4.0 (Griffies et al. 2004) with 24 vertical levels (of thickness ranging from 10m at the top to 315m at the bottom) and 2°x2° horizontal resolution. The ocean basin is 60° wide, spans from 70°S to 70°N, and has a flat bottom that is 3.9 km deep. Circumpolar channels with various sill depths are opened in the sub-polar regions of both hemispheres to explore the impact of high-latitude zonally unconstrained flows. The ocean physics parameterizations are similar to the standard free surface MOM model incorporated in CM2.0. This OGCM has constant vertical tracer diffusivity of 0.5 cm$^2$/s. It applies the Gent-McWilliams skew flux scheme combined with a downgradient neutral diffusion that parameterizes the effects of mesoscale eddies using constant eddy tracer diffusivity of 800 m$^2$/s (Gent and McWilliams 1990; Griffies 1998). MOM4 uses a tracer-conserving convective scheme for instantaneous vertical adjustment of unstable water columns.

The dynamic-thermodynamic sea-ice model SIS (Winton 2000) is coupled within the ocean grid. The land model LM2.0 (Milly and Shmakin 2002) is configured with the atmospheric horizontal resolution. It is implemented as a collection of soil water reservoirs with constant water availability and heat capacity at each land cell. The excess precipitated water is redistributed back to the ocean at a nearby grid point. There are no mountains or glaciers, and surface albedo values are altered to obtain a realistic mean climate in the control experiments (for more details of ICCM setup see Farneti and Vallis 2009).

b. The role of ocean basin geometry
The only external forcing agents of the interhemispheric asymmetries in our experiments is the ocean basin geometry through different configurations of a circumpolar channel at subpolar latitudes. Figure 1 shows a schematic map and key geometric parameters of various ocean basins, as well as the integration timeline of our suite of experiments. The two control experiments, Exp1.0 and Exp1.0a, have a closed-basin equatorially symmetric configuration. They are initialized from no-flow symmetric initial conditions (IC) of potential temperature and salinity, and then integrated for 1500 years. Exp1.0 has zonally uniform IC with a prescribed main pycnocline. Exp1.0a starts from a dynamically quasi-balanced IC obtained from Exp1.0 outputs by using only the symmetric components (averaged from year 151 to 200). After 400 years of Exp1.0 integration, we branch out an additional set of tectonically-forced experiments through sudden opening of circumpolar channels (between 48° and 60° latitude) with various sill depths. Specifically, Exp1.1, Exp1.2, Exp1.3 and Exp1.4 have an idealized Drake Passage 102m, 480m, 2436m, and 3900m deep, respectively, while Exp1.5 features the NH equivalent that is 2436m deep. All non-zero restart fields for specific circumpolar channel cases are specified as the linear interpolation between eastern and western boundary values of Exp1.0 (at 01/01/0401) to avoid catastrophic numerical shock.

The unbalanced symmetric IC of Exp1.0 yields, from the start, fast dynamical adjustment and strong fluctuations that lead to deep MOC symmetry breaking after about 50 years (Figure 2a). Specifically, in Exp1.0 the deep-water is predominately produced in the SH (dashed black curve) and exported to the NH (red curve). The symmetric geometry and forcing of the control cases require the ensemble mean control climate to be symmetric. Different model realizations started from different IC should manifest climate asymmetry with different, randomly selected, interhemispheric signs. Exp1.0a (Figure 2b) develops, also on a multi-centennial time scale, the oppo-
The surface ocean circulation (averaged over the top 100m) in Figure 3a shows tropical, subtropical and subpolar gyres divided by zero wind stress (white) contours. The subpolar gyres are too wide in comparison to the North Atlantic due to an equatorward bias of the mid-latitude westerlies (Figure 3b). The SST (contours in Figure 3a) and surface salinity (shading in Figure 3a) distributions show influence of the precipitation pattern (shading in Figure 3b), surface currents (vectors in Figure 3a) and surface winds (vectors Figure 3b). The green (grey) horizontal lines

\[ \text{For example, SST}(y) = \frac{[\text{SST}(y) + \text{SST}(\text{-}y)]}{2} + \frac{[\text{SST}(y) - \text{SST}(\text{-}y)]}{2} = \text{SST}_s(y) + \text{SST}_a(y), \text{ where } \text{SST}_d(-y) = \text{SST}_s(y) \text{ and } \text{SST}_a(-y) = -\text{SST}_a(y). \] The basic, equatorially symmetrized, component of some fields is symmetric (e.g., } \theta, S, q, u, \text{ etc.), while in others is antisymmetric (e.g., } v, \psi, \text{ etc.).
in Figure 3a (3.b) mark the surface borders between the Hadley, Ferrell and polar cells. The red (positive) and blue (negative) contours in Figure 3b show the net surface heat flux distribution (positive upward). This distribution clearly reflects the influence of strong convergent boundary currents in the extratropical zones that coincide with a strong SST gradient which primarily manifest a strong heat release from the ocean.

The mean control climate in Figure 4a shows a well-structured meridional overturning mass streamfunction clearly displaying the atmospheric overturning cells. Figure 4b delineates the meridional distribution of the total planetary (black curve) and ocean (blue curve) energy transport along with the atmospheric moist static (red curve), dry static (purple curve) and latent (green curve) energy transport. The energy decomposition of the thermally direct Hadley circulation shows that the latent heat transport (primarily in the lower troposphere due to high specific humidity) is opposing the dominant dry static energy transport within the tropics (Trenberth and Stepaniak 2003). The realized values of the meridional heat transport components are approximately one-third of the real world values, which is expected since the sector atmosphere in only 120° long.

3. Unforced symmetry breaking

The possibility of multiple ocean equilibria, arising due to nonlinear interactions between ocean circulation and structure, and due to the inherent differences in heat and freshwater ocean-
atmosphere coupling\(^3\), has been studied for some time (e.g., Dijkstra and Ghil 2005). In a sense, our simplified symmetric CGCM is a modeling successor of Bryan (1986) numerical setup used to demonstrate for the first time the existence of the MOC interhemispheric asymmetry in a symmetric OGCM under symmetric surface forcing fields. The symmetry breaking and dominance of deep-water production in one hemisphere is caused by the advective ocean circulation-salinity feedback (Stommel 1961; Rooth 1982). An increase of surface salinity in subpolar region of one hemisphere, with the respect to the other, causes local intensification of deep-water production that leads to export of a relative excess of deep water to the other hemisphere and thus asymmetry in the deep MOC cell. Its surface branch advects additional subtropical high-salinity water towards the subpolar region with intensified deep-water production and further increases local surface salinity.

Internal variability spontaneously initiates the MOC and ocean asymmetry in our control closed-basin numerical setup. For example, Figure 2b shows that Exp1.0a gradually develops the dominant source of deep-water production in the NH (solid black curve), deep southward return flow across the equator (red curve). In the next subsection we analyze the time evolution of zonally collapsed anomalous surface fields, with respect to the symmetrized mean control state, critical for the development of interhemispheric asymmetry in the MOC and the associated anomalous surface heat flux in Exp1.0a.

\( ^a \) Development of key surface anomalies in a control experiment

\(^3\) There is a strong negative feedback between changes in SST and surface heat flux, while there is no direct dependence of surface freshwater flux on surface salinity.
The development of the anomalous northward upper-ocean transport of salinity tracer (shading in Figure 5a) that focuses the key evolution phase from Figure 2b) directly reflects buildup of the anomalous northward upper-ocean transport that constitute surface branch of the asymmetric, pole-to-pole deep MOC cell. It controls the evolution of asymmetry in surface salinity, most significantly in the extratropics (shading in Figure 5b poleward of green contours at about 36° latitude marking the poleward edges of the Hadley circulation). A decrease (increase) of salinity in the SH (NH) extratropics in Figure 5b coincides with a decrease (increase) of SST in Figure 5c, most substantially at the same latitudes, which is also due to the northward anomalous upper-ocean advection. At low temperature, water density is more sensitive to changes in salinity than temperature, hence surface salinity primarily controls long-term surface density and deep-water production in the subpolar region. The concurrent growth of SST asymmetry in the extratropics limits the growth of asymmetry in deep MOC and on oceanic long time scales induces an asymmetry in net surface heat flux (shading in Figure 5d) that the atmosphere must respond to. The surface heat flux anomalies in the extratropics have the opposite sign and much stronger amplitude than in the tropics.

The interhemispheric asymmetry in deep-water production is directly reflected in the asymmetry of SST Figure 5c) and net surface heat flux Figure 5d) at the poleward edges of the ocean basin beneath the polar cell. However, the strongest anomalies in all surface scalar fields in Figure 5 are located in the vicinity of subtropical-subpolar divide (black contours fluctuating about 42° latitude) beneath the Ferrell cell (between mid-latitude green contours). Hence, the anomalous meridional upper ocean salinity transport, a key element of the advective feedback, plays the most important role first during the poleward transition of upper-ocean water from the subtropical to subpolar gyre and then when reaching high-latitude sites of deep-water formation.
What is the underlying cause for the formation of these two distinct extratropical regions critical for the ocean heat release to the atmosphere?

b. Final steady-state surface conditions of a control experiment

The horizontal distribution of surface salinity asymmetry in the final steady state of Exp1.0a in Figure 6a (shading) shows the dynamically-controlled pattern of two key regions with the most pronounced anomalies in the extratropics: the extended region of convergence of the subtropical and subpolar western boundary currents and the eastern poleward sector of subpolar domain. The anomalies in these particular regions arise due to surface current anomalies (vectors in Figure 6a show them averaged over the top 100m) acting across the strong horizontal gradient in the symmetrized control state surface salinity (shading in Figure 3a).

The asymmetry pattern of surface currents in Figure 6a (vectors) shows that northward current anomalies along the entire western boundary and subpolar eastern boundary constitute the key contributions to the northward surface branch of deep MOC cell in Figure 2d. The contours in Figure 6a show that the two key extratropical regions of surface salinity asymmetry are also endowed with substantial asymmetry in SST due to anomalous surface currents across these regions with strong horizontal gradient in the control SST. The strong ocean forcing of the atmosphere occurs through SST change, hence there is the associated asymmetry in net surface heat flux. More precisely, contours in Figure 5b show anomalous latent heat flux (the key surface flux component for ocean heat release to the atmosphere) closely matching anomalous SST pattern in the extratropics in Figure 5a. In Exp1.0a anomalously high NH (low SH) SST in the extratropics leads to local anomalous release (uptake) of heat from (by) the ocean. The pole-to-pole deep MOC imposes the interhemispheric thermal gradient to the atmosphere most significantly
from the two specified extratropical regions. A weaker surface heat flux asymmetry in the tropics has the opposite sign.

c. Dynamic response of the atmosphere to the ocean asymmetry

The asymmetric surface heating of the atmosphere from the extratropics intrudes equatorward via large-scale eddy heat fluxes (*Kang et al.* 2008; *Kang et al.* 2009) and surface wind-evaporation-SST (WES) coupling in the region of the low-latitude easterlies (*Chiang and Bitz*, 2005; *Chiang et al.* 2008) generating an interhemispheric thermal gradient in the tropics. The low-latitude coupled atmosphere-ocean system responds by inducing an anomalous cross-equatorial Hadley cell ([Figure 7b]). The anomalous Hadley circulation facilitates the cross-equatorial AHT from the warmer to colder hemisphere (red curve in [Figure 7c]) as a response to cross-equatorial OHT from the colder to warmer hemisphere (blue curve in [Figure 7c]) controlled by the directionality of the surface branch of deep MOC. The Hadley circulation is thermally direct (e.g., *Dima and Wallace* 2003, *Webster* 2004), therefore the surface branch of the anomalous cell extends across the equator ([Figure 7b]) providing anomalous low-level moisture transport towards the warmer hemisphere (green curve in [Figure 7c]). Tropical atmosphere-ocean dynamics anchor the ascending branch of the anomalous Hadley cell and the maximum of tropical precipitation (shading in [Figure 6b] and blue curve in [Figure 7a]) in the warmer hemisphere, which is determined by the main source of deep-water production. In the extratropics, the induced asymmetry in precipitation (shading in [Figure 6b]) is opposing surface salinity asymmetry (shading in [Figure 6a]) emphasizing importance of asymmetry in surface circulation (vectors in [Figure 6a]).

Very gradual evolution of the tropical asymmetries on oceanic long time scales is characteristic for the deep-MOC-guided mechanism of the interhemispheric and tropical-extratropical
interaction and is shown, in the zonal mean sense, in Figure 7a. The buildup of the extratropical surface heat flux asymmetry\textsuperscript{4} (purple curve with NH maximum in Figure 7a) excites coherent tropical asymmetries with significant amplitude. In the tropics WES feedback (Xie 2004) plays an important role in local coupling of cross-equatorial wind stress (solid black curve with northward directionality in Figure 7a), tropical SST asymmetry (red curve with NH maximum in Figure 7a) and cumulative tropical precipitation asymmetry\textsuperscript{5} (blue curve with NH maximum in Figure 7a). The cross-equatorial “C-shape” of anomalous surface wind in Figure 6b is a signature of WES feedback that in deep tropics, on short time scales, in Exp1.0a connects the SH zone of stronger easterlies, stronger evaporation and lower SST with the NH zone of weaker easterlies, weaker evaporation and higher SST. The sign and magnitude of zonal mean tropical anomalies on multi-decadal and longer time scales in our model is controlled by the extratropical surface heat flux anomalies.

The extratropical excess (suppressed) heat release in the NH (SH) atmosphere makes it, in a thermal sense, the summer-like (winter-like) hemisphere due to a decrease (increase) of meri-

\textsuperscript{4} The asymmetry index of total extratropical net surface heat flux is defined as the half of the difference between total surface heat flux in the extratropics of the NH and the SH. Surface heat flux is positive upward, so positive (negative) values of this asymmetry index represent excess ocean heat release in the NH (SH) extratropics.

\textsuperscript{5} We use the total precipitation in the NH deep tropics, between the equator and 10°N, minus total precipitation in the SH deep tropics, between 10°S and the equator, that results with positive (negative) values if the ITCZ is in the NH (SH).
dional surface temperature gradient between the equator and extratropics in Exp1.0a. The Hadley, Ferrell and polar cells in the NH (SH) get weaker (stronger) in Figure 7b and manifest the associated asymmetries in the surface winds: weakening (strengthening) in the NH (SH) shown as anomalous surface wind vectors in Figure 6b. The equivalent behavior of unforced symmetry breaking on oceanic long time scales in the opposite direction is manifested in the evolution of Exp1.0 demonstrating the climate bistability of our closed-basin symmetric configuration. In the next section, we bring our study a step closer to the real world geometry by opening various circumpolar channels at subpolar latitudes.

4. Forced symmetry breaking

The forced change of the MOC is a powerful driver for change of the global climate because it can substantially alter ocean-atmosphere heat exchange in the extratropics. We externally force our coupled system through changes in the basin boundary conditions in time. This approach is conceptually motivated by tectonic history of our planet’s surface. Specifically, the sudden opening of various circumpolar channels in Exp1.1 through Exp1.5 (starting from Exp1.0 at 01/01/0401) forces an interhemispheric asymmetry in the extratropical ocean circulation and the MOC. What is the role of the circumpolar current? In this section we examine whether such boundary-forced change in the ocean circulation at subpolar latitudes alters the MOC and tropical climate in an equivalent manner as in the control experiments.

a. Development of key surface anomalies in a forced experiment

Exp1.3 opens the SH circumpolar channel approximately 2.5km deep close to the topography of Scotia Ridges in the South Atlantic that are the major obstacles to the Antarctic Circumpolar Current exiting the Drake Passage. Shading in Figure 8a shows that initial development of
southward anomalous upper-ocean salinity transport in Exp1.0, that intensifies SH deep-water
production (Figure 2a until year 400), is very quickly inverted in the SH after the channel opens.
The rapidly formed circumpolar flow prevents establishment of a net zonal pressure gradient,
and hence it constraints the geostrophic component of the circulation to have zero net meridional
flow above the sill level and suppresses meridional transport. Substantial weakening of poleward
salinity transport in the upper ocean, with respect to the symmetrized control state, shows as a
strong northward anomalous transport that rapidly reduces surface salinity south of the circumpolar
current (shading in Figure 8b). This locally decreases surface density, and suppresses
deep-water production and ocean heat release. The concurrent decrease of SST (shading in Figure 8c)
due to reduction of poleward transport of warm water, opposes surface salinity decrease
in control over surface density, but salinity change is more important at low temperatures. SST
decrease south of the circumpolar channel also causes sea-ice expansion and further weakens
upward surface heat flux at the poleward edge of the basin (shading in Figure 8d).

The transition of deep-water production to the NH is primarily facilitated via oceanic tele-
connection pathways using the Kelvin waves along the boundaries and at the equator, and the
westward Rossby waves in the basin interior (e.g., Kawase 1987, Johnson and Marshall 2004).
The signal about opening of circumpolar channel and consequent shut down of deep-water for-
mation in the SH is transmitted northward as anomalous deepening of isopycnals throughout the
basin (not shown). The equator acts as a high-frequency filter for change of the main pycnocline
depth (Johnson and Marshall 2004) and deep MOC source in the NH since the large-scale deep-
water production rate is proportional to square of the main pycnocline depth (e.g., Vallis 2006).
It takes several decades for anomalous surface salinity and temperature to rise significantly in the
NH extratropics (Figure 8b and 8.c) due to delayed intensification of the NH deep-water production.

The anomalous SST rise in the NH extratropics yields again the two key regions of surface net heat flux asymmetry formed close to the equatorward and poleward edges of the subpolar gyre. The opening of the SH circumpolar channel yields the strongest suppression of ocean heat release south of the circumpolar current in the polar cell, while in the NH the maximum of ocean heat release takes place in the region of intensified transformation of upper-ocean water from subtropical to subpolar gyre (shading in Figure 8d). The anomalies of net surface heat flux in the tropics and extratropics in Figure 8d have predominately the opposite sign in a hemisphere, and anomaly values in the tropics, due to the strong ocean-atmosphere coupling, are significantly smaller than in the extratropics.

b. Final steady state of a forced experiment

Surface conditions in Exp1.3 evolve to the steady state with the surface interhemispheric asymmetry shown in Figure 9. The circumpolar current in the SH disrupts poleward upper-ocean transport, most importantly along the eastern boundary in the subpolar domain (vectors in Figure 9.a), cooling (contours in Figure 9.a) and freshening (shading in Figure 9.a) the surface region of SH deep-water production. The resulting decrease of SH high-latitude surface density eventually moves the deep-water production to the NH. The northward orientation of the surface branch of the deep pole-to-pole MOC cell is evident as a strong anomalous northward flow along the western boundary in Figure 9.a. The northward anomalous advection across the extended western subtropical-subpolar divide is critical for the increase (decrease) of surface salinity in the NH (SH) extratropics. Ultimately, the anomalous northward eastern boundary flow in the NH subpolar domain injects additional salinity toward the region of deep-water source.
The surface current asymmetry pattern again manifests two key regions of anomalies in surface scalar fields of interest in the extratropics: in the vicinity of subtropical-subpolar divide and at the high-latitude region of deep-water formation. The extratropical SST asymmetry (contours in Figure 9.a) causes the dominant latent heat flux asymmetry (contours in Figure 9.b) that induces the climate response similar to the climate asymmetry in Exp1.0a, but with stronger magnitude. The surface wind asymmetry in Figure 9.b confirms that NH (SH) becomes, in a thermal sense, the summer-like (winter-like) hemisphere with weaker (stronger) winds. The tropical ocean-atmosphere system responds in similar manner as discussed in section 3.3. The anomalous Hadley cell in Exp1.3 has the same sign but stronger amplitude than in Exp1.0a (Figure 7b) and the ITCZ northward asymmetry is more pronounced (shading in Figure 9.b). Likewise, the anomalous components of ocean-atmosphere meridional energy transport in Exp1.3 have similar structure as in Exp1.0a (Figure 7c), but with higher amplitudes.

The stronger surface current and surface heat flux anomalies in Exp1.3 (Figure 9) as compared with Exp1.0a (Figure 6) lead us to expect stronger NH deep-water production in Exp1.3. The steady-state MOC streamfunction in Figure 10 confirms a stronger asymmetry in the deep MOC cell, with respect to Figure 2d, forced by the circumpolar flow in the SH that disrupts critical poleward salinity transport. The zonally averaged anomalous salinity in Exp1.3 (red-positive and blue-negative contours in Figure 10) shows impact of anomalous northward upper-ocean salinity transport (schematic red arrow in Figure 10). The SH upper ocean exports salinity to the NH and significantly freshens its source region. In the NH intensified deep-water production sequesters excess salt below the upper ocean primarily through the core of southward deep-water flow across the equator.
The surface and interior salinity asymmetry in Exp1.3 is a direct product of the asymmetry in ocean circulation, because in the extratropics asymmetry in precipitation (shading in Figure 10b) is opposing asymmetry in surface salinity (shading in Figure 10a). The blue and red arrows in Figure 10 schematically depict directionality of established interhemispheric water and heat cycle in Exp1.3 (and Exp1.0a). The gray arrows show the direction of the cross-equatorial Hadley circulation that is the critical element of interhemispheric interaction forced in our experiments by the asymmetry in deep MOC and surface heat flux from the extratropics. The upper branch of the anomalous Hadley cell transports excess atmospheric heat southward from the warmed hemisphere. The surface branch of anomalous Hadley cell brings excess moisture northward to the tropics of the warmed hemisphere where coupled ocean-atmosphere dynamics establishes the maximum of tropical precipitation (vertical blue lines in Figure 2 schematically point to the position of ITCZ).

c. **Climate sensitivity to sill depth of a circumpolar channel**

The opening of the Drake Passage and tectonic history of the entire circum-Antarctic pathway have had an important influence on the evolution of Cenozoic climate (e.g., Baker and Thomas 2004). The anatomy of physical and biogeochemical mechanisms responsible for the prevailing cooling over the last 65 million years continues to be a very active area of research. This gives us additional motivation to investigate the response of climate asymmetry to changes in the sill depth of the circumpolar channel. Comparison of Exp1.1, Exp1.2, Exp1.3 and Exp1.4 with sill depths of 102m, 480m, 2436m and 3900m (basin bottom) in the SH, respectively, enables us to examine the response of the upper-ocean meridional salinity transport and its role in the deep MOC and climate asymmetry.
The vertical distributions of zonally integrated anomalous meridional salinity transport in Figure 11 (shading) show that most significant change occurs from Exp1.0 to Exp1.2. Exp1.4 (not shown) with the sill depth matching bottom of the ocean gives result very similar to Exp1.3. When a circumpolar channel completely blocks the upper-ocean meridional transport (roughly top 500m), further deepening of the sill level induces no relevant change in the salinity decrease (contours in Figure 11) that suppresses deep-water formation poleward of the circumpolar current. In Exp1.1, below the sill level at 102m, there is still a significant net geostrophic component of the poleward upper-ocean flow. The steady-state MOC streamfunction of Exp1.2, Exp1.3 and Exp1.4 are essentially indistinguishable, while Exp1.1 has a similar but weaker deep pole-to-pole MOC cell (not shown).

The evolution of the deep MOC asymmetry\textsuperscript{6} in Exp1.2 (green curve), Exp1.3 (blue curve) and Exp1.4 (brown curve) in Figure 12.a is parallel after opening of their circumpolar channels. These three experiments manifest the same multi-decadal time scale for the transition of deep-water source from the SH in Exp1.0 to the NH. Exp1.1 (red curve in Figure 12.a) develops a weaker deep-water production in the NH on even longer time scale because there is still a sufficient amount of the subtropical upper-ocean high-salinity water being advected southward below

\textsuperscript{6} The deep MOC asymmetry index used is defined as the sum of the extratropical subsurface maximum in NH and minimum in SH of MOC streamfunction representing a low-order measure of difference in deep-water production between hemispheres. In our convection, a strong deep-water production in the NH (SH) is characterized by a high positive (low negative) subsurface extremum of the MOC streamfunction in the NH (SH) extratropics.
the circumpolar channel to prevent complete shut down of the SH deep-water production. These results show that forced deep MOC asymmetry strongly depends on how much of the upper-ocean meridional transport is vertically obstructed by the circumpolar flow.

Closely following the evolution of deep MOC asymmetry, the associated asymmetry of the net surface heat flux in the extratropics (Figure 12b) projects the ocean state asymmetry dependence on a circumpolar channel sill depth throughout the coupled global climate. The tropical ocean-atmosphere domain adjusts in all experiments as previously discussed by inducing a cross-equatorial Hadley circulation. Figure 12c and Figure 12d show that the zonally averaged surface cross-equatorial wind (i.e., surface branch of anomalous Hadley cell) and the total tropical precipitation asymmetry, respectively, reflect a similar dependence on sill depth that gets saturated as we lower the channel bottom below the main pycnocline depth (about 500m when averaged over the subtropical gyre). In our model the atmosphere cannot distinguish whether a circumpolar channel is 500m deep or it reaches all the way to the ocean bottom. Figure 12 overall shows the prevailing linear scaling of all pairs of the presented asymmetry indices stemming from the hemispheric location and strength of the deep-water source.

5. Conclusions and future directions

We have investigated the dynamics of interhemispheric asymmetry in ocean circulation and climate in an idealized CGCM. The unforced and forced symmetry breaking in the upper-ocean meridional salinity transport in the extratropics leads to a substantial asymmetry in the MOC and ocean structure. The associated asymmetry in the OHT and the SST breaks the coupled climate symmetry through the development of the key asymmetry in the extratropical surface heat flux. The two distinct regions of anomalous ocean heat release in the extratropics, organized by the
upper ocean dynamics, are the extended confluence region of subtropical and subpolar western
boundary currents beneath the Ferrell cell and the high-latitude region of deep-water production
beneath the polar cell. The resulting thermal asymmetry causes the interhemispheric interaction
that is mediated in the atmosphere across the equator via an anomalous Hadley cell. Its energy
transport partially compensates the cross-equatorial OHT in the opposite direction. Excess mois-
ture in the tropics of the warmer hemisphere anchors the maximum of tropical precipitation
there, which in the experiments with a circumpolar channel is always in the opposite hemisphere
from the channel. In our fully dynamical coupled climate model, the time evolution of interhe-
mispheric asymmetry of the mean tropical climate, including the shift of ITCZ, takes place on
multi-decadal to multi-centennial time scales determined by the development of the deep MOC
asymmetry.

The two control experiments with the same closed-basin symmetric geometry (started from
different symmetric IC) demonstrate the interhemispheric climate bistability due to the advective
feedback that amplifies asymmetry in the upper-ocean meridional salinity transport and the deep
MOC. The set of tectonically forced open-basin experiments with various circumpolar channels
further points to the importance of the upper-ocean meridional salinity transport for the evolution
of MOC. The opening of a channel in the SH subpolar domain enables the establishment of a cir-
cumpolar current that suppresses the poleward transport of salinity and suppresses the deep-
water formation in the SH. In the extratropics, surface salinity and density are more influenced
by the upper ocean circulation than by precipitation, while surface heat flux is critical for the
subtropical-to-subpolar water transformation and the formation of deep water. Lowering of the
channel sill through the upper part of a water column substantially alters the MOC and surface
heat flux asymmetry, leading to a drastic change in the tropical ocean-atmosphere system. Lowering the sill depth further below approximately 500m produces a saturated response.

The atmosphere quickly adjusts to the ocean asymmetry. The upper panel in Figure 13 shows that through the whole suite of experiments (including Exp1.5 that is the equatorially-mirrored case from Exp1.3), and in all transient and equilibrated states, the interhemispheric difference in the meridional upper-ocean salinity transport between the subtropical and subpolar gyre, that controls the deep MOC and extratropical surface heat flux asymmetry, is a good linear predictor of the cumulative precipitation asymmetry in the tropics. The anomalous northward (southward) upper-ocean salinity transport, most importantly at the subtropical-subpolar divide, yields the NH (SH) deep-water production and the tropical precipitation maximum north (south) of the equator. The lower panel in Figure 13 shows in a similar way that more asymmetric deep MOC leads to a deeper and wider lower equatorial pycnocline. This behavior reflects the activity of the oceanic wave teleconnections that utilize the equatorial Kelvin waves for the transmission of isopycnal anomaly signals carrying information about the deep MOC change between the hemispheres. Our model demonstrates that water-mass transformation in the extratropics can have a significant impact on the tropical pycnocline. A dependence of the upper-ocean tropical structure on the deep MOC asymmetry in a realistic CGCM could potentially reveal a mechanism for the MOC influence on the tropical ocean-atmosphere variability.

The climate transition from a closed-basin bistability to a circumpolar channel forced asymmetry by means of establishing a circumpolar current presents us with an intriguing result that the Southern Ocean circulation can exert (through the MOC and surface heat flux asymmetry) an important influence over the tropical circulation and the ITCZ. In the most general sense, the tropical circulation and precipitation are controlled in different regions around the globe by the
superposition of local and remote processes. This motivates us to consider the introduction of additional geometric elements, approximating real-world features, which have the potential to break the climate symmetry from the tropics and compete them against extratropical forcing agents.

The follow-up study compares the role of a slanted tropical coastline and a tropical zonal channel with the role of a circumpolar channel in the generation of the interhemispheric and tropical asymmetries. Further expansion from single-basin to multi-basin configurations will bring us closer to the real-world complexity through the introduction of an interbasin interaction and an asymmetric land-mass distribution. Another future direction of study is the increase in complexity of atmospheric physics. With a grey atmosphere we have explored only the minimal dynamic response of the atmosphere to the ocean asymmetry (Kang et al. 2009). The role of water vapor and cloud feedbacks in the interhemispheric and tropical-extratropical interaction merits investigations with both idealized and realistic geometries.

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