Global impacts of the Drake Passage on ocean circulation and climate as modulated by the Ismuth of Panama.

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DEDICATION

Je dédie ce document à tous ceux qui ont supporté ma prose plaintive exacerbé par mon anxiété lors de la rédaction ce cette thèse. Plus particulirement, je voudrais remercier ma compagne qui essuyât plus d'une fois mes excès de stress. Elle doppa ma confiance et ma motivation et me donna envie de prouver mes capacités. Je désir aussi dédider ce document á ma famille : ma mère qui crut toujours en moi, ma soeur qui présentement suit mes pas. Quant à mon père : l'existence de ce document est un premier accomplissement concret, j'espère donc que cette reconnaissance nourrira sa fierté. Grace eux, je n'ai qu'un seul objectif en tête et je suis plus que jamais prêt à le réaliser: La Science pour la Science et devenir le meilleur.

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ABSTRACT

The Eocene-Oligocene boundary marked the transition from a very warm to a much cooler global climate, and the first appearance of large ice sheets in Antarctica. The opening of the Drake Passage and hence the establishment of the Antarctic Circumpolar Current (ACC) has been proposed as a mechanism for the dramatic Southern Hemisphere cooling at this time. Previous modelling studies explicitly addressing the impact of the Drake Passage used models with simple representations of an atmosphere, and did not consider the Panamanian Seaway, which was open at the time, allowing Atlantic and Pacific waters to exchange. Here, a coupled, fully-dynamic climate model is used to simulate the ocean circulation and climate impacts of the Drake Passage as modulated by the presence or absence of the Ismuth of Panama. With the Panama Ismuth, closing the Drake Passage does not lead to a shutdown of northern overturning, as commonly observed in simpler models, and the temperature impact on Antarctica is similar to prior estimates. In this case, Antarctic cooling reflects the thermal isolation of Antarctica, as warm subtropical waters cannot pass the geostrophic barrier of the Drake Passage. Without the Panama Isthmus, a salinity threshold is reached in the North Atlantic, leading to the cessation of northern overturning and dominance of southern overturning. In the case with no Panama Isthmus, the cooling of surface air temperatures over Antarctica caused by the Drake Passage is 3 $\times$ larger than the case with a Panama Isthmus. The larger temperature change reflects the additional onset of inter-hemispheric overturning, transferring heat from the Southern Hemisphere to the Northern Hemisphere, as well as an atmospheric radiative feedback driven by changes in cloud distributions.

RÉSUMÉ

La frontière Éocène-Oligocène marque la transition d'un climat chaud à un climat globallement plus frais, et l'apparition de larges calottes glacière en Antarctique. L'ouverture du Passage de Drake et donc l'établissement du Courant Circumpolaire Antarctique a été proposé comme un mécanisme permettant le refroidissement drastique de l'hémisèphre sud à cette époque. Des expériences passées de modélisation traitant explicitement des impacts du Passage de Drake utilisent des modèles ne représentant l'atmosphère que de façon simple sans considérer la route maritime du Panama qui ouverte à cette époque, permettait des échanges entre l'Atlantique et le Pacifique. Dans cette étude, un modèle couplé et complètement dynamique est utilisé pour simuler les impacts du Passage de Drake sur la circulation océanique ainsi que sur le climat, tout cela modulé par la présence ou l'absence de l'Isthme de Panama. Avec un Isthme de Panama, la fermeture du Passage de Drake ne résulte pas en l'arrêt de la Circulation Méridienne du Nord comme comunément observé avec de modèles simples malgrés le fait que la réaction de température soit similaire aux estimations passées. Dans ce cas-ci le refroidissement est causé par une isolation thermale de l'Antarctique résultant en l'impossibilité des eaux subtropicales chaudes de franchir la barrière géostropique du Passage de Drake. Sans l'Isthme de Panama, un seuil de salinité est atteint dans l'Atlantique Nord conduisant a la céssation de la Circulation Méridienne du Nord ainsi que la domination de celle du sud. Dans le cas ou l'Isthme de Panama est enlevé, le refroisdissement de la température atmopshérique de surface sur l'Antarctique résultant de l'ouverture du Passage de Drake est 3 $\times$ plus importante que dans le cas ou l'Isthme de Panama est présent. Cette réaction de température plus intense est le résultat de l'enclenchement de la

Circulation Méridienne du Nord qui transfére de la chaleur de l'Hémisphère Sud à l'Hémisphère Nord et d'une réaction radiative de l'atmosphère résultant de changements dans la distribution des nuages

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Chapter 1
Introduction

The Eocene-Oligocene boundary, 34 Ma, marks the transition between the warm climate of the Eocene and the cooler climate of the Oligocene. This transition is accompanied by a sharp +1.5 ‰ increase in the δ^{18}O of benthic foraminifera associated with cooling and onset of permanent ice over Antarctica (Kennett and Shackleton 1975, Miller *et al.* 1987, Zachos *et al.* 1996, Diester-Haass and Zahn 2001), a +1 ‰ marine δ^{13}C excursion (Zachos *et al.* 1996), a drop in atmospheric CO_2 (Pagani *et al.* (2005), Pearson *et al.* 2009, Pagani *et al.* 2011) and a permanent deepening of the calcite compensation depth (Coxall *et al.* 2005).

Two mechanisms have been proposed as the driver for the onset of Southern Hemisphere glaciation. The first one was formulated by Kennett (1977) who suggested that the opening of the Drake Passage and hence the onset of the Antarctic Circumpolar Current (ACC) would have thermally insulated Antarctica enabling the growth of its ice sheet. The second mechanism places the Eocene-Oligocene boundary decline in atmospheric pCO_2 as the main driver for reaching the temperature threshold enabling the onset of permanent ice in the Southern Hemisphere (DeConto and Pollard 2003).

Whether CO_2 is considered or not, modelling experiments studying the opening of the Drake Passage used either very simple representations of oceans (DeConto and Pollard 2003) or no dynamic atmosphere (Nong *et al.* 2000, Sijp and England 2004, Sijp and England 2009, Sijp *et al.* 2009a) which could result in a lower climate sensitivity. We therefore concentrate on the climate impacts resulting from the the Drake Passage opening using a state of the art fully-coupled and fully-dynamic general circulation model.

Another gateway also needs to be considered. The Panama seaway, which only started restricting $\sim$ 14Ma, provided an equatorial pathway between the Pacific and the Atlantic at the time of ACC establishment. This study will therefore investigate the opening of the Drake Passage both with the presence and absence of the Panamanian Ismuth.

We start in this chapter with a comprehensive review of data compilations and modelling experiments related to the study of Southern Ocean gateways opening. Chapter two presents the model that will be used to study the different gateway configurations as well as the experimental design. Chapter three, the core of this thesis, presents the results and analysis - coupled climate impacts of the Drake Passage as modulated by the Ismuth of Panama - work that is to be submitted to Journal of Climate. Chapter five presents the conclusions of this thesis and suggests potential future work. Finally, an appendix presents a full freshwater budget for each simulation as well as the method employed.

1.1 Timing of the onset of the Antarctic Circumpolar Current

In the Eocene, two barriers prevented the establishment of a modern ACC. South America was connected to Antarctica preventing the formation of a circumpolar channel, while Australia wasn't separated yet from Antarctica forcing any potential current northward, around it. The establishment of a modern ACC was therefore only possible after both the opening of the Drake Passage and the Tasman seaway.

1.1.1 Timing of the opening of the Tasman gateway

The opening of the Tasman was first addressed by Kennett (1977) who estimated from tectonic reconstructions that a deep water pathway would only have been possible following the Eocene-Oligocene boundary. Stickley *et al.* (2004) integrate micropaleontological, sedimentological, geochemical and paleomagnetic data from ocean drilling program leg 189 (Exon *et al.* 2001) in the east Tasman plateau to provide a time evolution of the deepening of the Tasman gateway. They identify four phases in the deepening of the sill with initial shallow opening 35.5 Ma, increased deepening from 35.5 to 33.5 Ma, deepening to bathyal depth from 33.5 to 30.5 Ma and establishment of modern stable oligotrophic open ocean after 30.5 Ma.

1.1.2 Timing of the opening of the Drake Passage

The earliest identified magnetic anomalies pointed to an opening in the late Oligocene (Barker and Burrell 1977) although major plate motions placed the tip of the Antarctic Peninsula well to the east of the southern end of South America by 30Ma. Lawver and Gahagan (2003) stated that major plate motions require that an unrestricted deep passage for the ACC existed at the Drake Passage by 28 Ma, setting a date for the onset of ACC to 31 Ma.

More recent plate reconstructions, on the other hand, suggest that an initial shallow (<1000m) gateway opening formed in the middle Eocene, followed by a slow deepening that would have allowed deep waters to exchange 34 to 30 Ma (Livermore *et al.* 2005, Livermore *et al.* 2007). This is consistent with Scher and Martin (2006) who estimate using neodymium isotope ratios at the Aghulas Ridge an influx of shallow Pacific water to the Atlantic approximately 41 Ma.

These recent estimates set the order of events as follows : the onset of a proto-ACC with deep water exchange between the Pacific and the Atlantic through the Drake Passage in the late Eocene, followed by a rapid deepening of the Tasman gateway at the Eocene-Oligocene boundary allowing a fully mature ACC to form.

In the Eocene, the northern end of what is today Australia did not exceed 30 °S. A closed Tasman gateway would therefore only have created a large meander of the ACC. As we are interested in the establishment of the ACC we ignore the opening of the Tasman gateway keeping in mind that it would have had an additional impact beyond what is studied here.

1.1.3 Modelling the impacts of the Drake Passage opening

Two categories of modelling procedures studying the establishment of the ACC can be identified. The first one studies the climate and oceanic circulation responses resulting from closing the Drake Passage with modern paleo-geography and boundary conditions (Mikolajewicz *et al.* 1993, Nong *et al.* 2000, Sijp and England 2004, Sijp and England 2009). The second one addresses the relative contribution and importance of both pCO_2 and the opening of the Drake Passage to the Eocene-Oligocene cooling some with modern paleo-geography (Sijp *et al.* 2009b) and others with attempted reconstructions of Eocene bathymetry and boundary conditions (Huber and Nof 2006, Zhang *et al.* 2010).

Simulating the response of a closed Drake Passage with modern paleo-geography has been done with a variety of model complexities spanning ocean-only (Mikolajewicz *et al.* 1993, Nong *et al.* 2000) to ocean-ice models with simple representations of an atmosphere (Sijp and England 2004, Sijp and England 2009). With these more recent models allowing salinity and sea ice feedback controls on the Meridional Overturning Circulation (MOC), Sijp and England (2004) find, upon closing the Drake Passage that North Atlantic Deep Waters stop forming, a 3.7 °C surface air temperature warming zonally and little Antarctic sea ice. In this model, the atmosphere is not dynamic and uses simple parametrization of atmospheric moisture transport. Sijp and England (2009) revisit their study by using larger moisture diffusion coefficients to achieve more realistic atmospheric moisture transport to find upon closing the Drake Passage that NADW is still forming.

The relative contribution of atmospheric pCO_2 and opening of the Drake Passage to the formation of the Antarctic ice sheet is addressed by DeConto and Pollard (2003). The authors conclude that it is the CO_2 decline that drives the formation of the ice sheet while the opening of Southern Ocean gateways only played a secondary role. However, due to the long timescale span of ice sheet formation and orbital cycles, the authors use a very simple 50m 1-layer ocean in which opening of Southern Ocean gateway is represented through matching the heat transport to previous estimates (Toggweiler and Bjornsson 2000, Nong *et al.* 2000). These estimates are in the low-sensitivity spectrum estimate especially when looking at recent studies such as Sijp *et al.* (2009a), who find a greater sensitivity of Antarctic temperature changes to the closing of the Drake Passage when forced with high pCO_2.

Huber and Nof (2006) study the impacts of the Drake Passage opening under reconstructed Eocene bathymetry with a variety of atmospheric pcO_2 to find that changes in Southern Ocean gateways only played a minor role in the Eocene-Oligocene boundary cooling. However, coarse resolution models may have unrealistic simulations of flow in narrow basins and passages leading to unanticipated spurious results.

Finally, Zhang *et al.* (2010) also use a coupled model with reconstructed Eocene topography and high pCO_2 to find that the sensitivity to the Drake Passage opening is small. However, the authors spin up the high CO_2 simulation for 1500 years which is not enough to get correct deep ocean temperature and global steady state oceanic circulation. Furthermore, the closed Drake Passage experiments are run for only 500 years, which is insufficient to achieve steady state.

We therefore want to concentrate on the effect of the Drake Passage opening on climate sensitivity and ocean circulation with a more recent fully-coupled and fully-dynamic model. More specifically, we want to test with a model allowing dynamic moisture transport the result of Sijp and England (2009) who find a different circulation response to the opening of the Drake Passage when allowing more realistic parametrization of atmospheric moisture transport which would put at test previous sensitivity experiments.

1.2 Panama Isumth

At the Eocene-Oligocene boundary, the Panamanian seaway was opened, allowing waters to exchange between the Pacific and the Atlantic basins. It is therefore important to understand the effect of an opened Panamanian Ismuth on climate. Here we review the timing of this gateway closure as well as past modelling experiments investigating the climate and ocean circulation impacts of the formation of the Isumth of Panama.

1.2.1 Timing of the closing of the Isumth of Panama

In the mid-Miocene, the throughflow between South and North America progressively restricted until complete closure sometime in the Pliocene. The final closure of the Panama Seaway has been proposed as a mechanism for the intensification of the Northern Hemisphere Glaciation around 3 Ma (Keigwin 1982, Marshall *et al.* 1982, Bartoli *et al.* 2005). Although it seems clear that the two events are linked, the exact timing and causality between the two events remain uncertain (Berggren and Hollister 1974, Wefer *et al.* 1996, Haug and Tiedemann 1998; Driscoll and Haug 1998).

Paleorecords from the Aratro Basin show an initial restriction of the Panama seaway 12 to 13 Ma with continued shoaling 8 to 6 Ma. Evidence from the timing of the tectonic development in Central America suggest that deep waters probably stopped exchanging around 7 Ma (Molnar 2008). Surface water exchanges between the Eastern Equatorial Pacific and the Atlantic started diminishing around 4.4 Ma, leading to the build up of the modern Pacific-Caribbean salinity contrasts, the formation of the Western Atlantic warm Pool (Keigwin 1982, Haug *et al.* 2001, Steph *et al.* 2006) and rising temperature in the Caribbean (Groeneveld *et al.* 2008). The Panama Ismuth closed around 2 to 3 Ma (Marshall *et al.* 1982, Molnar 2008) coinciding with the onset of the Northern Hemisphere Glaciation.

1.2.2 Modeling the climate impacts of the Ismuth of Panama

Modelling studies have investigated the sensitivity of the climate system to an opening of the Panama Ismuth (Maier-Reimer *et al.* 1990, Mikolajewicz *et al.* 1993, Mikolajewicz and Crowley (1997), Murdock *et al.* (1997)). Upon opening the seaway, these early works find a flow of fresher Pacific water to the Atlantic, leading to a shutdown of the MOC, therefore reducing poleward heat transport in the Northern Hemisphere. A later study by Nisancioglu *et al.* (2003) finds that opening the Panama Ismuth still allows a significant amount (10 Sv) of NADW to be produced with a deep return flow into the Pacific. The closing/opening of the Ismuth and the resulting redistribution of heat in the Northern Hemisphere is also thought to have acted as a switch for the relative strength of the north-eastern and south-eastern African coastal upwelling system referred to as "the upwelling seesaw" (Prange and Schulz 2004). Later studies tried to relate the onset of the NHG to the final closure of the central America seaway.

The Panama hypothesis proposed by Keigwin (1982) states that the closure of the Panama Ismuth would have increased the MOC leading to the intensification of boundary currents - most notably the Gulf stream. This would in turn have increased northward heat transport and evaporation in the North Atlantic, hence increased moisture fluxes to the northern latitudes. One question that was raised is the relative importance of increased heat transport that would act to delay the NHG and the increased moisture transport which would feed the ice-albedo feedback and intensify the NHG. Klocker and Schulz (2005) find that while orbital forcing efficiently control the extension of the perrenial snow cover, the closure of the Panamanian Ismuth does not intensify the NHG. More recently, Lunt *et al.* (2008) find, forcing an ice sheet model with results from a coupled GCM, a 5 cm reduction in sea level upon closing the seaway, confirming that the closure of the Panama Ismuth might only have slightly enhanced or advanced the onset of the NHG. Finally, Schneider and Schmittner (2006) studied for the first time the impact of the closure of the Panama Ismuth on marine productivity and nutrient cycling. Upon shallowing the Panama Ismuth, they find a reduction in the North Atlantic biological productivity due to the reduced flow of nutrient-rich Pacific sub-surface waters. This in turn leads to the accumulation of nutrients in the Eastern Tropical Pacific and hence a strong increase in productivity.

The Panama seaway, which only started significantly restricting 12-13 Ma would therefore have provided an exchange pathway between the Pacific and the Atlantic at the time of Drake Passage opening. The response of the opening of the Drake Passage without an Ismuth of Panama has yet to be investigated with coupled models.

1.3 Onset of Southern Hemisphere glaciation

Beginning with the Eocene-Oligocene boundary (34 Ma), the Earth became increasingly glaciated (Zachos *et al.* 2001, Miller *et al.* 1987, Miller *et al.* 1991). The E-O boundary is characterized by a +1.5 ‰ marine δ^{18}O excursion that is well documented (Kennett and Shackleton 1975, Miller *et al.* 1987, Zachos *et al.* 1996, Diester-Haass and Zahn 2001, Coxall *et al.* 2005) and a 1km deepening of the calcite compensation depth (CCD) (Coxall *et al.* 2005). The relative importance of the temperature and the ice volume contribution to the $\delta^{18}O$ signal has been debated for a long time. Some attributed this positive excursion solely to temperature (Savin *et al.* 1975, Kennett and Shackleton 1975), some to moderate ice volumes (Keigwin 1980, Keigwin and Corliss 1986, Miller and Curry 1982, Murphy and Kennett 1986, Shackleton 1986) and others to significant ice volumes (Poore and Matthews 1984, Prentice and Matthews 1988).

More recently, benthic foraminiferal $\delta^{18}O$ measurement were combined with a deep sea temperature proxy (foraminiferal Mg/Ca ratio) as an attempt to decouple the temperature and ice volume signal (Lear *et al.* 2000, Lear *et al.* 2004, Billups and Schrag 2003). This attempt at decoupling temperature from ice volume failed as benthic foramineferal Mg/Ca are influenced by deep carbonate ion concentration (Elderfield *et al.* 2006) such that only foraminefera deposited above the CCD can be used as a temperature proxy. Instead, shallow water Mg/Ca ratios are used to show a cooling through the Eocene-Oligocene transition of approximately 2.5 °C (C.H. Lear *et al.* 2008, Katz *et al.* 2008). Furthermore, a recent study using organic bio-markers confirmed sea surface temperature cooling during the Eocene-Oligocene transition (Liu *et al.* 2009)

It is now agreed the $\delta^{18}O_{SW}$ contribution to the full $\delta^{18}O$ E-OP signal is of about 0.6‰, corresponding to approximately 80% of the present day east antarctic ice volume (Peck *et al.* 2010, C.H. Lear *et al.* 2008, Bohaty *et al.* 2012).

1.4 Changes in deep water formation sites through the Eocene-Oligocene boundary

It has been suggested that during the warm Eocene, deep waters were formed solely at high southern latitudes. Indeed, early studies infer from erosional events in seismic disconformity (Mountain 1992) and from benthic foraminifera $\delta^{13}C$ (Wright and Miller 1993) that the Southern Ocean was probably the dominant deep water source in the Eocene. This was further supported by Thomas and Bralower 2003 who used fish tooth neodymium isotopic reconstructions to find that both the Indian and the Atlantic deep and bottom waters were probably sourced by the Southern Ocean.

A first step towards the establishment of modern overturning was the onset of deep water formation in the Northern Hemisphere. Today North Atlantic deep water (NADW) is composed of waters from the Nordic seas and waters from the Labrador Sea. It is widely assumed that the first stages of significant deep water formation in the North Atlantic overflowed from the nordic seas because of their latitudinal position (Wright and Miller 1996,Davies *et al.* 2001, Thomas 2006) . This proto-NADW is often designated as Northern component waters (NCW). Early studies, estimated by correlating North Atlantic deep water circulation to Icelandic mantle plume activities (Wright and Miller 1996), the onset of NCW to be in the middle Miocene. The discovery of a new drift deposited in a southerly flow regime (Davies *et al.* 2001) leads to the conclusion that the onset of NCW was much earlier than previously estimated : in the late Eocene to early Oligocene. This is also supported by Thomas 2006 who presents fish tooth neodymium isotopic data suggesting the deep south-eastern Atlantic and southern Pacific were dominated by waters formed in the Southern Ocean until the early Oligocene. They attribute the early Oligocene divergence in neodymium isotopic values from the two locations to the onset of NCW.

Evidence therefore point to a circulation dominated by southern overturning in the Eocene with an early Oligocene onset of Northern overturning.

Chapter 2
Methods

2.1 The model

CM2Mc is a 3° resolution version of the Geophysical Fluid Laboratory coupled ocean-ice-atmosphere GCM which uses code similar to CM2.1 (Delworth *et al.* 2006). A complete description of the model can be found in Galbraith *et al.* (2011). The modular ocean model MOM4p1 is integrated with a grid of zonal resolution of 2.5°, varying in the meridional dimension according to latitude, with finest resolution at the equator of 0.6 °. It includes 28 vertical levels defined by pressure, the top eight being 10db thick and the lower levels increasing in thickness with depth. Partial bottom cells (Adcroft *et al.* 1997) allow realistic bathymetry. Lateral diffusion and skew diffusion of tracers along isopycnals is represented using the parameterization of Gent and Mcwilliams (1990) with a spatially varying diffusion coefficient, A_{GM}, as determined in CM2.1. The model uses a background vertical diffusivity of $0.1 \times 10^{-4}\ m^2 s^{-1}$ with intense vertical mixing near rough topography that is a function of stratification (Simmons *et al.* 2004).

The ocean circulation model is coupled to a fully dynamic 3D atmosphere and the GFDL thermodynamic-dynamic sea ice model (SIS). The atmospheric model is similar to the GFDL atmospheric model 2 (AM2) with a latitudinal resolution of 3°, a longitudinal resolution of 3.75° and 24 vertical levels. It has an explicit representation of the diurnal cycle of solar radiation, a 3-level cloud parameterization and a full hydrological cycle (Anderson *et al.* 2004).

This model is fully coupled and has no flux adjustments, enabling full atmosphere-ocean-sea ice feedbacks as well as oceanic salinity and temperature feedbacks.

2.2 Model biases

A complete model validation of CM2Mc has been done in Galbraith *et al.* (2011). Here we summarize the divergence of a spun up Control simulation from observations.

We note warm SST biases in the Southern Ocean as well as in equatorial upwelling regions and a cold bias in the North Pacific (figure 2–1). These biases are caused by regional imbalances in radiation resulting from misrepresentation of clouds. Low salinity biases in the south Pacific and Atlantic and high salinity biases in the North Pacific result from the misrepresentation of the Inter-tropical Convergence Zone (ITCZ) that is "split" in the Control simulation, a usual symptom of coupled models (figure 2–2). North Atlantic Deep Waters and Southern Ocean waters in CM2Mc tend to form as excessively warm leading to a global ocean temperature warm bias of 1.5 °C (4.5 °C compared to 3.0 °C for observation).

Fig 2–3 shows the global overturning in depth and density space as well as the Atlantic and Indo-pacific overturning. It has the usual northern and southern overturning with 23.6 Sv of maximum clockwise transport at 40 °N and 19.3 Sv of maximum anticlockwise transport at 30S. The Southern Ocean ventilates near the Antarctic coast (see density overturning : figure 2–3 (d)) and in the Weddel Sea (see ideal age : figure 2–3 (e)).

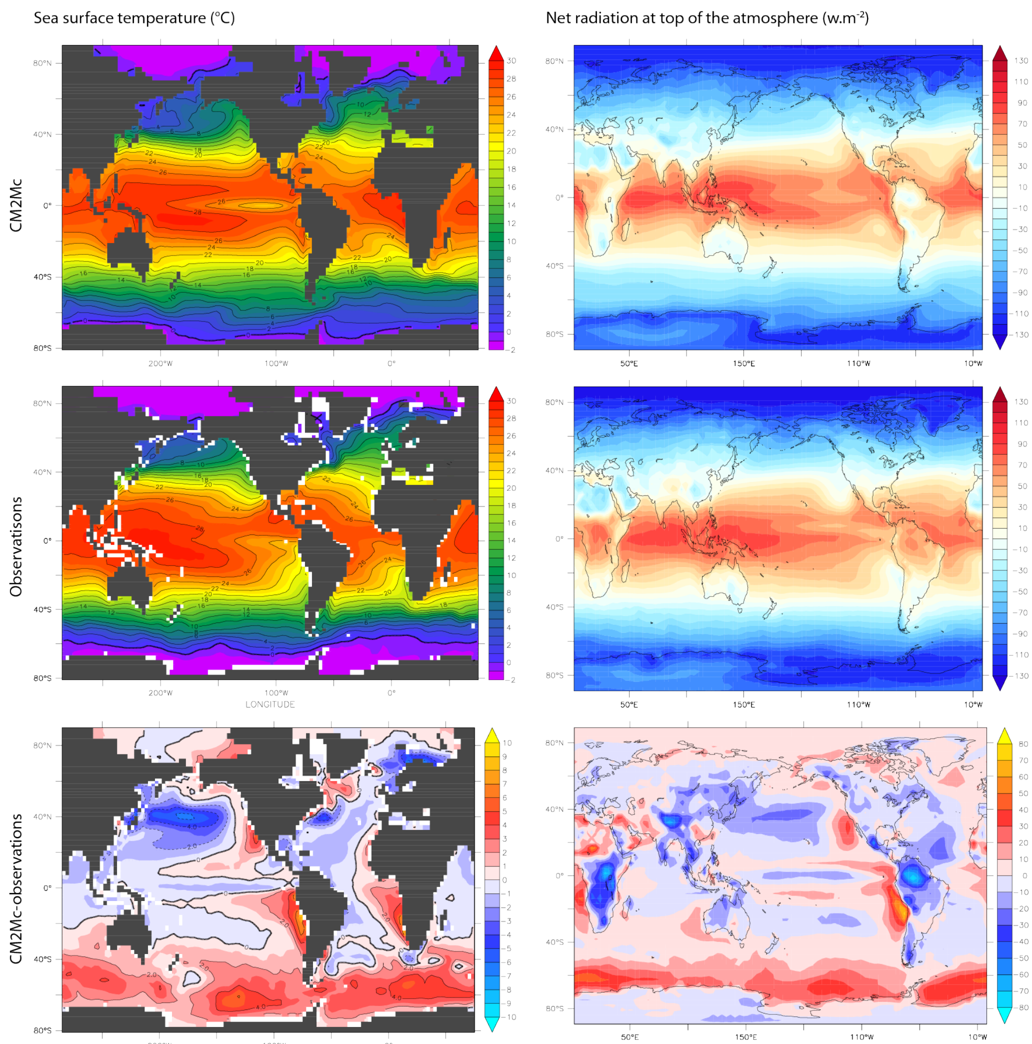


Figure 2–1: Simulated and observed sea surface temperature and radiation at top of the atmosphere as well as their differences

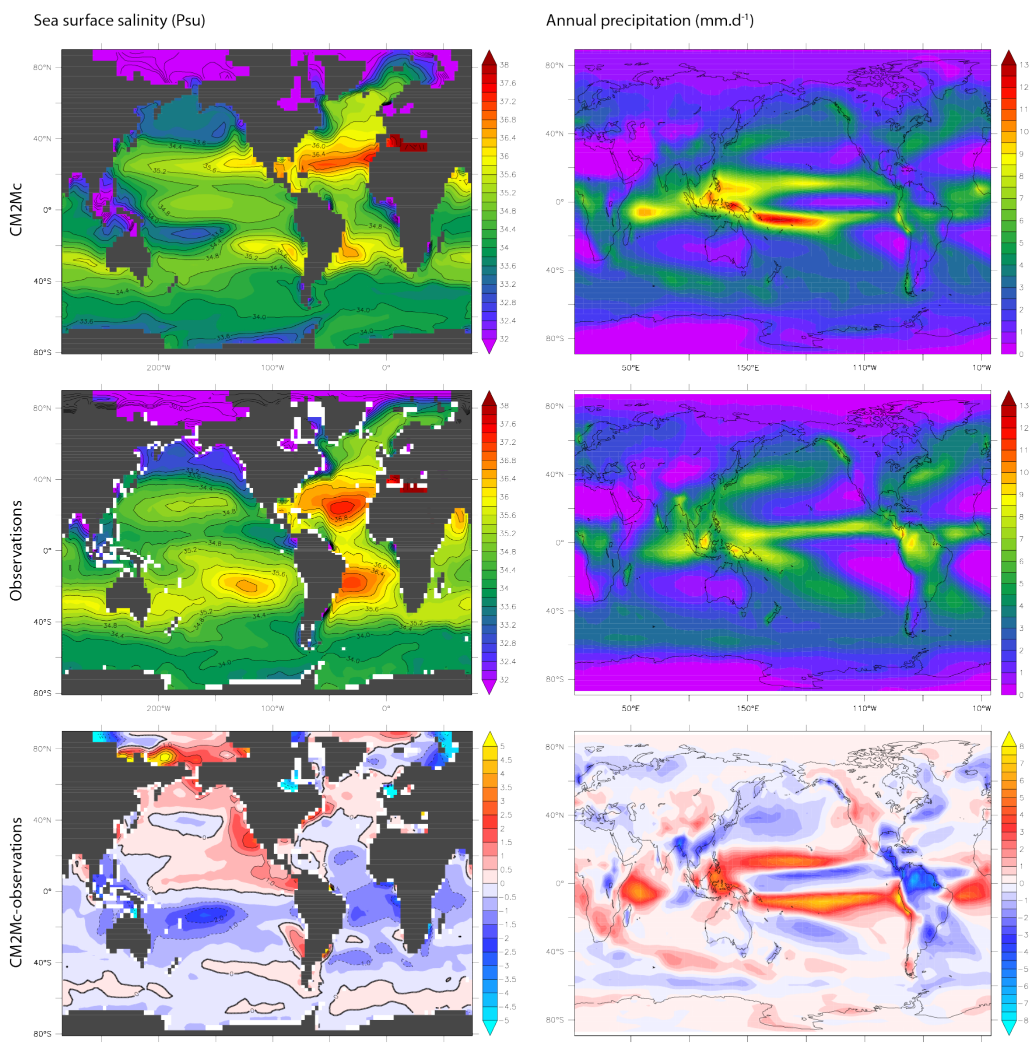


Figure 2–2: Simulated and observed sea surface salinity and precipitation as well as their differences

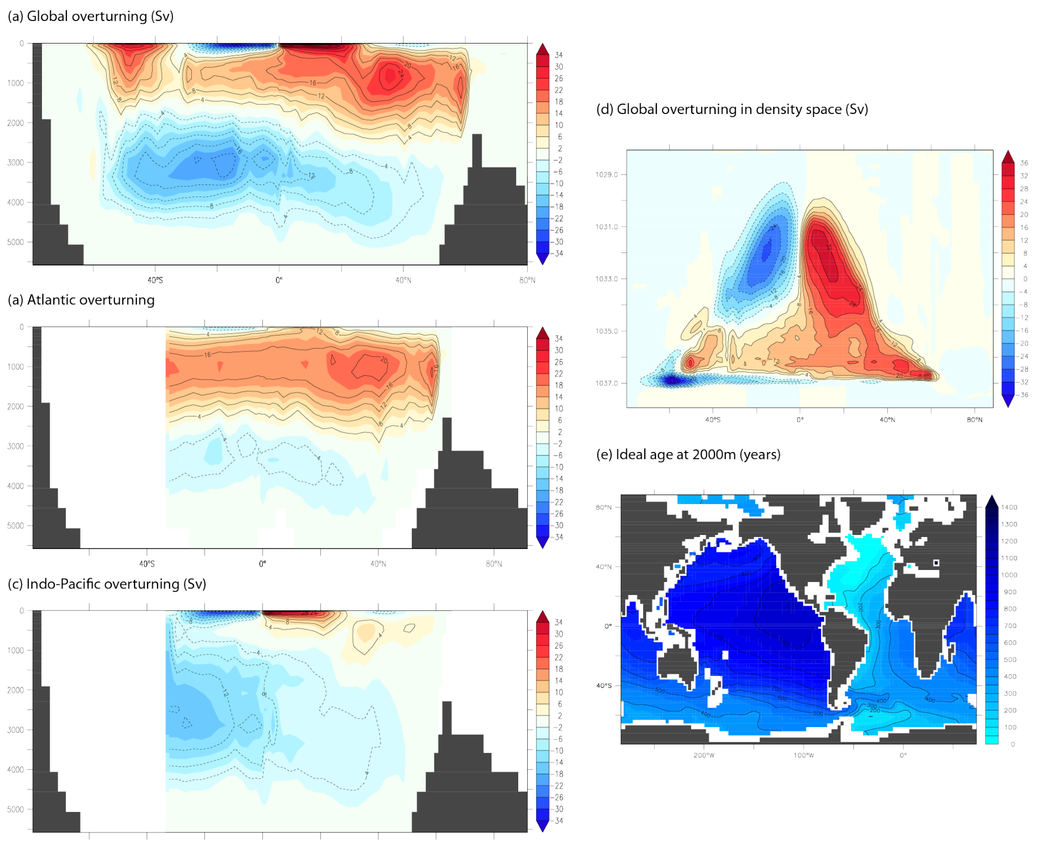


Figure 2–3: (a) Global overturning, (b) Atlantic overturning, (c) Indo-Pacific overturning, (d) Global density overturning and (e) ideal age at 2000m

Chapter 3
Coupled climate impacts of the Drake Passage modulated by the Ismuth of Panama (to be submitted to Journal of Climate)

3.1 Introduction

The Eocene-Oligocene boundary (34 Ma) marks an abrupt cooling of the Earth (Zachos *et al.* 2001, Miller *et al.* 1987, Miller *et al.* 1991). Tectonic events such as the closing of the Panamanian Ismuth 14-3 Ma and the opening of the Drake Passage 40-20 Ma have been the focus of many studies trying to link the consequences of those seaway changes to cooling events. In particular, it has been suggested that the Drake Passage opening played an important role in the abrupt Southern Hemisphere cooling of the Eocene-Oligocene boundary (Kennett 1977, Sijp and England 2004). This period is characterized by a +1.5 ‰ marine δ^{18}O excursion resulting both from cooling and the onset of permanent ice in Antarctica. Kennett (1977) was the first to suggest a causality between seaway changes and the Eocene-Oligocene boundary cooling, stating that the formation of the Antarctic Circumpolar Current (ACC) would have thermally insulated Antarctica enabling the growth of its ice sheet. Indeed, the Drake Passage plays a central role in setting the meridional overturning circulation (MOC) which transports and stores heat in the ocean.

At present, the MOC is viewed as follows (see Marshall and Speer 2012 for a detailed review) : dense salty waters sink in the Greenland and Labrador Sea flowing southward as North Atlantic Deep Water (NADW). Some of this water mixes upward through the Atlantic thermocline while the rest joins Circumpolar Deep Waters to upwells quasi-adiabatically along tilted isopycnals south of the ACC. Approximately 75% of the upwelled water flows north and gains buoyancy to become intermediate and mode waters to close the northern meridional overturning circulation. The remaining 25% loses buoyancy as it flows towards Antarctica and sinks as cold dense Antarctic Bottom Waters (AABW). This water is mixed with overlying waters throughout the world and ultimately mixes upwards across the thermocline or upwells in the Southern Ocean.

The land-free latitudinal band of the Drake Passage plays a central role in setting this meridional circulation, enabling the strong westerlies to slope the isopycnals to the surface, supporting the thermal wind balance for the strongest current in the world : the ACC. This was not always the case. In the Eocene, a meridional barriers prevented the existence of a circumpolar chanel : the Drake Passage. Sometime in the Eocene the southern tip of South America separated from Antarctica, opening the Drake Passage seaway. Recent plate reconstructions suggest that an initial shallow (<1000m) gateway opening formed in the middle Eocene followed by a slow deepening that would have allowed deep waters to exchange 34 to 30 Ma (Livermore *et al.* 2005, Livermore *et al.* 2007). The final ACC configuration was fully established when the last barrier, the Tasman gateway, deepened rapidly from the late Eocene to the early Oligocene (Exon *et al.* 2001, Stickley *et al.* 2004).

Following Kennett (1977)'s idea, numerous modelling efforts were made trying to assess the climate sensitivity and changes in oceanic circulation resulting from the establishment of an ACC. The modelling procedure is to apply a land bridge in a climate model thereby closing the Drake Passage. This was done with a variety of model complexities which span ocean-only (Mikolajewicz *et al.* 1993, Nong *et al.* 2000, Toggweiler and Samuels 1993), idealized ocean with simple representations of an atmosphere (Toggweiler and

Bjornsson 2000) to ocean-ice with simple representations of an atmosphere (Sijp and England 2004, Sijp and England 2009).

With a model allowing salinity and sea ice feedback controls on the meridional overturning circulation, Sijp and England (2004) find upon closing the Drake Passage a shut down of North Atlantic Deep Water (NADW) formation, a 3.7 °C of maximum surface air temperature warming zonally at high southern latitudes and little Antarctic sea ice. Sijp and England (2009) revisit their study by using larger moisture diffusion coefficients to achieve more realistic atmospheric moisture transports. They find no shutdown of NADW.

Unlike the prior studies in which only the Drake Passage was altered, model simulations have attempted to use reconstructed Eocene bathymetry and atmospheric pCO_2 (Huber and Nof 2006, Zhang *et al.* 2010). Huber and Nof (2006) find that changes in Southern Ocean gateways only played a minor role in the Eocene-Oligocene boundary cooling. However, 3 ° resolution models may have unrealistic simulations of flows in narrow basins and passages, leading to unanticipated spurious results. Also, Zhang *et al.* (2010) use a coupled model with reconstructed Eocene topography and high pCO_2 to find that the climate sensitivity to the opening of the Drake Passage is small. However, the authors spin up the high CO_2 simulation for 1500 years which is not enough to get correct deep ocean temperature and global steady state oceanic circulation. Furthermore, the closed Drake Passage experiments are run for only 500 years which is insufficient to achieve steady state.

The Panama seaway only started restricting significantly 14Ma and provided an equatorial pathway between the Pacific and the Atlantic. We therefore choose to consider the influence of the Panama seaway on the Drake Passage opening. Here we use a coupled model which has fully dynamic 3-D ocean coupled to a fully dynamic 3-D atmosphere allowing full ocean-atmosphere feedbacks. We start by looking at changes in oceanic circulation resulting from a closure of the Drake Passage with both the presence and absence of a Panamanian Ismuth. We then investigate the ocean mechanics and more particularly the link between changes in return path and vertical mixing as well as the role of salinity in setting the state of the locations of deep water sinking. Finally climate impacts are investigated through changes in heat transport.

3.2 Methods

3.2.1 The model

See Chapter 2 for a complete description of the model

3.2.2 Simulations

We perform two sets of two simulations to investigate the role of the Drake Passage on ocean circulation and climate. In the first set, the Drake Passage is closed - with the presence of the Ismuth of Panama - for comparison with previous work. In the second set of simulations, we investigate this same closure but under the more geologically-relevant configuration in which the Panamanian Ismuth is removed. The Drake Passage is closed by simply applying a land bridge between the southern tip of South America and the northern Antarctic peninsula while the Panamanian Ismuth is removed by changing four land cells to 2000 m deep ocean cells. The exact bathymetries used at each gateway are shown in figure 3–1. All other boundary conditions such as pCO_2, orbital configurations, land cover and ice sheets are kept at preindustrial levels. Each run is spun up for 3000 years while all the analysis is done on the averaged last hundred years of each simulation.

3.3 Global overturning circulation response

3.3.1 With a Panamanian Ismuth : open and closed Drake Passage

Previous studies aimed to isolate the influence of the Drake Passage throughflow on global climate by simply closing the Drake Passage with a land bridge

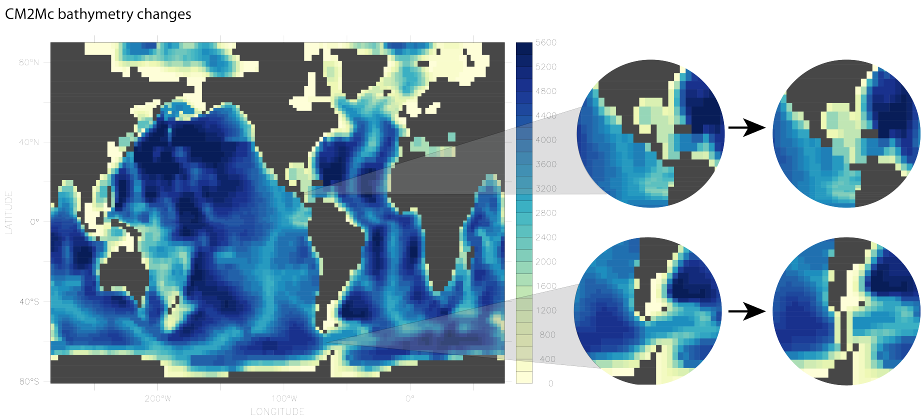


Figure 3–1: Changes in the CM2Mc bathymetry for the Drake Passage closure and Panamanian Ismuth removal.

Simulation		SMOC	NMOC	Gstrm	BraCu	BrSt	ITF	Panama	ACC
Panama Ismuth	Open DP	19.3	23.6	41.1	4.8	1.2	13.5	-	167.7
	Closed DP	3.3	21.7	32.9	0.7	1.7	16.5	-	-
No Pamama Ismuth	Open DP	18.6	19.9	41.7	26.10	1.5	2.6	19.7	152.2
	closed DP	29.6	0.0	26.6	46.5	0.6	8.2	18.1	-

Table 3–1: Various transports in Sverdrups ($10^6.m^3.s^{-1}$). SMOC is defined as the maximum anticlockwise transport at 30 °S, NMOC as the maximum clockwise transport at 40 °N. Gstrm stands for the total Gulf stream transport between 70 °W and 82 °W at 27 °N integrated from z = 0 to 1000m (northward positive), BraCu for the total Brazil current transport between 55 °W and 42 °W at 32 °S integrated from z = 0 to 1000m (southward positive), BrSt for the total transport through the bering straight, ITF to the total Indonesian through-flow transport (Pacific to Indian positive), Panama for the total Panama gateway transport (Pacific to Atlantic positive), ACC for the total transport trough the Drake Passage.

and keeping all modern boundary conditions as at present. Here we compare the ocean circulation response from our 3-D fully coupled, fully-dynamic atmosphere-ocean-ice model to these studies.

Figure 3–2 shows global overturning and ideal age (the age since the water was at the surface) for both open and closed Drake Passage configurations.

With an open Drake Passage we find the usual bipolar circulation with formation of deep waters in the North Atlantic (NADW) feeding northern overturning and formation of bottom waters near the Antarctic coast feeding the deeper southern overturning. As the Drake Passage is closed, NADW does not shut down. Rather, the circulation is dominated at all depths by northern overturning in the Atlantic with the suppression of the lower AABW cell. In the Indo-Pacific, formation of North Pacific Deep Waters (NPDW) onsets with its overturning cell restricted to high northern latitudes.

Previous studies usually found a shut down of northern overturning and a very vigorous southern overturning (Mikolajewicz *et al.* 1993, Nong *et al.* 2000, Sijp and England 2004). These results are in contradiction with our simulation that finds a circulation dominated by northern overturning in the Atlantic. However, these models are either ocean-only or use very simple representations of an atmosphere. In these simple atmospheres, there is no coupled wind response to changes in climate and advection of moisture is represented with simple diffusion parameterizations. Sijp and England (2009) therefore revisit their study by tuning their moisture diffusion coefficients to achieve more realistic atmospheric moisture transports. Enhanced moisture transport from the Atlantic to the Pacific increases the salinity keeping NADW from shutting down.

We find a surprisingly similar oceanic circulation to Sijp and England (2009) suggesting that the previous models, lacking realistic representation of atmospheric moisture transports, achieved an incorrect circulation in which the NADW formation shutdown threshold was reached.

3.3.2 No Panamanian Ismuth : open and closed Drake Passage

We first look at the effect of removing the Panamanian Ismuth (with an opened Drake Passage) on ocean circulation.

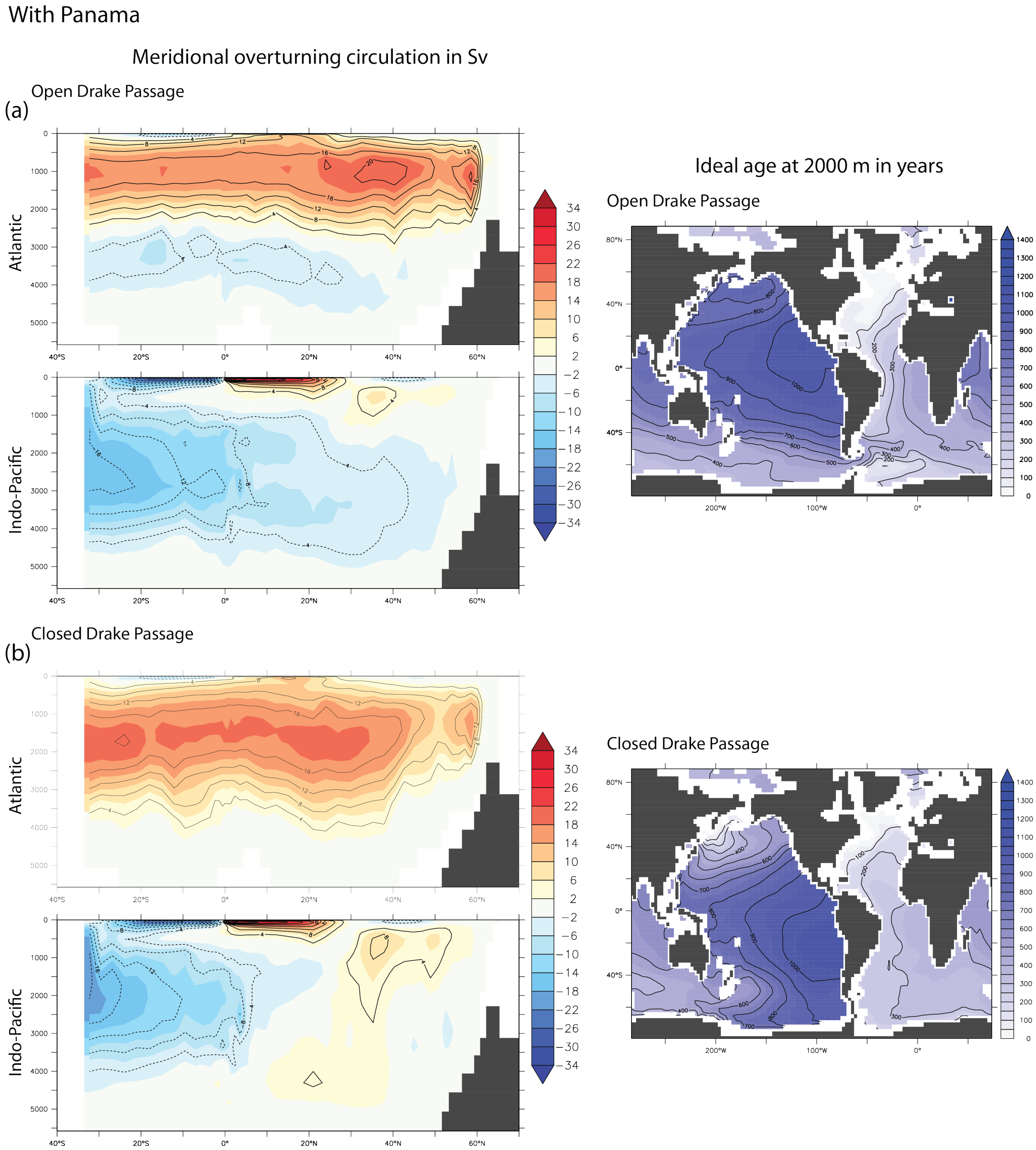


Figure 3–2: With Panama : Atlantic and Indo-Pacific overturning circulation as well as ideal age at 2000m for (a) an opened Drake Passage and (b) a closed Drake Passage

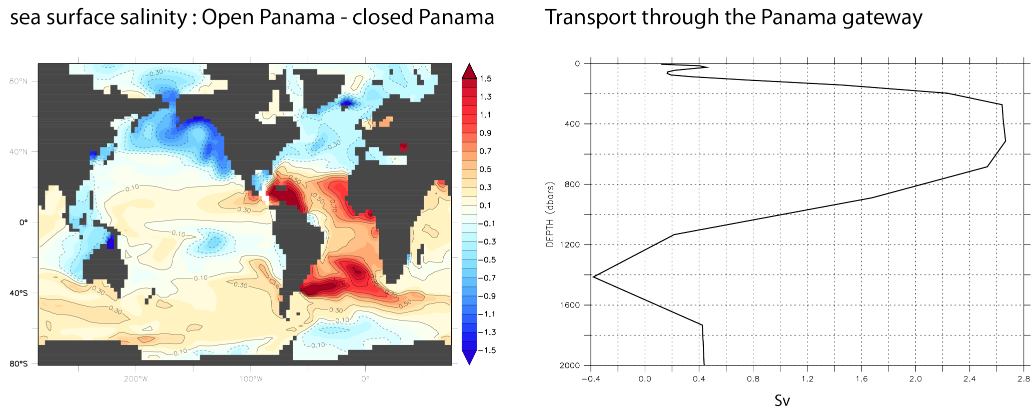


Figure 3–3: Changes in salinity resulting from the opening of the Panama gateway as well as transport through the gateway (positive is from Pacific to Atlantic).

Open Drake Passage

Keeping the Drake Passage open, we find upon removing the Panamanian Ismuth a similar global overturning structure to the modern configuration with both a northern overturning cell and a southern one. The net flow through the Panamanian seaway is from the Pacific to the Atlantic and results from the sea surface height gradient between the two basins. A total of 20 Sv is transported from the Pacific to the Atlantic (figure 3–3). The Gulf stream is therefore now sourced with a mixture of Atlantic subtropical waters as well as fresher subtropical Pacific waters. This results in a freshening of the North Atlantic (figure 3–3) and therefore a weakening of northern overturning (figure 3–4 (a)).

Past modelling studies have investigated the sensitivity of the climate system to an opening of the Panama Ismuth. Early studies (Maier-Reimer *et al.* 1990, Mikolajewicz *et al.* 1993, Mikolajewicz and Crowley 1997, Murdock *et al.* 1997) find upon opening the seaway, a flow of fresher Pacific water to the Atlantic leading to a shutdown of the MOC and therefore reduced poleward heat transport in the Northern Hemisphere. These studies, however, were using either ocean-only models or very simple representations of an atmosphere along with very simple mixing parameterization and flux corrections. Our results are consistent with later studies (Nisancioglu *et al.* 2003, Schneider and Schmittner 2006,Lunt *et al.* 2008) that use newer representations of ocean mixing and a simple representation of an atmosphere : they find that opening the Panama Ismuth still allows significant amount of NADW to be produced therefore weakening rather than shutting down northern overturning.

The opening of the Panamanian gateway therefore acts to freshen the North Atlantic which in turn weakens northern overturning. We now proceed to looking at the effect of a closed Drake Passage without a Panamanian Ismuth.

Closed Drake Passage

Without a Panamanian Ismuth, closing the Drake Passage leads to the shut down of northern overturning and the onset of a circulation dominated by strong southern overturning with 30 Sv of maximum transport at 30 °S(figure 3–4 b), table 3–5). As seen from the ideal age (figure 3–4 d), the deep ocean is ventilated through most of the Southern Ocean with no deep water formation in the Northern Hemisphere. Associated with the shut down of northern overturning and onset of strong southern overturning is a strong weakening of the Gulf stream (41 Sv to 25 Sv) and a great strengthening of the Brazil current (4.5 Sv to 40 Sv).

Our results our robust with Sijp and England (2009) suggesting that the oceanic circulation response does not depend on a coupled atmospheric response. However, a realistic atmospheric moisture transport has to be applied. Ironically, previous studies (Mikolajewicz *et al.* 1993, Nong *et al.* 2000, Sijp and England 2004) that did not consider the Panama Ismuth find upon closing the Drake Passage a shutdown of northern overturning which is achieved in this study only when the Ismuth of Panama is removed. This response is

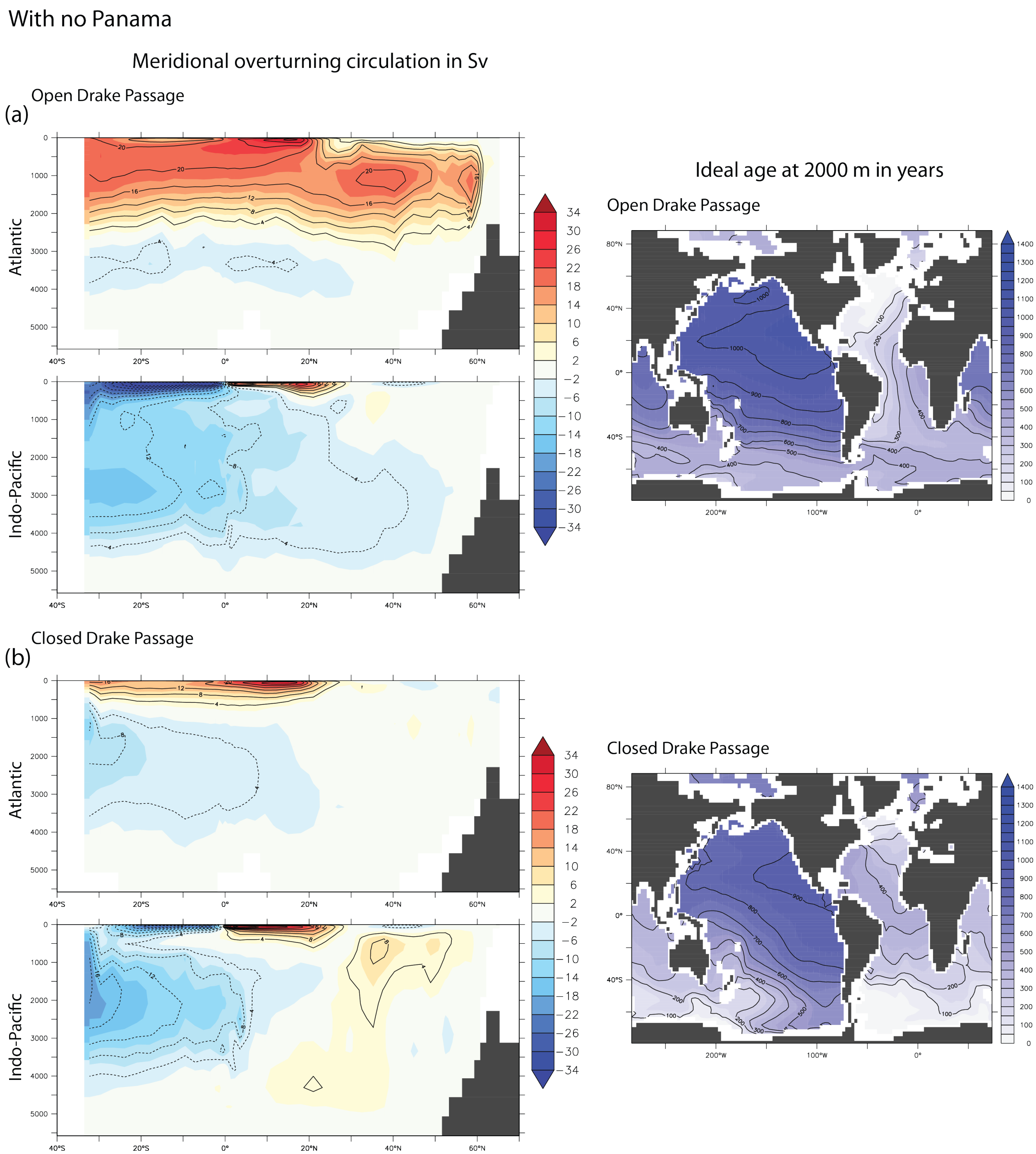


Figure 3–4: No Panama : Atlantic and Indo-Pacific overturning circulation as well as ideal age at 2000m for (a) an opened Drake Passage and (b) a closed Drake Passage

consistent with neodymium measurements from fish teeth (a useful ocean circulation tracer) which suggest that the oceanic circulation in the Eocene was dominated by waters of southern source (Thomas and Bralower 2003, Thomas *et al.* 2008).

3.4 Ocean mechanics

3.4.1 Changes in return path and vertical mixing

Changes in deep water return path

In the modern ocean, the return flow of deep water to the surface can be viewed as divided between low latitude upwelling through dyapycnal mixing and wind driven upwelling in the Southern Ocean. At the latitude of the circumpolar channel, there can be no net zonal pressure gradient. The southerly winds therefore tilt the isopycnals upward, allowing water below the sill depth of the Drake Passage to upwell quasi-adiabatic to the surface. As the Drake Passage is closed, a zonal pressure gradient can form and the quasi-adiabatic route from the ocean interior to the surface in the Southern Ocean is suppressed. Here changes in return paths associated with changes in gateway configuration are investigated.

Figure 3–5 shows simulated zonally and horizontally integrated northward transports below $\sigma_2 = 36.5$ kg.m^{-2} for the Atlantic and the Indo-Pacific basin in Sverdrups (10^6 m^3.s^{-1}). In addition, a table summarizing these transports through two sections (35 °S and 40 °N) and their differences among simulations. Conservation of mass requires that meridional differences in this transport reflect upwelling/downwelling through $\sigma_2 = 36.5$ kg.m^{-3}.

With modern bathymetry, 4.3 out of the 22.5 Sv exported southward at 40 °N are upwelled at low latitude in the Atlantic. An additional 8.9 Sv upwelled at low latitude in the Indo-Pacific giving a total of 13.2 Sv upwelled globally through $\sigma_2 = 36.5$ between 40 °N and 30 °S.

With the Panama Ismuth, closing the Drake Passage causes the total amount of upwelled waters at low latitude to increase to 23.1 Sv. This increase in global low latitude upwelling results mostly from an increased low-latitude upwelling in the Indo-Pacific resulting from increased export of Antarctic waters at 30 °S and onset of southward export of North Pacific deep water at 40 °N. There is an expected decrease in southward export of water from the Atlantic to be upwelled in the Southern Ocean. However, formation of deep waters in the North Atlantic decreases by a similar amount leading to similar low latitude upwelling in the Atlantic.

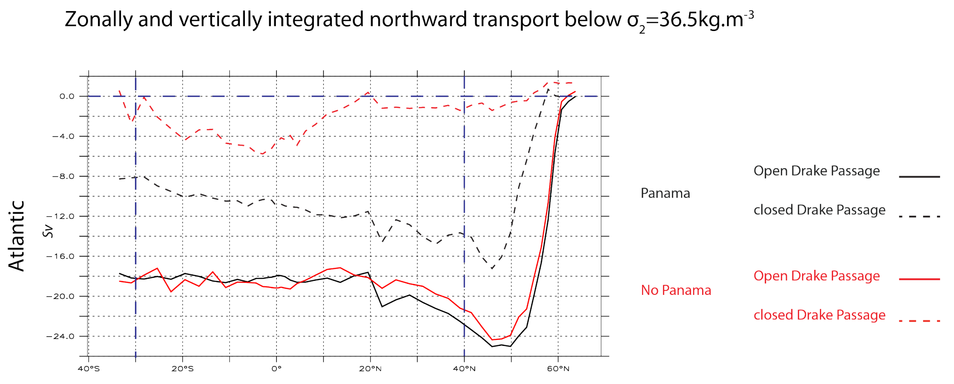
When removing the Panamanian Ismuth (and keeping the Drake Passage open), transports are similar. This is expected from the similar global circulation structure.

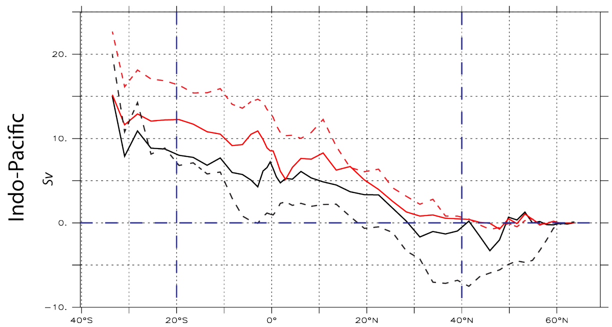
As the Drake Passage is closed, NADW stops forming as seen from the negligible transports in the Atlantic. Although large volumes of deep waters are formed in the Southern Ocean (see SMOC in table 3–1), most of it is recirculated in the Southern Ocean with only 16.1 Sv being exported northward at 30 °S. The total low latitude upwelling adds up to 13.6 Sv.

With the Panama Ismuth, closing the Drake Passage leads to a strong increase in low latitude upwelling, providing a return route to northern overturning which does not shut down, With no Panama Ismuth, no NADW forms and strong southern overturning onsets with a significant portion being recirculated in the Southern Ocean.

Changes in vertical mixing

The model employs the non-local vertical diffusivity profile (K-profile) parametrization of Large *et al.* (1994). A boundary layer thickness is calculated where mixing is strongly enhanced under the stabilizing or destabilizing influences of surface forcing. This boundary layer K profile is matched to





Simulation		Atlantic			Indo-Pacific			Total		
Panama	Drake Passage	T_{40N}	T_{30S}	ΔT	T_{40N}	T_{30S}	ΔT	T_{40N}	T_{30S}	ΔT
closed	open	-22.5	-18.1	4.3	-1.0	7.9	8.9	4.3	4.3	13.2
	closed	-13.7	-8.2	5.5	-6.8	10.8	17.6	5.5	5.5	23.1
open	open	-21.2	-18.7	2.5	0.5	11.6	11.1	-1.3	-1.3	13.6
	closed	-1.4	-2.7	-1.3	0.8	16.1	15.3	2.5	2.5	14.0

Figure 3–5: Simulated zonally and vertically integrated transports below σ_2=36.5kg.m^{-3} in the Atlantic and Indo-Pacific basins in Sverdrup. The variation in these transports, by continuity, reflects the upwelling through that ispycnal. Joined is a table summarizing quantified transports at 40 °N and 30 °S as well as the difference between the two, reflecting net low latitude upwelling through σ_2=36.5kg.m^{-3}

the interior values that are a function of shear instability (local gradient in Richardson number) and double diffusion. In addition, internal wave activity is parametrized following Simmons *et al.* (2004) by enhancing vertical mixing over rough topography and is a function of stratification. Here we look at changes in vertical mixing resulting from the simulated changes in global circulation.

Figure 3–6 shows simulated zonally and vertically integrated vertical mixing below 1000m as well as changes in the log of the vertically integrated vertical mixing resulting from the Drake Passage closure with and without a

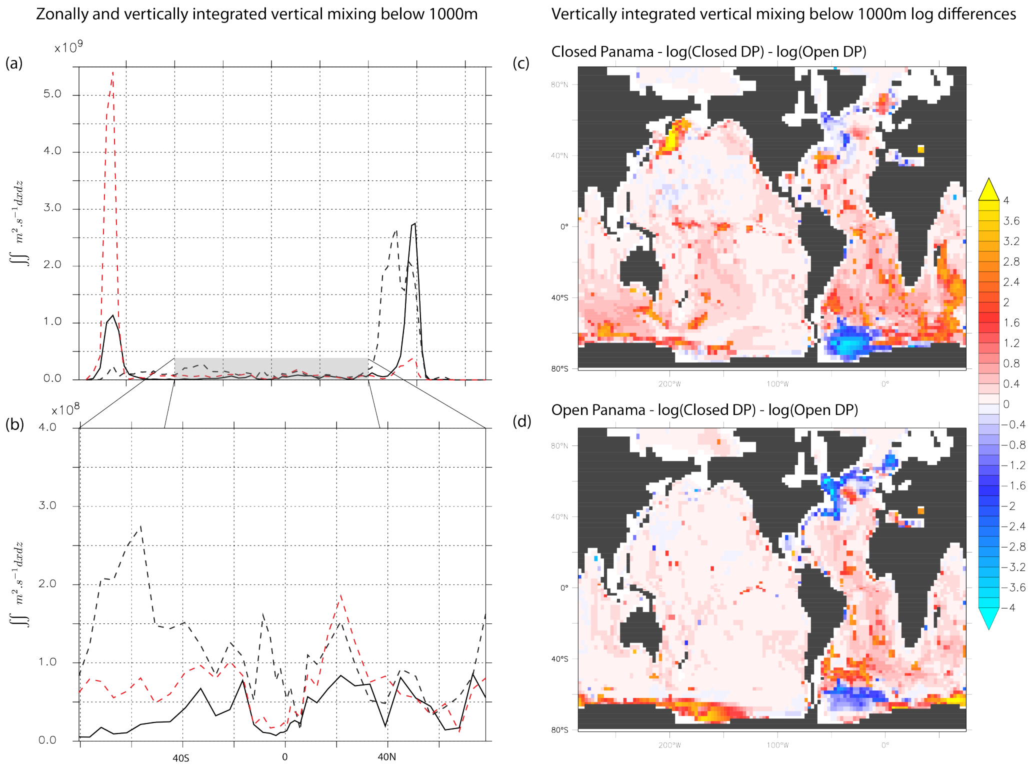


Figure 3–6: (a)/(b) Zonally and vertically integrated vertical mixing below 1000m for the four simulations and changes in the log of the vertically integrated vertical mixing resulting from the Drake Passage closure (c) with Panama and (d) without Panama.

Panamanian Ismuth. There are both changes in high latitude mixing associated with changes in convective sites as well as changes in low latitude vertical mixing related to changes in return paths.

With a Panamanian Ismuth, the shutdown of the convective region of the Weddel Sea and decreased Southern Ocean upwelling following the closure of the Drake Passage leads to a strong decrease in integrated vertical mixing in the Southern Ocean. The two high northern latitude maxima in integrated vertical mixing at high northern latitudes are associated with the presence NADW formation and onset of NPDW formation. The strong increase in low latitude upwelling is accompanied by a doubling of the globally integrated vertical mixing between 30 °S and 40 °N.

With no Panamanian Ismuth, the shutdown of NADW formation following the closure of the Drake Passage results in the suppression of the high northern latitude maxima in integrated vertical mixing. The very sharp increase in vertical mixing near the Antarctic coast is associated with the onset of southern overturning dominance where a significant part of the deep water formation is recirculated within the Southern Ocean as can be seen from the global overturning (see figure 3–4). The 50% increase in low latitude mixing is associated with increased recirculation of southern waters below σ_2=36.5.

These changes in low latitude mixing are due to a decrease in the stratification of the deep ocean, as shown by the zonally-averaged buoyancy frequency (figure 3–7 (a), (b)). This decrease in stratification appears to result from the absence of the ACC. When present, the ACC projects its stratification onto the deep ocean, producing a vertical density gradient to as deep as 2500 m (**?**). When the ACC is absent, the absence of deep stratification allows the available mixing energy to enhance vertical diffusion. At the same time, the fact that only a small range of density classes exist in the unstratified deep ocean reduces the opportunity for all but the densest surface waters to contribute deep water; thus, when the ACC is absent, the deep ocean becomes dominated by a single water mass.

3.4.2 The role of salinity

Warren (1983) and Broecker (1991) suggested that salinity played a central role in setting regions of deep water formation. They argued that because winter sea surface temperatures were similar at corresponding latitudes, it is the differences in freshwater forcing and resulting salinities that set regions of deep water formation. This argument was used to explain why deep water formation preferentially happens in the North Atlantic rather than in the North Pacific. Indeed, Warren (1983) explains that the atmosphere transports

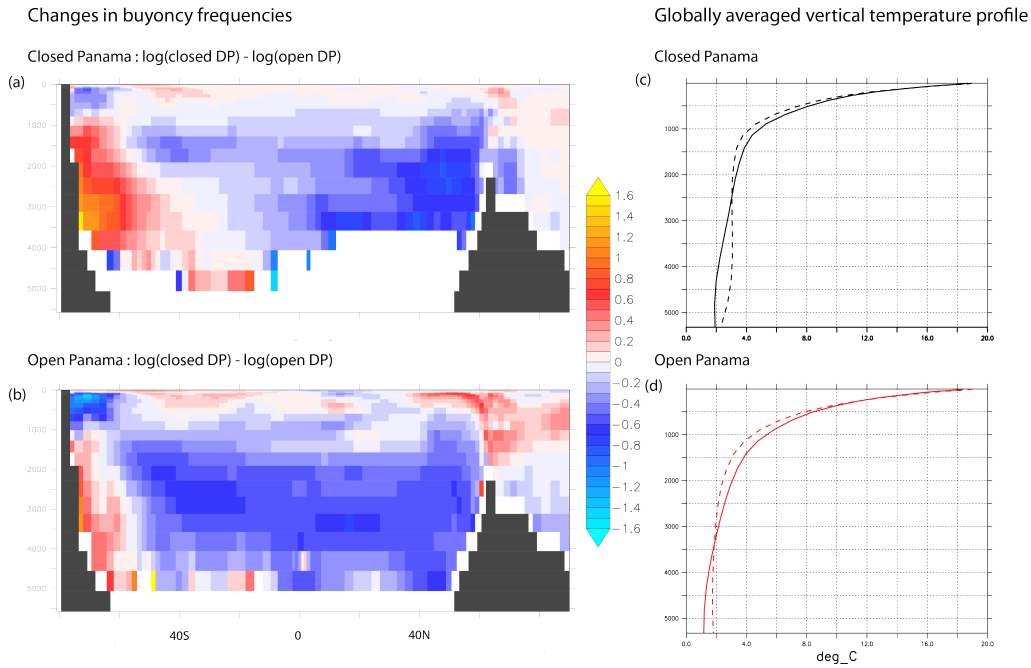


Figure 3–7: Changes in the log of the buoyancy frequency resulting from the Drake Passage closure (a) with Panama, (b) without Panama as well as globally averaged temperature profiles.

freshwater from the Atlantic basin to the Pacific through the low elevation Panama causing the North Atlantic to be more net evaporative and hence saltier than the North Pacific. As discussed previously, Sijp and England (2009) also show that the state of the meridional overturning circulation is sensitive to atmospheric moisture transport in their model. Here we explore the role of salinity to the meridional overturning circulation response resulting from changes in gateway configurations.

Figure 3–9 shows the simulated maximum density of sea water - calculated using the maximum monthly averaged value throughout the year - as well as the maximum value in space in four basins : the Southern Indo-Pacific, the South Atlantic, the North Atlantic and the North Pacific. This diagram therefore shows potential sources of deep water formation in T-S space. Water convects if it is denser than the water over which it is sitting. We therefore also plotted a contour of the mean deep ocean density in each simulation in order to get an approximate sense of the density contrasts between potential sources of ventilation and the deep ocean (note however that the deep ocean density also varies laterally and vertically). Because the temperatures are generally low, salinity plays a primary role in setting the densest waters.

There are two ways of changing salinity in regions of potential deep water formation. The first is through changes in ocean circulation, while the second through the balance of precipitation minus evaporation (PME). For the simulations analyzed here, regions of potential deep water formation are always saltier in the cases in which deep water is actively forming there. However, this does not identify the cause for these variations of salinity (figure 3–10).

Figure 3–8 shows differences in precipitation minus evaporation resulting from the closure of the Drake Passage, with and without a Panama Isthmus. With a Panamanian Ismuth, the closure of the Drake Passage produces a negligible change in atmospheric freshwater forcing. On the other hand, with no Panama Isthmus, the closure of the Drake Passage leads to a decrease in PME in the northern subtropics, an intensification of the southern ITCZ and an increase in the southern subtropics PME. Table 3–2 shows the total freshwater contribution from PME, runoff and calving for different basins. With no Panamanian Ismuth, the Drake Passage closure leads to a doubling in net freshwater contribution in the region of NADW formation and to a 20 % reduction in Southern Ocean PME, increasing the density of southern waters while decreasing the density of North Atlantic waters. Both changes can be attributed to changes in sea surface temperature, with more positive PME over cooler water.

In addition, regions of deep water formation tend to receive an advective input of salty subtropical waters, drawn in to replace the subsurface outflow

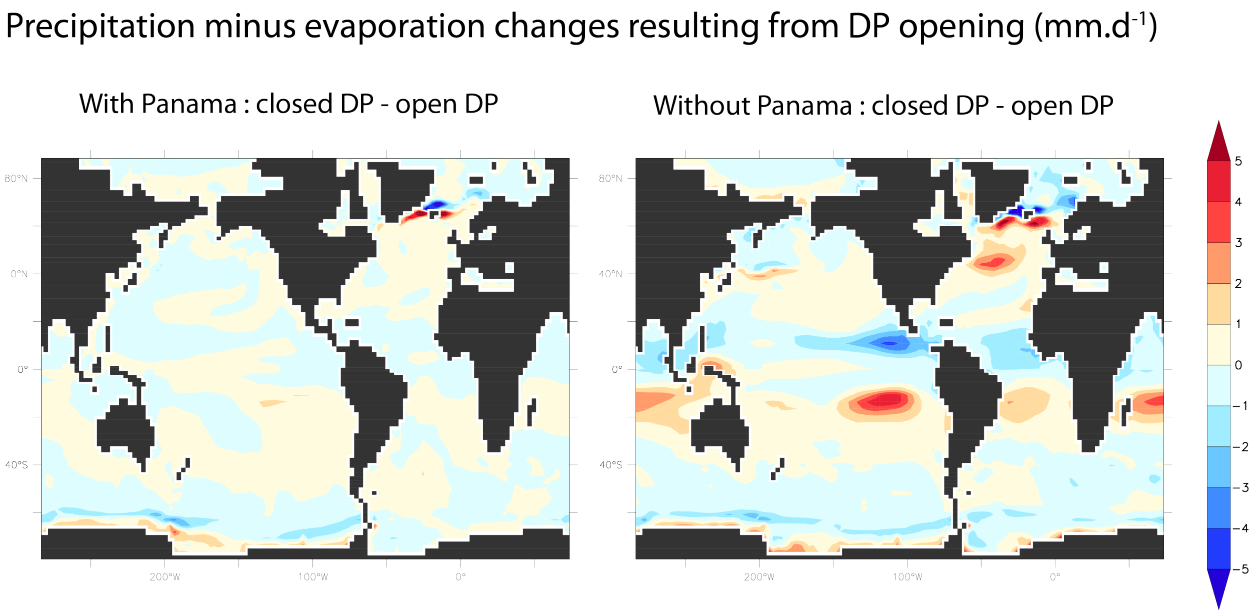


Figure 3–8: Simulated changes in precipitation minus evaporation resulting from the Drake Passage opening in mm.d^{-1}

of deep waters. This polar salinity feedback strengthens the overturning circulation by increasing the density in regions of deep water formation. As salty subtropical waters are advected to high latitudes, the density of deep water formation sites increases, leading to enhanced overturning and therefore greater salinity.

simulation	With Panama		Without Panama	
Basin	Open DP	Closed DP	Open DP	Closed DP
North Atlantic	-0.50	-0.47	-0.57	-0.54
South Atlantic	-0.19	-0.23	-0.10	-0.17
North Pacific	-0.04	-0.10	-0.10	-0.36
South Pacific	0.04	0.12	0.08	0.36
Indian	-0.27	-0.26	-0.22	-0.05
Southern Ocean	0.77	0.77	0.74	0.61
Arctic	0.19	0.17	0.06	0.18

Table 3–2: Freshwater : Precipitation - Evaporation + River + Calving in Sverdrup. See the Appendix for the basin specifications as well as a full freshwater balance.

With this in mind, we go on to explain the role of salinity in the reversal of overturning dominance that occurs when the Drake Passage opens (without

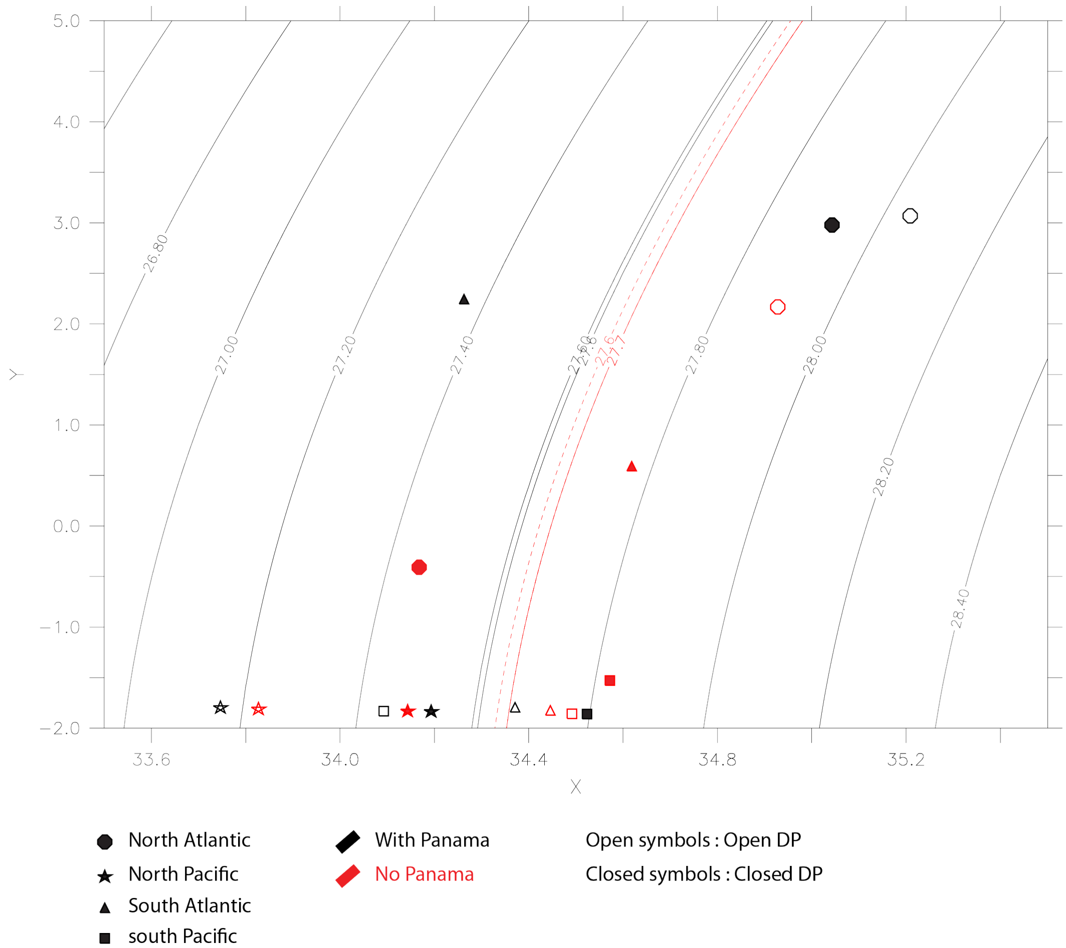


Figure 3–9: Maximum density of sea water - calculated using the maximum monthly averaged value as well as the maximum value in space - split up in four different basins : The North Atlantic, the North Pacific, the South Atlantic and the south Indo-Pacific. Red symbols are opened Panama while black symbols represent closed Panama. Open symbols represent opend Drake Passage while filled symbols represent closed Drake Passage. A contour of the deep ocean (below 1000m) density has been plotted for each simulations.

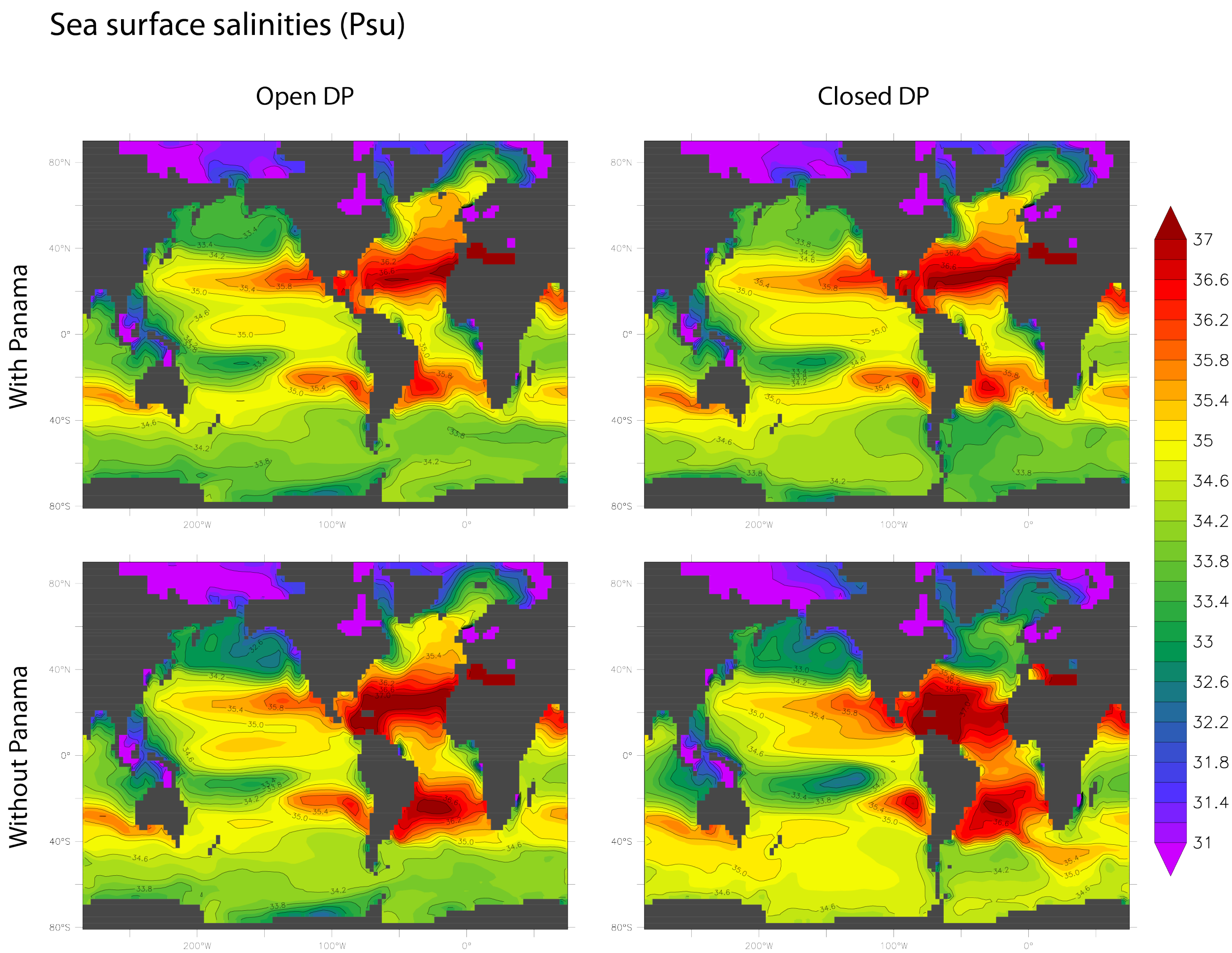


Figure 3–10: Simulated sea surface salinities for the four gateway configurations

a Panama Isthmus). The strong southern overturning and the ability of the Brazil current to reach high southern latitudes keep the Southern Ocean salty. Meanwhile, the absence of NADW formation results in both weak inter-gyre exchanges and a weak Gulf stream while the North Atlantic stays fresh. With the Drake Passage open, the prevention of geostrophic flow of surface waters to high southern latitudes cuts off the advection of salty subtropical waters, allowing the positive PME to freshen the Southern Ocean. As a corollary of this, more salt is now available in the low latitude Atlantic to be transported to high northern latitudes. A salinity threshold is reached where NADW becomes dense enough to ventilate the deep ocean, thereby drawing in greater subtropical salty waters and strengthening through the polar salinity feedback.

This salinity threshold can also be observed when considering the different circulations resulting from the Drake Passage opening with and without an Ismuth of Panama. With a Panama Ismuth, the salinity threshold is not crossed and northern overturning remains present. Even if geostrophic transport to high southern latitudes is now possible, the Southern Ocean stays fresh. Only without the Ismuth of Panama does the contribution from the fresher Pacific causes the Atlantic to cross the salinity threshold, suppressing deep water formation in the North Atlantic.

3.5 Climate impacts

3.5.1 Temperature changes

Closed Panama Ismuth : Opening the Drake Passage

Upon opening the Drake Passage there is a decrease in surface air temperature (SAT) of up to 4 °C zonally over Antarctica. It is the thermal isolation of the Southern Ocean from warm subtropical waters that leads to the cooling near the coast of Antarctica. Also, the strengthening in northern overturning

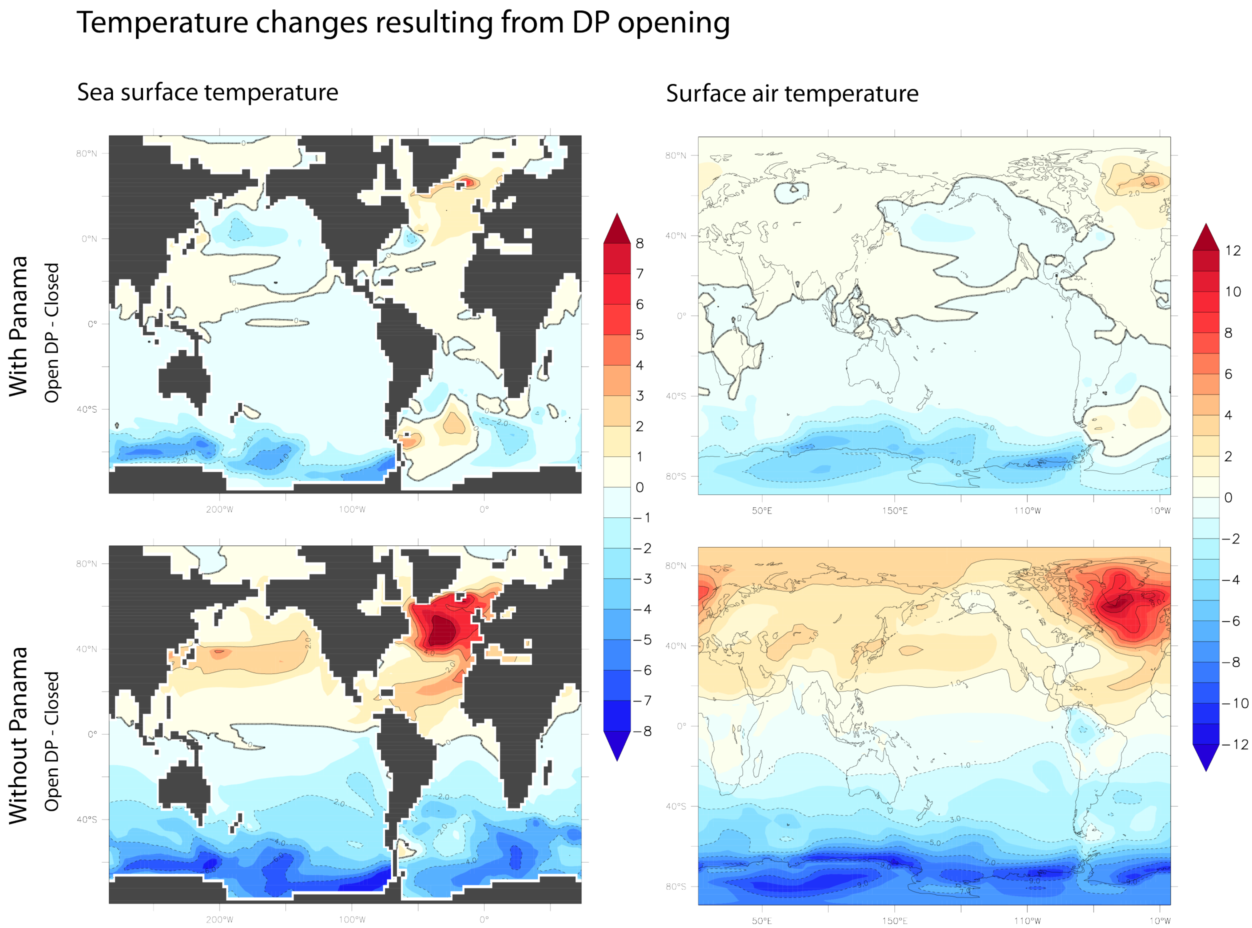


Figure 3–11: Sea surface and surface atmospheric temperature differences resulting from the Drake Passage opening with a Panamanian Ismuth (a and b) and without a Panamanian Ismuth (c and d).

results in warming over the North Atlantic while the suppression of NPDW results in a cooling over the North Pacific.

Opened Panama Ismuth : Opening the Drake Passage

There are much stronger temperature responses with no Ismuth of Panama upon opening the Drake Passage. Zonally averaged SAT cool by up to 9 °C zonally over Antarctica and warm by up to 4 °C zonally at high northern latitudes. Two factors contribute to this strong response. The first is the thermal isolation of the Southern Ocean as explained in section 3.5.1. The second one is the establishment of northern overturning leading to increased northward advection of subtropical waters through increased inter-gyre exchange and a doubling of the Gulf stream (table 3–5). Ultimately this can be seen as "heat piracy" from the Northern Hemisphere to the Southern Hemisphere concept which will be explained in more details in terms of oceanic heat transport (section 3.5.2)

A similar temperature response is found compared to studies with similar experimental set-ups (Sijp and England 2004). The more geologically relevant experiment on the other hand, that is the opening of the Drake Passage with no Panamanian ismuth does lead to the shutdown of northern overturning and hence results in a much stronger response with approximately 3× the response obtained by Sijp and England (2004). These results therefore suggest that the role of the establishment of a latitudinal band free of a meridional barrier on Southern Hemisphere glaciation might have been underestimated.

3.5.2 Heat transport

Total heat transports

Kennett (1977) suggested that opening the Drake Passage would have thermally insulated Antarctica allowing its ice sheet to grow. In other words, the southward oceanic heat transport would have been greatly reduced south of the newly established ACC.

Total heat transport does not vary significantly between the different simulations (Figure 3–12). The simulation with the most drastic change in global circulation (with a Panama Isthmus and closed Drake Passage) has a smaller high latitude heat transport and slightly higher cross equatorial transport. Although the changes in total heat transport are small, they conceal significant changes in oceanic heat transports (figure 3–13).

Stone (1978) argued that total heat transport should be independent of internal processes such as atmospheric and oceanic circulation. He states this

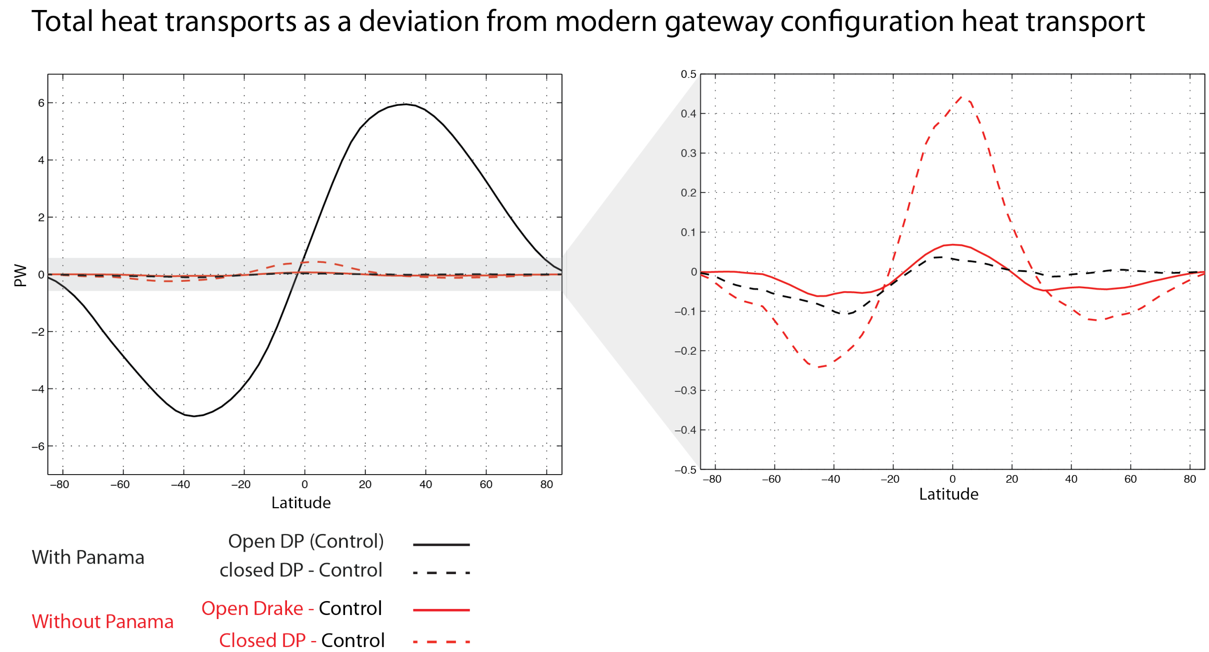


Figure 3–12: Total zonally integrated northward heat transports as a deviation of the modern gateway configuration simulation

based on the idea that meridional atmospheric heat transport is very efficient in keeping outgoing long-wave radiation uniform with latitude. That is, the atmospheric heat transport is mostly dependent on the temperature gradient and acts to diffuse heat meridionally. Enderton and Marshall (2009) find, using an idealized water planet model, that there are only slight variations in total heat transport despite large differences in oceanic heat transport among different simulations. The slight changes in total heat transport in their simulations occur because of the differences in meridional albedo gradient between the different climates, resulting from the presence of ice caps. Here, the only noticeable changes in total heat transport are the result of significant changes in meridional gradients in albedo resulting from changes in sea ice at high latitudes and changes in cloud cover at low latitudes.

The climate impacts resulting from the changes in gateway configurations are therefore more a consequence of the change in the partitioning of heat transport rather than its total. Changes in oceanic heat transport result directly from gateway configuration changes and are therefore the main driver of the climate impacts.

Oceanic heat transports

Figure 3–13 shows the simulated total, Atlantic and Indo-Pacific northward oceanic heat transport. Open Drake Passage simulations have a near-zero heat transport just south of 40 °S associated with the absence of meridional barriers at this latitude. This feature disappears as the Drake Passage is closed enabling geostrophic transport of heat to the Southern Ocean.

The total oceanic heat transport is modulated both by shallow circulation and inter-hemispheric circulation. As seen from figure 3–13, the Atlantic oceanic heat transport is dominated by the inter-hemispheric circulation associated with northern overturning while the Indo-Pacific oceanic heat transport is dominated by the shallow circulation. Overall, the heat transport is strongest in the subtropics where shallow wind driven cells transport heat poleward, while the inter-hemispherical circulation transfers heat from one hemisphere to the other and therefore has the effect of inducing an asymmetry in the heat transport by shifting the curve vertically.

Opening the Drake Passage : changes in oceanic heat transport

With a Panama Isthmus, opening the Drake Passage does not lead to changes in the structure of oceanic heat transport. Cooling at high southern latitude results from the "geostrophic barrier" that prevents heat transport across the latitudes of Drake Passage, as seen from the near-zero heat transport at 40 °S. However, there is no other significant change in heat transport.

In contrast, without a Panama Isthmus, much more significant changes in oceanic heat transport occur. Not only does the "geostrophic barrier" become established with the ACC but inter-hemispheric circulation leads to a strong

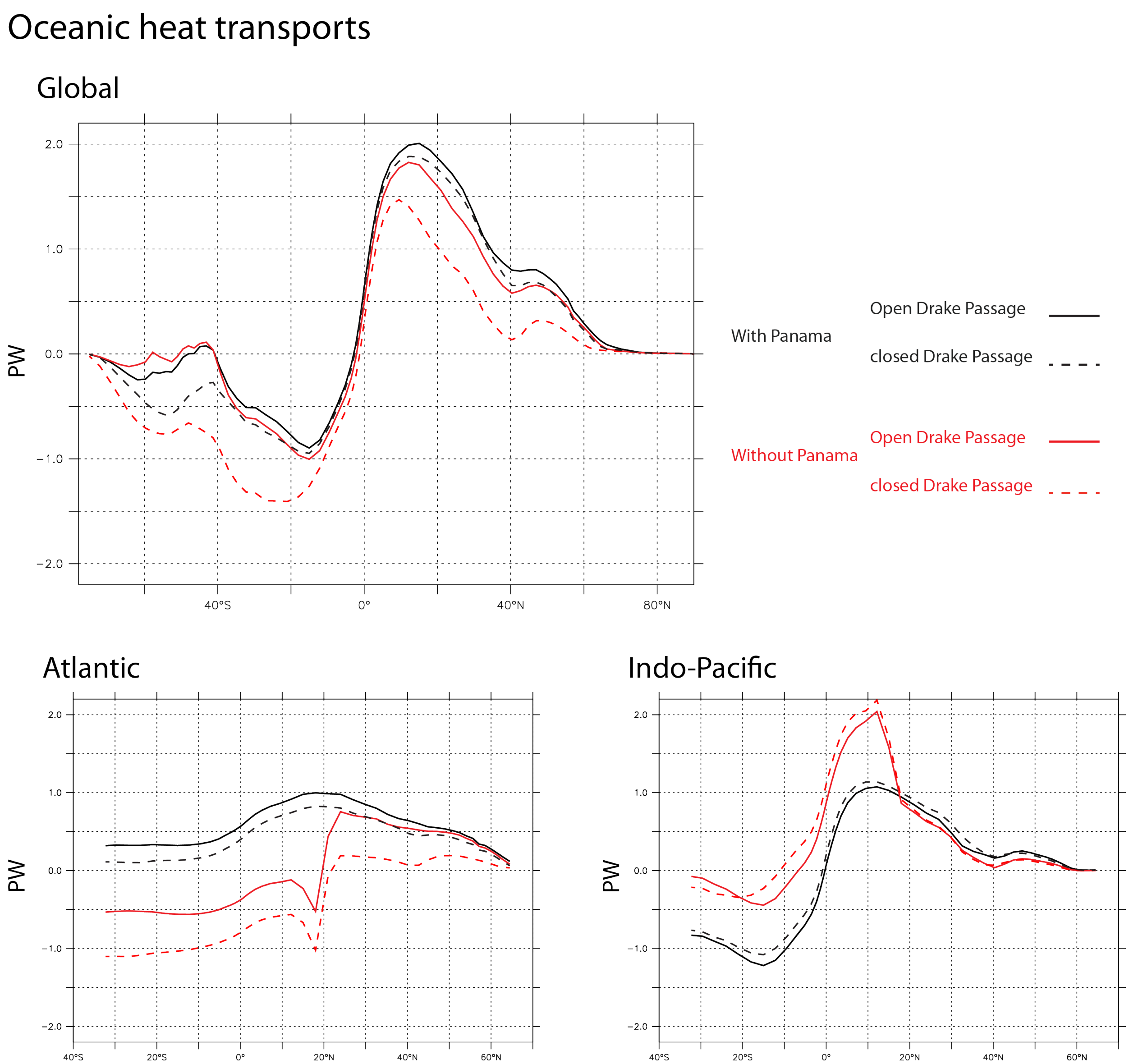


Figure 3–13: Simulated zonally and vertically integrated northward global, Atlantic and Indo-Pacific oceanic heat transports in Petawatts (10^{15} w).

vertical shift of the heat transport curve resulting in stronger heat transport in the Northern Hemisphere and weaker transport in the Southern Hemisphere. Increased cross-equatorial heat transport, which can be described as increased "heat piracy" from the Southern Hemisphere to the Northern Hemisphere, forms a major component of this. Kennett (1977)'s idea of "thermal isolation" is therefore only part of the story ; it is the establishment of the ACC coupled with the onset of northern overturning that results in the large overall change in oceanic heat transport.

3.5.3 Atmospheric radiative feedbacks

One can wonder why the climatic impacts are much stronger in this study than in previous modelling experiments. It is a positive radiative feedback that enhances the climate response to the opening of the Drake Passage for the case of major ocean circulation reorganization.

The annually-averaged net radiation at the top of the atmosphere (TOA) is the sum of net downwelling shortwave minus outgoing longwave radiation at the TOA. Since the shortwave arriving from the sun at the TOA is constant in the model, changes in the radiation balance must arise either through changes in the reflected fraction of shortwave (albedo) or in the outgoing longwave radiation. Longwave radiation at the TOA is controlled by the emission temperature, which can be somewhere close to the surface where the sky is clear, or the altitude at which cloud cover exists. Since high clouds emit at a low ambient temperature, while low clouds emit at a high temperature temperature, low clouds tend to increase the outgoing longwave radiation relative to high clouds.

Figure 3–14 (a) shows differences in net radiation at the TOA from the opening of the Drake Passage both with (black) and without a Panama Isthmus (red). With the Panama Isthmus there is only a small change in the net radiation at the TOA resulting from the Drake Passage opening. On the other hand, opening the Drake Passage without a Panama isthmus leads to an overall decrease in net radiation at the TOA in the Southern Hemisphere and an overall increase in net radiation at the TOA Northern Hemisphere. This change in atmospheric radiation balance therefore acts as a positive feedback to the cooling/warming signal in the southern/Northern Hemisphere.

Figure 3–14 (b) shows that the radiative change is accounted for by changes in longwave at low latitudes and changes in reflected shortwave at higher latitudes that overcome the longwave signal resulting from changes in surface temperatures. Changes in reflected shortwave at the TOA are mostly the result of changes in total cloud cover as seen from figure 3–14 (c) with some of the signal resulting from changes in sea ice. Changes in longwave at the TOA are the result of changes in cloud height. Increased high clouds and decreased low cloud in the Northern Hemisphere act to enhance the warming there while decreased high clouds and decreased low clouds in the Southern Hemisphere act to enhance the cooling.

Figure 3–14: (a) Net radiation at top of the atmosphere (TOA) differences resulting from the Drake Passage with and without a Panamanian Ismuth. (b) Net radiation at the TOA differences, shortwave up at TOA difference and long wave up at TOA differences resulting from the Drake Passage opening without an Ismuth of Panama. (c) Total, low and high cloud cover differences resulting from the Drake Passage opening without a Panamanian Ismuth.

Chapter 4
Conclusion

We have four major results from the analysis of the ocean circulation and climate impacts resulting from the establishment of the ACC.

First, closing the Drake Passage - with an Ismuth of Panama - does not lead to the shutdown of northern overturning. The resulting global overturning is very similar to Sijp and England (2009) suggesting that previous models in which NADW stopped forming lacked sufficiently strong atmospheric moisture transports from the Atlantic to the Pacific. On the other hand, closing the Drake Passage without a Panamanian Ismuth does lead to the shutdown of NADW and onset of strong southern overturning.

Second, the closing of the Drake Passage results in the suppression of the Southern Ocean upwelling leading to changes in return paths for deep water and leads to changes in vertical mixing. With a Panamanian Ismuth, there is a strong increase in low latitude upwelling, accompanied by a doubling in the integrated low latitude vertical mixing. Southern Ocean mixing is suppressed while strong mixing appears in the North Pacific. Without a Panamanian Ismuth, the mixing associated with NADW formation shuts down while the onset of strong deep water formation in the Southern Ocean leads to very high mixing values there.

Third, a polar salinity feedback is identified in which a salinity threshold provides a strong positive feedback in regions of potential deep water formation. If a polar ocean becomes salty enough to start overturning (crossing the salinity threshold), it draws in more salt from the subtropics and modifies the global salt distribution. In the geologically relevant case - with no Panama

Isthmus -, opening the Drake Passage cuts off the advection of salt to south of the ACC leading to redistribution of salt globally. The North Atlantic can then become salty enough to start overturning, drawing salts from the subtropics and reinforcing the onset of northern overturning.

Finally, there is a very strong temperature response from opening the Drake Passage in a coupled model with no Panama Isthmus. The temperature response greatly exceeds that previously reported in the literature for simpler models and those in which the role of Panama was ignored. In particular, the cooling of surface air temperature over Antarctica is $3\times$ stronger than cooling estimates from Sijp and England (2004). This cooling is the result of both isolation of high southern latitudes from subtropical waters as well as the onset of inter-hemispheric overturning resulting in heat piracy from the Southern Hemisphere to the Northern Hemisphere. Also, the temperature change resulting from the change in heat transport is enhanced by a radiative feedback in which changes in cloud cover and cloud height reduce the net radiation at the TOA in the Southern Hemisphere and increase the net radiation at the TOA in the Northern Hemisphere.

In this study, other boundary conditions such as atmospheric pCO_2 and changes in land ice cover were not considered. We suggest that future work explore the interactions between the opening of the Drake Passage, a reduction in pCO_2 and the onset of permanent ice on Antarctica.

Appendix : global freshwater budget

Fluxes of mass, salt and freshwater through a vertical section are given by :

$$M = \rho v dA, S = \rho s v dA, F = M - S = \rho v(1-s)dA, \tag{4.1}$$

Where M, S and F represent mass, salinity and freshwater fluxes. dA is a vertical section given by dxdz. ρ is in unit of kg.m^{-3}, v in m.s^{-1} and S in kg$_{salt}$.kg$_{water}{}^{-1}$. In an enclosed domain, conservation of mass requires that :

$$P - E + R = \oiint M = \oiint \rho v dA, \tag{4.2}$$

$$0 = \oiint S = \oiint \rho v s dA \tag{4.3}$$

We normalize the salt conservation equation to a reference salinity S_0=0.03471 (Globally averaged ocean salinity). Since $\oiint S/s_0 = 0$ we can write :

$$P - E + R = \oiint (M - S/s_0) = \oiint \rho v(1 - s/s_0)dA \tag{4.4}$$

The integral on the right hand side is the freshwater transport which tells us about the freshwater contribution to an enclosed basin relative to the mean salinity of the ocean. We use this equation to calculate the simulated freshwater transports between defined basins.

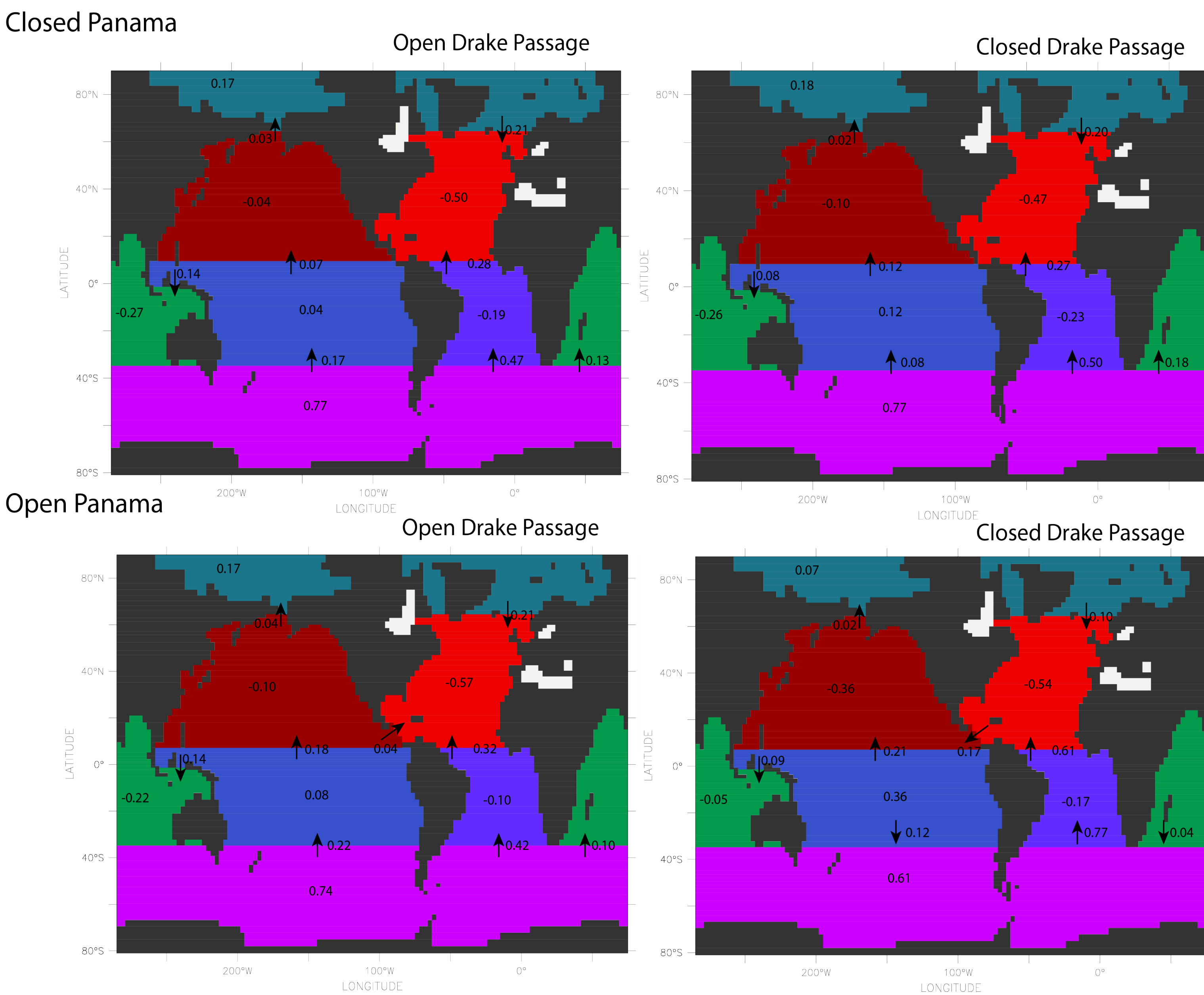


Figure 4–1: Precipitation - Evaporation + Calving + Rivers for the North, South Atlantic and Pacific oceans, the Indian, Southern and Arctic ocean as well as the resulting freshwater transports between the basins. Units are in Sverdrup (10^9 kg.s^{-1})

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