Chapter II

Paper I

Fundamental aspects of the thermohaline gyre circulation in an idealized North Atlantic Ocean

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submitted to *Journal of Marine Research*, 2007

ABSTRACT: The steady-state thermohaline circulation in a simplified North Atlantic Ocean is simulated using a z-level ocean general circulation model (MITgcm). The main scope is to investigate how surface buoyancy forcing and basin configuration interplay to form both horizontal and vertical circulations. In particular, we combine different surface forcing with the presence or absence of a continental shelf. The shelf is instrumental to model a cyclonic circulation at high latitudes, and results in modifications of both the hydrography along the northern boundary, and the strength and location of the downwelling circulation. The "subpolar" gyre consists of a shelf trapped current that persists even in the absence of local surface forcing. Wind forcing sets the Ekman circulation in the upper layer, but is not essential for sustaining the high latitude cyclonic gyre, and does not significantly influence the deep flow.

The introduction of a zonal ridge mimicking the Greenland-Scotland Ridge largely modifies local and basin-wide dynamics. The northward heat and volume transports are reduced, and their structure modulated. In the presence of both a ridge and a continental shelf, the circulation in the northern basin is achieved to a larger extent by its horizontal component, and to a lesser extent by the overturning circulation, compared to the case without a shelf.

2.1 Introduction

The northward transport of heat in the North Atlantic Ocean is of great importance to the temperate climate of northern Europe. The heat is carried by the large-scale ocean circulation, and associated with the meridional overturning circulation (MOC): upper water moves northward, releasing heat to the atmosphere; the consequent cooling at high latitudes increases the density of surface water sufficiently to cause a part of the fluid column to overturn. The dense water is hence distributed in the vertical, and spread out under the influence of gravity and rotation, mainly as deep western boundary currents. The deep waters progressively upwell through the effect of vertical mixing at lower latitudes and Ekman suction, particularly over the Southern Ocean. The water then returns north as surface water, thus closing the circuit (Broecker 1987; 1991).

In this study, we focus on the thermohaline part of the North Atlantic circulation, where the fundamental balance is between the input of heat in the tropical Atlantic, causing diapycnal mixing and upwelling, and the northern heat loss associated with deep water formation and sinking. The relevance of the thermohaline loop is to some extent debated as the oceans are mechanically driven by winds and tides as pointed out by, e.g., Munk and Wunsch (1998). A part of this energy input is nevertheless accounted for implicitly in the thermohaline approach through the parameterized diapycnal mixing. Furthermore, even if the surface buoyancy forcing does not drive the circulation in an energetic sense, it can modulate changes in the ocean circulation. Surface buoyancy loss has a fundamental influence on the transports of heat and salt both in modeled and real oceans, since the northward surface flow must be transformed into deep waters to complete the overturning (Kuhlbrodt et al. 2007).

Many fundamental aspects of the thermohaline dynamics in the real ocean need a better understanding. A question of particular interest is which factors control the sinking rate and hence the intensity of the MOC. A better understanding of where the sinking actually takes place, and how sensitive the mass transport is to changes in the atmospheric forcing configurations, is necessary to understand the ocean circulation and its role in climate. In this context, idealized analytical and numerical model studies have contributed to important insights to main aspects of the Atlantic circulation and its sensitivity. A common configuration is a one-hemisphere ocean general circulation model (GCM) forced by zonally averaged fields at the surface. A shortcoming of many idealized models is that the basins do not include lateral topography, which has been shown to have important qualitative implications for the modelled circulation (Winton 1997; Spall and Pickart 2001; Walin et al. 2004; Nilsson et al. 2005). Sloping lateral boundaries generally result in a more realistic circulation and density structure. Winton (1997) stressed the damping effect of topography on the baroclinic modes, and argued that the presence of coastal topography accommodates a conversion of the potential energy associated with a baroclinic flow into the motion of a more barotropic current. He found that a cyclonic northern boundary current, a “subpolar gyre”, results when sloping sidewalls are included in a model geometry with a flat bottom. In a recent study by Nilsson et al. (2005), the flow forced by a prescribed zonal sea surface temperature (SST) was analysed in a bowl-shaped basin. They found that the gently sloping boundaries give rise to a topographically trapped barotropic current, which is necessary to spread the warm and buoyant water to the northernmost region.

Exploring the dynamics in the sinking regions, previous studies (e.g., Marotzke and Scott 1999; Spall and Pickart 2001) have highlighted the difference between deep convective mixing and the actual sinking. Their numerical simulations show that the two processes are not directly linked, and that they can occur in different locations. Furthermore, there is negligible net vertical transport associated with convection (Send and Marshall 1995). In the experiments by Marotzke and Scott (1999), an increasing convective activity does not automatically increase the intensity of the mass transport associated with the overturning.

In this paper, key aspects of the thermal circulation in idealized geometries are re-examined in order to analyze whether and how strongly simple lateral topography influence the modelled sinking and convective mixing in the subpolar North Atlantic Ocean. Our study adds an analysis of the sensitivity of the circulation to various buoyancy forcing configurations (i.e., prescribed SST structures) combined with the influence of the model bathymetry. Spall and Pickart (2001) modelled an Atlantic circulation forced by zonally uniform wind and non-zonal prescribed SST. Even though this more realistic forcing assists the formation of a cyclonic subpolar gyre, we show that the presence of non-vertical sidewalls is a necessary to produce a double-gyre structure as in the North Atlantic.

This paper is organized as follows. Section 2 briefly describes the ocean model and the numerical experiments. Section 3 presents the idealized numerical simulations that examine the strength and structure of the North Atlantic circulation, the location and rate of deep-water formation and vertical mass transport in the subpolar gyre prescribing different surface forcing and basin geometries. This study explicitly examines the joint effect of the lateral topography and surface buoyancy forcing on high latitudes circulation. The results are discussed in section 4, and conclusions are given in section 5.

2.2 The ocean model and the numerical experiments

2.2.1 Model setup

All simulations are done with the MIT general circulation model (MITgcm, Marshall et al. 1997a, b). The model equations are solved on spherical z-levels using a staggered C-grid. The model domain is an idealized representation of the North Atlantic Ocean of 60° width, extending from the equator to 80°N, with a constant depth of 4350 m. The horizontal resolution is 2° × 2°. There are 26 vertical levels whose spacing increases from 50 m at the surface to 250 m at the bottom. The density is assumed to be function of temperature only, using a linear equation of state with a thermal expansion coefficient equal to 2×10^{-4} $°C^{-1}$.

Laplacian horizontal and vertical viscosities are 5×10^{4} m^{2} s^{-1} and 10^{-3} m^{2} s^{-1}, respectively. The vertical diffusivity is 10^{-4} m^{2} s^{-1}. There is no Laplacian diffusion horizontally. Isopycnal mixing by eddies is parameterized using Gent and McWilliams (1990) with a background value of 10^{3} m^{2} s^{-1}. There is no heat flux through the solid boundaries, and no-slip boundary conditions are applied (free-slip conditions give qualitatively similar results). A convective adjustment scheme mixes statically unstable water columns by averaging adjacent levels.

2.2.2 The numerical experiments

A suite of experiments is presented in this paper (see table 1). Two basin geometries are used: one with vertical lateral boundaries (VB-class of experiments) and one with an 800m deep and 2° wide continental shelf that surrounds the basin (CS-class). The flow is forced by a prescribed SST with a restoring time of 50 days. A 1 °C difference between the model ocean's top layer and the prescribed SST corresponds to a surface heat flux of 35 W m^{-2}. A part from one twin experiment, there is no wind. The zonally uniform SST shown in Figure 1 constitutes the reference twin experiments VB and CS. The model is initiated with a uniform temperature of 14 °C.

To highlight the sensitivity of the numerical results to the model configuration, experiments are carried out where the SST profile is modified. In experiments VB40, CS40, and VB60, CS60, the SST is kept constant north of 40°N and 60°N, respectively (Figure 1). In VBA and CSA, we rotate the reference SST field so that the lowest (highest) temperature is in the northwest (southeast). A further sensitivity study (VBW and CSW) is done adding a zonal wind stress (Figure 1) to the reference cases VB and CS.

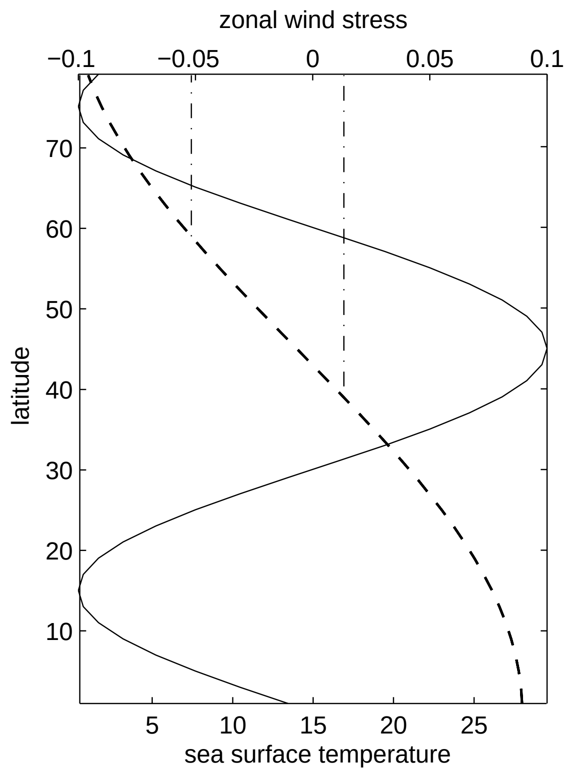


Figure 1. Prescribed meridional SST (in °C) in the reference experiments (dashed line), VB60 and CS60, and VB40 and CS40 (dashed-dotted line), and zonal wind stress (in N m^{-2}) applied in the experiments VBW and CSW (solid line).

The Greenland-Scotland Ridge (GSR) strongly influences the circulation and the distribution of water masses in the Nordic Seas; it acts as a barrier to the warm Atlantic inflow and the cold overflow waters. Volume and heat transports across an idealized ridge are investigated in the simulations VBR and CSR, where a zonal ridge is added at 60°N. The ridge is 800 m deep, and has a meridional extent of 400 km at its base, and 200 km in the upper part.

The model circulations presented below are steady-state, following a spin-up of a few thousand model years.

	Lateral topography	Surface forcing
VB	No topography	zonal SST
CS	continental shelf	zonal SST
VB40	No topography	constant SST north of 40°N
CS40	continental shelf	constant SST north of 40°N
VB60	No topography	constant SST north of 60°N
CS60	continental shelf	constant SST north of 60°N
VBA	No topography	non-zonal SST
CSA	continental shelf	non-zonal SST
VBW	No topography	zonal SST and wind
CSW	continental shelf	zonal SST and wind
VBR	Ridge	zonal SST
CSR	continental shelf and ridge	zonal SST

Table 1. Names and characteristics of the numerical experiments.

2.3 Results

Idealized single-hemisphere models have contributed significantly to the understanding of the dynamics associated with the circulation of the Atlantic Ocean. In this section, we first introduce our reference experiments and briefly review how even small modifications in the lateral geometry have a large impact on the circulation. On this background, we present our simulations that highlight the sensitivity of the circulation to variations in the buoyancy forcing and in the basin configuration.

2.3.1 Sensitivity to lateral topography

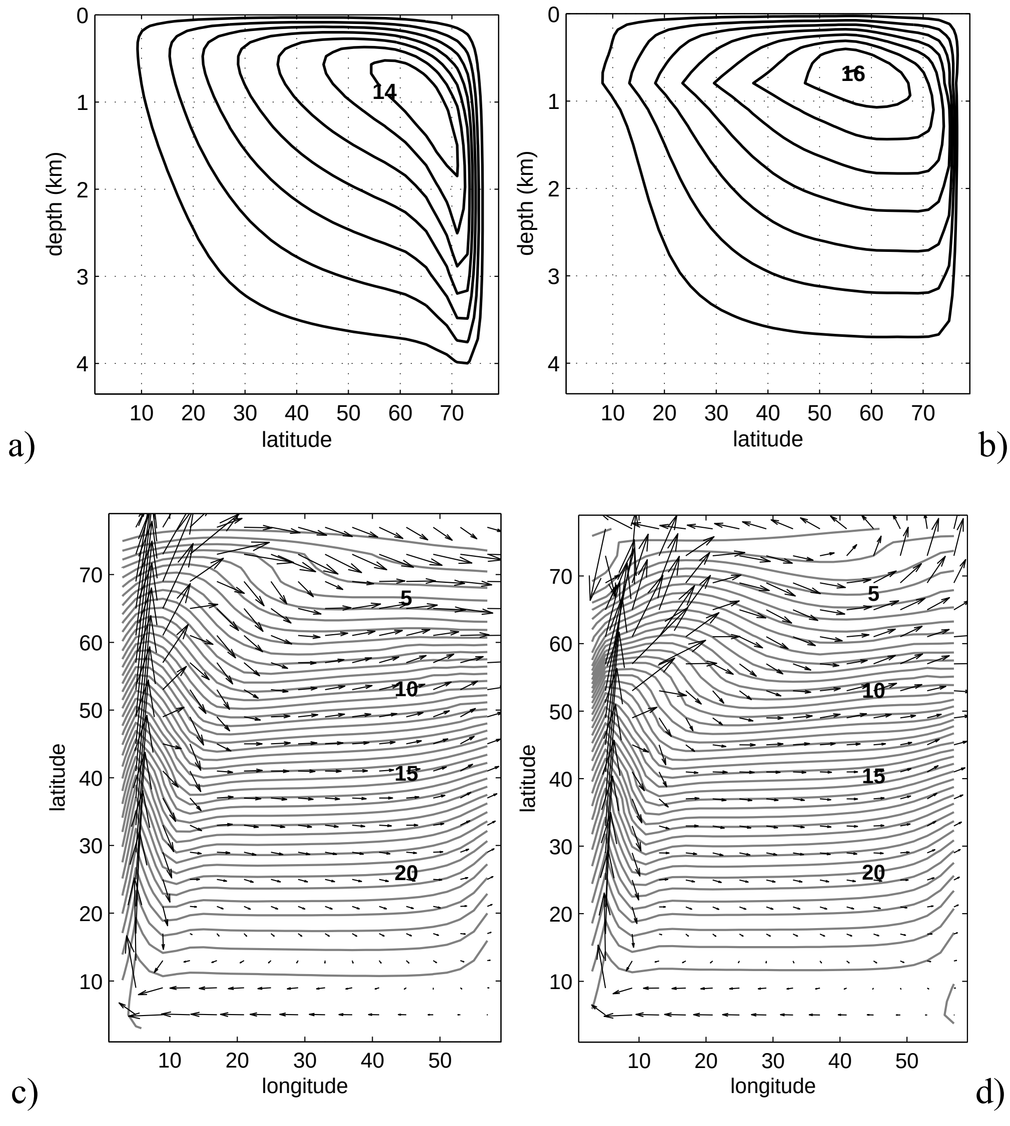
The experiments VB and CS are the reference for the sensitivity study. VB simulates an idealized North Atlantic Ocean basin with a flat bottom and no lateral topography. The only difference in CS is the presence of an 800 m deep coastal shelf of 2° width around the basin. The main features of the circulation in both basins are in agreement with previous studies (e.g., Winton 1997; Marotzke and Scott 1999; Spall and Pickart 2001; and Nilsson et al. 2003). In both VB and CS, the net meridional volume transport has the unicellular structure extending over the whole model domain, typical of these studies (Figures 2a, b). The maximum transport is about 16 Sv (the observation-based estimate by Ganachaud and Wunsch (2000) is 15 ± 2 Sv).

The MOC is nevertheless very sensitive to the lateral boundary configuration. Although similar at low latitudes, its structure and strength at high latitudes are largely modified by the presence of the shelf. The overturning cell's core in VB is approximately at 64°N and 1km depth with a narrow downwelling limb north of it (Figure 2a), while the overturning maximum in CS is located near 56°N at the depth of the shelf (Figure 2b). It is a general feature in the latter class of experiments that the depth of the maximum overturning is approximately at the depth of the shelf break (Winton 1997; Park and Bryan 2000).

The horizontal circulations differ fundamentally, particularly at high latitudes. In VB, the essentially geostrophic response to the prescribed SST is a single anticyclonic gyre in the upper-layer that covers the entire basin. The western boundary current (WBC) extends all the way to the northern wall and then continues zonally to the eastern wall where a wide downwelling to the bottom takes place (Figures 2c, e). This is also where the coldest surface water, and thus convective mixing, is found. This "longitudinal overturning" balances the meridional SST gradient, which in turn set up the zonal density gradient that leads to the meridional overturning (Marotzke and Scott 1999).

A more realistic double-gyre structure emerges in the presence of the shelf (Figure 2d). The “subpolar” gyre extends about 20° meridionally, and includes the extension of the WBC that separates and moves eastward at 60°N, and a shelf-trapped barotropic current. As it completes the cyclonic loop, it submerges to join the deep western boundary current flowing south. This boundary flow moves the sinking and convection regions. The warm northward eastern boundary current, which turns cyclonically along the northern wall, pushes the location of the coldest water to the west where also the strongest vertical mass transport occurs. The downwelling of surface water in the eastern subpolar region is greatly reduced in CS compared to VB, and is limited to the depth of the shelf (Figure 2f). The double gyre circulation causes the maximum overturning to shift southward.

The effect of the different dynamics in the north is further underlined by the mixed layer depth (MLD), defined as the depth at which the temperature decreases by 0.5° C from the surface value (Monterey and Levitus 1997). The VB mixed layer deepens from approximately 1km depth in the northwest to the bottom in the northeast (Figure 2e); the warm subtropical water enters the subpolar region with the buoyant WBC associated with a shallow mixed layer. The situation in CS is the opposite because of the subpolar gyre that makes the mixed layer deepen from the northeast to the bottom in the west (Figure 2f).



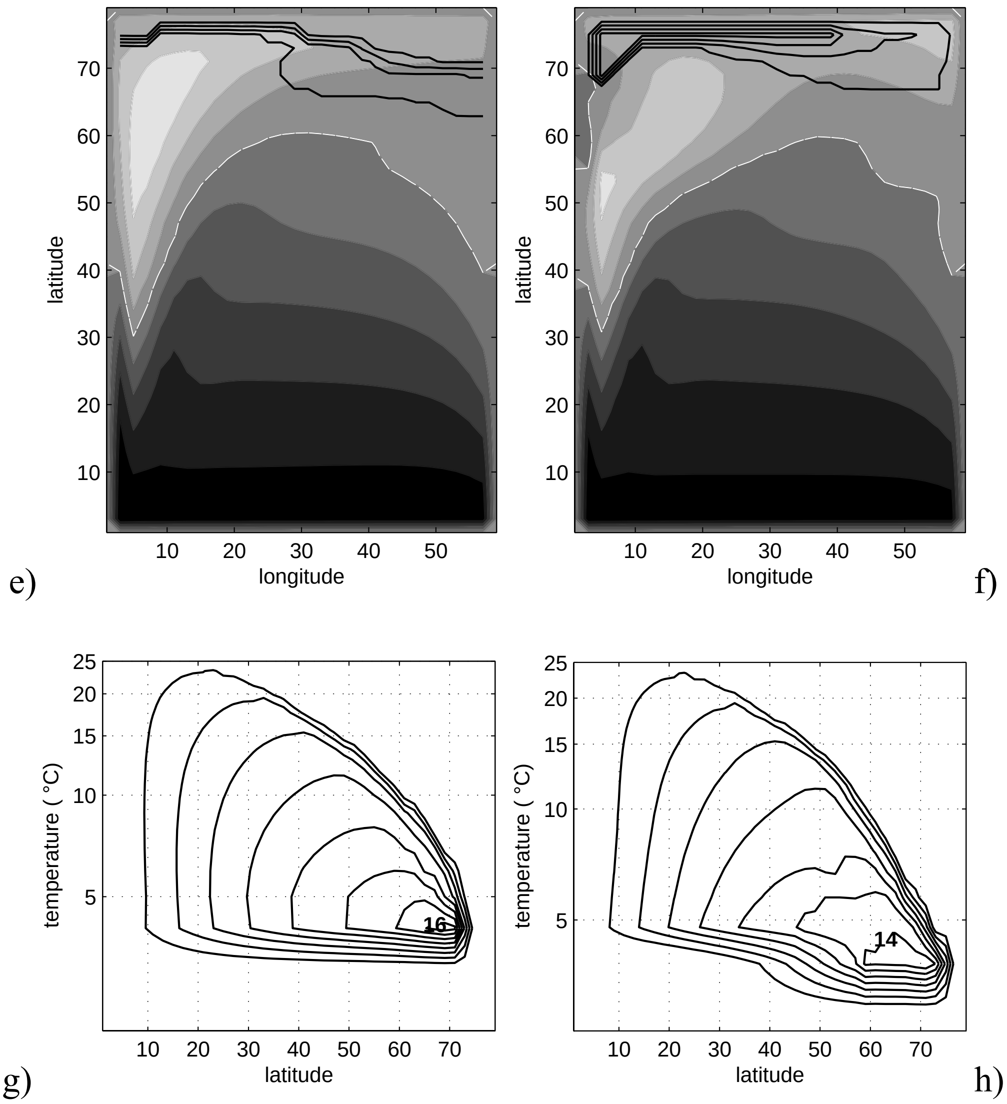


Figure 2. (a, b) Meridional overturning transport (in Sv, contour interval is 2 Sv). (c, d) Horizontal velocity (arrows) and temperature (in °C, contour interval is 0.5 °C, grey lines) at the surface. (e, f) Mixed layer depth (in km, contour interval is 1 km, black lines), and surface heat fluxes (in W m^{-2}, contour interval is 35 W m^{-2}, shaded). White lines mark 0 W m^{-2}. Light colors indicate heat loss to the atmosphere. (g, h) Meridional diapycnal transport (in Sv, contour interval is 2 Sv) for experiments VB (left) and CS (right). Contour intervals do not change in the next figures (if not explicitly specified).

The meridional heat transport is calculated as the vertical and zonal integral of the advective and diffusive heat flux to the north (relative to the temperature which minimizes it in each zonal section). The maximum transport in both simulations is about 0.35 PW at 40°N (Figure 3), in agreement with, e.g., Park and Bryan (2000). The observation-based estimate of Ganachaud and Wunsch (2003) for the real Atlantic Ocean is 1.27 ± 0.15 PW at 24°N. The diapycnal transport, the overturning obtained by zonally integrating along isotherms, shows a similar sensitivity to the basin geometry as the MOC, but the patterns appear more alike since the deep circulation takes place in a very narrow temperature range (Figure 2g, h).

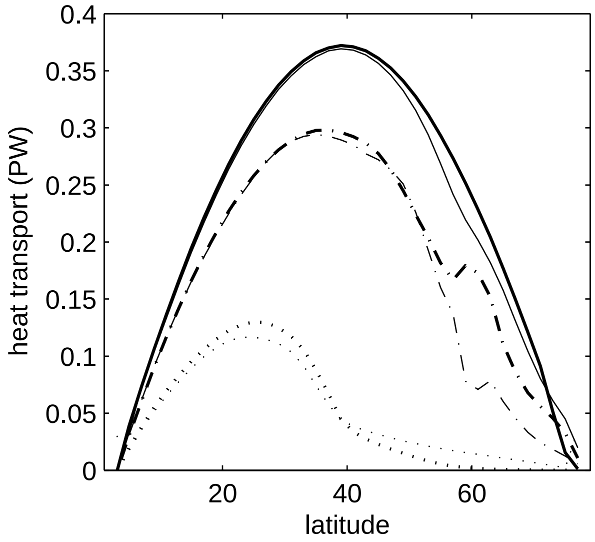


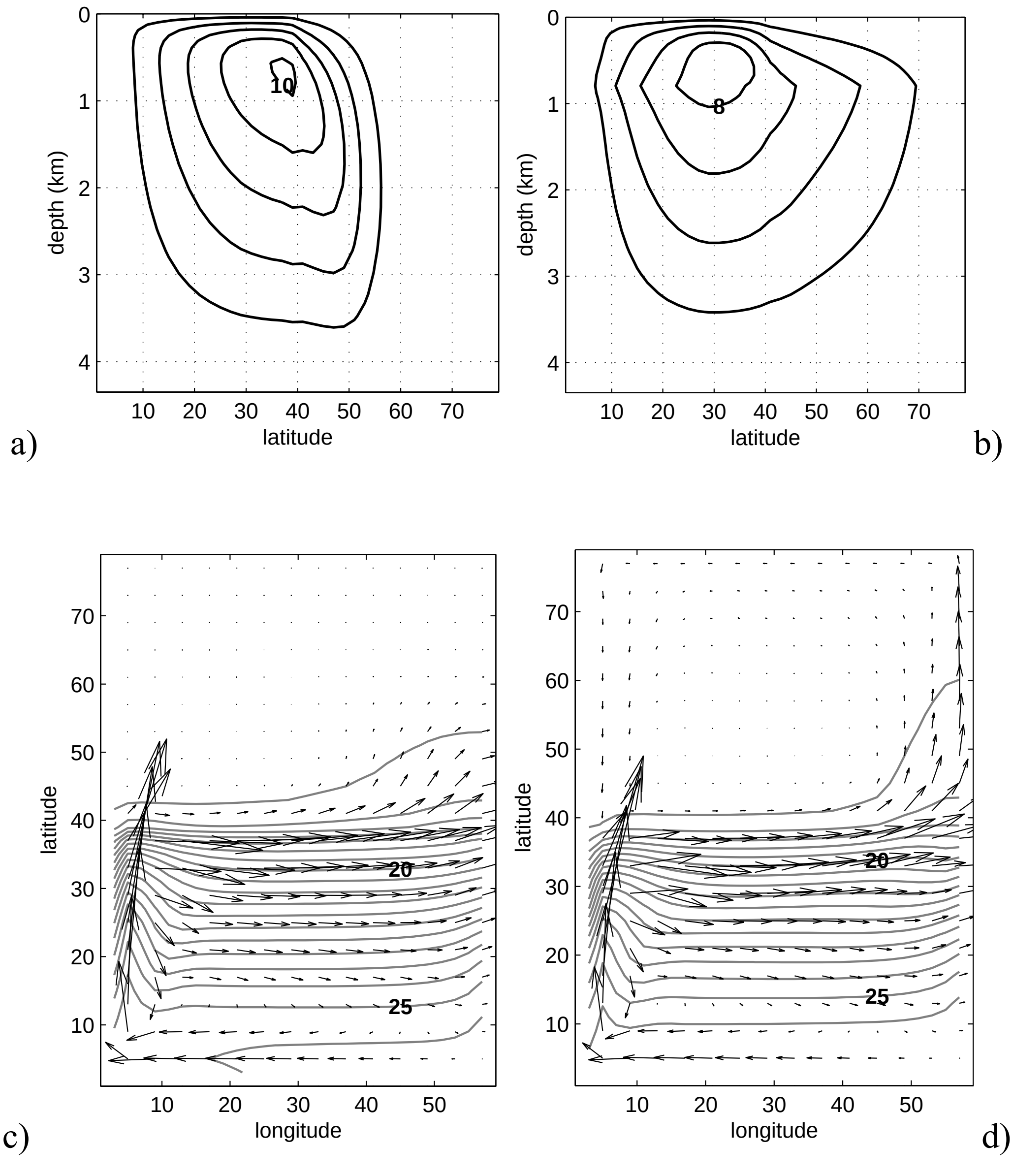
Figure 3. Maximum heat transport (in PW) as function of latitude for experiments VB (thick solid line), CS (thin solid line), VB40 and CS40 (dashed lines), VBR and CSR (dashed-dotted lines).

2.3.2 Interplay of buoyancy forcing and basin configuration

The main scope of this paper is to investigate how surface buoyancy forcing and basin configuration interplay to form the (idealized) Atlantic circulation. In particular we combine different SST patterns with the presence or absence of a continental shelf.

In the experiments VB40 and CS40, the prescribed SST is held constant north of 40°N. This is motivated by the theory of Nilsson et al. (2005) which suggests that the northern circulation can be remotely set by buoyancy forcing in the lower latitudes. However, while the experiment VB40 reproduces the basic features of VB, the circulation is essentially restricted to the area forced by a varying SST (Figure 4a, c).

The maximum volume transport of about 10 Sv is located immediately south of 40°N, and only 1 Sv overturns north of 50°N. The WBC deflects to the east with the constant SST to the left. Upon reaching the eastern wall, the flow spreads a few degrees to the north and sinks. The water does mainly change its properties at mid latitudes as shown by the diapycnal overturning in Figure 4e. The heat transport of about 0.1 PW peaks at 25°N over the warm WBC, and is negligible beyond 45°N.



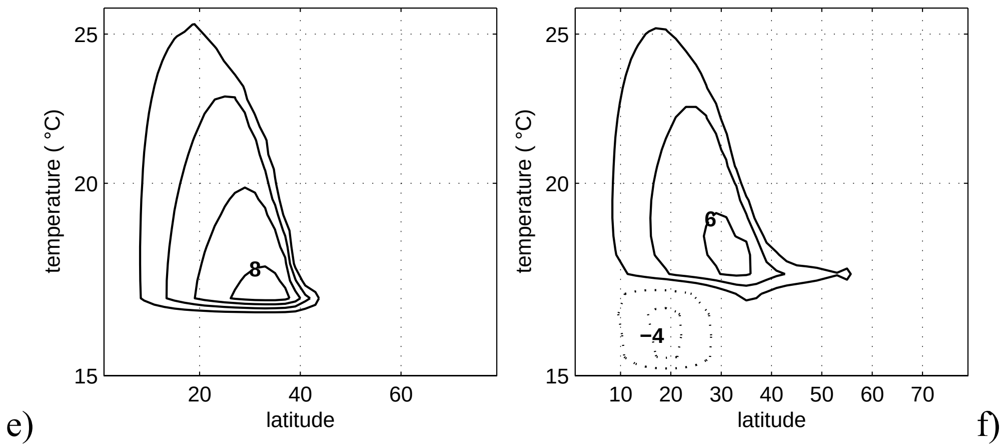


Figure 4. (a, b) Meridional overturning transport (in Sv). (c, d) Horizontal velocity (arrows) and temperature (in °C, grey lines) at the surface. (e, f) Meridional diapycnal transport (in Sv) for experiments VB40 (left) and CS40 (right).

The sensitivity to the constant SST is fundamentally different in the basin with the shelf (CS40). The structure of the overturning cell is very unlike VB40, but qualitatively similar to CS. Although the mass transport is reduced in the northern domain, the overturning cell extends over the whole basin. The maximum of 10 Sv is located at 30°N, at the depth of the shelf, and in contrast to VB40, there is a significant 5 Sv overturning north of 50°N (Figure 4b). The surface circulation consists of an anticyclonic gyre in the region with a varying SST, but there is (as in CS) a cyclonic current along the shelf in the northern part (Figure 4d). This gyre is weaker than in CS, but it is nevertheless distinct. The strongest sinking is at mid-latitudes next to the eastern wall (as in VB40), but it is limited by the depth of the shelf (as in CS). There is downwelling beyond shelf depth along the northern boundary, with a northeast maximum and a secondary limb in the northwestern corner. Different vertical transport gives different temperature at depth: CS40 has about 1 °C warmer bottom water than VB40 because of the supply of warmer waters in the north. The diapycnal overturning shows the continuous cooling of the WBC south of 40°N, in consistence with the upper thermal boundary condition (Figure 4f). There is a 3 Sv diapycnal overturning north of 40°N, but this covers a marginal temperature range with negligible water mass transformation. The above carries over to the twin experiments VB60 and CS60 (not shown). This case is less distinct as the area with a constant SST is much smaller.

Additional simulations were performed in order to investigate further the sensitivity of the circulation to the atmospheric forcing. A less idealized pattern of the surface heat flux was obtained by applying the reference SST gradient at an angle, with the coldest (warmest) temperature in the northwest (southeast). This constitutes the twin experiments VBA and CSA. The qualitative differences between the VB- and CS-class of experiments do not appear to be sensitive to the specific form of SST. The thermal wind from the "angled" SST does however introduce an upper-layer flow to the northeast. Even in the basin without a shelf (VBA), the WBC parts with the boundary at 60°N and there is sinking all along the northern wall (not shown). A significant barotropic circulation and a subpolar gyre are still exclusive to the experiment with the shelf. There are also some notable differences within CS and CSA: in the latter experiment, the coldest surface temperature and convection move away from the boundaries and are found in the central subpolar gyre (Figure 5).

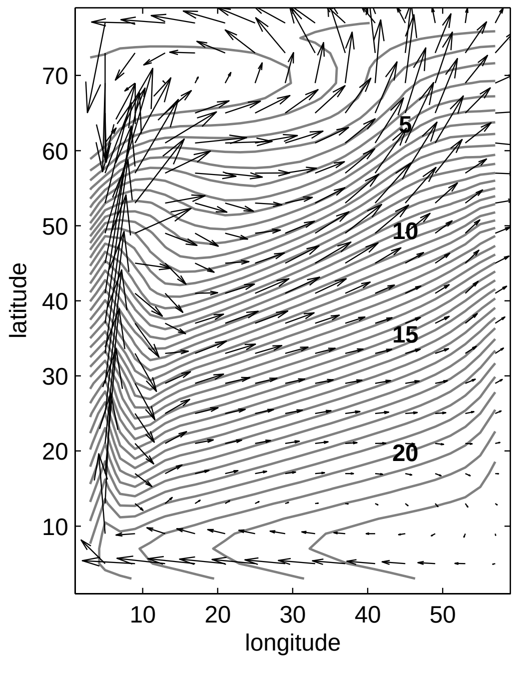


Figure 5. Horizontal velocity (arrows) and temperature (in °C, grey lines) at the surface for experiment CSA.

There is no wind in the experiments discussed so far. For completeness, wind is added to VB and CS, constituting the experiments

VBW (not shown) and CSW. The wind stress profile (Figure 1) is an idealized zonal climatology for the North Atlantic (Spall and Pickart 2001). The wind produces the expected Ekman cells (Jayne and Marotzke 2001). The depth of these cells is about 200 m at low latitudes, and 100 m at mid-latitudes (Figure 6a).

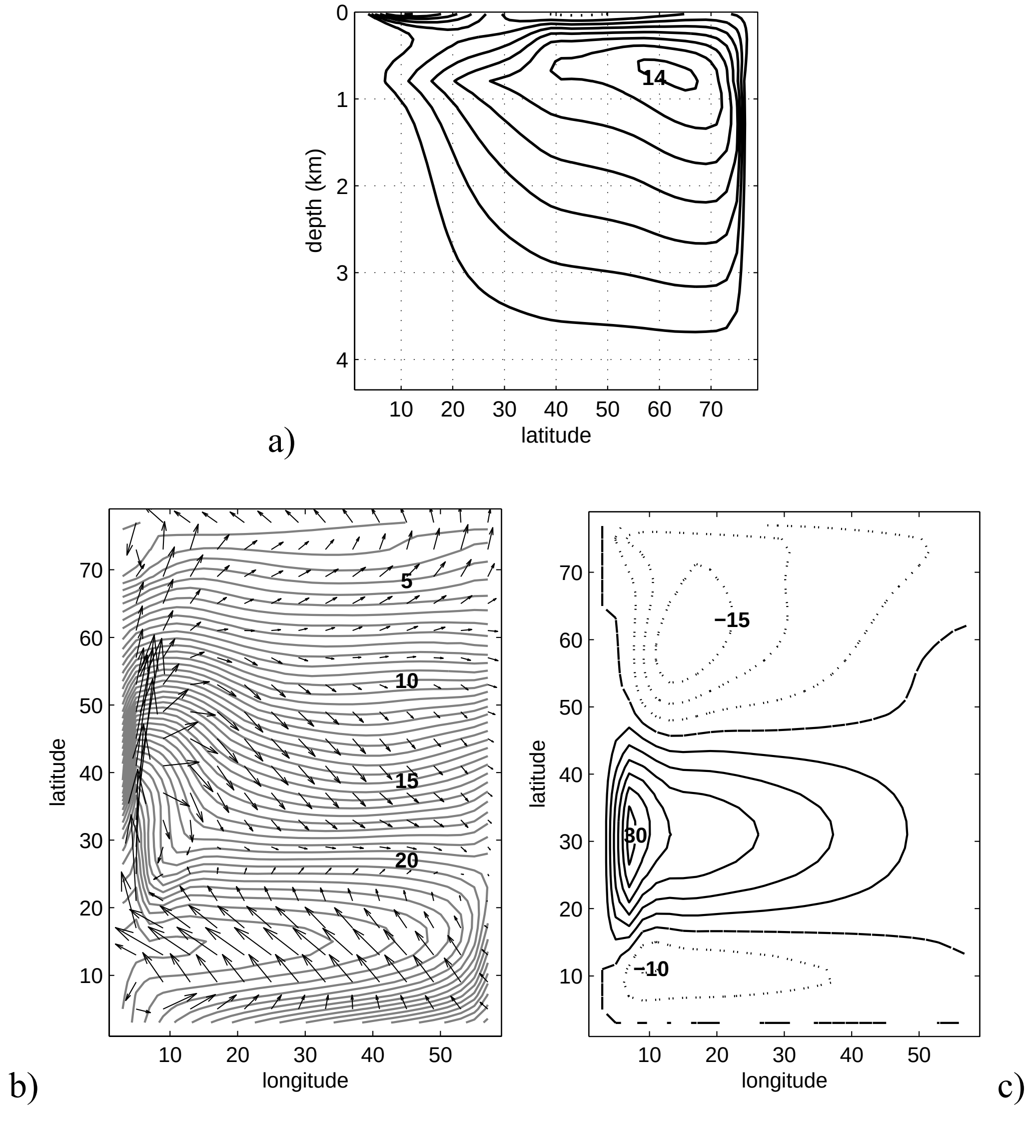


Figure 6. (a) Meridional overturning transport (in Sv). (b) Horizontal velocity (arrows) and temperature (in °C, grey lines) at the surface. (c) Barotropic streamfunction (in Sv, contour interval is 2 Sv, negative contours are dotted) for experiment CSW.

The horizontal gyre structure and the western intensification are consistent with the applied wind stress (Figure 6b, c; Munk 1950). The directly wind-driven circulation aside, there is a striking similarity with the reference simulations. Below the Ekman layer, both vertical and diapycnal overturning show little sensitivity to the wind. The presence of the wind neither affects the subpolar mixed layer structure, and the locations of the coldest water and deep sinking are comparable to VB and CS.

2.3.3 Sensitivity to a zonal ridge

The exchange of water with the Nordic Seas over the Greenland-Scotland Ridge (GSR) is a fundamental component of the Atlantic circulation (Hansen and Østerhus 2000; Drange et al. 2005). We performed the experiments VBR and CSR to investigate the effect of a zonal ridge on the modelled circulation. The ridge crosses the basin at 60°N and 800 m depth.

The overturning structure in CSR is shown in Figures 7a, b. The overturning is reduced and the depth of the northern cell is limited by the introduction of the ridge. The maximum volume transport of about 9.5 Sv is located at 46°N, 500 m depth, and 3.5 Sv cross the ridge. There is an additional 1 Sv overturning within the northern basin. The total water mass transformation is 11 Sv, with 3 Sv extending beyond the ridge (the observed diapycnal overturning across the GSR is 6 Sv, Hansen and Østerhus 2000). Because of the reduced flux of warm water that moves northward, the deep northern (southern) basin is colder (warmer) than that in CS.

The surface flow consists of an anticyclonic-cyclonic double gyre covering the North Atlantic–Nordic Seas basins, respectively (Figure 7b). The WBC separates at the latitude of the ridge in several branches. The northernmost branch is a part of the cyclonic gyre north of 65°N. The structure of this cyclone is very similar to the one seen in CS, but the deepest sinking in the northwest is now limited to 2 km because of the ridge (Figure 7b, c). There are also two mirror branches parallel to the ridge immediately north and south of it that reach the eastern wall and sink. South of these there is the anticyclonic subtropical gyre.

In VBR the horizontal and vertical circulations have the general basin-wide characteristics of VB, but volume and heat fluxes are reduced due to the ridge as expected. A notable feature is that the northern overturning extends all the way to 3 km depth without the restriction of the shelf (not shown).

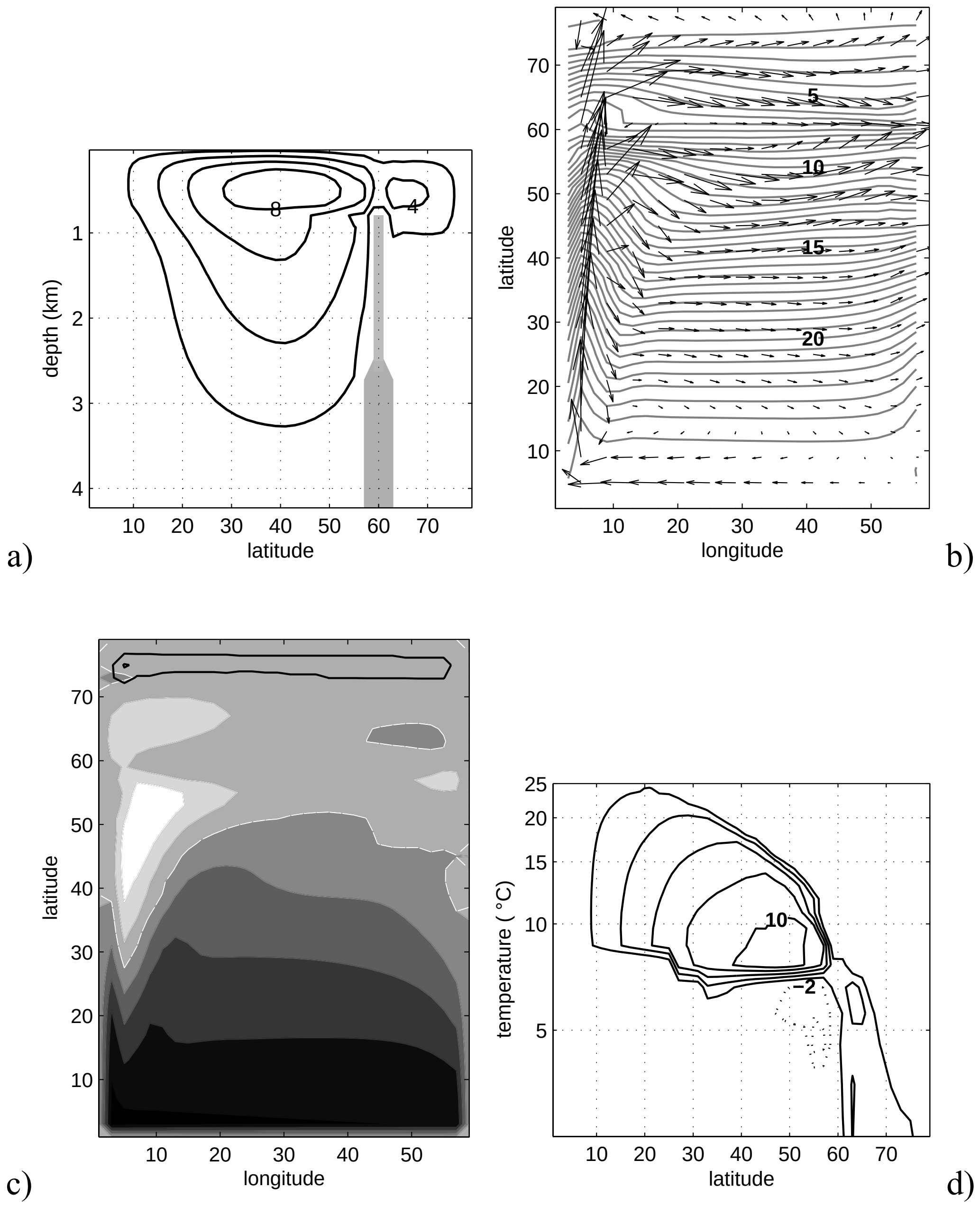


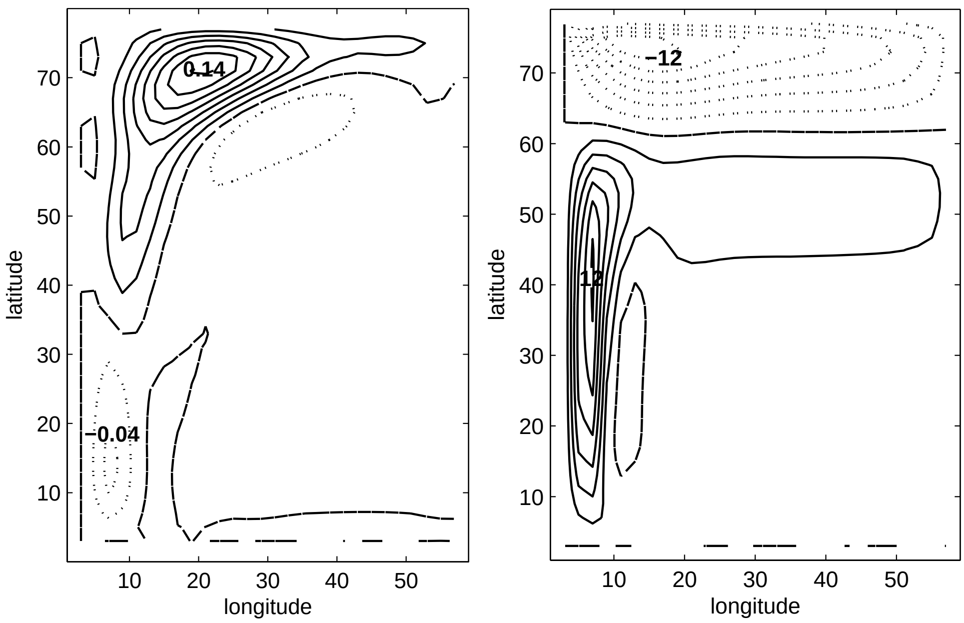
Figure 7. (a) Meridional overturning transport (in Sv). (b) Horizontal velocity (arrows) and temperature (in °C, grey lines) at the surface. (c) Mixed layer depth (in km, black lines), and surface heat fluxes (in Wm^{-2}, shaded). White lines mark 0 Wm^{-2}. Light colors indicate heat loss to the atmosphere. (d) Meridional diapycnal transport (in Sv) for experiment CSR.

2.4 Discussion

The steady large-scale circulation in an idealized North Atlantic Ocean has been investigated in a series of numerical simulations. The comparison of simulations with and without a continental shelf (CS- and VB- class, respectively) emphasizes the sensitivity of high latitudes dynamics to both the basin geometry and the surface forcing. As first pointed out by Winton (1997), we show that the presence of lateral topography is instrumental for the circulation in the subpolar region, using the simplest shelf configuration possible. The shelf substitutes the commonly used “staircase” sidewalls and bowl-shaped basins. The VB-runs, with a flat bottom and vertical sidewalls (e.g., Marotzke and Scott 1999; Nilsson et al. 2003), lack the characteristic double-gyre structure of the North Atlantic (Figure 2c). The addition of the one-grid-point wide shelf in CS causes a double-gyre circulation with a WBC that separates between the subtropical and subpolar gyres (Figure 2d). The northern gyre is a relatively strong, shelf-trapped circulation as found in previous studies with sloping boundaries (Winton 1997; Spall and Pickart 2001; Nilsson et al. 2005). The lateral topography leads to the separation of the WBC and supports the cyclonic gyre through the bottom pressure torque associated with the shelf (part of the so-called “JEBAR” effect; Myers et al. 1996) that becomes a dominant term in the barotropic vorticity balance. In the case of vertical sidewalls, this support is absent, and the WBC is trapped in the frictional “Munk layer” next to the western wall (Winton 1997).

The fundamental influence of the shelf led us to perform sensitivity experiments with different shelf geometries (not shown). Deeper or wider shelves do not qualitatively change the dynamics of the system, nor does a lateral topography that slopes in a series of steps over a horizontal scale of 6°. The influence of the shelf decreases when its depth increases since the buoyancy anomaly needs to penetrate down to the isobaths that guide the barotropic flow to make an impact. It becomes negligible for shelves deeper than 2.5 km.

The circulation is essentially baroclinic in the VB-class of experiments, as shown in Figures 8a, c. The shelf gives rise to a basin wide barotropic circulation with the distinct double-gyre structure (Figures 8b, d): an anticyclonic gyre in the south (formed by the continuation of the WBC re-circulating in the interior of the basin), and a cyclonic gyre in the north (due to the flow along the shelf). Nilsson et al. (2005) describe both analytically and numerically how a cyclonic gyre results from the combination of lateral topography and buoyancy loss like that of CS. The barotropic flow depends non-locally on the buoyancy forcing from the conservation of circulation. It increases (decreases) if the large-scale buoyancy gradient increases (decreases). The latter explains the presence of a subpolar gyre in the experiments with a shelf and a constant SST prescribed in the north. While the circulation in VB40 and VB60 essentially reproduces the reference characteristics in basins virtually limited to the region with varying SST, in CS40 and CS60 the shelf still supports a basin-wide circulation with a cyclonic gyre in the area of constant SST. The overturning maxima shift southward (close to the northern limit of the region with varying SST), but the overturning cells extend over the whole basin (Fig. 4b). There is of course little water mass transformation in the area of uniform SST (Fig. 4f) as the surface flow is rapidly equilibrated with the constant temperature above.



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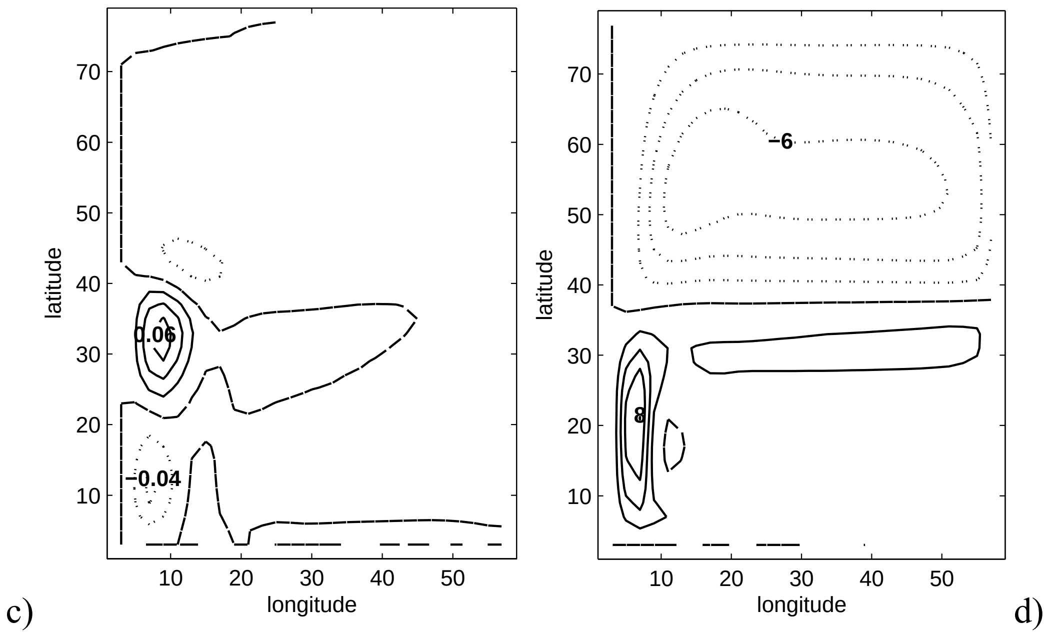

Figure 8. Barotropic streamfunction (in Sv) for experiments (a) VB, (b) CS, (c) VB40, (d) CS40. Contour interval is 0.02 Sv and 2 Sv in the VB- and CS-class of experiments, respectively. Negative contours are dotted.

The modifications in high-latitude circulation are reflected in the vertical stratification and surface temperature, and thus the locations of sinking and convection. These two processes are important in understanding the MOC. The processes of convection (diapycnal overturning) and sinking (vertical overturning) are not the same and not necessarily collocated (Marotzke and Scott 1999). Convective mixing homogenizes an unstably stratified water column, e.g., following surface buoyancy loss, and there is little net sinking associated with it (Send and Marshall 1995). The two processes are fundamental in setting the properties of the deep water masses (Straneo 2006). If they are not collocated (as in CSA), the deep waters are influenced both by the coldest SST brought to depth by convection and the warmer water brought down by the sinking. If they are (as in CS), the deep waters are fed by the coldest surface waters (Figure 9). The properties of the deep ocean are therefore very much set by the gyre configuration. The WBC is the supplier of warm water to the north in VB, while the cyclonic boundary current is the supplier in CS. Since the latter is colder than the WBC (the eastward interior flow loses heat while crossing the basin), the heat flux to the northern region is reduced. Bottom temperatures in CS are generally colder than in VB as a consequence.

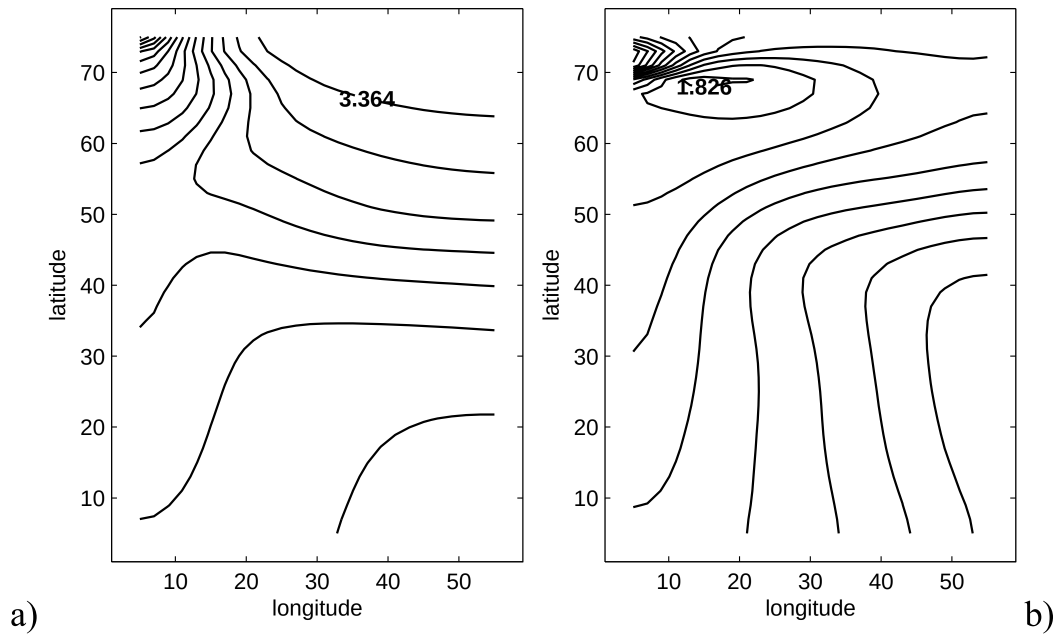

Figure 9. Bottom temperature (in °C, contour interval is 0.0005 °C) for experiments CS (left) and CSA (right). Coldest isotherms are labeled.

Although the main contrasts are between VB- and CS-experiments, there are important sensitivities to the buoyancy forcing within a topographic domain. A slight change in the spatial structure of the prescribed SST, with the coldest temperature over the northwest (CSA), produces a circulation more comparable to the real North Atlantic Ocean: the coldest surface layer and convection move away from the boundaries and are found in the central subpolar gyre, i.e. open ocean convection (Figure 5; Schmitz and McCartney 1993). This pattern is also produced by Spall and Pickart (2001), but it should be noted that their simulations include wind forcing.

The sensitivity to the wind is investigated in VBW and CSW. Even if the barotropic gyres in general reflect the wind pattern, the structure of the shelf-trapped flow in CSW is similar to that in CS. The comparison between VBW and CSW emphasizes the role of the shelf: while the barotropic flow in the former case is solely due to the surface wind stress, the latter is shaped by both wind stress and bottom pressure terms

(Figure 6c). The wind is therefore not essential for sustaining the double-gyre circulation in these experiments.

The profiles of poleward heat transport are almost identical within all the shelf/no-shelf twin experiments (Figure 3). This may seem surprising, but it appears to have a simple explanation: the surface heat flux is given by the difference between the model's surface temperature and the prescribed SST. Although surface heat flux patterns are highly sensitive to the gyre structures (Figure 2), the zonally averaged surface temperature and hence heat flux do not change much within a twin experiment.

Topographic constraints play an important role in the real North Atlantic Ocean. A major example is the Greenland-Scotland Ridge. The experiments VBR and CSR simulate an idealized North Atlantic-Nordic Seas system with an 800 m deep zonal ridge. The presence of the ridge makes the local circulation very complex. A detailed discussion is beyond the scope of this study, but there are also more regional and basin-wide changes. The ridge blocks deeper waters from being exchanged with the northern basin so that the hydrography of the two sub-basins, in particular below the depth of the ridge, is modified by the decreased northward transports of heat and volume (cf. Figure 3a in Hansen and Østerhus 2000; Iovino et al. 2007). The reduction of the heat transport implies a decreased heat loss to the atmosphere. Indeed the dense water formation takes place predominantly south of the ridge. A comparison of the two ridge experiments also emphasizes the impact of the shelf on the dynamics, particularly in the north. In VBR the heat transport and water mass transformation north of the ridge are essentially part of the vertical overturning circulation, whereas in CSR they are mainly achieved by the horizontal circulation. The presence of the northern cyclonic gyre in CSR can be explained as in CS. The barotropic current at the eastern high latitudes plays an essential role in the horizontal advection of warm water in the northern basin. It is the cyclonic slope current that carries the transformation of Atlantic inflow in dense overflow in the real Nordic Seas (Mauritzen 1996a,b; Rudels et al. 1999).

We performed a series of simulations similar to Roberts and Wood (1997) varying the geometry of the ridge (not shown). The structures of the vertical and diapycnal overturning, and the double-gyre circulation do not change, but the strengths of these do vary as the exchange between the sub-basins is very sensitive to the ridge-geometry (Iovino et al. 2007).

2.5 Concluding remarks

We have presented a study of the equilibrium thermohaline circulation's sensitivity to (idealized) surface forcing in simplified geometries representing the North Atlantic Ocean, using the *z*-level MITgcm. Simple changes in the combination of buoyancy forcing and basin configuration drastically affect the numerical results. The simulations confirm the previous finding (e.g., Winton 1997) that lateral topography, in our case a continental shelf, is crucial in shaping the double-gyre circulation in the North Atlantic Ocean (Figure 2). The emergence of the subpolar gyre consequently modifies the deep sinking and convective mixing. The overturning in the northern North Atlantic is controlled by a variety of components, including the atmospheric forcing. We have shown how the subpolar gyre remains even in the case of negligible surface forcing at high latitudes (Figure 4). This may be considered a simple illustration of how a circulation may be maintained under an ice-covered northern ocean. Furthermore, we show that adding wind does not change the fundamental difference between the circulations in the two reference configurations. The wind does set the near-surface circulation, but there is little impact below (Figure 6). The introduction of a zonal ridge (like the Greenland-Scotland Ridge) modifies both the local and basin-wide dynamics (Figure 7). Although CSR is very idealized, we suggest that it does reflect some of the basic dynamics at work in the Nordic Seas, where a nearly-barotropic slope current advects warm Atlantic water northward. In agreement with Walin et al. (2004), we find that the barotropic flow over the shelf (at the same depth as the ridge) is essential for the thermohaline exchanges between the basins, traditionally considered to be of baroclinic nature (Hansen et al. 2001). The presence of the northern cyclonic gyre depends on the presence of the continental shelf (and not of the ridge). This underlines the general finding that the modeled thermohaline gyre circulation depends on the interplay between the surface forcing and the topographic constraints.

Acknowledgements. We thank Dr. Ben Marzeion and Prof. Michael A. Spall for their valuable comments. This work was support by the *Polar Ocean Climate Processes* (ProClim) project funded by the *Norwegian Research Council*.

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