The parameterisation of Mediterranean-Atlantic water exchange in the Hadley Centre model HadCM3, and its effect on modelled North Atlantic climate.

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Abstract

Multiple palaeo-proxy and modelling studies suggest that Mediterranean Outflow Water (MOW) is an important driver of Atlantic Meridional Overturning Circulation (AMOC), particularly during periods of weak overturning. Here, we employ the HadCM3 ocean-atmosphere General Circulation Model (GCM) to investigate the effect of using different parameterisations of Mediterranean-Atlantic water exchange on global ocean circulation and climate. In HadCM3, simulating flow through the Gibraltar Straits with an 'open seaway' rather than a 'diffusive pipe' causes a shoaling and strengthening of the MOW plume. This reorganises shallow Atlantic circulation, producing regional surface air temperatures anomalies of up to +11 °C and -7.5 °C. We conclude that when investigating the influence of MOW on modelled ocean circulation and climate, an accurate parameterisation of Mediterranean-Atlantic exchange is important and should match observed fresh water and salinity flux constraints. This probably cannot be achieved through a simple 'diffusive pipe' with depth invariant mixing coefficient.

Keywords: Marine gateway; Gibraltar Straits; Mediterranean outflow; North Atlantic circulation; Atlantic Meridional Overturning Circulation.

1. Introduction

Mediterranean Outflow Water (MOW) is thought to play an important role in maintaining the pattern and vigour of Atlantic Meridional Overturning Circulation (AMOC), particularly during periods of weaker North Atlantic Deep Water (NADW) formation (Bigg and Wadley, 2001; Artale, et al., 2002, Voelker et al., 2006; Rogerson et al., 2010, 2012; Penaud et al.,

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Non-standard abbreviations: GIN (Greenland-Iceland-Norwegian) Seas, MOW (Mediterranean Outflow Water), NOS (Narrow Open Seaway), WOS (Wide Open Seaway).

2011). Artale et al. (2002) showed that the vertical position of the MOW could have a major impact on the structure of the AMOC. Furthermore, MOW can also have important influence on the variability and stability of the AMOC (e.g. Calmanti et al., 2006) who showed that in a box model the variability of the AMOC was influenced by whether the MOW mixed with newly formed deep water (variability reduced) or helped maintain an interior salinity gradient.

Therefore it is important that Global General Circulation Models (GCMs) well represent the Mediterranean-Atlantic water exchange, which occurs today through the Gibraltar Straits. However, with a depth of < 300 m at the main sill and a width of < 14 km at its narrowest point (Candela, 1991; Gómez, 2003), the Gibraltar Straits are shallow and narrow. Simulating changes in water exchange through such gateways presents a particular challenge for global-scale modellers, and where they cannot be resolved by the GCM grid and bathymetry, there are two main choices; (i) to explicitly resolve the gateway with an unrealistically wide and deep seaway (henceforth referred to as an 'open *seaway'*), or (ii) to parameterise the exchange by using a 'pipe' that transfers water properties between the two basins.

Both of these options have previously been used in GCM studies investigating the effect of changes in Mediterranean-Atlantic exchange on North Atlantic circulation and the importance of MOW in governing global climate. For example, investigating the link between Mediterranean-Atlantic exchange and AMOC strength for the Quaternary, (Bigg and Wadley, 2001; Rogerson et al., 2010) use a wide open seaway to capture flow through the Gibraltar Straits. On the other hand, Rahmstorf (1998) and Chan and Motoi (2003), employ a pipe to infer the effect of MOW on climate, replacing the thermal and salinity properties of two-grid boxes either side of the Straits by their combined mean at each timestep. More recently, Wu et al. (2007) investigated the impact of adding a physically based representation of Mediterranean outflow compared to having a closed straight. They found large changes to the ocean temperatures at the outflow level (~ 1100 m) but relatively small impact on the surface climate of the North Atlantic, with temperatures changing by less than 1 ^{o}C. Here, we examine the robustness of these results by investigating the impact of a somewhat simpler parameterisation within a higher resolution model, specifically the Hadley Centre coupled atmosphere-ocean model, HadCM3. We contrast the results of the parameterisation to simulations with an open configuration (open seaway versus pipe configurations). It is crucial that palaeo, modern and future-projection experiments examining the impact of changes in Mediterranean-Atlantic exchange take gateway representation into account.

2. Methods

2.1. Model Description

The model used for this investigation is the UK Met Office's fully coupled atmosphere-ocean GCM HadCM3 version 4.5. The atmosphere component of HadCM3 has a horizontal resolution of 2.5° x 3.75°, 19 vertical layers – based on the hybrid vertical coordinate scheme of Simmons and Burridge (1981) – and a timestep of 30 minutes. Included in its physical parameterisations are the radiation scheme of Edwards and Slingo (1996), the convection scheme of Gregory et al. (1997) and the MOSES-1 land surface scheme (Cox et al., 1999). The ocean model has a horizontal grid resolution of 1.25° x 1.25° and 20 vertical levels, as described by Johns et al. (1997), designed to give maximum resolution towards the ocean surface. Physical parameterisations in the ocean component include an eddy-mixing scheme (Visbeck et al., 1997), isopycnal diffusion scheme (Gent and Mcwilliams, 1990) and a simple thermodynamic sea-ice scheme of ice concentration (Hibler, 1979) and ice drift and leads (Cattle et al., 1995). The model has been shown to reproduce modern sea surface temperatures well without needing to apply unphysical 'flux adjustments' at the ocean-atmosphere interface (Gordon et al., 2000).

The ocean grid is aligned with the atmosphere grid and the coupling occurs once per model-day, when the constituent models pass across the fluxes accumulated over the previous 24 model-hours, interpolating and averaging across the different grids to accommodate the different resolutions. River discharge to the ocean is also implicitly modelled through the instantaneous delivery of continental runoff to the coasts, according to grid-defined river catchments and estuaries. For a more detailed description of the model and its components, including improvements on earlier versions, see Gordon et al. (2000) and Pope et al. (2000).

Although HadCM3 may no longer be considered a 'state of the art' GCM, its relatively fast model-speed (compared to more recent versions) allows us to run long-integrations of several centuries, so that ocean circulation reaches near steady-state for our experiments.

2.2. Mediterranean-Atlantic exchange

The exchange of water between the Mediterranean and Atlantic is parameterised in HadCM3 by what we will here refer to as a diffusive pipe, whereby thermal and saline properties are partially mixed between the two basins according to the temperature and salinity gradients across the Gibraltar Straits. This net flux of heat and salt is calculated for two corresponding pairs of grid boxes, either side of the Straits, in the upper 13 ocean levels (0 to 1 km depth, as defined by the local basinal bathymetry) and at every timestep. To overcome the restrictions of horizontal resolution and bathymetric depth, the parameterisation uses a coefficient of exchange to control how much of each grid box is mixed. This effectively restricts the volume of exchange to ~ 1 Sv of easterly and westerly 'flow' through the Gibraltar Straits, which is close to observational values (> 0.74 ± 0.05 Sv) (García-Lafuente et al., 2011). Thus, a realistic Mediterranean-Atlantic transport flux is achieved, even though the gateway is too shallow and narrow to be resolved in the model's land sea mask and bathymetry. For further details, see 'Appendix A5' by Gordon et al. (2000).

The modelled exchange is a good reproduction of the two-layer flow structure observed for modern exchange through the Straits (Bethoux and Gentili, 1999), with a surface eastward flow of North Atlantic Central Water into the Mediterranean and a deeper westward flow of Mediterranean Outflow Water (MOW) into the Atlantic. The interface lies roughly halfway between the surface and sill depth. This diffusive pipe set-up comprises our 'control' experiment.

2.3. Experiment design

To test the sensitivity of modern climate to the representation of Mediterranean-Atlantic water exchange, we performed three experiments in HadCM3 in which everything is identical except for the representation of flow through the Gibraltar Straits. We used a pre-industrial climate set-up with modern continental configuration, and all experiments were initialised from the output of the publicly released HadCM3 spin-up simulation, published by Gordon et al. (2000). Each experiment was integrated over 500 years which is similar, but slightly longer than, Wu et al. (2007).

For our different representations of Mediterranean-Atlantic exchange, we replaced the Diffusive Pipe (our control) with a Narrow Open Seaway (NOS) and a Wide Open Seaway (WOS). For these experiments, the standard pipe configuration was disabled and part of the land-bridge connecting Spain to Morocco was transformed into an ocean channel that, similar to the pipe, is constrained by model bathymetry and so has an equivalent depth (~ 1 km). The channels for the NOS and WOS experiments are 139 km (one grid box) and 417 km (three grid boxes) wide, respectively. Such seaways are common to several models (with widths depending on resolution of model) and can change both the transport properties and the nature of the physical parameterisation (from diffusive to advective).

For all three experiments, we examined the temporal evolution of the results. The near surface climatology reaches near steady state fairly rapidly (~200 years) with the global mean temperatures changing by less than 0.02 °C per century and with similar trends (but with much higher temporal variability) for temperatures in the region of the Gulf of Cadiz and the Western Mediterranean. Similarly small trends exist for salinity, except in the Western Mediterranean where there is a discernible drift until about year 400 after which the trend is small compared to the natural variability. We therefore calculate all climatologies from the mean values for the final 100 years of the simulations.

The water properties of the three simulations within the Western Mediterranean and Gulf of Cadiz are relatively comparable. The near surface inflow water to the Mediterranean is characterized by temperatures of 16.3, 16.6, 17.1 °C and salinity of 35.9, 35.8, and 35.8 psu for the control, NOS and WOS simulations respectively. These should be contrasted to observations of 15.5 °C and 36.2 psu (Hopkins, 1999) showing the modelled inflow is slightly too warm and fresh. Though not perfect, the model biases are comparable to those in Wu et al. 2007.Similarly the modelled outflow source waters are 13.8, 14.8, 14.9 °C and salinity of 39.6, 38.9 and 38.9 psu which again are comparable to observations (13.8 °C and 38.4 psu) and Wu et al (2007).

Similar to previous studies using an open seaway for Mediterranean-Atlantic exchange (Bigg and Wadley, 2001; Rogerson et al., 2010), both NOS and WOS result in stronger easterly and westerly flow through the Gibraltar Straits than the PIPE control experiment (4 Sv, compared to 1 Sv). However, the elevated salt export to the Atlantic achieved with these experiments (2.0 psu Sv) is closer to observational values (1.5 psu Sv) (Bryden et al., 1994) than the salt exported by the pipe in our control (0.6 psu Sv).

3. Results and Discussion

Observational data (Boyer et al., 2009) shows that today, a distinct MOW plume spreads in the North Atlantic at a depth centred 1000-1500 m, where it mixes with North Atlantic intermediate waters. Others (Stanev, 1992; Mauritzen et al., 2001; McCartney and Mauritzen, 2001; New et al., 2001; Bower et al., 2002; Voelker et al., 2006) have suggested that this MOW plume preconditions the North Atlantic, providing an important source of warm, saline waters for NADW formation, thus contributing towards driving the AMOC. In the following discussion, we compare the effect of using NOS and WOS on North Atlantic circulation and global climate, versus using a pipe.

3.1. Effect on the AMOC

The pipe (control) parameterisation of Mediterranean-Atlantic exchange produces a saline tongue that descends the continental slope to spread westwards in the North Atlantic, centred at a depth of 1500 m approx. (Fig. 1). By running an experiment with no Mediterranean-Atlantic exchange, we find that, similar to Chan and Motoi (2003) and Rahmstorf (1998), this protrusion of warm, saline waters contributes directly to the southward-bound component of the AMOC, strengthening the export of NADW to the Southern Ocean by ~ 1 Sv. Contrary to Chan and Motoi (2003), on the other hand, this has no discernible impact on Southern Hemisphere climate under modern conditions in HadCM3. However, given that the strengthening represents only a small change in the relatively stable and strong AMOC regime, and that it affects only deep and bottom water currents, our results are unsurprising.

With respect to the control, both open seaway parameterisations cause a shoaling of some of the deeper-spreading MOW (Fig. 1). This arises because using an open seaway produces a larger water transport but more realistic salt flux than the control with a dilution of salt in the exchanged water mass. This in turn also results in stronger density gradient and hence an intensification of the existing circulation producing a stronger and further-reaching plume centred at a depth of 1000 m, though the deeper components of MOW do remain. The new plume is sufficiently shallow to be entrained in the northward-bound currents, increasing the supply of warm, high-salinity intermediate water to high latitude sites of NADW formation – the North Atlantic, the Greenland-Iceland-Norwegian (GIN) Seas and the Barents Sea – where it emerges near the surface and enhances overturning, increasing the depth of maximum AMOC strength by 200 m in both NOS and WOS. This strengthens the deep southbound flow, centred at a depth of 2000 m (approx.), by around 2 Sv and 5 Sv for NOS and WOS, respectively. The deep AMOC component is stronger for WOS because the Gibraltar Straits are centred further north than for NOS, setting a greater portion of the MOW plume on a northward flow-path towards the high latitude regions of overturning, with less dilution first occurring in the central North Atlantic. This also explains the increase in deep Atlantic salinity, observed for WOS (Fig. 1c).

However, in both open seaway parameterisations, the climate signature associated with the increases in AMOC strength and depth is localised (Fig. 2). The enhanced supply of warm, saline waters to the GIN Seas increases the potential temperature in the upper 500 m of the water column, leading to a reduction in sea-ice cover and hence a reduction in surface albedo, which warms surface air temperatures. This positively feeds back into localised warming at the sites of sea-ice reduction, resulting in an annual mean surface air temperature anomaly of up to +4.5 °C for NOS and +3.5 °C for WOS, with respect to the control (Fig. 2). This effect is particularly enhanced during the boreal winter months, when deep water formation is strongest and deepest, sea-ice loss is greatest (up to - 35 %) and surface air temperatures are warmest in the GIN and Barents Seas (up to + 11.0 °C and + 6.5 °C for NOS and WOS, respectively), compared to the pipe configuration.

3.2. Effect on the North Atlantic gyres

The shoaling of westward-spreading MOW and its subsequent mixing with overlying North Atlantic waters in the open seaway experiments increases the contribution of warm, high salinity waters to the subtropical gyre, causing it to strengthen and deepen. The enhanced anti-cyclonic ocean circulation pushes northwards towards the mouth of the Labrador Sea, weakening the subpolar gyre and restricting it to latitudes above 50 °N for both NOS and WOS, compared to ~ 45° N in the control. This weakening and high-latitude confinement of the subpolar gyre reduces the exchange of water taking place between the North Atlantic and the Labrador Sea. With less warm surface Atlantic water mixing with the cooler polar waters already in the basin, Labrador Sea cools in the upper 200 m of the water column by up to 1.1 °C for NOS and 2.6 °C for WOS, compared to pipe. This leads to an increase in Labrador Sea-ice cover, raising the surface albedo and cooling the air above. The regional decrease in surface air temperature further enhances sea-ice formation, closing the positive feedback loop and resulting in a steady-state increase in Labrador sea-ice concentration of up to ~ 40% and a local mean annual air temperature anomaly of up to -3.5 °C (Fig. 2). Again, the feedback is strongest during the boreal winter, when sea ice formation is most prevalent, resulting in a temperature anomaly of up to - 6 °C for NOS and up to -7.5 °C for WOS.

Similar to the effect on the AMOC, and also because of the more northerly injection of MOW to the North Atlantic, the effect on the North Atlantic gyres is greatest for WOS. For this experiment, the enhanced subtropical gyre is so strong and persists so far north below the subsurface, that it confines the subpolar gyre to the upper ~ 100 m of the water column, compared to the upper 1000 m for the pipe and NOS experiments. Thus, with a Wide Open Seaway, strong northward flow of Atlantic waters along the western boundary to the southern-tip of Greenland reinforces the restriction of flow into and out of the Labrador Sea, isolating the basin and enhancing sea surface cooling, increasing sea-ice formation and thus amplifying the surface cooling.

However, the strengthening of the North Atlantic subtropical gyre achieved with WOS and NOS, and the corresponding weakening of the subpolar gyre, also acts to restrict the exchange of water between the Atlantic and the GIN Seas. As a result, less relatively warm, high-salinity shallow water from the North Atlantic reaches as far north as the GIN and Barents Seas than for the pipe. Although this cooling effect is more than compensated for by the warming discussed in 3.1 Effect on the AMOC, it is so strong in the case of WOS that the surface air temperature anomalies observed for the GIN and Barents Seas are reduced compared to NOS (Fig 2.).

3.3. A North Atlantic 'hotspot'

A culmination of increased salt and heat supply from MOW to northward flowing intermediate currents, and the restricted outflow of relatively cool Labrador Sea water to the North Atlantic, raises the salinity and temperature of the upper 1500 m to create a 'hotspot' of relatively warm and salty water, centred around 48° N and 40° W in the shallow-intermediate layers (Fig. 3 shows the upper 600 m at this point). In our control, a cool, fresh, shallow tongue of combined Labrador Sea outflow and St. Lawrence River discharge protrudes into the North Atlantic centred at 75 m depth (Fig. 3a and b). In NOS and WOS, the limited exchange between the Labrador Sea and the Atlantic Ocean reduces this injection of relatively cool, fresh surface waters to little more than the contribution made by the St. Lawrence River. The resulting increase in salinity in the upper 100 m of the water column overrides the concurrent warming, to increase surface density (Fig. 3c), reducing shallow-intermediate water stratification and deepening the North Atlantic mixed layer by up to 120 m for NOS and 150 m for WOS. Following the increased MOW-supply directly northwards and from the subtropical gyre in WOS compared to NOS, and the further reduction in

Labrador Sea outflow, the increase in surface salinity and hence potential density is greatest for WOS, resulting in the deeper mixed-layer.

The compounded effect of increased mixing and shallow-ocean warming in NOS and WOS releases more heat to the overlying atmosphere, compared to the pipe. Raised surface air temperatures produce an increase in local evaporation-precipitation, amplifying the surface salinity anomaly. In the modern ocean, the cool tongue of Labrador Sea outflow is not observed as far west as in our control (Boyer et al., 2009), so it is unlikely that changes in Labrador Sea exchange would have such a great effect on North Atlantic ocean temperature. Nevertheless, in our modelled North Atlantic, this positive feedback loop reaches a steady-state mean annual air temperature increase of up to +3.0 °C for NOS and +3.5 °C for WOS (Fig. 2), with an overall 42.0 % increase (+1.01 mm day^{-1}) and 46.0 % increase (+1.11 mm day^{-1}) in local evaporation-precipitation, respectively. The effect is notably stronger for WOS than for NOS, due to greater mixing and the warmer shallow-intermediate North Atlantic.

4. Summary and conclusions

In the HadCM3 GCM, we find that representing the Gibraltar Straits as an open seaway, rather than with a diffusive pipe, causes significant but localised climate anomalies in the high latitude Northern Hemisphere by three main positive-feedback mechanisms, associated with the shoaling and northward-shift of the MOW plume:

(i) The increased northward flow of warm, high salinity intermediate waters of MOW-origin enhances NADW formation in the GIN and Barents Seas, reduces local sea-ice cover by up to 35 %, thus lowering surface albedo, and increases surface air temperature by up to 11° C.

(ii) The increased contribution of warm, saline, MOW-origin waters to the North Atlantic subtropical gyre strengthens its circulation and weakens the adjacent subpolar gyre. This reduces the ocean heat-exchange with the Labrador Sea, increasing local sea-ice cover by up to 40 %, raising surface albedo and reducing surface air temperatures by up to 7.5 °C.

(iii) The increased northward contribution of relatively warm, high-salinity MOW-origin water to the North Atlantic and the reduced contribution of relatively cool, fresh Labrador Sea outflow enhances vertical mixing in the North-Western North Atlantic. A combination of increased mixing and overall upper-ocean warming elevates local surface air temperatures and evaporation. This amplifies the surface salinity perturbation and further reduces the vertical density gradient in the shallow-intermediate Atlantic. The feedback culminates in a steady-state surface air temperature anomaly of up to + 3.5 °C.

The changes in salinity gradients do not produce statistically significant changes in the interannual and interdecadal variability of the AMOC, as predicted from the box model of Calmanti et al 2006. However the length of simulations are not conclusive in this respect.

In short, changing the way Mediterranean-Atlantic exchange is modelled in HadCM3 alters North Atlantic intermediate water characteristics and structure, causing a significant reorganisation of ocean circulation. Although this has little widespread impact on the global climate, it results in large, localised surface air temperature anomalies of several °C over the North Atlantic.

However, it is important to interpret these results carefully, and not all global GCMs will have the same sensitivity to MOW. Our results show a stronger response than Wu et al, 2007. However, some of the circulation changes at depth are very similar but the Hadley Centre model shows a stronger surface signal of change. It is difficult to know why the models have a different surface response. Resolution may be one issue but it is likely to be more complex.

It is also possible that the anomalies observed in this study are inflated by the fourfold increase in water-transport through the Gibraltar Straits, arising from the use of an open seaway rather than a diffusive pipe, although the associated enhanced salt exports are in good agreement with observed values. To address the discrepancy between the water transport and salt export achieved across the Gibraltar Straits, we propose that future use of the pipe parameterisation in HadCM3 should incorporate a coefficient of exchange that is varied with depth, to replace the constant coefficient of exchange that is currently employed (given as μ in 'Appendix A5' by Gordon et al., 2000). This would be a better way to ensure that both a realistic water transport and a realistic salt flux can be achieved, rather than pairing a reasonable water transport with an unrealistic salt flux (as achieved with our diffusive pipe configuration) or vice-versa (as achieved with our open seaway configurations). Alternatively, the more physically based parameterisation used in Wu et al, 2007 should b used.

Furthermore, it is evident that the North Atlantic shallow circulation and regional climate simulated with a diffusive pipe in HadCM3 more closely match observational data than those simulated with an open seaway. On the other hand, with a diffusive pipe the MOW plume is a few hundred metres too deep in the North Atlantic, causing it to flow only into the deeper southbound currents, rather than contributing towards NADW formation. Thus, to model North Atlantic intermediate water column structure and the drivers of AMOC faithfully, it is necessary to have a MOW plume centred at 1000 m.

In conclusion, our results clearly show that when assessing ocean and climate sensitivity to changes in MOW, the idiosyncrasies associated with the chosen method of model gateway representation should be considered carefully. We suggest that there are three key features of Mediterranean-Atlantic exchange that determine the role of MOW in governing the pattern and vigour of the modern AMOC; water transport, salt export, and the depth of the MOW plume. Given that these features could be even more crucial for assessing MOW's influence on a weaker AMOC, both in future and palaeo contexts, it is important to simulate them faithfully. Therefore, for any GCM that cannot resolve the Gibraltar Straits, we propose that using an advective pipe with a depth-variable coefficient of exchange would be the most reliable way to assess the influence of Mediterranean-Atlantic exchange on ocean circulation and climate.

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Figures

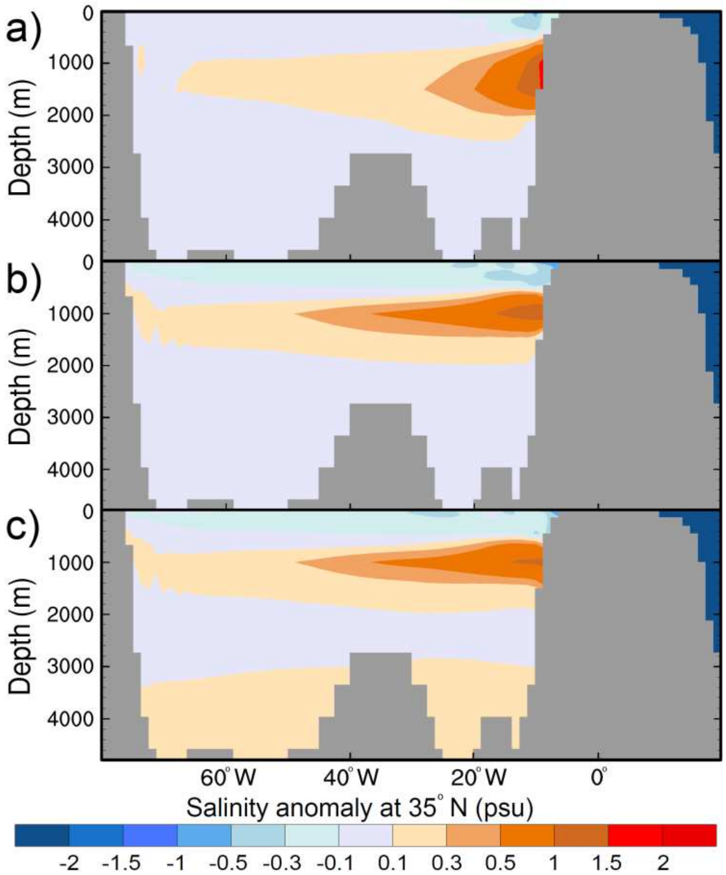

Figure 1. Mean annual ocean salinity anomalies caused by Mediterranean Outflow Water across the North Atlantic basin at 35 °N. The anomalies are caused by representing Mediterranean-Atlantic exchange using (a) a diffusive pipe (our control), (b) a narrow open seaway and (c) a wide open seaway, with respect to there being no Mediterranean-Atlantic exchange in the model. Bathymetry is shown in dark gray.

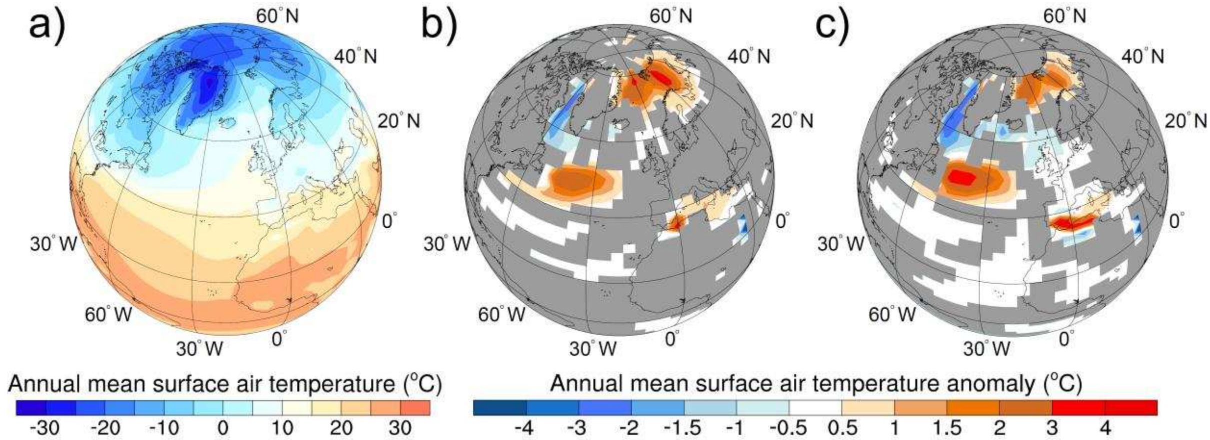

Figure 2. Mean annual surface air temperatures (a) and surface air temperature anomalies (b) and (c). The surface air temperatures in (a) are produced using a diffusive pipe (our control) for Mediterranean-Atlantic exchange. The surface air temperature anomalies are produced by replacing this diffusive pipe with (b) a narrow open seaway and (c) a wide open seaway. Areas with < 95 % significance using student t-test are shaded dark gray for (b) and (c).

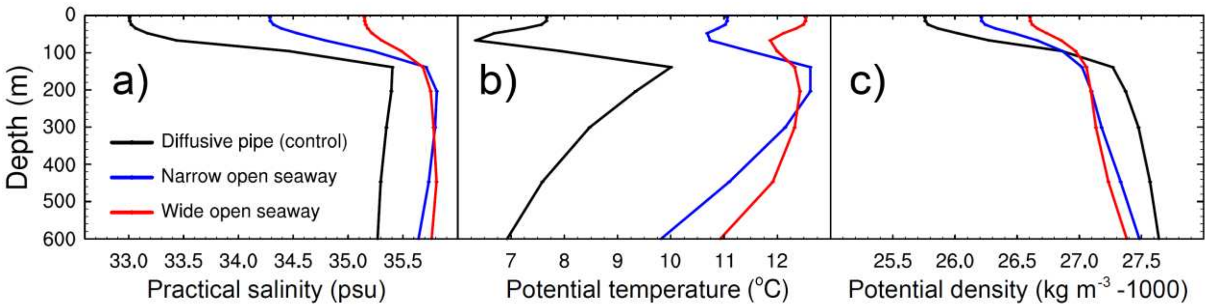

Figure 3. Water column characteristics in the upper 600 m of the North Atlantic Ocean 'hotspot', centred at 48° N, 40° W. This includes (a) the potential temperature, (b) the practical salinity and (c) the potential density properties produced using a diffusive pipe (our control), a narrow open seaway and a wide open seaway to model Mediterranean-Atlantic exchange. Potential densities are given as anomalies from 1000 kg m^{-3}.