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

3

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23

24 **Abstract**

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

38

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

41

42 **1. Introduction**

43 Mediterranean Outflow Water (MOW) is thought to play an important role in maintaining
44 the pattern and vigour of Atlantic Meridional Overturning Circulation (AMOC), particularly
45 during periods of weaker North Atlantic Deep Water (NADW) formation (Bigg and Wadley,
46 2001; Artale, et al., 2002, Voelker et al., 2006; Rogerson et al., 2010, 2012; Penaud et al.,

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

47 2011). Artale et al. (2002) showed that the vertical position of the MOW could have a major
48 impact on the structure of the AMOC. Furthermore, MOW can also have important influence
49 on the variability and stability of the AMOC (e.g. Calmanti et al., 2006) who showed that in a
50 box model the variability of the AMOC was influenced by whether the MOW mixed with
51 newly formed deep water (variability reduced) or helped maintain an interior salinity
52 gradient.

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

62 Both of these options have previously been used in GCM studies investigating the effect
63 of changes in Mediterranean-Atlantic exchange on North Atlantic circulation and the
64 importance of MOW in governing global climate. For example, investigating the link
65 between Mediterranean-Atlantic exchange and AMOC strength for the Quaternary, (Bigg and
66 Wadley, 2001; Rogerson et al., 2010) use a wide *open seaway* to capture flow through the
67 Gibraltar Straits. On the other hand, Rahmstorf (1998) and Chan and Motoi (2003), employ a
68 *pipe* to infer the effect of MOW on climate, replacing the thermal and salinity properties of
69 two-grid boxes either side of the Straits by their combined mean at each timestep. More
70 recently, Wu et al. (2007) investigated the impact of adding a physically based representation
71 of Mediterranean outflow compared to having a closed straight. They found large changes to

72 the ocean temperatures at the outflow level (~ 1100 m) but relatively small impact on the
73 surface climate of the North Atlantic, with temperatures changing by less than 1 °C. Here,
74 we examine the robustness of these results by investigating the impact of a somewhat simpler
75 parameterisation within a higher resolution model, specifically the Hadley Centre coupled
76 atmosphere-ocean model, HadCM3. We contrast the results of the parameterisation to
77 simulations with an open configuration (*open seaway* versus *pipe* configurations). It is crucial
78 that palaeo, modern and future-projection experiments examining the impact of changes in
79 Mediterranean-Atlantic exchange take gateway representation into account.

80

81 **2. Methods**

82 **2.1. Model Description**

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

97 The ocean grid is aligned with the atmosphere grid and the coupling occurs once per
98 model-day, when the constituent models pass across the fluxes accumulated over the previous
99 24 model-hours, interpolating and averaging across the different grids to accommodate the
100 different resolutions. River discharge to the ocean is also implicitly modelled through the
101 instantaneous delivery of continental runoff to the coasts, according to grid-defined river
102 catchments and estuaries. For a more detailed description of the model and its components,
103 including improvements on earlier versions, see Gordon et al. (2000) and Pope et al. (2000).

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

107

108 **2.2. Mediterranean-Atlantic exchange**

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

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

128

129 **2.3. Experiment design**

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

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

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

154 The water properties of the three simulations within the Western Mediterranean and Gulf
155 of Cadiz are relatively comparable. The near surface inflow water to the Mediterranean is
156 characterized by temperatures of 16.3, 16.6, 17.1 °C and salinity of 35.9, 35.8, and 35.8 psu
157 for the control, NOS and WOS simulations respectively. These should be contrasted to
158 observations of 15.5 °C and 36.2 psu (Hopkins, 1999) showing the modelled inflow is
159 slightly too warm and fresh. Though not perfect, the model biases are comparable to those in
160 Wu et al. 2007. Similarly the modelled outflow source waters are 13.8, 14.8, 14.9 °C and
161 salinity of 39.6, 38.9 and 38.9 psu which again are comparable to observations (13.8 °C and
162 38.4 psu) and Wu et al (2007).

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

169

170 **3. Results and Discussion**

171 Observational data (Boyer et al., 2009) shows that today, a distinct MOW plume spreads in
172 the North Atlantic at a depth centred 1000-1500 m, where it mixes with North Atlantic
173 intermediate waters. Others (Stanev, 1992; Mauritzen et al., 2001; McCartney and Mauritzen,
174 2001; New et al., 2001; Bower et al., 2002; Voelker et al., 2006) have suggested that this
175 MOW plume preconditions the North Atlantic, providing an important source of warm, saline
176 waters for NADW formation, thus contributing towards driving the AMOC. In the following
177 discussion, we compare the effect of using *NOS* and *WOS* on North Atlantic circulation and
178 global climate, versus using a *pipe*.

179

180 **3.1. Effect on the AMOC**

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

191 With respect to the control, both *open seaway* parameterisations cause a shoaling of some
192 of the deeper-spreading MOW (Fig. 1). This arises because using an *open seaway* produces a
193 larger water transport but more realistic salt flux than the *control* with a dilution of salt in the
194 exchanged water mass. This in turn also results in stronger density gradient and hence an
195 intensification of the existing circulation producing a stronger and further-reaching plume

196 centred at a depth of 1000 m, though the deeper components of MOW do remain. The new
197 plume is sufficiently shallow to be entrained in the northward-bound currents, increasing the
198 supply of warm, high-salinity intermediate water to high latitude sites of NADW formation –
199 the North Atlantic, the Greenland-Iceland-Norwegian (GIN) Seas and the Barents Sea –
200 where it emerges near the surface and enhances overturning, increasing the depth of
201 maximum AMOC strength by 200 m in both *NOS* and *WOS*. This strengthens the deep
202 southbound flow, centred at a depth of 2000 m (approx.), by around 2 Sv and 5 Sv for *NOS*
203 and *WOS*, respectively. The deep AMOC component is stronger for *WOS* because the
204 Gibraltar Straits are centred further north than for *NOS*, setting a greater portion of the MOW
205 plume on a northward flow-path towards the high latitude regions of overturning, with less
206 dilution first occurring in the central North Atlantic. This also explains the increase in deep
207 Atlantic salinity, observed for *WOS* (Fig. 1c).

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

219

220 **3.2. Effect on the North Atlantic gyres**

221 The shoaling of westward-spreading MOW and its subsequent mixing with overlying North
222 Atlantic waters in the *open seaway* experiments increases the contribution of warm, high
223 salinity waters to the subtropical gyre, causing it to strengthen and deepen. The enhanced
224 anti-cyclonic ocean circulation pushes northwards towards the mouth of the Labrador Sea,
225 weakening the subpolar gyre and restricting it to latitudes above 50 °N for both *NOS* and
226 *WOS*, compared to ~ 45° N in the control. This weakening and high-latitude confinement of
227 the subpolar gyre reduces the exchange of water taking place between the North Atlantic and
228 the Labrador Sea. With less warm surface Atlantic water mixing with the cooler polar waters
229 already in the basin, Labrador Sea cools in the upper 200 m of the water column by up to 1.1
230 °C for *NOS* and 2.6 °C for *WOS*, compared to *pipe*. This leads to an increase in Labrador Sea-
231 ice cover, raising the surface albedo and cooling the air above. The regional decrease in
232 surface air temperature further enhances sea-ice formation, closing the positive feedback loop
233 and resulting in a steady-state increase in Labrador sea-ice concentration of up to ~ 40% and
234 a local mean annual air temperature anomaly of up to -3.5 °C (Fig. 2). Again, the feedback is
235 strongest during the boreal winter, when sea ice formation is most prevalent, resulting in a
236 temperature anomaly of up to - 6 °C for *NOS* and up to -7.5 °C for *WOS*.

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

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

254

255 **3.3. A North Atlantic ‘hotspot’**

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

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

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

283

284 **4. Summary and conclusions**

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

- 289 (i) The increased northward flow of warm, high salinity intermediate waters of MOW-origin
290 enhances NADW formation in the GIN and Barents Seas, reduces local sea-ice cover by
291 up to 35 %, thus lowering surface albedo, and increases surface air temperature by up to
292 11° C.
- 293 (ii) The increased contribution of warm, saline, MOW-origin waters to the North Atlantic
294 subtropical gyre strengthens its circulation and weakens the adjacent subpolar gyre. This

295 reduces the ocean heat-exchange with the Labrador Sea, increasing local sea-ice cover by
296 up to 40 %, raising surface albedo and reducing surface air temperatures by up to 7.5 °C.

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

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

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

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

317 It is also possible that the anomalies observed in this study are inflated by the fourfold
318 increase in water-transport through the Gibraltar Straits, arising from the use of an *open*
319 *seaway* rather than a *diffusive pipe*, although the associated enhanced salt exports are in good

320 agreement with observed values. To address the discrepancy between the water transport and
321 salt export achieved across the Gibraltar Straits, we propose that future use of the *pipe*
322 parameterisation in HadCM3 should incorporate a coefficient of exchange that is varied with
323 depth, to replace the constant coefficient of exchange that is currently employed (given as μ
324 in ‘Appendix A5’ by Gordon et al., 2000). This would be a better way to ensure that both a
325 realistic water transport and a realistic salt flux can be achieved, rather than pairing a
326 reasonable water transport with an unrealistic salt flux (as achieved with our *diffusive pipe*
327 configuration) or vice-versa (as achieved with our *open seaway* configurations).
328 Alternatively, the more physically based parameterisation used in Wu et al, 2007 should b
329 used.

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

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

345 using an *advective pipe* with a depth-variable coefficient of exchange would be the most
346 reliable way to assess the influence of Mediterranean-Atlantic exchange on ocean circulation
347 and climate.

348

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355

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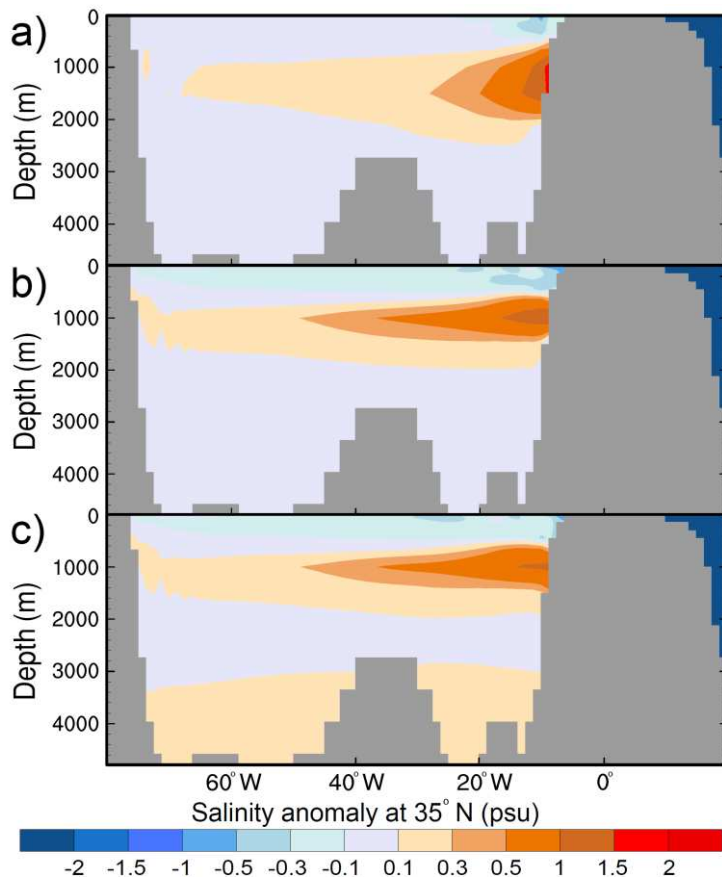
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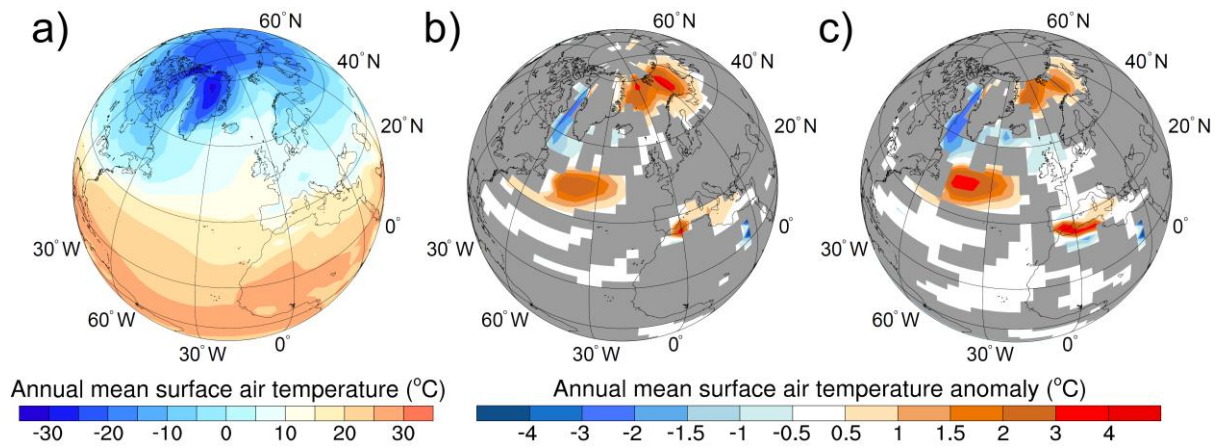
448 **Figures**



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

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Figure 2. Mean annual surface air temperatures (a) and surface air temperature anomalies (b)

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and (c). The surface air temperatures in (a) are produced using a *diffusive pipe* (our control)

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for Mediterranean-Atlantic exchange. The surface air temperature anomalies are produced by

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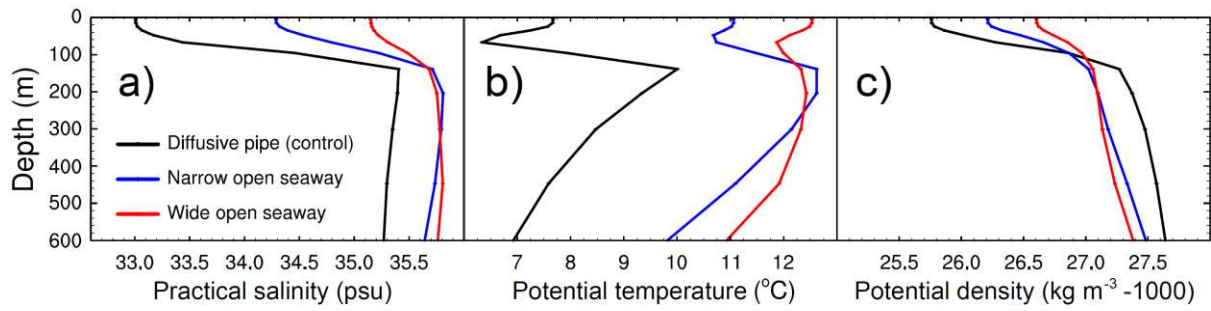
replacing this *diffusive pipe* with (b) a *narrow open seaway* and (c) a *wide open seaway*.

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Areas with < 95 % significance using student t-test are shaded dark gray for (b) and (c).

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Figure 3. Water column characteristics in the upper 600 m of the North Atlantic Ocean

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‘hotspot’, centred at 48° N, 40° W. This includes (a) the potential temperature, (b) the

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practical salinity and (c) the potential density properties produced using a *diffusive pipe* (our

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narrow open seaway and a *wide open seaway* to model Mediterranean-Atlantic

469

exchange. Potential densities are given as anomalies from 1000 kg m⁻³.