Mediterranean outflow water in a changing climate: predictions from two ocean models

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We have used two quite different ocean models to investigate how a change in the freshwater balance over the Mediterranean basin or a change in North Atlantic Central Water might result in different Mediterranean product water in the North Atlantic thermocline. The models are the Marginal Sea Boundary Condition of *Price and Yang* [1998], which is heavily simplified and parameterized, and the HYbrid Coordinate Ocean Model of *Xu et al.* [2006b], which is a comprehensive isopycnal ocean model that is here run in a highly resolved configuration. These two models give similar predictions for the sensitivity of MOW product water. Specifically, 1) The product water T/S properties are remarkably insensitive to a change of the outflow source water T/S, and yet the product water T/S is quite sensitive to a change of the T/S properties of the oceanic water. This asymmetry arises from the dilution of MOW source water caused by entrainment. 2) The volume transport of the product water is equally sensitive to a change in either the source water density or the oceanic water density. Thus a (small) increase of the deep water salinity in the Mediterranean basin will be expected to result in a somewhat greater volume of MOW product water having only a very slightly greater salinity than is found at present.

1. Modeling deep water production

Most deep and intermediate water masses of the world ocean can be traced back to a dense outflow from one of a handful of marginal seas [*Warren*, 1981], the Mediterranean Sea [*Baringer and Price*, 1997], the Denmark Strait [*Girton and Sanford*, 2003], the Faroe Bank Channel [*Price*, 2004], the Red Sea [*Peters and Johns*, 2005], and the Antarctic slope plumes [*Gordon et al.*, 2004]. These outflows carry the dense water resulting from air-sea interaction into the deep ocean, and set the water properties of the deep ocean. The downward mass flux and the spreading of outflow water masses initiate the cold side of the overturning circulation.

The representation of marginal sea outflows in ocean general circulation models (OGCMs) is a substantial challenge, arising partly from the difficulty of prescribing the diapycnal mixing processes taking place between the outflow and the overlying oceanic water. This diapycnal mixing, often idealized as entrainment, significantly alters the water properties and the volume transports of the product water that enters the deep ocean. *Xu et al.* [2006a] put forth an entrainment parameterization based on the results of a high resolution, non-hydrostatic model. A regional simulation of the Mediterranean outflow using the HYbrid Coordinate Ocean Model [HYCOM; *Bleck*, 2002; *Chassignet et al.*, 2003] with this parameterization was evaluated by comparing to field data from the Gulf of Cádiz Expedition (1988) [*Price et al.*, 1993]. The simulation reproduces well the observed characteristics of Mediterranean outflow water (MOW) in the Gulf of Cádiz [*Xu et al.*, 2006b].

The HYCOM regional configuration is useful for examining the mesoscale hydrodynamics and mixing dynamics of an outflow, but it is not so suitable for simulations of climate time scales on which a changing marginal sea outflow could influence the deep ocean. Climate models that might do this typically have horizontal resolution that is about one order of magnitude less than is needed for an explicit representation of the Mediterranean or the Faroe Bank Channel outflows.

A method of representing marginal sea outflows in climate models was suggested by *Price and Yang* [1998] and termed the marginal sea boundary condition, or MSBC. As the name implies, the MSBC collapses the deep water formation processes — exchange between the marginal sea and the open ocean, and descent and entrainment of the outflow on the continental slope — into what amounts to a side-wall boundary condition for an OGCM. The exchange, treated as a hydraulic model in MSBC, converts the surface inflow of oceanic water into an outflow source water; and a rotating, entraining density current model then transforms the source water into the final outflow product water by entraining oceanic water.

The MSBC approach to modeling deep water formation by a marginal sea seems appropriate from the oceanic perspective since the outflow water mass transformation takes place within one grid cell of a typical ocean climate model. The MSBC has some success reproducing the state of the present Mediterranean outflow, at least with regards to its transport, and mean temperature and salinity. Of greater interest here is that the MSBC also makes a clear and somewhat surprising set of predictions of the MOW product water that would follow a change of the climatological air-sea fluxes over the Mediterranean basin, or, a change of the North Atlantic Central water through which the MOW descends within the Gulf of Cádiz. In particular, the MSBC predicts that, 1) the product water T/S properties are remarkably insensitive to a change of the outflow source water T/S, and yet quite sensitive to a change of the T/S properties of the oceanic water. 2) The volume transport of the product water is about equally sensitive to a change in either the source water density or the oceanic water density. This sensitivity of the MOW product water is the crucial aspect for simulating climate change, and it is our goal here to evaluate the degree of sensitivity in the HYCOM regional model. To the extent that the HYCOM model is far less constrained by modeling assumptions than is the highly simplified MSBC, then this comparison could be regarded as an interim test of the MSBC, the theme of much of this note. But even aside from the MSBC, this study may also be viewed as an attempt to understand/forecast the change in MOW induced by long time scale variations over the Mediterranean sea or elsewhere in the North Atlantic Ocean; see [*Curry et al.*, 2003] for documented changes in salinity over the North Atlantic.

2. Configurations of the experiments

The HYCOM domain (13.0 $\sim$ 3.08 °W, 34.2 $\sim$ 40.6 °N) includes the Northeast Atlantic Ocean, the Gulf of Cádiz, the Strait of Gibraltar, and a small part of the western Mediterranean Sea, where the source density is prescribed by relaxing T and S toward specific profiles. It has a horizontal resolution of 0.08 ° and 28 σ_2 layers in the vertical. A three-month mean velocity of the simulated MOW plume, using climatological T, S as initial conditions in the western Mediterranean Sea, is presented in Fig. 1a. As shown in detail in *Xu et al.* [2006b], the product water T/S and the volume transport are in good agreement with the observations. This simulation is taken as the reference upon which sensitivity experiments are based.

Typical vertical profiles of the T, S, and density ρ in the Mediterranean Sea and the Gulf of Cádiz are illustrated in Fig. 1b. Dynamically the most important quantity is the density contrast between the two basins evaluated at the sill depth in the Strait of Gibraltar at 300 m. It has a value of $\Delta\rho \approx 2.0\,\mathrm{kg\,m^{-3}}$ in the reference case. Two sets of HYCOM experiments are designed to investigate the sensitivity of the outflow product water to imposed variations of the outflow source water and the oceanic water. Each set begins from the same reference state, and consist of four sensitivity experiments in which the density of the source or oceanic is shifted up and down by 10% and 20% of $\Delta\rho$.

- **Source water changes:** T, S, and ρ fields in the Gulf of Cádiz are the same as in the reference experiment. In the Mediterranean Sea, T is also the same as in the reference experiment, while ρ is shifted by a spatially uniform value, $\pm 10\%$ and $\pm 20\%$ of $\Delta\rho$. The salinity is then calculated from ρ and T.

- **Oceanic water changes:** T, S, and ρ fields in the Mediterranean Sea are the same as in the reference experiment. In the Gulf of Cádiz, T is also the same as in the reference experiment, while ρ is shifted by the same spatially uniform values noted above and S is then calculated from ρ and T.

The MSBC model equations are given in *Price and Yang* [1998]. The T/S profiles in the Gulf of Cádiz for the HYCOM are very similar to the profiles of *Price and Yang* [1998] (Fig. 1b). In order to make the reference states of the MSBC and HYCOM nearly identical, we have made changes to three of the independent, geophysical variables that have to be provided to the MSBC (see Table 1). In the MSBC the Mediterranean source water properties are the result of prescribed air-sea heat and fresh water flux over the Mediterranean basin and exchange with the North Atlantic. *Price and Yang* [1998] ignored the small but not quite negligible heat flux over the Mediterranean basin, of about 5 - 10 W m^{-2} as inferred from the heat budget of the Mediterranean basin. Variable fluxes (an E-P of $0.35 \sim 0.75\,\mathrm{m\,year^{-1}}$ and a heat flux of $6.0 \sim 7.6\,\mathrm{W\,m^{-2}}$) are specified in order to have outflow source water from MSBC that is closely consistent with that from HYCOM. Also, *Price and Yang* [1998] took the depth of entrainment to be 400 m, which appears to be the upper side of the depth range over which the Mediterranean outflow entrains, roughly 400 m to 700 m judging from the HYCOM regional model. We have here set the entrainment depth to be 600 m. Clearly then, the reference state of the MSBC is the result of some modest tuning, and is not fully (or blindly) predicted. This is likely true of every ocean model solution if one construes parameter tuning and model configuration to be the ends of a continuum, model development. The issue is whether the chosen values or model configurations are within a plausible range, and we believe that they are for both HYCOM and MSBC. However, the reference state is not the central issue here, because our intent is to examine the sensitivity of product water transport to source water density, say, which is only slightly dependent upon the reference state of the models. This sensitivity is due almost entirely to model dynamics and is thus a genuine prediction of the models.

3. Results

3.1. Imposed source water change

Snapshots of salinity distribution at a meridional section in the Gulf of Cádiz (8.6 °W) from HYCOM are presented in Fig. 2a,d. As the density (and salinity) of the outflow source water increases, a larger amount of the Mediterranean outflow water is introduced into the Gulf. The product water has a slightly higher value of maximum salinity and equilibrates at slightly denser and deeper isopycnic layers.

In HYCOM simulations, MOW is defined as the water mass below the North Atlantic Central Water with salinity $\mathrm{S} \geq \max(\mathrm{S}_c, \mathrm{S}_0 + \Delta\mathrm{S})$, where S_0 is the initial mean salinity profile in the Gulf and $\Delta\mathrm{S}$ and S_c are constants of 0.05 psu and 36.0 psu, respectively. *Xu et al.* [2006b] find that this definition is adequate to capture all the newly-formed MOW in the Gulf. Based on this definition, the volume transport Q, salinity $\overline{\mathrm{S}}$, temperature $\overline{\mathrm{T}}$, and depth $\overline{\mathrm{D}}$ of the outflow plume are calculated from $\mathrm{Q} = \int_0^W \int_{z_1}^{z_0} u\, dz\, dy$, $\overline{\mathrm{T}} = A^{-1} \int_0^W \int_{z_1}^{z_0} \mathrm{T}\, dz\, dy$, $\overline{\mathrm{S}} = A^{-1} \int_0^W \int_{z_1}^{z_0} \mathrm{S}\, dz\, dy$, $\overline{\mathrm{D}} = 0.5 \int_0^W (z_1 + z_0)\, dy$, where z_0 and z_1 are the upper and lower interface of the MOW plume, W and A are the meridional span and the cross-sectional area of the outflow plume. These quantities are zonally averaged between latitudes $6^\circ \sim 5.5\,^\circ$W and $9^\circ \sim 8\,^\circ$W for the source and product water masses, respectively. Finally, time averaging is applied to determine mean properties in HYCOM.

A comparison of HYCOM and MSBC solutions under conditions of different source water densities is presented in Fig. 3. Overall, the MSBC and HYCOM indicate comparable variations of the source and product water transports, and T/S (density). As the outflow source water becomes saltier and denser, the increased density contrast significantly increases the amount of entrainment, and thus the volume transport of the product water. The variation in product water salinity is thus virtually eliminated via increased entrainment. The variations of the temperature and depth is also in good agreement between MSBC and HYCOM results.

3.2. Imposed ocean water changes

The snapshots of the salinity distributions from HYCOM experiments with ambient ocean water change are shown in Fig. 2b,e. Compared to Fig. 2a,d, the outflow salinity in the Gulf of Cádiz varies much more. The magnitude of the variation ($\sim 1\,\mathrm{psu}$) is nearly the same as that of the oceanic water change. As a result, the simulated MOW equilibrates in denser isopycnic layers but at shallower depths.

To be consistent with the varying ambient ocean water profiles, the constant S_c is shifted by -0.53, -0.265, 0.265, and $0.53\,\mathrm{psu}$ in defining the MOW in the four sensitivity experiments. The comparison between HYCOM and MSBC is summarized in Fig. 4. The increase of density in the oceanic water reduces the density contrast between the outflow source water and the oceanic water, and this leads to weaker entrainment and thus a smaller volume transport of outflow product water. Weaker entrainment means less dilution of the outflow. Since the outflow begins with the same source water properties, the salinity of the outflow product water varies much more than in the previous scenario of imposed source water change. Overall, the comparison shows similar trends in the outflow product water between HYCOM and MSBC.

To quantify the variations in the outflow product water properties relative to changes in outflow source water and ambient ocean water, we define five non-dimensional quantities, $(\frac{\Delta\rho}{Q_s})\frac{dQ_s}{d\rho}$, $(\frac{\Delta\rho}{Q_p})\frac{dQ_p}{d\rho}$, $(\frac{\Delta\rho}{S_p})\frac{dS_p}{d\rho}$, $(\frac{\Delta\rho}{T_p})\frac{dT_p}{d\rho}$, $(\frac{\Delta\rho}{D_p})\frac{dD_p}{d\rho}$, where subscripts s and p denote outflow source and product water, and where Q, S, T, and D are volume transport, salinity, temperature, and equilibrium depth of the outflow product water (Table 2). These quantities can be interpreted as the variation, normalized by their reference values, induced by the variation of density contrast. The most pronounced result is that the volume transport is equally sensitive to $\Delta\rho$ variation caused either by the source water or oceanic water. However, the outflow product salinity is at least one order more sensitive to changing oceanic water than to changing source water for the reasons laid out above.

4. Summary and discussion

Climate models will clearly require highly parameterized and simplified models of deep water production by marginal seas. the MSBC collapses all the water mass transformation process into a side-wall boundary condition. MSBC predictions of varying MOW are compared here to those from a comprehensive ocean model, HYCOM. The comparison suggests that while the MSBC does not resolve any detailed aspects of the outflow plume, it does reproduce closely comparable variations of outflow product water associated with changes in both the outflows source water and the oceanic water, i.e., volume transport, T/S properties, and equilibrium depth. In particular, both models show that a) changes in the oceanic water leads to very significant changes in the product water T/S, while comparable change in the source water produce very little change in the product water. The sensitivity to source or oceanic water changes, measured by the logarithmic derivative, differs by a factor of about 10 or more. b) However, the volume transport of the outflow product water is about equally sensitive to a change in the density contrast brought about by changing the source water or the oceanic water. Of all the things that might influence the sensitivity of an outflow to the ocean environment, evidently the ones included in the MSBC — nearly geostrophic velocities, Froude number closure of the entrainment process, and the steepest (but still moderately large scale) topography — are evidently the ones that count the most in the present context.

To close we want to point out that this study has considered only the most obvious effects of a marginal sea outflow, namely the transport and T/S of the product water that enters the open ocean. These also happen to be the only things that the present MSBC deals with. The substantial cross-stream variation of the real Mediterranean outflow is missed altogether by the MSBC, but is predicted by HYCOM; the potential vorticity flux [*Kida*, 2006] associated with an outflow is more imposed than predicted by the MSBC but is, again, predicted by HYCOM. If we knew these aspects of outflow dynamics as well as we think we know the gross transport and T/S properties, and if they are found to be important in climate scale ocean models, then they might perhaps be added to a future MSBC.

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(a)

(b)

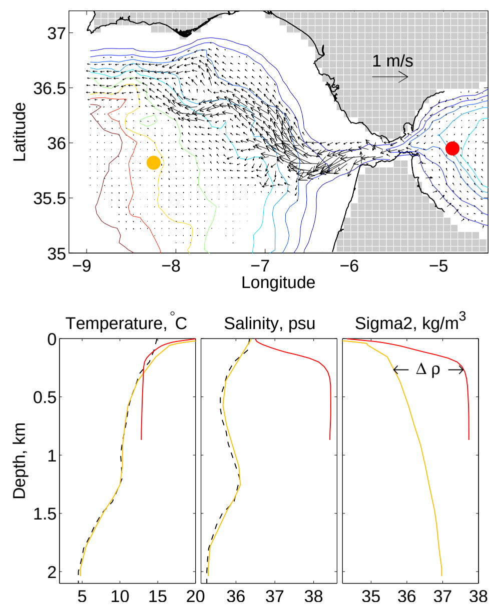

Figure 1. (a) The mean velocity field of the Mediterranean outflow plume in the Gulf of Cádiz from HYCOM regional model. Contour levels for bottom topography are 200, 400, 600, 800, 1000, 1500, 2000, 2500, and 3000 m. (b) T(z), S(z), and $\rho(z)$ in the Mediterranean Sea (red) and in the Gulf of Cádiz (orange) from the reference experiment. $\Delta\rho = 2\,\mathrm{kg\,m^{-3}}$ marks the reference density contrast between the two basins. The black dash lines show the ocean profiles from *Price and Yang* [1998].

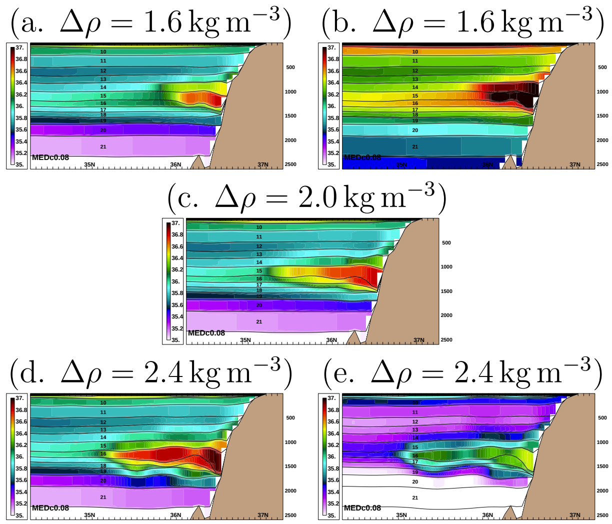

Figure 2. Snapshots of salinity distribution at 8.6 °W calculated by HYCOM in five experiments with different density contrasts. The middle panel (c) is the reference case. (a) and (d) are the cases with outflow source water changes. (b) and (e) are the cases with ambient ocean water changes.

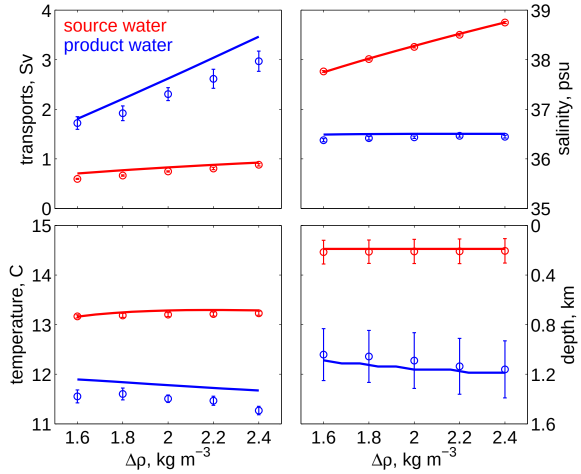

Figure 3. Results from MSBC versus HYCOM in the case of outflow source water change. Lines are from MSBC and circles are the HYCOM results. Error bars represent the standard deviation for transport, salinity and temperature, and the mean upper and lower interface of outflow plume for depth in HYCOM results. The red and blue colors represent the outflow source and product waters, respectively.

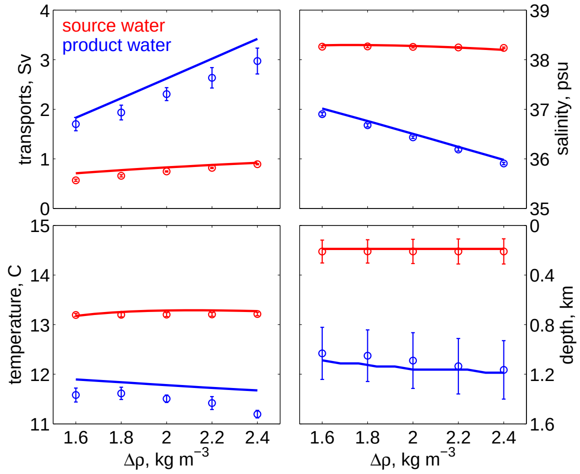

Figure 4. The same as Figure 3 but for experiments in which the ocean water was changed. Note that the transport, temperature and equilibration depth shown here are very similar to those found in Figure 3. The salinity difference between source and product water is also similar to Figure 3.

Table 1. Parameters of the MSBC for the Mediterranean outflow: ϕ (°), W (km), and d_s (m) are the latitude, width, and sill depth of the Strait of Gibraltar. A ($10^6\,\mathrm{km}^2$), Q ($\mathrm{W\,m^{-2}}$), and E-P ($\mathrm{m\,yr^{-1}}$) are the area of the Mediterranean Sea, heat flux (negative indicates heat loss from the marginal sea), and evaporation minus precipitation. α is the continental slope. d_e (m) is the depth at which entrainment takes place. "-" means no change with respect to *Price and Yang* [1998].

	ϕ	W	d_s	A	Q	E-P	α	d_e
PY98	36	20	300	2.5	0	0.7	0.012	400
Here	-	-	-	-	$6.0 \sim 7.6$	$0.35 \sim 0.75$	-	600

Table 2. The normalized derivatives in cases of (a) outflow source water change and (b) ocean water change. The numbers in square brackets show MSBC results and the others HYCOM results.

	$\frac{\Delta\rho}{Q_s}\frac{dQ_s}{d\rho}$	$\frac{\Delta\rho}{Q_p}\frac{dQ_p}{d\rho}$	$\frac{\Delta\rho}{S_p}\frac{dS_p}{d\rho}$	$\frac{\Delta\rho}{T_p}\frac{dT_p}{d\rho}$	$\frac{\Delta\rho}{D_p}\frac{dD_p}{d\rho}$
(a)	0.963	1.352	0.005	-0.062	0.272
	[0.668]	[1.577]	[0.001]	[-0.047]	[0.215]
(b)	1.100	1.376	-0.068	-0.084	0.304
	[0.645]	[1.516]	[-0.071]	[-0.047]	[0.215]