On the Variability of the Mediterranean Outflow Water in the Atlantic Ocean

Part I: Source of the Mediterranean Outflow Water Variability

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Abstract

The source of Mediterranean Outflow Water (MOW) variability in the Atlantic Ocean is not fully understood. Positive MOW trends in temperature and salinity observed during 1955-1993 in the area west of the Gulf of Cadiz have reversed in the 2000s. Part I of this study investigates circulation changes in the Atlantic as a possible source of the MOW variability in this region. Using a 1/3° North Atlantic configuration of the HYbrid Coordinate Ocean Model combined with the Marginal Sea Boundary Condition model (MSBC) [*Price and Yang*, 1998], we perform two simulations forced by either climatological or interannual atmospheric fields. The comparison of the two simulations demonstrates that interannual forcing is able to reproduce variability in the MOW similar to what has been observed. Since the property changes for the source waters that constitute the MOW show no appreciable trends, we conclude that MOW variability in the last 60 years is indeed a consequence of a circulation change in the North Atlantic. Part II of this study analyzes how the interannual atmospheric forcing induces these circulation changes by separating the mechanical effect of the wind stress from the impact of the buoyancy forcing on the MOW.

KEYWORDS: Mediterranean Water, Outflow, Long-term Variability, North Atlantic Ocean.

1. Introduction

The Mediterranean Overflow Water (MOW) is a saline and warm water mass principally occupying the intermediate depths of the eastern North Atlantic (Figure 1). This water mass is produced from the transformation of fresh and warm surface Atlantic waters into dense and salty Mediterranean water. Entering the marginal sea by the Strait of Gibraltar, the Atlantic water is gradually modified during its eastward progression in the Mediterranean Sea through air-sea interactions and mixing processes. These modifications lead to the formation of salty and relatively cold intermediate and deep-water masses [see review by *Pinardi and Masetti*, 2000]. A portion of these dense water masses then flows back toward the Strait of Gibraltar, reaching it after 5 to 15 years [*Artale et al.*, 2006]. The Mediterranean Sea Water (MSW) then cascades along the slope in the Gulf of Cadiz and mixes with the ambient North Atlantic Central Water (NACW) to form the MOW. Reaching its buoyancy depth around 1100 m [*Candela,* 2001], the MOW then spreads northward and westward into the Atlantic interior.

The MOW has long been recognized as an important contributor to the heat and salt content of the North Atlantic [*Zenk,* 1975*; Reid,* 1979]. Many past studies have focused on its pathway to the northeastern Atlantic and its possible contribution to the preconditioning of deep-water mass formation in key areas of the global thermohaline circulation such as the Nordic seas and the Labrador Sea [*Reid,* 1979*; Lozier et al.,* 1995; *Iorga and Lozier*, 1999*; McCartney and Mauritzen,* 2001*; Lozier and Stewart,* 2008]. Understanding its variability is therefore important. Investigating the evolution of the MOW properties between 1955 and 1993, *Potter and Lozier* [2004] (*PL04*) calculated the MOW temperature and salinity trend in a box designated as the reservoir [10ºW, 20ºW, 30ºN, 40ºN]. In this particular area, they found a positive temperature trend of 0.101 ± 0.024 ºC/decade that far exceeds the Atlantic Ocean temperature trend [*Levitus et al.*, 2000] and a positive salinity trend of 0.028 ± 0.0067 psu/decade [*PL*04] for this time period. A more recent study by *Leadbetter et al.* [2007] compared the results of a WOCE vertical transect repeated along 36ºN in 1959, 1981, and 2005 between 10ºW and 20ºW. Their findings are consistent with those of *PL04*, i.e., a warming/salinification in the transect between 1959 and 1981. However, they found a cooling/freshening between 1981 and 2005.

There are three possible sources impacting the variability of the MOW properties in the study area defined by *PL04* as the reservoir: (1) a change in the MSW properties, (2) a change in the NACW properties, or (3) a change of circulation of the Atlantic Ocean that would result in a shift of the MOW main core location in the reservoir.

Several studies describe the intrinsic variability of the Mediterranean Sea water properties associated with its thermohaline circulation [*Lacombe et al.*, 1985; *Béthoux et al.*, 1990; *Béthoux and Gentili*, 1999]. In particular, *Béthoux and Gentili* [1999] found a positive trend of 0.035 ºC/decade in temperature and 0.011psu/decade in salinity of the Western Mediterranean Deep Water (WMDW) and a trend of 0.068 ºC/decade and 0.018 psu/decade of the intermediate layers over the period 1959-1997. More recently, *Rixen et al.* [2005] described the variability of the two components of the Mediterranean water at Gibraltar: the Western Mediterranean Deep Water and the Levantine Intermediate Water. They found a positive trend of 0.035 ºC/decade in temperature and 0.011 psu/decade in salinity of the Western Mediterranean Deep Water (600-m bottom layer) and an increase of salinity of about 0.011 psu/decade, but nearly no trend in temperature of the Levantine

Intermediate Water (150-600-m layers) based on data from 1950 to 2000. These trends, however, are smaller than those observed by *PL04*. In addition to the slowly evolving property changes associated with these trends, the thermohaline circulation of the Mediterranean Sea is also susceptible to abrupt modifications on short time scales (~10 years). Indeed, between 1990 and 1997, a major event called the Eastern Mediterranean Transient caused important changes in the distribution of the water mass in the eastern basin and especially in the intermediate water masses [*Lascaratos et al.*, 1999]. The main site of formation of the Eastern Mediterranean Deep Water shifted from the Adriatic Sea to the Aegean Sea. The signature of this abrupt event was detected in an analysis of MSW data from 2003-2004 at the Strait of Gibraltar by *Millot et al.* [2006]. The analysis showed a warmer (+0.3ºC) and saltier (+0.06psu) MSW than the one observed in the 1980s and 1990s. This finding, however, is opposite to the findings of *Leadbetter et al.* [2007], who observed a cooler/fresher MOW in 2005 than in 1981. Finally, *Lozier and Sindlinger* [2009], using backward calculations, showed that a MSW salinity trend of +0.149 ± 0.037 psu/decade (10 times larger than *Rixen et al.* [2005]) would be necessary to reproduce the MOW observed trend in the reservoir between 1950 and 2000. Thus, these authors concluded that MSW is unlikely to be the source of the MOW variability.

A second possible source of the MOW variability in the Atlantic is the variability of the entrained waters in the Gulf of Cadiz, specifically, the NACW. *Rhein and Hinrichsen* [1993] and *Baringer and Price* [1997] hypothesized that the variability of this water plays a more important role than the MSW variability in the variability of the MOW since the mixing rate for forming the MOW is approximately 30% of the MSW to 70% of the NACW around 7.30ºW. Thus, the signature of the entrained water is by definition more important than the signature of the MSW in the variability of the MOW properties. *PL04* showed the variability of the NACW immediately outside the Gulf of Cadiz to be the reverse of the MOW variability during the 1955-1993 period, with trends of ~ -0.08 ºC/decade and ~ -0.02 psu/decade at 500 m. This cooling and freshening was also shown by *Leadbetter et al.* [2007]. To assess the importance of the NACW and MSW variability in the MOW variability, *Lozier and Sindlinger* [2009] estimated the MOW salinity variability at the exit of the Gulf of Cadiz using an NACW with constant properties (i.e., no trend of NACW imposed) and MSW salinities reconstructed from the NCEP/NCAR evaporation minus precipitation (E-P) products over the period 1950-2000 as inputs to the *Price and Yang* [1998] Marginal Sea Boundary Conditions model (MSBC). Then, assuming a reservoir of constant volume, *Lozier and Sindlinger* [2009] derived from the MOW variability at the exit of the Gulf of Cadiz the MOW variability in the reservoir. The resulting MOW salinity trend is 0.015 ± 0.007 psu/decade at the exit of the Gulf of Cadiz and 0.0024 ± 0.0014 psu/decade in the reservoir, an order of magnitude smaller than the trend observed by *PL04*. This result shows that even with no trend, the NACW variability cannot be responsible for MOW variability in the Atlantic Ocean. As concluded by *Lozier and Sindlinger* [2009], a change of circulation of the Atlantic (i.e., third hypothesis) has to be considered as the main source of the MOW variability in the reservoir.

The main goal of this study is to understand the variability of the MOW in the Atlantic Ocean by investigating the validity of the latter hypothesis using an ocean model. In part I of this study, we evaluate the effectiveness of a 1/3º North Atlantic configuration of the Hybrid Coordinate Ocean Model (HYCOM) in reproducing the

MOW and we indeed show that MOW variability in the last 60 years is a consequence of a circulation change in the North Atlantic. In the second part of this study (part II, this issue), we investigate the impact of each component of the atmospheric forcing (i.e., wind stress and buoyancy fluxes) on the MOW and describe the mechanisms responsible for the MOW variability and pathways in the North Atlantic over the last 60 years.

The paper is organized as follows: the ocean model configuration is described in section 2; the examination of a circulation change as a source of the MOW variability is presented in section 3. Finally, the summary and conclusions are presented in section 4.

2. The 1/3º North Atlantic HYCOM Configuration

2.1. Description of the Model Configuration

HYCOM [*Bleck,* 2002; *Chassignet et al.,* 2003; *Halliwell,* 2004] is configured for the North Atlantic Ocean. The 1/3º resolution model domain extends from 90°W to 30°E and from 20°S to 70°N (Figure 6) and does not include the Mediterranean Sea. The bottom topography is derived from DBDB5 [*National Geophysical Data Center,* 1985]. The vertical discretization in HYCOM combines pressure coordinates at the surface, isopycnic coordinates in the stratified open ocean, and sigma coordinates over shallow coastal regions. Twenty-eight hybrid layers whose σ_2 target densities range from 23.50 to 37.48 kg/m^3 are used. The initial conditions in temperature and salinity are given by the General Digital Environmental Model [GDEM3; *Teague et al.,* 1990]. Relaxation to climatology is applied at the northern and southern boundaries in 10° buffer zones. Vertical mixing is provided by the KPP model [*Large et al.,* 1994].

The climatological atmospheric forcing used in CLIM is derived from the 1979-1993 ECMWF climatology (ERA15). To account for synoptic atmospheric variability, 6-hourly wind stress anomalies corresponding to a neutral El Niño period (September 1984-September 1985, from Southern Oscillation Index) are added to the monthly wind stresses; wind speed is obtained from the 6-hourly wind stresses. The heat and freshwater fluxes are calculated using bulk formulae during model simulations. The heat flux is derived from surface radiation, air temperature, specific humidity, wind speed, and model sea surface temperature (SST). The freshwater flux consists of an E-P budget plus a relaxation to observed climatological surface salinity with a 30-day time scale. Evaporation is calculated from bulk formulae using wind speed, specific humidity, and model SST. Precipitation is given by COADS. CLIM is integrated for a total of 89 years.

The interannual atmospheric forcing used in INTER covers a period of 59 years from 1948 to 2006 and is derived from the NCEP/NCAR reanalysis. To be consistent with the climatological forcing, we keep the ERA15 mean and add the 6-hourly NCEP anomalies to produce the atmospheric forcing. No interannual variability in precipitation is prescribed. INTER is integrated for 59 years starting from year 30 of CLIM (spin-up period).

2.2. Description of the MSBC

Characteristics of the MSBC model are illustrated schematically in Figure 2. Using information about Atlantic surface waters in the Gulf of Cadiz (T_{atl}, S_{atl}, ρ_{atl}) and the heat and evaporation budget (*Q*, *E-P-R*) over the Mediterranean Sea, the model first computes the properties (T_{gib}, S_{gib}, ρ_{gib}) and transport (Tr_{gib}) of the MSW at Gibraltar. The model then calculates properties (T_{out}, S_{out}, ρ_{out}) and transport (Tr_{out}) of the final overflow water by entraining the NACW properties (T_{ent}, S_{ent}, ρ_{ent}) into the MSW. The reader is referred to *Price and Baringer* [1994] and *Price and Yang* [1998] for a more detailed explanation of the model. Although the MSBC is a relatively simple model of the outflow process, results have been shown to be as accurate as numerical model results using the parameterization of *Xu et al.* [2007] for the Mediterranean outflow region.

2.3. Implementation and Parameters of the MSBC in HYCOM

Since the model resolution (1/3º) is not sufficient to resolve the physical processes of the overflow in the Gulf of Cadiz, we implement the MSBC model in HYCOM. The Gulf of Cadiz becomes a boundary zone (between ~6ºW *to* ~8ºW) where the MSBC model determines the water properties, depth range, and transport of the overflow water entering the Atlantic basin. Inputs to the MSBC model are either specified or provided by the model at grid points just west of the Gulf of Cadiz boundary zone.

Specified inputs are the mass (E-P-R) flux and the net surface heat flux (Q) averaged over the Mediterranean Sea and the depth where the entrainment occurs. *Price and Baringer* [1994] prescribe values of 0.7 m/y and 0 W/m^2 for the freshwater and heat flux, respectively. In the observations, the freshwater flux of the Mediterranean Sea has been estimated between 0.52 m/y and 0.96 m/y [*Garrett,* 1996; *Béthoux and Gentili,* 1999], and the averaged net heat flux has been estimated at -7 W/m^2 with variations of ±15 W/m^2 between 1945 and 1990 [*Garrett et al., 1993*]. The values of 0.55 m/y and -13 W/m^2 were found to provide MSW properties close to the observations for this configuration of HYCOM. In the Gulf of Cadiz, most of the entrainment occurs in the first 50 km outside the Strait of Gibraltar between 350 m and 600 m [*Price and Baringer,* 1994]. Since the Gulf of Cadiz boundary zone expands to 8ºW, where the entrainment occurs in the lower depth range of the observations, the depth of the entrainment was set to 625 m.

The inputs provided by HYCOM (highlighted in blue in Figure 2) to the MSBC model are the Atlantic inflow temperature and salinity (T_{atl}, S_{atl}) averaged over the upper 140 m just west of the Gulf of Cadiz boundary zone, and the temperature and salinity of the entrained NACW (T_{ent}, S_{ent}) at the prescribed depth of 625 m. The MSBC outputs (highlighted in red in Figure 2) include four transports: Tr_{atl}, Tr_{gib}, Tr_{ent}, and Tr_{out}, with the first two being equal and opposite to each other. The outputs also include the temperature and salinity of the Gibraltar outflow (T_{gib}, S_{gib}) and the MOW (T_{out}, S_{out}). The corresponding densities are calculated using the model equation of state.

Implementation of the MSBC in HYCOM is not straightforward because the MOW, which has a temperature and salinity calculated by the MSBC, must be accepted by interior isopycnic layers such that the target isopycnic density in each accepting layer is preserved. Technical details of the MSBC implementation are presented in the Appendix.

3. Examination of a Change of Circulation as a Source of the MOW Variability

To test the viability of the hypothesis that changes in the MOW result from a change in the circulation of the Atlantic Ocean, we use the 1/3º Atlantic Ocean configuration of the HYbrid Coordinate Ocean Model (HYCOM) described in section 2 and perform two simulations, CLIM and INTER, forced by climatological atmospheric fields (steady-state simulation) or interannual atmospheric fields (realistic simulation), respectively. The realistic simulation covers the period 1948-2006; for the purpose of comparing the results with observed trends, the focus is on the period 1955-1993.

3.1. Main Features of the MOW as Modeled by HYCOM

Before comparing the MOW modeled variability with the MOW observed variability, we assess the suitability of the model to reproduce the observed main features of the MOW properties and circulation. The general shape of the tongue in the Atlantic Ocean in CLIM and INTER is similar to the shape of the tongue in the GDEM3 climatology (Figures 7a, b). The MOW outflow enters the basin in layers σ_2=36.38 kg/m^3 and σ_2=36.52 kg/m^3 (layers 14 and 15 of the model), isopycnal surfaces that are neutrally buoyant around 1100 m in the vicinity of the Gulf of Cadiz. The salty water (S > 35.40 psu) spreads westward to 40ºW and northward to 50ºN, as in GDEM3. The vertical structure of the MOW is also very similar to GDEM3 (see Figure 1), although the main core presents a greater westward and vertical extension in our experiments. Indeed, salinity greater than 36 psu can be found as far as 20ºW, and most of the MOW spreads in the Atlantic between 800 m and 1300 m. The averaged salinity of the MOW reservoir is slightly larger in our experiments (35.97 psu for CLIM, 35.96 psu for INTER) than in the climatology (35.84 psu), mostly because of the larger westward extension of the tongue. The difference of salinity between INTER and CLIM shows that INTER is saltier west of 25ºW and slightly less salty between 10ºW and 25ºW within the reservoir and north of the reservoir (Figures 7e, f). The averaged distribution of the MOW has therefore shifted in INTER compared with the distribution in CLIM. Nonetheless, the main characteristics of the tongue remain close to the characteristics of the observed tongue in both simulations, and we consider the model suitable to investigate the variability of the MOW.

3.2. Comparison Between the Observed and Modeled NACW and MOW Variability

To verify that the difference in the modeled salinity field (between CLIM and INTER) is caused by a change in the Atlantic circulation (via the different forcing fields) and not by a difference in the MOW properties at the exit of the Gulf of Cadiz (S_{out}, Tr_{out}) in the model, we compare CLIM and INTER NACW properties, MOW properties and the MOW transport variability at the exit of Cadiz. We place these modeled properties in an observational context by including the observed properties in this comparison. As the number of observations is not sufficient, the observed MOW properties and transport at the exit of Cadiz (S_{out}, Tr_{out}) are derived from observed MSW properties and transports (S_{gib}, ρ_{gib}, Tr_{gib}) as well as observed NACW properties (S_{ent}, ρ_{ent}) using the MSBC as is done in the ocean model. Since the properties of both water masses are density compensated, the focus here is on the salinity (Figure 5).

3.2.1. Observed and Modeled NACW Variability

The observed NACW properties (S_{ent}, ρ_{ent}) used as inputs to the MSBC model are retrieved from the hydrographic database HYDROBASE 2 [*Curry*, 2001]. This hydrographic database includes data from the World Ocean Database 2001 and 2005, the WOCE hydrographic program, and the MEDAR/MEDATLAS II [*MEDAR group*, 2002], and has been subjected to a quality control following the method described by *Lozier et* *al.* [1995]. Our analysis includes data located only in the Gulf of Cadiz (i.e., between 9ºW and 7ºW). To avoid introducing the signal of the MOW as it descends along the northern slope of the Gulf of Cadiz, we limited our study area to the domain between 34ºN and 36ºN. Here, the data are extracted at 600 m.

The variability of the observed 3-year running mean salinity anomaly for the 1950-2003 period is presented in Figure 5a. The NACW salinity at 600 m is stable between 1950 and 2003 with variations of the order of ±0.05 psu except in 1984 when the salinity anomaly peaks at +0.1psu. A possible explanation for this spike is a heaving or a vertical expansion of the underlying MOW during this year. Temperature shows the same variability as the salinity (not illustrated), leading to a stable density between 1950 and 2003. The salinity trend (+0.0025±0.0040 psu/decade; r^2=0.01) and the density trend (0.0008±0.0024 kg/m^3/decade; r^2=0.00) are negligible between 1955 and 1993 (time period of the *PL04* study).

The modeled NACW properties used as inputs to the MSBC in HYCOM present no significant variation (< ±0.05 psu) or trend in CLIM throughout the simulation (Figures 5a). In INTER, the amplitude of the NACW salinity variations between 1950 and 2006 are comparable to those present in CLIM. The NACW salinity trend in INTER is slightly greater than the observations (0.0084 ± 0.0021 psu/decade, r^2=0.39) for the period 1955-1993 but is still significantly smaller than the observed MOW reservoir trend.

3.2.2. Observed and Modeled MOW Salinity Variability

To estimate the observed MOW variability at the exit of Cadiz (S_{out}, Tr_{out}), we use as inputs to the MSBC the observed NACW properties (S_{ent}, ρ_{ent}) described in the last section and the MSW properties (T_{gib}, S_{gib}, ρ_{gib}) extracted from the MEDAR/MEDATLAS II oceanographic data set [*MEDAR group*, 2002]. Since no long-term measurement of properties at the Strait of Gibraltar is available, we assume the MSW properties have the same variability as the properties of the 150-600-m layer of the western Mediterranean basin, i.e., the region west of the Sicily Strait (12ºE), as analyzed by *Rixen et al.* [2005] for the period 1950-2000. The evolution of the MSW salinity is stable at 38.46 psu between 1950 and 1970; it then increases to reach 38.50 psu in 2000 [See *Rixen et al.* 2005, Figure 2]. The MSW salinity trend between 1955 and 1993 is 0.0110 ± 0.0015 psu/decade (r^2= 0.57).

The MOW salinity (S_{out}) variability derived from the observations mainly reflects the observed NACW salinity variability (S_{ent}) (Figure 5b). Consequently, the MOW salinity (S_{out}) trend presents a trend close to zero (-0.0001 ± 0.0038 psu/decade; r^2=0.00), similar to the observed NACW trend. The modeled MOW salinity anomaly in CLIM stays close to zero during the simulation. In INTER, the variability of the MOW salinity at the exit of Cadiz reflects the variability of the NACW salinity as seen in the observations (Figure 5b) and presents a slightly positive trend for the period 1955-1993 that remains exceedingly small relative to the changes occurring in the reservoir (+0.0086 ± 0.0018 psu/decade; r^2=0.39).

3.2.3. Observed and Modeled MOW Transport

Since variations of MOW transport (Tr_{out}) can potentially affect the amount of salt imported into the reservoir, we examine the time evolution of the MOW transport out of the MSBC model computed (a) from observations and (b) in HYCOM (Figure 5c).

The observed MSW transport (Tr_{gib}), used as input to the MSBC model to calculate Tr_{out}, is the transport estimated by *Lozier and Sindlinger* [2009] for the period between 1950 and 2000 from the maximal exchange formulation of *Bryden and Kinder* [1991], varying from 0.78 Sv to 0.90 Sv (1Sv = 10^6 m^3/s) with an average value of 0.80 +/- 0.31 Sv during this time period, in agreement with the *Baringer and Price* [1997] estimations of MSW transport. The resulting MOW transport (Tr_{out}) derived from the observations presents variations of ~ ± 0.2 Sv (Figure 5c). Minimum in 1952 (-0.18 Sv), the transport anomaly increases till 1962 (+0.15 Sv) and decreases again till 1974 (-0.18 Sv). The transport anomaly then constantly increases till 2000 (+0.05 Sv). The estimated trend between 1955 and 1993 is close to zero (+ 0.0033 ± 0.0096 Sv/decade). Therefore, the observed transport does not contribute to the property trends in the reservoir.

The modeled MOW transport anomaly in CLIM is stable and close to zero throughout the simulation. In INTER, the modeled MOW transport anomaly varies with the same amplitude as the observations (~ ± 0.15Sv). The variability of the modeled transport is however not in phase with the transport derived from the observations with an increase from -0.1Sv in 1950 to +0.15Sv in 1975 before a decrease to -0.1Sv in the 2000s. Despite this difference in the variability, the modeled transport trend between 1955 and 1993 is as in the observations close to zero with 0.0024 ± 0.0082 Sv/decade.

Although the variability of the modeled and observed NACW and MOW may differ, the modeled and observed trends of the water mass properties involved in the MOW trends in the reservoir are similar and close to zero. We now estimate the modeled MOW variability in the reservoir as modeled by HYCOM.

3.3. Modeled Variability of the MOW in the Reservoir

To see if the model reproduces the observed trends in the reservoir despite property trends close to zero at the exit of the Gulf of Cadiz, we calculate the modeled variations of the MOW properties inside the reservoir. We compute the mid-depth maximum salinity anomaly of each grid point and average over the reservoir as in *PL04*. The temperature and density anomalies are those corresponding to the mid-depth maximum salinity anomaly (Figure 6). The MOW properties in CLIM remain quite stable for 40 years. Then, the salinity and temperature slightly increase for the last 20 years of the simulation (Figures 6a, b). The drift of the model over the last 60 years of CLIM corresponds to a trend of 0.0057 ± 0.0012 psu/decade (r^2=0.39) for the salinity and 0.028 ± 0.002 ºC/decade (r^2=0.39) for the temperature.

The evolution of the properties in INTER presents a significant salinity (+0.3psu) and temperature (+0.08ºC) increase in the mid-1970s. The salinity and temperature then stabilize at these high values in the 1980s and begin to slowly decrease till the end of the simulation in 2006. No variation of density occurs during the simulation. The salinity and temperature trends (Table 1) are comparable (in the error bars) to the observations of *PL04* with 0.0212 ± 0.0028 psu/decade (r^2=0.69) and 0.108 ± 0.011 ºC/decade (r^2=0.72), respectively. The observed MOW trends are thus reproduced in INTER for the period 1955-1993. This implies that a change of circulation of the Atlantic Ocean is responsible for the MOW variability between 1955 and 1993. This is confirmed by the fact that the MOW salinity tongue in INTER exhibits a larger westward extension than in CLIM (Figures 4e, f).

Finally, one can assess the model's ability to reproduce the variability after 1993, by comparing Θ/S profiles (potential temperature/salinity) of INTER averaged between 10ºW and 20ºW at 36ºN with the profiles of *Leadbetter et al.* [2007] for 1959, 1981, and 2005 (Figure 7). Although INTER presents saltier and warmer outflow than the observations (Figure 7a) and the climatology GDEM3 (in green, Figure 7b), the simulation reproduces the warming and salinification between 1959 and 1981 and the cooling and freshening between 1981 and 2005. One is therefore able to reproduce The observed MOW variability in the reservoir over the last 60 years with interannually varying atmospheric forcing and trends close to zero at the exit of the Gulf of Cadiz.

4. Summary and Conclusions

In this study, we investigate the possibility that a change of circulation of the Atlantic Ocean is responsible for the MOW variability off the coast of Portugal (area defined as the reservoir by *Potter and Lozier* [2004]) by using the Hybrid Coordinate Ocean Model (HYCOM).

Configured for the North Atlantic and combined with the Marginal Sea Boundary Condition model (MSBC), two 59-year simulations, forced by either a climatological forcing (steady-state simulation) or an interannual atmospheric forcing (1948-2006 period) are performed. The modeled trends in the reservoir are well reproduced in the interannual simulation when compared with the observations. Furthermore, the comparison of the salinity patterns between the two simulations shows a MOW tongue that is expanded more westward in the interannual simulation than in the climatological one. To verify the modeled MOW variability in the reservoir is due to a shift of the

Atlantic circulation and not to misrepresentation of the modeled water masses present in the Gulf of Cadiz, we compare the modeled results to the variability of the observed NACW and MOW in the Gulf of Cadiz. As the number of observations is not sufficient, the observed MOW properties are derived from the observed MSW and NACW using the MSBC model as is done in HYCOM. The results show an agreement between the model and the observations with trends close to zero for both the NACW and MOW (properties and transport) at the exit of the Gulf of Cadiz. This confirms that the cause of the MOW variability is a change of circulation of the Atlantic Ocean in INTER. Since the MOW properties remain stable in CLIM, the variability of the atmospheric forcing is therefore responsible for the variability of the MOW in the Atlantic Ocean.

Part II of this study (this issue) will explain the mechanism involved in this pathway shift of the MOW inside and outside the reservoir by separating the mechanical effect of the wind stress from the impact of the buoyancy forcing on the Atlantic Ocean circulation, considering a constant property MOW.

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APPENDIX: Implementation of the MSBC model in HYCOM

The first step in implementing the Price-Yang MSBC model is to define the Gulf of Cadiz boundary zone at the initialization stage of each model run. The meridional boundary of this zone must be located sufficiently far to the west of the Strait of Gibraltar so that water depths exceed 1500 m to permit the unimpeded injection of overflow water. The meridional boundary is therefore chosen as the first column of grid points west of the Strait where a maximum depth of 1500 m is encountered at two or more grid points within this column. This column is defined by index i_1. All grid points in and to the east of this column within the Gulf of Cadiz are then considered to be part of the boundary zone. The latitude range over which water is exchanged between the interior Atlantic and the boundary zone consists of all grid points in this column beginning with the first point located south of the latitude of the Strait and extending northward to the Iberian coast. These rows are defined by indices j_1 to j_2. The required input variables for the MSBC model, T_{atl}, S_{atl}, T_{ent}, and S_{ent} (Figure 2) are obtained from the first column of grid points to the west of the boundary longitude (index i_1-1). The MSBC model always sets current velocity to zero at all u and v grid points within the boundary zone. It also initially resets the temperature, salinity, and layer thicknesses at all p grid points within the boundary zone to their climatological values, with the exception of the model layers that receive the injected MOW.

The primary difficulty associated with injecting Mediterranean overflow water is that this water must be accepted by interior isopycnic layers with discrete target densities that do not match the density of the overflow water. The simplest way to do this would be to identify the model layer located just west of the boundary zone that spanned the MOW injection depth calculated by the MSBC model, inject the MOW transport calculated by MSBC into this layer with the temperature and salinity values calculated by the MSBC model, and then rely on the hybrid vertical coordinate grid generator to re-establish isopycnic conditions in the layer. However, this requires the grid generator to move model interfaces large distances during each time step, which induces large numerical diffusivity and produces highly uneven layer thicknesses in the MOW tongue west of the Gulf of Cadiz. It was therefore necessary to inject the water in a manner that preserved the isopycnic target densities in the receiving layers.

The first step of this procedure is to identify the two isopycnic layers with target potential densities that bracket the MOW density calculated by the HYCOM equation of state:

$$\sigma_{out} = \sigma(T_{out}, S_{out}, p_0),$$

where p_0 is the reference pressure and potential density is calculated in sigma units. All overflow water is accepted by these layers, denoted by indices k_1 and k_2, and separated by interfaces located at pressure depths p_{k1}, p_{k2}, and p_{k3} (Figure 8). The procedure to partition the MOW injection into the two layers is designed to ensure, to the greatest extent possible, that the mass-weighted average temperature of the injected water equals T_{out} calculated by the MSBC model. Within the boundary zone, the salinity in the two selected layers is set to S_{out} calculated by the MSBC model, and then the temperature in each layer is set to

$$\begin{aligned} T_{k1out} &= \sigma^{-1}\left(\sigma_{k1}, S_{out}, p_0\right) \\ T_{k2out} &= \sigma^{-1}\left(\sigma_{k2}, S_{out}, p_0\right), \end{aligned}$$

where σ^{-1} signifies the inversion of the equation of state built into HYCOM to calculate temperature from potential density and salinity, and where σ_{k1} and σ_{k2} are the isopycnic target potential densities of the two layers. The pressure depth of the intermediate interface p_{k2} within the boundary zone is then reset to

$$\widehat{p}_{k1} = \begin{Bmatrix} p_{out} + (0.5 - q)(p_{k2} - p_{k1}) & q \le 0.5 \\ p_{out} + (0.5 - q)(p_{k3} - p_{k2}) & q > 0.5 \end{Bmatrix},$$

where

$$q = \frac{T_{k1out} - T_{out}}{T_{k1out} - T_{k2out}},$$

and where p_{out} is the central pressure depth of the injected overflow water. Note that q must be bounded between 0 and 1 because these limits can be exceeded due to the nonlinear equation of state since the two layers were selected based on their target potential densities and not temperature. The interface pressure depths above and below the two layers are then given by

$$\begin{aligned} \widehat{p}_{k1} &= \widehat{p}_{k2} + p_{k1} - p_{k2} \\ \widehat{p}_{k3} &= \widehat{p}_{k2} + p_{k3} - p_{k2} \end{aligned}.$$

All other interfaces above and below these three within the boundary zone are set to their climatological mean pressure depths, except to maintain a minimum thickness of 5 m.

With layer thicknesses and water properties set at all of the grid points within the boundary zone, MOW injection into the interior Atlantic is accomplished by partitioning the total zonal transport U_{out} provided by the MSBC model among the two accepting layers as

$$\begin{aligned} Tr_{k1} &= (1-q)Tr_{out} \\ Tr_{k2} &= qTr_{out} \end{aligned},$$

It is implemented by controlling the zonal velocity at the column of u grid points located immediately west of column i_1 of the pressure grid points that represent the offshore edge of the boundary zone. The zonal transport of the injected water in each layer is distributed over both the layer thickness and the meridional distance between grid point rows j_1 and j_2. To ensure that there is no net zonal transport between the interior Atlantic and the boundary zone, the other two zonal transports at the edge of the boundary zone calculated by the MSBC model (Tr_{atl} *and* Tr_{ent}) must also be accounted for. Both of these transports are distributed over the same latitude range (from j_1 to j_2) as Tr_{out}, , but Tr_{atl} is distributed over the upper 140 m while Tr_{ent} is distributed over the depth range between 140 m and p_{k1}.

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Tables:

Experiments	Salinity trend (psu/decade)	Temperature trend (ºC/decade)	Density trend (kg/m^3/decade)
Observations	0.0283±0.0067 r^2=0.88	0.101±0.024 r^2=0.72	0.00 r^2=0.02
CLIM	0.0057±0.0012 r^2=0.39	0.028±0.002 r^2=0.39	-0.00 r^2=0.07
INTER	0.0212±0.0028 r^2=0.69	0.108±0.011 r^2=0.72	-0.00 r^2=0.53

Table 1: Salinity, temperature, and density trends between 1955 and 1993 in the MOW reservoir for the observations, CLIM, and INTER; r^2 is the coefficient of determination.

Figures:

Figure 1: (a) Salinity averaged on layers 14 and 15 (σ_2=36.38 kg/m^3 and σ_2=36.52 kg/m^3) from the GDEM3 climatology and (b) its vertical sections at 36ºN.

Figure 2: Schematic of the exchange at the Strait of Gibraltar. S_{atl} corresponds to Atlantic waters, S_{gib} corresponds to Mediterranean Sea Water at Gibraltar (source water), S_{ent} corresponds to NACW entrained water, and finally, S_{out} corresponds to outflow water. Variables in green are prescribed, variables in blue are given by HYCOM, and variables in red are calculated by the MSBC model.

Figure 3: Bathymetry (m) of the 1/3º Atlantic configuration of HYCOM.

Figure 4: Salinity averaged on layers 14 and 15 (σ_2=36.38 kg/m^3 and σ_2=36.52 kg/m^3) and over the 59 years of simulation for (a) CLIM and (c) INTER. Vertical salinity section at 36ºN for (b) CLIM and (d) INTER. (e) and (f) difference between INTER and CLIM.

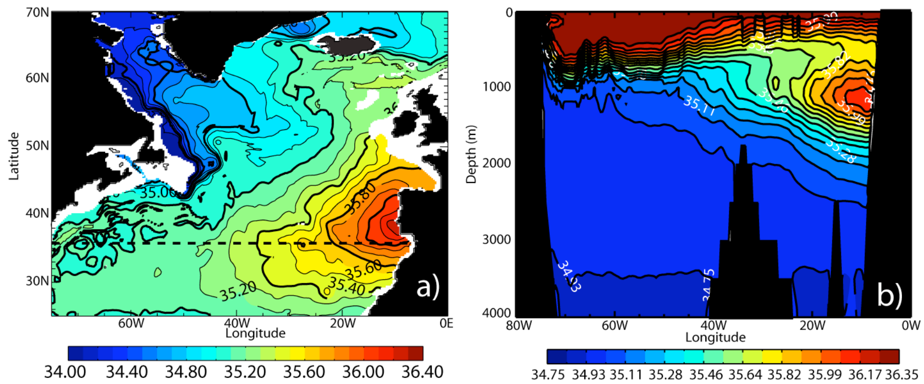
Figure 5: (a) Evolution of the 3-year running mean anomaly of salinity of the NACW introduced in the MSBC model for CLIM (black), INTER (gray), and extracted from the HYDROBASE dataset at 600m in the Gulf of Cadiz (dotted-black). (b) Evolution of the anomaly of salinity of the MOW calculated by the MSBC model for CLIM, INTER, and the observations (N.B.: using the Rixen dataset for the salinity at Gibraltar). (c) Evolution of the anomaly of the MOW transport for CLIM, INTER, and the observations. The vertical dashed lines bound the Potter and Lozier period.

Figure 6: Evolution of the anomaly of (a) salinity, (b) temperature, and (c) density for CLIM (black) and INTER (gray) averaged over the Potter and Lozier box [10ºW,

20ºW, 30ºN, 40ºN]. The vertical dashed lines bound the Potter and Lozier period.

Figure 7: Mean θ/S profiles of a repeated section (1959 in black, 1981 in red, and 2005 in blue) at 36ºN between 10º-20ºW at the depth of the MOW (a) from *Leadbetter et al.* [2007] and (b) for INTER. The mean profile of the climatology GDEM3 is presented in green.

Figure 8: Schematic diagram illustrating the two layers chosen to accept the MOW injected from the Gulf of Cadiz boundary zone (right) into the interior North Atlantic (left). The solid arrows illustrate the partition of the MOW transport between the two layers while the dashed line shows the central pressure depth of the injected water calculated by the MSBC model.



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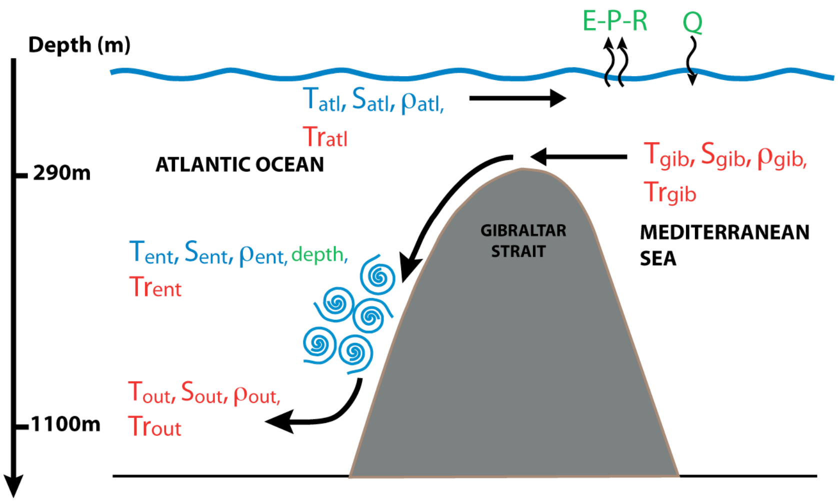

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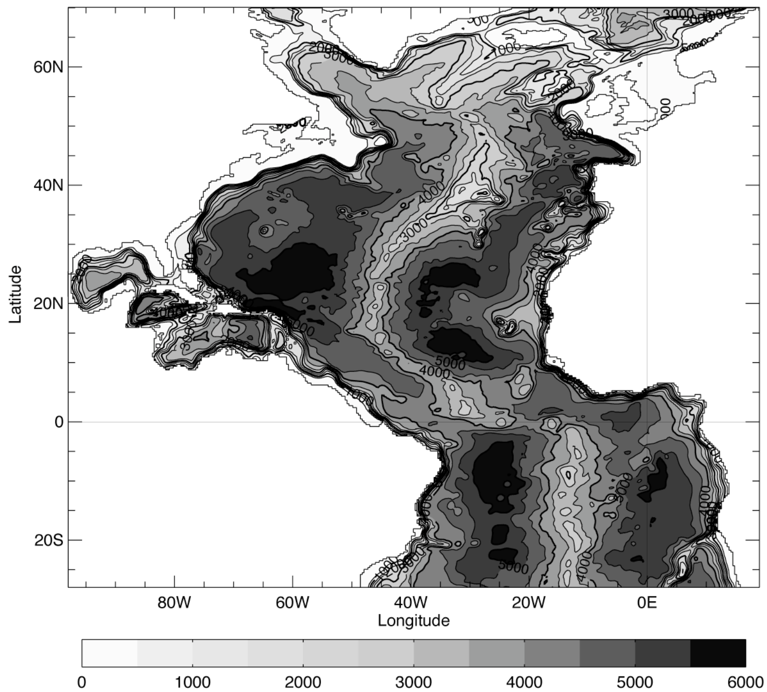

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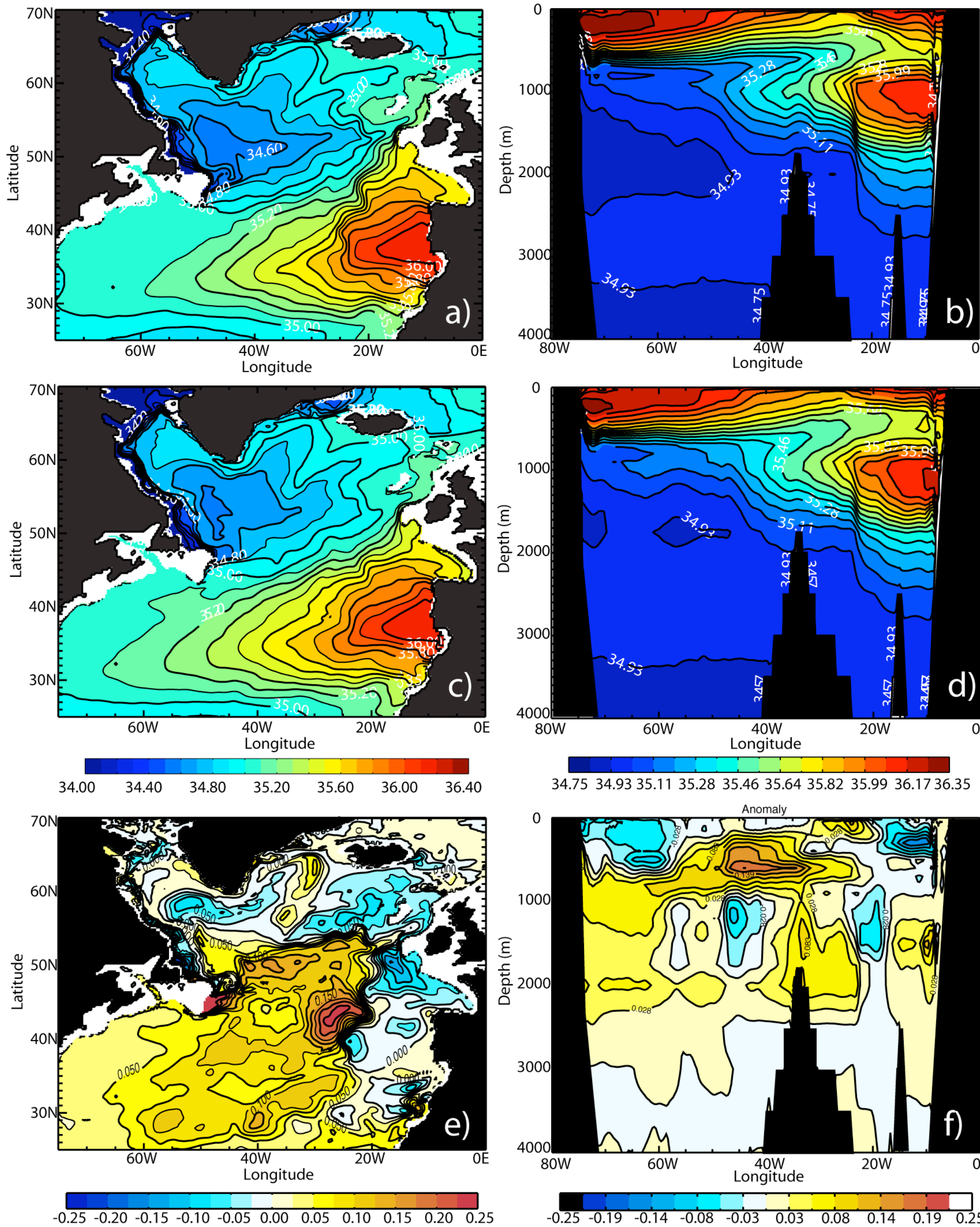

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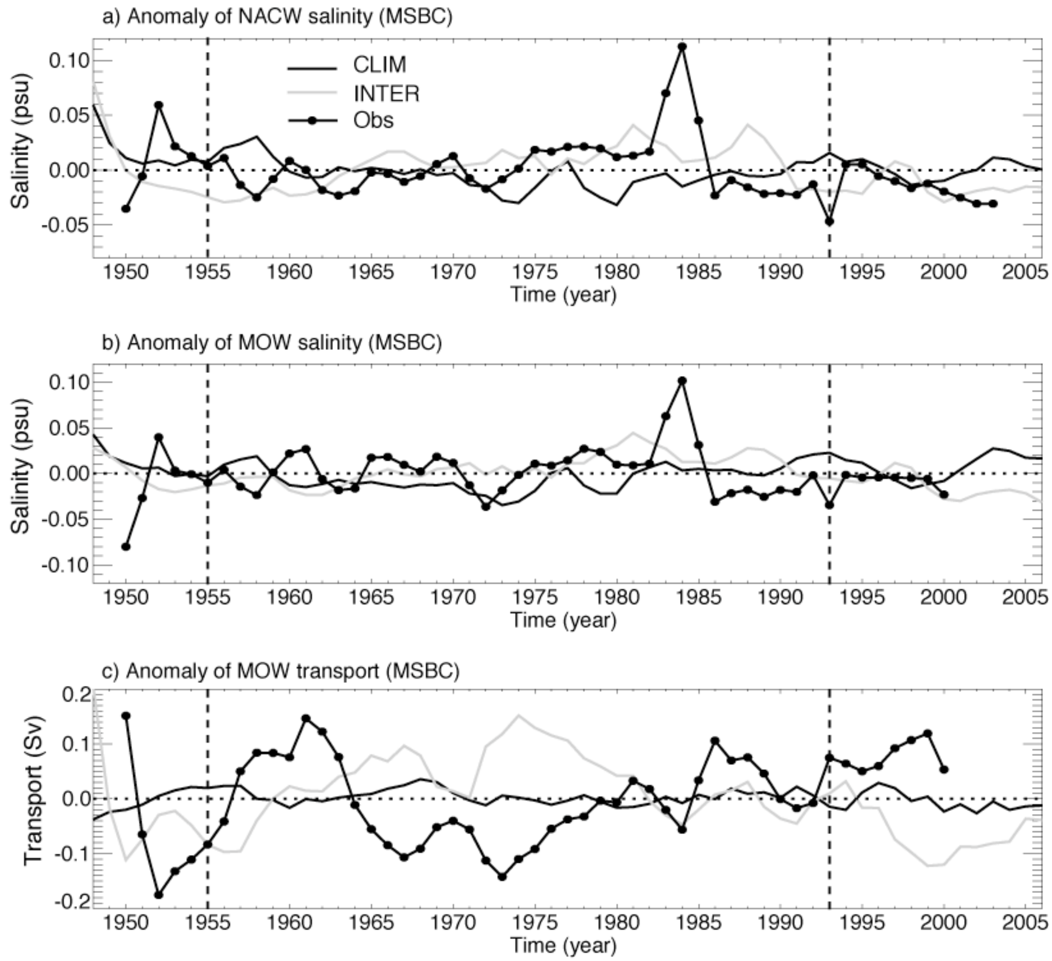

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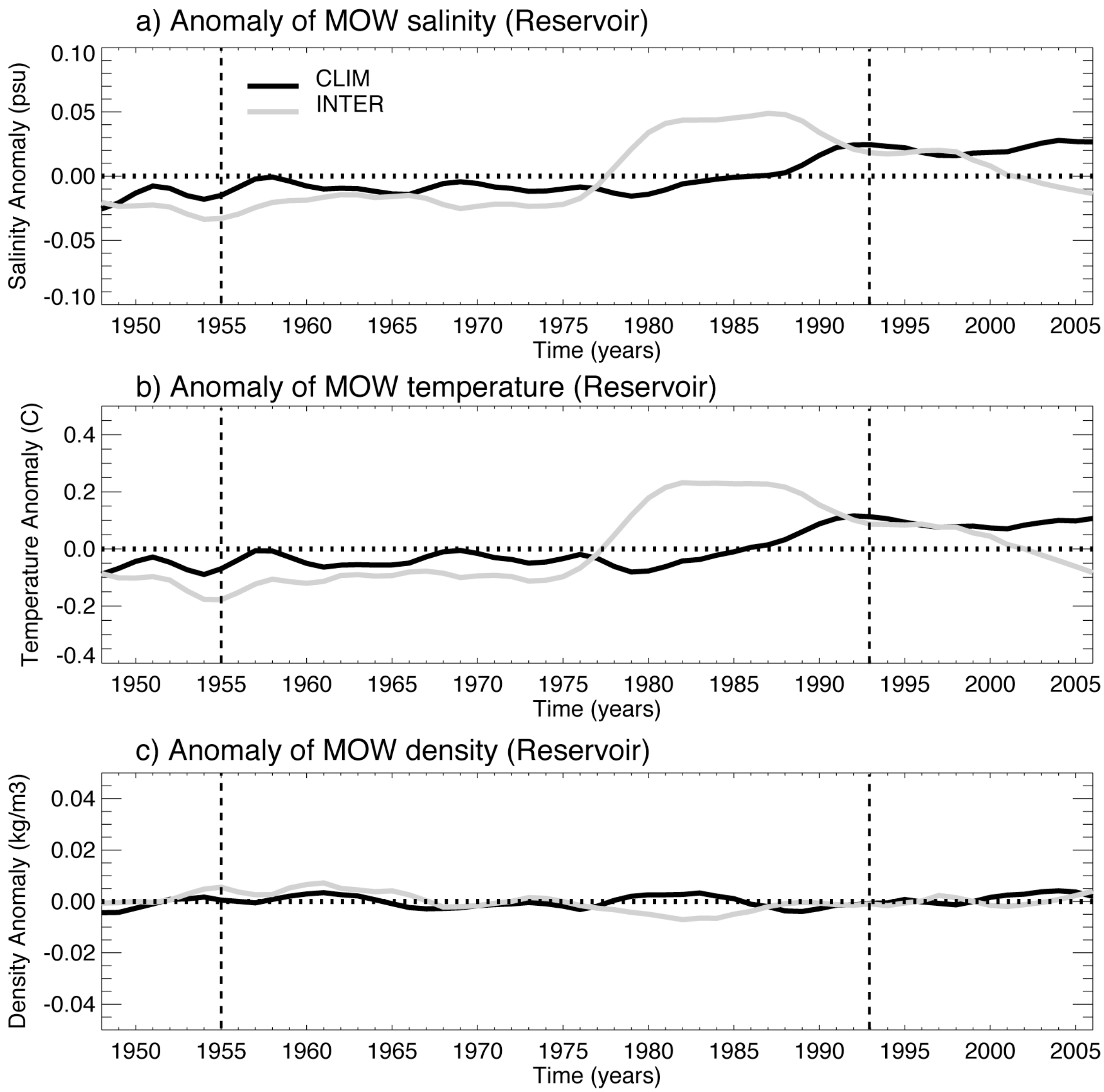

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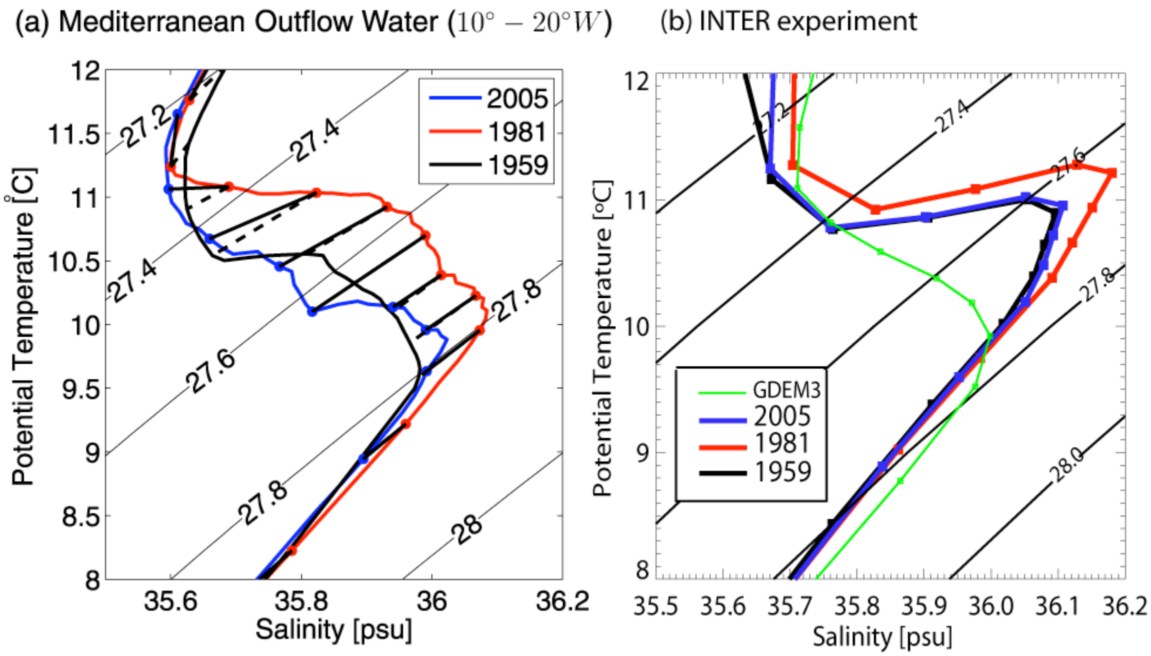

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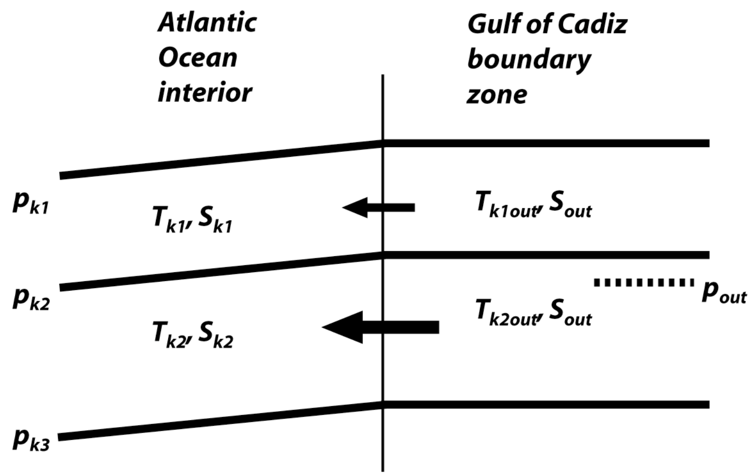

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