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Interannual variability of the Mediterranean outflow observed in Espartel sill, western Strait of Gibraltar

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[1] Four-year time series of observations in Espartel sill at the western part of the Strait of Gibraltar have been analyzed in order to investigate the variability of the Mediterranean outflow. It is assumed that the observed variability comes from the changing properties of the dense waters that are located at the maximum depth from where they can be uplifted in the upstream basin (Alborán Sea, inside the Mediterranean Sea) and evacuated through the strait. From this perspective, the following three mechanisms are investigated: (1) the replenishment of the deep basin by newly formed Western Mediterranean Deep Water that, depending on its density, can either uplift old resident waters or lay above them leaving in any case a cold signature in the temperature series; (2) the presence/absence of the energetic anticyclonic gyres in the Alborán Sea, particularly the western one, which can transfer momentum to the underlying Mediterranean vein and provide it with additional energy to ascend over the sills of the strait; and (3) the meteorologically enhanced flows that follow the rapid changes of atmospheric pressure over the western Mediterranean basin, which would be able to aspire deeper waters residing in the upstream basin. The three mechanisms act on different timescales, from annual in case (1) to monthly in case (2) to weekly in case (3) although these two latter are modulated annually by the seasonal prevalence of the western Alborán gyre in summer and of the strong meteorologically driven fluctuations in winter. The mechanisms overlap at annual timescales making it difficult to separate out the different contributions.

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1. Introduction

[2] The thermohaline forcing that drives the primary circulation of the Mediterranean Sea along with its relatively small dimension makes this basin specially sensitive to the air-sea fluxes across the surface, a situation of particular concern under the global climatic change to which this sea responds faster than other open oceanic regions. Actually, there are a few studies published over the past several decades that evidence changes in deep water properties, more specifically, a warming and salting (the question of whether or not there is a trend in density is unclear), with a nonnegligible man-induced origin [*Bethoux et al.*, 1990, 1998; *Leaman and Schott*, 1991; *Rohling and Bryden*, 1992; *Krahmann and Schott*, 1998; *Rixen et al.*, 2005].

[3] Since the Strait of Gibraltar is the only significant connection of the Mediterranean Sea with the open ocean, the Mediterranean water flowing out over its sills into the Atlantic ocean must carry the footprint of the climatic variability, which makes the Strait a privileged site for monitoring the changes taking place in the Mediterranean. Despite the high strategic oceanographic importance of this site, it has been only recently that a program promoted by the Mediterranean Science Commission (CIESM, http://www.ciesm.org/marine/programs/hydrochanges.htm) has undertaken a systematic monitoring of the outflow at the Camarinal sill (CS) and Espartel sill (ES) in the Strait of Gibraltar (see Figure 1). The station at CS was installed by the Centre d'Océanologie de Marseille/Laboratoire d'Océanographie et de Biogéochimie in early 2003 [see *Millot et al.*, 2006] while the monitoring site at ES started measuring by autumn 2004 under the Spanish funded program INGRES. This paper deals with observations collected by the latter, which have been already analyzed partially by *García-Lafuente et al.* [2007].

2. Monitoring Station at ES

[4] The station, installed in October 2004 at 35° 51.7′N, 5° 58.6′W (Figure 1) in the main, southern channel of Espartel

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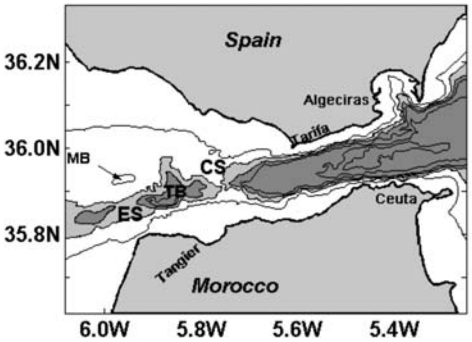

Figure 1. Map of the Strait of Gibraltar showing the main topographic features mentioned in the text. CS and ES indicate Camarinal and Espartel sills, respectively. TB is for the Tangier Basin located between both sills and MB indicates the submarine ridge of Majuan Bank to the north of ES south channel. Contours indicate 100, 290 (light-shaded area chosen to highlight the maximum depth of 297 m in CS), and 400 m (medium-dashed contour) and 500, 700, and 900 m, which are not labeled to keep the map clear.

section, consists of an uplooking 75 kHz Acoustic Doppler Currentmeter Profiler (ADCP) at 20 m above the seafloor, which profiles the water column in 8-m thick bins to a depth above the Mediterranean–Atlantic layer interface, whose mean depth here is around 190 m [*Sánchez Román et al.*, 2009]. A Conductivity Temperature (CT) probe, aimed at sampling the denser Mediterranean water flowing out the Mediterranean Sea through ES, is placed 15 m above the seafloor, between the ADCP and the bottom. Potential temperature ϑ, salinity S and σ_ϑ were derived from the CT observations.

[5] Currentmeter observations have been used to estimate the Mediterranean outflow, a task that must face two key issues: the first is the position of the interface, which cannot be always computed directly from the velocity field because tidal currents make the flow be unidirectional during part of every tidal cycle. Under such circumstances, a material (salinity) interface must be used instead. In ES, however, the Mediterranean layer does not fully reverse regardless the strength of tidal currents, which otherwise are greatly reduced in the lower layer (M2 amplitude of less than 40 cms^{-1} [*Sánchez Román et al.*, 2009]) due to the permanent hydraulic control exerted by topography in Espartel sill [*Farmer and Armi*, 1988; *Sannino et al.*, 2007]. The bidirectionality of the exchange is only lost by tidal inversions of the Atlantic layer. As a result the surface of maximum vertical shear of horizontal velocity is always satisfactorily detected by the ADCP and it is a quite good proxy of the instantaneous position of the Mediterranean-Atlantic interface [*Sánchez Román et al.*, 2009]. This interesting fact makes ES be more suitable than CS for monitoring the outflow. A second issue of concern is the cross-strait structure of the outflow and the existence of a minor, secondary channel north of Majuan Bank (Figure 1) through which a small amount of Mediterranean water flows out. Numerical simulations presented by *Sánchez Román et al.* [2009] suggests that the outflow overestimation that arises when using a single station in the middle of ES southern channel is nearly balanced by the ignored contribution through the northern channel and the correction derived from the cross-strait structure of the velocity field in the southern channel. All these corrections have been applied to the outflow estimations discussed below (see *Sánchez Román et al.* [2009] for further details).

3. Origin of the Outflow Variability

[6] The outflowing Mediterranean water is a mixture of intermediate and deep waters residing in the Mediterranean Sea, basically Levantine Intermediate Water (LIW) formed in the eastern Mediterranean, which flows across the Strait of Sicily into the western basin, and the Western Mediterranean Deep Water (WMDW) formed in the Gulf of Lions in the western Mediterranean, which occupies the bottom layer. This water mixes with LIW in the Tyrrhenian Sea giving place to the so-called Tyrrhenian Deep (or Dense) Water, TDW [*Rhein et al.*, 1999; *Millot et al.*, 2006], though a new hypothesis of TDW being the result of deep convection inside the Tyrrhenian Sea was also formulated by *Fuda et al.* [2002]. This water overlies the WMDW, plays a significant role in the circulation of intermediate layers in the western Mediterranean [*Rhein et al.*, 1999] and may also contribute to the Mediterranean outflow [*Millot et al.*, 2006]. Winter Intermediate Water (WIW) formed in the Catalan Sea in the western basin is another water mass identifiable in the western Mediterranean with potential to influence the outflow characteristics. However, LIW is thought to contribute the bulk of the outflow.

[7] The hypothesis for the variability of the outflow and its properties is that the depth from which the deep water can be suctioned out of the Mediterranean Sea is occupied by water of different characteristics throughout the different seasons and/or years. The physical mechanism behind the hypothesis is the aspiration of deep water from the adjacent, upstream basin (the Alborán Sea) by a relatively swift overflow across the strait sill, a mechanism already explored by *Stommel et al.* [1973] theoretically and by *Whitehead* [1985] with the help of a laboratory model for the Alborán Sea-Strait of Gibraltar system and also by *Astraldi et al.* [2001] for the case of the Ionian basin-Strait of Sicily. *Stommel et al.* [1973] and *Whitehead* [1985] argued that waters from around 700 m depth or more in the Alborán basin could be aspired over the main sill of Camarinal and they would leave their ϑ-S footprint in the outflow, particularly in the near-bottom portion that is monitored by the ES station. That depth of aspiration is roughly located in the transitional layer between LIW and WMDW in the Alborán basin [*Parrilla et al.*, 1986; *Kinder and Bryden*, 1990] and any vertical motion of the layer will change the ϑ-S characteristics of the water located at the depth from which it can be aspired.

[8] Different causes could be argued for the variability: first, the internal processes within the Mediterranean Sea, mainly the winter formation of deep waters that would fill the deep and/or bottom layers with newly formed dense water. If this water is dense enough to reach the bottom, it would uplift ancient resident deep waters and make them available for being suctioned out through Gibraltar; if not, it would lay over the ancient, denser deep water and remain at intermediate layers from where it can be drained out directly. On the other hand, the presence of mesoscale structures such as the Western Alborán anticyclonic gyre (WAG) and Eastern Alborán anticyclonic gyre (EAG) influence the depth at

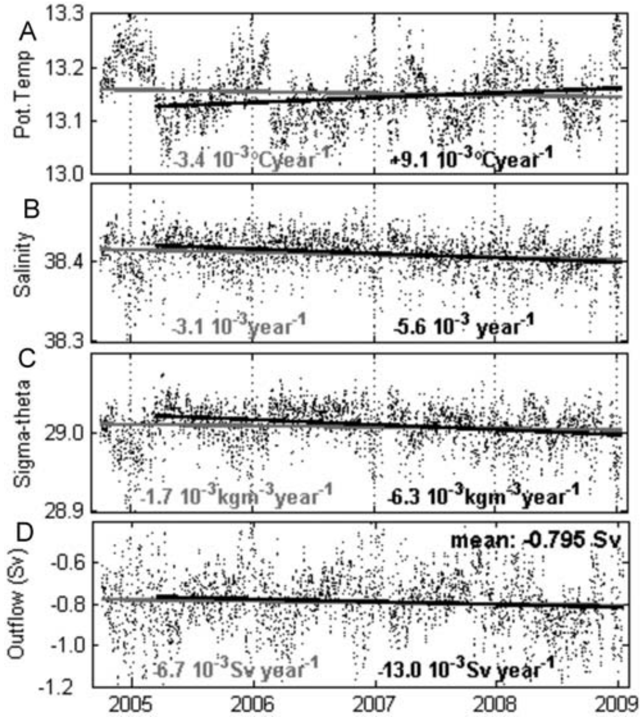

Figure 2. (a) Potential temperature, (b) salinity, and (c) $\sigma\theta$ of the $\sigma_{\vartheta_{\max}}$ subseries (see text for details). (d) The subinertial, tidal-free outflow through ES. Straight lines are lineal trends for the whole period of observations (gray line and numbers) and for the period from 15 March 2005 onward (black line and numbers).

which deep waters can be found in the water column. Intuitively, if there is no WAG, deeper waters are allowed to move upward and reach depths from which they are more easily ventilated through the Strait. There is, however, an opposite possible effect: in the Alborán Sea the WMDW occupies the entire basin beneath the LIW, usually below 700 m, but in the south the WMDW is banked against the African slope at shallower depths and behaves like a westward flowing boundary current [*Bryden and Stommel*, 1982; *Parrilla et al.*, 1986; *Kinder and Bryden*, 1990]. In case of a well developed WAG, the westward-going branch of the gyre that flows along the African shore with typical velocities of 1 ms^{-1} at the surface [*Tintoré et al.*, 1991; *García-Lafuente et al.*, 1998, *Viúdez et al.*, 1998], is able to transfer momentum downward that can be used to accelerate the WMDW vein and help uplift this water above the Gibraltar sills: the proportion of WMDW in the outflow would be increased in detriment of LIW. In absence of the WAG the Atlantic water flows along the African shore in the Alborán Sea [*Vargas-Yáñez et al.*, 2002; *Flexas et al.*, 2006] and the former mechanism of WMDW suction will not work, which in turn favors a greater contribution of LIW to the outflow. The meridional distribution of these water masses in Alborán basin, with LIW (and WIW eventually) flowing mainly along the Spanish coast and WMDW banked along the African shore [*Parrilla et al.*, 1986; *Kinder and Bryden*, 1990], would enhance the effect of the WAG on the variability of the ϑ-S characteristics of the outflow. Whatever the mechanism, some degree of correlation should be expected between the observed variability and the presence or absence of these mesoscale gyres. Finally, an overflow enhanced by favorable meteorological conditions could be able to uplift waters from greater depths that, having slightly different characteristics, would also contribute to the observed variability. All these scenarios are explored in section 6.

4. Other Datasets

[9] The main bulk of data comes from the monitoring station at ES (see section 2). Additionally, satellite observations and atmospheric data have been used in this study. Altimetry data have been downloaded from Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) free site (www.aviso.oceanobs.com). The data are sea level anomalies referred to the 1993–1999 average and combine information from different missions, which significantly improves the estimation of mesoscale signals [*Le Traon and Dibarboure*, 1999; *Le Traon et al.*, 2001]. All standard geophysical and environmental corrections have been applied.

[10] Daily atmospheric pressure data as well as monthly averaged heat and freshwater fluxes over the Mediterranean have been retrieved from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR). First type of data are of interest to investigate the subinertial, meteorologically forced outflow variations driven by atmospheric pressure changes [*Candela et al.*, 1989; *García-Lafuente et al.*, 2002a], while the second type are necessary to compute buoyancy fluxes and, hence, to have realistic proxy for deep water formation.

5. Observed Interannual Variability of the Outflow

[11] Strong mixing between Mediterranean and Atlantic water driven by tides in the Tangier basin (Figure 1) induces important tidal fluctuations of temperature and salinity in the outflow at ES. These fluctuations reach the bottom where variations as large as $\Delta\vartheta = 0.5$°C and $\Delta S = 0.2$ are registered regularly at 15 m above the seafloor in the same tidal cycle. Tidal variability was removed by extracting the densest sample recorded in every semidiurnal tidal cycle, which transforms the original series of ϑ, S and σ_ϑ into new ones sampled with semidiurnal periodicity, approximately, representing the deepest Mediterranean water able to leave definitely the Mediterranean Sea. We shall refer to them as $\sigma_{\vartheta_{\max}}$ subseries. Figure 2 shows the time evolution of ϑ, S and σ_ϑ of $\sigma_{\vartheta_{\max}}$ subseries along with their linear trends (obviously short-term trends or interannual variability) computed for the whole period (gray lines and numbers) and from March 2005 onward (black). We have proceeded so to highlight the effect of the very harsh winter of 2005 when an extraordinary formation of WMDW took place in the Gulf of Lions [*López-Jurado et al.*, 2005; *Schroeder et al.*, 2006, 2008; *Font et al.*, 2007; *Smith et al.*, 2008]. The event is particularly evident in the time series of ϑ, which shows many values above 13.2°C previously to March 2005 that drop quickly down to $\vartheta < 13.1$ in March. As a consequence, ϑ trend of the whole series is negative but it becomes positive if pre-March 2005 data are removed. Winter 2005 interrupted the reported warming trend of deep Mediterranean layer [*López-Jurado et al.*,

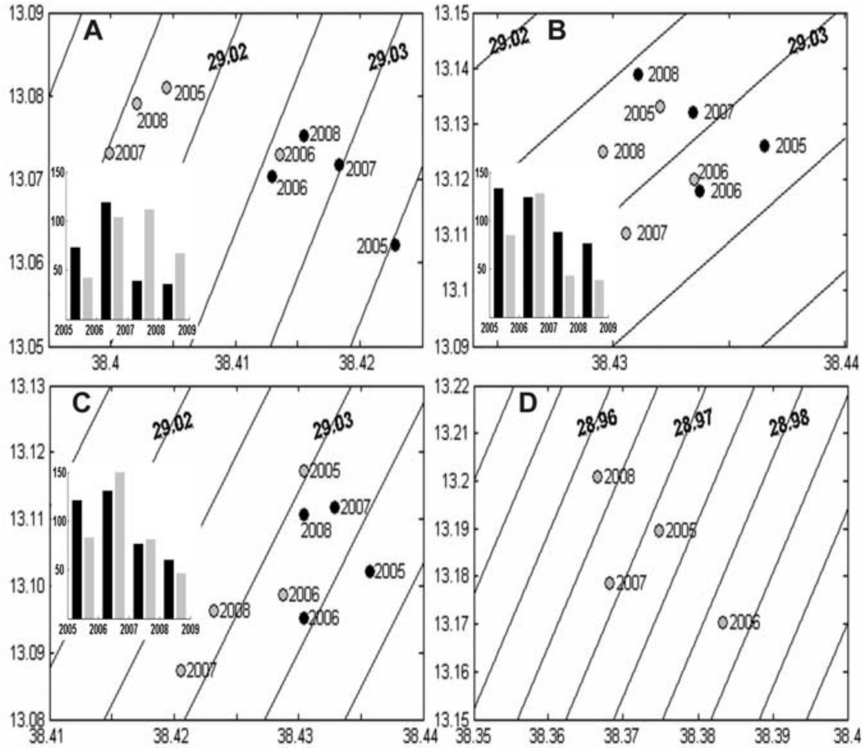

Figure 3. Potential temperature/salinity diagrams showing the mean values of samples (a) cooler than 13.10°C in $\vartheta_{\min}$, (b) saltier than 38.42 in $S_{\max}$, and (c) denser than 29.02 in $\sigma_{\vartheta_{\max}}$ subseries. In all cases, black circles are for February–May period and gray circles are for July–October. Bar diagrams indicate the number of observations in which the variables verified the imposed constrictions, with the same color code. (d) The yearly mean of all available observations.

2005; *Font et al.*, 2007], which seemingly was recovered after this very cold winter. Trends of S and σ_ϑ are negative in both cases although they are more negative if pre-March 2005 data are removed. Salinity contributes about twice more than temperature to the computed density trend.

[12] In addition to the $\sigma_{\vartheta_{\max}}$ subseries, two other extreme series were extracted from the observations to investigate the seasonal and interannual variability of the water characteristics: $\vartheta_{\min}$ and $S_{\max}$. The procedure was similar to that followed for the $\sigma_{\vartheta_{\max}}$ case but selecting the coldest ($\vartheta_{\min}$) or saltiest ($S_{\max}$) samples. Figure 3a shows the mean ϑ-S value of $\vartheta_{\min}$ samples colder than 13.10°C in February–May and July–October periods, which we shall refer to as "winter" and "summer" periods, respectively, for shortness. Bars indicate the number of observations (i.e., number of semidiurnal cycles) verifying the "cold" condition in every period. Bar height is therefore proportional to the amount of colder water evacuated during each season. Figures 3b and 3c are the same as Figure 3a for water samples saltier than 38.42 in $S_{\max}$ and denser than 29.02 in $\sigma_{\vartheta_{\max}}$ subseries, respectively. Figure 3d shows the annual mean of ϑ-S values using more than 17.000 observations per year.

[13] Observations show tendency to be saltier in winter than in summer, regardless the filter rule imposed to select extreme values. Year 2006 is an exception in the sense that there are no differences between summer and winter characteristics, suggesting a rather uniform outflow throughout the year. It is also the year with the greatest number of tidal cycles satisfying the cut-off rules. These facts explain the location of the 2006 annual ϑ-S mean when considering all observations (Figure 3d). However, winter 2005 shows, by noticeable margin, the coldest (Figure 3a), saltiest (Figure 3b) and densest (Figure 3c) outflowing waters, features that disappear in the summer of this year. On the other hand, summer of years 2007 and 2008 show the lighter outflowing water (Figure 3c) because of its relatively low salinity. These years also have less observations fulfilling the cut-off rules, which agrees with the aforementioned trends identifiable in the time series of extremes.

[14] The outflow computed has a mean value of −0.795 Sv and a negative linear trend (more outflow) of 0.013 Sv year^{-1} (Figure 2), which comes from an unusual large mean flow of −0.847 Sv during 2008, higher than the −0.788, −0.785 and −0.749 Sv registered in 2005–2007, respectively. Obviously, we should not speak of trend (in the long-term sense) but of interannual variability, a caution that also applies to the trends of the other variables presented in Figure 2. The outflow has a seasonal variability with larger values in early spring (Figure 2) a fact that led *García-Lafuente et al.* [2007] to relate the seasonality with the winter processes of WMDW formation. In 2008, however, the outflow peaked in summer with a mean value exceeding −0.9 Sv, the largest found during any season throughout the life of the monitoring station.

6. Analysis of Possible Scenarios

[15] The observed variability of the outflow is now analyzed from the perspective of the driving forces. As commented in section 3, we consider three different sources,

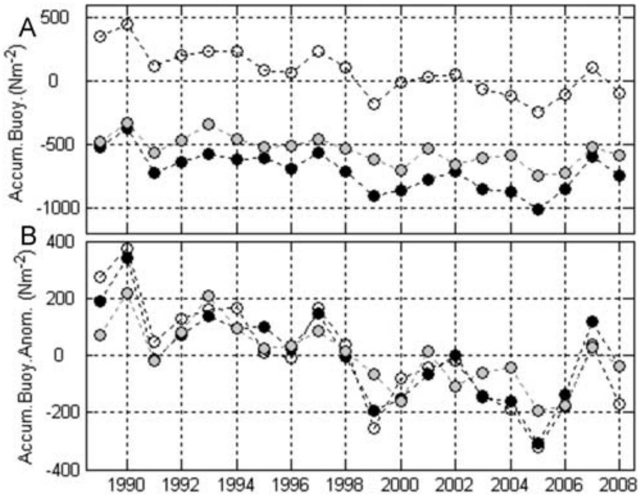

Figure 4. (a) Accumulated buoyancy (time integral of the buoyancy flux, in Nm^{-2}) over the Gulf of Lions from 1988 to 2008 from NCEP data. White circles are the yearly accumulated buoyancy from April to March of the next year, with positive (negative) value indicating flux into (out of) the ocean, that is, gain (loss) of buoyancy by seawater. Black circles are for the October–February (both months included), the period of buoyancy loss, and gray circles are for the preconditioning period (November–January). Ticks in x axis mark the previous period; for instance, 2008 represents the accumulated buoyancy from April 2007 to March 2008 (white circle), from October 2007 to February 2008 (black circle), and from November 2007 to January 2008 (gray circle). (b) The same as Figure 4a but for anomalies referred to 1988–2008 period.

which we refer to as climatic, meteorological and upstream forcing in the following discussion.

6.1. Climatic Forcing

[16] To assess the influence of WMDW formation in the seasonal and interannual variability of the outflow, we have examined the buoyancy fluxes in the Gulf of Lions (40°–43°N, 2°–8°E approximately). Buoyancy fluxes are not the only ingredient of deep water formation processes, which are also dependent on the horizontal advection [see *Schroeder et al.*, 2006, 2009] and on the circulation pattern during winter, the period of deep water formation. However, they provide a realistic idea of the harshness/mildness of climatic forcing and represent a good proxy of the importance of the WMDW formation processes and, hence, of the volume of deep water formed.

[17] Figure 4 shows the accumulated buoyancy (time integral of the buoyancy flux) per surface unit averaged over the Gulf of Lions from 1988 to 2008. When considering the integral over whole years (white circles) all years before 2002, except 1998, have positive values, suggesting little formation of deep water during that period (in correspondence with the climatic evidence that 90s was the warmest decade on the records) and a negative trend. Accumulated buoyancy losses during winter (October–February, black circles) and during November–January (the "preconditioning phase," gray circles) behaves similarly, although with less marked negative trend. From year 2003 onward, the situation changed and year 2005 (more specifically, winter 2004–2005) exhibited the largest losses regardless the period selected to carry out the integration. Winter 2005–2006 was not as harsh as the previous one but it held a very hard preconditioning phase that finally led to important WMDW formation as well [*Schroeder et al.*, 2008]. These authors suggest a mean rate of formation of 2.4 Sv of very dense WMDW during these two years or, equivalently, 1.5 10^{14} m^3 in this period, which is nearly 1 order of magnitude greater than the historically reported values based on observations of the 1990s decade [*Send et al.*, 1995; *Rhein*, 1995].

[18] The sudden drops of potential temperature in late winter of years 2005 and 2006 showed in Figure 2 would be the signature of the strong events of WMDW formation in winter of these years, as suggested by *García-Lafuente et al.* [2007]. The larger volume of deep water evacuated through Gibraltar in 2006 (bar size in Figure 3c) and its homogeneity (closeness of summer and winter circles, Figure 3c) with respect to the other years should be ascribed to the accumulative effect of those events that filled the bottom of the basin with newly formed WMDW, uplifting old resident deep waters [*Schroeder et al.*, 2008, Figure 3] illustrates this uplifting that started in year 2005). Winter 2006–2007 was very mild (Figure 4) and was followed by the also mild winter of 2007–2008. No formation of WMDW dense enough to reach the bottom is expected under these conditions. Actually the densest water flowing out in winter 2007 had the same density as the one flowing out in summer 2006 (Figure 3c) while the densest waters flowing in summer 2007 and winter and summer 2008 were clearly lighter. The yearly mean of all observations (Figure 3d) shows that the outflow of year 2008 was the less dense observed in the 4 monitored years. An explanation would be the draining of dense water during the previous years that was not replaced by new and dense enough (to reach the bottom) WMDW like that formed in the two previous winters.

6.2. Meteorological Forcing

[19] The daily atmospheric pressure series (p_a) from NCEP data set, averaged over the Western Mediterranean basin, has been decimated by cubic interpolation to generate new series matching the time interval of $\sigma_{\vartheta_{\max}}$ subseries. The tidal-free outflow series has been also subsampled to the same interval to investigate correlations between potential temperature of $\sigma_{\vartheta_{\max}}$ subseries and the outflow. In the following discussion the absolute value of the outflow will be considered in order to get a more intuitive sign of the correlation coefficients of the correlated variables, particularly those involving the outflow. The correlation coefficient is not high, a moderate -0.24 (the greater the outflow, the cooler the water) with the outflow leading the potential temperature by one lag, i.e., 12 h approximately. However, it exhibits marked seasonal fluctuations. Figure 5a shows the correlation computed with series 3 months long (gray circles) and illustrates the existence of an annual cycle that peaks in winter with correlation better than 0.5. Therefore an enhanced outflow, which is basically achieved by increased outflowing velocities (notice that the interface height also participates in the outflow computation), is able to uplift denser, cooler water from Alborán Sea. The short observed delay suits well with a cause-effect relationship.

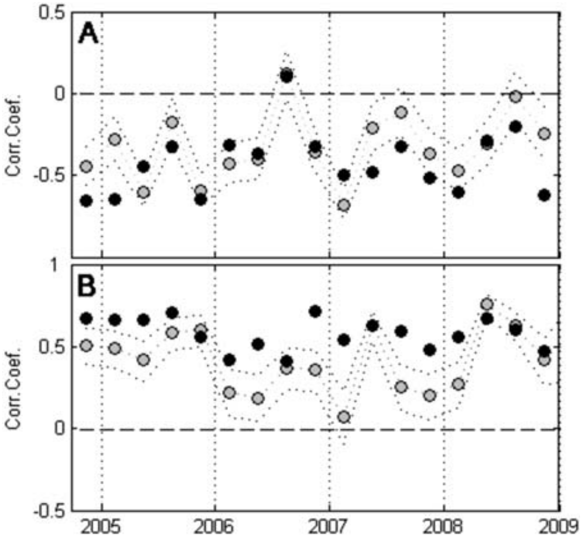

Figure 5. (a) Correlation coefficient between the potential temperature of $\sigma_{\vartheta_{max}}$ subseries and the outflow (Figures 2a and 2d) computed for each season. First circle of each year is for January–March months, second circle of each year is for April–June, third circle of each year is for July–September, and forth circle of each year is for October–December. Grey circles are for the original series, and black circles are for the high-passed component. Dashed lines indicate the lower and upper bounds for a 95% confidence interval of the coefficient of the original series (gray circles). (b) Same as Figure 5a but for the outflow and the averaged atmospheric pressure over the western Mediterranean.

[20] At subinertial timescales, the fluctuations of the exchanged flows are driven by variations of p_a over the Mediterranean basin, particularly over its western basin [*Candela et al.*, 1989; *García-Lafuente et al.*, 2002a]. Outflow and p_a series show poor correlation of around 0.3, indicating that the greater the atmospheric pressure, the greater the outflow. Again the correlation fluctuates throughout the year (Figure 5b) with a tendency to greater values (over 0.5) in winter-spring.

[21] In both cases, correlation increases significantly when considering the high-frequency component of the series. Black circles in Figures 5a and 5b show the correlation of the high-passed series (cut-off frequency 8 day^{-1}) of outflow, ϑ and p_a. The correlation of the whole new series improves to -0.47 in case of Figure 5a and to 0.60 in Figure 5b. As mentioned by *García-Lafuente et al.* [2002b], the inflow/outflow variations only take place when p_a is changing, the faster and greater its variation, the larger the induced change of flows. Typically, the largest p_a variations happen in winter-spring during the passing of atmospheric lows, which lay in the frequency range of few days. Hence the increased correlation of the high-frequency contribution during those seasons. Therefore a second mechanism able to drain denser water out of the Mediterranean in winter-spring would be the mechanical effect of the atmospheric pressure variations acting on the sea surface. Notice the pulsating nature of this mechanism that contrasts with the smoother draining linked to the filling/emptying of the deep water reservoir discussed in section 6.2. Notice also that summer months, with a rather stable and slowly varying p_a, is not a favorable season to trigger this mechanism.

6.3. Circulation in the Upstream (Alborán Sea) Basin

[22] The Mediterranean water flowing out through the strait comes from the Alborán Sea where it has been residing for undetermined time. This section investigates whether or not the strong and recurrent mesoscale features that characterize the Alborán Sea circulation, i.e., the WAG and EAG, may influence the type of water evacuated through the strait and, if so, to speculate about the physical mechanism behind.

[23] The widely used technique of empirical orthogonal function (EOF) decomposition [see, e.g., *Preisendorfer*, 1988] has been applied to the AVISO altimetry data in order to obtain indices describing the variability of WAG and EAG. Figures 6a and 6b show the spatial pattern of the first and second empirical modes, which account for a 42% of the variability in the altimetry series. Mode 1 captures the features of the EAG while mode 2 appears to be the most important contributor to WAG variability. Time coefficients of both modes, which determine the time variability of the associated spatial patterns, are presented in Figures 6c and 6d. Taking into account the sign in Figures 6a and 6b, positive time coefficients would indicate well developed gyres. Potential temperature, salinity and σ_ϑ in the $\sigma_{\vartheta_{max}}$ subseries have been weekly averaged to match the weekly sampling interval of altimetry data and the resulting ϑ series has been plotted in Figures 6c and 6d for comparison. It shows a very good visual correspondence with the opposite of mode 2 coefficients and rather poor with mode 1. Figures 6e and 6f show the lagged correlation between different variables and the coefficients of modes 1 and 2, respectively. For small lags it is only mode 2 that is significantly correlated with the physical variables, all correlations showing a well-distinguishable peak at around +1 week, with mode 2 leading the variables. Correlations are close to -0.6 (0.6) for potential temperature (σ_ϑ), slightly less for salinity, the outflow showing the poorest correlation of 0.27.

[24] The positive lag indicates that a well developed WAG (positive time coefficients of mode 2) leads the observation of cooler, saltier and denser water through ES. Physically, this lag makes sense if we think the WAG itself as a potential source of energy that can be eventually transferred downward to the underlying layer. The presence of the WAG facilitates the drainage of greater volume of cooler water, which must be interpreted in terms of more WMDW contributing to the outflow in detriment of LIW. The mechanism would be that commented in section 3 of transfer of momentum downward from the surface that would be used to accelerate the WMDW vein and help uplift this water above the Gibraltar sills. The peak at 1 week lag is a reasonable cause-effect delay if this explanation applies. On the other hand, the poor correlation between mode 1 time coefficients and the outflow variables suggests that the presence/absence of the EAG has no influence in the outflow variability.

7. Summary and Conclusions

[25] The observations collected at ES exhibit large time variability, the strongest one associated to tides. It must be removed since this work focuses on longer timescales that are relevant for issues related to deep Mediterranean ventilation

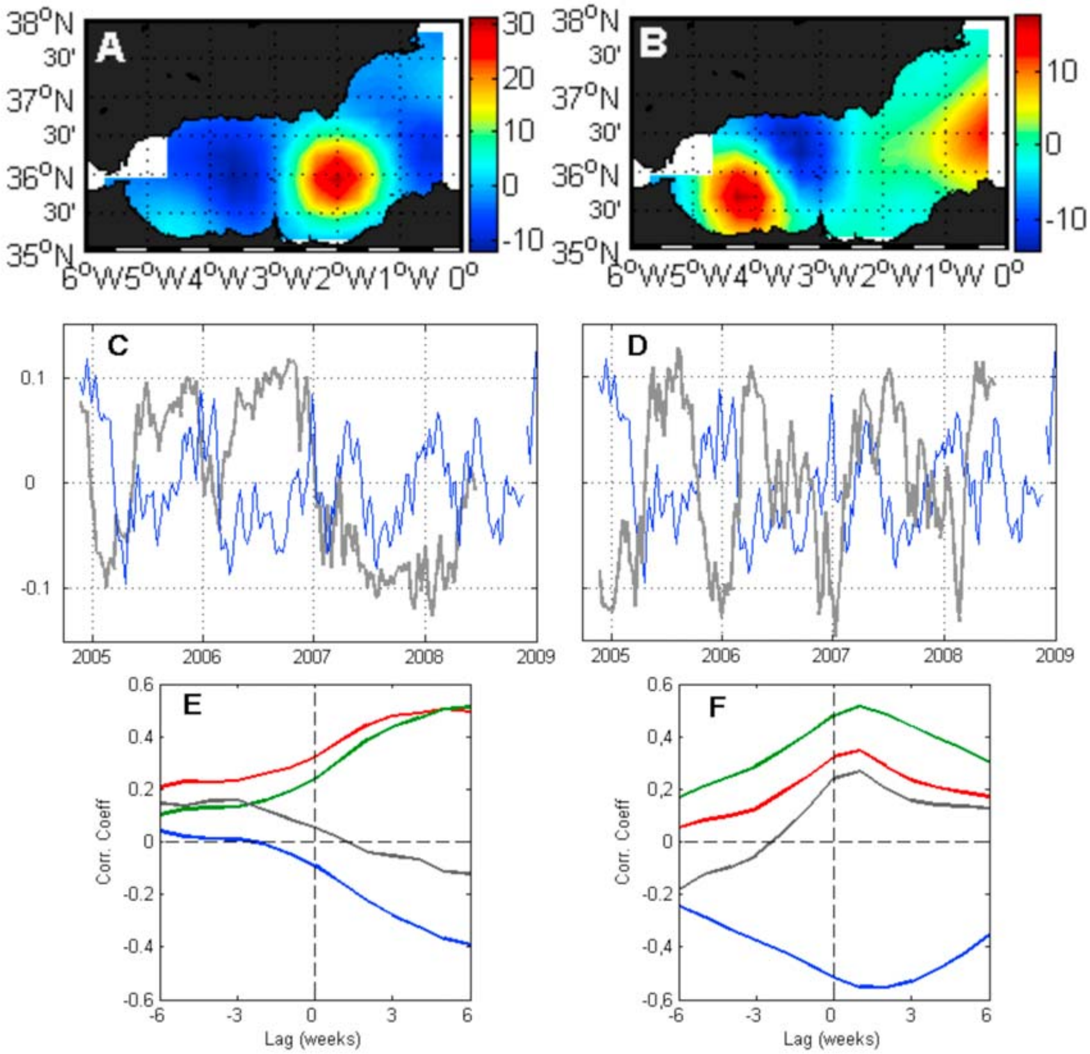

Figure 6. (a) Spatial pattern of the first EOF (mode 1). Units are in cm according to the color scale on the right. (b) Same as Figure 6a but for the second mode. (c) Time coefficients of mode 1 (dimensionless, thick gray line) and weekly averaged potential temperature after removing the mean value (blue line). Altimetry series ends in June 2008; temperatures are showed until the beginning of 2009. (d) Same as Figure 6c but for the time coefficients of mode 2. (e) Lagged correlation between mode 1 time coefficients and potential temperature (blue line), salinity (red line), σ_ϑ (green line), and outflow (black line). Positive lags are for time coefficients leading the other series. (f) Same as Figure 6f but for time coefficients of mode 2.

and renewal of deep waters as well as for studies related to the man-induced (or not) climatic change in the Mediterranean area. The easiest way of removing tidal variability is to select the densest sample of water recorded every tidal cycle and then consider this sample as representative of the water that would have been flowing out in absence of tides. Time series of hydrological variables thus obtained, which are roughly sampled every 12.5 h, are the starting point of the analysis carried out. The series exhibit important fluctuations whose origin has been investigated by examining three candidate driving forces, each of them acting at different timescale.

[26] The first one is the climatic forcing driving the thermohaline circulation of the Mediterranean Sea. In particular, we have focused on the Gulf of Lions area where WMDW is formed in late winter early spring. Using buoyancy losses as a proxy (Figure 4) we have illustrated the harshness of winters 2004–2005 and 2005–2006, which produced a large volume of very dense WMDW that reached the bottom [*López-Jurado et al.*, 2005; *Schroeder et al.*, 2006, 2008; *Font et al.*, 2007; *Smith et al.*, 2008]. Cool pulses of dense water were observed in ES in early spring of 2005 and 2006, which were interpreted as the signature of these formation events, a topic already dealt with by *García-Lafuente et al.* [2007]. These authors also speculate about the lag between the events of WMDW formation and the detection of cool pulses in ES to put forward a delay of few weeks, the time an internal wave propagating at $c \sim 1$ ms^{-1} (a typical speed of mode 1 wave for the winter stratification of the western Mediterranean Sea) will take to move from the Gulf of Lions to Gibraltar. The observed cool signature matches this lag (a short lag for an annual signal indeed) though a more accurate estimation is not possible due to uncertainty on the occurrence of the events of WMDW formation. The outflowing water during these pulses was

likely old resident WMDW uplifted by the denser, newly formed one. The extraordinary volume of water formed these winters [*Schroeder et al.*, 2008] accumulated recent WMDW in the bottom layer and facilitated the drainage of old water, which was flowing out during all year 2006 rather steadily. Next winters of 2006–2007 and 2007–2008 were mild with low buoyancy losses (Figure 4) suggesting a poor production of WMDW, if any. As a consequence, the cool pulses were not observed or, at least, not so clearly. In addition, the outflow of year 2008 (Figures 3c and 3d) consisted of the less dense water observed since the beginning of the monitoring experiment. Surprisingly it was also the year of maximum yearly average outflow because of the strong flow observed that summer. This behavior does not match the theoretical result obtained in the hydraulic theory of maximal two-layer exchange that flows are proportional to the square root of the density difference between layers [*Bryden and Kinder*, 1991]. In any case, an important part of the observed variability in the outflow appears to be directly linked to the climatic forcing over the WMDW formation area.

[27] A second source of variability is the meteorologically driven fluctuations of the flows through Gibraltar. It works at shorter timescale, typically few days coinciding with the pass of atmospheric systems over the basin, and has a pulsating nature when compared with the annual timescale of the climatic forcing. Nevertheless, the strong variance of p_a over the western Mediterranean during winter-spring, associated to the passing of lows, suggests that this mechanism is triggered exclusively during these seasons (see correlations in Figure 5), thus contributing to a quasi-annual signal that would overlap the climatic one. At the end, it acts by uplifting deeper waters due to the increased velocities of the outflow forced by rapid increases of p_a over the western Mediterranean basin [*García-Lafuente et al.*, 2002b].

[28] The third mechanism investigated is the variability of the surface pattern of circulation in the upstream (for the outflow) basin. The Alborán gyres, more specifically the WAG, could influence the outflow in two opposite ways. One intuitive way should be that it hampers the outflow of WMDW (some kind of blocking) if it is fully developed because it penetrates deeper in the basin pushing this water mass downward to a depth from which could hardly be uplifted. This speculation assumes a nonmeridional structure of Mediterranean waters in the Alborán Sea. Actually, this is not true since LIW and, eventually, WIW accumulate and flow in the northern half of the basin while WMDW preferably banks against the African slope. Taking into account this distribution, a second possibility arises that a well developed WAG, whose south branch flows westward at high speed over the WMDW, can transfer momentum and accelerate the WMDW vein, facilitating its drainage. The EOF analysis of altimetry data helps solving this dichotomy suggesting the second possibility as the actual mechanism. It is supported by the fact that mode 2 time coefficients, the mode that captures the WAG, correlate negatively with ϑ and positively with the outflow and with S and σ_ϑ, (Figure 6), indicating that the stronger the WAG, the greater the outflow and the denser/cooler (and hence the deeper) the evacuated water. Therefore, a well-developed WAG influences the proportion of LIW and WMDW in the outflow, which in turn explains part of its variability. The WAG is usually more developed in summer [*García-Lafuente et al.*, 1998; *Vargas-Yáñez et al.*, 2002; *Flexas et al.*, 2006], which favors uplifting of cold WMDW during this season. The recurrent observation of cold water flowing out through ES in summer months (Figure 2) would be connected to this prevailing situation.

[29] The three scenarios have different timescales, from annual in the first case to weekly in the second case (1 week is a representative period for the crossing of atmospheric systems over the area [see *García-Lafuente et al.*, 2002a, 2002b]) to monthly in the last case (one month is a typical period for the WAG to be formed and/or disappear [see *García-Lafuente et al.*, 1998; *Flexas et al.*, 2006]). However, cases two and three are modulated by an annual signal in the sense that the pulsating nature of the atmospheric forcing takes place more often in winter-spring while the permanence of a well developed WAG is typical of summer. Therefore, the three mechanisms contribute to the annual (and, hence, the interannual) observed variability. Their joint contribution depicts a complex pattern of variability from which the individual contributions are not assessed straightforwardly.

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