Interannual salinification of the Mediterranean inflow

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Received 29 June 2007; revised 29 August 2007; accepted 8 October 2007; published XX Month 2007.

[1] Hydrological decadal trends of Mediterranean waters (MWs, e.g., salinification of ~0.01/decade) have been imputed to local environmental changes, hence assuming unchanged inflowing Atlantic water (AW), which is an unchecked hypothesis. To better understand the long-term changes in the sea, an autonomous CTD has been moored, among others, on the Moroccan shelf in the strait of Gibraltar. We show that the inflowing AW salinity displays a marked seasonal variability, due to mixing conditions, and a huge interannual variability, having continuously increased by ~0.05/year in 2003–2007; the AW yearly trend is dozens times larger than the MWs decadal one. The ~0.20 overall salinification being associated with a ~0.12 kg/m^3 densification, reliable data analyses and numerical models dealing with the sea functioning must definitely consider the interannual variability of the inflow. Autonomous CTDs are efficient instruments and the variance criterion is a valuable data selection technique. **Citation:** Millot, C. (2007), Interannual salinification of the Mediterranean inflow, *Geophys. Res. Lett.*, *34*, LXXXXX, doi:10.1029/2007GL031179.

1. Introduction

[2] At seas and oceans scales, the potential temperature (θ) and salinity (S) variability is generally inferred from the statistical analysis of historical ship-based data sets (bottle samplings, CTD and XBT profiles, underway surface records). Local averages (few-degree "lat-lon" space scale, monthly time scale) over years give mean seasonal signals, and linear regressions give decadal (/dec) trends (all trends thereafter are >0). The S trend in the upper Atlantic across 24°N [*Curry et al.*, 2003], as near 20–40°N [*Boyer et al.*, 2005], is ~0.02/dec. Surface S trends in the northeastern Atlantic in the 1980s–1990s reach 0.04/dec, with relatively low values (~0.01/dec) just west of the strait of Gibraltar [*Reverdin et al.*, 2007]. There, the 0–200-m layer of Atlantic water (AW) likely to flow into the Mediterranean Sea is characterized by S ~36.0–36.5, θ ~13.5–20°C and potential density σ ~26.5–27.0 kg/m^3.

[3] In the sea, trends (~0.03°C/dec, ~0.01/dec) of some typical Mediterranean waters (MWs) were hypothetically attributed either to anthropogenic modifications, especially the Nile damming [*Rohling and Bryden*, 1992], or to local climatic changes [*Béthoux et al.*, 1990]. Considering mainly the much larger warming (~0.3°C/dec) of AW off Spain [*Pascual et al.*, 1995], *Millot* [1999] emphasized that this could hardly be due to processes having occurred in the eastern basin only. Both former hypotheses implicitly assuming that AW has had stable characteristics over decades, which had never been verified, *Millot and Briand* [2002] hypothesized that the sea could just be a place convenient for evidencing trends occurring in the upper nearby Atlantic.

[4] Even though decadal linear trends of hydrological parameters generally represent only a few % of the total variance, they must be specified and understood since they are of major importance at human (~decadal) scale and they evidence longer (~secular) scales. Now, links exist between hydrological parameters and societally relevant interannual climatic signals such as NAO for both the Atlantic [e.g., *Reverdin et al.*, 2007] and the sea [e.g., *Rixen et al.*, 2005], and most of the variance occurs at seasonal and lower (meso) scales. To correctly resolve such relatively short time scales, ship-based instruments can nowadays be efficiently complemented by arrays of moored CTDs [e.g., *Delcroix et al.*, 2005].

[5] In the sea, time series from moored CTDs have already provided valuable information [*Fuda et al.*, 2002]. There, to specify the "long-term changes", i.e. changes that are not seasonal and have months-to-years scales [*Millot and Briand*, 2002], such time series are expected to provide descriptions and computations, such as correlations between different places, that will allow in fine a better understanding of the processes. The CIESM Hydro-Changes program was then elaborated (http://www.ciesm.org/marine/programs/hydrochanges.htm) with the leading idea to maintain CTDs in key-places (passages, zones of MWs formation), on short (~10 m) easily manageable sub-surface moorings for 1–2 years (yr) before servicing; CTDs being just a few meters above the bottom, their nominal depth is the bottom depth. Among others [*Fuda et al.*, 2007], two CTDs operated since Jan. 2003 in the strait of Gibraltar (Figure 1) to monitor the in- and out-flows to and from the sea were serviced in Apr. 2004, Nov. 2005 (CTDs replacement) and Mar. 2007. One CTD, set at ~270 m at Camarinal Sill South, has allowed showing that the outflowing MWs have been temporarily warming and salting since the mid 1990s, being in the early 2000s much warmer (~0.3°C) and saltier (~0.06) than ~20 yr ago, a probable consequence of the Eastern Mediterranean Transient [*Millot et al.*, 2006]. The other CTD, set at ~80 m on the Moroccan shelf to monitor the inflowing AW, allows in fact monitoring both the inflow and part of the outflow; major results for the inflow are presented hereafter.

2. Data Analysis

[6] The CTDs (Sea-Bird SBE37-SMs) have sensors flushed before sampling mainly to prevent sedimentation on the conductivity cell. Convenient nominal accuracies (0.002°C, 0.0003 S/m), resolution (0.0001°C, 0.00001 S/m) and stability (0.0024°C/yr, 0.0036 S/m/yr), and a several-year autonomy (1-h sampling) make the deployment duration limited mainly by the mooring resistance. Calibrations made by the manufacturer before Jan. 2003 and after Nov.

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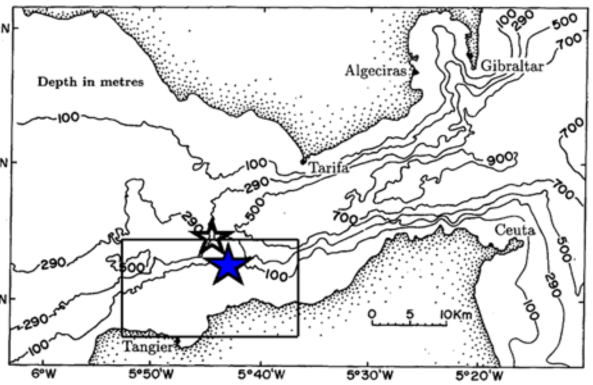

Figure 1. The study area. The blue star locates the 80-m mooring site (35°52.8′N–5°43.5′W), and the empty star locates the 270-m one. The CTD profiles in Figure 2 were acquired in the rectangular zone (35°55′N–35°47′N–5°53′W–5°37′W), mainly north of the site but also as far south as ∼35°50′N.

2005 lead to drifts (+0.000065°C/yr, −0.00036 S/m/yr) much lower than the nominal values (sensors are relatively good); assuming a linear drift during this 33-month period leads to increase the last *S* values by 0.008. Thanks to the short mooring length, the GPS accuracy and the shallow and smooth depth, positions/immersions are easily maintained. The data set is thus very reliable.

[7] Almost no ship-based CTD profiles are available to illustrate the stratification on the shelf near the mooring site. In the vicinity, most of the 275 profiles in the MEDATLAS database [*MEDAR Group*, 2002] were collected during experiments "Lynch-702-86" (70 profiles, Nov. 1985), "GIB1" (106 profiles, early Apr. 1986) and "GIB2" (90 profiles, Sep. 1986; information similar to "Lynch-702-86"). The GIB1 and GIB2 *S*-profiles (Figure S1) show AW and the MWs in the ranges 35.8–36.4 and 38.3–38.4, resp., with the AW-MWs interface at 20–200 m.[1] In stratified conditions (GIB2), *S*(AW) increases from 35.8–36.0 at the layer base to 36.2–36.4 at the surface, and wintertime mixing (GIB1) reduces the *S*(AW) range to 36.10–36.35. Both θ and σ profiles (Figures S2 (θ) and S3 (σ)) are monotonous and more seasonally variable, but all 3 parameters are potentially efficient to separate AW (S < 37, θ > 13.5°C, σ < 28 kg/m^3) from the MWs (S > 38, θ < 13.25°C, σ > 29 kg/m^3). Classically, early spring is more favorable than fall to sample "pure" AW, i.e. to get data representative of an unstratified and unmixed (with the MWs) AW.

[8] The GIB1,2 profiles having been collected within relatively short periods, the 20–200-m displacement of the AW-MWs interface is mainly due to the huge internal tide, so that AW and the MWs can be measured at ∼80 m, most often at different levels within each layer thanks to the tide. The time-series in Figure 2 show that, except during neaps (near d#13) when the tide is mainly diurnal, the CTD clearly samples successively, on a semi-diurnal basis, AW (*S* ∼ 36.0–36.5) and the MWs (*S* ∼ 38.4–38.5; note the ∼0.1 increase from the GIB1,2 data [*Millot et al.*, 2006]). However, data representative of relatively pure AW (or MWs) have to be selected.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL031179.

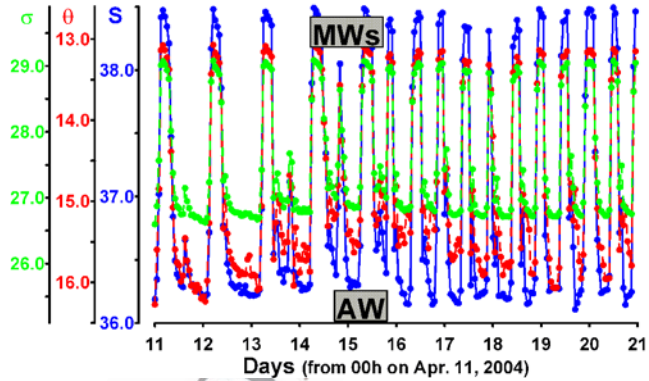

Figure 2. The 10 days of the 1-h *S* (blue), θ (red), and σ (green) time series.

[9] A simple "limit criterion" (e.g., *S* < 36.9) selects ∼24000 (out of 36600) data (Figure 3). This non-objective criterion does not eliminate data indicative of mixing with the MWs, cannot provide any representative mean and gives a biased selection with long-term changes. Nevertheless, the lowest *S* data document the seasonal variability expected from the GIB1,2 data set and display a 50-month overall increase (trend ∼0.033/yr, coefficient of determination r^2∼0.04).

[10] A more objective "tidal criterion" that considers the lowest *S* value during each semi-diurnal (12 h) cycle selects 3050 data. It does not have the limit criterion's defaults and gives a more reliable trend (∼0.046/yr, r^2∼0.22). However, no information is provided about the significance of a

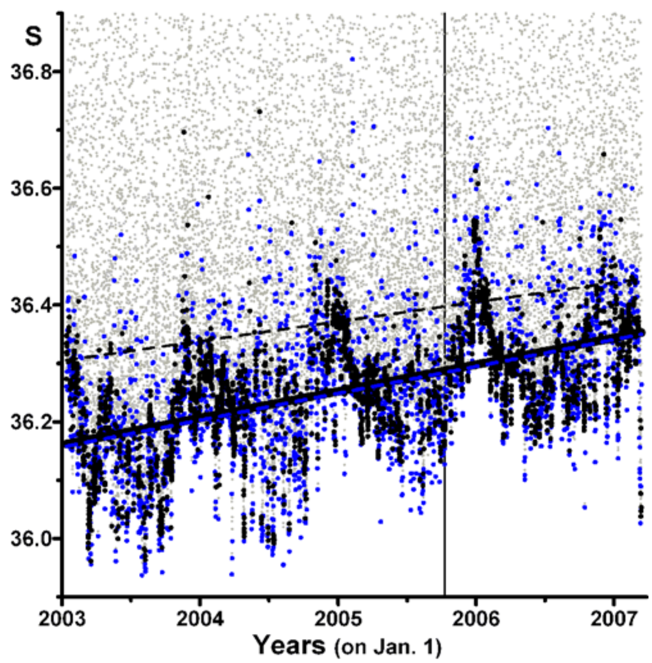

Figure 3. The *S*(AW) selection. *S* data selected with the limit criterion (grey dots; trend: black dashed line), the tidal criterion (blue dots; trend: blue dashed line), and the variance criterion (black dots; trend: black solid line); see text for details. The vertical line specifies the CTD replacement.

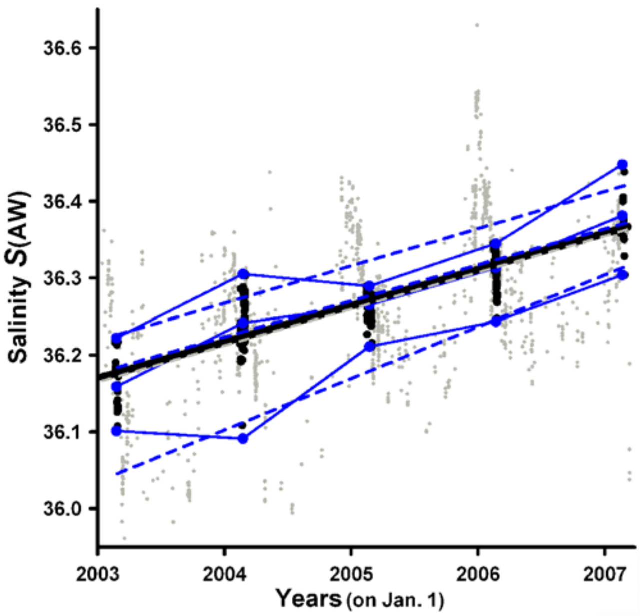

Figure 4. Distribution of the S(AW) data. The 1444 triplets (grey dots; trend: grey dashed line), the 274 triplets during the 5 most favourable Feb. periods (black dots; trend: black solid line), and the minimum $S_{\min}$, mean S_{mean}, and maximum $S_{\max}$ values during each of these periods plotted in the middle of the periods (blue dots connected by solid blue lines; trends: blue dashed lines).

selected data, i.e. whether it represents pure AW, or stratified AW or AW more or less mixed with the MWs. Selecting the "minimum-minimorum" over some given period could provide information on the S minimum value at the AW layer base but, to be reliable, such a representation of pure AW would need a continuous S record (note that all values we measured are > 35.9 while values < 35.9 were measured during GIB2). Also, no information is provided by the tidal criterion about the number of similar data measured during the tidal cycle, which is important since a data representative of a given water must be measured "quite a while".

[11] A selection as objective and informative as possible is made with a "variance criterion" that selects only the data for which the standard deviation (sd), computed with the data before and the data after, is lower than an arbitrary chosen limit that quantifies "homogenization"; data selected in such a way can represent either pure water or water well mixed with others. Choosing a limit larger or lower allows selecting more or less data representative of more or less homogeneous water at one's convenience, but still in a fully objective manner (more arguments and details about the variance technique are given by C. Millot (manuscript in preparation, 2007a)). The same amount of 3050 S data is selected with a sd limit = 0.011399. Even though isolated S minima selected with the tidal criterion, which are actually representative of AW unmixed with the MWs, are missed with the variance criterion, data are distributed over similar ranges and lead to a similar trend ($\sim$0.046/yr, $r^2 \sim 0.29$). To select a data set even more representative of homogeneous AW, not only S but also θ and σ should be considered similarly since all parameters are potentially efficient. To be consistent with the selection from the more-classical tidal criterion, 3050 S, θ and σ data were selected with specific sd limits (0.011399 in S, 0.051456 in θ, 0.013510 in σ). Data for each parameter being selected at possibly different times, simultaneous data form triplets (1444) that sharpen the selection and, being selected in a fully objective manner, form the best set of data representative of relatively homogeneous AW. The trend associated with these 1444 S data is $\sim$0.047/yr ($r^2 \sim 0.30$, Figure 4).

3. Discussion

3.1. Salinification at 80 m

[12] Even though the sd-selected data spread over a relatively wide range and can be encountered all year long, they display a marked seasonal variability (maximum in winter, minimum in summer, amplitude $\sim$0.4). Homogeneous AW is more easily observed in late winter-early spring (Figures 4 and S4): at this time and place, the AW layer is i) not seasonally stratified yet and ii) no more mixed with the MWs as during the winter; the sd-selected data set in early spring-late winter thus provides the most reliable representation of pure AW salinity and is noted S(AW). On average, data/triplets are relatively numerous in late Feb. (Figure S4) so that considering the sole 15-day periods starting on Feb. 15 leads to 24, 59, 105, 70 and 16 triplets (274 in total) for 2003–2007 and a trend of 0.047/yr ($r^2 \sim 0.72$). The mean values for each period (S_{mean}) are 36.159, 36.242, 36.265, 36.313 and 36.381, their trend is still 0.047/yr ($r^2 \sim 0.96$) and the 2003–2007 S_{mean} increase is $\sim$0.22; $S_{\min}$ and $S_{\max}$ trends are similar ($\sim$0.067/yr and $\sim$0.048/yr).

[13] Whatever the criterion, period, parameter and statistical variable used to objectively identify pure AW, the lowest S values have increased, in 2003–2007, by $\sim$0.047/yr, hence by $\sim$0.188; this almost regular/linear increase might have to be considered also (even if possibly lower) during the previous and forthcoming years. All trends being clearly significant (t-test), we retain nominal values of $\sim$0.05/yr and $\sim$0.20 for 2003–2007. If necessary, the S(AW) trend is validated by the S(MWs) data that are spread over a lower range and do not display any significant trend (not shown). Now, how representative of the whole AW layer the 80-m time series is?

3.2. AW Layer

[14] It is known that S variations are forced mainly at the surface so that a S increase in the upper AW layer leads to a σ increase, hence to a de-stratification of the layer (and *vice versa*). As compared to the S data, the θ and σ ones (Figures S5 (θ) and S6 (σ)) a more interannually variable, AW having been relatively warm and light in 2004 and 2007; θ does not display any significant trend while σ increases by $\sim$0.118 kg/m^3 in 2003–2007 (nominal value $\sim$0.12 kg/m^3). A $\sim$0.188 salinification (with $\theta \sim 15.5$°C at 80 m) leading to a $\sim$0.145 kg/m^3 densification, the σ interannual trend mainly results from the S one.

[15] The $S_{\min}$ (36.101, 36.091, 36.211, 36.244, 36.304) and $S_{\max}$ (36.222, 36.305, 36.290, 36.345, 36.448) for the 5 15-day Feb. periods being consistent with the expected ranges, most of the values representative of the AW layer were probably sampled. The interface oscillating at 20–200 m (Figures S1, S2, and S3), i.e. near the 80-m sampling depth,

the lowest values at the layer base necessarily correspond to $S_{\min}$. The upper AW layer non-stratification during such periods suggests that the highest values correspond to $S_{\max}$; but even larger actual maxima necessarily encounter a trend similar to the $S_{\max}$ one (if not, the upper layer would be stratified in winter). The 2003–2007 $S_{\min}$ trend cannot result from the sole mixing/de-stratification of the AW layer (the $S_{\max}$ trend would be < 0), as due for instance to waves amplitude increasing over years. Therefore, the $S_{\min}$, S_{mean} and $S_{\max}$ trends account for a 2003–2007 salinification of the whole AW layer in the study area.

[16] The mooring site is in the central-southern part of the strait, relatively far from the Moroccan coast. AW being more frequent than MWs during neaps (e.g., Figure 2), 80 m is above the mean level of the AW-MWs interface there. Furthermore this interface is sloping down southward so that most AW is found in the southern part of the strait, a 4-year regular trend cannot be specific to the study area and is representative of the whole Mediterranean inflow, hence to the surface water in the nearby Atlantic.

3.3. Consequences for the Sea and the Ocean

[17] Even though this is not a result of our own data analysis, it must first be emphasized that the S decadal trends now available for AW likely to enter the sea [e.g., *Reverdin et al.*, 2007] are similar (~0.01/dec) to those for the MWs within the sea. Because MWs are nothing else than AW transformed by the E-P forcing, decadal trends similar for AW and the MWs account for no major changes in the transformation (contrary to what is usually thought). This supports the former hypothesis [*Millot and Briand*, 2002] that the sea could just be a place convenient for evidencing trends occurring at a much larger scale. Consequently, environmental/transformation changes within the sea could have had an importance in global change much lower than previously thought [e.g., *Johnson*, 1997].

[18] To be noticed is that θ decadal trends of AW and the MWs in the sea can result from a S (in fact σ) decadal trend of AW entering the sea since less wintertime cooling is then needed for AW to reach the critical density that will lead it to sink and be transformed into the MWs. Accurate computations can hardly be made since the AW decadal trends (inferred from relatively few underway surface records) are less significant than the MWs ones (inferred from numerous CTDs profiles, at least for the deep water of the western basin).

[19] Whatever the relationships between the decadal trends in and out of the sea, can the clear S(MWs) decadal trend (over ~4 dec) be related to the clear S(AW) interannual trend (over ~4 yr) that is dozen times greater? The interannual trend cannot be extrapolated to the former decades since S(AW) values in 2003 are close to those in the mid 1980s and before. It might reveal a recent (last years only since no similar interannual trend has been observed yet for the MWs) unique dramatic change in the nearby Atlantic, but we are not aware of any relevant information. It might also reveal a huge permanent interannual S(AW) variability, the 2003–2007 salinification hence having to be somehow compensated by an equivalent (past or forthcoming) freshening in order to match the decadal trends.

[20] The interannual variability being hardly specified with the sole ship-based opportunistic data sets available up to now in both the sea and the ocean, we think it has been largely underestimated and must imperatively be correctly resolved. Additionally, it seems hardly conceivable that reliable data analyses and numerical models dealing with the functioning of the sea and considering the interannual variability of the forcings could avoid taking into account the interannual variability of the inflow characteristics (~0.2 over 4 yr), and its seasonal variability (amplitude ~0.4) as well.

[21] Densification of the AW layer has consequences for the outflow since both strongly mix within the strait [e.g., *Bryden et al.*, 1994]. In addition, contrary to what is generally assumed, all major MWs can be recognized in the outflow and they are less vertically superposed than horizontally juxtaposed, all of them hence mixing with AW (C. Millot, manuscript in preparation, 2007b). Interannual modifications of the inflow thus directly lead to interannual modifications of the whole outflow that should be sensed at the 1000–1200-m Mediterranean level in the Atlantic.

4. Conclusion

[22] Thanks to the internal tide and to the specific conditions in the strait of Gibraltar, a unique CTD moored at 80 m on the Moroccan shelf allows monitoring correctly the hydrological characteristics of both the inflowing AW and the MWs outflowing there.

[23] In 2003–2007, the AW has encountered a huge salinification (~0.05/yr, i.e. ~0.2) together with mainly consequent densification (~0.03 kg/m^3/yr, i.e. ~0.12 kg/m^3). Such an interannual trend cannot be extrapolated to decades but shows how large the interannual variability of the inflow characteristics can be. In addition, AW decadal trend values now available for the nearby ocean being similar to those of the MWs, former hypotheses about the latter only involving changes in the sea as well as their possible consequences at global scale are weakened; the Mediterranean Sea could just be a place convenient for evidencing changes occurring at the surface in the nearby Atlantic.

[24] For the sea, not only studies about hydrological trends but also studies about dense water formation and circulation, which take into account the interannual variability of the forcings, must take into account the interannual variability of the inflow. Due to mixing in the strait, direct consequences for the outflow and the global ocean cannot be ignored too.

[25] Finally, this analysis, together with previous and on-hand ones, account for the reliability of autonomous CTDs and for their efficiency to monitor long-term changes in specific locations. A variance criterion appears to be an efficient and fully objective technique to select data representative of homogeneous water, pure water being then differentiated from water well mixed with others according to scientific knowledge in the study area.

[26] **Acknowledgments.** I thank i) Frédéric Briand, general director of CIESM (Commission Internationale pour l'Exploration Scientifique de la mer Méditerranée), for his consequent and permanent support, ii) Youssef Tber for his enthusiasm in initiating the monitoring there, iii) the SHOMAR (Service Hydrographique et Océanographique de la Marine Royale du Maroc) for its efficient logistics, iv) Jean-Luc Fuda and Gilles Rougier for their help during the servicing, and v) both reviewers. This is

a contribution to the Hydro-Changes CIESM program (http://www.ciesm.org/marine/programs/hydrochanges.htm).

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