# The Western Mediterranean Deep Water: A proxy for climate change

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[1] Reconstructions of Mediterranean ocean temperature fields back to 1950 show a proxy relationship between heat content changes in the North Atlantic and the Western Mediterranean Deep Water (WMDW) formed in the Gulf of Lions in winter, because of consistent air-sea heat fluxes over these areas, strongly correlated to the North Atlantic Oscillation (NAO). **Citation:** Rixen, M., et al. (2005), The Western Mediterranean Deep Water: A proxy for climate change, *Geophys. Res. Lett.*, *32*, L12608, doi:10.1029/2005GL022702.

## 1. Introduction

[2] The oceans act as a buffer in regulating the climate, because of the large heat capacity and mass of water. Natural modes of atmospheric variability such as the NAO [*Hurrell*, 1995], the state of which is described by a pressure difference between the Azores and Iceland, impose wind stress and heat flux on the ocean. The first mode of variability of Sea Surface Temperature (SST) and upper 300 m heat content in the North Atlantic (NA) are positively correlated to NAO [*Masina et al.*, 2004]. In the Mediterranean, sea level changes are linked to the NAO by the combined effect of atmospheric pressure anomalies and changes in the evaporation and precipitation [*Tsimplis and Josey*, 2001]. In the Western Mediterranean (WMED), NAO potentially affects water transport as in the Corsica Channel [*Vignudelli et al.*, 1999]. Conversely, SST in the Eastern Mediterranean [*Luterbacher et al.*, 2004, and references therein] (EMED), and temperature (T) in the Adriatic and the Aegean in the upper layer (0–200 m) [*Tsimplis and Rixen*, 2002] were found to be anti-correlated to NAO. This anti-correlation probably played an important role [*Demirov and Pinardi*, 2002] in establishing the "Eastern Mediterranean Transient"(EMT) [*Roether et al.*, 1996; *Klein et al.*, 2000], when the Aegean took over the deep water production of the EMED from the Adriatic in the early 1990s, involving massive changes in the deep waters and circulation of the Mediterranean [*Malanotte-Rizzoli et al.*, 1999; *Larnicol et al.*, 2002]. In turn, through the exchange between the Mediterranean and the Atlantic Ocean at the Gibraltar Strait, these changes may affect the general circulation in the NA [*Reid*, 1979], which is a major site of dense water formation for the global thermohaline circulation.

## 2. Methods

[3] The Mediterranean can be regarded as a miniature ocean because of many similarities [*Béthoux et al.*, 1999] in processes with the Global Ocean (GO). Yet, little work has been done in providing an integrated picture of T and salinity (S) changes in the Mediterranean [*CIESM*, 2002] because of the absence of a comprehensive hydrographic data set. Following the MEDAR joint effort to rescue, archive and control the quality of Mediterranean and Black Sea data [*MEDAR Group*, 2002], a new climatology was built. Some 291209 T and 124264 S profiles have been quality checked according to international standards and interpolated at 25 standard vertical levels [*MEDAR Group*, 2002]. These data were then interpolated on a 0.2°*0.2° grid by a Variational Inverse Model (VIM) [*Brankart and Brasseur*, 1998]. This approach, statistically equivalent to objective analysis, is numerically more efficient and suitable for the complex Mediterranean geometry [*Rixen et al.*, 2001]. The correlation length and the signal-to-noise ratio have been calibrated by Generalised Cross Validation [*Brankart and Brasseur*, 1998]. Moving temporal Gaussian running windows of 3, 5 and 10 years were used to obtain 3-year, pentadal and decadal variability for each standard level and month. The results for the 3-year running window were only exploited in the WMED, and not in the EMED because of large spatio-temporal gaps in the data distribution, especially before the 1970s. When and where there are only few data, the VIM solution tends towards a climatic background field obtained by a semi-normed analysis [*Brankart and Brasseur*, 1998]. Data closer than 15 km from the coastlines or in areas shallower than 50 m were rejected to avoid biases by coastal processes in the interpolation algorithm. The statistical error maps for individual horizontal fields were obtained from the VIM, by statistical analogy with optimal interpolation [*Rixen et al.*, 2001] and used in a Monte-Carlo approach to derive the vertically averaged T and S error time series. The VIM has been validated against optimal interpolation and simple spatio-temporal box-averaging. These were usually within one error standard deviation of our method, except before the 1970s in the EMED.

## 3. Results and Discussions

[4] Three layers representative of the major water masses in the Mediterranean were considered [e.g., *Robinson et al.*,

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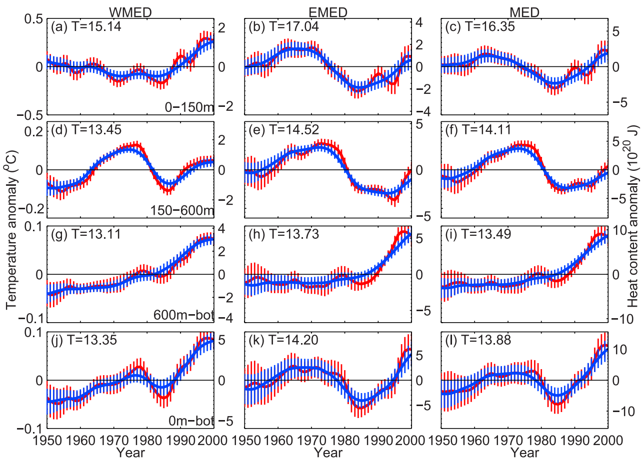


**Figure 1.** Pentadal and decadal variability of temperature for the period 1950–2000 for different areas and water volumes. From left to right: Western Mediterranean, Eastern Mediterranean and entire Mediterranean. Time series of volume mean temperature (°C, left scale) and heat content ($10^{20}$J, right scale) anomalies. From top to bottom: layers 0–150 m, 150–600 m, 600 m-bottom and 0 m-bottom. Running temporal Gaussian windows are 10 years (blue) and 5 years (red). Vertical bars for each yearly estimate represent ±1 error standard deviation. Mean reference temperatures (°C) are shown for each plot.

2001]: the surface layer down to 150 m dominated by the inflow of Atlantic waters, the intermediate layer between 150–600 m dominated by the warm and salty Levantine Intermediate Waters (LIW) formed in the EMED, and a layer below 600 m where cold and dense waters (DW) formed both in the WMED and EMED are found.

[5] Figures 1 and 2 show the time series for the period 1950–2000 of the ocean heat and salt content anomalies and corresponding volume mean T and S anomalies relative to the mean over the same period for the WMED, EMED and entire Mediterranean.

[6] In the surface layer, the WMED T decreases slowly until the mid-1980s then warms significantly (Figure 1a), whereas the EMED undergoes marked cooling between ~1970 and the mid-1980s, then warming again slowly (Figure 1b). Attention is drawn to the strong similarity in shape and magnitude (not shown) between annual sea surface temperature (SST) anomalies in the WMED and in the NA at similar latitude [*Kushnir*, 1994]: their correlation reaches 0.43, statistically significant at 99% (using the 1-year running mean and a common 40 year period). Note also the T drop in both basins in 1991–1992 on the 5 year time series. S increases in the WMED (Figure 2a) from the mid-1960s until the late 1980s when it decreases suddenly. In the EMED (Figure 2b), there is a slow steady increase in S until 1992 after which S decreases.

[7] In the intermediate layer (Figures 1d–1f), in contrast to the surface layer, T in the EMED and WMED has a similar temporal behaviour. The cooling in the EMED that began around 1980 was explained by atmospheric anomalies over the Mediterranean [*Brankart and Pinardi*, 2001]. Thus there is no warming trend at intermediate layers, but only decadal variability. S increases more rapidly in the WMED than in the EMED (Figures 2d and 2e). Previous studies [*CIESM*, 2002] have suggested that the drop in T and the simultaneous slight drop in S in the early 1990s in the EMED may be due to the uplift of fresher and colder Eastern Mediterranean DW during the EMT.

[8] The bottom layer shows a monotonic increase of T in both sub-basins (Figures 1g and 1h), with a sharp increase during the last 15 years. S also increases monotonically in the WMED but oscillates in the EMED. The trends of T and S in the WMDW have been tentatively linked to anthropogenic greenhouse effects [*Béthoux et al.*, 1990], to a decrease in precipitation since the 1940s [*Béthoux et al.*, 1998; *Krahmann and Schott*, 1998], and to man-induced reduction of the freshwater inflow [*Rohling and Bryden*, 1992]. In the EMED (Figures 1h and 2h), T and S strongly increased in the early 1990s, following the EMT [*Theocharis et al.*, 1999]. A recent study [*Josey*, 2003] noted an extreme prolonged period of heat loss in the Aegean in the mid-1970s that is indicative of a potential previous episode of major DW formation [*CIESM*, 2002] in the Mediterranean, as suggested by the strong peak of S around the mid-1970s (Figure 2h). The Western Mediterranean heat (Figure 1j) and salt (Figure 2j) contents increased almost steadily. In the Eastern Mediterranean, where surface temperature is anti-correlated to NAO, no long-term trend is found: the variability has some similarities with the WMED but shows a long term oscillatory pattern.

[9] A general increase of heat and salt content (Figures 1l and 2l), ~[1.3–1.5] $10^{21}$ J and ~[1.4–1.6] $10^{14}$ $m^3$ respectively, occurs over the whole Mediterranean for the period 1950–2000, corresponding to volume mean T and S anomalies of ~[0.09–0.10]°C, and ~[0.035–0.04] respectively, the actual values depending partially on the temporal window. The last decade was probably the warmest during the last 50 years for both the WMED and the whole Mediterranean (>95% confidence level) in agreement with recent findings for the atmosphere at European [*Luterbacher et al.*, 2004] and Mediterranean [*Xoplaki et al.*, 2003] scale.

[10] In Figure 3, we show horizontal plots of vertically averaged T and S differences between periods 1990–2000 and 1960–1970 for each layer. While T and S have

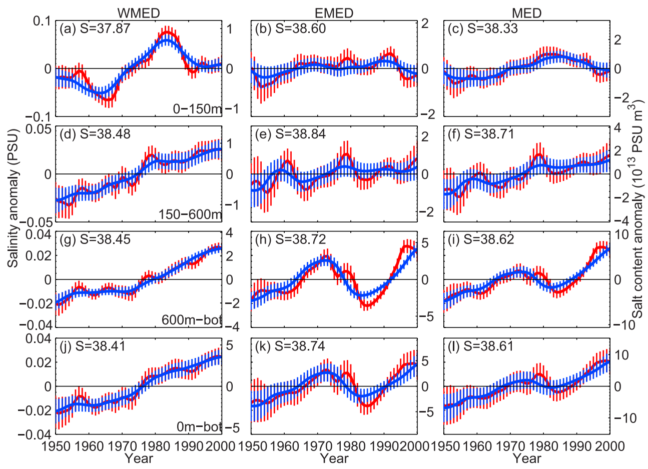


**Figure 2.** Same as Figure 1 but for volume mean salinity (left scale) and salt content ($10^{13}$ $m^3$, right scale) anomalies. Mean reference salinities are shown for each plot.

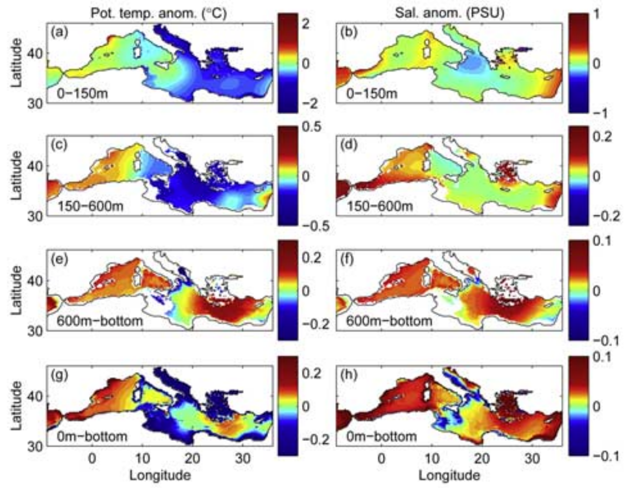


**Figure 3.** Differences between periods 1990–2000 and 1960–1970 of volume mean temperature (°C, left) and salinity (right). From top to bottom respectively: layers 0–150 m, 150–600 m, 600 m-bottom and 0 m-bottom. The periods have been chosen to include and illustrate the major events occurring in both the Western and Eastern Mediterranean.

generally increased in the Mediterranean below 600 m, the T in the EMED has decreased between the two decades in both upper and intermediate layers. In the deep layers, the signal of the EMT is visible from the spreading of warm and salty water in the deeper layers of the EMED (Figures 3e and 3f). These pictures show the difference between the WMED and the EMED T and S anomalies: while the WMED is dominated by salting and warming, the EMED shows the EMT signature in the DW superimposed on cooling of surface and intermediate waters. Thermohaline changes in the Mediterranean are therefore different in the WMED and EMED in the upper and deep layers, except at intermediate depths, where similarities can be found in the dominating LIW water mass.

[11] A mechanistic explanation for the changes in the WMDW can be found by examining the NCEP-NCAR [*Kistler et al.*, 2001] winter (January to March) heat flux reanalyses over the NA and the Gulf of Lions where the WMDW is produced in winter (Figure 4a). The NA heat flux variability is dominated by two opposing contributions: the Labrador Sea with strong heat flux anomalies anti-correlated to NAO (−0.72, >99.99% conf. lev.) and the rest of the NA with more moderate flux anomalies correlated to NAO (0.61, > 99.99% conf. lev.). The resulting total net heat fluxes over the NA remains however positively correlated to NAO (0.32, > 95% conf. lev.) because of the smaller area contribution of the Labrador Sea. In the Gulf of Lions, the heat flux anomalies are very well correlated to NAO (0.48, >99% conf. lev.), which explains some 23% of the variability.

[12] The winter time-integrated NCEP heat fluxes anomalies over the Gulf of Lions (Figure 4b) agree very well with the time series of the MEDAR 3-year temperature anomalies of the WMDW during the period 1960–2000, which in turn agree well with the pentadal (5-year) temperature anomalies of the NA [*Levitus et al.*, 2000, 2005] and corresponding integrated heat flux anomalies over the area. Both WMDW and NA heat content time series show a clear almost steady heating, slightly interrupted during the early 1980s. Similarities between NA, GO and the major oceans heat content changes were already explained by global warming [*Levitus et al.*, 2000, 2005]. Correlations between WMDW and the NA and GO reach 0.81 and 0.74 respectively (both >99% conf. lev. with 10 degrees of freedom). The magnitude of changes in the WMDW is intermediate between the changes of NA and GO. However, the WMDW seems to warm faster during the last 15 years. Results before 1963 for the NA and before 1967 for the Gulf of Lions are less consistent, due to the scarcity of data [*Kistler et al.*, 2001].

[13] The 50-year Mediterranean climatology provides evidence for consistent temperature changes in the WMED and the NA, explained by similarities in the atmospheric heat fluxes anomalies strongly correlated to NAO. The

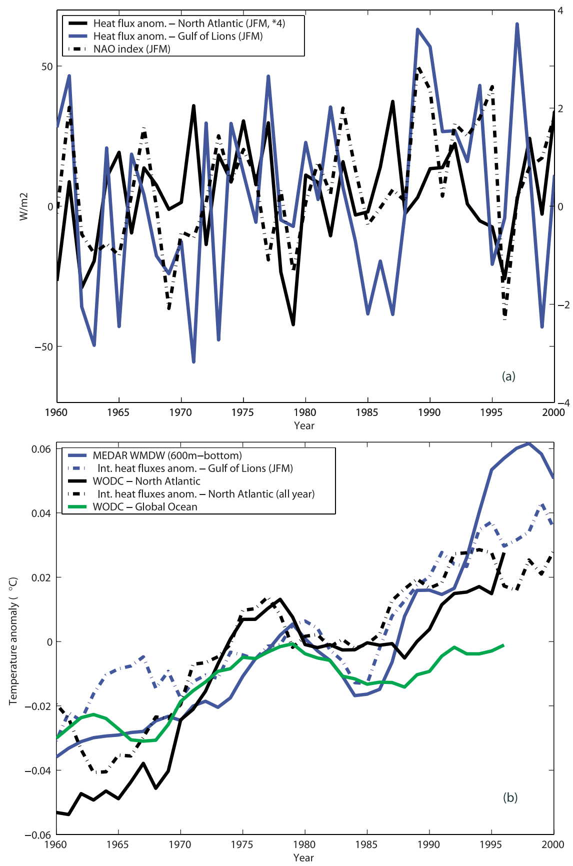


**Figure 4.** Time series of heat flux and temperature anomalies over period 1960–2000. **A** Winter time series (January to March) of NCEP-NCAR heat fluxes anomalies ($W/m^2$, left axis) over the North Atlantic (black, multiplied by 4), the Gulf of Lions (blue) and the corresponding NAO index (right axis, black). **B** Times series of temperature anomalies (°C) of the MEDAR Western Mediterranean Deep Water (3-year running window, blue), the pentadal North Atlantic (black) and the Global Ocean (green), and time integrated NCEP-NCAR heat fluxes over the Gulf of Lions (JFM, dashed blue) and the North Atlantic (all-year, dashed black).

cumulated effect of these anomalies is in very good agreement with corresponding heat content changes in the WMED and the NA. The WMDW and the NA temperature time series have the same trends for the same reason. This suggests that the WMDW (or winter integrated heat fluxes of the Gulf of Lions) may be a new valuable proxy for estimating NA temperature variability, because of its lower sampling cost and easier access. The results also provide some evidence that the influence of the North Atlantic climate over the Mediterranean is stronger than previously thought.

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## References

Béthoux, J. P., B. Gentili, J. Raunet, and D. Tailliez (1990), Warming trend in the Western Mediterranean Deep Water, *Nature*, *347*, 660–662.

Béthoux, J.-P., B. Gentili, and D. Tailliez (1998), Warming and freshwater budget change in the Mediterranean since the 1940s, their possible relation to the greenhouse effect, *Geophys. Res. Lett.*, *25*, 1023–1026.

Béthoux, J., B. Gentili, P. Morin, E. Nicolas, C. Pierre, and D. Ruiz-Pino (1999), The Mediterranean Sea: A miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic, *Prog. Oceanogr.*, *44*, 131–146.

Brankart, J.-M., and P. Brasseur (1998), The general circulation in the Mediterranean Sea: A climatological approach, *J. Mar. Syst.*, *18*, 41–70.

Brankart, J.-M., and N. Pinardi (2001), Abrupt cooling of the Mediterranean Levantine Intermediate Water at the beginning of the 1980s: Observational evidence and model simulation, *J. Phys. Oceanogr.*, *31*, 2307–2320.

CIESM (2002), *Tracking Long-Term Hydrological Change in the Mediterranean Sea*, *CIESM Workshop Ser.*, *16*, 134 pp., Monaco.

Demirov, E., and N. Pinardi (2002), Simulation of the Mediterranean Sea circulation from 1979 to 1993: Part 1. The interannual variability, *J. Mar. Syst.*, *33–34*, 23–50.

Hurrell, J. W. (1995), Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitations, *Science*, *269*, 676–679.

Josey, A. S. (2003), Changes in the heat and freshwater forcing of the Eastern Mediterranean and their influence on deep water formation, *J. Geophys. Res.*, *108*(C7), 3237, doi:10.1029/2003JC001778.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.

Klein, B., W. Roether, G. Civitarese, M. Gacic, B. Manca, and M. D'Alcala (2000), Is the Adriatic returning to dominate the production of Eastern Mediterranean deep waters?, *Geophys. Res. Lett.*, *27*, 3377–3380.

Krahmann, G., and F. Schott (1998), Longterm increases in Western Mediterranean salinities and temperatures: Anthropogenic and climatic sources, *Geophys. Res. Lett.*, *25*, 4209–4212.

Kushnir, Y. (1994), Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions, *J. Clim.*, *7*, 141–157.

Larnicol, G., N. Ayoub, and P. Le Traon (2002), Major changes in Mediterranean Sea level variability from seven years of TOPEX/Poseidon and ERS-1/2 data, *J. Mar. Syst.*, *33–34*, 63–89.

Levitus, S., J. I. Antonov, T. P. Boyer, and C. Stephens (2000), Warming of the world ocean, *Science*, *287*, 2225–2229.

Levitus, S., J. I. Antonov, and T. P. Boyer (2005), Warming of the world ocean, 1955–2003, *Geophys. Res. Lett.*, *32*, L02604, doi:10.1029/2004GL021592.

Luterbacher, L., D. Dietrich, E. Xoplaki, M. Grosjean, and H. Wanner (2004), European seasonal and annual temperature variability, trends and extremes since 1500, *Science*, *303*, 1499–1503.

Malanotte-Rizzoli, P., B. B. Manca, M. Ribera d'Alcalà, A. Theocharis, A. Brenner, G. Budillon, and E. Ozsoy (1999), The Eastern Mediterranean in the 80s and in the 90s: The big transition in the intermediate and deep circulations, *Dyn. Atmos. Oceans*, *29*, 365–395.

Masina, S., P. Di Pietro, and A. Navarra (2004), Interannual-to-decadal variability of the North Atlantic from an ocean data assimilation system, *Clim. Dyn.*, *23*, 531–546.

MEDAR Group (2002), *Mediterranean and Black Sea Database of Temperature, Salinity and Biochemical Parameters and Climatological Atlas* [4 CD-ROMs], Ifremer Ed., Plouzane, France. (Available at http://www.ifremer.fr/sismer/program/medar/)

Reid, J. (1979), On the contribution of the Mediterranean Sea outflow to the Norwegian-Greenland Sea, *Deep Sea Res., Part A*, *26*, 1199–1223.

Rixen, M., J.-M. Beckers, J.-M. Brankart, and P. Brasseur (2001), A numerically efficient data analysis method with error map generation, *Ocean Modell.*, *2*, 45–60.

Robinson, A., W. Leslie, A. Theocharis, and A. Lascaratos (2001), Mediterranean Sea circulation, in *Encyclopedia of Ocean Sciences*, vol. 3, pp. 1689–1705, Elsevier, New York.

Roether, W., B. Manca, B. Klein, D. Bregant, D. Georgopoulos, V. Beitzel, V. Kovacevic, and A. Luchetta (1996), Recent changes in Eastern Mediterranean deep waters, *Science*, *271*, 333–335.

Rohling, E., and H. Bryden (1992), Man-induced salinity and temperature increases in the Western Mediterranean Deep Water, *J. Geophys. Res.*, *97*, 11,191–11,198.

Theocharis, A., K. Nittis, H. Kontoyiannis, E. Papageorgiou, and E. Balopoulos (1999), Climatic changes in the Aegean Sea influence the Eastern Mediterranean thermohaline circulation (1986–1997), *Geophys. Res. Lett.*, *26*, 1617–1620.

Tsimplis, M. N., and S. A. Josey (2001), Forcing of the Mediterranean Sea by atmospheric oscillations over the North Atlantic, *Geophys. Res. Lett.*, *28*(5), doi:10.1029/2000GL012098.

Tsimplis, M., and M. Rixen (2002), Sea level in the Mediterranean: The contribution of temperature and salinity changes, *Geophys. Res. Lett.*, *29*(3), 2136, doi:10.1029/2002GL015870.

Vignudelli, S., G. Gasparini, M. Astraldi, and M. Schiano (1999), A possible influence of the North Atlantic Oscillation on the circulation of the Western Mediterranean Sea, *Geophys. Res. Lett.*, *26*, 623–626.

Xoplaki, E., F. J. Gonzalez-Rouco, J. Luterbacher, and H. Wanner (2003), Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs, *Clim. Dyn.*, *20*, 723–739, doi:10.1007/s00382-003-0304-x.

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