Scientific Report – ESF Exchange Grant 2008

Mediterranean Climate Variability and Predictability (MedCLIVAR)

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Applicant's name: Dr. Katrin Schroeder

Project Title: Concurrent effects of the atmospheric forcings and the EMT propagation on the new salty and warm deep water observed in the Western Mediterranean

Applicant's Institution: CNR-Institute for Marine Sciences, Pozzuolo di Lerici, Italy

Host Institution and Supervisor: National Oceanography Centre, Southampton, United Kingdom. Prof. Harry L. Bryden (H.Bryden@noc.soton.ac.uk)

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Scientific Report – ESF Exchange Grant 2008

Mediterranean Climate Variability and Predictability (MedCLIVAR)

This project was proposed for the ESF-MedCLIVAR grants to support the scientific visit of Dr. Katrin Schroeder, Postdoc research fellow in the CNR Institute for Marine Sciences of La Spezia (Italy), for spending 16 weeks at the National Oceanography Centre in Southampton (United Kingdom), in the Ocean Observing and Climate Research Group.

Purpose of the visit

The aim of the study carried out during my visit in Southampton was to investigate the causes of a recent abrupt change in the deep heat and salt contents of the western Mediterranean Sea (WMED), which has been originated during two convective events, in winter 2004/2005 and in winter 2005/2006. The new anomalous deep water has modified the deep vertical stratification. The relations of the observed abrupt change with atmospheric forcings as well as with long-term trends in the intermediate water properties have been investigated, in order to give a better insight on the Mediterranean dynamics and feedback mechanisms. To understand to which extent the propagation of the Eastern Mediterranean Transient (EMT) from east to west is responsible for the abrupt salting and warming of the deep WMED, is of fundamental importance in this context. The observed changes and their explanation could provide a starting point for the assessment of the possible repercussion of the Mediterranean dynamics on other regions, such as the Atlantic Ocean. The project falls within one of the main MEDCLIVAR scientific objectives, which is to understand the mechanisms responsible for the long-term as well as abrupt changes of water mass characteristics, for variability of dense water formation processes and of vertical stratification in the Mediterranean Sea.

Several studies have revealed the abundant formation of a new anomalously warm and salty Western Mediterranean Deep Water (WMDW) during winters 2004/2005 and 2005/2006. This new WMDW is characterized by a peculiar stratification, suggesting the presence two new deep water masses (probably formed by either open-ocean and on-shelf convection), interacting with the ambient water. In the abyssal plain of the Western Mediterranean Sea (WMED), the new deep water showed temperatures of 12.85 - 12.88 °C and salinities of 38.455 - 38.473 below 2000 m depth. The layer it occupies has become several hundreds of meters thicker, with total increases of salinity and temperature of

ΔS=0.024 and Δθ=0.042 °C, respectively, near the bottom of the example station shown in Figure 1 (south of the Balearic Islands, at 5 °E, 38 °N).

If the exceptionally severe conditions of winter 2004/2005 were responsible for the huge deep water production, its anomalous properties can be related to a progressive increase of heat and salt content in the intermediate layer. The intermediate salt and heat accumulation is likely to be due to the arrival of water of eastern origin affected by the Eastern Mediterranean Transient (EMT) event, which took place in the Eastern Mediterranean Sea between the late 1980s and mid 1990s.

The proposed project aimed to determine the relative contribution of the atmospheric forcing (air-sea heat and freshwater fluxes) and the advection of anomalously salty and warm intermediate water to the convection region, in causing the massive renewal of the WMDW and determining its thermohaline properties.

The work is based on previous studies presented at the 3rd ESF-MedCLIVAR Workshop (Schroeder et al.2008a).

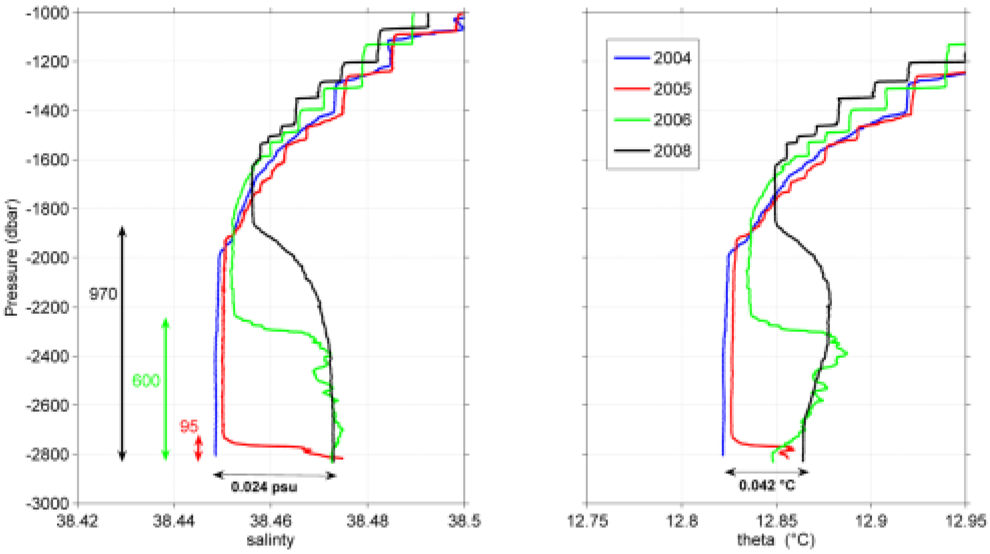


Figure 1: Vertical profiles of salinity and potential temperature measured at an example station in the Algerian basin (5 °E, 38 °N) in October 2004 (blue), June 2005 (red), October 2006 (green) and November 2008 (black). The vertical arrows indicate the thickness of the layer occupied by the nWMDW in the different years, while the black horizontal arrows indicate the total salinity and temperature increase at the bottom between 2004 and 2008.

Description of the work carried out during the visit

During the 16 weeks of the visit, I focused my work on analyzing observations and air-sea fluxes datasets with the aim of supporting the above mentioned hypotheses.

During the first weeks I have carried out a preliminary programming work, in order to access, read, plot and manipulated the air-sea flux data from the NCEP/NCAR reanalysis dataset and the NOC climatological fields. The routines have been written in MATLAB. At the same time, I completed the bibliography related to this project.

After the determination of the fields of air-sea fluxes (heat, freshwater and density fluxes) above the north-western Mediterranean, from the NOC climatology and the NCEP/NCAR reanalysis dataset, we realized that both datasets may have a too coarse spatial resolution to compare the influences of atmospheric forcings and lateral advection. The following weeks have therefore been spent in involving researchers from the Centre National de Recherche Météorologiques, CNRM/Météo-France in the project, with the aim of having access to a dynamical downscaling of the ERA-40 air-sea fluxes. The resolution of this downscaled dataset is 50 km in the Mediterranean area. The involved researchers were Dr. Samuel Somot and Dr. Marine Herrmann, who is also participating in a resulting manuscript.

With the use of the high-resolution fields, I have set up a way to quantitatively assess the contribution of heat/freshwater losses and the anomalous lateral advection of heat/salt in determining the warming and salting of the new deep water. The work has been completed using values for a specific grid point, but is still in progress since I want to try different types of averages, to evaluate the sensitivity of the calculation.

The last weeks of my visit have been spent in analyzing long-term heat and salt contents trends in a station located just upstream the convection area, with the specific aim of assessing if the hypothesized values for lateral heat/salt advection to the convection area are realistic and consistent with hydrographic observations.

Further activities during my visit have included a seminar that I held for the Ocean Observing and Climate Research Group of the NOC, a seminar held at the Imperial College of London, a practical lesson for the Master Course “Introduction to Physical Oceanography” (Prof. H.L. Bryden), about the analysis and the identification of water masses. During the first weeks I attended also the Medclivar Summer School, where I have held the same practical lesson about water masses, and the 3rd Medclivar Workshop in Rhodes (Greece).

Description of the main results obtained

Data Set and Methods

Recently the Italian National Research Council (CNR) has conducted several surveys in the north-western Mediterranean Sea, with the R/V Urania (see composite map in Schroeder et al., 2008b). For the purpose of this study we have used only few CTD stations: the station shown in Figure 1 (south of the Balearic Islands, at 5°E, 38°N, visited in October 2004, June 2005, October 2006 and November 2008), in order to illustrate the temporal evolution of the new deep properties and stratification; and station Lx in the Gulf of Lions (visited in April 2005), shown in Figure 2 (red dot). Pressure, salinity, potential temperature and dissolved oxygen were measured with a CTD SBE 911+. The probes were pre- and post-calibrated at the NATO Undersea Research Centre in La Spezia (Italy). During the cruise CTD salinity measurements were checked against samples analysed with a Guildline Autosal salinometer.

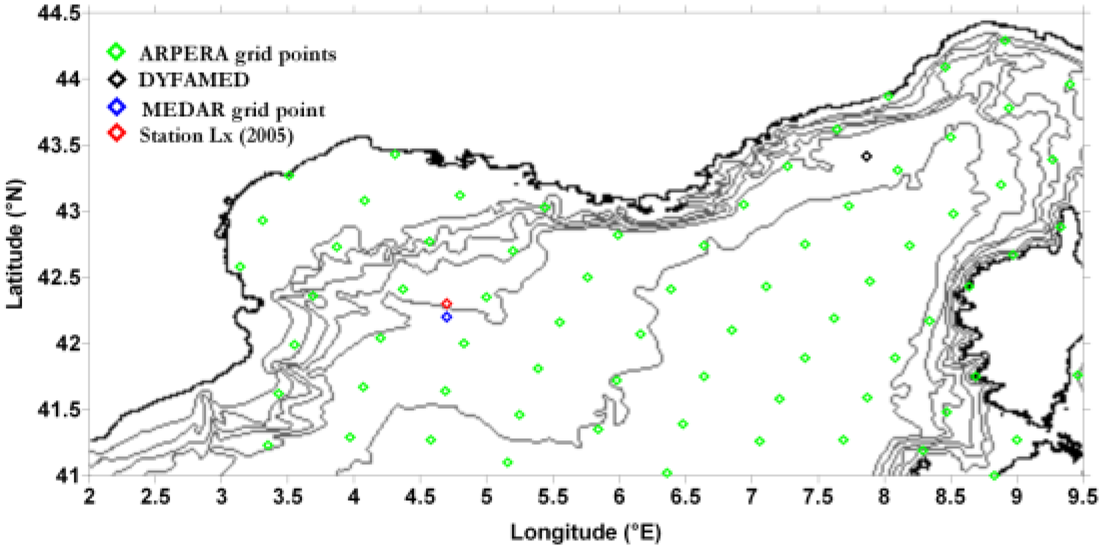


Figure 2: Map

CTD data collected almost every month by the Observatoire Océanologique de Villefranche sur Mer Service d'Observation (http://www.obs-vlfr.fr/sodyf/home.htm) at the DYFAMED site (Figure 2), were used to observe the temporal evolution of salinity and potential temperature in the Ligurian Sea, for the period 1995-2007.

Finally, we used data from one grid point of the MEDAR/MEDATLAS II dataset (MEDAR Group, 2002). This dataset was produced from observations that were quality controlled and interpolated onto a regular spatial grid. The processing is described at http://modb.oce.ulg.ac.be/backup/medar/medar.html. Climatological data, which we use here, can be downloaded for the whole Mediterranean, with a vertical resolution of 5 m near the surface to 500 m at the bottom. We have used the annual average profile of temperature and salinity corresponding to the Gulf of Lions at 42.2 °N and 4.7 °E (Figure 2). For the air-sea fluxes analysis we used the ARPERA, a dynamical downscaling of the ERA-40 fields, which grid points in the study area are shown in green in Figure 3.

Forcings during the recent winters

Air-sea fluxes: heat, freshwater and buoyancy

First of all, the climatology of the air-sea fluxes terms were defined, using the NOC climatology. In Figure 3 the following long-term means are shown for the months November-March: net heat (Q_{net}), net evaporation (E-P), latent heat (Q_E), shortwave (Q_{SW}), evaporation (E), precipitation (P), atmospheric specific humidity (q_a) and wind stress (Tau).

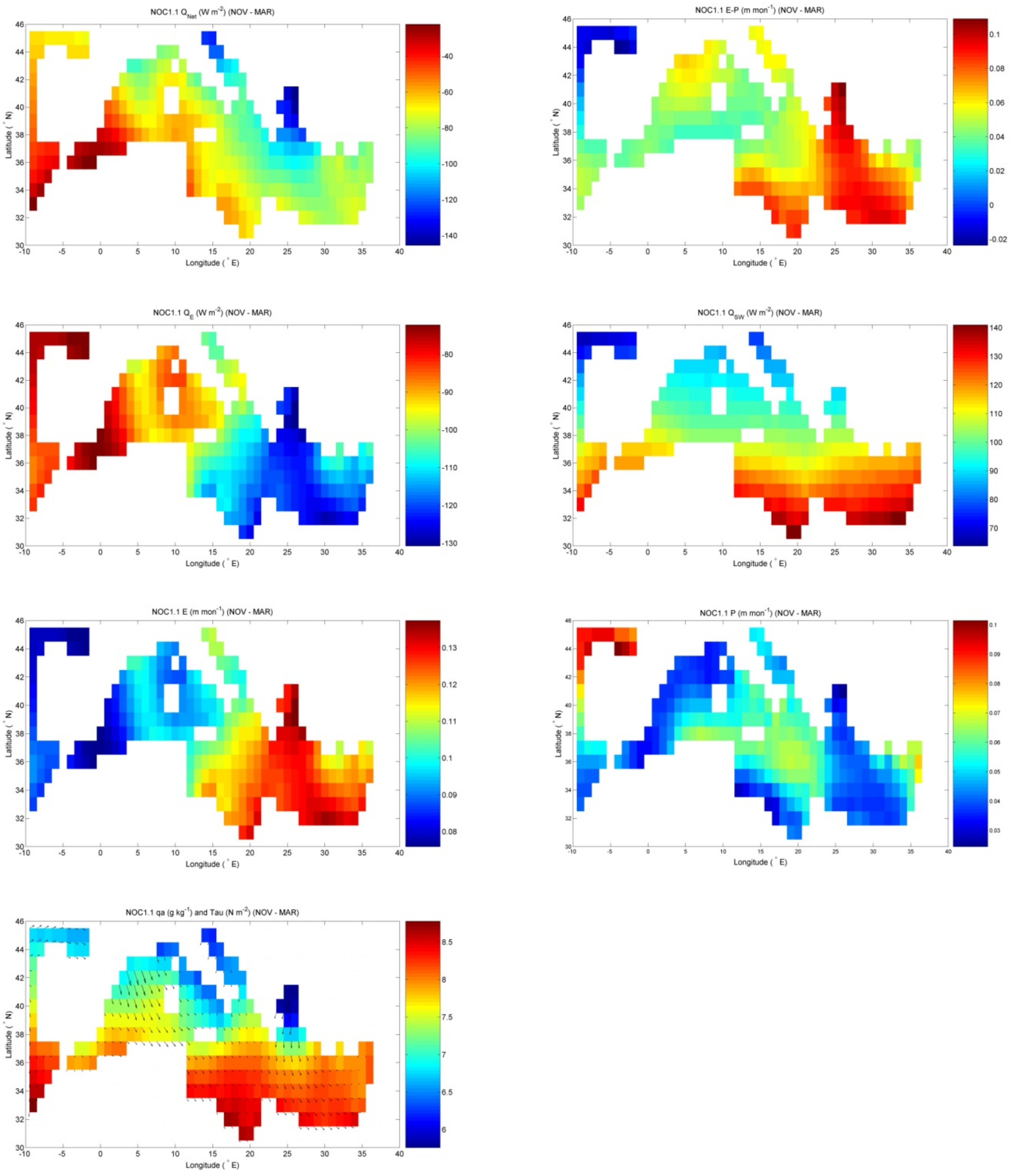


Figure 3: Climatological fields of air-sea fluxes terms.

The winter 2004/05 was particularly severe, with very strong north-west winds, as exemplified in Figure 4, showing the monthly wind field in January 2005, from the NCEP reanalysis dataset. The very strong Mistral wind, which is the most important factor controlling the deep convection in this area is clearly evident.

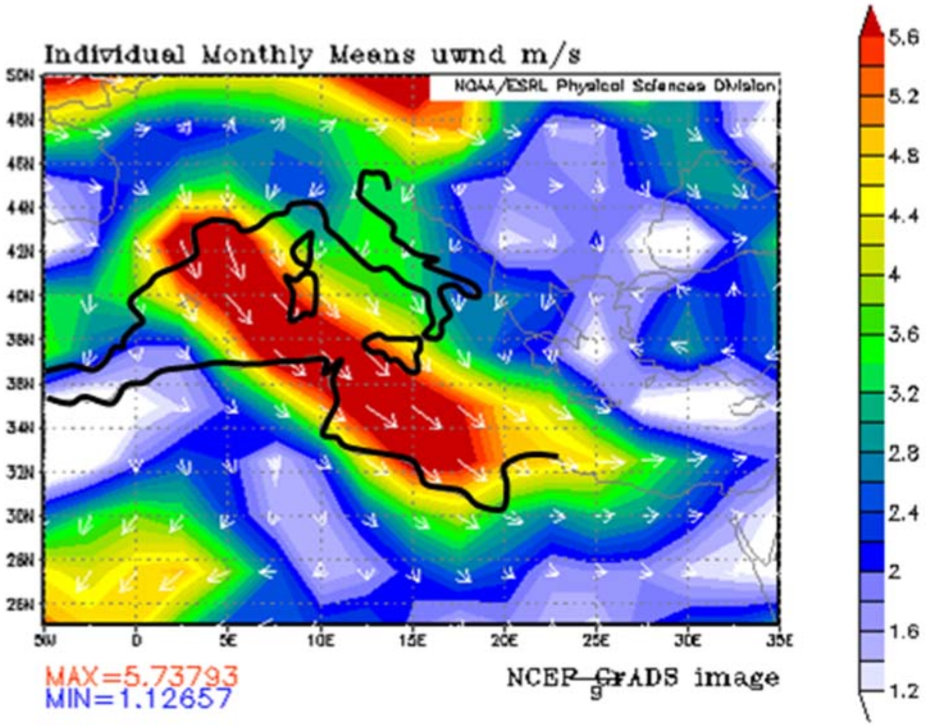
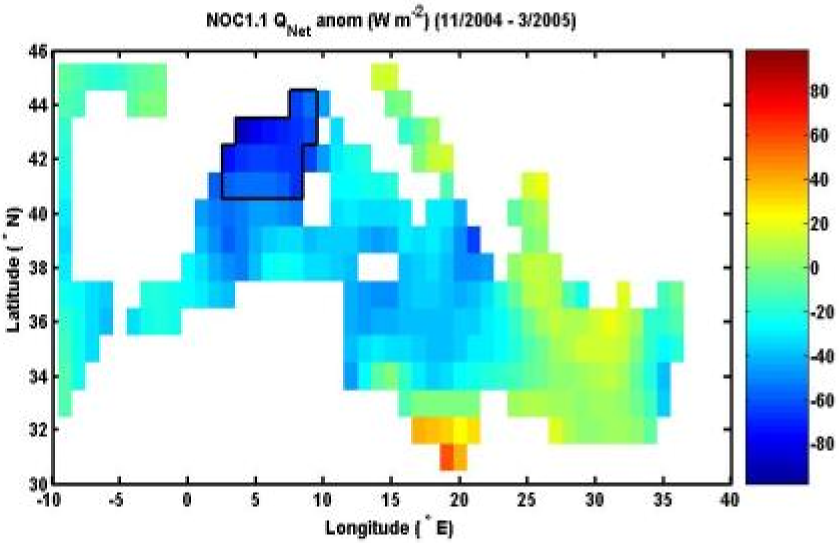


Figure 4: Wind field in January 2005, from NCEP/NCAR

If we take a look at the fields taken from the NOC climatology and compute the anomalies of the net heat loss and the evaporation during winter 2004/2005 (November 2004 - March 2005), we will see that the this winter was very severe, in terms of atmospheric forcings, with strong heat loss from the ocean to the atmosphere and strong evaporation, mostly due to the wind field showed in Figure 4.



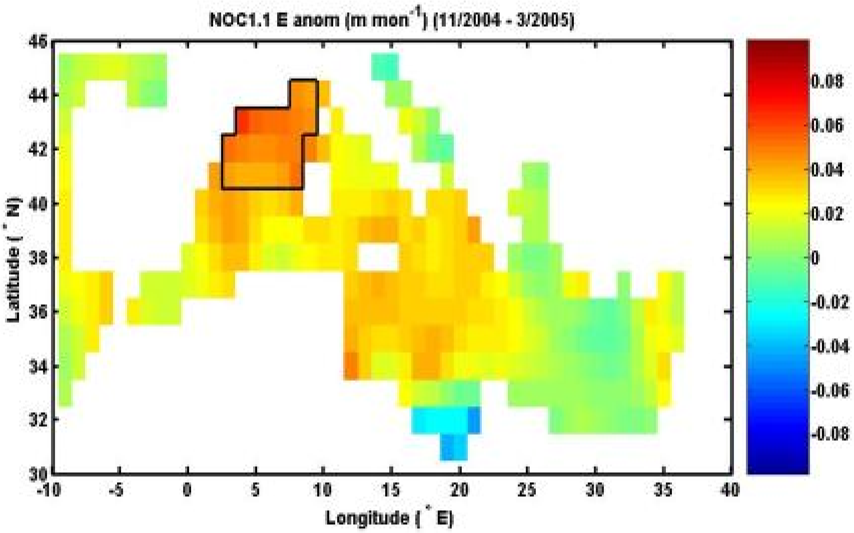


Figure 5: Net Heat and Evaporation anomalies during winter 2004/2005.

The combined impact of the net heat flux and evaporation on the buoyancy of water in the sea surface layer is expressed in terms of the density flux following the analysis of Schmitt et al. (1989). The total density flux, F_ρ, into the ocean surface is given by the following equation:

$$F_\rho = -\rho\left(\alpha \frac{Q_{Net}}{\rho c_P} - \beta S \frac{E-P}{(1-S)}\right) = F_T + F_S$$

where ρ is the density of water at the sea surface, c_P is the specific heat capacity of water, and S is the sea surface salinity. The terms α and β are the thermal expansion and haline contraction coefficients, respectively. For the purpose of the analysis, the density flux is split into thermal, F_T, and haline, F_S, contributions. I have computed the daily density fluxes in the convection area for the two winters (2004/05 and 2005/06), represented in Figure 6, distinguishing between the two terms F_T and F_S. In winter 2004/2005 we see at least 4 events where the density exceeded this threshold of $3 \cdot 10^{-5}$ kg m^{-2} s^{-1}, while during winter 2005/2006 there were only two events that reached the same threshold. In both cases we may note that the net evaporation, that means the haline term in the equation, has a weaker impact on the total density flux, than the heat loss, which is given by the thermal term.

NCEP/NCAR reanalysis data set is used to place the severe air-sea flux anomalies that occurred in the north-western Mediterranean Sea in winter 2004/05 in the context of the forcing over the longer 60-year period from 1948 to 2008. Figure 7 displays the anomalous winter net evaporation and net heat fluxes in the convection area from 1948 to 2008. We see that the winter 2004/2005 was characterized by the highest anomalies in both terms since 1948, with a net E-P anomaly higher than 0.05 m/month and a net heat loss anomaly higher than 80 W/m^2. The following winter, when there was deep water production as well, was not that severe, and the anomalies were of the order of 0.01 m/month for net evaporation and 50 W/m^2 for the net heat loss.

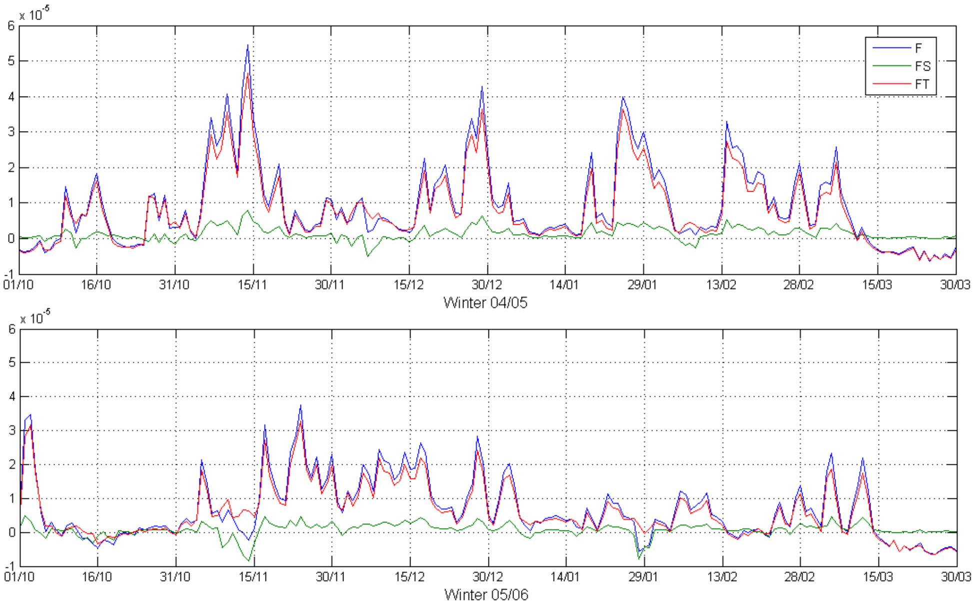


Figure 6: Daily density fluxes (in kg m^{-2} s^{-1}) during the two winters.

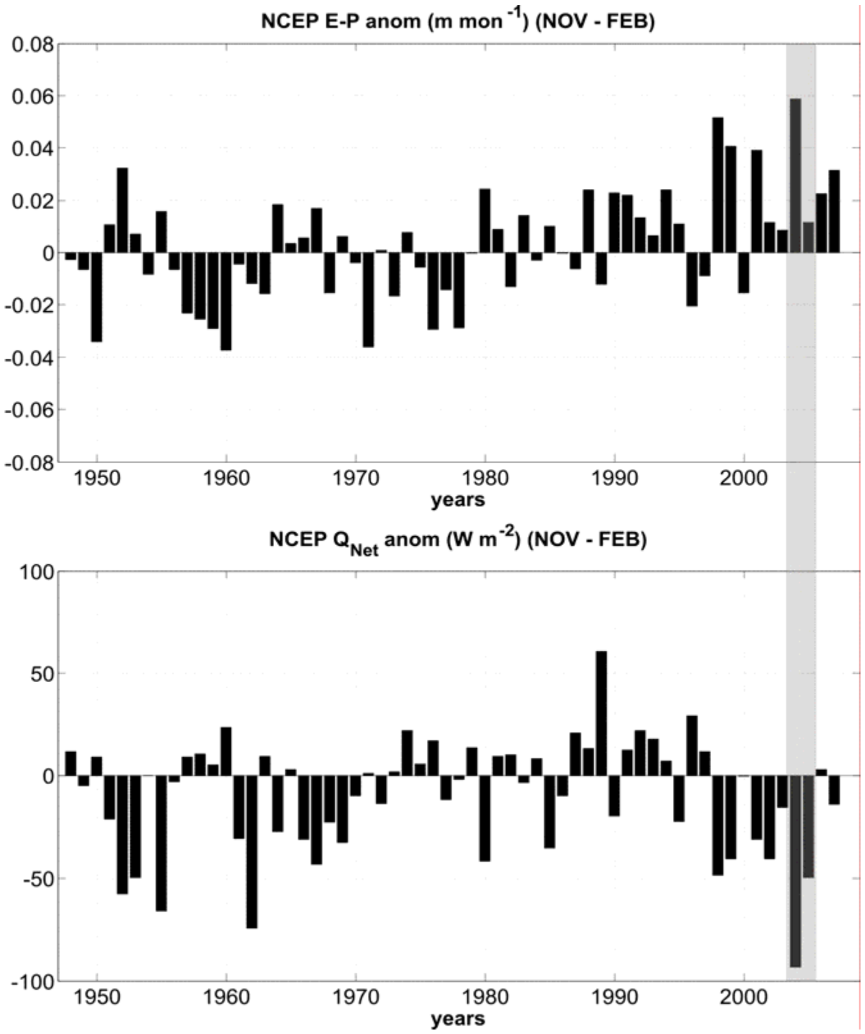


Figure 7: Anomalous winter (NDJF) net evaporation and net heat flux in the north-western Mediterranean Sea for NCEP/NCAR for 1948–2008. Year values refer to the year in which the January of each winter occurs.

Hydrographic conditions

Until 2004 the heat and salt contents of the water column just upstream of the convection area (represented by the DYFAMED station, see Figure 2) has significantly increased (Schroeder et al., 2006). The temporal variability of the hydrographic properties of the salinity maximum (representative for the LIW core) at this site are shown in Figure 8: both temperature and salinity seem to have reached maximum values during 2004, i.e. the year before the first anomalous DWF occurred.

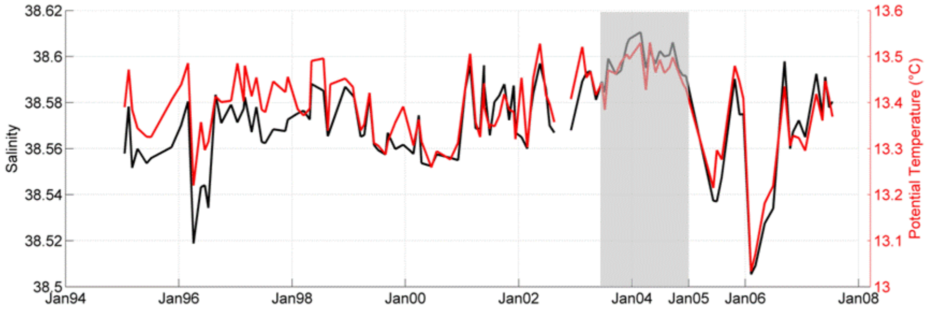


Figure 8: Temporal evolution of the mean salinity (black) and temperature (red) at the Dyfamed station in the LIW core (salinity maximum).

During winter 2004/2005 deep convection occurred mainly in the Gulf of Lions and in the Catalan subbasin. These sites may have received by lateral advection a higher amount of salt and heat before the onset of convection. The winter 2005/2006 has shown deep convection just in the area of the DYFAMED station, and the CTD casts of the beginning of 2006 reveal it (Figure 9). The December cast shows a quite clear stratification and the differences between surface, intermediate and deep layers are well evident. On the other hand, the February profile is almost completely homogeneous, from the surface to the bottom at a constant density of 29.1 kg m^{-3}. This feature suggest the occurrence of convection down to the bottom at the DYFAMED site, giving an indication on its timing as well: the event has taken place at some moment between the 19th December and the 7th February. Using Argo floats, Smith et al. (2008) hypothesized a DWF event in the Ligurian Sea somewhat later, between 26th February and 8th March 2006, but this may depend on the position of the floats during that period.

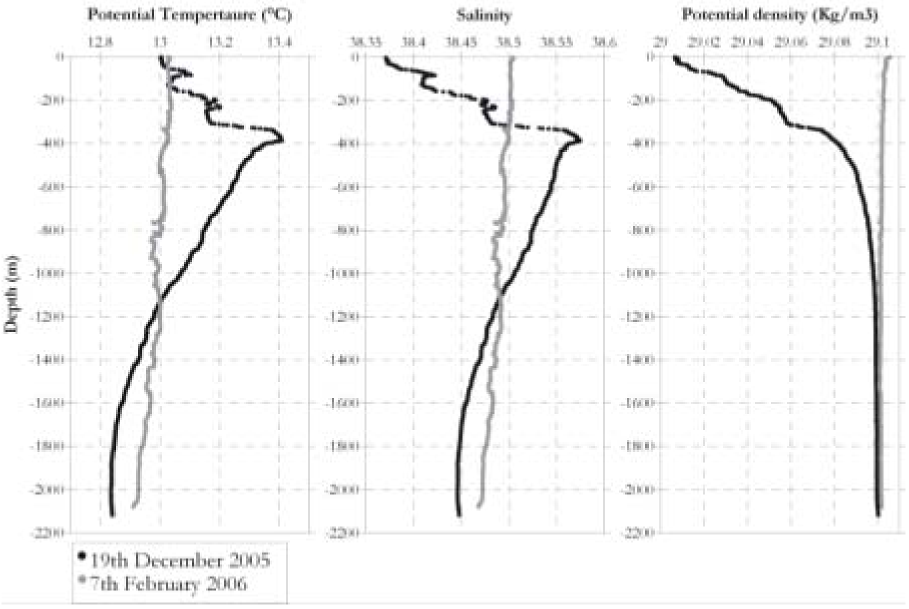


Figure 9: Vertical profiles of potential temperature, salinity and potential density at the Dyfamed station using two consecutive CTD casts: in December 2005 (black) and in February 2006 (grey).

The stratification of the water column is expected to determine if deep convection may occur as well as the intensity of the convection itself. In Figure 10 the mean buoyancy frequency for three layers in the DYFAMED site from January 2002 to July 2007 is plotted. To try to separate the effects of temperature and salinity on N^2, we superimpose N^2_{temp}, that is the buoyancy frequency at a constant salinity of 38, and N^2_{sal}, i.e. the buoyancy frequency at a constant temperature of 13 °C.

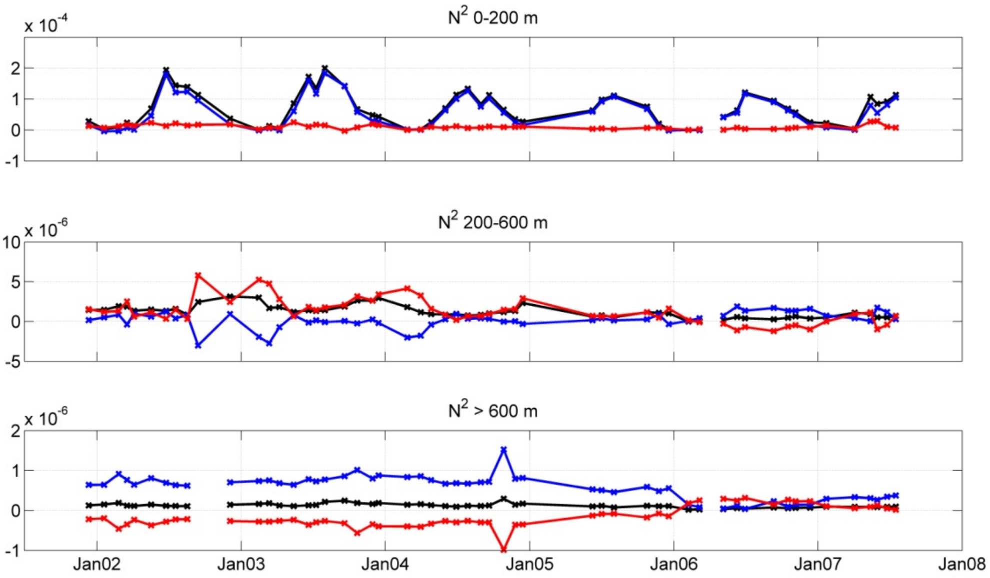


Figure 10: Temporal evolution of the buoyancy frequency (see text) at the Dyfamed station: N^2 (black), N^2_{temp} (blue) and N^2_{sal} (red) in s^{-2}, for three different layer (0-200 m,200-600 m and 600 m-bottom).

The top layer shows a strong seasonal variability of stratification: this is obviously related to a warming, during summer, building a stratification (mainly thermally driven, see Figure 10a) which is then eroded during winter by cooling. The intermediate layer exhibits a stratification which is mainly balanced by salinity, while temperature tends to have a destabilizing effect (N^2_{temp} is often negative). In the deep layer, the situation is the opposite, with a stabilizing effect due to temperature and a destabilizing effect due to salinity. In fact, until January 2006, N^2_{sal} is always negative and N^2_{temp} is always positive. If we consider now the pre-winter periods, we may note that stratification was not particularly weak before the onset of convection in early 2005 in the Gulf of Lions, but as was discussed in the previous paragraph, deep convection could take place and reach the bottom layer because of the anomalous strength of winter 04/05. On the other hand, the stratification before winter 05/06 was particularly weak in all layers, and even if the air-sea fluxes were not so strong during this second winter, deep convection could occur and reach the bottom in the Ligurian Sea. An interesting feature, which has never been observed in the whole time series, is that after this second DWF event, there was a reversal of the behaviour of temperature and salinity in affecting the stability of the water column: the intermediate layer is temperature stabilized (and N^2_{sal} is negative) and the deep layer is salinity stabilized (and N^2_{temp} is negative). This structure, which we further discuss in section 3.2.2, lasted for about one year, while until the beginning of 2007 the previous stratification seems to re-establish.

As we have seen in the previous section winter 2005/2006 was not so severe, nevertheless in the DYFAMED station a DWF event have been observed, which gave origin to a saltier, warmer and denser deep water (Figure 11).

In October 2005 the deep water column exhibited a monotonic decrease of temperature and salinity with depth at a density of 29.10 - 29.11. As we have seen in Figure 9, in February 2006 the water column was almost completely homogenized, at the same density of 29.11. The new WMDW is well evident after restratification and in May 2006 we may observe that the deep salinity and temperature have strongly increased, reaching a density 29.12. These observations may suggest that the hydrographic preconditioning has played a major role in determining the properties of the new WMDW, since the atmospheric forcings were not particularly intense as in the previous winter.

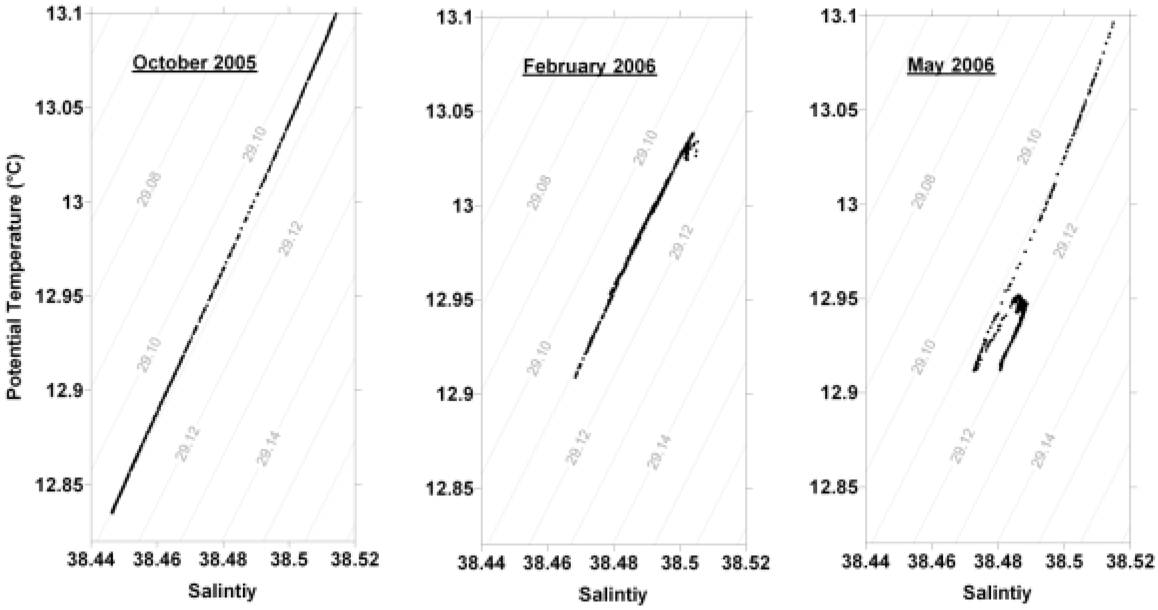


Figure 11: TS diagrams at the Dyfamed station in October 2005, February 2006 and May 2006.

Relative importance of air-sea fluxes and preconditioning on the new WMDW properties

We have tried to assess the relative importance of the atmospheric forcings during winter 2004/2005 and the EMT propagation in determining the properties of the new WMDW. Schroeder et al. (2008b) claimed that if the exceptionally severe conditions of winter 2004/2005 could have been responsible for the huge deep water production (as pointed out also by Lopez-Jurado et al., 2005), its anomalous characteristics may be due to the progressive heat and salt accumulation in the intermediate layer of the WMED during the previous years.

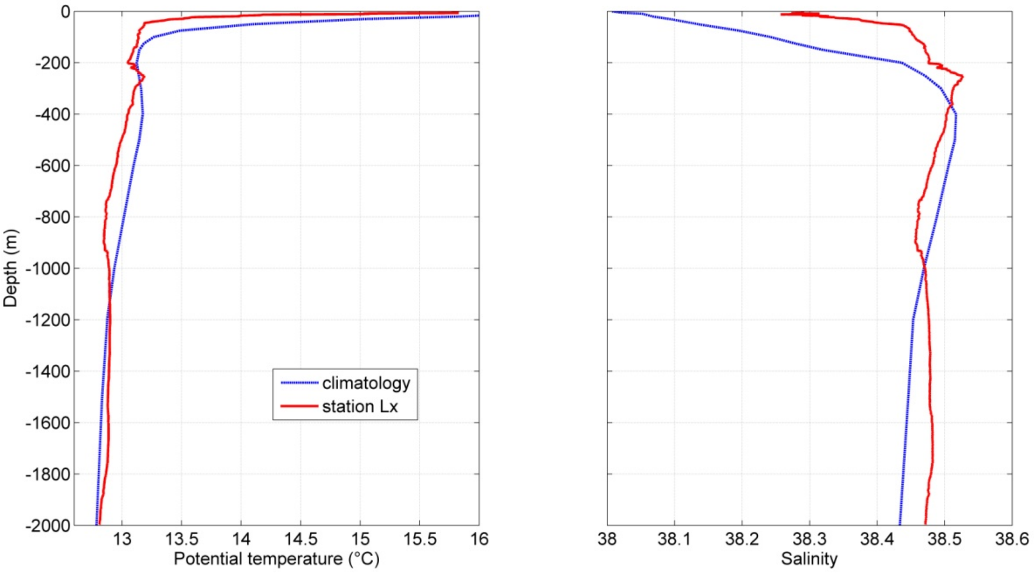


Figure 12: vertical θ and S profile of the MEDAR climatological profile for and station Lx

As we have reported in the previous sections, winter 2004/2005 showed the strongest heat loss and net evaporation since 1948. But, even if exceptional, could these conditions alone have produced the warm and salty new deep water? If they had acted onto a climatological water column in the Gulf of Lions, what would have been its resulting heat and salt content? As "climatological" water column, we chose the θ/S profile of the MEDAR/MEDATLAS climatology (MEDAR Group, 2002), corresponding to the annual mean (3-years window) of 2002 at 42.2 °N and 4.7 °E (Figure 2), with a depth of 2000 m. This point was selected in order to compare it with a real CTD cast of April 2005 at 42.3 °N and 4.7 °E (z=1996 m). In the following computations, we thus compare a pre-winter profile (the MEDAR climatological profile) with a post-winter profile in the same location (Figure 2).

First of all we computed the total heat and salt contents of the water column, before and after the winter convective event, using the following formulas and considering the profiles being representative for an area of 1 m2:

$$HC = \int_{z=0}^{H} \rho(z)C_P(z)\theta(z)Adz \qquad (1a)$$

$$SC = \int_{z=0}^{H} \rho(z)S(z)Adz \qquad (2a)$$

where A is the unit area, H is the depth of the water column (1996 m), C_P is the specific heat and ρ is the potential density. Dividing equations (1a) and (2a) by H, gives us an estimate of the average heat and salt content per unit of volume:

$$< HC >= \frac{1}{H}\int_{z=0}^{H} \rho(z)C_P(z)\theta(z)Adz \qquad (1b)$$

$$< SC >= \frac{1}{H} \int_{z=0}^{H} \rho(z) S(z) A dz \qquad (2b)$$

Gulf of Lions	**MEDAR (pre-winter)**	**Lx (post-winter)**	**Δ**
HC (J m^{-2})	$1.0560 \cdot 10^{11}$	$1.0498 \cdot 10^{11}$	$-6.24 \pm 3.13 \cdot 10^{8}$
SC (g m^{-2})	$7.8926 \cdot 10^{7}$	$7.8992 \cdot 10^{7}$	$6.63 \pm 2.19 \cdot 10^{4}$
<HC> (J m^{-3})	$5.28 \cdot 10^{7}$	$5.25 \cdot 10^{7}$	$-0.03 \pm 0.0015 \cdot 10^{7}$
<SC> (g m^{-3})	$3.9562 \cdot 10^{4}$	$3.9595 \cdot 10^{4}$	33 ± 10.9

Table 1: Heat and salt content of the two profiles and the differences between them.

Table 1 shows the total and average heat content (in J m^{-2} and J m^{-3}, respectively) and the total and average salt content (in g m^{-2} and g m^{-3}, respectively) for both profiles. The last column indicates the differences between the two profiles, with the errors being computed taking into account the error field which is associated to the MEDAR profile of temperature and salinity: there is a total heat loss of -6.24 ± 3.13 · 108 J m^{-2} and a total salt gain of 66.3 ± 21.9 kg m^{-2} for the whole water column, which means that on average each m^{3} along the water column has experienced a heat loss of -0.03 ± 0.0015 · 107 J m^{-3} and a salt gain of 33 ± 10.9 g m^{-3}. It is worth to note that the error of the heat exchanges is higher than the error of the freshwater exchanges (about 50% and 33%, respectively).

We then wanted to verify if the observed changes are consistent with the heat and freshwater fluxes from the daily ARPERA dataset (downscaled ERA40 reanalysis), from 1st October 2004 to 31st March 2005. The grid point we have chosen is the closest one to the selected: 4.83°E, 42 °N. Figure 13 shows the integrated total heat loss and net evaporation during that period. Until the beginning of November, the forcings were quite weak and both, the integrated heat and freshwater losses do not differ significantly from zero. From then on we can identify about four periods of strong heat and freshwater losses, in agreement with what Smith et al. (2008, their figure 15) found in the Catalan subbasin using NCEP reanalysis data. According to the ARPERA field, the total heat loss between October and March (figure 13a) was -3.833 · 10^{9} J m^{-2}. But actually from table 1 we know that the observed decrease of heat content of the water column was only 16 % (8-24%) of this value, about -0.624 ± 0.313 · 10^{9} J m^{-2}. One explanation is that the convection region has received laterally a higher amount of heat, in accordance with the accumulation of heat shown by Schroeder et al. (2006) and Gasparini et al. (2005). A further reason for this difference could be the fact that during the convection the region has laterally received heat and exported dense water, mainly due to mesoscale structures, as shown by Herrmann et al. (2008, their figure 5d). This means that the difference between the heat loss to the atmosphere and the heat content in the post-winter water column is not only due to the hydrographic preconditioning, but also to the import of warm water and the export of dense water during the event itself.

With regard to salt, since mass should be conserved, the addition of a freshwater flux to the water column must be accompanied by the removal of the same amount of seawater from the water column. Similarly, the removal of a certain amount of freshwater, due to evaporation, must be accompanied by the replacement of the same amount of water by adjacent seawater, which results in a net addition of salt to the water column. Thus, a salt gain for the whole depth range of 66.3 kg m^{-2}, if only due to vertical air-sea fluxes, would correspond to a net evaporation given by:

$$E - P = \frac{\Delta SC\left[gm^{-2}\right]}{S_{mean}\left[gKg^{-1}\right]\rho_0\left[Kgm^{-3}\right]} \qquad (5)$$

where S_{mean} is the mean salinity of the water column (38.44 in this case) and ρ_0 is the density of freshwater. An (E-P) of $1.725 \pm 0.57 \cdot 10^3$ kg m^{-2} over the 6-month period results from this calculation (about 3.45 m yr^{-1}): this corresponds to the net evaporation that would have been necessary to increase the salt content of the water column. From the reanalysis we computed that the integrated net evaporation (Figure 13) was only $0.75 \cdot 10^3$ kg m^{-2} (about 1.5 m yr^{-1}): this amount could have induced a salt gain of just 28.8 kg m^{-2} in the water column we considered. From table 1 it results clear that the net evaporation during this winter, even if very high compared to the climatology for this season, could have induced only 43 % (33-65%) of the actual observed increase in the salt content. These considerations lead us to assume that the convection region has received a further contribution of salt of about 37.5 ± 21.9 kg m^{-2} through lateral advection. This conclusion is consistent with a salt accumulation due to the EMT propagation, as hypothesized by Schroeder et al. (2006, 2008b). This phenomenon could have been responsible of about 57% of the observed salinity increase.

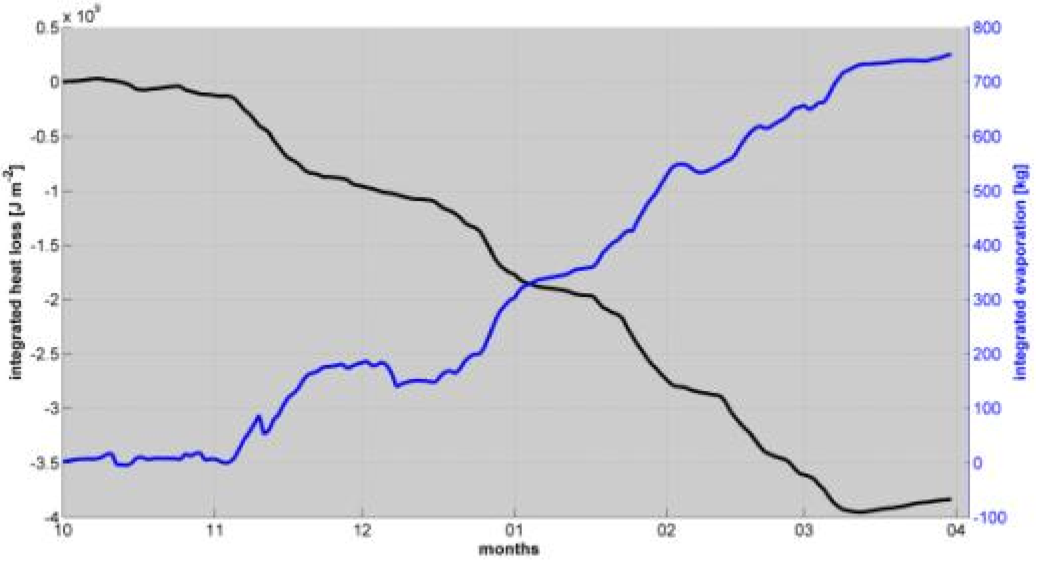


Figure 13: Integrated heat loss (black) and net precipitation (blue) from the ARPERA downscaling, in the period 1/10/2004-31/3/2005.

As we have seen in both cases, the heat and the salt contents, the observations are consistent with a progressive heat and salt accumulation induced by the EMT. In figure 14 we schematize the results of the previous calculation. A total heat advection of $3.21 \pm 0.313 \cdot 10^9$ J m^{-2} means an average heat advection per unit of volume of $1.61 \pm 0.16 \cdot 10^6$ J m^{-3} (with H=1996 m). On the other side, a total salt gain of 37.5 ± 21.9 kg m^{-2} means an average salt gain per unit of volume of 18.76 ± 10.9 g m^{-3} (with H=1996 m) due to lateral advection. It is noteworthy to stress that those values may be underestimated, since we are not considering the occurrence of import/export of light/dense water during the convection itself. As suggested by Herrmann et al. (2008), this is mainly due to mesoscale structures (import of light water) and the bleeding effect (export of dense water), i.e. the drainage of new deep water off the convection area into the boundary current flow.

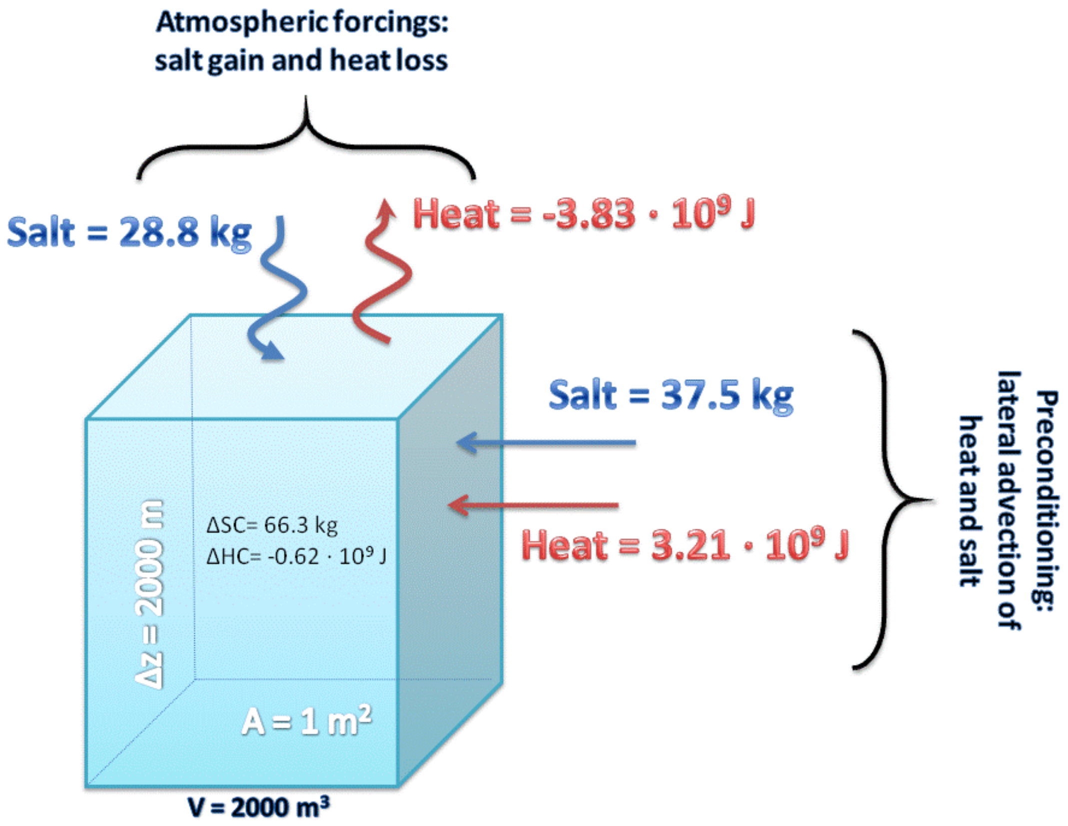


Figure 14: Scheme of the atmospheric forcings and the lateral advection acting onto a water column in the Gulf of Lions

To verify if the values of heat and salt advection computed above are realistic, we analyzed the DYFAMED data in order to find some consistency. The DYFAMED site is just upstream from the convection region (286 km between DYFAMED and Lx). This part of the work is still in progress and constitutes a subject of future collaboration with the host institution, which is aimed also to the submission of a manuscript in preparation about this study.

Previously we have shown the temporal evolution of the S_{max} vein properties n the DYFAMED site from 1995 to 2007 (fig. 8). Both temperature and salinity show a significant increasing trend, at least until fall 2004, with a marked acceleration from 2001 onwards. An abrupt reduction is visible after winter 2004/2005, probably due to the transfer and the export of heat and salt to the newly formed WMDW. During 2006 the heat and salt contents restarted to increase again.

We will analyze the average salt content increase over the whole water column during the recent years, to see if such an increase is able to explain the above mentioned difference.

Conclusions

The north-western basin of the Mediterranean Sea plays an important role, because it is one of the few sites in the world where a dense water mass is produced. Past studies have demonstrated the tendency of the deep waters in the WMED towards higher heat and salt contents since the '50s. Nevertheless these significant trends could not be responsible for the changes observed in the whole WMED in 2005 and in 2006. Since the early '90s an increase in temperature and salt in the deep and intermediate waters of the WMED has been observed and attributed to the propagation of the Eastern Mediterranean Transient (EMT) towards the WMED (Gasparini et al., 2005). The influence of the EMT on the new deep water observed starting from 2005 has been discussed in Schroeder et al. (2006). Initially the EMT has induced a heat and salt injection to the deep waters of the Tyrrhenian Sea, but after 2001 its influence was felt mainly at intermediate levels, becoming gradually warmer and saltier. In winter 04/05 this signal has been transferred to the deep layer of the western basin as a result of the deep convection processes taking place in the Gulf of Lions. Here, during winter, dry and cold air initially mixes the AW and the WIW with the underlying, warmer and saltier LIW. Further heat loss leads to formation of WMDW. The formation of the WMDW depends on a preconditioning period, followed by violent mixing. Finally the deep water formed spreads out of the convective region (Rhein, 1995). Send et al. (1999) suggested that variable deep water formation driven by varying local atmospheric forcings linked to NAO-related variability is responsible for the observed changes in the deep water characteristics. Manca et al. (2004) have identified trends in the deep waters of the Eastern Mediterranean of similar order of magnitude as those estimated in the western basin by Béthoux et al. (1990) implying either a common atmospheric origin or a communication of the changes from one basin to the other most likely trough the LIW.

Béthoux and Gentili (1999) argue that while the warming trend can be explained by greenhouse-effect-related warming of the sea surface between 1940 and 1995, the salinity trends require a rate of increase in the water deficit of the Mediterranean of the order of 0.10 m year^{-1}. In order to achieve such a high value, it is necessary to consider not only the damming of the major Nile and Ebro rivers, but also a small increase in evaporation and decrease of the net Black Sea outflow.

A suggestive hypothesis is that internal ocean processes might prove to be crucial in determining the basic state of the circulation, onto which the atmosphere exerts its own variable forcing, and that both are important in determining what equilibrium will be reached. From this point of view, air-sea interaction would remain the principal driving force of the Mediterranean circulation, but the occurrence of extreme events would depend on the contemporary presence of the appropriate oceanic conditions (Artale et al., 2006).

As it was the case of the Eastern Mediterranean Sea (EMED), where the production of dense water in the Aegean Sea during the '90s, i.e. during the EMT, had induced a significant uplifting of the isopycnals in the Ionian subbasin, the huge new deep water production occurred in the WMED in winters 2004/2005 and 2005/2006 seems to have had similar consequences, with about 800-900 m upward displacement of the old WMDW within two years. Considering that in the EMED the EMT produced an uplifting of the old Eastern Mediterranean Deep Water (EMDW) of about 500 m, what we are observing now in the WMED is even more significant. In the future it will be necessary to assess the effect on the Mediterranean Outflow (MO) toward the Atlantic Ocean and when this will be visible.

Future collaboration with host institution

As I mentioned before, part of future collaborations will try to verify if the values of heat and salt advection computed above are realistic, by analyzing the DYFAMED data, in order to find some consistency. This part of the work is aimed also to the submission of a manuscript in preparation about this study.

Projected publications/articles resulting or to result from your grant

We are preparing two papers and a contribution to the EGU 2009 Conference (Medclivar Session, CL60, Mediterranean climate variability and change):

- Recent abrupt warming and salting of the Western Mediterranean Deep Water: the roles of atmospheric forcing and lateral advection, *Schroeder K., Josey S. A., Herrmann M., Grignon L., Gasparini G.P., Bryden H.L.,* manuscript in preparation.
- Relative importance of the variability of preconditioning on deep convection in the Gulf of Lion, NW Mediterranean, *Grignon L., Smeed D., Schroeder K., Bryden H.L.,* manuscript in preparation.

- The role of atmospheric forcing and lateral advection in setting the properties of the Western Mediterranean Deep Water formed in winters 2004/05 and 2005/06, *Schroeder K., Josey S.A., Herrmann M., Grignon L., Gasparini G.P., Bryden H.L.*, abstract submitted to Session CL60, EGU 2009.

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