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Abrupt warming and salting of the Western Mediterranean Deep Water after 2005

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Abrupt warming and salting of the Western Mediterranean Deep Water after 2005

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Outline

- Aim of the study
- What happened in the deep WMED?
- Forcings
  - Air-Sea Fluxes
  - Heat and salt contents of the water column
  - Lateral heat and salt advection
- Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005
- Conclusions

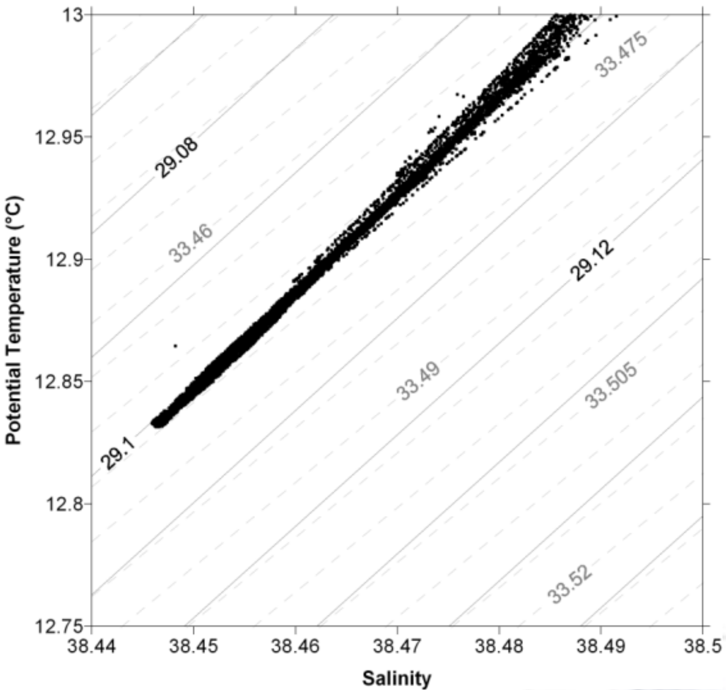
Aim of the Study

To investigate the causes of a recent abrupt change in the deep heat and salt contents of the western Mediterranean Sea, which has been originated during two convective events, in winter 2004/2005 and in winter 2005/2006.

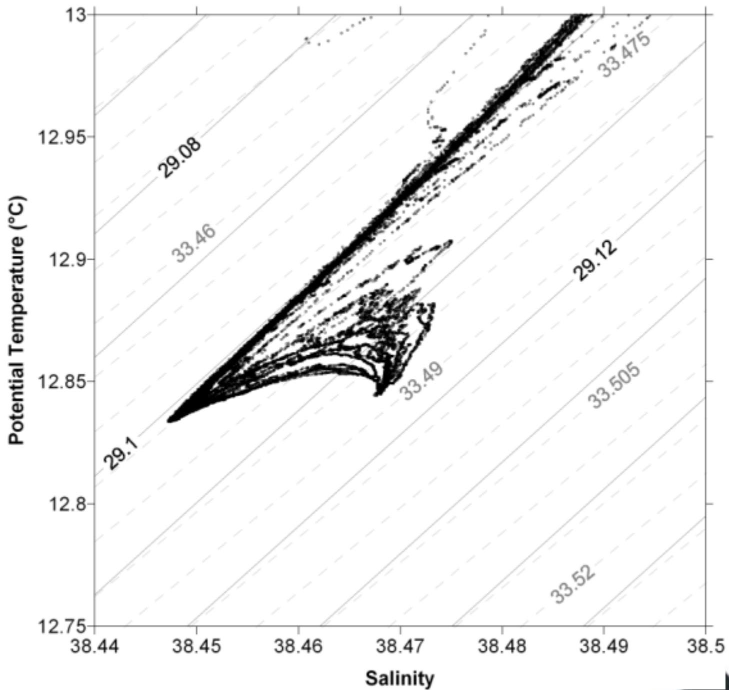
What was the role of the atmospheric forcings (air-sea heat and freshwater fluxes) and the advection of anomalously salty and warm intermediate water to the convection region?

What happened in the deep WMDW?

Firstly during the 2005 cruises an unusual deep stratification was observed, which is now present in almost the whole basin.

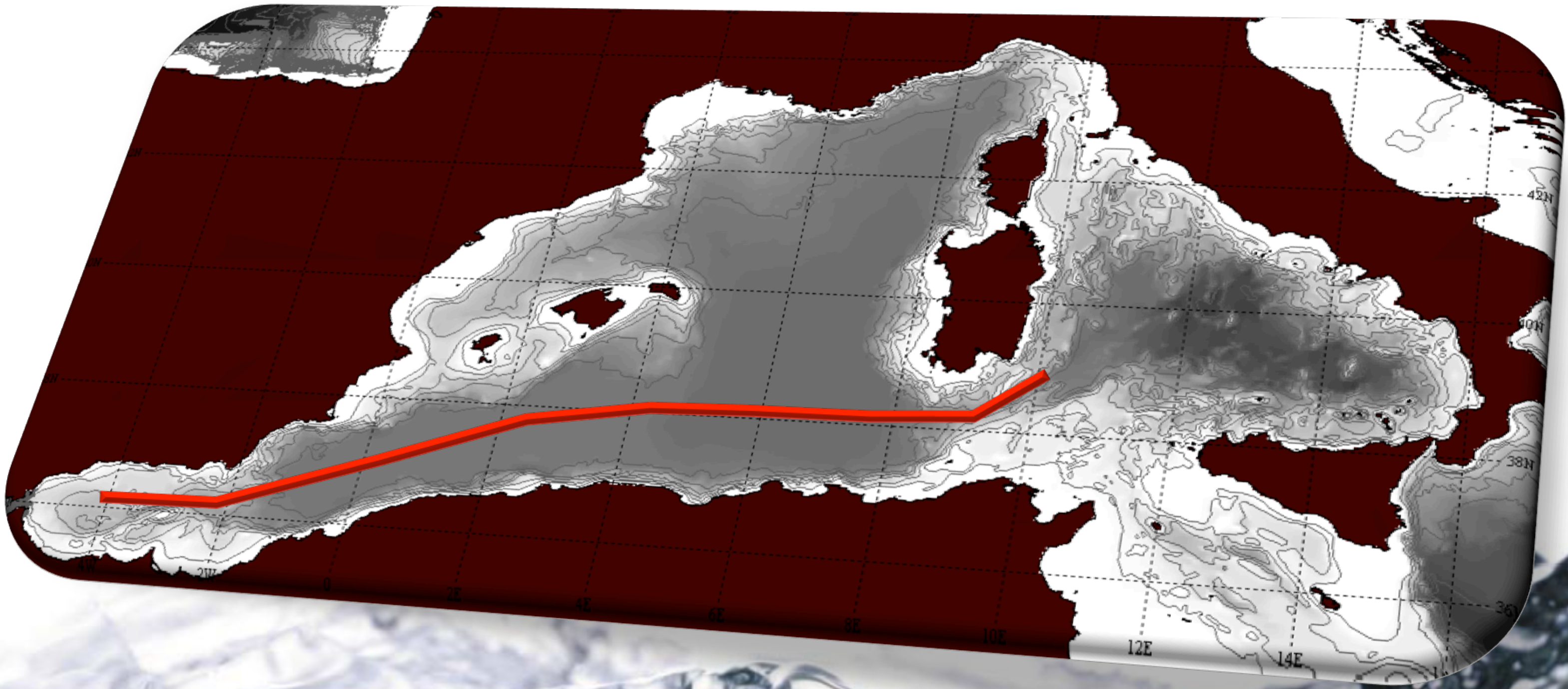


classical WMDW structure (before 2005)



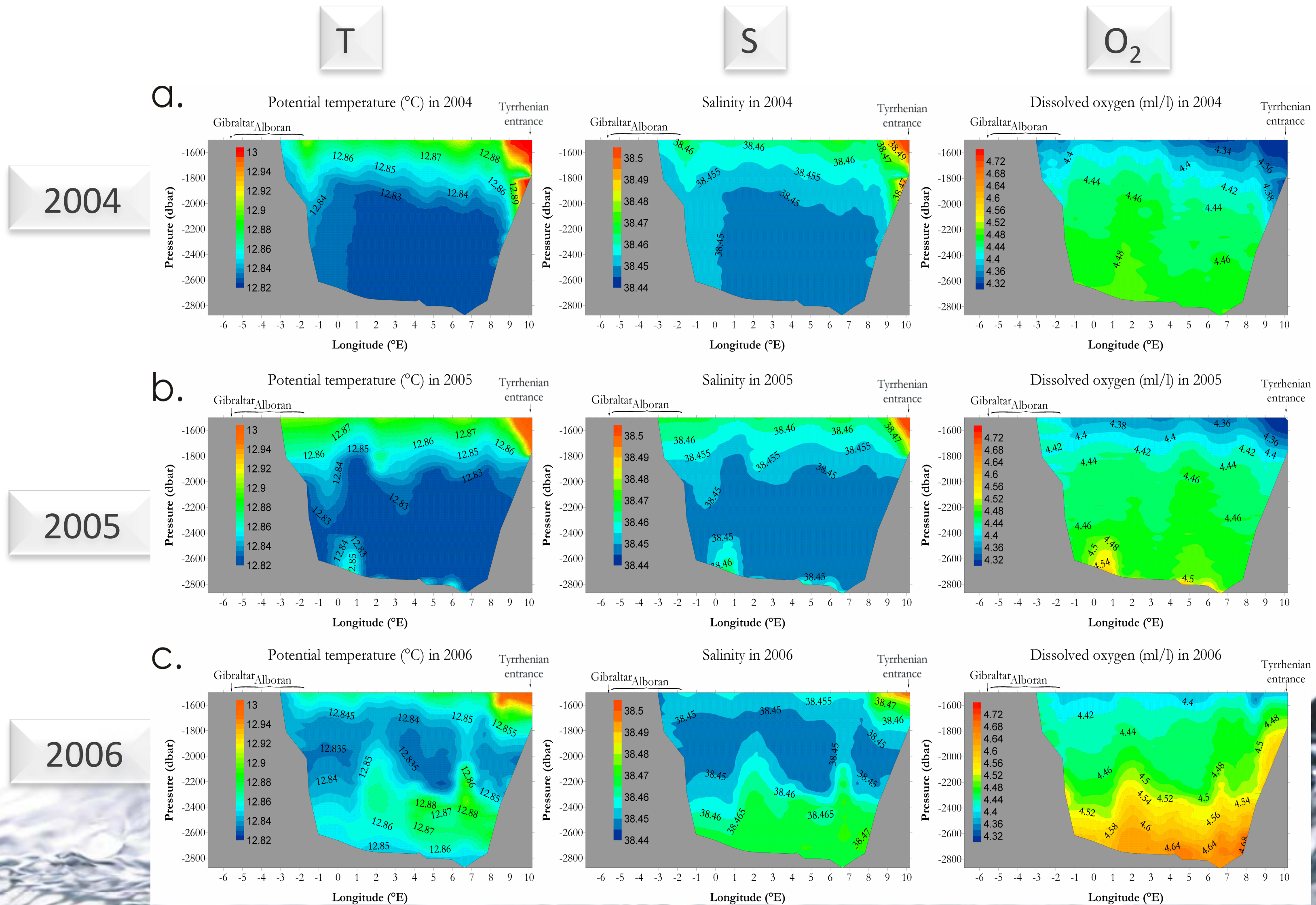
Deep layer structure after DWF in 2004/2005 and then in 2005/2006

What happened in the deep WMDW?



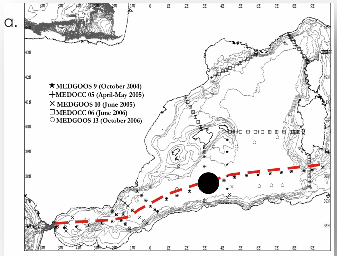
(*Schroeder et al., 2008*)

What happened in the deep WMDW?



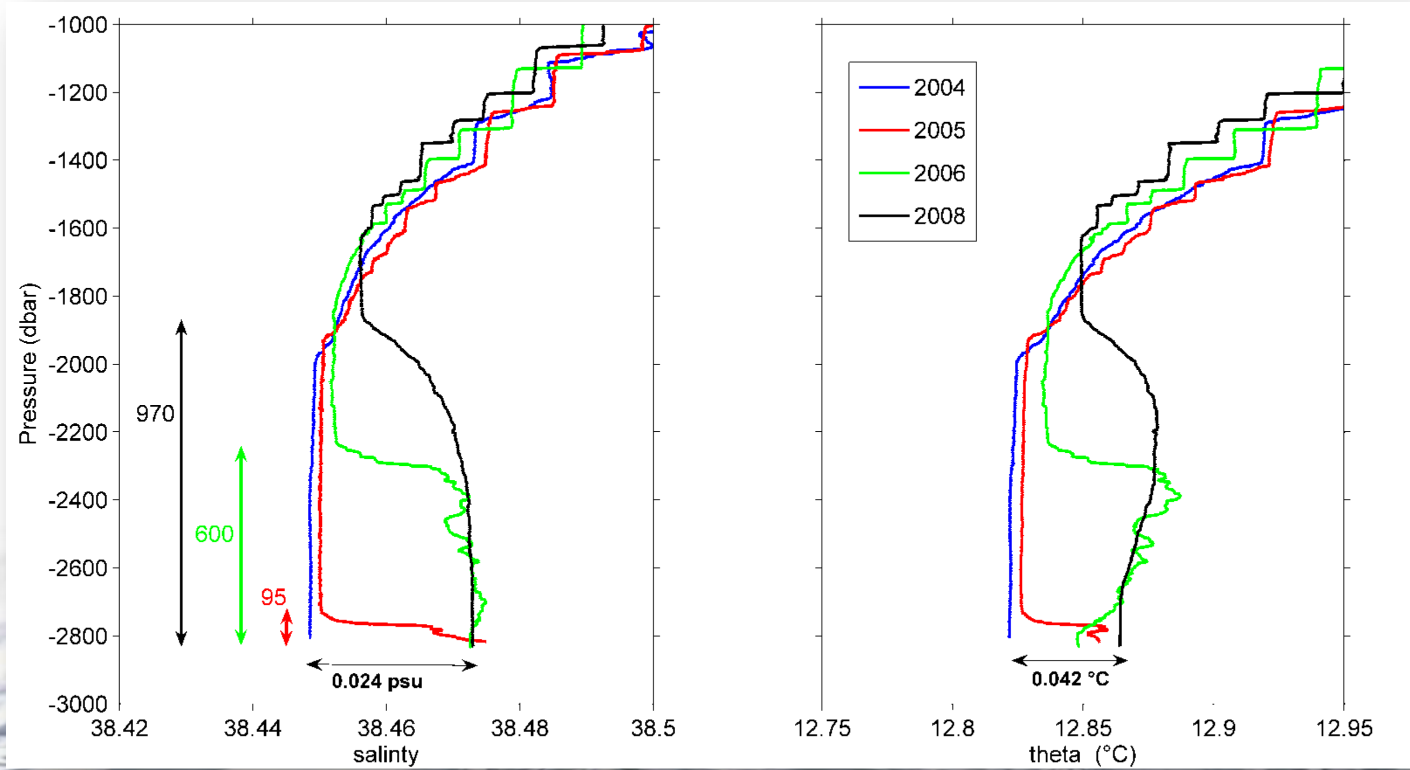
(*Schroeder et al., 2008*)

What happened in the deep WMDW?



south of the Balearics, 5 °E, 38 °N

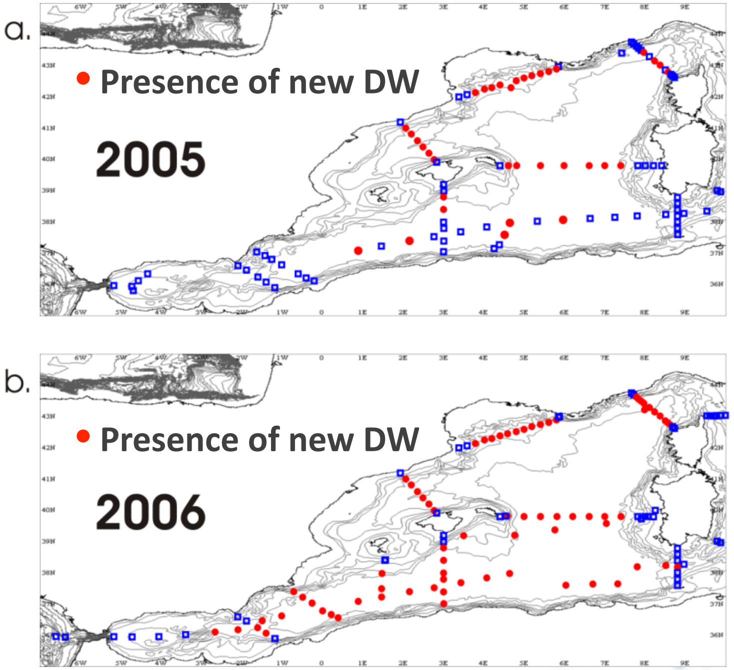
Winters 2004/2005 and 2005/2006: abundant formation of a new anomalously warm and salty WMDW in the NW-Med.
Between 2004-2008, in the abyssal plain of the WMED, the layer the new deep water occupies has become several hundreds of meters thicker, with total increases of $\Delta S=0.024$ and $\Delta\theta=0.042$ °C near the bottom.

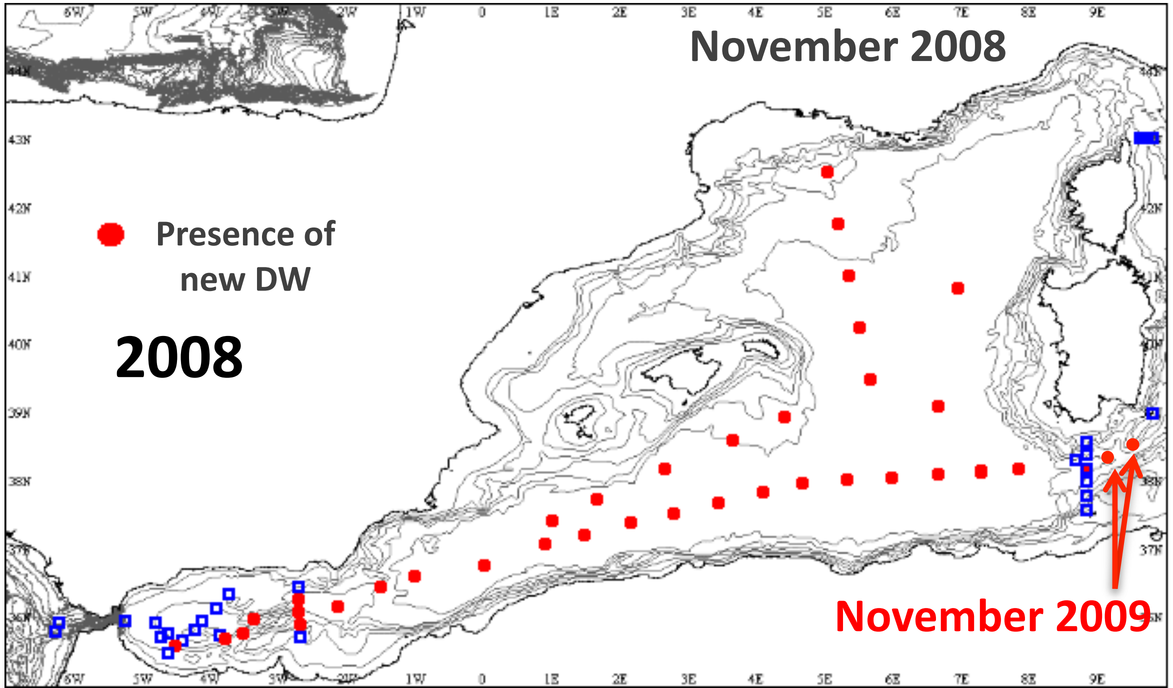


(*Schroeder et al., 2010*)

What happened in the deep WMDW?

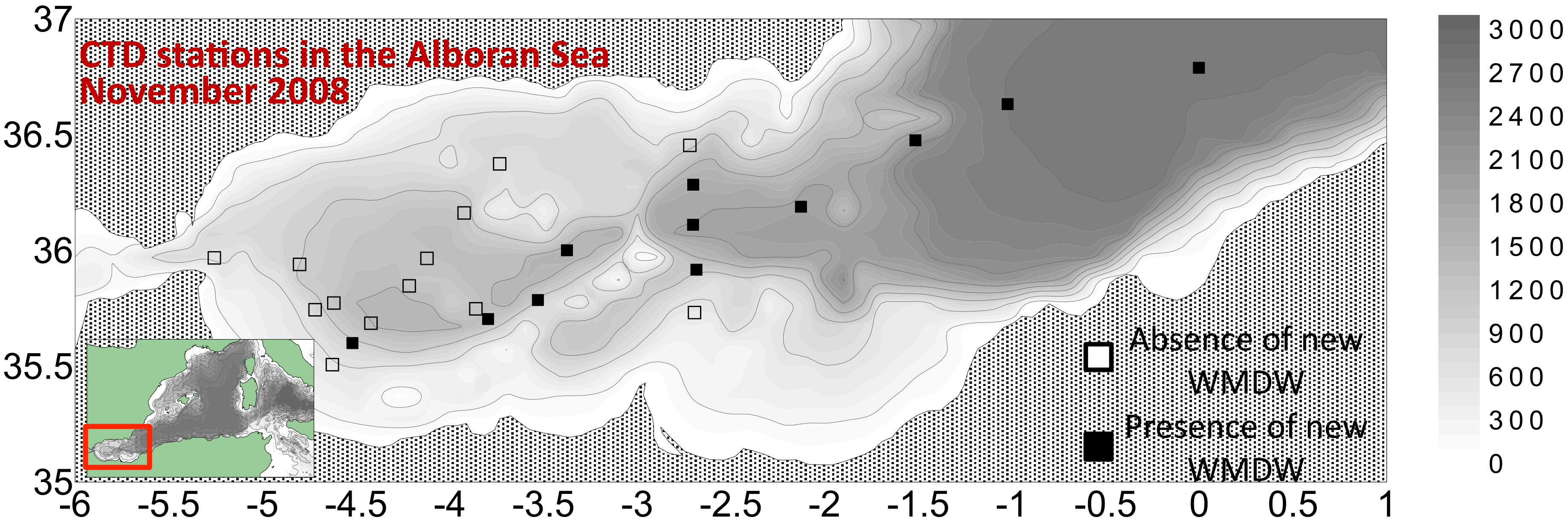
Schroeder et al. (2008)





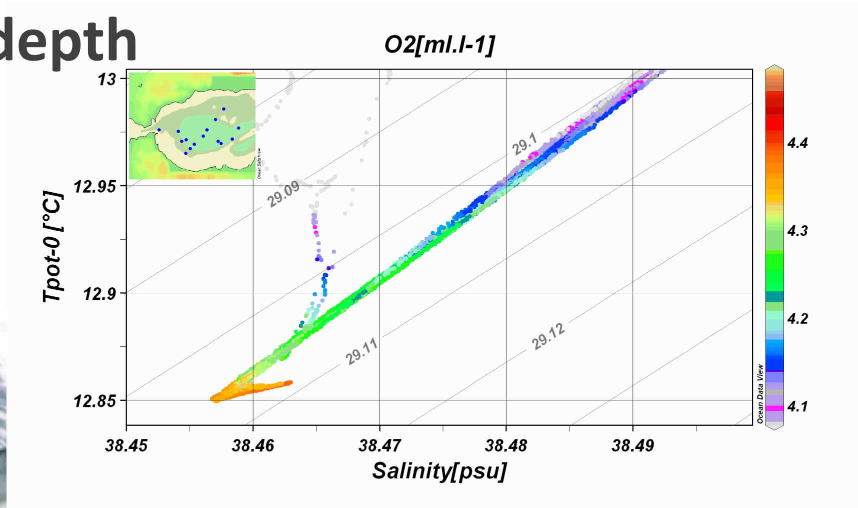
Each year the signature became evident in wider and wider regions, allowing a time-scale estimate of the spreading. The univocal identification of the new DW was possible thanks to the particular shape in the TS diagram

What happened in the deep WMDW?



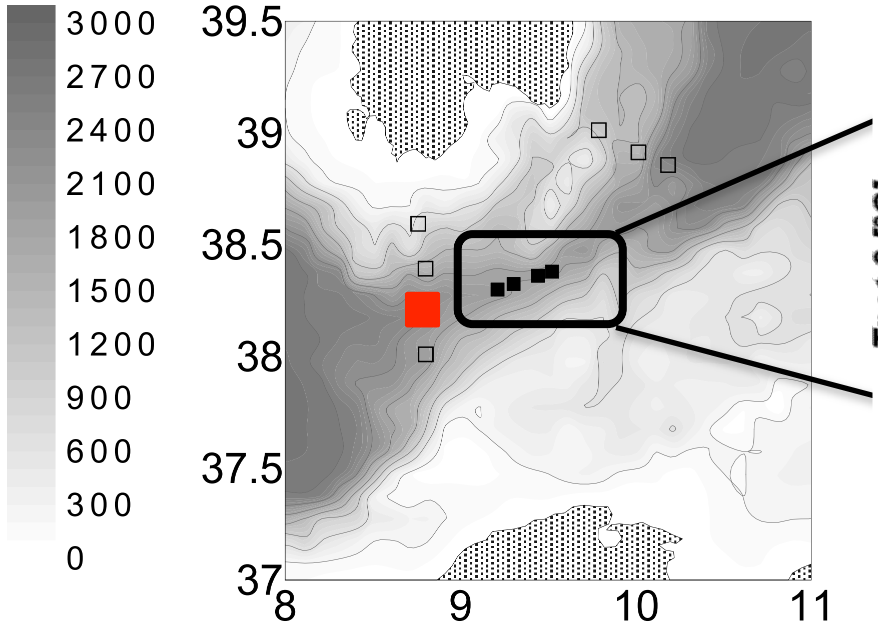
At some stations nWMDW < 1000 m depth

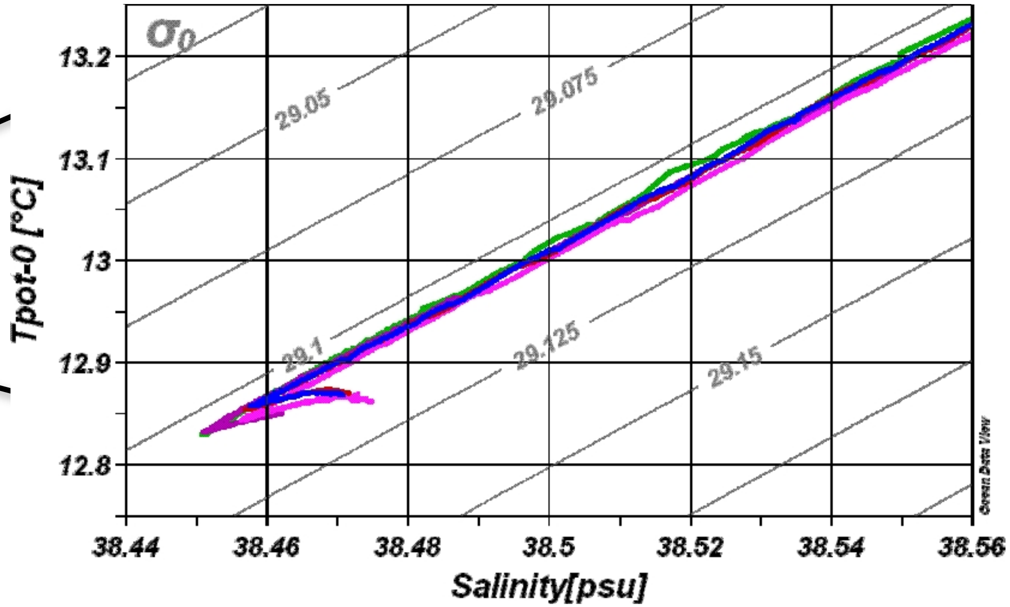
→ accurate estimate of the **temporal scales** of its **spreading**: a DW formed in Feb-Mar '05 in the NW-MED has almost reached Gibraltar in **33 months**



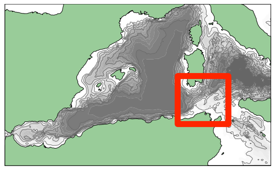
What happened in the deep WMDW?

CTD stations in the Sardinian Channel - November 2009





2005 2006 2007 2008 2009



□ Absence of new WMDW

■ Presence of new WMDW

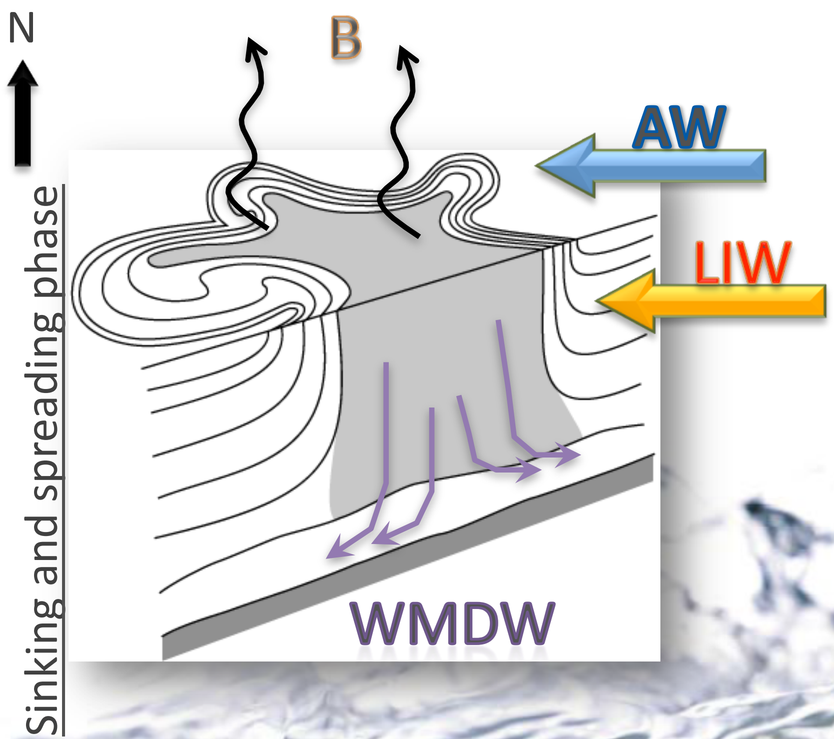
More recent data (Nov. 2009) seem to detect an **increased presence of the new DW signature** along the axis of the canyon in the Sardinia Channel, on the way to the Tyrrhenian Sea: the **new WMDW has just got over the sill** dividing the Algerian basin and the Tyrrhenian

Forcings

Deep water properties and their variability are due to:

1)Preconditioning (heat /salt content and structure of the water column before the onset of convection)

2)Atmospheric forcings (heat, freshwater, buoyancy fluxes)



Combination of **surface heat/freshwater losses** and **lateral convergence of heat/freshwater** sustains the deep convection

Steady state

balance

removal of heat/ freshwater by the atmosphere ⟺ **supply of those properties** by the ocean

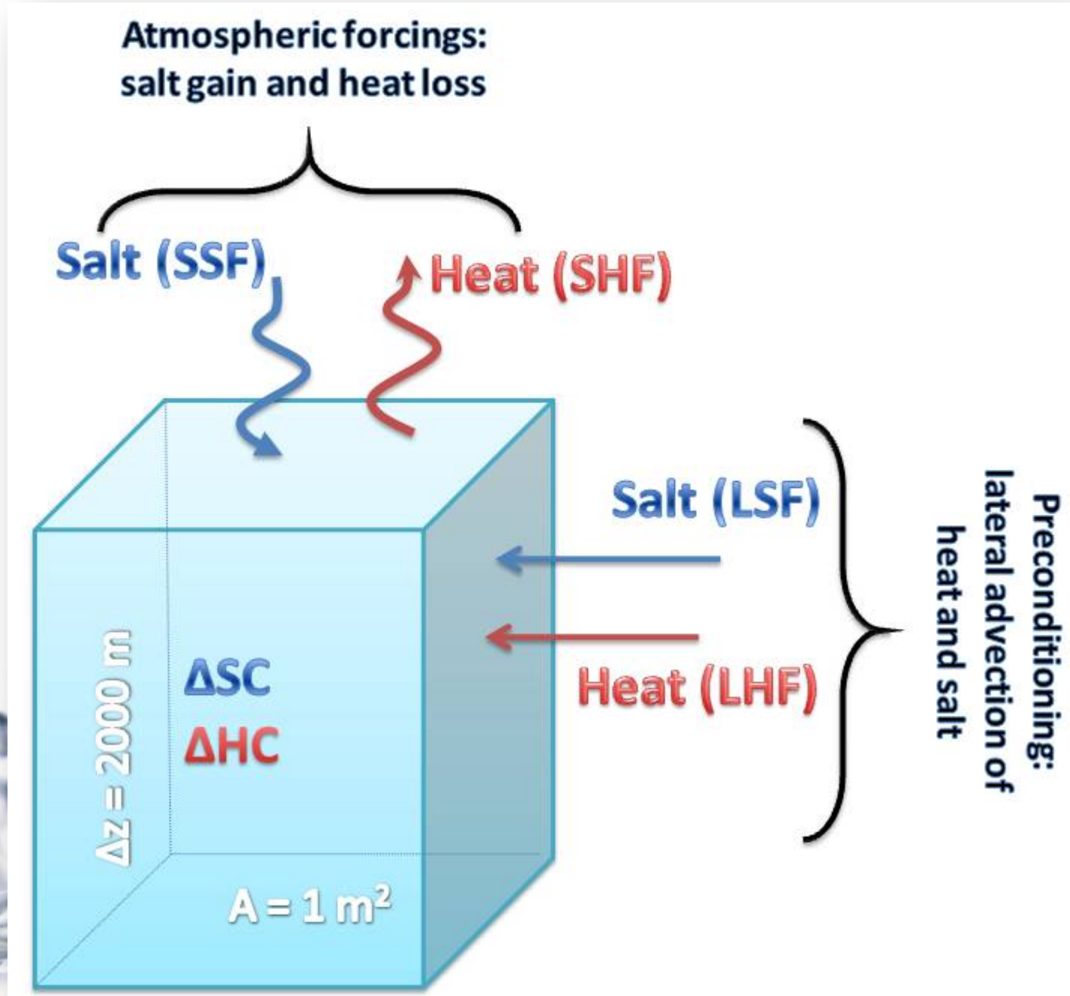
Forcings

In an idealized water column, the heat and salt content might change due to:

lateral advection of heat and salt
→ **Lateral Heat Flux (LHF) and Lateral Salt Flux (LSF)**

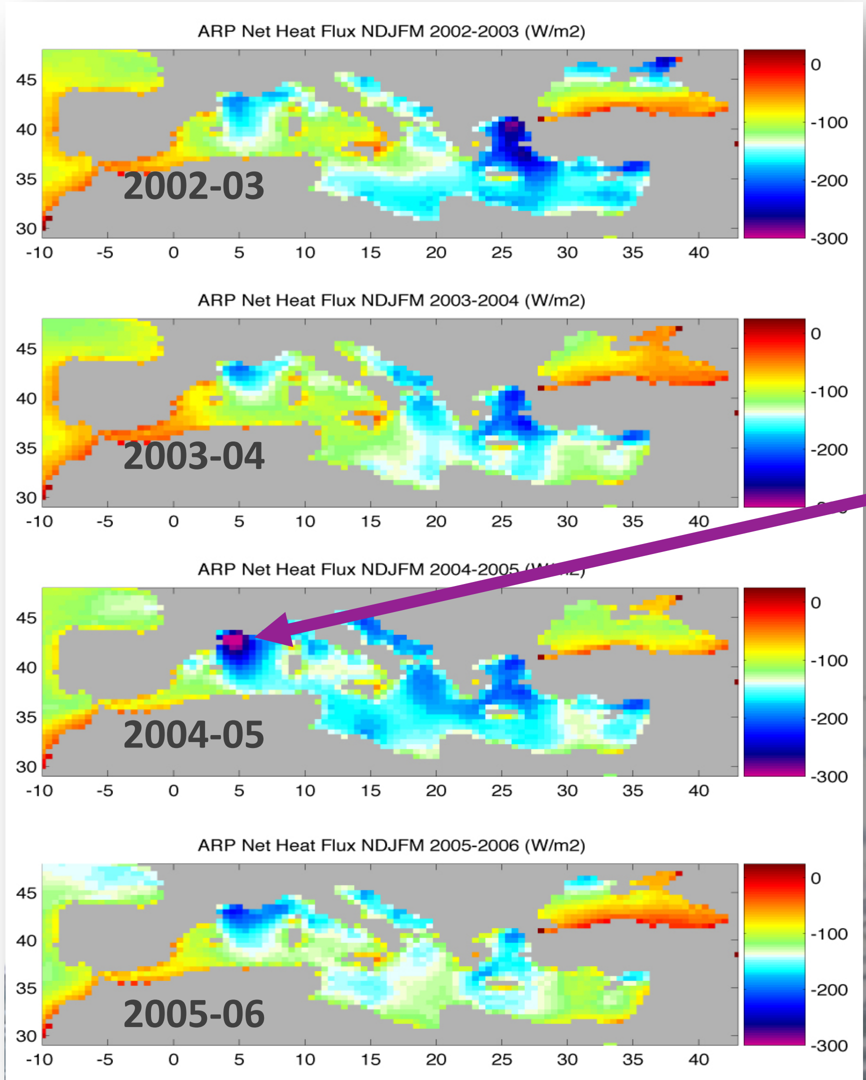
heat and freshwater exchanges with the atmosphere
→ **Surface Heat Flux (SHF) and Surface Salt Flux (SSF)**

$$\Delta HC = LHF + SHF$$
$$\Delta SC = LSF + SSF$$



Forcings: Air-sea fluxes

Fields of heat and freshwater exchange are determined from a daily high-resolution downscaling of the ECMWF, ARPERA (mean resolution 50 km)



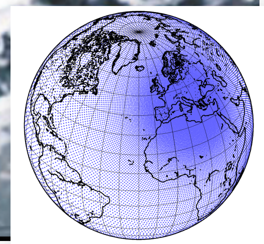
ARPERA net **surface heat fluxes** over the last winters (NDJFM)

Typical winter mean heat loss in convection area is about **180 Wm^{-2}**.

Winter **2004-2005** has extreme losses which average to **300 Wm^{-2}**.

Winter **2005-2006** also strong but less intense than 2004-2005.

(*Schroeder et al., 2010*)

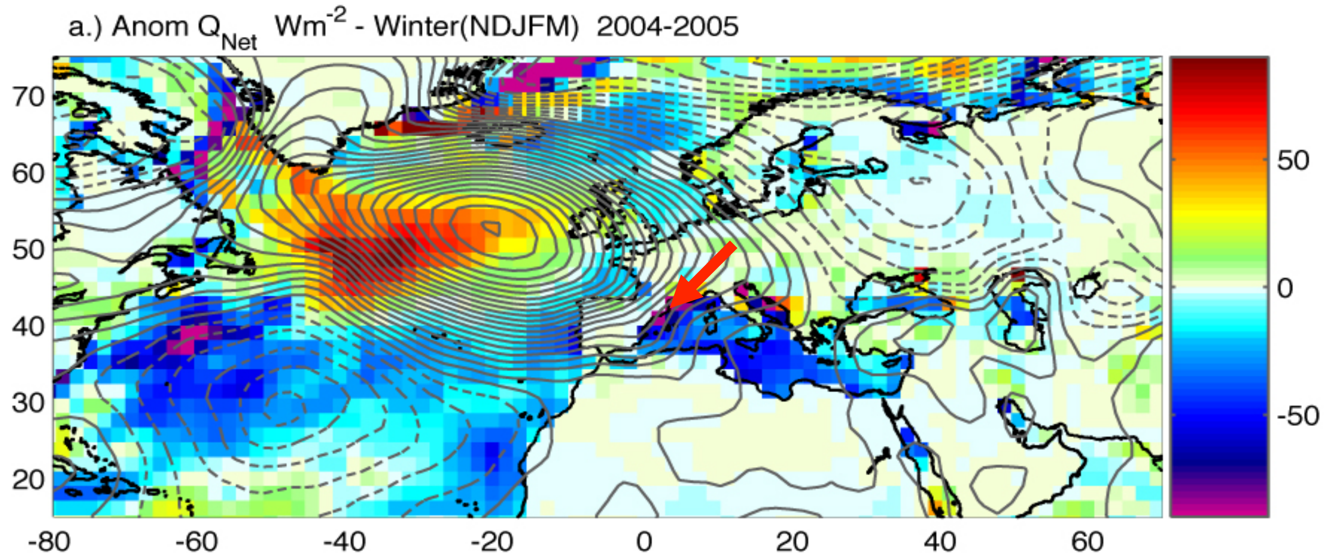


Forcings: Air-sea fluxes

Large scale 500 mb pressure field (contours, 0.5 mb intervals positive values solid) and net heat flux anomaly for winter 2004-2005 from NCEP reanalysis

Strong heat loss in convection region associated with **advection of cold dry air** by intense north-easterly flow.

The mean large-scale pressure field more similar to **negative phase** of 2nd mode of variability (the **East Atlantic Pattern**) than 1st mode (the North Atlantic Oscillation). Winter 2004-05 EAPI = -0.61, NAOI=0.31.



(*Schroeder et al., 2010*)

Forcings: Air-sea fluxes

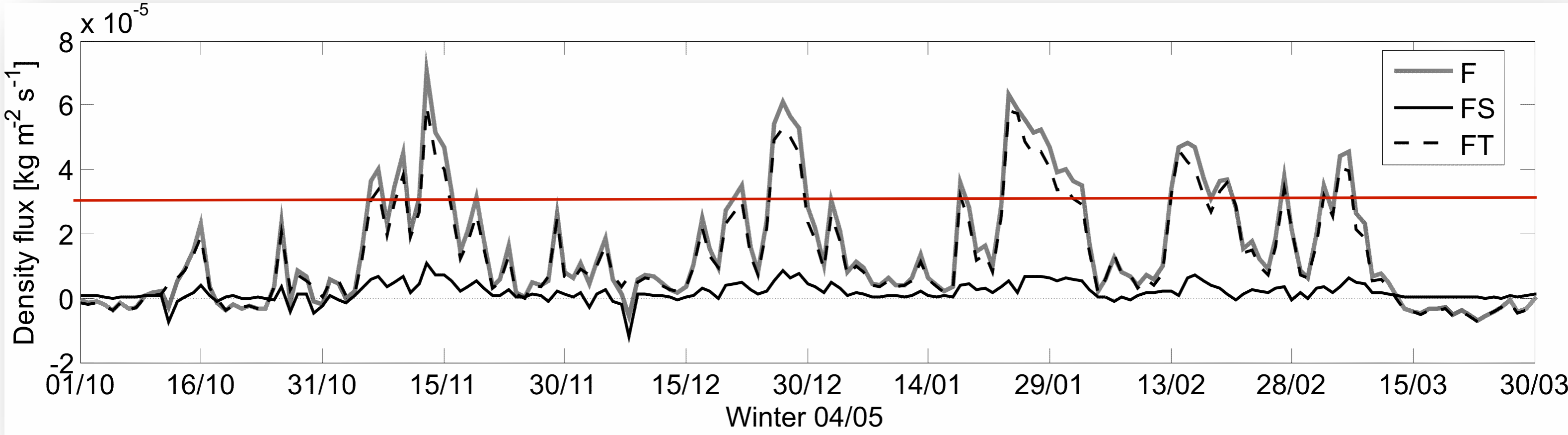
Daily density fluxes from ARPERA in the Gulf of Lions in winter 2004/2005 (kg m^{-2} s^{-1})

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

(*Schmitt et al., 1989*)

Combines the **net heat flux** with the **net evaporation**
Note that with g=-9.8 m/s^2, this parameter is related to the **buoyancy flux** (an increase in density at the surface corresponds to a buoyancy loss)

4 events with $F_\rho > 3\ 10^{-5}$ kg m^{-2} s^{-1}
(max 5.2 10^{-5} kg m^{-2} s^{-1})



E-P has a rather weak impact on the total density flux

(*Schroeder et al., 2010*)

Forcings: Air-sea fluxes

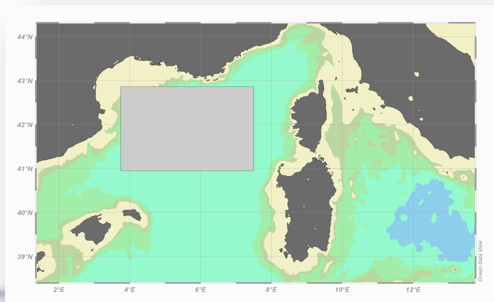
Anomalous winter net evaporation and net heat flux in the NW-MED (3.75-7.50 °E; 40.95-42.86 °N) from 1948 to 2008 (NCEP/NCAR reanalysis dataset).

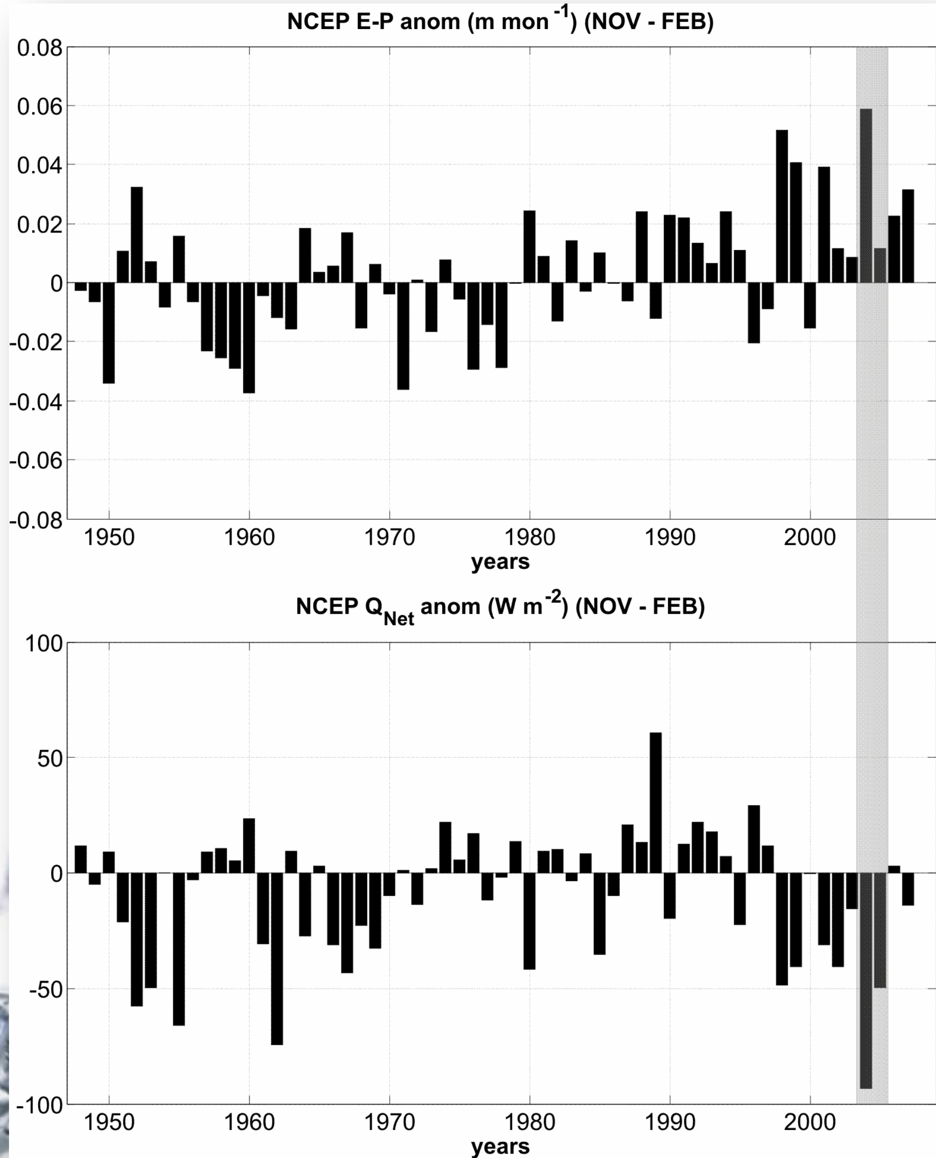
Winter 04/05

<u>highest anomalies since 1948</u>

E-P > 0.05 m month^{-1}

Q_{net} > 80 W m^{-2}





Forcings: Air-sea fluxes

ARPERA heat flux terms for 1x1 degree box centered on convection region

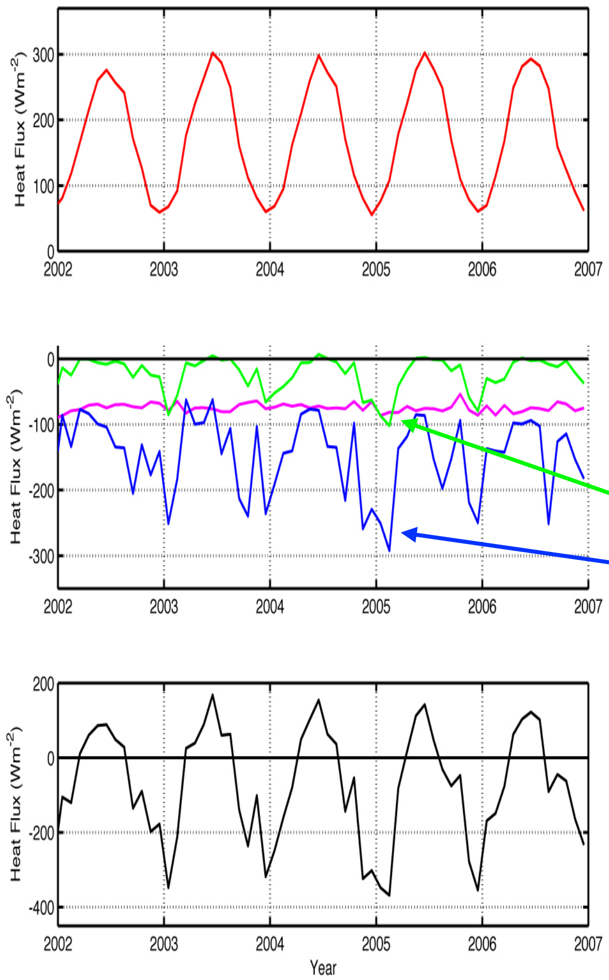
Shortwave Q_{SW}

Sensible Q_H

Longwave Q_{LW}

Latent Q_E

Net Q_{NET}



$$Q_{NET} = Q_E + Q_H + Q_{LW} + Q_{SW}$$

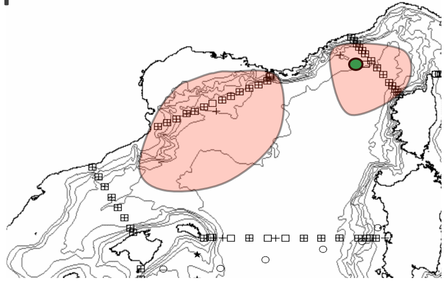
Winter 2004-2005 net heat flux anomaly is driven by extreme latent and sensible heat loss.

(*Schroeder et al., 2010*)

Forcings: Heat and salt contents of the water column

DYFAMED: monthly CTD

upstream the convection area

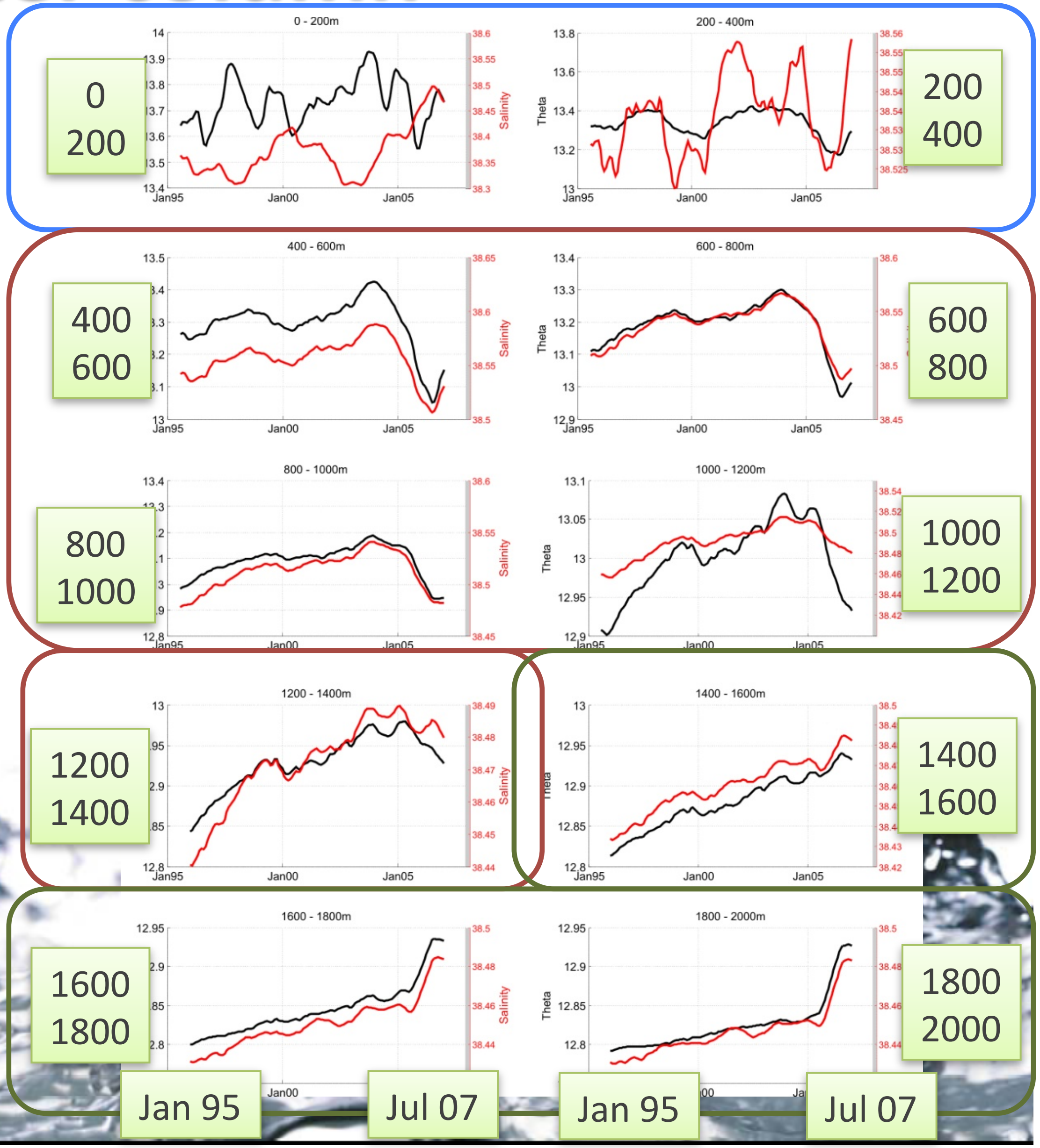


Overall warming and salting in each layer

0-400: oscillating, after 2002 marked S increase in 0-200 m.

400-1400: increasing T and S until end 2004, then a strong decrease

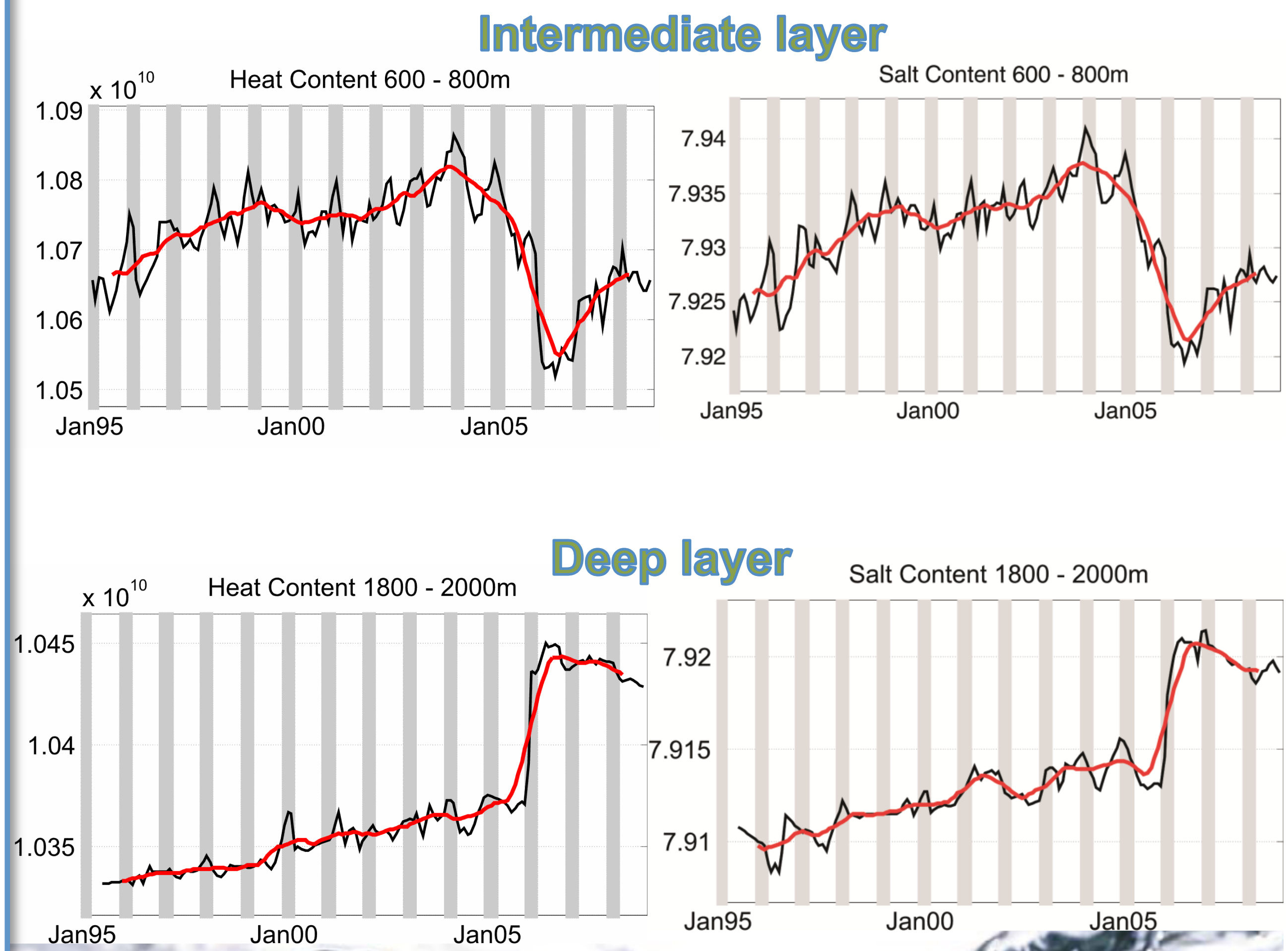
1400-2000: increasing T and S, acceleration after the recent DWF



Forcings: Heat and salt contents of the water column

This opposite behavior suggests an internal salt and heat redistribution between the **intermediate** and the **deep** layers during the DWF events.

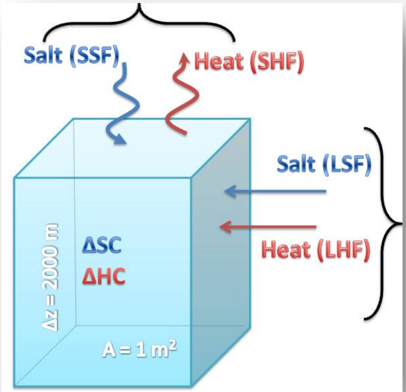
The new deep water is therefore likely to have gained its anomalously high S and T mainly from the **intermediate** layer, which during the preceding years has been **accumulating heat and salt**



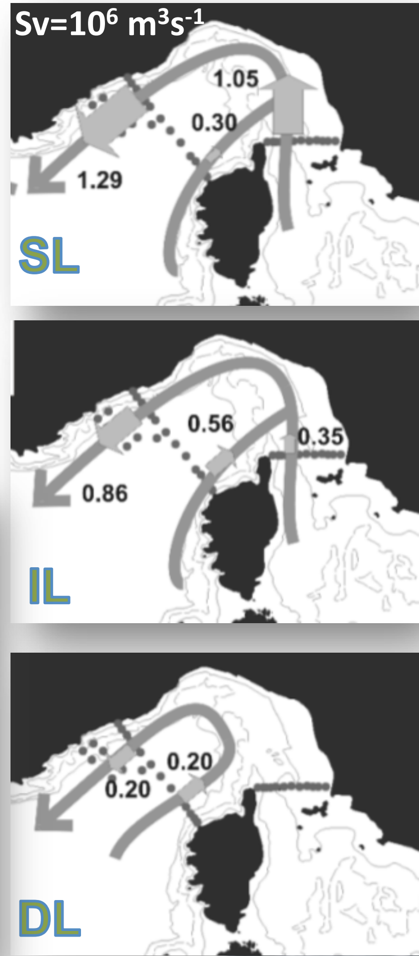
(*Schroeder et al., 2010*)

Forcings: Lateral heat and salt advection

A total amount of **85×10^6 kg s^{-1} of salt** and **0.12 PW of heat** is **advected** westward along with the boundary current **toward the convection region** in the Gulf of Lions.
A contribution of about **63% comes from the Tyrrhenian Sea**, while the rest is brought by the current west of Corsica.
The **main contributions** to the westward lateral advection of heat and salt is due to the **surface and intermediate layers**.



	Mass (Sv)	Heat (PW)	Salt (10^6 kg s^{-1})
Between Tyrrhenian and Ligurian Seas			
Surface layer	1.05	0.060	42
Intermediate layer	0.35	0.015	11
Total	1.40	0.075	53
From Ligurian Sea to Gulf of Lions			
Surface layer	1.29	0.067	47
Intermediate layer	0.86	0.047	34
Deep layer	0.20	0.006	4
Total	2.35	0.12	85

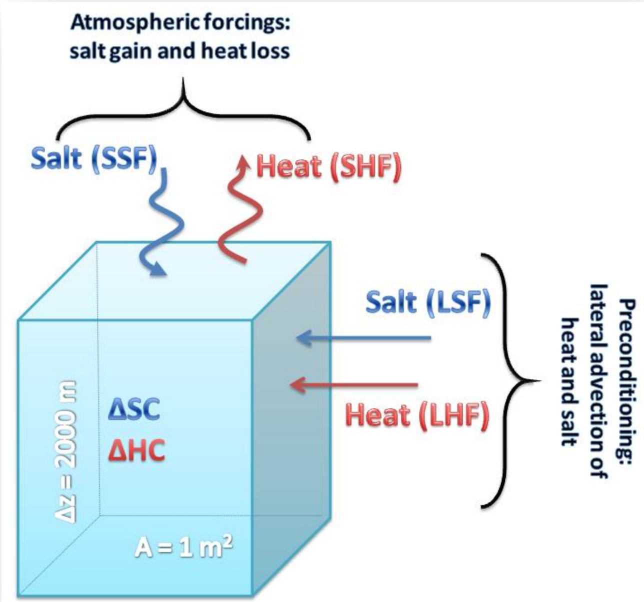


(*Schroeder et al., 2008*)

Forcings: Lateral heat and salt advection

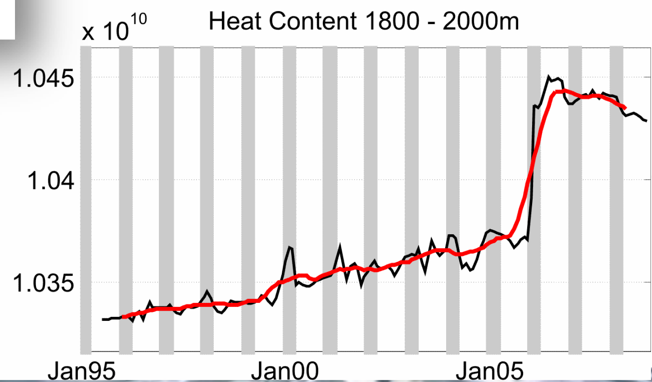
The **heat and salt content variations** are the result of a combination of heat and freshwater exchanges with the atmosphere (**surface fluxes**) and the lateral advection from the surrounding ocean (**lateral fluxes**) and vertical mixing between layers

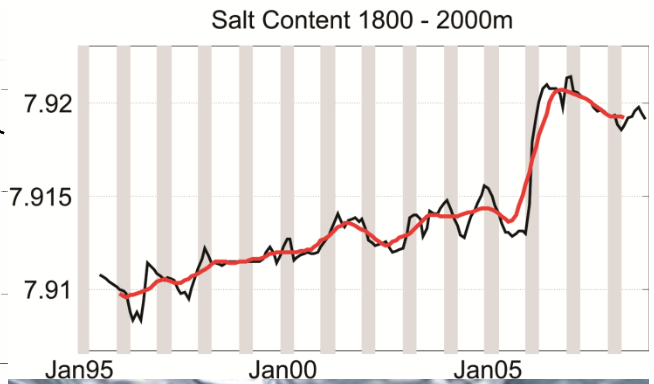
This is assumed to be negligible except during convection



$$\Delta HC = LHF + SHF$$
$$\Delta SC = LSF + SSF$$

$$LHF = \Delta HC - SHF$$
$$LSF = \Delta SC - SSF$$

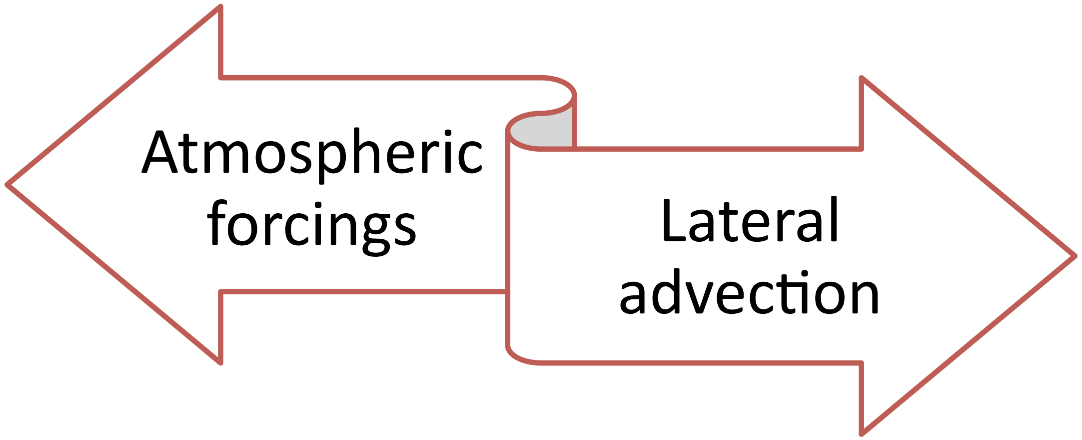




(*Schroeder et al., 2010*)

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

Assessment of the relative importance of



in setting the properties of the new WMDW formed in winter 2004-2005

HYPOTHESIS

if the exceptionally **severe winter** 2004/05 was responsible for the **huge deep water production**, its **anomalous characteristics** may be also due to a progressive **heat and salt accumulation** in the intermediate layer during the previous years.

Under that assumption, the **presence of saltier water** would require less heat to be removed to reach a density high enough for sinking to great depths.

→ **The resulting DW is saltier and warmer**

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

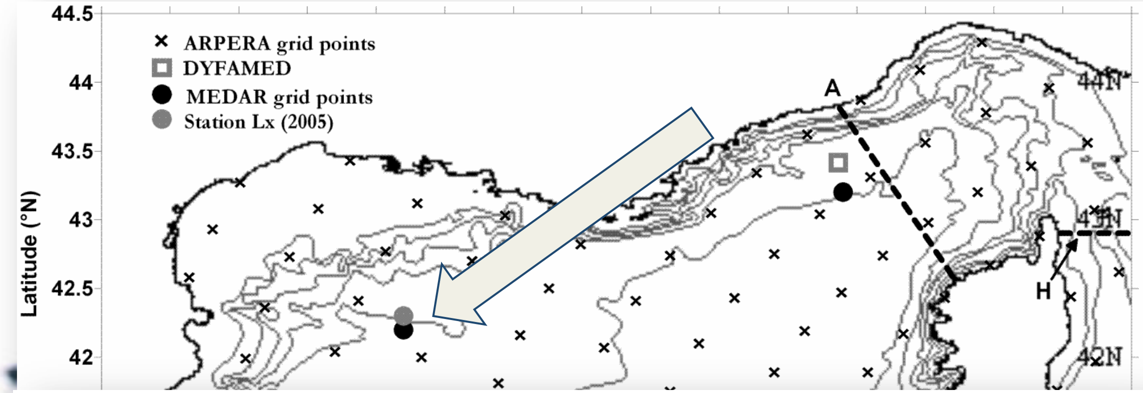
Winter 2004/05 showed the strongest heat loss and net evaporation since 1948

? Could these exceptional conditions 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 the resulting heat and salt content?

"Climatological" water column: MEDAR/MEDATLAS climatology at 42.2°N, 4.7°E (z=2000 m)

→ hypothetical pre-winter profile supposed to be on place before the onset of strong heat and freshwater losses



Gulf of Lions	MEDAR Station[a] (Prewinter)	Lx Station (Postwinter)	Δ
HC (J m^{-2})	$1.0560 \pm 3.13 \times 10^{11}$	1.0498×10^{11}	-6.24×10^{8}
SC (kg m^{-2})	$7.8926 \pm 2.19 \times 10^{4}$	7.8992×10^{4}	66.3
<HC> (J m^{-3})	$5.28 \pm 0.0015 \times 10^{7}$	5.25×10^{7}	-0.03×10^{7}
<SC> (kg m^{-3})	39.562 ± 0.011	39.595	33×10^{-3}

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

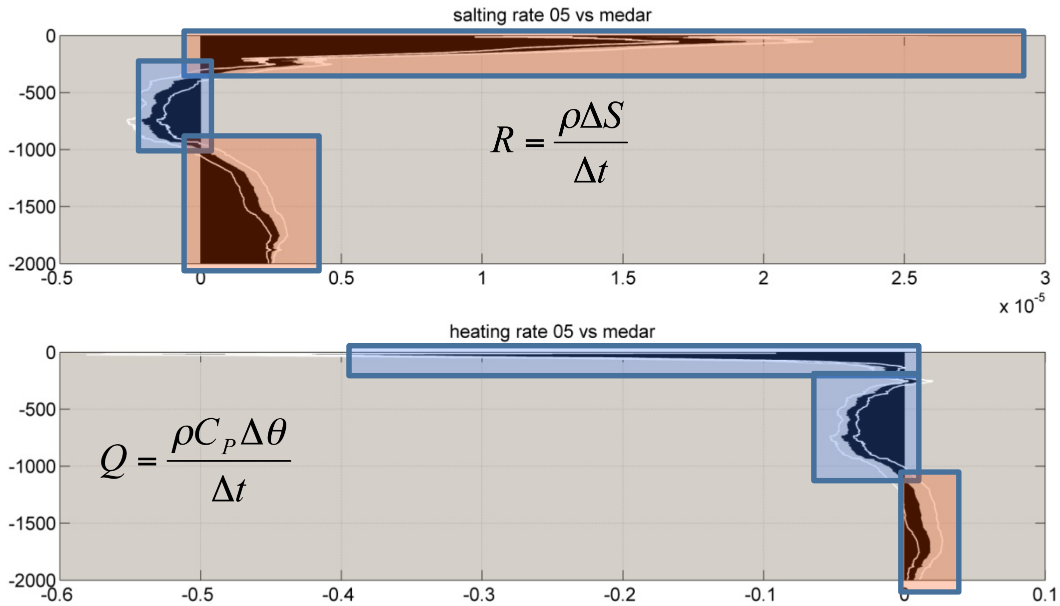
Even if exceptional, could the severe winter conditions alone have triggered the formation of such warm and salty new deep water?

If they had acted onto a climatological water column in the Gulf of Lions, what would have been its resulting heat and salt content?

Heat/salt content of a climatological water column

vs

Heat/salt content of the (observed) post-winter water column



Vertical distribution of salt (g m^{-3} s^{-1}) and heat (W m^{-3}) changes between the post-convection profile and the climatological profile in the Gulf of Lions

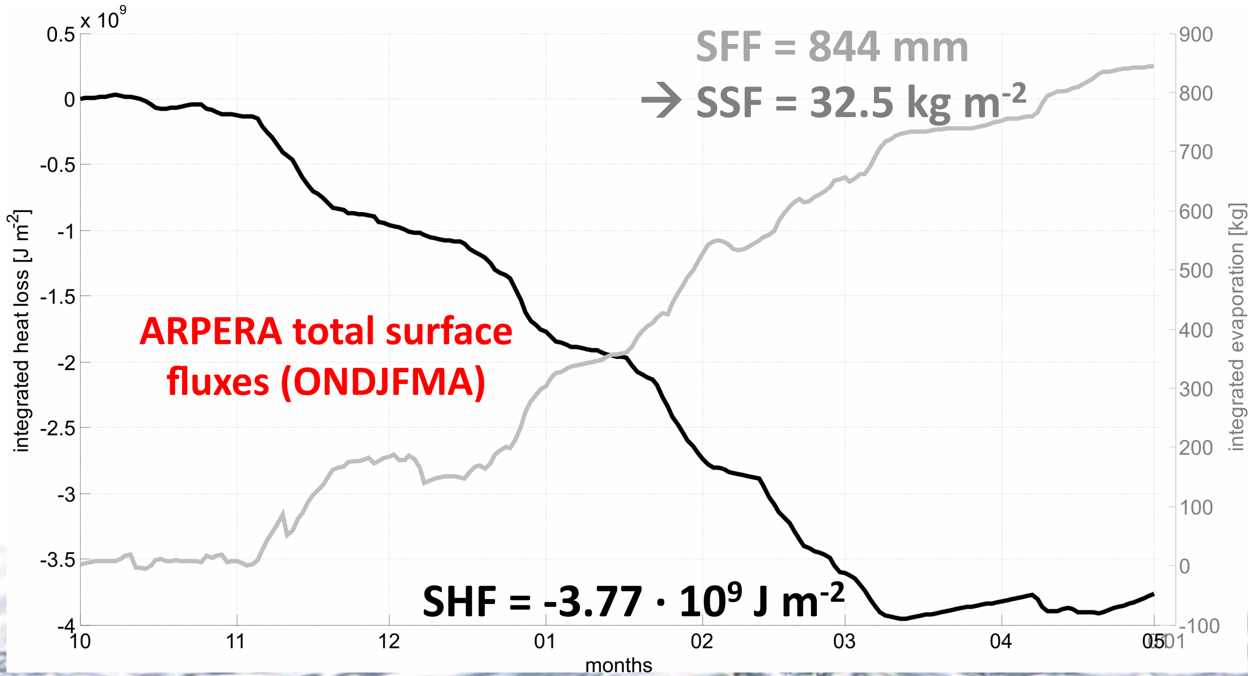
(*Schroeder et al., 2010*)

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

In the absence of any **lateral advection** of heat/salt, the total heat/salt content change would be equivalent to the net **surface** heat/salt **flux** over the water column.

$$-6.24 \cdot 10^8 \text{ J m}^{-2} = \Delta HC = SHF + LHF$$

$$66.3 \text{ kg m}^{-2} = \Delta SC = SSF + LSF$$



Legend

SHF/SSF surface heat/salt flux

SFF surface freshwater flux

LHF/LSF lateral heat/salt flux

ΔHC/ ΔHC heat/ salt content change

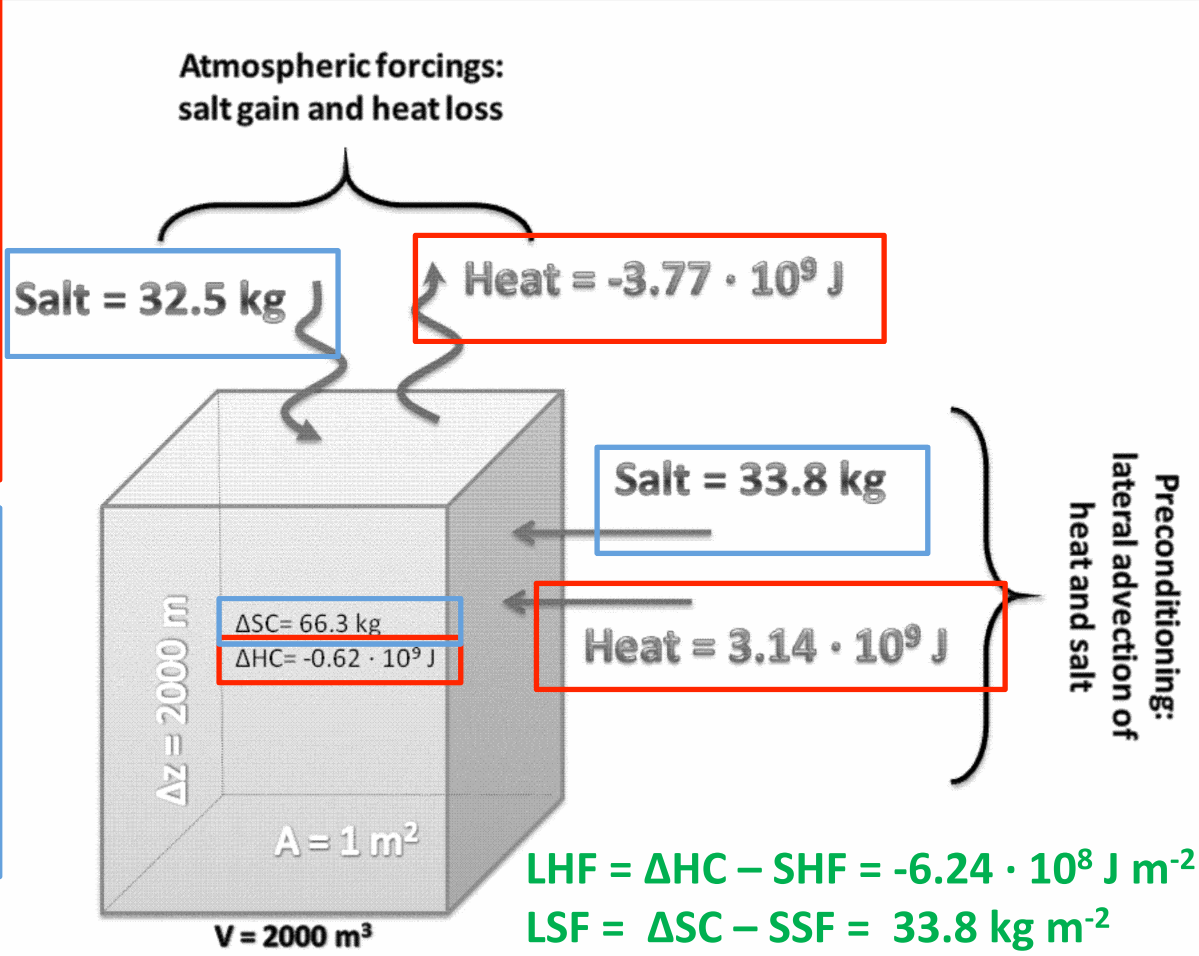
(*Schroeder et al., 2010*)

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

The convection region has received laterally a higher amount of heat and salt, in accordance with the long-term accumulation of heat and salt

The large net heat loss should have induced a strong cooling of the water column which actually cooled only slightly
→ before the convective period a higher amount of heat was advected, almost compensating the loss to the atmosphere.

The net evaporation during this winter, even if very high compared to the climatology for this season could have induced only **49%** of the actual observed increase in the salt content.



LHF = ΔHC – SHF = $-6.24 \cdot 10^{8}$ J m^{-2}

LSF = ΔSC – SSF = 33.8 kg m^{-2}

(*Schroeder et al., 2010*)

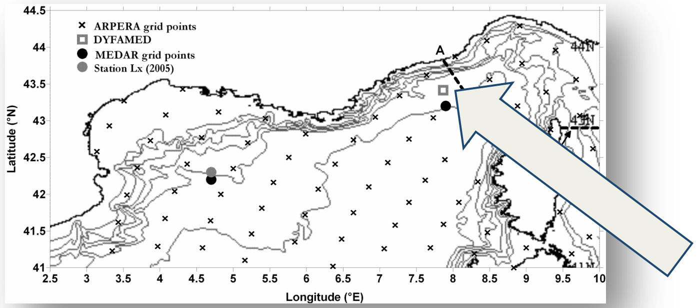
Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

Are these values computed for the lateral fluxes realistic?

Comparison with DYFAMED

LHF = 3.14 · 10^9 J m^{-2} → 1.57 · 10^6 J m^{-3}

LSF = 33.8 kg m^{-2} → 16.9 · 10^{-3} kg m^{-3}



anomalies of heat and salt contents in the water advected toward the convection region

We checked if the heat/salt contents at DYFAMED have increased with respect to climatology and in which layers

→ we assume that the water undergoing convection in winter 2004/05 was in the DYFAMED region in fall 2004.

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

Our Estimates

LHF = $3.14 \cdot 10^9$ J m^{-2}

LSF = 33.8 kg m^{-2}

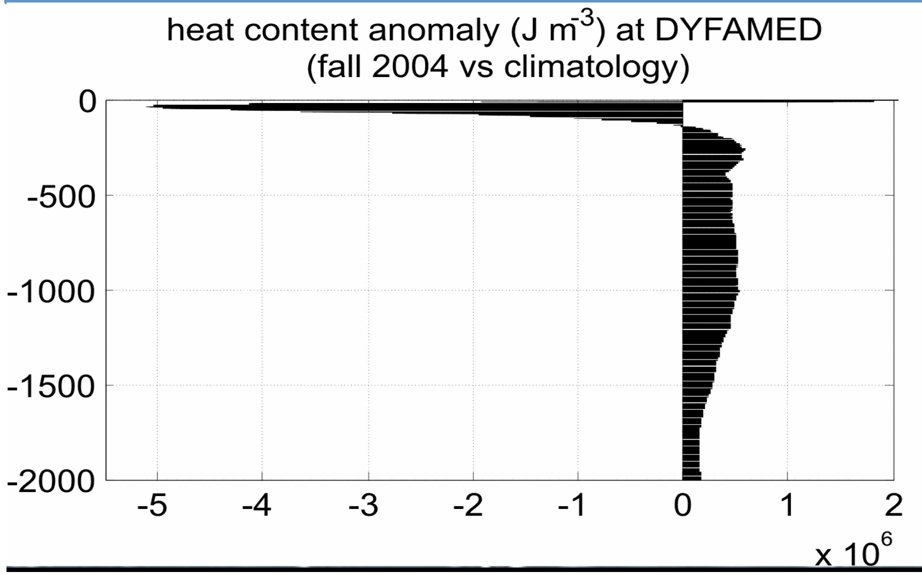
Anomalies at DYFAMED

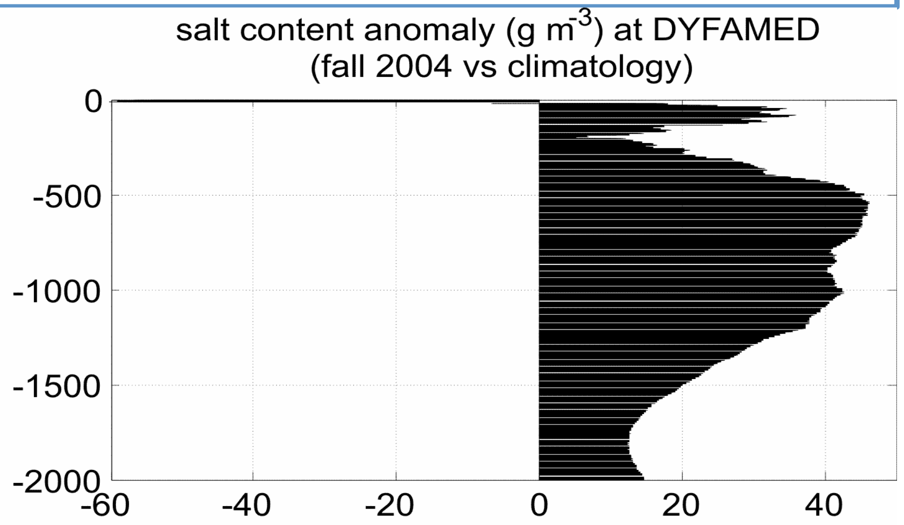
Heat content: $0.44 \cdot 10^9$ J m^{-2}

Salt content: 57.0 kg m^{-2}

The heat content anomaly is one order of magnitude smaller than the estimated LHF

The observed salt content anomaly in the Ligurian Sea would have been more than enough to explain the estimated LSF to the convection region: the main contribution is due to the **intermediate layer**, with a peak at 500–700 m, typically occupied by the LIW coming from the eastern basin.

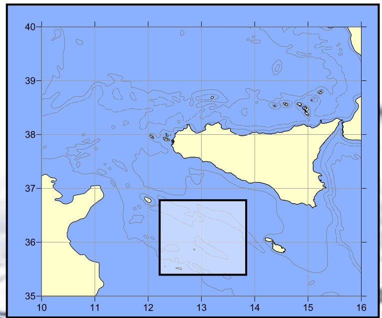


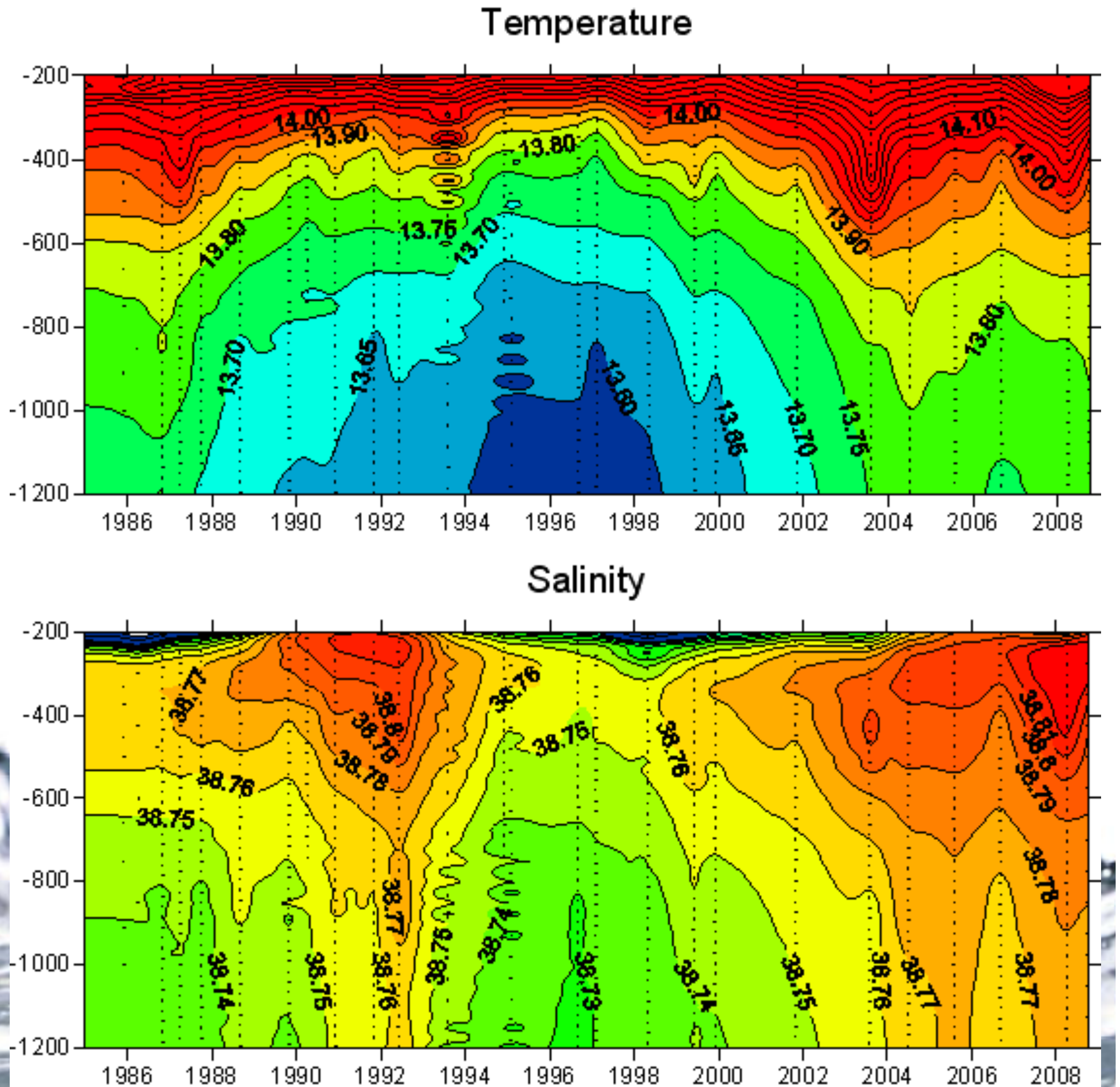


(*Schroeder et al., 2010*)

Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

More salt and heat is continuously arriving from the Eastern Mediterranean



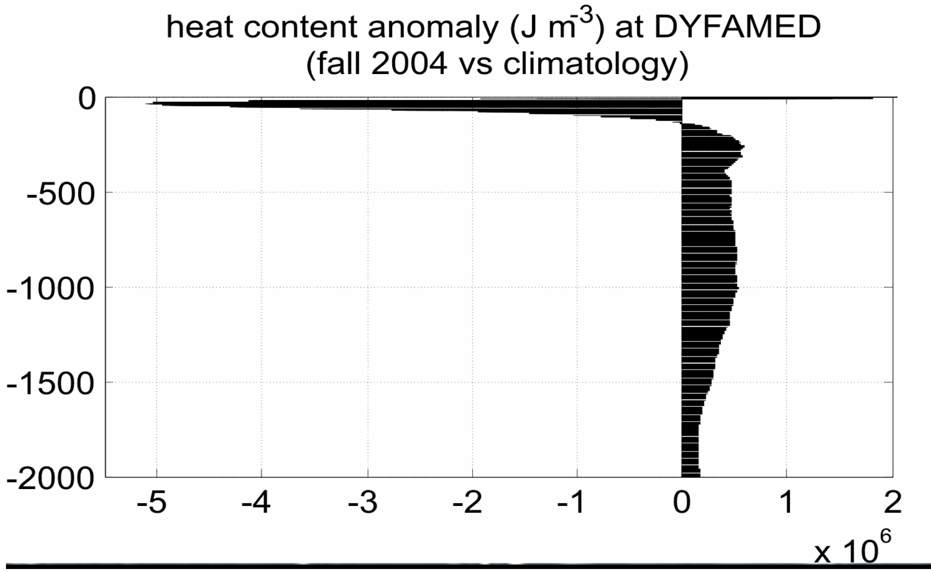


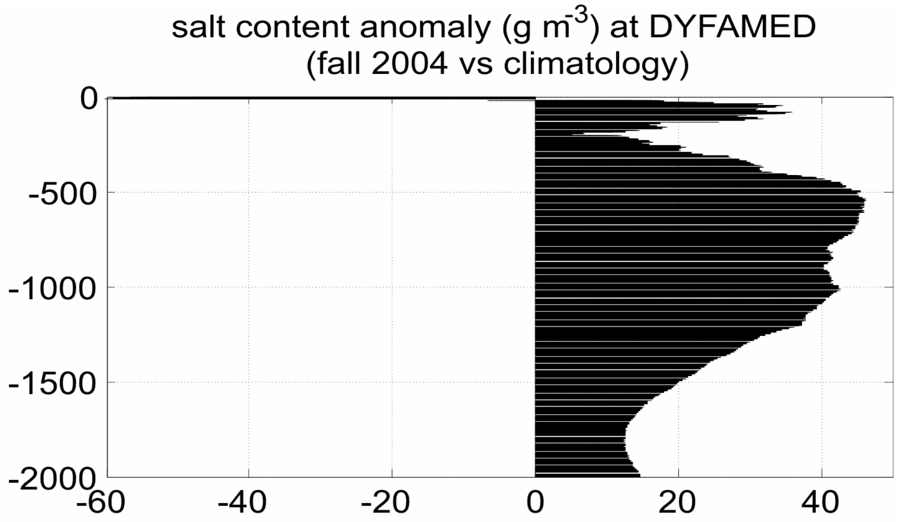
Impact of surface and lateral fluxes on the new WMDW properties in winter 2004–2005

The hypothesis of a major role of **lateral salt advection** in setting the new WMDW properties is consistent with observations.

On the other hand, the increased heat content in the Ligurian Sea is **not sufficient** to explain the required lateral heat advection to the convection region:

-the region has **exported heat** *during* the convection, due to mesoscale structures
-the strong heat loss to the atmosphere during winter 2004–2005 mainly **removed the heat accumulated during summer 2004**





(*Schroeder et al., 2010*)

Outlook and future priorities

- The deep water properties and their variability are mainly due to the **hydrographic preconditioning** (heat and salt content and structure of the water column before the onset of convection), and to the **atmospheric forcings** (heat, freshwater and buoyancy fluxes during the convection period)

- Starting from 2005, a **thermohaline anomaly** is spreading throughout the western basin, filling its deeper part below 1500–2000 m depth, significantly accelerating the ventilation of the deep layers. This phenomenon has been called **the Western Mediterranean Transition**

- With regard to the driving meteorological terms, we found that the 2004–2005 field had a much stronger east-west pressure gradient in the WMED than in the previous winters and seems to resemble the **negative phase of the East Atlantic Pattern**

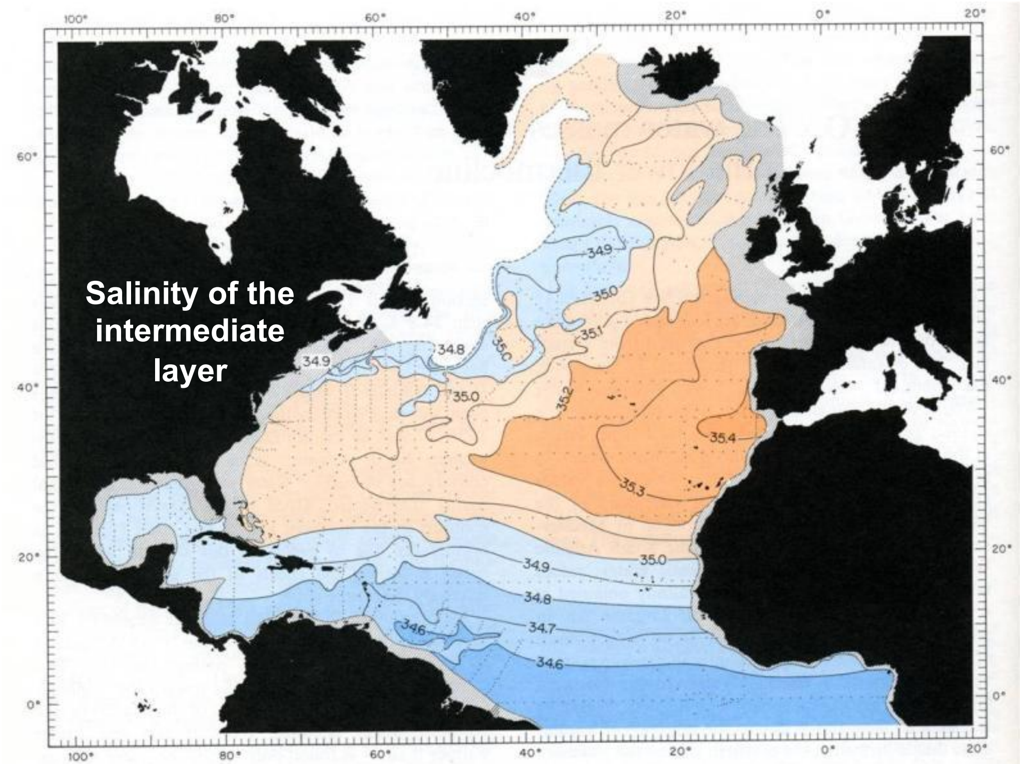
Outlook and future priorities

- After the DWF events there were simultaneous salt and heat **increases in the deep layer** (1200–2000 m) and salt and heat **decreases in the intermediate layer** (400–1200 m).

- This evolution suggests that the increased temperature and salinity observed in the new WMDW is mainly due to **internal salt and heat redistribution** between intermediate and deep layers.

- 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**

Outlook and future priorities



The Mediterranean, being a direct and continuous **source of warm and salty water**, plays a substantial role in the heat and salt contents and water formation processes in the northern Atlantic.

→ understanding the interannual variability of the Mediterranean Sea itself, has a more global importance than previously thought.

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