High resolution realistic modelling of dense water formation in the north-western Mediterranean

(programs MerMex and HyMeX)

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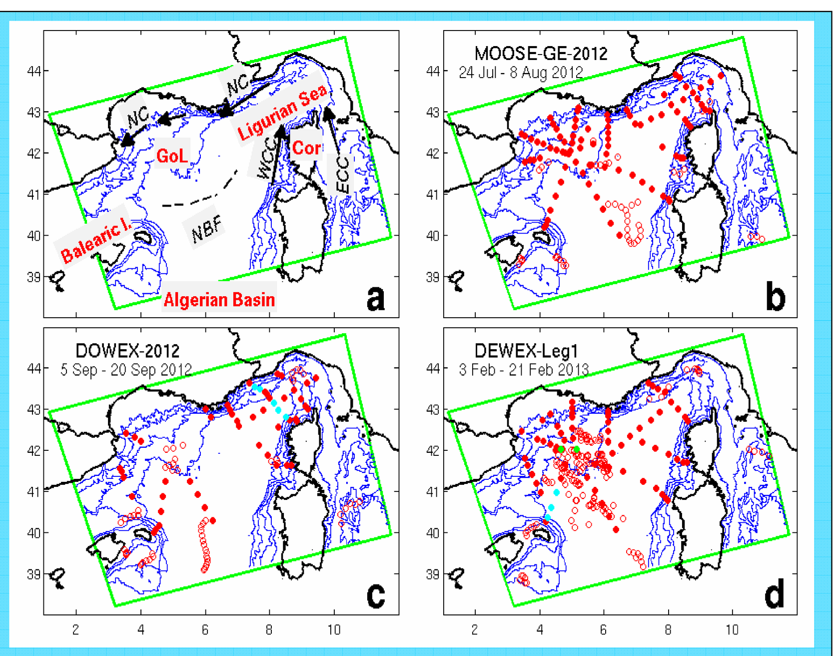
1.1 Objectives

The huge effort on dense water formation undertaken as part of the HyMeX and MERMEX programs completed by the regular monitoring by the MOOSE program makes it possible to study in details the different phases of dense water formation: the preconditioning in fall, the formation in winter and dispersion in spring and summer. In this study, a mass budget is calculated over the convection area and the role of the different physical processes is discussed.

1.2 Methodology

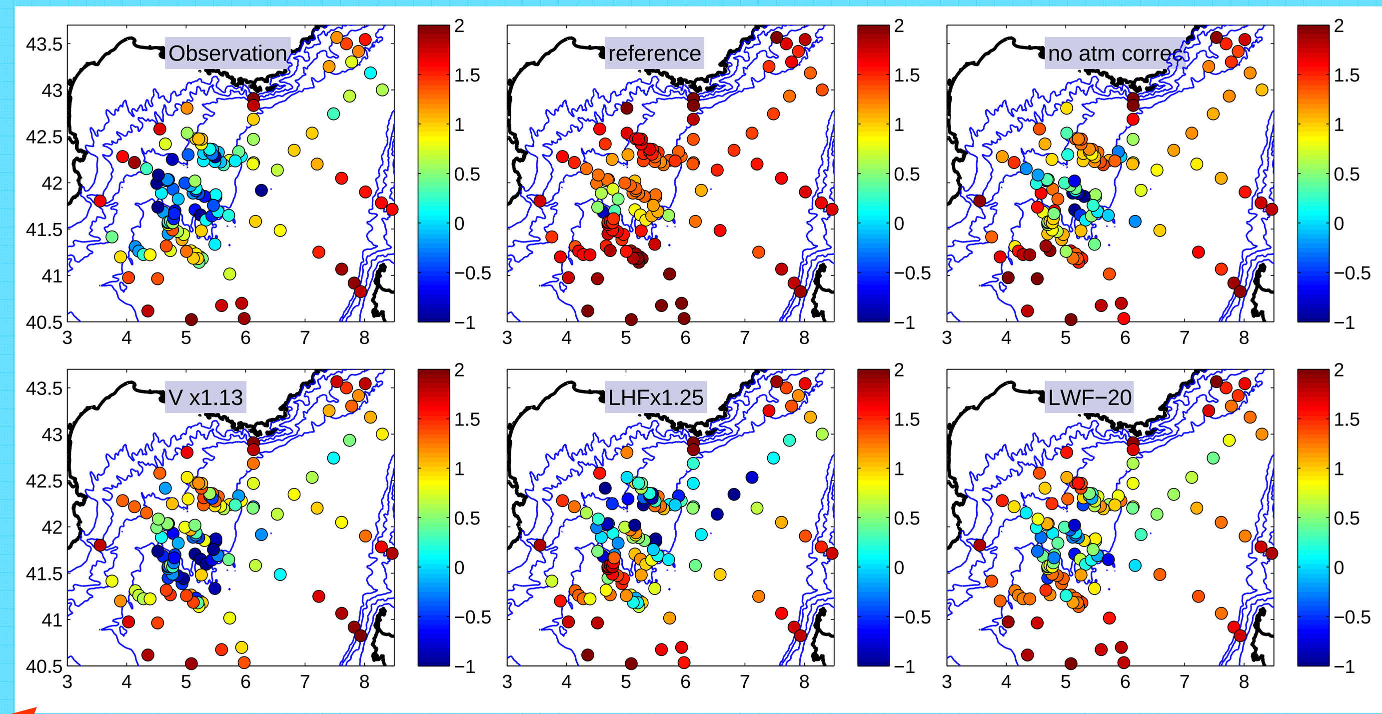
A high resolution (1km) 3D simulation is constrained with observations to accurately reproduce the convection during winter 2012-2013. The Symphonie model is initialized with the MERCATOR analyses. Major point for the realism of the simulation, the initial state is improved using corrections deduced from CTD from the MOOSE 2012 cruise – see frame b- (Estournel et al., subm.). The atmospheric forcing is based on the bulk formulae of Large and Yeager calculated with the ECMWF one-day forecasts. Ocean atmosphere fluxes have to be as accurate as possible in order to correctly represent the convection history. For this objective, 10 simulations have been performed with variations of the wind, latent heat flux (multiplicative term) and heat budget (additive term). The simulations which are the closest of the observations of February 2013 (see frame d) are further analysed.



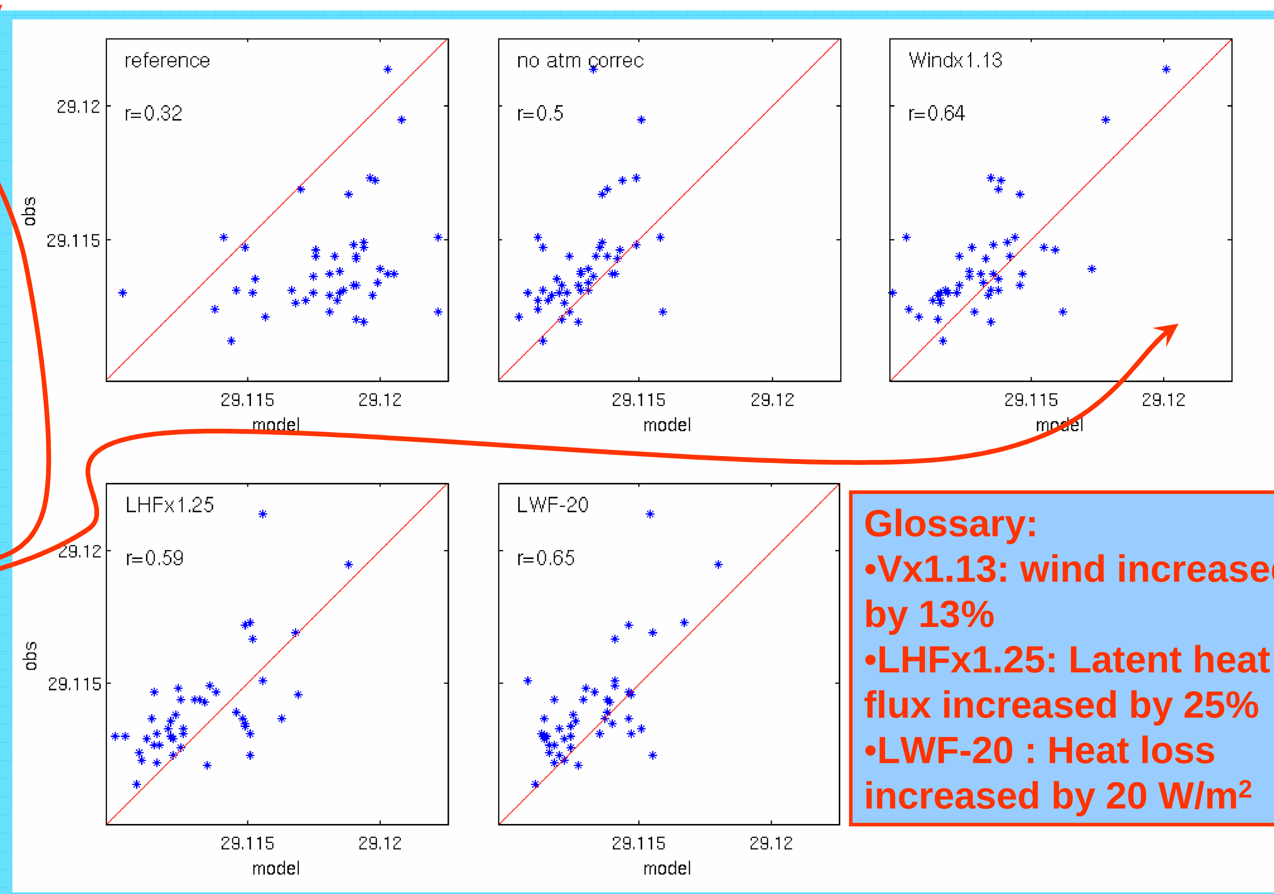
Numerical domain. The points correspond to the observations available during the different cruises of the annual cycle 2012-13

1.3 Simulations and Validation

Several simulations are compared to observations of February 2013. Here the **decimal log of the stratification index at 1000m in kg/m2** represented at the CTD and Argo points. The small values in blue correspond to the largest mixing in the centre of the Gulf of Lion. The « reference » simulation without initial state correction is too much stratified. The other simulations use a corrected initial state. The simulation without increased OA fluxes (no atm correc) presents an improved deep mixing even if still too low. Simulations with increased fluxes perform better.



Comparison with observed potential density at 2000m. The « reference » simulation (with a biased initial state) has densities too low and not correlated to observations. The correlation is strongly increased when the initial state is corrected and still increased when surface fluxes are increased. In the following analysis, we use the simulation with the 13% wind increase which is the closest to observations.

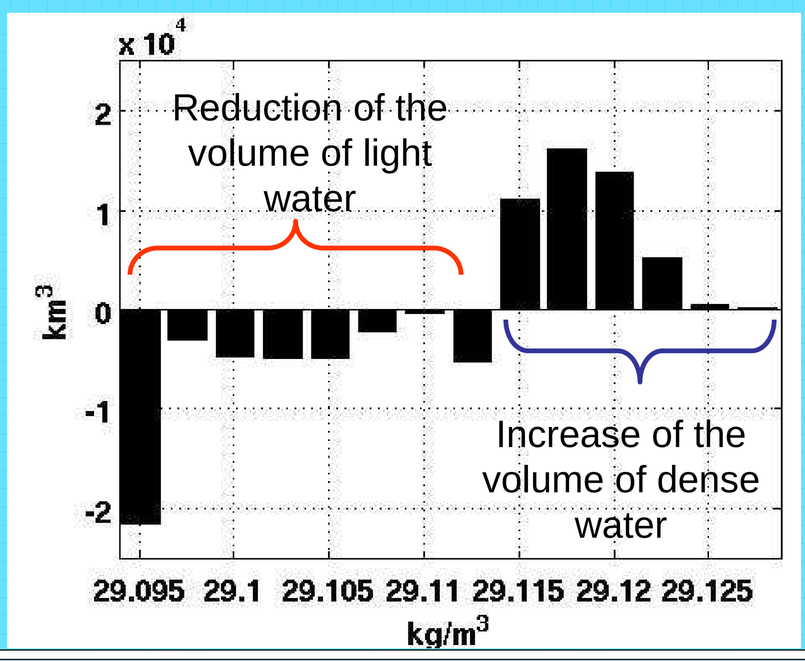


Glossary:
- **Vx1.13: wind increased by 13%**
- **LHFx1.25: Latent heat flux increased by 25%**
- **LWF-20 : Heat loss increased by 20 W/m²**

1.4 Estimation of the volume of dense water

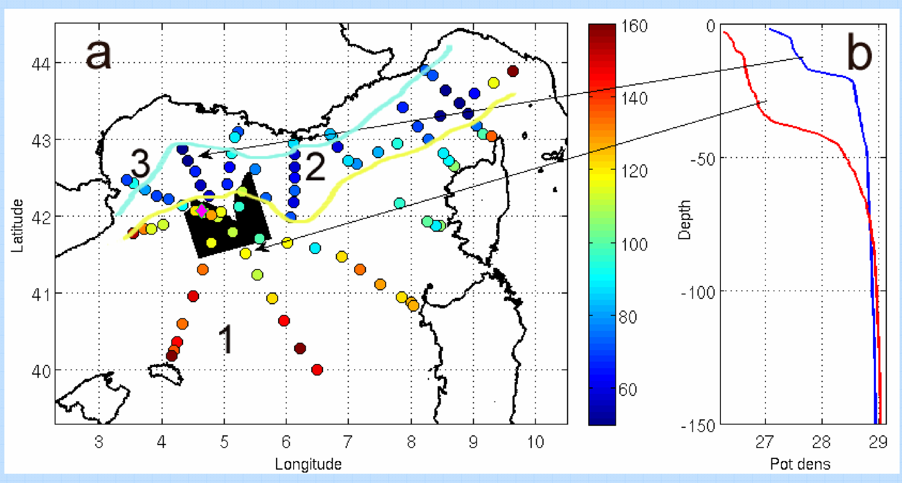
Our « best » simulation produces a volume of dense water of 50.000 km3 equivalent to a mean annual production of 1.6 Sv.

Difference between the volume after the end of convection and September 2012 calculated in density classes.



2. Destratification in autumn: importance of frontal processes

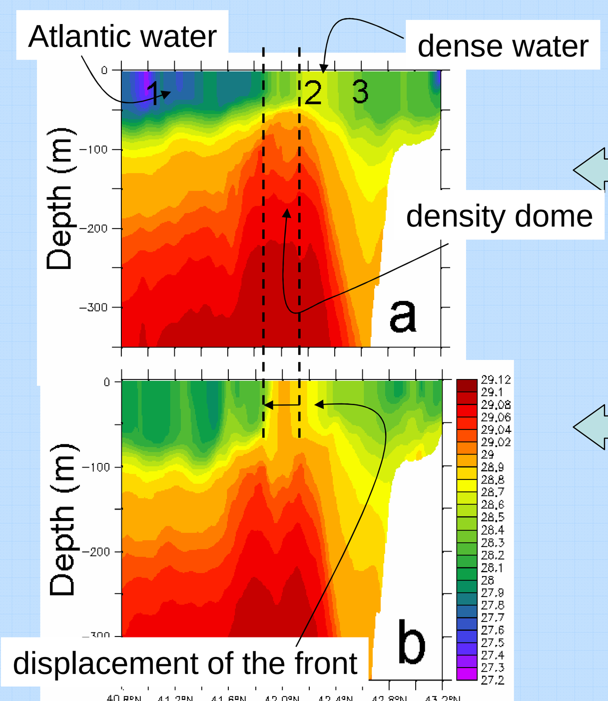
2.1 Surface stratification in summer



northwest- southeast section of density before (a) and after (b) the wind event of late November

On the left, the **stratification index** (SI) relative to 200m is calculated from all the CTD of Moose2012. The center of the winter convection zone ~42°N 5°E is in summer in the light Atlantic waters (high stratification index in red). Dense waters (low stratification index in blue) are confined to the north. **These two water masses are separated by the North Balearic Front**. On the right, typical density profiles of the two regions are shown

$$SI(Z)=\int_{Z}^{0}(\rho(Z)-\rho(z))\,dz$$

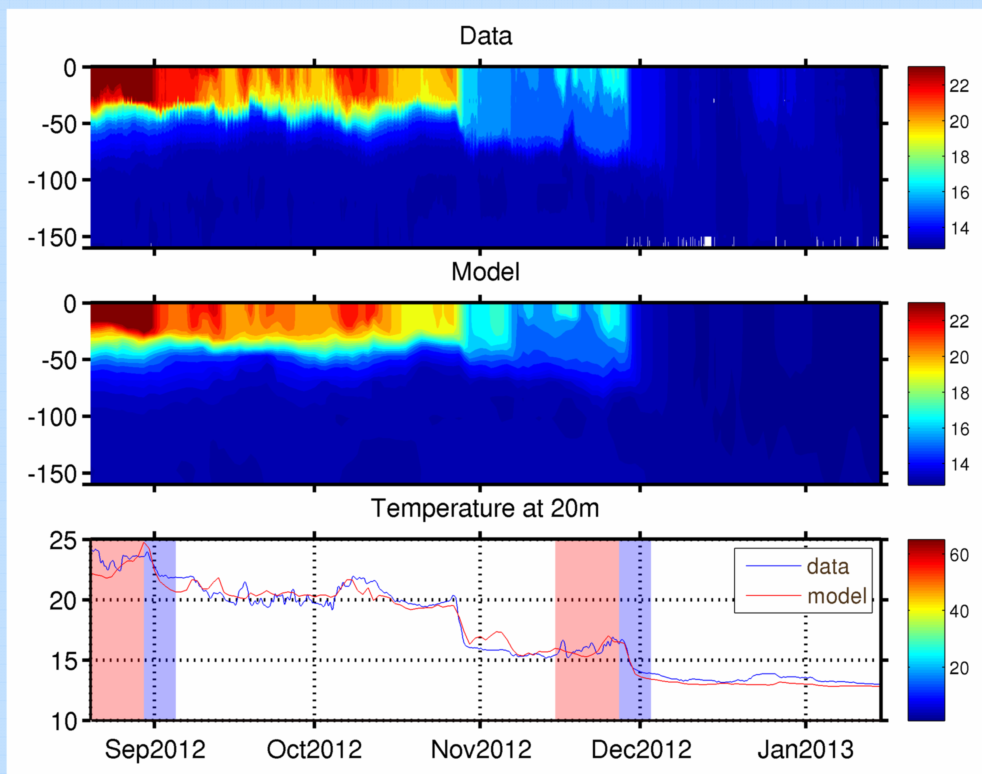


Impact of the wind on the position of the front

When the north **wind is weak** and the stratification is strong (summer, early fall), a thin layer of light Atlantic waters (region 1) spreads northward over the dense water (region 2). This situation leads to the stratification map shown above.

When the **north wind blows**, the Ekman transport pushes the surface waters south-westward. The North Balearic front is shifted to the South (here by ~30 km). As the wind has a down-front component in this region, it induces an Ekman buoyancy flux (scalar product of the wind stress and horizontal density gradient) which adds to the classical surface buoyancy flux to produce an important thickening of the MLD.

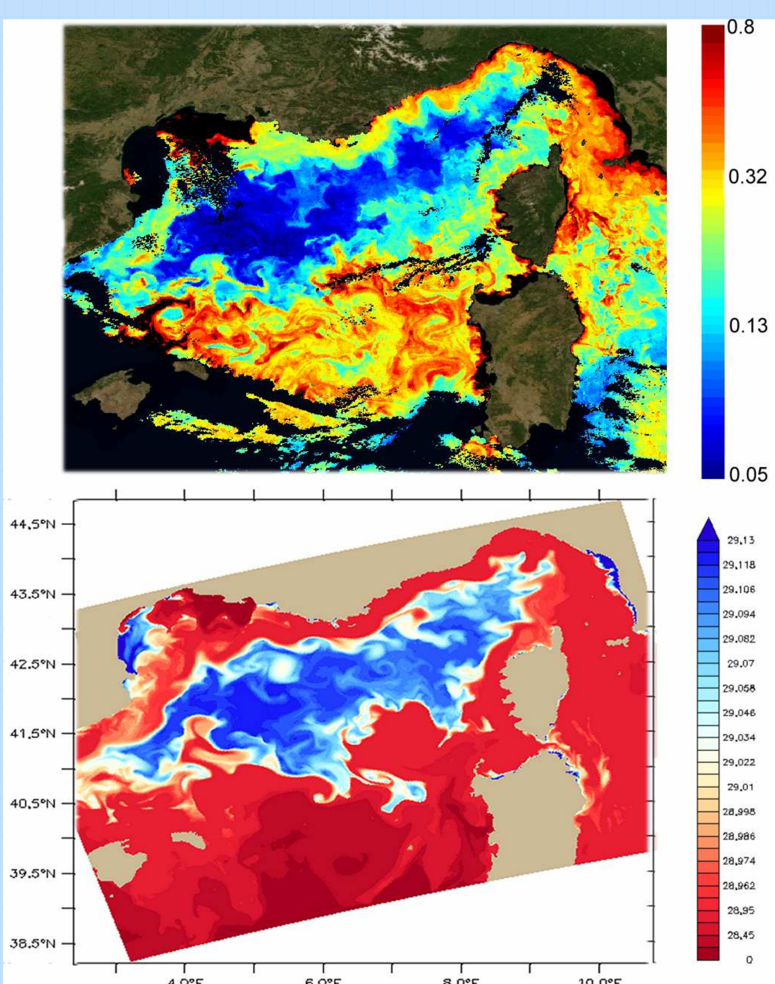
2.2 Evolution of the MLD in autumn



During autumn, the processes detailed on the left, due to the alternance of the low and strong wind conditions and their impacts on the North Balearic Front explain the alternance of strong cooling (blue bars) and low warming (pink bars) superimposed on the general cooling of the surface waters observed at the LION buoy. The LION buoy do not observe 1D processes!

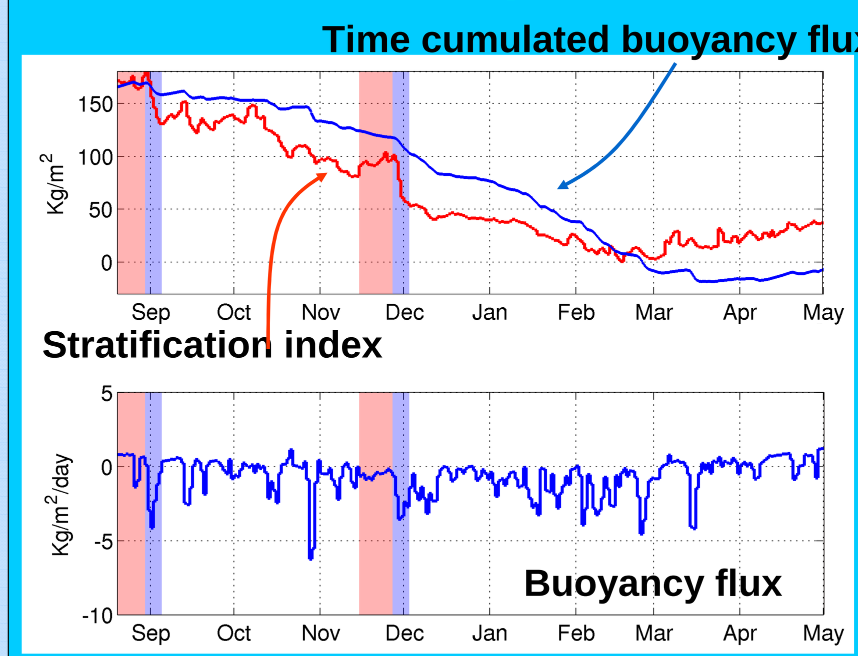
Note that the simulation very well reproduces the observed chronology.

3. Mesoscale structures in winter



In winter, because of the thickening of the MLD, the front between the convective layer and light water became baroclinically unstable. As shown on an ocean color image of 19 February 2013 (top), meanders developed and light and dense waters (respectively rich and poor in chlorophyll) interpenetrate. The size of these structures was rather well represented by the numerical model, as shown by the surface potential density map averaged over the same day (bottom). In both cases, structures of about 20 km can be seen at the periphery of the mixed patch together with filaments of about 10 km in width developing inside the patch. The 1 km model resolution appears relevant to represent the wide range of scales present in the convective area.

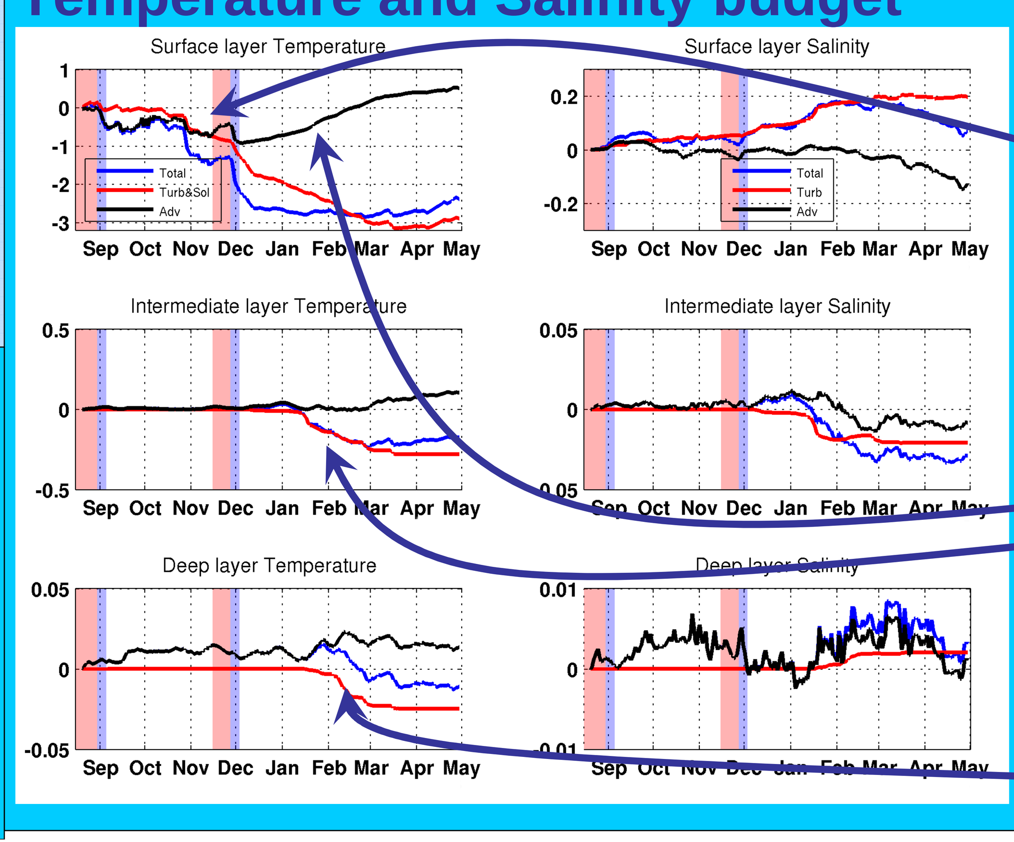
4. Vertical processes vs horizontal processes - Budget



Integrated over **autumn** (Sept, Oct and Nov) and the "convection" box, the decrease of the stratification index (red) is stronger than the decrease due to surface fluxes (blue) meaning that **horizontal processes destrafify**.
The low wind periods (pink bars) are associated to an increase of stratification while strong destratification and cooling are visible during strong wind periods (blue bars).

In **winter** (Jan, Feb and March), the decrease of the stratification index is slower than imposed by surface fluxes meaning that **horizontal processes stratify**.

Temperature and Salinity budget



A budget has been calculated in the convection zone over the three main layers. The black curve corresponds to advection and the red one to 1D processes (turbulent mixing and solar heating).

<u>**In autumn**</u>, advection tends to cool and densify the water column as the temperature decrease of the water mass is higher when the front shifts to the south than the inverse trend when the front goes back to the north. This is a result of the Ekman buoyancy flux along the parts of the front where the wind is // to the isopycnals. Turbulent+solar fluxes represent about 60% of the total fluxes and advection 40%

<u>**In winter**</u>, advection stratifies the water column mainly in the surface layer. The stratifying effect of advection represents 58% of the destratifying effect of surface fluxes.
In mid-January, convection mixes the intermediate layer with the surface layer. The effect of entrainment of intermediate waters in the mixed layer is to decrease their mean temperature and salinity as the maximum of their properties is diluted by mixing with surface water.
The deep layer is progressively mixed from the end of January.

5. Conclusion

Importance of Ekman buoyancy flux in autumn along the North Balearic Front: high contribution to the destratification of the « future » convection zone and to its widening

Importance of advection in winter counterbalancing the effect of surface buoyancy fluxes