

Interactive comment on “Dynamics of North Balearic Front during an autumn Tramontane and Mistral storm: air–sea coupling processes and stratification budget diagnostic” by Léo Seyfried et al.

Léo Seyfried et al.

leo.seyfried@aero.obs-mip.fr

Received and published: 6 September 2018

Response to Referee 2

Authors' Answer: The paper has been revised according to the comments from the reviewers and we thank both reviewers for their very helpful comments and suggestions. Our point-by-point response is inserted in the reviewer's comments.

Reviewer's Comment: The paper presents an original study of the North Balearic Front dynamics during a strong wind event, combining observations, high-resolution coupled

C1

modelling and stratification budget. The authors give a complete overview of the atmospheric event and of the ocean front evolution. The validation of the coupled simulation is very convincing. The use of a stratification budget seems very promising in particular to better understand the coupled mechanisms involved. Nevertheless, the fact that the equations are not fully detailed and that the residual term is not described but finally appears as a dominant term, gives the impression that only a part of this budget is considered. Consequently, I suggest some major revisions to improve the paper before accepting its publication.

So, my main comment concerns the stratification budget (section 6) which is very briefly presented:

First, it could be very helpful to give a physical view of EBF. Reading Thomas and Lee (2005), I understood it is a destabilizing flux leading to convection and frontal intensification, but clearly I am not sure about my interpretation.

AA: Rephrased and Added sentences p10, line 9 to 23 : “The stratification variation of water column can be modified through diabatic processes and horizontal or vertical advection of buoyancy. Most models assume that the stratification budget is essentially driven by one-dimensional turbulent mixing of heat and water at air-sea interface. Following Merstens and Schott (1998) the air-sea exchanges induce a surface or diabatic buoyancy flux can be diagnosed as :

$$B_0 = g\alpha \frac{Q_{net}}{\rho_0 C_p} + g\beta SSS(E - P) \quad (1)$$

where B_0 is the diabatic buoyancy flux in $\text{m}^2 \text{s}^{-3}$, α the thermal expansion coefficient in K^{-1} , C_p the specific heat capacity in $\text{J kg}^{-1} \text{K}^{-1}$, β the saline contraction coefficient, SSS the sea surface salinity, E the evaporation and P the precipitations in m s^{-1} .

This one-dimensional approximation is suitable if the ocean is horizontally homogeneous. In reality, mesoscale and submesoscale structures populate the ocean. Theses

C2

structures are marked by horizontal buoyancy fronts. As shown by Thomas and Lee (2005) and Thomas and Ferrari (2008), the stratification can be significantly modified by interactions between these fronts and Ekman flow generated by frictional forcing. When the winds are down-front, the density advection of dense water over light water by Ekman transport destabilizes the water column and triggers convection. This process destratifies the water column by Ekman advection of buoyancy and mixing through the mixed layer. On the contrary when the winds are up-front the Ekman flow yields an Ekman advective restratification in the surface layer. Following Thomas and Taylor (2010), the frictional forcing induces a wind-driven or Ekman Buoyancy Flux (EBF) which can be diagnosed as :

$$EBF = -\frac{g}{\rho_0} \vec{M}_e \cdot \vec{\nabla}_h \rho_{(z=0)} \quad (2)$$

where EBF is the Ekman Buoyancy Flux in $m^2 s^{-3}$, $\vec{M}_e$ the Ekman transport (Eq. 3) in $m^2 s^{-1}$, $\vec{\nabla}_h$ the horizontal gradient, g the gravitational acceleration and $\rho_{(z=0)}$ the surface density in $kg m^{-3}$.

$$\vec{M}_e = \frac{\hat{z} \times \vec{\tau}}{\rho_0 \zeta_a} \quad (3)$$

where $\hat{z}$ is the vertical unit vector, $\vec{\tau}$ the wind stress in $N m^{-2}$, and ζ_a the absolute vorticity in s^{-1} .

RC: p10, line 10: "the friction induced a wind-driven or Ekman Buoyancy Flux (EBF) given by:"

AA: Modified

RC: Where does equation 6 come from? There is no residual term in equation 13 of Thomas and Lee (2005)? What is the value of H considered? Is the equation valid for any H or is there a limit considering the depth of the Ekman layer?

C3

AA: I think you want to talk about equation 5. The variation of the water column stratification between times T1 et T2 can be approximated by the integral of the buoyancy flux that applies on the water column between time T1 and T2. As described above, two types of buoyancy flux generated by the air-sea exchanges can be distinguished: The diabatic buoyancy flux generated by the heat and water exchanges and the Ekman buoyancy flux generated by frictional forces. Equation 13 of Thomas and Lee (2005) corresponds to the sum of these two fluxes. As shown by Thomas and Ferrari (2008), diabatic processes and frictional forces are the only processes that can generate and destroy stratification. Our stratification budget diagnosis aims at assessing the competing roles of the diabatic buoyancy flux and Ekman buoyancy flux on the stratification evolution. However, the stratification of the water column can also be modified by horizontal and vertical advection of buoyancy. There is several sources of buoyancy advection in the water column (geostrophic circulation, frontogenesis, Ekman pumping, ...) which are in our budget induced in the so called residual term. The computation of these three terms (diabatic buoyancy flux, Ekman buoyancy flux and residual) provides a rough estimate of their respective contributions to the stratification evolution.

In our case we considered $H = 250$ m with $H > MLD$. Tests were performed with $H = 1000$ m and $H = 1500$, the results remain unchanged. In theory, the equation of Ekman buoyancy flux is valid as long as $MLD \gg$ Ekman layer depth. However, Thomas and Lee (2005) show that this hypothesis is not crucial and the MLD can be of the same order of magnitude as the Ekman layer. In our case, the Ekman layer depth is about 30 m and the MLD about 50m.

To clarify Equation 5, we added this paragraph p10 l23: " The stratification index variation at depth H (with $H = 250$ m, $H > MLD$) between times T1 and T2 can be approximated by the integral of buoyancy mass flux between times T1 and T2 (Eq 5). In order to evaluate the competing roles of the diabatic and Ekman buoyancy fluxes on stratification variation, these two term are diagnosed and compared to the stratification variations. Finally, to close our stratification budget diagnosis we evaluate the resid-

C4

ual term corresponding to other potential sources of horizontal and vertical advection of buoyancy (geostrophic circulation, frontogenesis, Ekman pumping, ...) that are not directly diagnosed in this study".

RC: Maybe, one possibility to clarify this section is to give an enlarged description of the reasoning in an annexe. Obviously, the idea is not to reproduce the work from Thomas and Lee (2005) but to try to give the main insights.

AA: The work of Thomas and Lee (2005) is now more detailed in section 6 (see above).

RC: Concerning the residual term, it appears later in the text that you can attribute its value to horizontal advection or vertical advection/Ekman pumping. How? If there is a way, you must extract these terms from R and plot their values to complete the stratification budget.

AA: Extract the different terms of the residue is not the purpose of the paper which aims to compare the respective impact of diabatic processes and frictional forces on the evolution of stratification. In future work it would be interesting to calculate a buoyancy flux generated by Ekman pumping. However, this computation is not straightforward in a 3D realistic simulation.

RC: Finally, in section 7, it could be also interesting to discuss the possible limitations due to the hydrostatic assumption or to the convection parameterization in the ocean model.

AA: One limitation of turbulence parameterization is that the turbulence at surface is driven only by atmospheric forcing. Large Eddy Simulation (LES) with explicit resolution of turbulence shows that turbulence can also be generated through frontal instabilities (Thomas et al. 2013). It would be interesting to set up an realistic LES configuration in NWMS (currently too expensive) to explicitly solve turbulence and convective processes and to compare to our hydrostatic simulation.

Other comments:

C5

RC: p2, lines 2-9: There is a kind of mixing between front/current in the very first sentence of the introduction. In my opinion, it could be helpful to describe the cyclonic circulation with the various branches/currents and then how it constrains/forms the surface density gradient?

AA: Rephrased sentences: "The surface circulation in the North Western Mediterranean Sea (NWMS) is formed by a cyclonic oceanic gyre (Fig. 1). This cyclonic gyre is closed to the north and west by the Northern Current (Millot, 1999), and to the east by the West Corsica Current (WCC) (Fig. 1). The south branch of the surface gyre is defined by a frontal zone, the so-called North Balearic Front (NBF). The NBF is an extension of the Balearic Current (BC), from the Balearic Sea to the Ligurian Sea (Font et al., 1988). This surface density front (100-200 m deep) separates the warm and fresh Atlantic Water (AW) which has recently entered the south of the basin from the colder and saltier AW present in the center of cyclonic gyre (Millot and Taupier-Letage, 2005). This front forms a "Lagrangian barrier" (Mancho et al., 2008) which plays an important role on the nutrients budget and planktonic ecosystem (Estrada et al., 1999) and marine ecosystems distributions (Gannier and Praca, 2007; Cotté et al., 2011)."

RC: p2, line 21: "maintained strong precipitation offshore and over the southeastern French coasts"

AA: Done

RC: p2, lines 30-32: I am curious to know if there is any action of the perpendicular wind component?

AA: There is a perpendicular wind component but we have not studied its impact.

RC: p4, lines 20-21: It appears from fig 4 that the effective resolution of the OSTIA and Copernicus products are much larger than the indicated resolution (6 and 1 km, resp.). This is somehow mentioned p6, line 25 ("The horizontal resolution of the latter...of the model. "), but could be rapidly indicated in this section 2.2 or commented.

C6

AA: Rephrased and added sentences: “The first analysis is the global OSTIA product (Donlon et al., 2012), the horizontal resolution of which is about 6 km. This product is used in the ECMWF operational model. The second analysis is the Mediterranean Copernicus product (Buongiorno et al., 2013) provided at higher resolution (about 1 km). The spatial resolutions indicated above refers to the resolution at which the data are provided but not to their effective resolutions. ”

RC: p6, line 34: replace “extremity” by “end”.

AA: Done

RC: p8, lines 4-5 should not be in italic.

AA: Done

RC: p8, line 10: “Modified”: This is the first time this term appears. Could you explain it?

AA: This term correspond to the water mass named “Modified Atlantic Water (MAW)”, this water mass name is no longer used. “Modified” has been deleted.

RC: p9, line 16: Remove here the comment about density: “During strong wind event, evaporation dominated and led to an upward (positive) water flux.”

AA: Done

RC: p9, line 19: You may refer here to fig 2 (instead of fig 10a)?

AA: Done

RC: p10: See my main comment + Please, detail g,

AA: Done

RC: ρ_{00} , Q_{net} and F_w ; Some sentences should not be in italic.

AA: Done

C7

RC: p12, line 14: “during IOP16b”

AA: Done

RC: p13, line 26: “the front is less marked” this is not so clear for me from figs 4 and 7. Are you talking about a smoothing? a reduction of the temperature difference?

AA: We are talking about a reduction of the density gradient. “the front is less marked” has been replaced by “the surface density gradient is less marked”.

RC: p14, line 2: “For example, Thomas et al. (2016) show”

AA: Done

RC: p15: refs Drobinski et al. and Ducrocq et al. 2014; In addition, I think URLs in this “References” section must refer to the “doi.org” pages.

AA: The references are generated directly by Latex with the copernicus template.

RC: Figure 5: precise “observation” or “simulation” on each panel if possible. For (c), the caption tells it is the simulation bias but it seems to be more ‘glider minus simulation’

AA: Corrected.

RC: Figure 7c: The red contour is not visible.

AA: The red contour is not drawn in the figure c. The caption has been modified.

RC: Figure 8 is difficult to read. Please consider here to plot separately the density sections for 25 oct., 30 oct. and the differences.

AA: Figure 8 has been modified for better visibility.

RC: Figure 10: Please, improve the resolution in order to distinguish the arrows. Precise in the caption if the arrows are for the wind or the wind stress + a reference length for vectors must be added.

AA: The resolution has been increased. The arrow corresponds to the wind stress, this

C8

information added in the caption and a reference length for vectors is given.

RC: Figure 14: the plots of “B0+EBF” are not necessary

AA: The plots of “B0+EBF” has been deleted.

Interactive comment on Ocean Sci. Discuss., <https://doi.org/10.5194/os-2018-14>, 2018.

C9

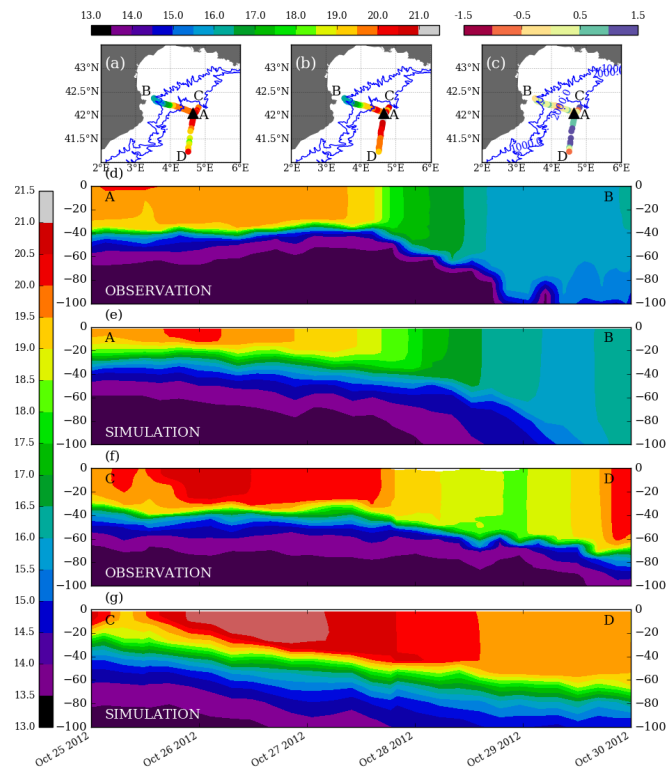


Fig. 1. SST measurement (a), simulation (b) and bias of the simulation (c), along the trajectory of the glider Eudoxus (moving westward) and Campe (moving southward). Vertical section of potential temperature

C10

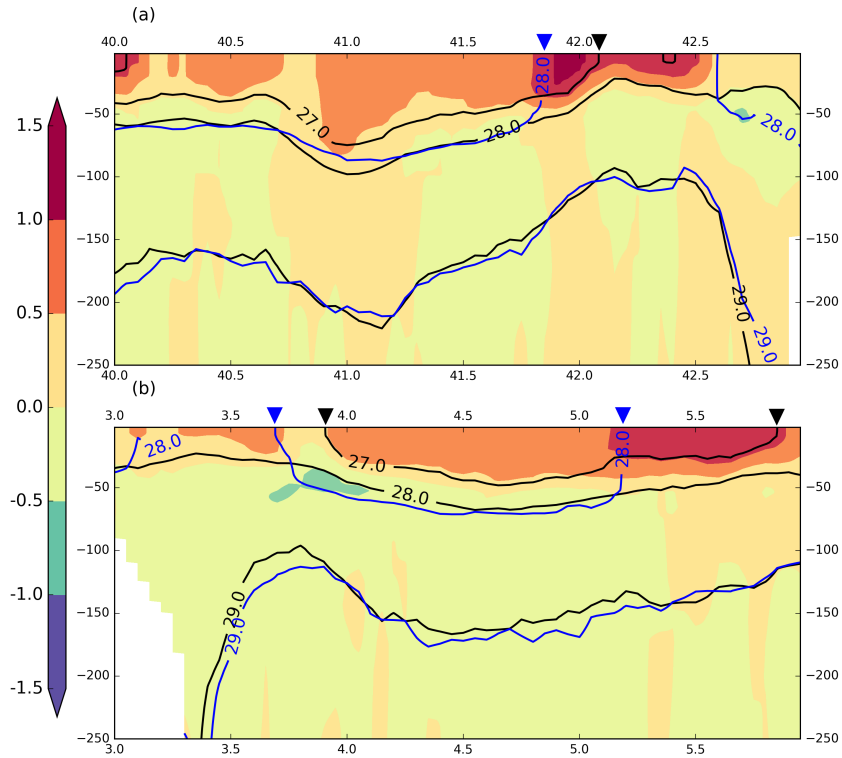


Fig. 2. (a) South-North section at 4.65°E and (b) West-East section at 41.7° N (see Fig. 7 for their positions) of the potential density difference between 0000 UTC on 30 Oct

C11

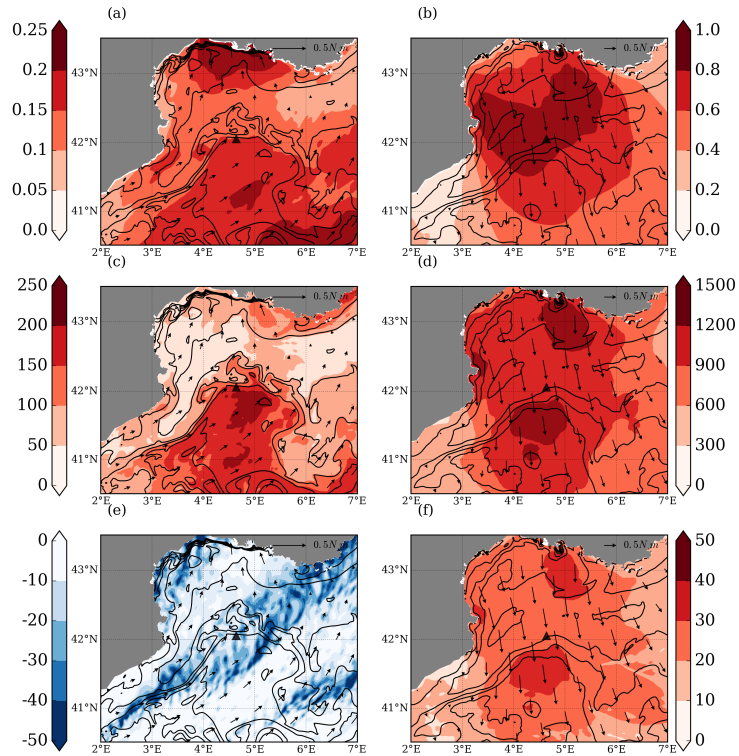


Fig. 3. (a and b) wind stress (N m^{-2}), (c and d) net surface heat flux (W m^{-2}), (e and f) surface water flux (mm day^{-1}) averaged over IOP16a (left column) and IOP16b (right)

C12

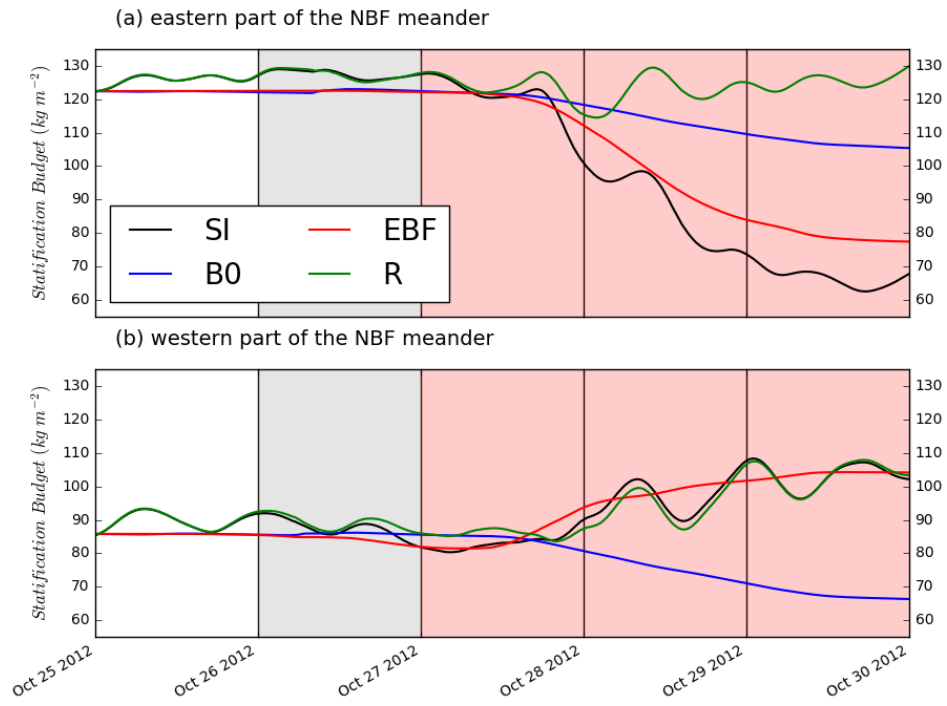


Fig. 4. Time series of the different terms of the stratification budget diagnosis (SI in black, diabatic buoyancy flux in blue, Ekman buoyancy flux in red and residual in green)