Response to the comments of the Ref. 3

C. 1: The manuscript encompassing a comprehensive introduction of the experimental apparatus and methodology followed by the authors and everything is very well conducted, except the relative role (scale ratio) of the central part of the tank respect to the sloping part. In fact, looking the figure 7 in the manuscript seems that the dynamics driven by the slope domain dominates on those generate in the flat domain, making difficult distinguishing the difference between the two dynamics. This isn't irrelevant to make more realistic the comparison with the northern Ionian Sea circulation in section 4.

Reply: *We thank the Referee very much for this comment and as our reply we added Appendix A (text below) where we present the similarity criteria between the laboratory experiment and the real ocean.*

"Appendix A: Dynamical similarity

The fundamental part of the experimental design is to achieve a "dynamical similarity" between the real-ocean and laboratory. In our case, to simulate the Adriatic overflow into the Ionian basin and to reproduce the North Ionian Gyre (NIG) reversals in the laboratory, two relevant non-dimensional numbers are considered to evaluate the dynamical similarity.

First, the Burger number gives the ratio between the internal Rossby radius of deformation and the geometrical scale of the Ionian basin/the rotating table for the experiment. Considering the depths of both, the laboratory and Ionian basin, the Coriolis parameter f and the density anomaly, expressed using the reduced gravity g', we obtain a similarity between ocean and laboratory phenomena from the experimental values indicated in section 2.1 Experimental design of the manuscript and in the Appendix B (see below). In particular, the combination of those values with an experimental slope of s=0.1 yields a Burger number of B_u=0.1 like the one observed in the ocean.

Another important similarity that should exist is between the in situ and laboratory ratios of the topographic slope and the initial geostrophic slope, which means that the non-dimensional number $S=g's(fV)^{-1}$, with V the initial (Adriatic) overflow velocity, must be preserved in the laboratory experiments. Considering these values for both the Ionian basin and Adriatic outflow and the similarity of Burger number, we selected the topographic slope of 0.1 in order to fall within the similarity values of the in situ conditions ranging approximately as $2.4<S<9.4$.

Finally, the experiments also preserved dynamical similarity accounting for frictional effects by considering the Ekman non-dimensional numbers."

"Appendix B: Turbulent diffusion

The turbulent diffusion could be estimated both in the central deep and the slope domain. In both areas the turbulent diffusivity can be associated with a stratified shear layer. The energy of a typical eddy of size L in this shear layer is of the order $E_t \sim (\varepsilon L)^{2/3}$, with ε being the dissipation rate in m^2s^{-3}, whereas the energy associated with buoyancy and shear is $E_b \sim (NL)^2$ and $E_s \sim (\partial u/\partial z L)^2$, respectively. Here $N^2 = -g(\partial\rho/\partial z)/\rho$ is the Brunt-Väisälä frequency and $\partial u/\partial z$ is the vertical shear.

Balancing turbulent and forcing components yields a buoyancy length (i.e., the Ozmidov length scale) $L_o = (\varepsilon N^{-3})^{1/2}$ and a shear length $L_s = (\varepsilon <\partial u/\partial z>^{-3})^{1/2}$. This latter scale was defined *initially by Corrsin (1958) as the smallest scale at which anisotropy effects resulting from a large-scale shear are carried out by the turbulent cascade.*

For low Richardson numbers the effect of shear dominates the effect of buoyancy, therefore the relevant quantity to define the mixing scale is the shear, while for large Richardson numbers the relevant quantity is the Brunt-Väisälä frequency N. The smaller of these lengths limits the typical eddy size.

Odier et al. (2012) proposed a model based on the Prandtl mixing length model with characteristic mixing length L_m *to relate the turbulent eddy diffusivity* ν_t *to the velocity fluctuations and gradients in a stratified shear layer. They showed that* L_m *was proportional to* L_s *so that the turbulent diffusivity can be evaluated using:*

$$\nu_t \sim L_s^2 \langle \partial u / \partial z \rangle.$$

In the tank experiments, we estimate, $\varepsilon \approx O(10^{-2}\ m^2 s^{-3})$ *from the PIV measurements,* $N=0.1\ s^{-1}$, $\langle \partial u/\partial z \rangle \approx O(1\ s^{-1})$. *Introducing these values in the above expression we obtain for* $L_o \approx 3$ *m and for* $L_s \approx 0.1$ *m; hence, the length scale will be determined by shear since* $L_o > L_s$ *so that our estimate gives* $\nu_t \sim 10^{-4}\ m^2 s^{-1}$ *for the tank experiments. Using a velocity scale, the Nof speed* $U=0.1\ ms^{-1}$ *and the vertical scale of the gravity current of* $h=0.05$ *m, the normalized turbulent diffusivity gives* $\nu_t (Uh)^{-1} \sim 0.02$. *We also expect that at higher Richardson numbers, as typical in the ocean, the length scale will be determined by buoyancy, since* $L_o < L_s$, *so that our oceanic estimate may be a bit high. Parametrizations in ocean models (Lane-Serff and Baines 2000) have used values in the range* $0.032 < \nu_t < 0.70\ m^2 s^{-1}$ *for typical overflow scenarios. Critical to extrapolating to oceanic conditions is a systematic exploration of the dependence of the mixing lengths on turbulence intensity and on the degree of stratification as measured by the Richardson number.*

Lane-Serff and Baines (2000) also proposed a relation to evaluate the turbulent diffusivity based on scales that are easier to extrapolate for oceanic overflows, which reads:

$$\nu_t = (4k^2 Q f^2)(g' s^2)^{-1},$$

where Q is the injected volume transport of the gravity current, k is taken to be 2.5×10^{-3} *(a typical value for oceanographic flows, e.g., Lane-Serff 1993, 1995; Bombosch and Jenkins 1995). This gives for the values of the Adriatic outflow into the Ionian Sea* $Q \approx 10^5\ m^3 s^{-1}$, $f=10^{-4}\ s^{-1}$, $g'=0.003\ ms^{-2}$ *and* $s=0.02$ *giving* $\nu_t \approx 0.02\ m^2 s^{-1}$. *Rare in situ observations of upper ocean turbulent mixing, stratification and currents in the Adriatic Sea resulted in the estimates of the eddy diffusivity in the central part of the basin (Peters and Orlić, 2005). The values are however much smaller than those presented above due to weak shear and strong stratification combined with large Richardson numbers. Using* $U=0.1\ ms^{-1}$ *as a typical velocity scale and a typical vertical length scale of the overflow of* $h=200$ *m, one obtains a normalized turbulent diffusivity of* $\nu_t (Uh)^{-1} \approx 0.001$ *for the real flow conditions in the Ionian Sea, which is smaller than the laboratory value (0.02). Note that if the expression of Lane-Serff and Baines (2000) for the rotating platform conditions is applied to oceanic environment, the value of the constant k needs to be adapted to larger values, since the Reynolds number is smaller in the laboratory conditions than in the real ocean (see Lane-Serff 1993, 1995; Bombosch and Jenkins 1995).*

1) Bombosch, A. and Jenkins A. : Modeling the formation and deposition of frazil ice beneath the Filchner–Ronne Ice Shelf. J. Geophys. Res., 100, 6983–6992, 1995.
2) Corrsin S. : Local isotropy in turbulent shear flow, National Advisory Committee for Aeronautics RM 58B11, 1958.
3) Lane-Serff, G. F. : On drag-limited gravity currents.,Deep-Sea Res. I, 40, 1699–1702, 1993.
4) Lane-Serff, G. F. : On meltwater under ice-shelves, J. Geophys. Res., 100, 6961–6965, 1995.
5) Lane-Serff, G. F. and P. G. Baines: Eddy formation by overflows in stratified water. J. Phys. Ocean., 30, 327–337, 2000.
6) Odier, P., Chen J. and R. E. Ecke: Understanding and modeling turbulent fluxes and entrainment in a gravity current, Phys. D: Nonlin. Phen., 10.1016/j.physd.2011.07.010, 2012.
7) Peters, H. and M. Orlić: Turbulent mixing in the springtime central Adriatic Sea. Geofizika, 22, 1-19, 2005."

C2 Moreover is very confusing the theoretical and modelling equations that are used to analyze the experimental results: the equation 1 is not the same used by the cited paper of Lee-Lueng, F. and Davidson, R. A. (A note on the barotropic response of sea level to time-dependent wind forcing. J. Geophys. Res., 100, C2, 24955-24963, 1995) that use a classical linear barotropic vorticity equation, may be the authors have to use a different reference.

Reply: As our response to this comment, we simply removed the reference saying that we will be treating the well-known linear barotropic vorticity equation for an f-plane approximation with the sloped bottom in radial coordinates for the surface layer without wind-stress forcing. We also defined the radial coordinate being perpendicular to isobaths and negative downslope.

C3 However, the most relevant matter is related to the stratification that, at the end, is the core problem of the manuscript. It is well know that a good representation of the ocean dynamics is a three-layer system and this is this is confirmed even in this case as is well evident in the figure 2c (experiment 27), specifically around the 75th day in which we see the respond of the pressure to the injection of the density anomaly and subsequence stratification in three layer (or a continuously stratification see references), is very interesting the impact of the redistribution of density and pressure within the water column in the figure 3 (and also figure 5) experiment 27 at the same day (around the 75th). These figures are the most interesting of the manuscript and at the same time are those that demonstrate the weakness of the theory presented in this manuscript: actually, can't demonstrate the opposite vorticity at the 75th day and the corresponding kinetic energy anomaly in the lower layers. However, despite this experimental evidence and the same recognition as the authors themselves that the dynamics follow at least a two-layers system, even so at the end the equation that the authors used is written in a one-layer formulation. This is not irrelevant for physical point of view. Is matter of fact that dealing with one-, two- or three-layer formulation of the QG equation, produce a different vorticity relation between the several interfaces along the water column (see Sokolovskiy paper and all reference herein). This is true either in the flat or in the slope domain and finally on the comparison with the realistic example of the Ionian Sea. In conclusion, the circular rotating tank experiment shows in an impressing way (this could be more impressing with a different scale ratio between the slope/flat domain), the adjustment of the vorticity along the continuously stratified water column (and its dependence from the layers-thickness distribution) when it is subjected to a density anomalies: first along the slope and afterwards during the spreading of the anomaly density flow along the flat bottom; finally is very arduous to do some comparison, in the present version of the manuscript, between the tank experiment and what was observed in the northern Ionian sea in 2012.

Reply: *The Reviewer is right when he argues that the evolution of a 2-layer and 3-layer system differs. However, in the present paper we do not attempt to determine the evolution of the eddying dynamics of the system. Our focus is on the dynamics of two homogeneous layers and the relationship between their thickness and the relative vorticity which is constrained for every layer by the conservation of potential vorticity (PV) in each of them, independently of the dynamics above and below it. So, the conservation of PV is ensured in a single layer, and it does not depend on how many layers stay above or below. In addition, we reduce the effect of the horizontal advection on our analysis by considering horizontal averages over larger areas (central and slope). Please, note also that the flow is not advected from one layer to the other.*

We thank the Reviewer for highlighting the event of the 75th day in experiment 27 which is really a special event. We examine more carefully the flow pattern evolution during that event (please, see Fig. R1). One can see the isolated maximums of the radial and tangential velocities in the deep layer at the site of the density profiling (Cp3). These are linked to the passage of a mesoscale anticyclonic eddy around the 75th rotation day in the vicinity of the vertical profiling sensor. Indeed, the formation and passage of the eddy in the vicinity of the vertical profiling site is clearly seen from the horizontal distributions of the velocity vectors (Fig. R2). This eddy then causes an anomaly in the vertical density distribution and the transient thickening of the pycnocline layer, as well as in the relationship between the vorticity rate of change and the rate of change of the bottom layer thickness (see Fig. 3 in the original paper text). For the rest of the experiment the PV equation for the flat bottom describes adequately the dynamics of the bottom layer.

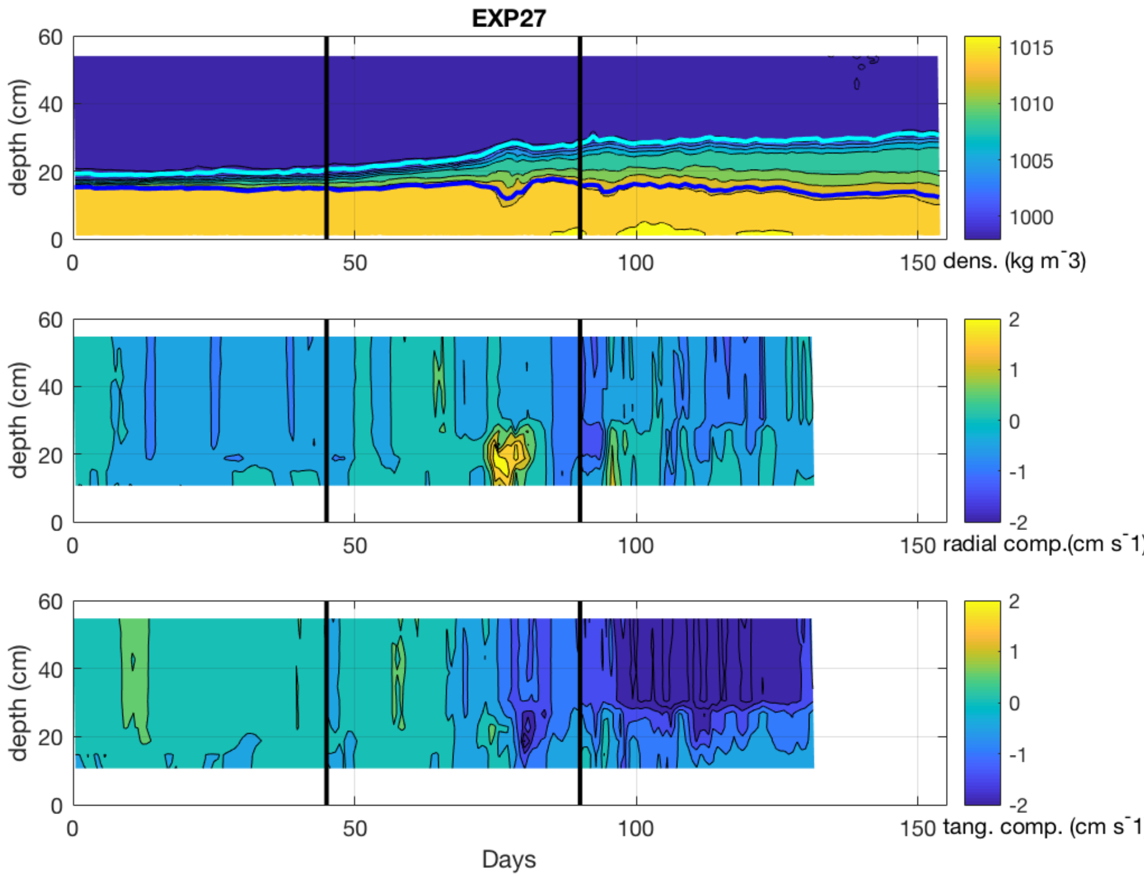
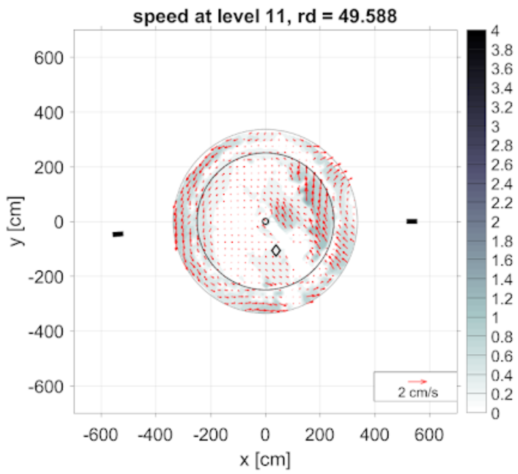
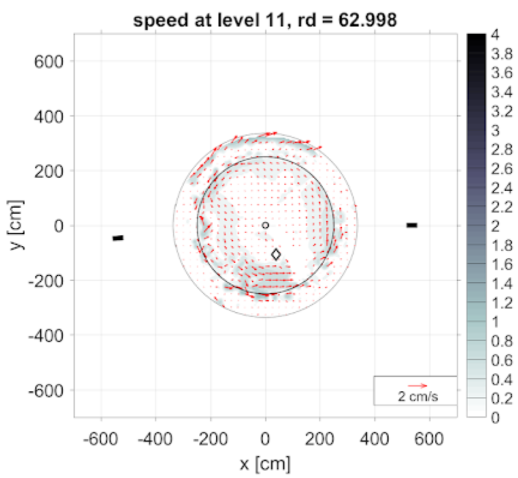
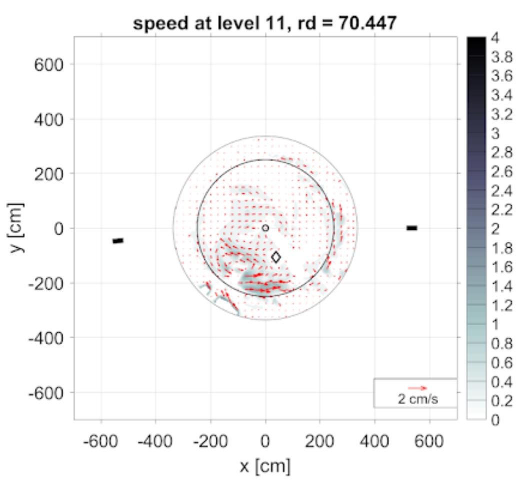
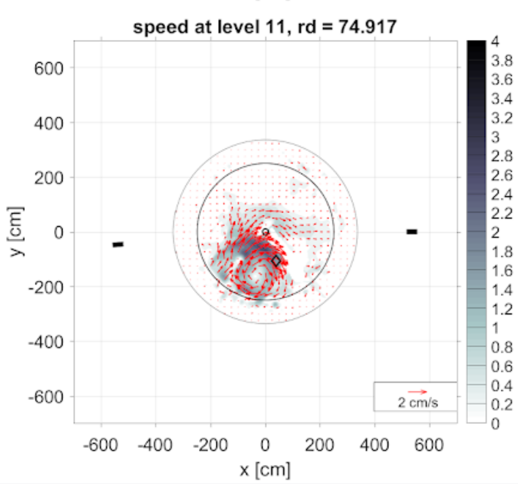


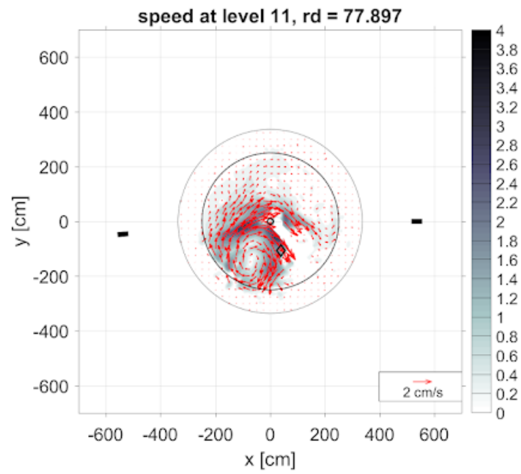
Fig R1: Hovmoller diagram of the density evolution (upper panel), of the radial (middle panel) and the tangential velocity component (bottom panel) for experiment 27.

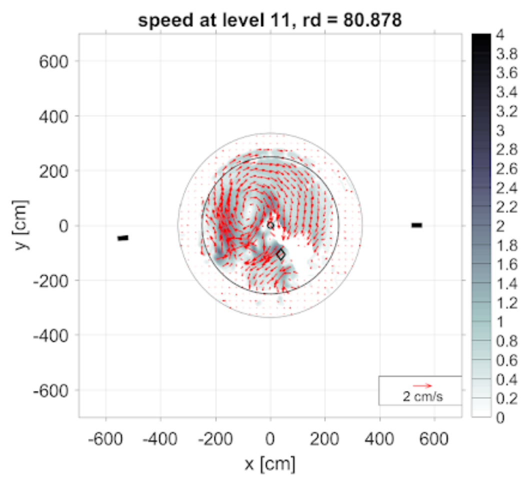

speed at level 11, rd = 49.588
y [cm]
x [cm]
2 cm/s

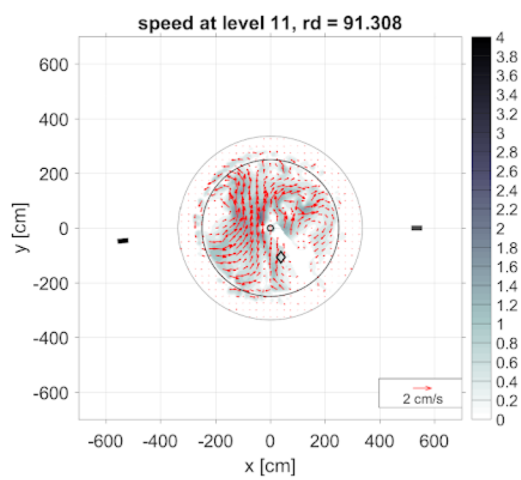

speed at level 11, rd = 62.998
y [cm]
x [cm]
2 cm/s


speed at level 11, rd = 70.447
y [cm]
x [cm]
2 cm/s


speed at level 11, rd = 74.917
y [cm]
x [cm]
2 cm/s


speed at level 11, rd = 77.897
y [cm]
x [cm]
2 cm/s


speed at level 11, rd = 80.878
y [cm]
x [cm]
2 cm/s


speed at level 11, rd = 91.308
y [cm]
x [cm]
2 cm/s

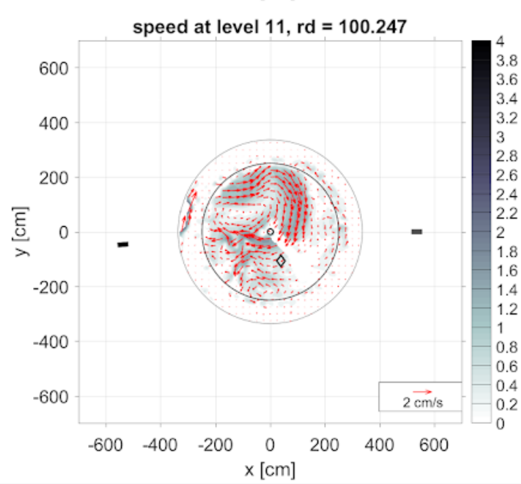

speed at level 11, rd = 100.247
y [cm]
x [cm]
2 cm/s

Fig. R2 Evolution of the flow field in the lower layer of the rotating platform during experiment 27. The level and rotation days are indicated above each panel. The diamond indicates the location of the conductivity probe Cp3, and the two bars indicate the location of the two dense water sources.

See also below the new Figure 1 inserted in the revised version of the manuscript according to the request of Ref 1:

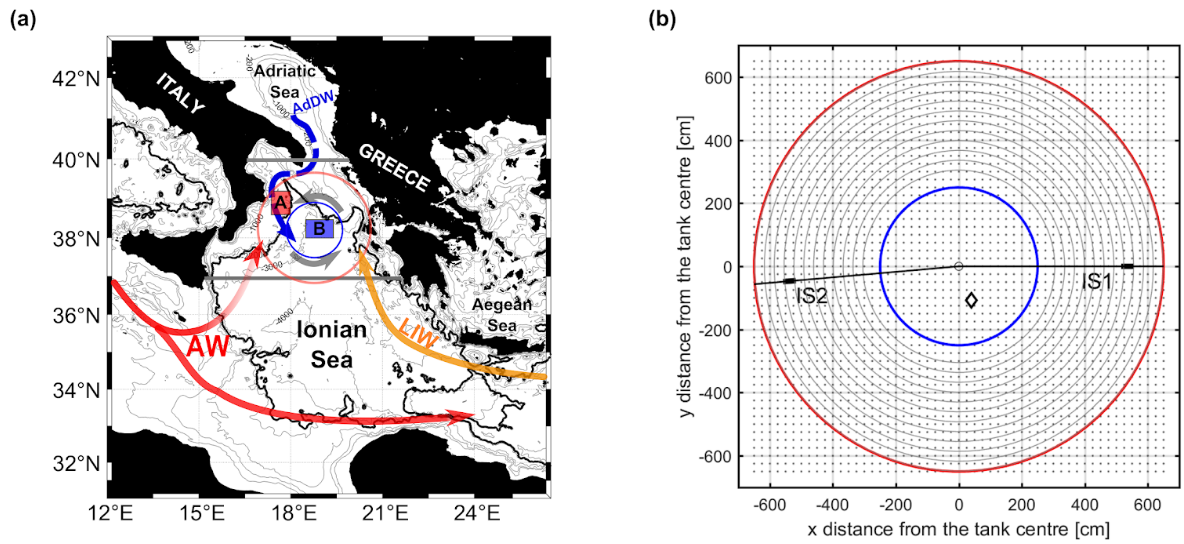


Figure 1: (a) Map of the study area in the Ionian basin with a simplified circulation scheme, which changes accordingly to the BiOS regime. Grey horizontal lines indicate the geographical limits within which the mean vorticities above and below the 2200m isobath were calculated. Rectangles A and B indicate the areas where density data (CMEMS reanalysis) were averaged. Concentric rings represent the simplified laboratory tank scheme. Acronyms: AW = Atlantic Water, LIW = Levantine Intermediate Water, AdDW = Adriatic Deep Water; (b) a view of the tank: the slope area is between the red and blue, deep flat-bottom area is inside the blue ring. Dense water injectors are placed at IS1 and IS2. A diamond near the centre shows a location of the Cp3 profiler. Concentric grey rings indicate intersections of the laser sheet levels with the slope. Grey dots indicate a regular x-y grid for tank velocity field (subsampled every 5 nodes for clarity). The map in (a) was created from the bathymetry data ETOPO2v2, NOAA, World Data Service for Geophysics, Boulder, June 2006, doi: 10.7289/V5J1012Q) using the MATLAB software.

Minor revision:

- Line 326 “level 1” is referred to inclined laser sheet levels 1 of the Figure 1?

Reply: Yes, it is.

- Line 451 at which model is referred? Please give more details;

Reply: We clarified this point in section 2 Data and methods:

“We compare the current fields in the rotating tank and in the real ocean for a particular condition when a circulation inversion event was observed in the northern Ionian Sea. Regarding the real ocean, for the surface we use the altimetry data, while for the deep layer conditions we use outputs from the hydrodynamic model of the Mediterranean Forecasting System. The latter concerns the physical reanalysis component, originating from the Copernicus Marine Service MEDSEA_REANALYSIS_PHYS_006_004 dataset (CMEMS Reanalysis) supplied by the Nucleus for European Modelling of the Ocean (NEMO) (Simoncelli et al., 2019). The model has a horizontal grid resolution equal to 1/16˚ (ca. 6-7 km) and 72 unevenly spaced vertical levels. We use the following variables: 3D monthly mean and daily mean temperature, salinity, and horizontal current components (eastward and northward) covering the entire Mediterranean Sea (https://doi.org/10.25423/MEDSEA_REANALYSIS_PHYS_006_004 https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=MEDSEA_MULTIYEAR_PHY_006_004).“

From then on, we specify everywhere in the text that we deal with the CMEMS Reanalysis fields, including the Line 451:

“By comparing the outputs of the CMEMS Reanalysis (which assimilates the in-situ data) and the vertical profiles of those ARGO floats, that were active in the northern Ionian during 2012, we observe that the Reanalysis absolute density values are typically larger than float densities (not shown). However, temporal variations of both data sets are consistent. Thus, we reconstruct the evolution of the density fields on the continental slope and in the deep area of the northern Ionian Sea using only the data from the CMEMS Reanalysis and compare it with the vorticity variations at the surface and in the deep layer (i.e., 1000 m depth, Fig. 12).”

- figure 1 the word “cp3” is not clear;

Reply: The meaning and location of the Cp3 is now introduced in the new Figure 1. In addition, the caption of the old Fig. 1 (now Fig. 2) also indicates the meaning of the Cp3.

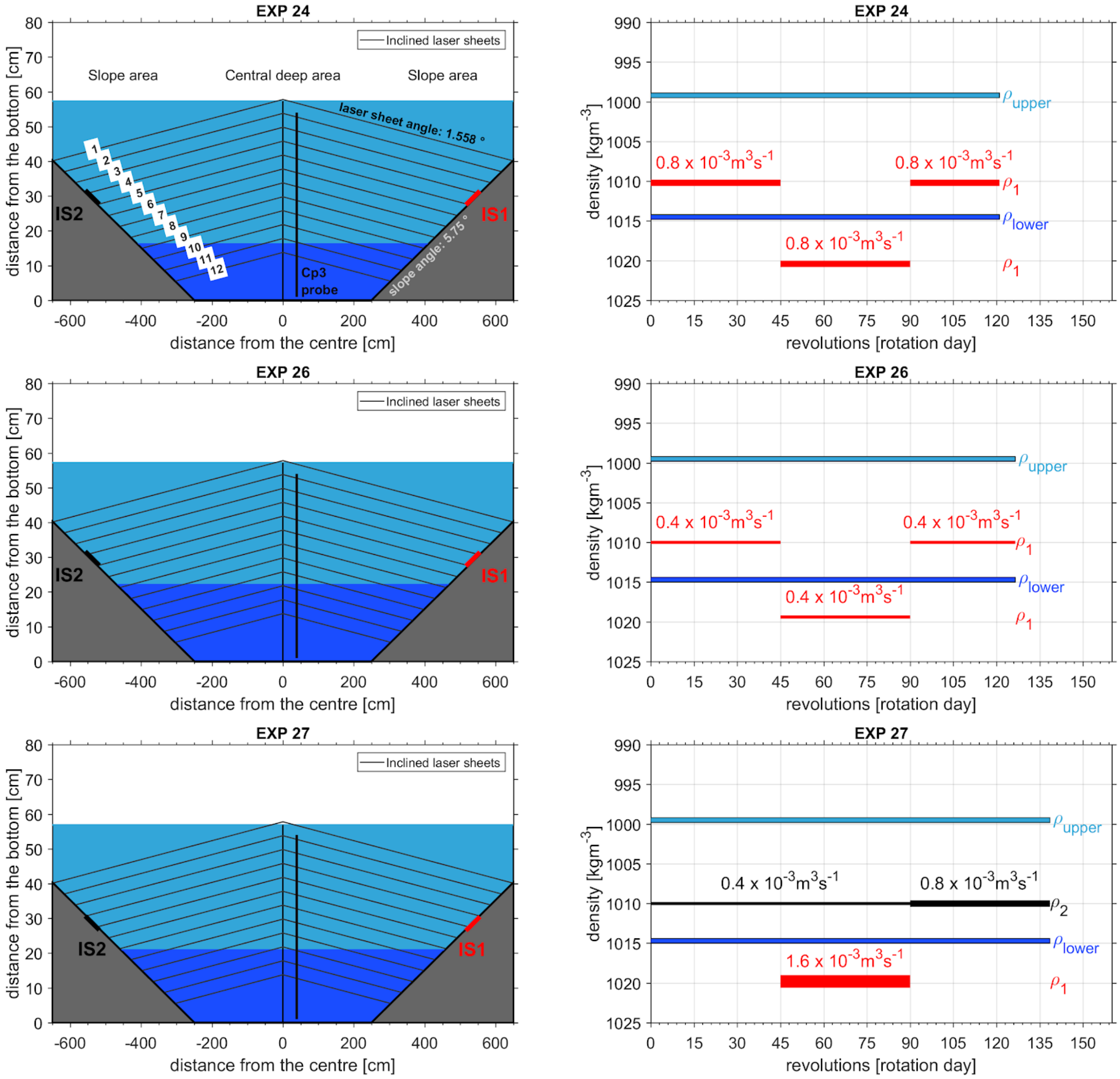


Figure 2: Scheme of the rotating tank section (not to scale) and density configuration for the three experiments discussed in the paper, EXP 24, EXP 26 and EXP 27. Left hand side: cross section with a central deep area, a slope, and injectors IS1 and IS2; blue/cyan patches refer to the lower/upper layers; numbers from 1 to 12 indicate inclined laser sheet levels. A vertical bar near the tank center denotes a vertically profiling conductivity probe Cp3 providing data on temporal density variations with depth. Right hand side: initial density in the lower/upper layers (blue/cyan lines); density and discharge rate of the injected water (red/black color from IS1/IS2); the thickness of the red and black lines corresponds to discharge rates during various phases (for details see Tables 1 and 2). Only EXP 27 has both injectors active.

figure 2 in the color tab 0-15 means that the range of density is between 1000-1015?

Reply: The Reviewer is right, and figures have been re-done using density instead of density anomalies.