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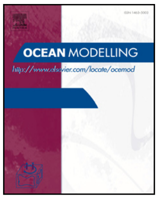

Mixed layer formation and restratification in presence of mesoscale and submesoscale turbulence

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ABSTRACT

Recent realistic high resolution modeling studies show a net increase of submesoscale activity in fall and winter when the mixed layer depth is at its maximum. This submesoscale activity increase is associated with a reduced deepening of the mixed layer. Both phenomena can be related to the development of mixed layer instabilities, which convert available potential energy into submesoscale eddy kinetic energy and contribute to a fast restratification by slumping the horizontal density gradient in the mixed layer. In the present work, the mixed layer formation and restratification were studied by uniformly cooling a fully turbulent zonal jet in a periodic channel at different resolutions, from eddy resolving (10 km) to submesoscale permitting (2 km). The effect of the submesoscale activity, highlighted by these different horizontal resolutions, was quantified in terms of mixed layer depth, restratification rate and buoyancy fluxes. Contrary to many idealized studies focusing on the restratification phase only, this study addresses a continuous event of mixed layer formation followed by its complete restratification. The robustness of the present results was established by ensemble simulations. The results show that, at higher resolution, when submesoscale starts to be resolved, the mixed layer formed during the surface cooling is significantly shallower and the total restratification is almost three times faster. Such differences between coarse and fine resolution models are consistent with the submesoscale upward buoyancy flux, which balances the convection during the formation phase and accelerates the restratification once the surface cooling is stopped. This submesoscale buoyancy flux is active even below the mixed layer. Our simulations show that mesoscale dynamics also cause restratification, but on longer time scales. Finally, the spatial distribution of the mixed layer depth is highly heterogeneous in the presence of submesoscale activity, prompting the question of whether it is possible to parameterize submesoscale effects and their effects on the marine biology as a function of a spatially-averaged mixed layer depth.

1. Introduction

Ubiquity of the submesoscale activity in the ocean surface layer has been revealed by observations of high resolution satellite sea surface temperature and chlorophyll images, such as those from the space shuttle (Scully-Power, 1986; Munk et al., 2000). This last decade, an increase of the computational power, has seen numerous studies focusing on submesoscale dynamics in numerical models based on two kinds of simulations; (i) using realistic coastline and bottom topography (Capet et al., 2008a, 2008b, 2008c, 2008d; Marchesiello et al., 2011; Mensa et al., 2013; Sasaki et al., 2014), or (ii) idealized, mainly based on baroclinic zonal jets in periodic channels (Klein et al., 2008; Lévy et al., 2010; Klein et al., 2011; Haney et al., 2012; Ponte et al., 2013; Thomas et al., 2013).

Some idealized studies have shown that submesoscale dynamics are strongly ageostrophic (Klein et al., 2008, 2011) leading to vertical velocities of O(40 m day^{-1}) (Ponte et al., 2013). Therefore, although submesoscales have small spatial scales (O(few km)) and short time scales (hours to days) the associated vertical velocities can bring nutrients from greater depth than in lower resolution models (Rosso et al., 2014), which may contribute significantly to the closure of the global nutrient budget (Klein and Lapeyre, 2009). They can also result in modifications of the large scale circulation (Lévy et al., 2010) by altering the position and the intensity of the subtropical and subpolar gyre.

Another impact of submesoscale activity is the restratification of the mixed layer through mixed layer instabilities (MLIs) (Nurser and Zhang, 2000; Boccaletti et al., 2007; Fox-Kemper et al., 2008). Boccaletti et al. (2007) studied the restratification of an idealized

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mixed layer by destabilization of a density front by MLIs in a zonal channel. They showed a complete restratification accomplished over a few days after the MLIs reach finite amplitude. This finding is complementary to previous results of Haine and Marshall (1998) who studied the formation of a mixed layer front by applying a differential cooling on a homogeneous stratified fluid in a zonal channel. They showed that baroclinic waves in the mixed layer are important agents of buoyancy transport and can be so efficient that the convective process all but ceases, therefore limiting the deepening of the mixed layer.

A correct representation of the mixed layer depth (MLD) in a numerical model is a priority when considering ocean heat content and heat exchange between ocean and atmosphere, either for the climate (Romanou et al., 2013; Sallee et al., 2013; Liu and Wang, 2014) or in the case of tropical cyclones (Lin et al., 2009; Shay and Brewster, 2010; Seo and Xie, 2013). As resolving the submesoscale is beyond the scope of current climate, global and some regional models, Fox-Kemper et al. (2008) proposed a parameterization of the restratification induced by MLIs in coarse resolution models, which consists of an overturning streamfunction confined to the mixed layer and proportional to the strength of the horizontal surface density gradient and the MLD. In a companion paper, Fox-Kemper and Ferrari (2008) show that the equivalent MLI heat fluxes estimated from observed surface eddy kinetic energy using the Fox-Kemper et al. (2008) parameterization are of the same order of magnitude as the atmospheric flux, suggesting that restratification by MLIs could be a leading order process for the mixed layer.

The predominance of MLIs for the submesoscale dynamics of the mixed layer has been confirmed by recent realistic high resolution modeling studies from Capet et al. (2008d), Mensa et al. (2013) and Sasaki et al. (2014), showing a net increase of submesoscale activity in fall and winter associated with the deepest mixed layers. Such a seasonality in the submesoscale field has recently been confirmed from observations by Callies et al. (2015). While Capet et al. (2008d) could not see any submesoscale-induced restratification in the shallow domain of the Argentinian shelf, Mensa et al. (2013) found a mixed layer 25% shallower in a submesoscale permitting high resolution nested domain ($\sim$2 km) compared to its parent eddy resolving ($\sim$8.5 km) model of the Gulf Stream area. Since mesoscale fronts are present all year long in this region, Mensa et al. (2013) concluded that this fall/winter APE increase available to MLIs is controlled by the MLD. Shallowing of the mixed layer by MLIs is also reported by Marchesiello et al. (2011) in their numerical study of tropical instability waves when the submesoscale is resolved.

Among the studies cited above there exists a significant gap between simulations using realistic coastline and topography and highly idealized ones, most of those latter being initialized with a preexisting mixed layer and front. Furthermore, results from idealized experiments are not in full agreement with each other. For instance Fox-Kemper et al. (2008) noted that vertical heat fluxes from MLIs are small compared to ocean-atmosphere heat fluxes during active convection periods, while Haine and Marshall (1998) previously showed that MLIs can be active during convective process and even overtake them. It has been also shown by Taylor and Ferrari (2010) that in the early stage of the mixed layer formation, Symmetric Instability (SI) can limit the deepening of the mixed layer. They also highlight that such SI will arise when the Richardson number is beyond unity.

Furthermore, while idealized studies focus on a single realization of a restratification event, studies based on realistic models focus on averaged MLD resulting from various atmospheric events. Moreover, it has been demonstrated that oceanic convection due to atmospheric cooling is preconditioned by the mesoscale activity (Legg et al., 1998), suggesting that ensemble simulations are needed to robustly investigate the effect of MLIs on the MLD.

In the present work we use an idealized domain wide enough to allow fully developed mesoscale dynamics and fine enough to permit submesoscale dynamics produced by destabilization of mesoscale fronts, and we focus on the effect of the submesoscale on a single mixed layer formation and restratification cycle forced by a buoyancy flux. We aim to address the following questions: (i) Are MLIs able to counter balance the convection during mixed layer formation? (ii) How much do they speed up the restratification once convection is stopped? For statistical reliability of the results, the analyses were based on ensemble simulations.

The paper is organized as follows: Section 2 covers the modeling setup, describing the ensemble simulations and diagnostics used; Section 3 presents results for a reference simulation and for the different resolutions; the findings are then discussed in Section 4.

2. Methods – modeling setup

Mixed layer formation and restratification were studied by cooling a turbulent zonal jet in a periodic channel. The impact of the submesoscale dynamics is highlighted through the comparison of different horizontal resolutions either allowing submesoscale activity (2 km) or not (10 km), plus an intermediate resolution (5 km) and is quantified through MLD, restratification rate, buoyancy fluxes, and conversion of available potential energy into eddy kinetic energy.

2.1. The numerical model

We use the numerical NEMO model (Madec, 2008), which solves the three-dimensional primitive equations in spherical coordinates discretized on an Arakawa C-grid. Aiming to keep the configuration as simple as possible, the vertical mixing coefficients are set constant with values of $1.2 \cdot 10^{-4}$ and $1.2 \cdot 10^{-5}$ m^2 s^{-1} for momentum and tracers respectively and the convective processes are mimicked using an enhanced vertical diffusion parameterization which increases vertical momentum viscosity and tracers diffusity to 100 m^2 s^{-1}, where static instability occurs. This setup is similar to the configuration of Boccaletti et al. (2007). In our study, as the mixed layer is forced exclusively by a surface buoyancy flux generating static instabilities, the use of the enhanced vertical diffusion with constant background mixing coefficients instead of a turbulent closure such as TKE (Turbulent Kinetic Energy) or k-ϵ seems appropriate. This was confirmed by experiments made with TKE instead of the constant background diffusivity (not shown), which do not display large qualitative differences. The linear equation of state depends on temperature only and the model is set up with a z vertical coordinate and a linearized free-surface formulation (Roullet and Madec, 2000). A third order upwind biased (UBS) advection scheme, for which diffusivity is equal (in a one dimensional advection problem) to $\frac{1}{12}|U|\Delta x^3$, where $|U|$ is the absolute local velocity and Δx the grid spacing (Marchesiello et al., 2009), is used for both momentum and tracers. It has been recently shown by Mohammadi-Aragh et al. (2015) that the spurious diapycnal mixing induced by such diffusive schemes during the restratification phase of a baroclinic instability, can lead to some change in the background potential energy. In the present study, the sensitivity to the choice of advection scheme is not considered, as we focus on the effect of spatial resolution.

2.2. The baroclinic jet

The Antarctic Circumpolar Current (ACC) has been often idealized as a zonally symmetric baroclinic jet (McWilliams and Chow, 1981; Klein et al., 2008, 2011) to study the generation of baroclinic instability and associated mesoscale and submesoscale dynamics. This idealized baroclinic jet (hereafter refereed as BJET) is simulated