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Submesoscale circulation in the northern Gulf of Mexico: Surface processes and the impact of the freshwater river input

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ABSTRACT

The processes and instabilities occurring at the ocean surface in the northern Gulf of Mexico between 96.3°W–86.9°W and 25.4°N–30.7°N are investigated with a regional model at submesoscale-permitting horizontal grid resolution (i.e., HR with $dx = 1.6$ km) over a three-year period, from January 2010 to December 2012. A mesoscale-resolving, lower resolution run (LR, with $dx = 5$ km) is also considered for comparison. The HR run is obtained through two-way nesting within the LR run. In HR quantities such local Rossby number, horizontal divergence, vertical velocity, and strain rate are amplified in winter, when the mixed layer is deepest, as found in other basins. In the model configuration considered this amplification occurs in surface waters over the continental slope and off-shore but not over the shelf. Submesoscale structures consist of a mixture of fronts and eddies generated by frontogenesis and mixed layer instabilities, with elevated conversion rates of available potential energy (APE) into eddy kinetic energy (EKE). In all quantities a secondary maximum emerges during the summer season, when the mixed layer depth (MLD) is shallowest, barely 15–20 m. The secondary peak extends to the coast and is due to the intense lateral density gradients created by the fresh water inflow from the Mississippi River system. Submesoscale structures in summer consist predominately of fronts, as observed in the aftermath of the 2010 *Deepwater Horizon* oil spill, and their secondary circulations are impeded due to the limited depth of the mixed layer. Freshwater river input is key to the submesoscale activity in summer but modulates it also in winter, as shown with a sensitivity run in which the riverine inflow is absent. Implications for transport studies in regions characterized by intense freshwater fluxes and for submesoscale parameterizations are discussed.

1. Introduction

Processes occurring at the oceanic submesoscales, between about 100 m and few tens of kilometers horizontally, critically impact transport and mixing in the upper ocean, modify the mixed layer stratification, and dominate the relative dispersion of tracers and floats on comparable scales (Capet et al. 2008b; Zhong and Bracco 2013). The submesoscales are bounded by the geostrophic quasi-two-dimensional mesoscale at larger scales, where the Earth's rotation and the vertical stratification control the dynamics, and by the ageostrophic three-dimensional turbulence at smaller scales, where the effect of planetary rotation is negligible. Submesoscale processes are therefore affected by a weakening of the geostrophic constraint and provide mechanisms to transition energy from the balanced geostrophic mesoscales to the dissipation scales (McWilliams 2008; McWilliams et al. 2001; Molemaker et al. 2005; Molemaker et al. 2010; Muller et al. 2005). Process modeling to resolve these scales has advanced our understanding of those dynamics (Boccaletti et al. 2007; Capet et al. 2008b; Fox-Kemper et al. 2008; Fox-Kemper et al. 2011; Gula et al. 2014; Molemaker et al. 2010; Taylor and Ferrari 2011), while oceanic observations are generally confirmatory but scarce (McWilliams et al. 2009a; D'Asaro et al. 2011; Poje et al. 2014; Shcherbina et al. 2013). In the present work we characterize submesoscale features in the northern Gulf of Mexico (hereafter GoM). This basin hosts important benthic and pelagic fisheries (NOAA, 2012), as well as more than 20,000 natural hydrocarbon seeps (Peccini and MacDonald, 2008). Between April and July 2010, the northern GoM was severely impacted by the *Deepwater Horizon* spill, the largest oil spill in history, that released about 3×10^5 t gas and between 6 and 8×10^5 t oil in the open waters (Joye et al. 2011; McNutt

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et al. 2012). During the spill six data-assimilating ocean models were used to track and forecast the oil trajectory through virtual particles (Liu et al. 2011). The horizontal resolution of the models was 5 km or coarser, and none of them was able to capture the complexity of the surface circulation in the region between the wellhead and the Mississippi River mouth, as portrayed by SAR images of the surface oil. The images, together with aerial photos, revealed the presence of numerous, spatially coherent, submesoscale frontal structures, several tens of kilometers long and less than a few kilometers wide, that became more prominent from the end of May onward and contributed to the oil transport and convergence in the late spring and early summer of 2010 (e.g., Fig. 3 in Walker et al. 2011). The prevalence of frontal structures in the northern GoM during the summer was further confirmed by the Grand Lagrangian Deployment (GLAD) conducted in August 2012 (Poje et al., 2014). Current modeling (Mensa et al. 2013) and observational (Callies et al. 2015) evidence supports the existence of a seasonal cycle of submesoscale flows with a minimum during the summer season because their energization depends on the mixed layer depth (MLD). For a given lateral buoyancy gradient, the shallower is the mixed layer, the less energetic is the submesoscale flow. The surface buoyancy of the northern GoM, however, is subject itself to seasonal and interannual variability due to the presence of large freshwater inputs through the Mississippi–Atchafalaya River systems.

In this work we investigate the origin of the frontal structures observed in the summer of 2010 with a process oriented study using a regional ocean model at submesoscale-permitting resolution (dx = 1.6 km) over a three-year period, from January 2010 to December 2012 with the hypothesis that the freshwater river input into the northern Gulf may force lateral density gradients that in turn fuel frontogenesis also during the summer season, despite the shallow mixed later. Comparing the statistical properties of this integration with properties derived from a lower resolution (dx = 5 km) run, we identify when, where, and how fronts and more generally submesoscale dynamics impacts the surface circulation of the northern GoM with a focus on the off-shelf region (i.e. the area characterized by waters deeper than 200 m). The submesoscale field is characterized in terms of its statistical distribution throughout the year, generation mechanisms, and, most importantly, dependence on freshwater fluxes.

Our analysis elucidates some the challenges faced by modelers when trying to predict the trajectories of surface tracers in the northern GoM or more generally any ocean region characterized by substantial freshwater inputs and active submesoscale flows.

2. Model setup, domain and forcing fields

We adopt the Regional Oceanic Modeling System (ROMS), a free-surface, terrain-following, hydrostatic, primitive-equation model (Marchesiello et al. 2003), and we implement the Institut de Recherche pour le Dèveloppement (IRD) version of the code, ROMS-AGRIF 2.2 (Debreu et al. 2012). The model domain extends between 97.98°W–80.38°W and 18.02°N–31.02°N (Fig. 1). The horizontal resolution of the grid is 5 km, and the vertical resolution is 70 terrain-following layers with enhanced resolution near the surface (no less than 15 layers in the upper 200 m in the deepest areas) and close to the bottom. We took advantage of the two-way nesting capability of ROMS-AGRIF to introduce a nested (child) grid with horizontal resolution of 1.6 km covering the region between 96.31°W–86.93°W and 25.40°N–30.66°N (Fig. 1). The model bathymetry is derived from ETOPO2 (Sandwell and Smith 1997), is interpolated at 5 km horizontal resolution and then transferred to the child grid without modifying the smoothing. In the following we focus on the nested area, comparing results for the parent (LR for low resolution) and child (HR for high resolution) grids. Differences between the two simulations, however, are not limited to the nested region, as shown in Fig. 2, due to the nature of the two-way nesting technique.

ROMS-Agrif is forced by 6-hour surface wind stresses and daily heat fluxes from the European Centre for Medium-Range Weather Forecast ERA-interim reanalysis (Dee et al. 2011; Poli et al. 2010) from December 2009 to December 2012. The resolution of the atmospheric forcing fields is approximately 80 km. At the open ocean boundaries ROMS is nudged to monthly fields derived from HYCOM - NCODA (Hybrid Coordinate Ocean Model - Navy Coupled Ocean Data Assimilation) ocean prediction system (GOMI0.04 expt_30.1) over the period 2009–2012 (http://www7320.nrlssc.navy.mil/hycomGOM). Tidal forcing is generally small in the GoM but for near-shore locations (DiMarco and Reid 1998; Reid and Whitaker 1981), and is neglected. The northern GoM stratification is strongly affected by the freshwater inflow of the Mississippi-Atchafalaya River system, which is generally greatest between May and June and smallest around October. In the key set of integrations discussed in this work only the mean seasonal cycle of the fresh water flux is retained. This is achieved by nudging the surface salinity field to the World Ocean Atlas 2009 (WOA09) monthly climatology (Antonov et al. 2010) with a time scale of 60 days. Further details on this set-up and the validation of the modeled mean circulation are provided in the Appendix. A two-way nested sensitivity run without surface salinity nudging or river forcing is then performed for the year 2010 after an adeguate spin-up (HR_{NOFW}). The goal of this simulation is to further quantify the role of the freshwater forcing.

3. The annual cycle of surface submesoscale dynamics

In analyzing the distribution of mesoscale and submesoscale features in the northern GoM, four characteristics of the basin should be kept in mind. Firstly, the northern GoM has a wide, shallow continental shelf, defined in the following as the region where the water column is less than 200 m deep, that extends for O(100) km everywhere except in the region between the Mississippi Canyon and the Mississippi River delta; secondly, the continental slope is rather steep to the east of the Mississippi Fan, and broader and more complex to the west; thirdly, the surface layers are influenced by the input of freshwater by the Mississippi-Atchafalaya River system that usually intensifies in late spring and summer; finally the atmospheric circulation is characterized by two distinct seasons with Southeasterlies winds blowing between April and August and stronger Northeasterlies being predominant from September to March. Spring and summer winds can display substantial variability in their directionality particularly to the east of the Mississippi river mouth, and are generally weaker than in fall or winter except for the occasional passage of tropical storms. Fall and winter winds are stronger on average and their intensity varies greatly on time scales of two or three days due to synoptic scale storms.

To isolate the role of freshwater inputs we performed a year-long sensitivity run where no nudging or river inflow are prescribed. The HR_{NOFW} simulation is spun-up for two months from the same December 2009 initial conditions used for the HR case and then run from January to December 2010. Shelf waters shallower than 50 m in proximity of the Atchafalaya and Mississippi mouths retain a portion of the salinity anomaly contained in the initial conditions (Fig. 3). In this section we compare model outcomes from HR, LR and when deemed relevant HR_{NOFW}.

We stress that this process study focuses on integrations that retain the seasonal cycle of the freshwater fluxes but not their interannual variability. The resolution adopted, the smoothing of bathymetric features smaller than 5 km, the use of surface salinity nudging to WOA09 data, and the temporal (6-hourly) and spatial