Predictability of mesoscale circulation throughout the water column in the Gulf of Mexico

by

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Abstract

The predictability of the mesoscale circulation in the Gulf of Mexico is evaluated using an ensemble of four integrations for the period 2000-2008 using the Regional Ocean Modeling System (ROMS). In all four runs ROMS is forced by identical, monthly varying, heat and momentum fluxes. We explore the role of initial conditions, boundary conditions, atmospheric forcing, and resolution in the Mississippi plume area, on the potential predictability of the Gulf circulation at scales of 20 km or greater. The potential for predictability varies regionally and seasonally. The modeled circulation is mainly atmospherically forced in the coastal areas and dominated by chaotic mesoscale activity in the central portion of the basin. The mesoscale circulation in the top 1000 m of the water column does not correlate with the one below it except for a limited number of small areas. The potential for predicting the circulation at depths deeper than 1000 m is limited by the intrinsic variability of the eddy field and by the unavailability of a continuous monitoring system that extends below the surface.

Key words

Gulf of Mexico, predictability, deep circulation, mesoscale.

1. Introduction

The Gulf of Mexico circulation has been measured extensively, in particular over the last few years. Continuous observational records, however, are limited to the surface, via satellite measurements, and to the coastal and shelf areas, and only sporadic in waters deeper than ~ 800 m (see <http://data.gcoos.org/>). Predicting the Gulf of Mexico circulation is still challenging not only at the submesoscales (10 km or less) but also at scales greater than 10-20 km, as evidenced in the aftermath of the Deepwater Horizon spill in 2010, when different data assimilative models, run in both hindcast and forecast mode at resolutions reaching 0.04° , diverged in their predictions of surface oil trajectories, and more generally of current behaviors (Liu et al., 2011). The evaluation of those divergent solutions, and improvements in the representation of oil behavior in sea water, have allowed modelers to obtain more realistic representations of the observed oil trajectories in subsequent works (e.g. Adcroft et al., 2010; Chan et al., 2011; Klemas, 2010; Paris et al., 2012). With the discovery of deep oil plumes (Camilli et al., 2010; Joye et al., 2011), however, it became apparent that during the Deepwater Horizon emergency response a reliable prediction of the deep circulation in the Gulf would have been as important as modeling the drifting of oil at the surface.

In this paper we focus on the predictability of the mesoscale circulation in the Gulf of Mexico. More specifically, we pose two questions: Is the deep (> 1000 m) mesoscale circulation of the Gulf of Mexico predictable, and if so on which time scale? Are surface mesoscale processes in any way related to the ones that take place in deep waters, so that the reliability of the surface dynamics representation in a model may be used as indicator of the representation of the deep circulation as well?

Predictability in the ocean is limited whenever high levels of kinetic energy are concentrated at spatial scales of few tens of kilometers, usually in the form of eddies or fronts, as their behavior is often chaotic. Also, models allow to assess only the potential predictability of a given climate (ocean and/or atmospheric) system due to their intrinsic limitations, as noticed by Lorenz, (1984): models use equations that approximate physical laws; those equations are usually reduced to the minimum possible number of variables by omission of terms that are very small compared to other terms; the ocean (or atmosphere) state is expressed by a finite number of grid points.

While keeping those limitations in mind, we try to answer the questions posed above by exploring a) the impact of small variations in the initial conditions, and b) the role of the boundary conditions, in the evolution of the Gulf of Mexico circulation at the ocean mesoscales. We do so considering an ensemble of four eddy-resolving model runs, configured accordingly to the description presented in Section 2. The mean model circulation is described and evaluated in section 3. We discuss in section 4 the interannual variability of the surface circulation, and in particular of the Loop Current, Loop Current eddies and the Yucatan Channel transport. We then analyze the model potential predictability in the whole water column in Section 5, and the relationship between surface and deep mesoscale circulation in Section 6.

2. Model setup and domain

The Gulf of Mexico circulation is modeled using the Regional Ocean Model System (ROMS). ROMS is a free-surface, terrain-following, hydrostatic ocean model (Marchesiello et al., 2003) and we implement the IRD version of the code, ROMS-Agrif 2.1 (Debreu et al., 2012). All integrations are on a 5 km horizontal resolution grid that covers the Gulf within the region delimited by (97.9751° W, 80.3849° W) and (18.0236° N, 31.0788° N) (see Figure 1). The vertical resolution is 35 terrain-following layers, with no less than 17 in the upper 500 m in the

deepest areas. The minimum depth is set at 5 m. The model bathymetry is derived from Etopo2v2 and it has been smoothed using a Shapiro smoother with r_{MAX} of 0.35, where r_{MAX} is defined as a ratio of the maximum difference between adjacent grid cell depths and the mean depth at that point (Penven et al., 2008). This is the maximum slope of topography allowed in order to have negligible pressure gradient errors.

Figure 1. Model Domain. Subregion A indicates the nested grid at 1.6 km horizontal resolution for two of the runs analyzed and subregion B the Loop Current area considered in the analysis in section 4.2. Temperature and salinity profiles locations are marked as green and red dots.

We analyze four integrations. They are all initialized from a run forced by momentum and heat fluxes monthly averaged over the period 1958-2008. The fluxes are from the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kistler et al., 2001). The model has open boundaries to the east and south that are nudged to monthly fields derived from Soda 2.1.6 (Carton and Giese, 2008), again averaged over the period

1958-2008. The seasonal cycle of all forcing and boundary fields is therefore repeated identically over all years and the interannual variability in the boundary and atmospheric forcings is removed. A stationary state is reached after two years, and the integration is continued for another ten. Three simulations that retain the interannual variability (ITD for interannually time dependent, in the following) are then performed covering the period 2000-2008, and are initialized using the last January of the simulation described above with the addition of a random perturbation to the velocity field. The amplitude of the perturbation is such that differences between original and perturbed velocities at each model grid point amount to 5% or less. The ITD runs are forced with monthly varying NCEP/QUICKSCAT blended winds from the Colorado Research Associates (version 5.0) (Millif et al., 2004; Chin et al., 1998) and NCEP reanalysis surface heat fluxes. To avoid long-term drifts in the SSTs associated with errors in the NCEP surface fluxes (Josey, 2001), the surface heat fluxes in all runs corrected once a month using the National Oceanographic and Atmospheric Administration (NOAA) extended SST (Smith and Reynolds, 2004) at a resolution of $2^\circ \times 2^\circ$. Over the period considered the correction modifies the NCEP fluxes by at most 4%. The boundary conditions are again from Soda 2.1.6 but the interannual variability is now retained. In two of the ITD runs (ITD1 and ITD2), we exploit the two-way nesting capability of ROMS-Agrif (Debreu et al., 2012), and introduce a nested area with horizontal resolution of 1.6 km covering the region comprised between $(93.0253^\circ \text{ W}, 87.0290^\circ \text{ W})$ and $(26.6930^\circ \text{ N}, 30.8770^\circ \text{ N})$ (see Figure 1, subdomain A). The nested area includes the Mississippi and Atchafalaya river mouths and a large portion of the shelf in the northern Gulf. The location of the Deepwater Horizon (MC252) is also included in the nested domain and is indicated in Figure 1.

The fourth simulation is a variation of the ITD integrations. Instead of interannually varying boundary conditions, we adopt the climatological ones (we refer to this run as BClim in the following) used in the spin-up run, but we retain the interannual variability in the atmospheric fluxes. BClim helps us isolating the role of the year-to-year variability in the transport of Atlantic water into the Gulf and role of the atmospheric fluxes in the model representation of its circulation. In all runs the fresh-water river input, that plays a fundamental role in setting the density gradients in the Gulf, is directly simulated prescribing the monthly river runoff input of the major rivers, Mississippi, Atchafalaya, Sabine, Brazos, and Grande. The runoff series are from U.S. Geological Service and U.S Army Corps of Engineering and are available at least with monthly frequency over the period 2000-2008.

3. Gulf of Mexico mean circulation and model validation

The large scale circulation of the Gulf of Mexico can be approximated to a two layer system (Hamilton, 1990, 2009; Sturges, 1993; Welsh and Inoue, 2000). The upper layer extends from the surface until 1000 - 1200 m depth, and its circulation is dominated by the presence of the Loop Current (LC) that brings salty and warm waters from the Caribbean Sea into the Gulf. The LC path starts in the Yucatan channel and ends in the Straits of Florida, influencing the dynamics along the Florida shelf in its transit (He and Weisberg, 2003; Weisberg et al., 2000). Sometimes, the LC is confined in the south part of the Gulf, others it extends northward reaching the Louisiana-Mississippi shelf break before looping and returning to Florida (Wiseman and Dinnel, 1988). The LC transit in the Gulf is accompanied by the formation of small cyclonic and anticyclonic eddies through instabilities and interaction with the bathymetry (Hamilton, 2009), and, occasionally, by the detachment of large anticyclonic eddies, known as Loop Current eddies or Rings. LC eddies travel through the Sigsbee Deep and extend in the vertical to 800 – 1000 m

(Hamilton 1990; Lee and Mellor, 2003; Nowlin et al., 2000). The Rings may interact with the anticyclonic surface flow in the northwest of the basin while dispersing anticyclonic vorticity (Di Marco et al., 2005; Lee and Mellor, 2003), and usually loose coherency once they reach the continental shelf on the western boundary. The circulation in the southeastern part of the Gulf, in the so-called Bay of Campeche (BOC), is cyclonic and driven by the mean wind stress over this area (Vazquez de la Cerda et al., 2005). Geopotential and sea surface high (SSH) anomalies highlight the permanent cyclonic, gyre-like, circulation within 18°N-22°N and 92°W-97°W, which is amplified and confined by the bathymetry. Its variability results from changes in the size, position and intensity of the gyre and it is linked to the interaction with northern gulf eddies originated mostly from the LC (Nowlin et al., 2000; Perez-Bruins et al., 2012; Vazquez de la Cerda et al., 2005).

The wind stress is the main driver of the circulation in the Tamaulipas-Veracruz shelf (Tave), Louisiana-Texas (Latex) shelf and the west Florida shelf (DiMarco et al., 2005; Weisber and He, 2003; Zavala-Hidalgo et al., 2003). Wind and circulation vary seasonally in the Latex shelf (Di Marco et al., 2000; Ohlmann and Niiler, 2005), while no clear seasonal variability has been found in the Florida shelf (Ohlmann and Niiler, 2005). The variability of the anticyclonic circulation in the central – western portion of the basin is driven by a combination of wind stress and LC eddies (Dehaan and Sturges, 2005; Lee and Mellor, 2003; Nowlin et al., 2000; Sturges, 1993).

Below the top 800 – 1200 m, the analysis of historical current-meter mooring data and floats reveals a cyclonic circulation underneath of the LC, in the west central part of the Gulf, and in the BOC. Field measurements demonstrate that the deep circulation in those regions is influenced by topographic Rossby waves (TRWs), intrusions of cold deep water from the

Caribbean and vortex stretching (DeHaan and Sturges, 2005; Hamilton, 1990, 2009; Kolodziejczyk et al., 2012; Perez-Brunius et al., 2012; Salas-Perez and Granados-Barra, 2008; Vazquez de la Cerda et al., 2005). TRWs play an important role in the deep circulation of the northwest Gulf, where they manifest as intensification of deep currents over steep bathymetry (Rhines, 1970), and in the Sigsbee escarpment, where the bottom energetic currents are aligned and trapped, and TRWs refract and are reflected by the bathymetry (Hamilton and Lugo-Fernandez, 2001; Hamilton, 2007,2009; Dukhovskoy et al., 2009).

In the eastern Gulf the circulation at depth is cyclonic and fed by LC water, as shown by DeHaan and Sturges (2005) using historical data, and by Lee and Mellor (2003) with model simulations. In the Bay of Campeche the deep circulation is cyclonic, as in the upper layer, and driven by the wind stress curl and the local bathymetry. Vidal et al. (1992) using hydrographic data in this region established that the collision of LC eddies with the south west shelf transfers mass and angular momentum to the south, causing the formation of a cyclonic eddy in the BOC. This was not confirmed by the current meters mooring data analyzed by Perez-Brunius et al. (2012) for the period 2007-2010, that suggest that the variability in the Bay of Campeche is locally driven.

3.1. Model Validation

To evaluate the model climatology we consider the geostrophic velocities derived from altimeter products, the velocities measured in the Yucatan Channel (YC) and the temperature and salinity profiles collected during a 2000 Northeast Gulf of Mexico cruise and others assembled in the World Ocean Atlas 2009 (WOA09). First, we compare the surface model geostrophic velocities during the integration period (2000-2008) and the ones derived from the Maps of Absolute Dynamic Topography & absolute geostrophic velocities (MADT) Aviso altimeter data

174 (<http://www.aviso.oceanobs.com/duacs/>). MADT data extend to the coast and have been
175 reprocessed by Ssalto/Duacs in 2010 -2012 to include improvements specific to coastal areas as
176 the application of algorithms from PISTACH (Coastal and Hydrology altimetry product), and
177 parameterizations that better fit the coastal signal characteristics. For this comparison we
178 grouped the data over two periods defined according to the mean wind patterns in the Gulf
179 region. The Gulf of Mexico atmospheric circulation is indeed characterized by two distinct
180 seasons: Southeasterly winds blow between April and August, and Northeasterlies are
181 predominant from September to March. Using sea level atmospheric pressure time series,
182 Zavala-Hidalgo et al., (2003) attributed the seasonality of the wind patterns in the Gulf to the
183 temporal and spatial variation of two high-pressure systems. From September to March the
184 leading wind pattern results from the high-pressure systems that move from the continental
185 United States into the Gulf, while from April to August the mean winds arise from the
186 intensification and westward displacement of the Bermuda high. Figure 2 compares the seasonal
187 means of the meridional geostrophic velocity (similar results are found for u_g) and its standard
188 deviation in Aviso and in the four model integrations (no differences are found in the mean
189 circulation between ITD and BClim). The velocities and deviation of the mean state associated
190 with the Loop Current are the strongest in the domain and they are clearly distinct from anything
191 else. The dynamics in the West part of the Gulf are dominated by eddies shed by the LC. Due to
192 the randomness of the eddy behavior the velocities associated with them are partially hidden in
193 the mean fields. Model and observations exhibit similar spatial patter in the standard deviation
194 fields. The model, however, shows larger deviations from the mean in the west part of the Gulf
195 than the altimeter data, likely due to the presence of numerous mesoscale eddies with diameter of
196 20-40 km that may be missed in the altimeter data (see Figure 18 for examples of such eddies).

Figure 2. Top two rows: time mean meridional geostrophic velocity v_g (m/s); and bottom two rows: v_g standard deviation, averaged for the periods April to August (left panels) and September to March (right panels). (a)-(b) and (e)-(f) Aviso (c)-(d) and (g)-(h) ROMS model.

To insure a good representation of the deep circulation in the basin a model must simulate correctly the transport through the Yucatan Channel. The averaged YC transport in the ITD simulations is 21.43 ± 0.01 Sv to the northwest, oscillating between 12Sv and 30Sv during the period considered, and is 24.26 Sv in BClim. The ITD ensemble spread is used to quantify the uncertainty and such spread is very small (0.01 Sv), indicating that the boundary conditions, identical in the three runs, force the transport. Figure 3(a)-(b) shows the mean transport direction and time series from one of the ITD runs (the time series are indistinguishable within the ITD ensemble). The modeled YC transport (2000-2008) compares well with the observations collected during the Canek program (Sheinbaum et al., 2002) over the period September 1999 to June 2000. The observational estimate is of a net transport of 23.8 ± 1 Sv. Also, the observed mean velocity field along the Yucatan Channel (Figure 2(a) in Sheinbaum et al., 2002) is in excellent agreement with one in the ITD integrations (Figure 3(c) below).

Figure 3. (a) Yucatan Channel (YC) transport time series from ITD1. The negative sign is indicative of transport in the NW direction (b) Mean multiannual tranport direction at YC, and (c) Mean v velocity component at YC.

The validation is completed comparing modeled and in-situ salinity and temperature profiles over the two seasons identified previously in correspondence of points 1 to 4 in Figure 1. The salinity profiles (Figure 4 (a)-(d)) from model (red lines) and the 2009 World Ocean Atlas

221 (WOA09) (blue lines) have overall similar shape. The model underestimated the sharpness of the
222 salinity gradients between the base of the mixed-layer and the main thermocline. However, the
223 disagreement between modeled and observed salinity is limited to 0.25 psu at most. Better
224 agreement is found in the shape of the temperature profiles. In general the model is warmer than
225 WOA09 in the first 1000 m of the water column by up to 1°C. Modeled means, however, cannot
226 be expected to be identical to those in WOA09, since the first were calculated averaging nine
227 model years, while the WOA09 database averages all –sparse in time - available records from
228 1955 until 2006. Panels (e) and (j) display temperature and salinity profiles for locations 5, 6 and
229 7 in Figure 1. The observed profiles (in blue) are from CTD (Conductivity, Temperature, and
230 Depth) measurements collected by the Northeast Gulf of Mexico (NEGOM) program in Cruise
231 N9 in July 29 and August 1 of 2000, while the modeled ones (in red) correspond to July 30 of
232 2000 for one of the ITD integrations. The comparison between model and observed profiles
233 clearly improves when using data from the period we simulate, particularly at depth, but we have
234 a limited number of stations available in deep waters.

Figure 4. Salinity (left) and temperature (right) profiles at the locations marked in Figure 1. Panels (a) to (h): Model (red lines) and WOA09 seasonal means (blue lines) at locations 1 to 4. Panels (i) and (j): Model (in red) and in situ profiles collected during Cruise 9 of the NEGOM project (blue lines) at locations 5 to 7 on July 29 and August 1, 2000.

4. Interannual variability - Model and Observations

As mentioned, the circulation in the Gulf of Mexico is dominated by the presence of the Loop Current and by the occasional detachment of a Loop Eddies. In the following, we analyze the model representation of the Loop Current variability, its relationship with the Yucatan Channel transport, and the formation and detachment of the Loop Eddies.

4.1. Loop Current variability

To quantify the temporal variability of the LC we consider the monthly Eddy Kinetic Energy (EKE) anomalies over the region bounded by [90°W - 80°W] and [18°N - 30°N] (region B in Figure 1), which encompasses the full path of the LC, from its entrance at the south model boundary to its exit at the east boundary. The EKE is computed as $EKE = \left[\left(u'^2 + v'^2 \right) \right] / 2$, where u' and v' are the anomalies of the zonal and meridional velocity components, respectively. The anomalies are calculated subtracting first the total mean, u and v , over the simulation period (2000-2008) at each grid point, and then the monthly averages, in order to remove the seasonal cycle. Figure 5 compares the monthly EKE anomalies time series derived from satellite altimeter data (Aviso) to the ones from the ITD integrations (a-c), and BClim (d). The average correlation coefficient (cc) between model and observed EKE anomalies time series in the period 2000-2008 is $cc = 0.43 \pm 0.11$ for the ITD runs and $cc = 0.06$ for BClim, while the correlation between the EKE time series of different ITD runs varies from 0.56 to 0.67. The difference between ITD and BClim provides a first indication that the variability imposed by the boundaries is fundamental for the correct representation of the LC dynamic, as already noticed by Chang and Oey (2010a); Ezer, et al., 2003; Oey (1996, 2004) using idealized integrations.

The temporal agreement between the EKE anomalies in the ITD runs and in the satellite data improves considerably SODA performances (the correlation between surface EKE anomalies in SODA and Aviso is $cc=0.17$), likely due to the better representation of the mesoscale variability in ROMS, and is not too far from the correlations obtained using data assimilative models of analogous resolution. For example, the correlation between EKE anomalies in the eastern Gulf in the Hycom-expt. 20.1 integration (Chassignet et al., 2007; Counillon F. and L. Bertino, 2009; <http://hycom.org/dataserver/goml0pt04/expt-20pt1>) and Aviso for the period 2003-2008 and over the same area is 0.63. Incidentally, over the integration period considered, the mean EKE time series is particularly high in 2003, and all ITD runs capture this feature, but not BClim or SODA.

Figure 5. Time series of mean EKE anomalies in the region $[90W - 80W]$ and $[18N - 30N]$ from simulations and Aviso (a) ITD 1-3, BClim, and (b) Soda 2.1.6

To establish the statistical significance of the correlations above, we computed the Eulerian time scale (T_E) for the basin, defined as the integrals of the autocorrelation functions. T_E was calculated following Chiswell and Rickard (2008), as

$$T_E = \int_0^{\infty} r_e(\tau) d\tau \quad (1)$$

$$r(\tau) = \lim_{\Gamma \rightarrow \infty} \left[\frac{\frac{1}{\Gamma} \int_0^{\Gamma} u'(t) \cdot u'(t+\tau) dt}{\frac{1}{\Gamma} \int_0^{\Gamma} u'^2(t) dt} \right] \quad (2)$$

where r_e is the autocorrelation function, τ is the lag, and u' is the Eulerian velocity anomaly. Given that the model output has been saved every 10 days during the nine years of integration, the correlations were calculated with $\Delta\tau = 10$ days. The autocorrelation and Eulerian time scale were computed separately for the zonal and meridional velocity components for six locations along the coast, and six grid points distributed over the deeper central basin (see Figure 6). Independently on the group, the first zero crossing of autocorrelation functions happens after less than 50 days at the surface and 30 days at 1500 m depth and the cumulative integrals provide T_E of 25 and 15 days at most for surface and deep circulation, respectively. Therefore, with a conservative estimate, we consider the EKE anomalies to be uncorrelated on a scale of 50 days or longer for the sea surface and one month or longer for the deep layer (below 1000 m). Using a t-test with 60 degrees of freedom (7 per each year of integration), the correlation between ITD runs and observations is significant at the 95% level if it is above 0.25.

Figure 6. (a) Zonal and meridional Eulerian autocorrelation and (b) cumulative integrals of autocorrelations as a function of lag at the sea surface and at 1500 m

The EKE time series provide information only on the spatial averaged representation of the surface circulation in the eastern part of the Gulf. Moving on to the pattern distribution of the EKE anomalies in the whole Gulf, we plot the correlation between the modeled EKE anomalies time series and Aviso data at each grid point (Figure 7). Large correlations are concentrated in specific dynamical features of the Gulf of Mexico: the LC, the Yucatan Channel region, and the Latex and Tave shelves (Figure 7 (a)-(c)). In the shelf areas, however, the quality of altimetry data decreases due to the high frequency ocean response to tidal and atmospheric forcing, difficulties in estimating the mean sea level pressure, and radiometer footprints (see for example Hu et al., 2013). The west part of the Gulf, away from the shelf region, displays the lowest correlations in all runs. Its dynamic is affected by eddies originated in the LC and in Bay of Campeche that propagate chaotically.

The simulated circulations along the Latex and Tave are analogous in ITD and BClim runs. Along the shelves the wind forcing drives most of the variability, and several works (Cho et al.,

309 1998; Cochrane and Kelly, 1986; Nowlin et al., 1998; Waker et al., 2005; Zavala-Hidalgo et al.,
 310 2003) have shown that the along-coast wind stress is highly correlated with the local currents.
 311 Given the wind strong seasonality, we calculate the slope of the regression
 312 $(\sum_{i=1}^n (xi - \bar{x})(yi - \bar{y})) / \sum_{i=1}^n (xi - \bar{x})^2$ where x : Aviso data, y : model results) for the
 313 geostrophic velocities anomalies (separated in u_g and v_g components), shown in Figure 8 for one
 314 of the ITD runs (the other two being very similar) and BClim during September to March and
 315 April to August. The agreement between model and satellite data is better (slopes close to 1)
 316 over the Latex and Tave Shelves in boreal spring and summer, when the wind blows toward the
 317 coast, for both components of the velocity on the Tave shelf and for u_g over the Latex shelf. The
 318 LC pathway, on the other hand, is characterized by significantly larger correlations in boreal fall
 319 and winter for both velocity components than in spring and summer.

Figure 7. Spatial correlation between the model and Aviso EKE anomalies. (a), (b), (c), ITD simulations, and (d) BCLim. Areas where correlations are higher than the 95% significance level are contoured

Figure 8. Slope of the regression (model - ITD2 and Bclim – versus Aviso) of the geostrophic velocities component anomalies for the April to August (left panels) and September to March (right panels) seasons.

4.2. Yucatan Transport and its relation with Loop Current extension and West Gulf conditions

As shown in the previous sections, the internal variability of the Gulf of Mexico dynamics is strongly influenced by the LC. The ITD runs are can represent a statistically significant portion of such variability, but not BClim. Thus, the variability of the inflow at the southern boundary of our domain carries important information that commands the LC path in the Gulf.

The interaction between the North Atlantic Ocean, Caribbean Sea and the Gulf of Mexico has been studied in a variety of idealized and/or quasi-realistic modeling experiments by Oey and collaborators. For example, Oey and Lee (2003) performed and analyzed a simulation including annual and monthly climatology boundary conditions, prescribed constant transport at 55W, and time depended wind forcing. The authors conclude that the correct estimation of the YC transport is essential for simulating the Gulf of Mexico dynamics, as all the dynamic information from the Atlantic and Caribbean Sea contributes to it. The links between the YC transport and the LC variability, Loop Eddy shedding, and the overall dynamics in the Gulf of Mexico have been further investigated in a number of studies (Chang and Oey, 2010a; Ezer et al., 2003; Le Henaff et al., 2012; Oey, 2004). In those papers, the model setup always includes some combination of steady or climatological (monthly varying but not interannually varying) boundary conditions and/or atmospheric forcing. The authors conclude that the LC variability (expansion, retraction and shedding) is correlated with the flow conditions in the YC. They found a correlation in the expansion of the LC and in the deep return flow below 800 m at the YC. Also, they conclude that while vorticity and transport fluctuations at the YC may explain the irregular eddy shedding, the LC behavior cannot be wholly explained in terms of YC flow conditions.

353 Our ITD setup differs from those previous studies since it includes interannually varying, time
354 dependent surface and boundary forcing, and it is therefore more realistic. We have already
355 shown that at the surface, the ITD integrations represent the EKE anomalies in good agreement
356 with the satellite data (see Figure 7) and the mean circulation around and south of the YC is well
357 reproduced (see Figure 3). If any dynamical link exists between the YC transport and LC
358 variability, then the spatial-mean EKE anomalies time series that represent the LC (Subdomain B
359 in Figure 1) should be temporally connected with the YC transport. The ITD simulations support
360 this idea, in partial agreement with Ezer et al. (2003); Oey (1996, 2004), Chang and Oey
361 (2010a), and Le Henaff et al. (2012), as well as observations by Candela et al. (2002). In our
362 runs the mean correlation between monthly EKE and YC transport anomalies is $cc = -0.42 \pm 0.10$
363 for the ITD ensemble and non significant for BClim (see Figure 9). Comparing the time series, it
364 is also clear that the EKE anomaly peak in 2003 is linked (and proportional) to the higher than
365 normal North-West transport in the YC in the same period.

Figure 9. Time series of mean EKE anomalies and Yucatan transport anomalies in (a) ITD1-3 and (b) BClim integrations. The range of the y-axes in panel (b) is half than in panel (a).

4.3. Loop Eddies

The LC transit is occasionally accompanied by the formation and detachment of large anticyclonic eddies, called Loop eddies or Loop Rings, sized between 150 and 300 km in diameter. Their surface temperature signature is often lost in seasonal heating of the upper water column, but sea surface anomalies are easily tracked by satellite altimetry (Leben and Born, 1993). Once formed, eddies move westward across the basin at a speed of approximately 2-5 km d^{-1} (Elliott, 1982; Vukovich and Crissman, 1986), and persist for months to years until they

377 decay through interactions with the continental shelf. The eddy shedding process and driving
378 mechanism are not fully understood, and stochastic processes are likely to play a significant role
379 (Nowlin et al., 2000; Zavala-Hidalgo et al., 2006). Several hypotheses have been explored on the
380 controlling factors of the LC shedding, focusing primarily on the role of the wind forcing (Chang
381 and Oey, 2010b; Oey et al., 2003), of the Yucatan Channel transport strength (Bunge et al., 2002;
382 Ezer et al., 2003), of the variability in the circulation in the Florida Straits (Sturges et al., 2009),
383 of the potential vorticity fluxes into the Gulf (Candela et al., 2002; Oey and Lee, 2003; Oey,
384 2004). More recently, Lugo-Fernandez (2007) concluded that the LC and its eddy-shedding
385 behave as a nonlinear oscillator with a very short memory, with periodicity and amplitude linked
386 to the North Atlantic Oscillation (NAO).

387 A detailed Loop Ring separation analysis has been performed by Vukovich (2012) using sea
388 surface temperature, ocean color, sea surface height, and in-situ data from ships in the Gulf of
389 Mexico. Vukovich considered three periods: 1972-2010, 1972-2000, and 2001-2010 due to
390 changes in the eddy shedding periodicity. The average separation period between two
391 consecutive rings is ten months over 1972-2010, nine months over 1972-2000 and eleven months
392 for the period 2001-2010 (Leben, 2005; Sturges and Leben, 2000; Vokovich, 2007). In
393 particular, Vukovich (2012) identifies 13 shedding events between 2000 and 2008. Using the
394 absolute dynamic topography and absolute geostrophic velocities maps (MADT) from Aviso, we
395 find that 12 LC eddies separated from the main current. In the ITD and BClim runs we count 14,
396 13 15, and 15 shedding episodes, respectively, and we conclude that a reasonable, even if
397 slightly larger than observed, number of eddies detach from the LC in our simulations. Another
398 characteristic of the LC shedding is that Loop Eddies can form in any month of the year

(Vukovich, 2012) as shown in Figure 10, where we compare ROMS integrations and the Aviso data.

Figure 10. Distribution of the Loop eddies shedded in the period 2000-2008 as function of their month of detachment

Comparing each LC detachment in the model integrations and in the altimetry observations (Aviso), we find that the observed timing (plus or minus two weeks) of few - usually two or three - detachments is correctly reproduced in each run. Table 1 summarizes all Loop Eddy detachments and highlights the ones that match the observations. The greatest number of matches is found in ITD3, in August 2003, September 2004, and November 2007, and in BClim, where the boundary conditions do not vary interannually, in February 2006, again November 2007, and March 2008. Similarities between ITDs and Bclim runs results in terms of number and timing of LC eddies detachment suggest that the local atmospheric forcing in conjunction with

the Gulf bathymetry contribute to the shedding process, as proposed by Chang and Oey (2010b) and Le Henaff et al. (2012), but are not sufficient to determine the exact timing of each event.

Table 1. Eddies detached from LC in the period 2000-2008

Aviso	ITD1	ITD2	ITD3	BClim
	10-2000	06-2000	10-2000	11-2000
04-2001	05-2001	01-2001	01-2001	09-2001
	10-2001	08-2001	12-2001	
03-2002	05-2002	09-2002	07-2002	01-2002
	10-2002			07-2002
08-2003	05-2003	04-2003	02-2003	05-2003
		10-2003	08-2003	07-2003
				10-2003
09-2004	02-2004	11-2004	04-2004	03-2004
	11-2004		09-2004	
09-2005	07-2005	07-2005	04-2005	02-2005
		08-2005	11-2005	06-2005
02-2006	02-2006			02-2006
05-2006	07-2006	04-2006	04-2006	
10-2006		09-2006		08-2006
11-2007	06-2007	01-2007	01-2007	05-2007
	12-2007	07-2007	07-2007	11-2007
			11-2007	
03-2008				03-2008
04-2008				
07-2008	07-2008		08-2008	

The detachment of LC eddies in our simulations indicates that the LC behavior is governed by both an intrinsically variable and a forced (YC transport strength, atmospheric forcing, bathymetry constrains) component, as suggested, for example, by Oey and Lee (2003) and Nowlin et al. (2000). Transport and vorticity fluctuations in the YC, together with the wind forcing, contribute to the eddy detachment, but while a preferred tendency for LC shedding can be found for specific conditions of all three, they are not sufficient predictors.

5. Potential predictability of the Gulf of Mexico mesoscale circulation

Based on the comparison of ROMS integrations and satellite or in-situ observations performed so far, we can conclude that the predictability of the Gulf of Mexico circulation is limited when using a non-assimilative model. Systematic errors in our runs, however, may contribute to the limited reproducibility of the observed mesoscale circulation. Here we re-evaluate the potential predictability of the system focusing on the ensemble of simulations alone and assuming that one of them, ITD2, represents the ‘true’ state. To begin, we analyze the correlation between ITD2 and ITD1/ITD3/BClim for EKE and salinity anomaly fields at the surface and at 1500 m depth. Spatial correlation maps of the time series at each model grid point are presented in Figure 11 and Figure 12. At the surface, all simulations reproduce almost identical results in the Latex, Florida, Tave, and Yucatan shelves for both variables analyzed (up to correlations close or equal to 1). As pointed out in section 3, the modeled circulation and variability in those areas are mainly wind driven, and the incoming inflow at the ocean boundaries does not affect their reproducibility whenever the same atmospheric forcing products are used to force the model. The temporal resolution of the forcing fields and the horizontal resolution of the model, however, may cause an overestimation of the potential predictability in shallow areas in our runs. The ITD integrations also show a consistent representation of the surface circulation from the southern boundary to the Yucatan Channel, with most correlation coefficients between different ensemble members greater than 0.6, and slightly higher for salinity than EKE, particularly in the center of the domain. Correlations between ITD2 and BClim are mostly non significant in this area, with the exception of a small region along the northwestern coast of Cuba. High correlations in the EKE maps identify also the quasi-permanent cyclonic circulation in the South West of Campeche Bay, close to the Veracruz coastal area, in all four runs, and contour the LC extension

in the ITD2-ITD1 map (Figure 11-a), but not in the ITD2-ITD3 one (Figure 11-c). This inconsistency between ITD runs again indicates that internal chaotic variability plays an important role in the evolution of the LC, which is, for most part, not predictable if only external forcing fields and boundary conditions are known. At 1500 m depth EKE anomalies are not significantly correlated anywhere except south of the Yucatan Channel and only for the ITD runs, where the circulation is similarly constrained by the boundary conditions (Figure 12). Analogous maps are obtained for temperature and salinity (not shown). This suggests that the mesoscale variability at depth in the center of the Gulf is independent on the atmospheric forcing and boundary conditions, and the eddy formation, even when associated with bathymetric features, is chaotic, as found in other ocean basins (e.g. Bracco et al., 2008). Summarizing the results of this section so far, we have shown that the modeled circulation is chaotic and unpredictable in the central basin of the Gulf of Mexico, both at the surface and at depth, while is atmospherically forced along most of the shelves.

Figure 11. Spatial correlations of EKE anomalies (left) and sea surface salinity anomalies (right) between (a,b) ITD2 simulation and ITD1, (c,d) ITD3, and (e,f) BCLim. Areas where correlations are higher than the 95% significance level are contoured

Figure 12. Spatial correlations of EKE anomalies between ITD2 and (a) ITD1, (b) ITD3, and (c) BCLim at 1500 m depth. Areas with correlations higher than the 95% significance level are contoured

5.1. The role of model resolution

Two of the ITD integrations, ITD1 and ITD2, include a nested grid where the horizontal resolution increases to 1.6 km (Subdomain A in Figure 1) and submesoscale processes are partially resolved, while ITD3 resolves only the mesoscale circulation at 5km. The nested area contains the Mississippi and Atchafalaya river mouths, the Latex shelf, and includes the location of several natural oil seeps and of the Deepwater Horizon platform. From the analysis performed so far emerges that nested and not nested solutions provide a similar representation of the circulation both at the surface and at depth. As an example, in Figure 13 we show the vorticity field in the nested area from ITD1 and ITD3 in August 19th of 2000. Those two runs showed a

479 similar evolution of the Loop Current during the summer of 2000, but diverged later on. While
480 the representation of the details of the circulation increases in the 1.6 km solution at the Latin
481 shelf, all major frontal and mesoscale structures are common to the two runs, even if more
482 intense in the nested case. The greater intensity of the vorticity filaments does not affect the
483 predictability in this region at the surface or in the water column. North-south vertical sections of
484 salinity and vertical velocities across the Atchafalaya-Mississippi shelf are shown in Figure 14.
485 All panels include also a zoom on the shelf region from 28.5N to 29.8N. Salinity profiles are
486 very similar (See Figure 14 a-b and their insets), despite changes in the model representation of
487 the topography. The roughness of the sea floor, better resolved in the nested simulations, is
488 associated with the differences in the vertical velocities fields, with larger velocities the greater
489 the bathymetry gradients. Those differences are not sufficient to drive significant density
490 changes, or to modify the predictability skill of the model whenever monthly atmospheric
491 forcings are used. Indeed, an important caveat to this conclusion is that we imposed monthly
492 varying momentum and heat fluxes and they do not resolve the inertial frequency for the Gulf of
493 Mexico. The use of high frequency atmospheric forcing is likely to change more dramatically the
494 representation of vertical mixing by exciting quasi- and near-inertial waves as ageostrophic
495 expression of the mesoscale eddy field (Cardona and Bracco, 2012; Danioux and Klein, 2008),
496 and may potentially influence the density structure of the water column. Additionally, over the
497 continental shelf the resolution of the nested grid may not suffice to resolve the local Rossby
498 radius of deformation. On the other hand, we do not expect that the frequency of the atmospheric
499 forcing or the model resolution will change significantly the population of mesoscale eddies, and
500 therefore the predictability potential for the region at the scales we focus on.

Figure 13. Relative vorticity field in the nested area on August 19, 2000. (a) ITD3 (no nesting) and (b) ITD1 (nested). The solid white line indicates the cross-section shown in Figure 14.

Figure 14. Vertical profiles across the section indicated in white in Figure 13, from top to bottom, of salinity in psu and vertical velocity in m/s . Left: ITD3. Right: ITD1. Zooms in the shallow region from 28.5N until 29.8N are displayed as insets in each panel.

6. Deep and surface circulation connections

Moving finally to the potential predictability of the deep (>1000 m) circulation, we explore the relationship between the surface and deep mesoscale variability in the Gulf. The goal is to investigate if and where knowledge of the surface mesoscale dynamics (as provided for example by satellite data) can be used to infer valuable information about the variability at different depths. In other words, can an assimilative ocean model that provides a faithful representation of the surface mesoscale dynamics by assimilating satellite data, predict also the mesoscale variability at depth, in the absence of a set of continuous in-situ measurements? Such question is particular relevant for the Gulf of Mexico, where deep ocean drilling is likely to continue.

As mentioned in Section 3, the Gulf behaves, to a first order, like a two-layer system, with a top layer extending to approximately 1000 m, and one below it extending to the bottom. The two layers display different large scale circulation patterns (Hamilton, 2009). The first question we pose analyzing our runs, is relative to the role of mesoscale variability at depth. Its relevance to the circulation can be measured by the ratio of EKE and kinetic energy (KE). EKE is computed as described in section 4.1 and kinetic energy is simply $KE = [(u^2 + v^2)]/2$, where u and v are the zonal and meridional horizontal velocity components of the flow field, respectively, after removing seasonal cycle. We calculated the seasonal mean of EKE and KE ratio at the surface, 500, 1500, and 2000 m depth for all simulations. Results are almost identical between runs, and in the following we display only ITD1 (Figure 15). Regions with small EKE/KE values are indicative of limited mesoscale variability. In those regions, the knowledge of the mean currents is sufficient to describe the circulation. On the contrary, eddies, filaments and transient coherent structures dominate high EKE/KE ratio areas. At the surface, small EKE/KE ratio areas are found in correspondence to the Yucatan, Florida, Latex, and north part of Tave Shelves, where

the circulation is predominantly wind driven. Additionally, low EKE/KE values contour the inflow and outflow paths of the LC. Around the Florida and Yucatan shelves lower values of EKE/KE ratio characterize the fall-winter season, in association to Northeasterly winds, compared to spring-summer. On the other hand, ratios close to one populate the central basin of the Gulf, where mesoscale structures controls the dynamics. A similar analysis was conducted by Nakamura and Kagimoto (2006) in the North Atlantic using the output from an eddy-resolving model that integrated particles trajectories. The authors concluded that eddy mixing is repressed in small EKE/KE ratio areas, and that those regions act as mixing barriers. Particles traveling in small EKE/KE regions move along the mean flow, while, in contrast, they follow chaotic trajectories in large EKE/KE ratio areas where eddy mixing is large. This is in agreement with the analysis of particle trajectories in the Gulf of Mexico by Ohlman and Niiler (2005). The authors analyzed more than 750 surface drifters deployed over the northern Gulf shelf during the period 1993-1998 as part of the SCULP observational program, and concluded that the mesoscale circulation was responsible for moving the drifters away from the shelf, where were all released, and into the Gulf and then out in the Atlantic Ocean.

At 500 m and below EKE/KE ratios are not affected by the seasonality of the wind field and almost identical maps are obtained for both seasons. Low EKE/KE values linked with the inflow/outflow LC paths are still visible at 500 m, but not at 1000 m or below. The central part of the basin is consistently populated with high EKE/KE ratio values through the whole water column. Values around or lower than 0.5 can be found only at the south west corner of the Sigsbee deep and Bay of Campeche, where the deep water circulation is locally controlled by the bathymetry.

Figure 15. EKE/KE ratio in ITD1 for the period April to August (on left) and September to March (on right) . Top to Bottom: Surface, 500 m, 1500 m, and 2000 m

Next we consider the correlation between monthly anomalies of relative vorticity field at the surface and 500 m, 1000 m, 1500 m, and 2000 m for each grid point. The correlation maps are displayed in Figure 16. The mesoscale circulation at 500 m is highly correlated with the surface one (Figure 16-a). As described in section 3, LC and LC eddies disturbances extend to at least 800 m in the water column. Below 1000 m, correlations between vorticity at depth and at the surface decrease drastically. High values are restricted to mesoscale features formed by interaction of the mean flow with the bathymetry at the southwest corner of the Sigsbee Deep, around the Sigsbee Escarpment (around 26° N - 92° W), in the Latex Slope, and Mississippi Canyon. Below the Loop Current, immediately north of the Yucatan Channel, we also find correlations between 0.3 and 0.5. At 2000 m even fewer areas are significantly correlated with the surface, and those are concentrated at the Latex Slope, the southwest corner of the Sigsbee Deep, few spots in the Bay of Campeche, and in the central portion of LC path. This analysis suggests that the dynamics over most of the Gulf of Mexico are dominated by mesoscale features at all depths, the eddy component drives the kinetic energy evolution, and surface mesoscale structures are not representative of what happens below 1000 m.

In Figure 17 we then show the correlations between the monthly anomaly vorticity time-series at 2000 m and the ones at 1500 m, 1000 m, 500 m and again 5 m (this last map is obviously identical to Figure 16a). The mesoscale variability at depth is a better indicator of the structures found at 500 m than the surface mesoscale is of the structures at 1500 m. This suggests that the interaction of the deep currents with the topography is more important than the interaction between the atmospheric forcings and the surface circulation in influencing the dynamics across the water column. It is important to notice that if we had used velocities or EKE anomalies

581 instead of relative vorticity, maps would have shown lower correlation values (approximately
 582 0.15 lower everywhere).

583
 584 **Figure 16.** Correlation between monthly anomalies in relative vorticity at 5 m (surface) and (a)
 585 500 m, (b) 1000 m, (c) 1500 m, and (d) 2000 m depth. Areas where correlations are higher than
 586 the 95% significance level are contoured

587

Figure 17. Correlation between of monthly anomalies of relative vorticity at 2000m depth and at (a) 1500 m, (b) 1000 m, (c) 500 m, and (d) 5 m. Areas with correlations higher than the 95% significance level are contoured

The vorticity fields at different depths can provide further information about the structures (eddies in particular) that may extend through the two layers. Three examples are provided in Figure 18. They represent typical snapshots of the mesoscale variability in the Gulf. A video showing the evolution of the relative vorticity field from the surface to 2000 m in increments of 500 m from January 2002 to December 2005 in ITD3 is available as supplementary material. The video shows only four years, out of the eight we simulate, to limit the file size. The LC can be tracked to approximately 1000 m depth, but its signature is not always visible below it. This is evident in the snapshots from July 2006. At other times a small anticyclone of low intensity can be tracked to the bottom (i.e. in October 2003), bounded by Yucatan and West Florida Shelves.

602 Alternatively, a deep cyclonic circulation, bounded by topography in the eastern Gulf of Mexico,
603 is spun up by the LC below its southward eastern limb as described in Lee and Mellor (2003) (i.e.
604 in October 2007). The signature of the LC eddies is lost below 1000 m soon after their
605 detachment at all times. The cyclonic eddy at the southwest corner of the Sigsbee Deep, on the
606 other hand, can be tracked from the bottom to the surface most of the time, July 2006 being one
607 of the few exceptions. A large number of small vortices, both cyclonic and anticyclonic, of size
608 comparable to the Rossby deformation radius in the Gulf, populate the deep layer.

609 Focusing on the Deepwater Horizon site and around the location of most deep seeps, the
610 potential predictability of the bottom circulation given the surface one is very limited. Data
611 assimilative models will need, therefore, to include both satellite and in-situ data to infer the
612 details of the mesoscale circulation in the water column. In-situ data at locations where accidents
613 like the 2010 disaster have the potential to happen should be collected at high temporal
614 frequency (higher than the Eulerian time scale), and should be assimilated in ocean hindcasts and
615 forecasts to insure a proper representation of the mesoscale variability throughout the water
616 column.

Figure 18. Instantaneous relative vorticity field (unit s^{-1}). Top to bottom: Surface, 500 m, 1000 m, 1500 m, and 2000 m depth. Left to right: 22-October-03, 18 July 2006, and 21-October-2007. Black dots in panel (a) left to right: Garden Banks, Green Canyon and MC 252.

7. Conclusions

In this work we analyzed an ensemble of simulations performed with ROMS over the Gulf of Mexico covering the period 2000-2008 with the objective to investigate the predictability of its mesoscale circulation, both at the surface and in deep waters on intraseasonal time scales. In all runs, the model provides a good representation of the mean circulation features. The magnitude and spatial distribution of the mean geostrophic velocities, and the transport at the Yucatan Channel are well represented. The frequency of formation and the horizontal and vertical extension of the Loop Current eddies are realistically modeled. The shedding of the Loop Eddies differ in each run considered, and our analysis shows that the detachment of the Rings from the Loop Current is a chaotic process, even if more likely under certain wind forcing and LC strength conditions.

By comparing a simulation performed with climatological (monthly varying, but repeated identically every year) boundary conditions, with three runs that adopt interannually varying boundary conditions, we show that the interannual variability at the model boundaries affects the representation of the Loop Current strength and of the Yucatan Channel transport. On the other hand, the circulation in the Latex Shelf, Tave Shelf, and Bay of Campeche with the limitation of the resolution implemented, appears insensitive to the details of the model boundaries, is not affected by the Loop Current, but depends only on the atmospheric variability. The circulation in those areas is also characterized by low levels of eddy kinetic energy, and limited mesoscale variability. On the contrary, the circulation in the central basin is affected by the Loop Current extension and by the Rings, and overall dominated by mesoscale features.

The dominance of mesoscale variability extends to the whole water column. In most of the basin, mesoscale features are coherent in the top ~ 1000 m of the water column, and below it, but not

correlated between the surface and the deep layer. The Eulerian time scale for the top layer, extending from the surface to approximately 1000 m is 50 days; the Eulerian time scale below 1000 m is shorter, around 30 days, due to the smaller size, and higher speed, relative to the mean currents, of the lower layer eddies. Coherency throughout the whole water column is found only at the south-west corner of the Sigsbee Deep, at the south boundary of the Sigsbee escarpment where the topography constrains the formation and propagation of cyclonic eddies, and under the Loop Current, limited to the eastern Gulf.

The chaotic behavior associated with the propagation of the Loop Current eddies and the elevated mesoscale activity restrict the potential predictability of the system at intra-seasonal scales. Current data assimilative models have the potential of predicting the mesoscale circulation in the upper 1000 m over several days, given the Eulerian time-scale of the flow. However, the lack of coherency between the mesoscale features in the upper portion of the water column with the ones underneath limits the predictability at depth in the absence of a continuous monitoring system in most of the basin.

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