Cyclonic Eddies in the Gulf of Mexico: Observations by Underwater Gliders and Simulations by Numerical Model

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(Manuscript received 16 July 2014, in final form 20 October 2014)

ABSTRACT

Circulation in the Gulf of Mexico (GoM) is dominated by the Loop Current (LC) and by Loop Current eddies (LCEs) that form at irregular multimonth intervals by separation from the LC. Comparatively small cyclonic eddies (CEs) are thought to have a controlling influence on the LCE, including its separation from the LC. Because the CEs are so dynamic and short-lived, lasting only a few weeks, they have proved a challenge to observe. This study addresses that challenge using underwater gliders. These gliders’ data and satellite sea surface height (SSH) are used in a four-dimensional variational (4DVAR) assimilation in the Massachusetts Institute of Technology (MIT) general circulation model (MITgcm). The model serves two purposes: first, the model’s estimate of ocean state allows the analysis of four-dimensional fields, and second, the model forecasts are examined to determine the value of glider data. CEs have a Rossby number of about 0.2, implying that the effects of flow curvature, cyclostrophy, to modify the geostrophic momentum balance are slight. The velocity field in CEs is nearly depth independent, while LCEs are more baroclinic, consistent with the CEs origin on the less stratified, dense side of the LCE. CEs are formed from water in the GoM, rather than the Atlantic water that distinguishes the LCE. Model forecasts are improved by glider data, using a quality metric based on satellite SSH, with the best 2-month GoM forecast rivaling the accuracy of a global hindcast.

1. Introduction

Circulation in the Gulf of Mexico (GoM) is dominated by the Loop Current (LC), an extension of the western boundary current system of the North Atlantic Ocean that loops into the GoM. The LC enters the Gulf through the Yucatan Channel and exits through the Florida Straits. The LC occasionally extends far northward into the GoM, approaching the northern shelf break. This long extension of the loop will eventually separate to form an anticyclonic Loop Current eddy (LCE). Formation of an LCE by separation from the LC happens irregularly every several months, and there can be a number of LCEs in the GoM at one time. Prediction of LCE formation events is central to accurate forecasting of GoM circulation.

Cyclonic eddies (CEs), sometimes called Loop Current frontal eddies (Walker et al. 2009), exist on the periphery of the LC and LCE. These CEs are much smaller than the LCE, but they are thought to have a controlling influence on the LCE, including its separation from the LC (Vukovich and Maul 1985; Fratantoni et al. 1998; Schmitz 2005; Cherubin et al. 2006). The CEs appear and disappear within weeks and thus evolve much more rapidly than the LCE, which may stay intact for months. Thermohaline characteristics in CEs and LCEs are different, suggesting distinct origins (Paluszkiewicz et al. 1983). CEs and LCEs are readily observed by satellite (Vukovich 2007; Walker et al. 2003, 2005; Zavala-Hidalgo et al. 2003), with clear signals in sea surface temperature, sea surface height, and chlorophyll. Because the CEs are so dynamic and short-lived, they have proven a challenge to observe in situ, although there are some excellent published observations, including using hydrography, moorings, satellite-tracked drifters, and air-deployed expendable profilers (Hamilton 1992; Hamilton et al. 2002; Paluszkiewicz et al. 1983; Vukovich and Maul 1985). Here, we address the challenge of in situ observation using underwater gliders (Rudnick et al. 2004) that can have missions lasting several months, so they can be in place opportunistically when CEs appear.
The LC and LCEs are prominent features of the GoM circulation with a long and rich history of simulation and prediction. Early LC analysis and forecast studies in the GoM mainly used the Princeton Ocean Model (POM), which assimilated satellite sea surface height (SSH) and sea surface temperature (SST), and other in situ datasets using methods such as nudging (Kantha et al. 2005), a combination of nudging and optimal interpolation (OI) (Oey et al. 2005; Lin et al. 2007), and ensemble schemes (Yin and Oey 2007). A GoM assimilation system based on the Hybrid Coordinate Ocean Model (HYCOM) was developed by Chassignet et al. (2007), using an oceanographic implementation of multi-variate optimum interpolation (MVOI) known as the Navy Coupled Ocean Data Assimilation (NCODA) (Cummings 2005). Assimilation studies by Counillon and Bertino (2009b,a) used an ensemble OI method for the HYCOM-GoM model. Variational assimilation systems have been implemented for GoM circulation studies. For instance, the cyclic representer algorithm for the variational method was developed by Ngodock et al. (2007), using a simplified 1.5-layer reduced gravity ocean model. Powell et al. (2008) demonstrated a four-dimensional variational (4DVAR) assimilation and forecast system for the Intra-Americas Seas (IAS) using the Regional Ocean Modeling System (ROMS) model. Gopalakrishnan et al. (2013b) implemented a 4DVAR assimilation system for the IAS region using the Massachusetts Institute of Technology general circulation model (MITgcm) and its adjoint. A recent study by Xu et al. (2013) compared a local ensemble transform Kalman filter and OI assimilation for hindcasting and forecasting LC and LCEs in the GoM. Another recent study by Hoteit et al. (2013) developed a weekly ensemble analysis and prediction system for the GoM circulation based on the MITgcm–Data Assimilation Research Testbed (DART) ensemble Kalman filter system. Finally, Cardona and Bracco (2014) studied the GoM three-dimensional ocean predictability using a long-term forward ROMS simulation.

CEs have been the target of several modeling studies. Hurlburt (1986) reported that the formation of CEs was caused by baroclinic instabilities generated near the steep Campeche Bank topography. Cherubin et al. (2006) showed that CEs were generated by interaction of vortex rim instabilities and steep topography near the northern Campeche shelf. Le Hénaff et al. (2012) studied the dynamics and influence of CEs on the LCE shedding processes using HYCOM-GoM forward simulations. Finally, Huang et al. (2013) analyzed the evolution of CEs from an Atlantic Ocean general circulation model, based on the Parallel Ocean Program (POP), and reported that modeled CEs have a very coherent vertical structure with isotherm doming from 50- to 1000-m water depth in the simulations.

Our effort involves observations by gliders and the assimilation of glider data into a numerical model. The model can then be used to examine the system as a whole, as it assimilates the relatively sparse glider data with other available data, including especially satellite SSH. While the glider data are by reasonable measures sparse, they are the most complete source of vertical profiles in the GoM’s upper 1000 m. There are over 1000 glider profiles during the time period presented here, compared to 68 profiles from Argo floats (Roemmich et al. 2009). An advantage of gliders is that they can be positioned so that their profiles yield the most benefit to the model. We present results on how gliders improve model forecasts initialized from ocean state estimates using their data.

The paper is organized as follows: Section 2 presents the methods used including relevant aspects of the Spray underwater glider and a summary of the MITgcm assimilating model. Results are presented in section 3, with a focus on CEs as well as comparisons between observations and model hindcasts. A discussion and conclusions compose section 4.

2. Methods

a. Spray underwater glider

Since 2010, we have flown a series of glider missions in the GoM comprising over 1600 glider days, over 44000 km, and over 8000 dives. Our glider of choice is Spray (Sherman et al. 2001), used here to profile to 1000 m, completing a cycle from the surface to depth and back in about 6 h and traveling 6 km through water in that time. Here, we focus on two of these missions, which were done concurrently with the two gliders sampling different parts of the circulation (Fig. 1). The two Sprays, serial numbers 40 and 50, were deployed on 9 December 2011 and recovered on 19 April 2012; a duration of 132 days. Spray 40 was piloted to make repeated crossings of the LCE, covering 3504 km over ground and 2979 km through water and completing 551 dives. Spray 50 was used to search for CEs on the periphery of the LCE, covering 3722 km over ground and 2792 km through water and completing 522 dives. Differences between the two Sprays in distance covered through water had to do with slight variations in buoyancy, while differences in track length were caused by currents each Spray encountered and the piloting relative to those currents.

Each glider’s payload consisted of a Sea-Bird 41CP conductivity–temperature–depth (CTD) instrument and a Seapoint chromophoric dissolved organic matter (CDOM)
fluorometer, both plumbed inline to a Sea-Bird 5M pump, ensuring consistent flow through the sensors (\(\approx 10 \text{ cm}^3 \text{s}^{-1}\) flow rate). Small tributyltin inserts in the plumbing controlled the fouling of the sensors. Temperature and salinity were sampled every 8 s on ascent, and with a roughly 0.1 m s\(^{-1}\) vertical speed, this resulted in vertical resolution of about 0.8 m.

The depth-averaged velocity is determined for each glider dive (Fig. 2). Glider displacement through the water is estimated using observed pressure, pitch, and heading and assuming an angle of attack of \(3^\circ\) (Sherman et al. 2001). This displacement is differed from the GPS-measured displacement at the beginning and end of the dive to get the water velocity averaged along the glider’s path. We pilot the gliders to maintain a pitch of \(17^\circ\), so the glider’s path through water is nearly uniform in depth (Rudnick and Cole 2011), and the velocity can be taken as a depth average. This depth-averaged velocity has been proven accurate to 0.01 m s\(^{-1}\) (Todd et al. 2011) by comparing velocity before and after a turn using a method similar to that used for shipboard acoustic Doppler current profilers (Pollard and Read 1989).

For many calculations, glider data are objectively mapped (Bretherton et al. 1976) in the along-track direction. This mapping is done using a Gaussian autocovariance with a length scale of 50 km and a noise-to-signal ratio of 0.05 for noise uncorrelated between glider profiles. The map is done on level surfaces every 10 m in depth from 10 to 1000 m onto a horizontal grid of spacing 1 km in the along-track direction. This grid is then used for all subsequent calculations, especially those involving horizontal gradients, as in the calculation of geostrophic shear from the horizontal gradient of density. The horizontal gradients can then be interpreted as resulting from scales of about 50 km and larger. Absolute across-track geostrophic velocity is calculated by referencing the geostrophic shear to the depth-averaged velocity measured directly by the glider. This referencing is accomplished by subtracting the mean from vertically integrated geostrophic shear and then adding in the glider-measured depth-averaged velocity. Finally, integrating the shallowest absolute geostrophic velocity (at 10-m depth) produces an estimate of sea surface height along the glider’s trajectory.

A few comments on the effects of the gliders’ slowness may be helpful in interpreting the results, following Rudnick and Cole (2011). Every method of surveying the ocean, from ships to satellites, takes a finite amount of time, thus projecting temporal variability into horizontal structure. The most obvious manifestation of this effect for gliders is that observed structure with wave-lengths shorter than about 30 km is contaminated by unresolved internal waves, as revealed by comparisons between wavenumber spectra measured by gliders and by rapidly towed vehicles. The choice of 50 km as a length scale for objective mapping filters out this contamination. Gliders adequately resolve structure at larger scales.

Another aspect of slowness is that the low-frequency, nearly geostrophic circulation evolves during the time of the glider’s mission, as it would for any ship survey that takes a similar amount of time. In the following, we examine structure following a glider’s trajectory, and we
compare to model results following the same trajectory in space and time. The model hindcast, as it assimilates glider data at the correct time and place and it has appropriate dynamics, can then be used to interpret the structure observed along the glider’s trajectory.

b. **MITgcm**

The MITgcm (Marshall et al. 1997) integrates the primitive (Navier–Stokes) equations on a sphere under the Boussinesq approximation. The equations are written in \( z \) coordinates and are discretized using the centered second-order finite difference approximation in a staggered Arakawa C grid. The numerical code of the MITgcm is designed to enable computer generation of its adjoint model using the automatic differentiation tool Transformation of Algorithms in FORTRAN (TAF) (Giering and Kaminski 1998; Heimbach et al. 2002). We use the MITgcm-4DVAR Intra-Americas Seas (MITgcm-IAS) assimilating model (Gopalakrishnan et al. 2013a) for hindcasts using an approach based on the Estimating the Circulation and Climate of the Ocean (ECCO) system (Stammer et al. 2002). The hindcast involves minimization of a cost function subject to the following controls: 1) initial conditions for temperature and salinity, 2) open boundary conditions, and 3) atmospheric forcing. Adjusting these controls, through both forward simulation and use of the model’s adjoint, optimizes the hindcast. The final step of the hindcast is a forward simulation with the optimized controls so that the ocean state exactly obeys the model dynamics. Three assimilation experiments are performed: experiment 1 uses only along-track satellite SSH, experiment 2 uses temperature and salinity from the gliders in addition to SSH, and a control experiment assimilates no data. Forecasts of the GoM circulation are initialized from the optimized solutions for each of these hindcasts.

Some relevant details of the MITgcm-IAS model are as follows: The model domain extends from 8.5° to 31°N and from 98° to 72.5°W, covering the GoM, Caribbean Sea, and part of the Gulf Stream. The model is integrated on a \( \frac{1}{10} \), spherical polar grid, with 40 vertical \( z \) levels starting with 5-m spacing at the surface and gradually increasing spacing with depth. The bathymetry is extracted from 2-min Gridded Global Relief Data (ETOPO2). The model is operated in hydrostatic mode with an implicit free surface. The subgrid-scale physics is approximated by a diffusive operator of second order in the vertical. Vertical diffusivity and viscosity are parameterized by Laplacian mixing and by the \( K \)-profile parameterization (KPP) in the surface mixed layer (Large et al. 1994). In the horizontal, the diffusive and viscous operators are of second order and fourth order, respectively. Each state estimate starts with initial conditions and boundary conditions (temperature, salinity, and horizontal current) taken from the assimilated HYCOM/NCODA \( \frac{1}{10} \)° global analysis (Chassignet et al. 2007). The boundary conditions are sampled at 7-day intervals and adjusted daily using the adjoint method. The starting guess atmospheric forcing is calculated using a bulk formulation (Large and Pond 1981) with the atmospheric state from National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis-1 (NCEP–NCAR R-1) (Kalnay et al. 1996) surface fluxes and winds sampled every 6 h and adjusted daily. Monthly climatological runoff freshwater fluxes are taken from the ECCO global model state estimate. The optimization primarily adjusts the initial conditions. The optimized solution from the end of each assimilation period initializes the model forecasts. The forecast uses monthly climatologies for all forcing and boundary conditions, calculated from the same assimilated HYCOM analysis and NCEP–NCAR R-1 fluxes and winds. Sensitivity experiments comparing forcing and boundary conditions from the analyses to those from the climatologies show approximately 5% SSH differences in the LC region after 2 months, so neither surface forcing nor boundary conditions have a large effect on the LC evolution in these cases.

### 3. Results

The results are concerned with the characteristics of the LCE and CEs, especially their velocities, vorticities, and hydrographic structure. Where possible, we compare the results of glider observations and model hindcasts, with an eye toward determining the model’s strengths and limitations. With an understanding of the model’s abilities, we use the model to examine the three-dimensional structure that the glider cannot capture. Finally, model experiments are used to determine the value of glider observations in initializing forecasts.

Our first analysis focuses on results from Spray 50, which surveyed two CEs during its mission (Fig. 3). These eddies, observed during 27 December 2011–12 January 2012 (dives 80–140) and 16 March–1 April 2012 (dives 385–445), were unambiguously cyclonic, as quantified by least squares fits to simple linear velocity fields. The 1000-m depth-averaged velocity is fit to a model of solid body rotation in which the eastward \( u \) and northward \( v \) velocity components are given by

\[
  u = -\frac{\xi}{2} (y - y_0), \quad \text{and}
\]

\[
  v = \frac{\xi}{2} (x - x_0),
\]

where \( \xi \) is the geostrophic shear.
Here, \( \xi \) is relative vertical vorticity (twice the rotation rate of the CE), and \( x_0, y_0 \) denote the center position of the CE. A standard least squares fit is done (Table 1), where position is measured relative to the mean glider position over the given time period. The vorticity, normalized by the Coriolis parameter \( f \), is 0.20 and 0.17 for the two eddies. Taking this ratio of relative to planetary vorticity as a measure of the Rossby number, it follows that the momentum balance is not strictly linear and geostrophic and that nonlinear effects like curvature of the flow are emergent. The position of the center of the eddies relative to the mean position of the glider data is given by \( x_0 \) and \( y_0 \), whose relatively small values suggest that the observations were reasonably symmetrically distributed around the eddies. The root-mean-square (rms) misfit is about 0.1 m s\(^{-1}\) per datum, compared to rms measured velocities of 0.36 and 0.31 m s\(^{-1}\). So eddies in solid body rotation describe most, but not all, of the velocity variance. Taking this misfit as a measure of all the other sources of velocity that could cause error in the least squares fit, we derive an error in the estimated values of normalized vorticity of about 0.01. Finally, we relax the assumption of solid body rotation (i.e., that the eddies are circular) by fitting planes to the measured velocity. The resulting normalized vorticity must be larger, but is only slightly at 0.22 and 0.20 for the first and second CE, respectively. These results suggest that the CEs are not very noncircular. Taken together, the results of least squares fitting support the notion of eddies in near solid body rotation with normalized vorticities of about 0.2.

Satellite observations of SST and SSH help to understand where the glider trajectories were in relation to the LC and LCE. In Fig. 4, maps of Group for High Resolution Sea Surface Temperature (GHRSST) are shown with the 17-cm contour of Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) gridded SSH for reference. This particular contour of SSH is often used as the marker for separation of the LCE (Leben 2005), so when the first CE was observed, the LCE was recently separated and close to the LC. This CE was in a region to the northeast of the separation region. As is typical, the SST in the CE is cooler than in either the LC or LCE. The second CE, observed months later, was to the northeast of the LC that is extending well into the GoM. The SST in this second CE appears less cool and well defined than in the first CE.

The model hindcast shows the same general features in SST as the satellite observations (Fig. 4). In particular, the warm water associated with the LC and LCE is readily apparent. The first CE shows up clearly in the model as well as the satellite observations, while the second CE is less clear. The correspondence in general features between the hindcast and observations is notable in that the model does not assimilate SST.

The data produced by a glider are essentially a hydrographic section following the track of the glider. A salinity section from Spray 50 (Fig. 5a) crossed both the anticyclonic LCE and at least two CEs. The LCE is marked by anomalously deep isopycnals and by the salty water characteristic of the Atlantic. CEs are not especially apparent in the salinity section as they have the salinity of the water that extends through the GoM. Magenta bars at the top of the figure show the dives chosen as representative of CEs. The first CE was pressed against the side of the LCE, so the edges of the two eddies coincided, as the glider passed through the edge of the LCE on its way to the CE. The second CE was to the northeast of the LC (Fig. 4). Since the glider’s path took it across the northern tip of the LC on its way to the CE, there was no sign of plunging isopycnals indicative of Atlantic water. Spray 40 (Fig. 5b) was piloted to do repeated crossings of the LCE, so the section is

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**Table 1.** Results from fitting a model of solid body rotation to measurements of 1000-m depth-averaged velocity.

<table>
<thead>
<tr>
<th>Cyclonic eddy</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dives</td>
<td>80–140</td>
<td>385–445</td>
</tr>
<tr>
<td>( \xi/f )</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>( x_0 ) (km)</td>
<td>-3.4</td>
<td>26.7</td>
</tr>
<tr>
<td>( y_0 ) (km)</td>
<td>16.0</td>
<td>-2.5</td>
</tr>
<tr>
<td>Misfit (m s(^{-1}))</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Error in ( \xi/f )</td>
<td>0.011</td>
<td>0.015</td>
</tr>
</tbody>
</table>
composed of a series of isopycnal depressions corresponding with high salinities.

By sampling from the model grid along the glider trajectory, direct observations from the glider can be compared to the model hindcast (Fig. 5). The isopycnal displacements associated with the LCE are reasonably well reproduced by the hindcast. The reproduction of the density structure is encouraging, as it suggests that the model dynamics are correct and also lends confidence in low-frequency, geostrophically balanced velocity from the model. The structure in salinity agrees in general, but the maximum in the middle of the LCE is not strong enough in the model. That the hindcast underestimates the salinity maximum suggests that study of the details of thermohaline structure may not be a good use of the model. Details of salinity structure in the upper roughly 100 m are not well reproduced by the model. The shallow salinity structure is strongly affected by mixing processes that may be inadequately represented in the model. The shortcoming of the mixing simulation is practically expressed in the weighting of assimilated salinity data. The structure here is generally within the chosen a priori error of 0.2 psu. In any case, these shallow finescale thermohaline features are not the focus of the model, which is intended to reproduce larger-scale, nearly geostrophically balanced circulation.

The sections in Figs. 5a and 5b are produced from raw glider profiles without any objective mapping, so internal waves are seen as small-scale fluctuations in isopycnals. These displacements by internal waves are much smaller than those caused by the mesoscale eddies that are the focus of this paper. Subsequent analysis of objectively mapped fields is thus negligibly affected by internal waves.

Absolute across-track geostrophic velocity observed by the gliders reveal flow patterns in the eddies (Fig. 6). The gliders were deployed next to each other, and then flew into, and back out of, the LCE. Because the LCE was anticyclonic, the pattern of across-track geostrophic velocity was first to the left of the track on the way into the eddy and then to the right of the track on the way out. This pattern is seen in the first 600 km of the track of both gliders (Fig. 6). Across-track geostrophic velocity is easier to interpret for Spray 40 (Fig. 6b), as it was piloted to cross the LCE time after time. This sequence of crossings is apparent as vertical bands of red followed by blue, centered on isopycnic depressions. The geostrophic velocity is absolute, as it is referenced to the glider’s
measure of depth-averaged velocity, so the velocity is not zero at the bottom of the profiles at 1000 m. The CEs observed by Spray 50 (Fig. 6a), though more difficult to discern, are distinguished by elevations of isopycnals surrounded by flow first to the right (blue) and then to the left (red) of the glider track. With some interpretation, the across-track absolute geostrophic velocity does allow the identification of eddies.

Model hindcast across-track velocity reproduces that observed by the glider remarkably well (Fig. 6). Perhaps this good agreement, especially in the horizontal location of strong flow, is to be expected as the model hindcast of the density field is good and the momentum balance is nearly geostrophic. A close examination of Fig. 6 does reveal some areas of discrepancy between glider and model. In particular, the deep flow in the CEs is observed (Figs. 6a,b) to be much stronger than simulated in the model (Figs. 6c,d). Since the model is doing a good job of reproducing the density structure, this must be because of the model underestimating the strength of the barotropic pressure gradient.

SSH is a handy metric for analysis and comparison as it is measured by satellite, may be estimated from the glider surface geostrophic velocity, and is one of the primary results of the model (Fig. 7). The SSH implied by glider observations is calculated by horizontal integration of geostrophic velocity at 10-m depth (Fig. 7, blue line). The arbitrary zero of SSH is taken to be the beginning of the glider’s tracks as they were both deployed at the same location outside of any eddy. The reference for AVISO and model SSH (Fig. 7, red and green lines) is mean SSH over the region defined in Fig. 1. SSH from the three sources should be interpreted only for the changes along the glider trajectory, as the

![Fig. 5. Sections of salinity (color) and potential density (black contours) along the tracks of Spray (a) 50 and (b) 40 and the (c),(d) results from model hindcasts sampled along these tracks. The locations of profiles composing the sections are indicated by tick marks along the upper axes. Magenta bars at the top of (a) show the locations of cyclonic eddies of Fig. 3.](image)
absolute values have different references. The difference in SSH across the LCE is larger than 0.6 m, as reflected in all measures. Minima in SSH (near −0.2 m) on the track of Spray 50 (Fig. 7a) are indicative of CEs. The model inadequately reproduces the fluctuations associated with crossing the CEs, especially in the first CE (600–1100 km). This helps to explain why the model velocity is not strong enough in the CEs (Fig. 6). Comparison of the SSH of Fig. 7 with the 27 kg m$^{-3}$ isopycnal in Fig. 6 makes clear that much of the signal depends on hydrographic structure, so it is baroclinic. In fact, the correlation between SSH and isopycnal depth is about 0.9. This suggests that the barotropic contribution to SSH, as from the measured depth-averaged velocity, is small and/or strongly correlated with the baroclinic velocity.

The trajectory of Spray 50 took it through the LCE and then the first CE, providing an opportunity for comparison of the eddies’ structures. The depth-averaged across-track velocity, 10-m geostrophic velocity, and SSH are shown in Fig. 8 for the first 1100 km of the track of Spray 50. The interior of the LCE (0–600-km along-track distance) is marked by the high in SSH, and anticyclonic flow around the eddy is baroclinic in the sense that the 10-m across-track velocity is larger than the 1000-m depth-averaged velocity. In contrast, the flow around the CE (600–1100 km) is barotropic as the 10-m and depth-averaged velocities are nearly equal. The depth-averaged flow in the LCE is roughly the same as that in the CE. So, while the depth-averaged momentum is roughly equal between the LCE and CE, the CE is much more barotropic than the LCE.

The state estimates from the model allow a more thorough examination of the differences between the LCE and CE. Consider the state estimate from 31 December 2011 (Fig. 9), which includes the CE observed by the glider during the same time period. The LCE and CE
are clearly evident in SSH (Fig. 9a), as are their senses of rotation in terms of the 1000-m depth-averaged velocity. A zonal profile through the minimum in SSH marking the CE gives a difference in SSH approaching 1 m (Fig. 9b). This difference is broadly consistent with the glider observations (Fig. 8) considering that the glider likely did not pass through the exact center of either eddy. A zonal section of northward velocity shows the strong currents defining the eddies (Fig. 9c). Vertical profiles through these currents (Fig. 9d) demonstrate the difference in depth dependence. The CE velocity is nearly uniform with depth in the model, although the velocity is not as strong as in the glider observations. Note that the model did not assimilate velocity data from the glider. In summary, the model did a good job of simulating the SSH in the LCE and CE and did reproduce appropriate depth structure, although the magnitude of the depth-averaged current in the CE was weak. The finding that the CE is more barotropic than the LCE is supported by both model and data.

The water composing the LCE and CEs are of different origin according to the observed thermohaline characteristics. Profiles of potential temperature plotted against salinity are colored by the SSH in Fig. 10. The clear result for Spray 50 (Fig. 10a) is that the highest SSH (in the interior of the LCE) corresponds to salty water characteristic of the Atlantic on roughly the 25.5 kg m\(^{-3}\) isopycnal. Depressions in SSH (in CEs) correspond to fresher water of GoM origin. Even though large coherent CEs were not observed from Spray 40, the same pattern of elevated SSH corresponding with salty water, and vice versa, is readily apparent (Fig. 10b). The conclusion is that the LCE acts as a container of Atlantic water, while CEs are derived from the GoM.

The quality of the state estimate is assessed by the regionally averaged root-mean-square difference (RMSD) between model hindcast SSH and the AVISO-mapped SSH (Fig. 11). The region of the average is the central GoM basin, shown by the area enclosed by the box in Fig. 1. The state estimates were fit to along-track SSH observations with and without glider temperature and salinity profile data over the hindcast period of 1 or 2 months and were constrained to model dynamics with small control adjustments within prior uncertainty. The optimized solutions are not expected to match the mapped AVISO SSH product exactly, even during...
the hindcast period. The fit to the observations for short periods of 1 or 2 months was primarily accomplished by adjusting the initial condition controls. The RMSD between along-track SSH and mapped AVISO gridded SSH varied in time, ranging between 0.07 and 0.12 m (not shown). So an RMSD of about 0.1 m for any of the state estimates is no more than would be expected from the AVISO gridding algorithm. The successive assimilation windows are indicated by gray vertical dashed lines in the figure, showing one 1-month (December 2011) period and two 2-month periods (January–February 2012 and March–April 2012). The state estimate RMSD curves are smoother than those of the HYCOM/NCODA global analysis because of the dynamical constraints they must obey. The RMSD from the HYCOM/NCODA sequential analyses, which are expected to fit the observations at any given time better than the 4DVAR, give another indication of the uncertainty in the various maps. Of course, the ocean state is not completely specified by SSH, and the true skills of the AVISO and HYCOM/NCODA hindcasts are not known, but they are useful for comparison.

In all three windows, the hindcast from the state estimate without the glider observations (EXP1) generally has less RMSD with respect to AVISO maps than the experiment with glider data (EXP2) (Fig. 11a). This supports the hypothesis that the fitting can concentrate on the SSH data when no glider data are included. Even though the system is dynamically consistent throughout the assimilation period, the RMSD of the EXP1 hindcast stays within about 0.02 m of the RMSD between the HYCOM/NCODA global analysis (which is not required to be dynamically consistent) and the AVISO data and is sometimes smaller.

The 2-month forecasts from the optimized state at the end of each of these hindcasts are shown in Fig. 11b. These use climatological forcing and boundary conditions, so they are true forecasts, even though done using historical data. Although the EXP1 hindcast (red) does well on the altimetry, and its forecast starts off closer to the AVISO and HYCOM/NCODA maps than EXP2, its RMSD is generally worse than the control forecast initialized from HYCOM/NCODA global analysis (MIT-C, black) in the first two cases. This indicates that the state estimation could not improve on the HYCOM/NCODA analysis when given only SSH observations. The forecasts from the state estimates with the glider data (EXP2), which generally fit SSH more poorly

Fig. 9. SSH and velocity from a model hindcast on 31 Dec 2011, including a (a) map of SSH and 1000-m depth-averaged velocity, (b) SSH on a zonal line [dashed line in (a)] passing through the minimum in SSH, (c) northward velocity on this line, and (d) profiles of northward velocity at extrema on the edges of the LCE and CE. The locations of these extrema are marked by the dashed lines in (c).
during the hindcasts (Fig. 11a), have smaller RMSD than EXP1 toward the ends of the forecast periods, especially for March–April 2012. During the last few weeks of this 2-month forecast period, EXP2 RMSD remarkably approaches that of the HYCOM/NCODA global analysis. This result is consistent with the hypothesis that the glider is adding information toward improving the state estimate. The forecast improvements of EXP2 over EXP1 are likely because of additional subsurface information from the glider data, which should lead to a more accurate representation of the three-dimensional ocean state and a better initialization than for EXP1. The RMSD curves of the two state estimates in the final hindcast period (March–April 2012) appear more similar than in the other two periods, and the RMSD of the two forecasts initialized from these hindcasts are also similar, with EXP1 showing smaller RMSD at the end, although both show improvements over the MIT-C forecast. Why the glider data did not improve the forecast during this final period is an open question. Two possible factors are that the state of the LC system is different in the final period or that the glider sampling is more redundant with the SSH sampling, as suggested by the good hindcast fit for both EXP1 and EXP2. Taken together, the results suggest that initializations including glider data generally improve forecasts, although the evidence is not absolutely conclusive.

4. Discussion and conclusions

The observations and model results allow comparisons between the LCE and CEs. These comparisons are noteworthy as in situ observations of CEs are relatively rare because of their short lives and small sizes. There are three fundamental findings about CEs from this work. First, the Rossby number (Ro) for the upper 1000 m of CEs is 0.2. Second, CEs are much more barotropic than the LCE, although they are roughly equivalently energetic. Third, the CEs are composed of Gulf water while LCEs contain Atlantic water. These findings are discussed further below.

The CEs’ Ro of 0.2 suggests incipient nonlinearities. One of these nonlinearities is cyclostrophy, the momentum balance where the centrifugal force of a curved flow balances the pressure gradient (Holton 1979). In a gradient wind balance including both the centrifugal and Coriolis forces, the velocity is scaled by a factor of \((1 + \text{Ro}/2)^{-1}\), a reduction of about 10% in this case. The absolute geostrophic velocity calculated from glider data includes the directly measured depth-averaged component and the part due to geostrophic shear across the section. The neglect of curvature in the flow means that our estimate of geostrophic shear is high by about 10% in the CEs. But the CEs are essentially barotropic, so this is a very small bias to the absolute geostrophic velocity. The radius of an LCE is about 200 km, and the surface velocity is about 1 m s\(^{-1}\) so the Ro number relevant to curvature is about 0.2. Thus, our estimates of geostrophic shear in the LCE are low by about 10%. The 1000-m depth-averaged velocity is directly measured, so it appropriately includes any cyclostrophic effects. On the other hand, it also includes wind-driven flow, which is a small contributor to the depth average as it is distributed over 1000 m. Overall, the across-track geostrophic velocity observed by gliders appears to be a reasonable estimate, especially considering its general agreement with the model velocity that includes complete self-consistent dynamics.

A central result is that the CEs are essentially barotropic, as found both in glider observations and model
simulations. This finding can be understood as follows: Given a geostrophically balanced jet, the cyclonic side is denser at the surface. The cyclonic side must be less stratified if flow goes to zero, and there is no horizontal density gradient, at depth. Therefore, cyclonic eddies created by an instability of the jet should be more barotropic than anticyclonic eddies derived from the same jet. To the extent that the centrifugal force is important, as discussed above, this also tends to reduce shear. A glance at the sections in Figs. 5a and 6a make clear that the horizontal density gradient is much smaller in the CEs than the LCE, resulting in weak geostrophic shear. This result is reproduced in model simulations (Fig. 9), which retain the complete nonlinear dynamics, supporting this interpretation of the observations. The dichotomy between baroclinic anticyclonic eddies and barotropic cyclonic eddies has been investigated in laboratory studies and observations in the western boundary current of the North Pacific (Andres and Cenedese 2013). To our knowledge, our description of the barotropic nature of CEs is the most complete reported to date.

The CEs and LCE contain water of fundamentally different origins. The CEs are composed of fresh GoM water, while the LCE imports water from the Atlantic. It is reasonable to take CEs as the result of instabilities of the LCE (Cherubin et al. 2006). So the CEs contribute to the dissipation of the LCE. The CEs do not directly cause the GoM to get saltier through thermohaline eddy diffusion given their fresh interiors. However, to the extent that the CEs tease out salty filaments from the interior of the LCE, they can mix salinity as described in Paluszczkiewicz et al. (1983). As the main thermohaline signature of CEs is at depth, they are not easily identifiable in satellite SST (Walker et al. 2009), but their SSH is observable from space (Zavala-Hidalgo et al. 2003). In situ observations are necessary in further studies of the mixing caused by CEs.

The results of assimilation experiments suggest that glider data improve forecasts. Here, the specific measure of value is taken to be agreement with the AVISO SSH analysis averaged over a region of the GoM. In two out of the three forecast experiments, glider data resulted in better agreement with SSH at the end of 2 months (Fig. 11b). In one of these cases, the forecast is nearly as accurate as the HYCOM/NCODA global hindcast. So, there is clearly promise in using gliders in a modeling/observation forecasting system. Open questions include why the glider data did not help in one of the three forecasts and how to use gliders to best effect. While we do not yet have answers to these questions, our approach...
has been to use the gliders to cross strong gradients, with an eye toward the cyclonic regions. We anticipate further publication with more comprehensive analysis of many forecast realizations using glider data.

Our overarching intention was to present a novel way of observing and modeling the GoM using some of the newest techniques available. Underwater gliders have the distinct advantages of allowing both adaptable sampling and sustained operation. Pairing these observations with an assimilating model helps to overcome the unusual sampling patterns of gliders in swift currents, as the trajectories are neither straight nor exactly repeatable. The hindcast produced by the 4DVAR system provides a useful analytical tool, as it is faithful to the data and it obeys the model’s dynamics. Forecasts initialized with these hindcasts have shown promise. We envision a future where the kind of observing and modeling system we presented here becomes a standard approach for regional studies.

Acknowledgments. The Instrument Development Group at Scripps Institution of Oceanography was responsible for the success of Spray glider operations. We gratefully acknowledge several data sources: the Radar Altimetry Database System (RADS), AVISO, NCEP–NCAR reanalysis-1, the HYCOM consortium, and also thank the ECCO consortium and MITgcm development team. This work was supported through a cooperative agreement with BP. We thank two anonymous reviewers for their helpful comments.

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