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Sensors II

Forecasting Eddy Ulysses

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1. Introduction

The Loop Current and its associated anticyclonic eddies have been familiar impediments to deepwater operations in the Gulf of Mexico. Last year was no exception as Eddy Ulysses, the main Loop Current Eddy (LCE) event of the 2004 season, lingered for several months in the central Gulf. In an effort to forecast Ulysses and other LCE events, we developed a new Eddy Forecast System which became operational in September 2004. The forecast system features a revolutionary technology for model initialization and data assimilation. This technology makes use of dynamical understanding of physical processes controlling the eddy evolution providing a unique ability to reconstruct the ocean state from a limited set of observations. The ability to accurately reconstruct the ocean state at the time of forecast enables the system to predict the ocean evolution with significant skill. The forecast system was applied to forecasting Eddy Ulysses. Forecasts for 1 month forward in time were performed every week and made available in real time.

2. Background

A numerical forecast system, either weather or ocean, consists of an initialization component and a prediction component. The initialization component unites the observational data into a dynamical framework from which the prediction component can provide a forecast. The prediction component consists of a numerical model that begins with the "nowcast" produced from the initialization component and integrates the "laws of physics" forward in time to provide a forecast. Inaccuracies in either of these components will result in a poor forecast.

The quality of the prediction component (numerical model) can directly and significantly affect the quality of the forecast. For example, a model with low resolution or poor parameterization of the key dynamic effects can significantly deteriorate the forecast accuracy. However, the majority of the ocean forecast systems in use today use state-of-the-art, high-resolution models that faithfully reproduce the physical dynamics of the Loop Current and LCEs. Thus, the key differences between various forecast systems come primarily from the differences in their initialization components.

Most forecast systems use initialization procedures based on continuous statistical data assimilation. These systems rely on a numerical model (typically the same model that is used in the prediction component) to develop a balanced initial condition by running the model for some period of time prior to the forecast. This is called a spin-up run. In order to bring the initial condition close to observations, a continuous data assimilation is used during the spin-up run that "forces" the model to the "right" state. The advantage of this approach is that the resulting initial condition is well balanced and adjusted to the specific model configuration. Also, it is typically easy to automate which is a very important aspect of any operational forecast system. For these reasons, this method of initialization is the method of choice in modern weather forecast systems and is used by ocean models run by the Naval Research Laboratory [Rhodes, et al., 2002].

For the data assimilation method to work well, the data assimilation procedure during the spin-up run has to assimilate data throughout the entire three-dimensional space. In the case of weather forecasts, this requirement is relatively easy to satisfy due to the abundance of atmospheric profile data from radiosondes, aircraft, and satellite observations. In the ocean, however, subsurface observations are rarely available so surface observations are propagated through the water column using statistical correlations that are derived from a blend of different types of ocean features.

The vast majority of ocean forecast systems depend primarily or exclusively on satellite altimetry measurements for the initialization component. This is because satellite altimetry has global coverage and there is a statistical correlation between surface height and subsurface density structure. Nonetheless, there are downsides to relying on satellite altimetry alone. The altimetry data have low spatial and temporal resolution. The four polar orbiting altimeters in operation have repeat orbit times ranging from 10 days (JASON) to 35 days (ERS-2.) At best, the altimetry data provides a large scale picture of the ocean features (**Figure 1**). In addition, systems that use altimetry alone ignore all the other observational data streams used in Eddy Watch to track the Loop Current and eddies including satellite imagery, drifting buoys, Airborne Expendable Bathythermographs (AXBTs), shipboard surveys, and rig-mounted Acoustic Doppler Current Profilers (ADCPs.) The result is that the initializations and nowcasts are of reduced quality, and no matter how good the prediction component is, the forecast system will not provide skillful forecasts.

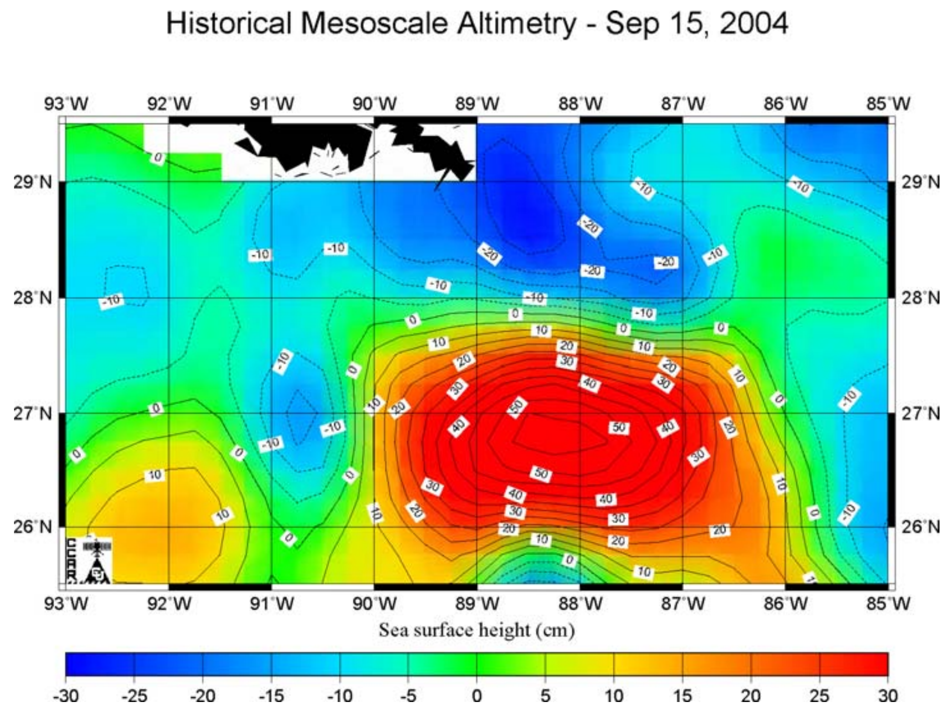

Figure 1. Satellite Altimetry analysis for 15 September 2004. (Courtesy of R. Leben CU-CCAR).

3. Eddy Forecast System

The Eddy Forecast System (EFS) uses an existing high-performance, high-resolution ocean model for the prediction component but a completely unique, feature-based initialization component. The essential underlying idea of a feature initialization approach is to extend limited real-time information with a historical knowledge of the typical structure and evolution patterns of LCEs [Robinson and Gangopadhyay, 1997]. This is analogous to "vortex bogusing" used so successfully in hurricane forecasting. This initialization procedure allows the use of all available oceanographic data, not just satellite altimetry.

The prediction component of the EFS uses the "MIT model" to solve the incompressible Navier-Stokes equations using hydrostatic, quasi-hydrostatic, or non-hydrostatic approximations with rigid-lid or free-surface options [Marshall, et. al, 1997]. The numerical integration scheme ensures that the evolving velocities are divergence free by solving the Poisson equation for the pressure with Neumann boundary conditions and then using this pressure to update the velocities. The model is also designed for parallel computation. The model is well-tested; it has been employed to study numerous phenomena whose scales range from centimeters up to many thousands of kilometers. For EFS, the numerical model is configured for a spatial resolution of 3 km and runs on a cluster of 10 computing nodes. A 30-day forecast run takes 2 hours of computing time.

The EFS initialization procedure describes mesoscale features with their three-dimensional potential vorticity (PV) structure instead of the more commonly used density and velocity structure. PV is defined for an isopycnal layer of stratified fluid as the ratio of the total vorticity to the thickness of the isopycnal layer, and PV is a physical characteristic of a flow that is conserved along the flow trajectories. Flow fields with PV varying along the flow trajectories are inherently unbalanced, and using an unbalanced initialization would result in a poor model solution and forecast. Using PV-based features instead of water density and current speed in the initialization procedure ensures that the initial conditions will be well balanced [Frolov, 2002]. A general form of the three-dimensional PV distribution within an LCE is specified by a set of analytical functions with several free parameters derived from historical events.

The initialization procedure consists of four steps. First, observational data are analyzed and the most significant eddy features are identified and characterized. This includes a description of the location, vertical density structure, shape, and swirl speed of the targeted LCE and surrounding smaller cyclonic eddies. Second, free parameters of the eddy PV feature model are determined from the measured eddy characteristics. Next, a full 3-D PV field for the region of interest is obtained by implanting the PV description of individual eddies into the horizontally homogeneous background PV field. Finally, a system of differential equations is used to convert the full PV field into corresponding 3-D density and velocity structure of the ocean which are used for the initial conditions for the prediction system.

The first two steps of the initialization procedure are performed manually for each forecast. A team of experienced forecasters conducts the data analysis and determines the approximate locations of eddies and their parameters. This can be time consuming and is partially subjective. The recent history of the eddy's evolution and the results of previous forecasts are used to aid in this process. The exact values of the free PV feature model parameters are calculated using a least square fitting technique. The last two steps of the initialization procedure are performed automatically as a computer program produces the initial density and velocity fields after the free parameters of the PV feature model are specified. These velocity and density fields are then used to initialize the numerical model for the prediction component.

Operationally, the initialization procedure is used to formulate a "nowcast" that is two to seven days prior to the actual date the forecast system is run. This allows us to develop a more accurate description of the ocean features. In addition, the model "spin-up" period is used to verify the prediction component is consistent with observations. This gives us a higher degree of confidence that the model forecast will be skillful.

4. Results

The EFS was first run operationally in August 2004. At that time, Eddy Ulysses had just separated from the Loop Current. By early September 2004, Ulysses covered all of Lloyd Ridge and Atwater Valley and portions of Mississippi Canyon, Green Canyon, and Walker Ridge (**Figure 2**). EFS was run once a week until November 2004 when the eddy migrated south of 26°N.

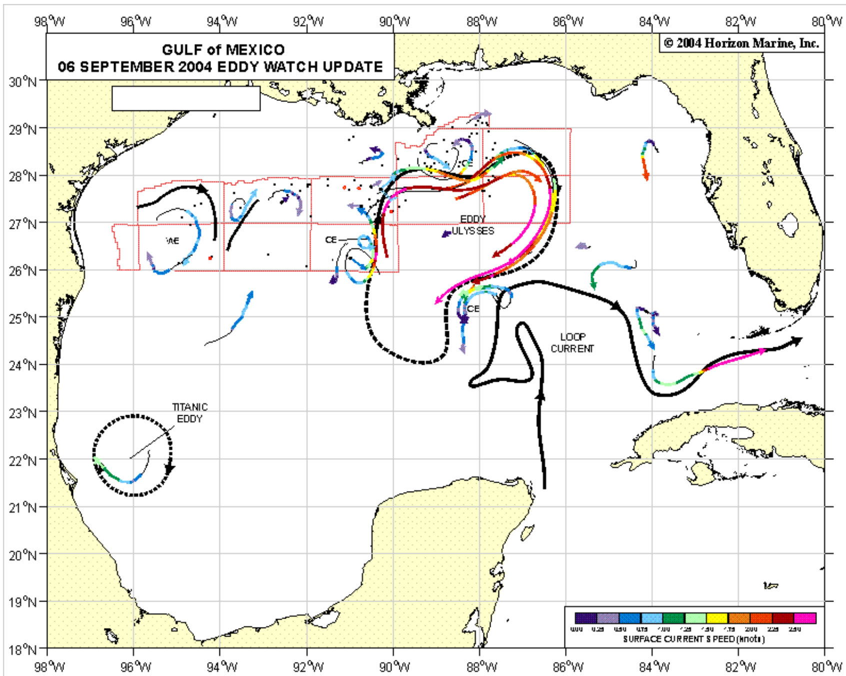

Figure 2. Eddy Watch Gulf of Mexico chart for 6 September 2004. The chart shows the location of Eddy Ulysses and the Loop Current.

The 15 September 2004 EFS run is used here as an example. The Eddy Watch chart for 15 September shows the location of the surface fronts and the trajectory of drifting buoys (**Figure 3**). There are three cyclonic eddies (labeled CE on the chart) located to the northeast, northwest, and south of Ulysses. The EFS initialization used the eddy descriptions from 9 September. (Note that the 15 September altimetry data are shown in Figure 1. The altimetry analysis shows Ulysses, but the location and strength of the surrounding CEs are not accurate.)

After a six day spin-up, the resulting nowcast for 15 September reproduces Ulysses with the surrounding cyclones (**Figure 4**). The analysis shows the direction (arrows) and magnitude (color contours) of the surface currents and the location of -6 and 12 cm surface height anomaly (SHA) contours. The SHA are useful for locating the approximate boundary around the features.

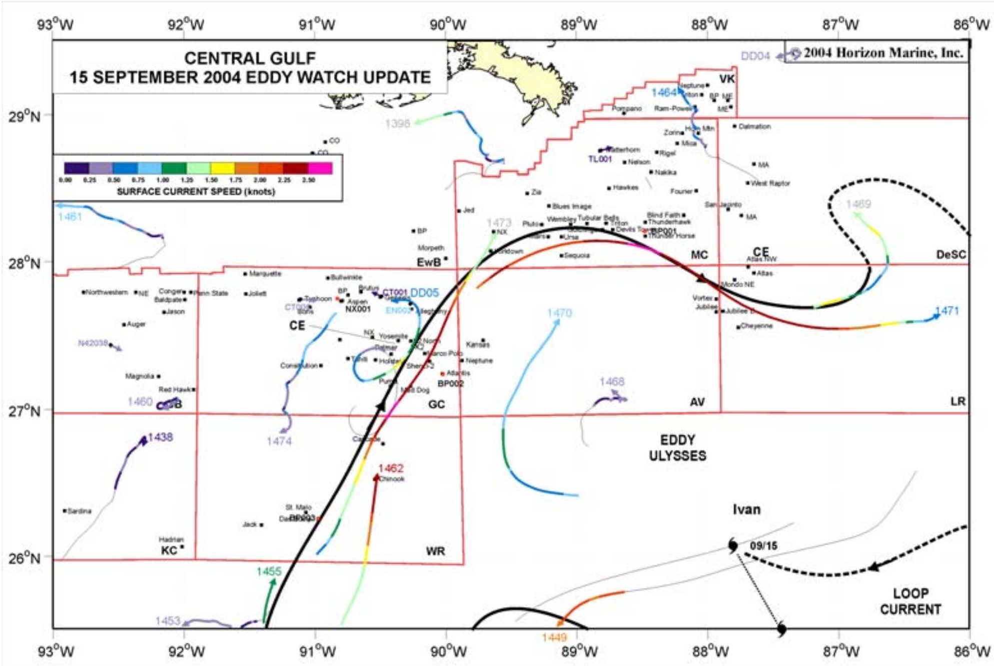

Figure 3. Eddy Watch central Gulf chart for 15 September 2005. This shows the location of Eddy Ulysses. Also indicated are cyclonic eddies (CE).

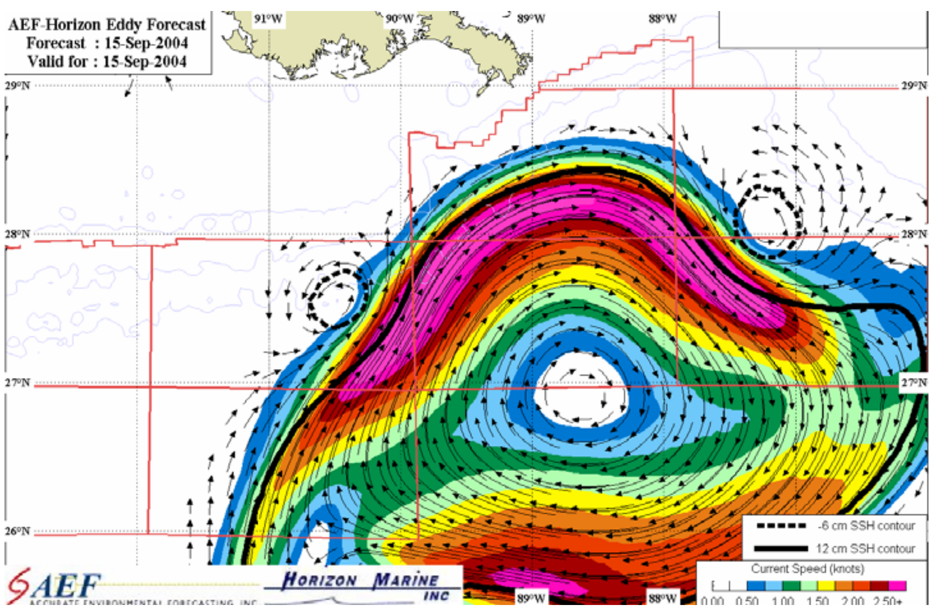

Figure 4. Eddy Forecast System nowcast for 15 September 2005.

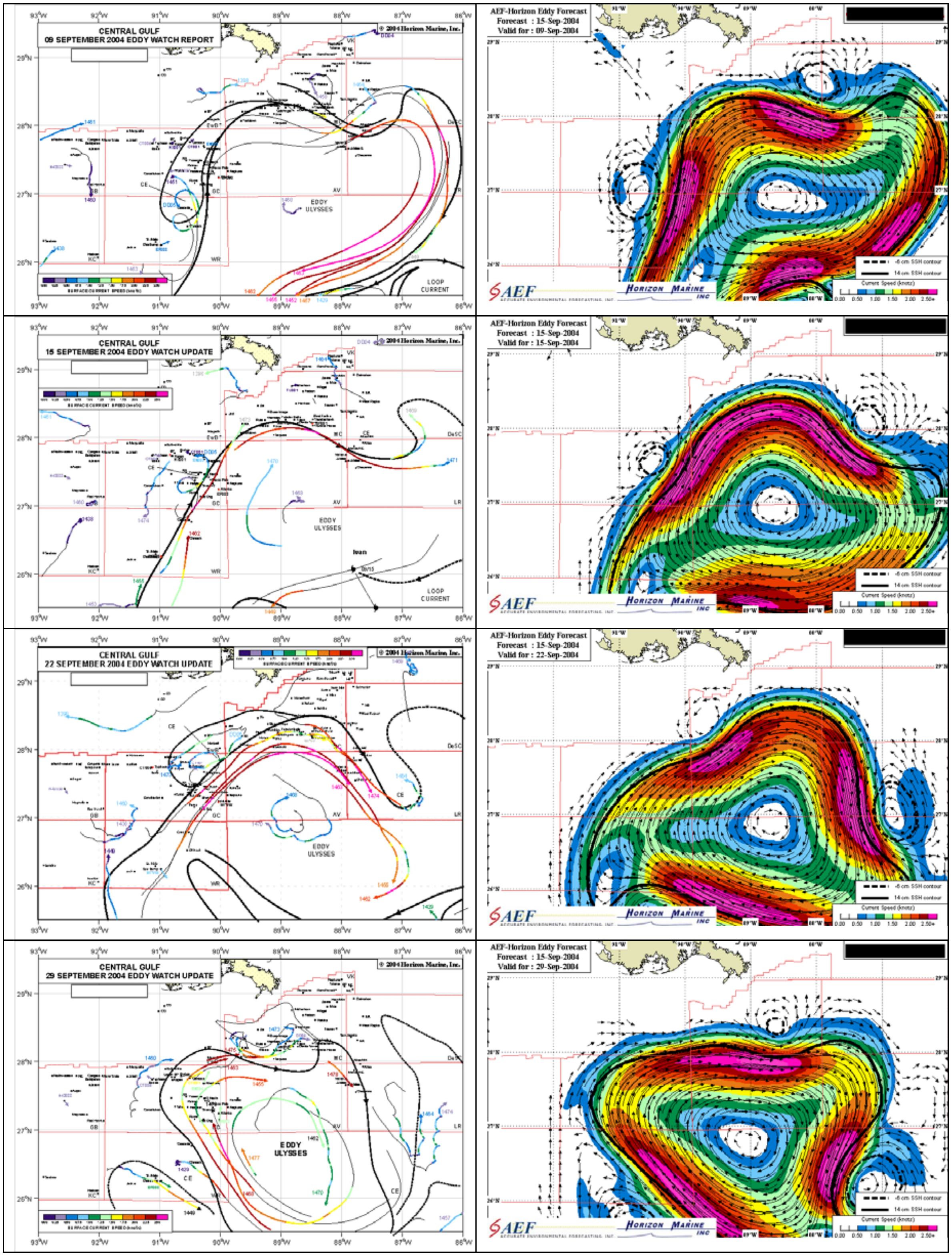

Figure 5. Comparison of Eddy Watch analysis and EFS forecasts from the 15 September 2004 forecast run.

The EFS provides a daily forecast analysis out to 30 days. **Figure 5** shows side by side comparison of the weekly Eddy Watch chart with the model fields for 15 September EFS run. (Note that this forecast is as it was issued operationally on 15 September.) Eddy Ulysses' elliptical shape rotated clockwise during this time period, and the CE moved clockwise around Ulysses as well. The EFS captures the rotation and movement of the features. The 14-day forecast (29 September) shows three CEs located to the north, southeast, and southwest of Ulysses and nearly the observed position for that day. Upon detailed examination of this forecast run, the EFS rotated these features a bit more slowly than they actually moved. However, the qualitative and quantitative skill of the forecast is quite good.

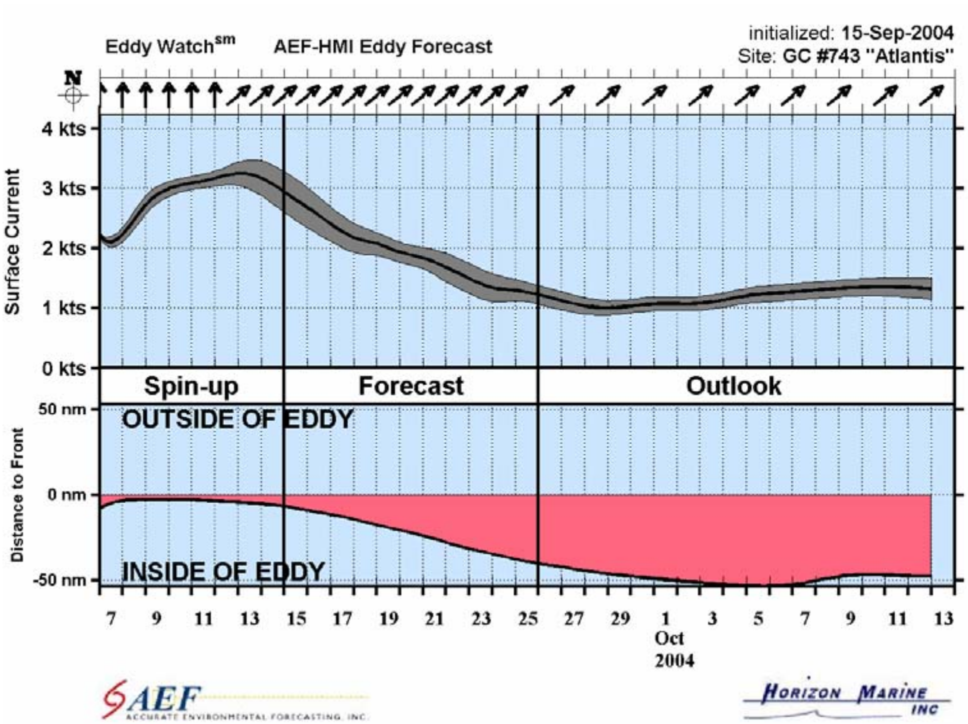

Figure 6. Example of a site-specific EFS forecast.

In addition to charts, EFS provides site-specific forecasts (**Figure 6**). The site-specific forecast shows the currents and the distance between the site and the LCE front. The horizontal shear can be quite strong, as is evident on the charts, with currents increasing from below 0.5 kts to above 2 kts over distances of only 10 nm. Thus, a small error in the location of the LCE in the forecast will cause a large error in the site-specific forecast. For this reason, we have chosen to show the minimum and maximum forecast currents (in gray shading) in a 6 nm radius around the site as well as the site-specific currents. The distance to the LCE edge is really the distance to the 12 cm SHA and indicates how close the site is to the edge of the LCE and whether the LCE is forecast to move closer to or away from the site.

5. Conclusions

EFS is constantly improving. We are also adjusting our observational program to include routine collection of temperature profiles inside LCEs specifically to improve the EFS initialization component. Originally, EFS could only forecast disconnected LCEs and not the Loop Current which has open boundary conditions. However, in the past six months, we have developed a technique to include Loop Current forecasts as well. We are presently using EFS to forecast Eddy Vortex and the Loop Current operationally as part of the Eddy Watch program. In addition, the staff has acquired more skill in formulating the feature initializations.

An objective analysis of EFS forecast skill for Eddy Ulysses is currently being undertaken by an independent third party. The results are not ready for this report. Our own internal analysis has shown that the system does have useful forecast skill. While the forecast is not perfect, we feel it is better than any other forecast system presently available. More importantly, it is proving to be a valuable tool to assist with decision making and planning of deepwater operations in the Gulf of Mexico.

6. References

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