Characterization of mesoscale eddies and detection of sub-mesoscale eddies derived from satellite imagery and HF radar off the coast of southwestern Puerto Rico

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Abstract— *Coherent sub-mesoscale features such as spiral eddies are known to be ubiquitous in the world's oceans. Yet, due to their complex geometry, they are often difficult to characterize. Sub-mesoscale ocean dynamics with characteristic dimensions on the order of kilometers have been found to play a major role in upper ocean stirring and mixing. Manifestations of these structures all around the Caribbean Coastal Ocean Observing System (CariCOOS) region have been found to influence coastal and oceanic waters impacting upper ocean hydrodynamics and biogeochemistry. CariCOOS modeling efforts in the region have yet to produce reliable forecasts of near coastal ocean dynamics. Owing to the growing demand for coastal ocean models yielding accurate forecast, CariCOOS has proposed the operational deployment of a 1/100 degree Regional Ocean Modelling System (ROMS) nested in the 1/36 degree resolution Navy Coastal Ocean Model (AMSEAS) which itself is nested in the Hybrid Coordinate Ocean Model (HYCOM), a global 1/12 degree data-assimilative hybrid isopycnal-sigma-pressure coordinates forecast system. Although the progression has been consistent, results urge the identification of possible skill performance constraints and phenomenological limitations. An inward approach has been adopted to assess the output of parent models versus observations from satellites, drifters, gliders, sea level measurements, buoys, and HF radars. Part of the adopted approach focuses on the characterization and daily-based detection of sub-mesoscale ocean dynamic features. CariCOOS observational assets and satellite imagery brings forth the ability to characterize quasi-permanent (or periodical) phenomena close to the coast. Thanks to the recent expansion of the CariCOOS High-Frequency (HF) radar network consisting of two long range (5 MHz) antennas on the southwestern coast of Puerto Rico, unprecedented spatial and temporal coverage will be available for this two-part study. For the first part, historical satellite altimetry, as well as other discrete observations, will be used to characterize the quasi-geostrophic mesoscale eddy signatures near the southwestern coast of Puerto Rico. On the second part, satellite imagery and HF radar capabilities to capture sub-mesoscale eddy phenomena will be assessed with the objective of implementing coherent structure detection algorithm based on a vector geometry method. A comparison between detected sub-mesoscale eddies with HF radars and available operational models (AMSEAS & HYCOM) will be qualitatively assessed.*

Keywords—*Sub-mesoscale; HF radar; eddy detection scheme*

I. INTRODUCTION

Eddie activity is a dominant feature in the upper ocean structure of the Caribbean Sea circulation [2]. In the Eastern Caribbean there are two well defined zonal bands of strong geostrophic mesoscale eddy (ME) activity centered near 15°N and 17°N, which coincide with two jets of the Caribbean Current [7] Although, it has been documented that these MEs contribute to offshore advection and dispersion of river plumes [5], buoyant matter and pollutants [4], or larvae [1]; they can also interact strongly with the inshore water dynamics (see Rodríguez-Abudo et al paper on this same proceeding).

Recently, the need for predicting meso and sub-mesoscale eddy interactions with the inshore circulation became particularly evident. A bulk carrier carrying 25,000 tons of coal, into the Yabucoa harbor, located off the southeast coast of Puerto Rico, reported an anomalous strong eastward drift which challenged the ship handling resources. This and previous analogous experiences led the harbor pilot to inquire CariCOOS if these could be predicted. The CariCOOS experimental ROMS model was not able to simulate the event which was later seen on ocean color (Chl a) satellite imagery. The goal of producing reliable hydrodynamic forecasts of the littoral waters prompted the study of ME interactions with the shelf and the detection of meso and sub-mesoscale ocean dynamics for the southwest region (Fig. 1). For this paper, high frequency radar (HFR) capabilities of capturing sub-mesoscale eddy features on the order of kilometers [10] close to the coast were explored through the implementation of a velocity vector geometry method eddy detection scheme [6]. Furthermore, comparisons between HFR and available operational models (AMSEAS & HYCOM) were qualitatively assessed as a preliminary effort in light of the necessity to assess model forecast efficiency in the CariCOOS region.

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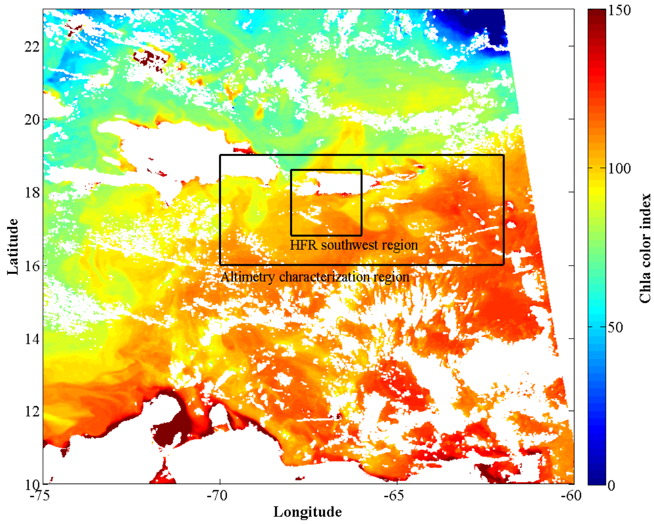

Fig. 1. *Chl-a color index image with the defined areas used in this study. HFR southwest region boundary box: [16.8N, 68W;18.6N, 66W]. Altimetry characterization region boundary box: [16N, 70W;19N, 62W].*

II. 2. Observations and Detection Scheme

A. Observations

Data used in the present paper are: satellite measured sea surface height anomalies (SSHA), satellite derived geostrophic velocity components (u & v), satellite chlorophyll-a (Chl-a) and alternate floating algae index (AFAI) images, and HFR measured surface velocity components (u & v).

Gridded surface height and surface geostrophic velocity data were downloaded from the NOAA AOML CoastWatch Caribbean/Gulf of Mexico Regional node website: http://www.aoml.noaa.gov/phod/dataphod/work/trinanes/INTERFACE/index.html. The near-real time data has a spatial resolution of 1/5° x 1/5° and a 2 day 10 hour temporal window over the study period of November 14, 2013 to July 31, 2015. Surface height data was detrended and geostrophic velocities were used to compute several eddy parameters such as eddy type, location, radius, vorticity, deformation rate and track on the eddy detection scheme.

Satellite imagery of Chl-a and AFAI with a resolution of 1km were downloaded from University of South Florida (USF) website: http://optics.marine.usf.edu/cgi-bin/optics_data?roi=ECARIB&current=1. The available data used encompasses the Eastern Caribbean Region, bounded at: 23°N, 60° W and 10°N, 75°W. This imagery was used to visually examine HFR capabilities of resolving sub-mesoscale eddy motions and locating eddy centers.

CariCOOS HFR network consist of 4 CODAR SeaSonde antennas. Two 13MHz antennas located on the west coast of P.R. and two 5MHz located in the southwest coast of P.R., (Fig. 2). These provide coverage of surface currents extending from the Mona Passage to as far south as 17°N and as far east as 66.3°W. The data used was collected between April 2015 to August 13, 2015, with a spatial resolution of 6km.

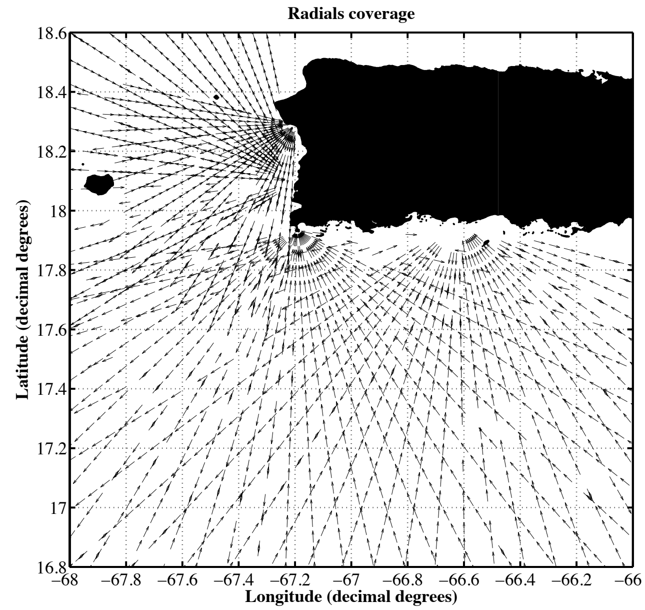

Fig. 2. *HFR radial coverage off the southwest coast, boundary box scale axis are defined by the study region shown in Fig. 1.*

B. Eddy detection scheme

The selected detection scheme based on velocity vector geometry has been verified and compared to other developed detection schemes found in the literature, such as the Okubo-Weiss and the winding angle methods. It has proved to have higher successful rates of detection than previous methods [6]. This method is based on the fundamental characteristics of coherent eddy velocity fields, defined by the Rankine vortex model. In it, azimuthal velocity increases linearly with radius from zero to a maximum value at the outside edge of the core and then decays in inverse proportion to its radius. The Rankine vortex is the solution to a uniform potential vorticity anomaly within the core radius. While this may not be the case for ocean eddies where the potential vorticity is likely not uniform, it does help identify the velocity field and capture coherent structures.

Based on the above characteristics, the following criteria is chronologically defined on the detection scheme method developed by [6]:

1. Along an east-west section crossing an eddy center, an inflection point of the *v* component of velocity must be met with increasing magnitude away from it on both directions.

2. Along a north-south section crossing an eddy center, an inflection point of the *u* component of velocity must be met with increasing magnitude away from it on both directions. The sense of rotation must match the one on the first criterion.

3. A velocity magnitude minimum within the region around the eddy center must confirm the previous criteria.

4. A constant sense of rotation must be maintained around the eddy center and this must also be true for two adjacent quadrants.

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Once all four criterions are satisfied the algorithm identifies the possible eddy centers in the evaluated region. The algorithm can be tuned for each site by defining its two principal parameters *a* & *b*. A series of sensitivity tests were performed with different parameter values, algorithm results were compared with manually detected eddies on Chl-a & AFAI satellite images (not shown).

Using the identified eddy center, its boundary is defined by the largest contour line of the calculated stream function around the center. With the stream function being defined by Lamb and Batchelor

$$\psi = \int_{nominal}^{final} -vdx + udy \qquad (1)$$

This is consistent with the concluding criterion, which requires that the magnitude of the velocity components must remain increasing along the defined eddy boundary. Fig. 3 ilustrates the visualization capabilities of the eddy detection scheme using altimetry data, portraiying the typical eddy rich field of the Eastern Caribbean region.

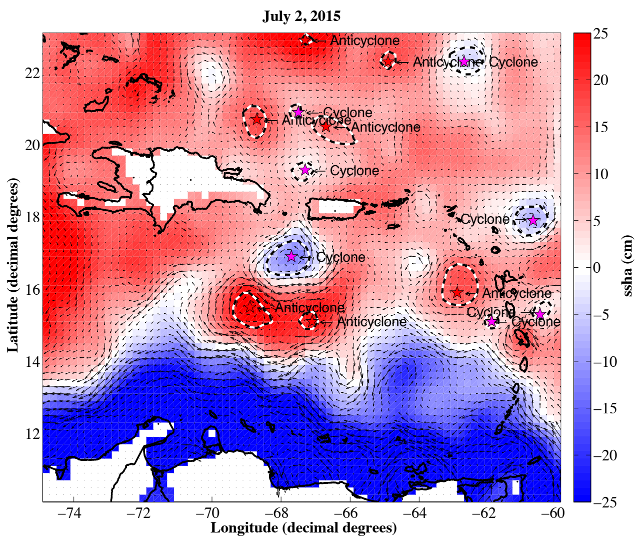

Fig. 3. *Eddy distribution snapshot of the Eastern Caribbean for July 2, 2015. Stars depict eddy centers and black and white lines their boundaries.*

III. RESULTS

A. Characterization

Satellite altimetry was used to characterize eddy parameters such as eddy radius (R), Rossby radius of deformation (L_d), vorticity (VOR) and swirl strength (SS); within the study region (Fig. 1, outer region). Available satellite data from November 14, 2013 to July 31, 2015 was used as the algorithm input variables for the detection of geostrophic MEs. Only MEs with significant lifetimes equal or longer than 3 days were used for this study, as it enhances the success rate of detection. Within this limits 85 MEs were detected during the study period of ~1.86 years. Of those, 62% were cyclones while only 38% were anticyclones (Fig. 4) showing a location preference for cyclonic eddies.

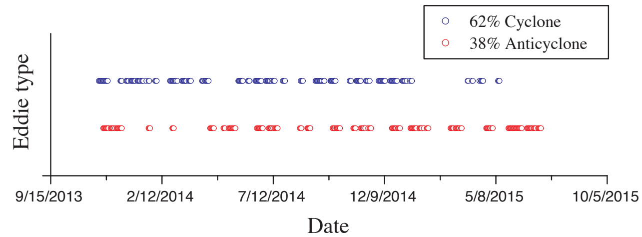

Fig. 4. *Detected eddy types for the selected region during the study period.*

In this study, eddy parameters are defined as the average parameter over each eddy area as detected with the vector geometry algorithm. Eddy radius was calculated as the mean of distances from the center to every point on the eddy boundary. Given that the eddy boundary is produced by the largest contour line of the calculated stream function, this radius is the estimation of the minimum radius. Following this the eddy radius of deformation for a barotropic ocean was calculated (Eq. 2) in order to normalize the estimated eddy radius and provide a stability criteria based on their characteristic deformation length.

$$L_d = \frac{U_0}{(Ro * f)} \; ; Ro = 1; \qquad (2)$$

where U_o is the characteristic flow velocity maximum found at the eddy boundary and f is the Coriolis parameter respective to the eddy center. Likewise, the eddy vorticity was obtained with

$$\omega = (\nabla \times U) \qquad (3)$$

where U is the flow velocity. This quantity was averaged over the eddy area. Local swirling strength was computed as in [9] and also averaged over the eddy area.

TABLE I. SUMMARY OF CHARACTERIZATION STATISTICS

	Detected MEs	R/L_d		VOR/*f*		SS/*f*	
		$\bar{x}$	σ	$\bar{x}$	σ	$\bar{x}$	σ
Cyclonic	62 %	3.11	1.41	0.26	0.106	0.12	0.053
Anticyclonic	38 %	2.5	1.34	0.15	0.087	0.13	0.043

The distribution of ME radius values studied here deviated from a Gaussian with a distinct skewness towards the smaller size (ranging from 20-50km) and a peak at 22.5km for both cyclones and anticyclones which relates to persistent cyclonic features seen with satellite imagery off the southwest coast. Particularly curious is the fact that the peak at 22.5km of radius coincides with the horizontal gridded altimetry resolution of 1/5° x 1/5° (22.25km). Please note that this is a result of the detection scheme employed. Since the eddy radius is being calculated as the mean distance from all the boundary points to its center we have the following caviat: Eddy centers are being localized using the input data grid points for positioning, but the boundary points are being generated through a stream function and are not strictly positioned on altimetry grid points. Due to this, it was possible to estimate some characteristic lengths below the available altimetry resolution grid.

Barotropic Rossby radius of deformation is used to normalize ME radii and estimate eddy stability or their likelyhood of being in geostrophic balance based on their characteristic length scale (radius). Fig. 5 shows that all detected cyclonic eddies for the region are stable, as well as the grand majority of anticyclonic eddies. Indicating the fact that they're in geostrophic balance (Ro << 1), thus they are less susceptible to instabilities and more energy conservative; opposite to sub-mesoscale processes and dynamics [10].

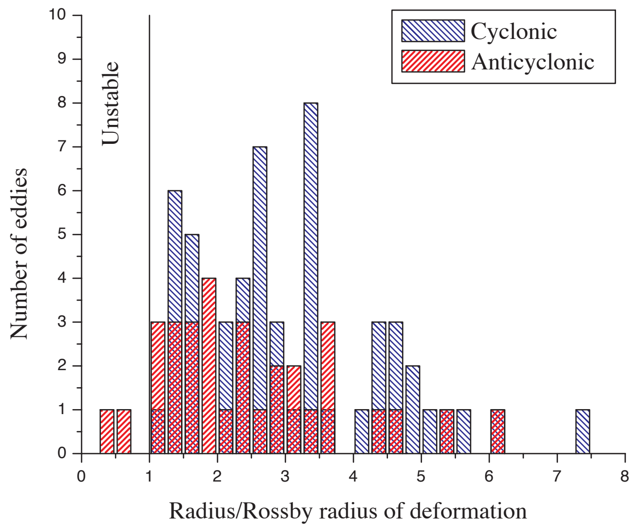

Fig. 5. *Histogram of eddy number per eddy radius normalized by the Rossby radius of deformation (for a barotropic ocean) estimated for each ME. The grand majority of MEs that reach the studied region show to be very stable, with a peak at 2.625 (only eddies with a lifetime equal or longer than 3 days are included in the analysis).*

The majority of the studied MEs have a radius below 50km indicating the fact that not many big eddies develop on the Eastern Caribbean as shown in [7]. On average, local cyclonic MEs are stronger in terms of relative vorticity, which is about twice that of the anticyclonic MEs (Fig 6).

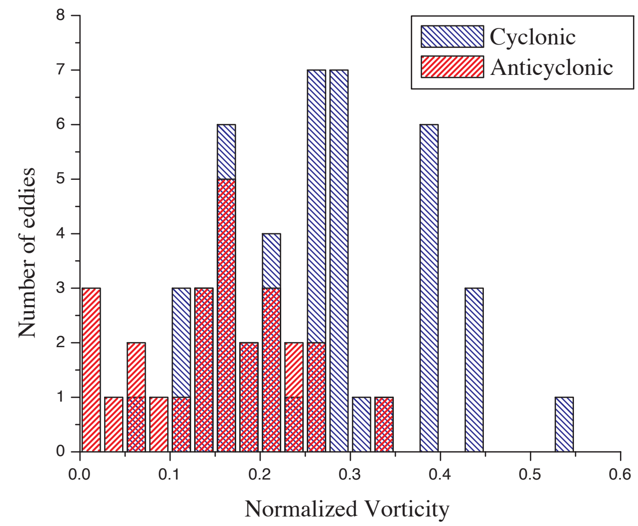

Fig. 6. *Histogram of eddy number per normalized (divided by the local planetary vorticity at each eddy center) eddy vorticity with a bin width of 0.025 (only eddies with a lifetime equal or longer than 3 days are included in the analysis). Here the absolute value of the anticyclonic vorticity was used for better visualization of the contrast between the two eddy types.*

The opposite is true for the locally estimated swirling strength, where the values for cyclonic and anticyclonic eddies are very similar (Fig. 7). Indicating similar inner structure coherency and possibly some axisymmetric geometry.

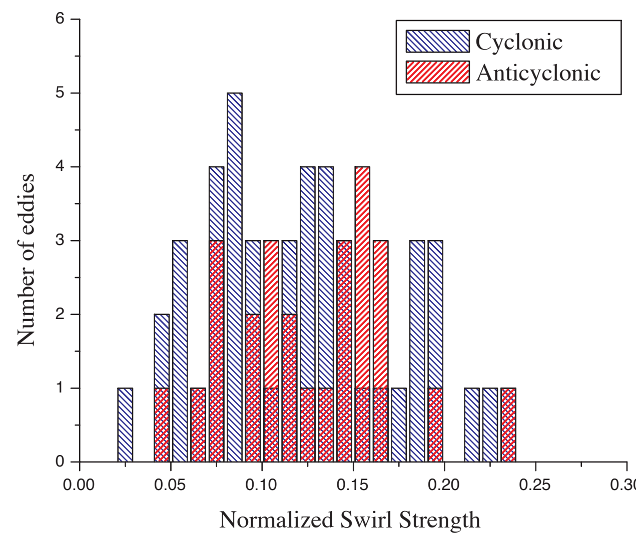

Fig. 7. *Histogram of eddy number per normalized (divided by the local planetary vorticity at each eddy center) eddy local swirl strength, binned at 0.01 (only eddies with a lifetime equal or longer than 3 days are included in the analysis).*

B. Detection of coherent structures

HFR capability to capture sub-mesoscale eddy phenomena is qualitatively assessed with the use of USF's satellite imagery color index of floating algae. For this purpose, HFR *u* and *v* velocity components were averaged over a 24-hour window concerning each day. This helps smooth out the data by filtering the tidal component and high frequency changes in velocities, making it more suitable for the eddy detection scheme. After a series of sensitivity tests, optimal performance was obtained by defining the algorithm parameters as $a = 3$ & $b = 2$. Successful sub-mesoscale eddy detection was attained over the available temporal window of the HFR observations by both the HFRs and satellite imagery. Here we highlight the sub-mesoscale (radius = 13.86 km) cyclone event that took place on August 13, 2015, just 45 km off the southwest coast of Puerto Rico (Fig. 8).

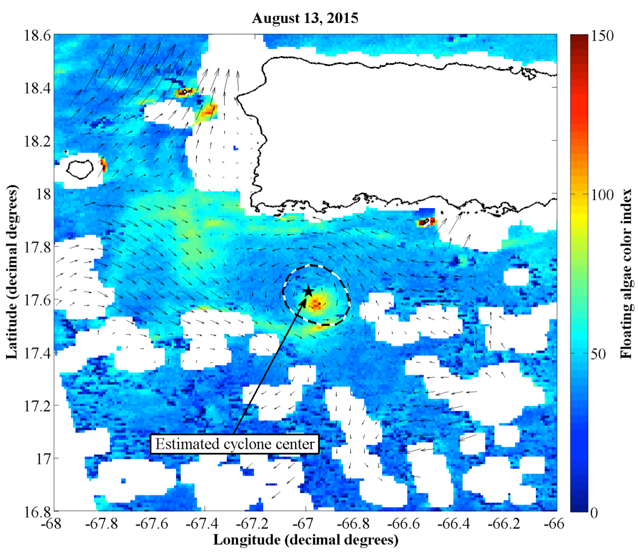

Fig. 8. *Cyclonic eddy detected using HFR data and AFAI satellite image as background color. Black star represents the detected eddy center which lies <8 km from the eddy center as suggested by the floating algae index (Sargasso) maximum.*

The detected cyclone is of particular interest because it has a patch of floating algae, presumably *Sargassum sp.*, entrained in its center, as suggested by USF's AFAI imagery. Estimated eddy radius was of 13.86 km and a barotropic Rossby radius of deformation of 5.77 km, making it a stable cyclonic eddy. In congruence with [10], this sub-mesoscale eddy feature only lasted 5-6 days. Its estimated center has an offset of <8 km from the eddy center as estimated by AFAI imagery, which was measured by utilizing the maximum value of the floating algae color index in that area. As part of the HFR assessment, eddy vorticity and local swirling strength were calculated in light of the fundamental definition of a Rankine vortex. As expected, eddy vorticity remained the same throughout the eddy core (Fig. 9), reminiscent of the solid-body rotation concept of coherent structures.

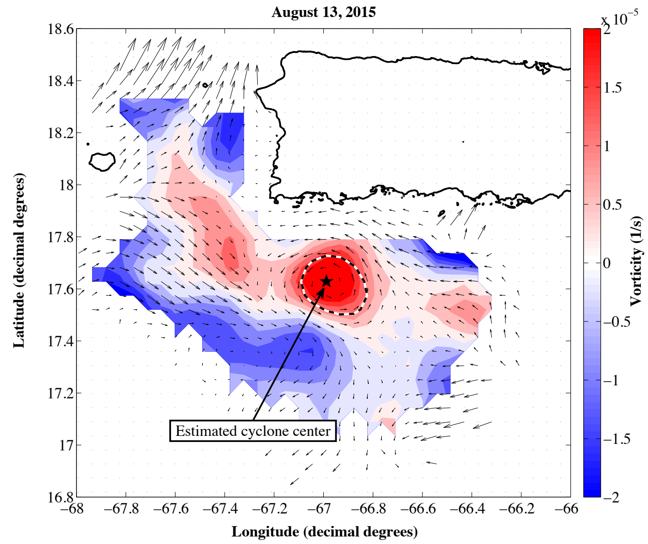

Fig. 9. *Cyclonic eddy detected using HFR data; background color represents the eddy vorticity, representative of the solid-body rotation definition. Black star represents the detected eddy center.*

Insights into the inner core structure coherency can be attained by analyzing the inward gradient vector of the local swirling strength (Fig. 10). Although such analysis is beyond the scope of this paper, the gradient can be used qualitatively for visualization purposes.

Utilizing this well-structured cyclonic feature, we can qualitatively visualize the capabilities of the available regional and global operational models (Navy Coastal Ocean Model American Seas [NCOM AMSEAS] with a 1/36° x 1/36° grid resolution, and the Hybrid Coordinate Ocean Model [HYCOM, graph not shown] with 1/12° x 1/12° grid resolution) to capture this sub-mesoscale feature.

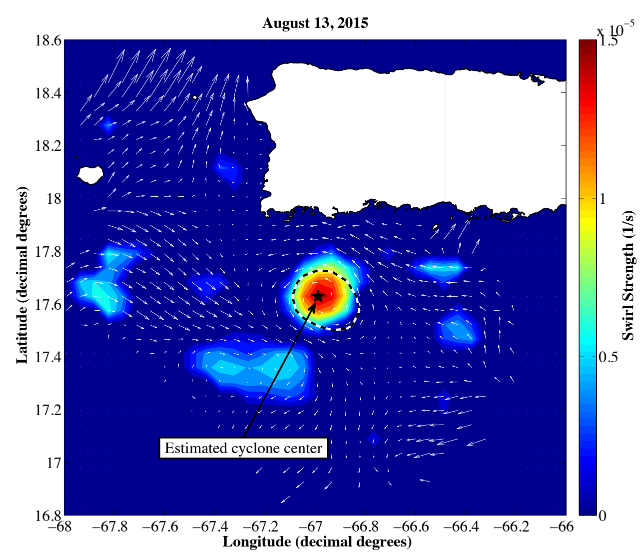

Fig. 10. *Cyclonic eddy detected using HFR data; background color represents the local swirling strength. Black star represents the detected eddy center.*

AMSEAS velocity data was processed in the same manner as the previously discussed HFR data, with the caveat of applying distinct parameters a = 4 and b = 3. Surprisingly enough, AMSEAS was not capable of resolving the well-structured signal of the sub-mesoscale cyclonic eddy southwest of Puerto Rico, even though its resolution doubles that of the HFR's. As seen on Fig. 11, both AMSEAS and satellite altimetry are not capable of capturing the cyclonic signal.

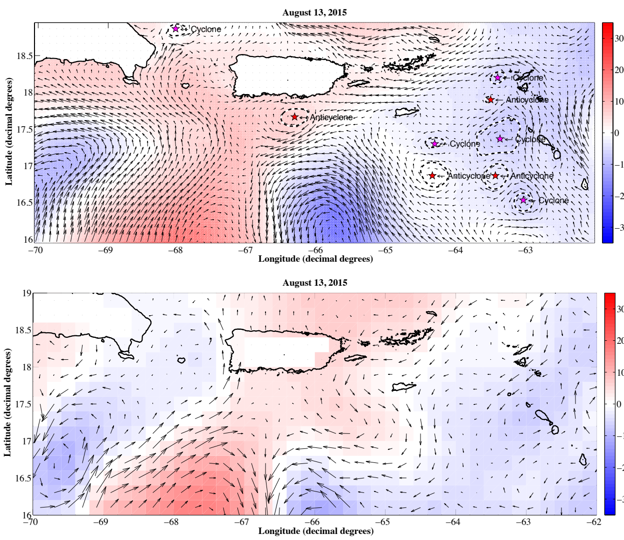

Fig. 11. *(Top) Detected eddies using AMSEAS data, velocity field resolution was downgraded for easier flow visualization. (Bottom) Satellite Altimetry data with detected eddies. SLA signal of the sub-mesoscale eddy in the southwest coast is not strong enough for it to be captured by satellite altimetry.*

In summary, during this study with HFR data of ~4.5 months, the only 2 persistent (lasting >3days) sub-mesoscale (1 cyclonic & 1 anticyclonic) eddy features detected with HFR off the southwest coast were not resolved by available operational models (AMSEAS & HYCOM), or by satellite altimetry products (used here); this may be due to the incapability of altimetry to capture sub-mesoscale structures due to signal contamination from high-frequency motions, incoherent internal tides and cross-track currents measurement noise [3]. However, HFRs are capable of correctly identifying sub-mesoscale coherent phenomena (Fig. 8, 9 & 10) as seen on satellite imagery, with a positioning offset of <8km. Proving to be the right asset in improving the sub-mesoscale eddy coverage available in the region; furthermore, it could be used as part of the data assimilation scheme for the available operational models.

IV. Conclusion

Accurate pin-point of the sub-mesoscale eddy center image overlaid with HFR surface velocities brings forth a qualitative and appealing product for future automated detection of coherent eddy structures in the southwestern region of Puerto Rico. By identifying and validating the effectiveness of the HFR detection success against satellite imagery, one can generate a new criterion based on eddy core vorticity uniformity and local swirling strength gradient that will aid in future implementation of an automated eddy detection system. While the CariCOOS HFR network only covers the southwest coast of Puerto Rico, satellite imagery shows sub-mesoscale processes not captured by altimetry that affect the whole CariCOOS region. This reinvigorates the need for HFR observations for improving our coastal dynamic knowledge, aiding in the error source assessment of available operational models for the region and their future asimilation.

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