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Evaluation of Search and Rescue Planning Tools on the West Florida Shelf

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Evaluation of Search and Rescue Planning Tools on the West Florida Shelf

by

Benjamin K. O'Loughlin

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science with a concentration in Physical Oceanography College of Marine Science University of South Florida

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ABSTRACT

The Coast Guard conducts over 20,000 search and rescue cases a year with approximately 5% of them occurring within the coastal waters of the West Florida Shelf (WFS). Each search effort is planned using the Coast Guard’s Search and Rescue Optimal Planning System (SAROPS) which uses model inputs to create composite probability distributions based on the results of Monte Carlo projections of thousands of particle trajectories. However, SAROPS is limited by the quality of model inputs and their associated errors. This study utilizes observations from three surface drifter deployments on the WFS to evaluate the effectiveness of available surface current models, including one model not currently in use by the Coast Guard. Additionally, the performance of high-frequency (HF) Radar observations is evaluated against the models. The HF Radar root-mean-square errors (RMSE) were found to be on the order of 10 cm/s, and a model created with objectively mapped HF Radar data was found to out-perform all available models. Additionally, a comparison of model skills (using a normalized Lagrangian separation method) showed the West Florida Coastal Ocean Model (WFCOM) to have better skill on both the inner and outer shelf regions of the WFS when compared to other models.
CHAPTER 1:
INTRODUCTION

1.1 Coast Guard Search and Rescue

The United States Coast Guard (USCG) is a multi-mission agency that falls under the Department of Homeland Security. The service can trace its roots back to 1790 when it began as the Nation’s first maritime service, the Cutter Revenue Service, but over the years other agencies such as the Life Saving Service and the Lighthouse Service were absorbed into the organization until it was morphed into its modern organizational structure (US Coast Guard, 2014). Although the USCG’s missions include all aspects of Maritime Stewardship, Safety and Security, it may be best known for its Search and Rescue (SAR) mission. Today the Coast Guard coordinates approximately 20,000 SAR cases annually with 4000 lives saved (US Coast Guard, 2016).

The USCG SAR areas of responsibility are split into two main Areas (Atlantic and Pacific). Each area is split into multiple Districts (or Regional Coordination Centers), and each District is further divided into Sectors (or Captain of the Port Zones). This study focuses on the Sector St Petersburg, FL area of responsibility, pictured in Figure 1.1, and includes a large portion of the West Florida Shelf (WFS) of the Gulf of Mexico (GOM). Sector St. Petersburg falls under the responsibility of the Tampa/St. Petersburg Captain of the Port (COTP) and reports the Miami Regional Coordination Center.
According to the SAR Statistics, St. Petersburg managed 1076 SAR cases in FY15 and averages over 1000 cases annually, making the St Petersburg Area of Responsibility (AOR) one of the highest SAR case concentration areas in the country.

![Depiction of USCG Sector St Petersburg AOR](image)

**Figure 1.1:** Depiction of USCG Sector St Petersburg AOR (U.S. Coast Guard, 2013).

An analysis of the SAR statistics shows that the majority cases in Sector St Petersburg’s AOR occur within 100 km from the shoreline and largely result from recreational vessels. Recreational boaters do not have the same safety equipment requirements as federally regulated commercial vessels and therefore many do not carry devices such as Emergency Position Indicating Radio Beacons (EPIRBs) and commercial grade life rafts with SAR Transponders (SARTs) that can significantly reduce search areas. Therefore, extensive search areas for small search objects without sophisticated signaling devices can require extensive resources and time. A clear understanding of the WFS circulation dynamics is vital to resolving SAR cases in an efficient manner to reduce the loss of life in order to meet USCG program goals.
The premier tool USCG SAR operational planners use to define search areas is the Search and Rescue Optimal Planning System (SAROPS). The system allows the operator to select the appropriate wind and current data from the USCG’s Environmental Data Server (EDS) to simulate particle trajectories based on specific search objects (Kratzke et al., 2010). SAROPS is a vast improvement from previous manual drift calculations and the antiquated Computer-Assisted Search Planning (CASP) that was implemented in the 1970s. An in depth review of SAROPS is provided in section 2.2. The system has been instrumental in helping the USCG achieve its SAR Program goal of an 85% success rate in saving lives when the Mariner is able to signal distress (US Coast Guard, 2013).

1.2 Statement of the Problem

SAROPS provides SAR planners an opportunity to take an analytical approach coordinating SAR responses, however it can be limited by a number of factors. The largest of these factors is applying the appropriate EDS products. For example, a planner could select a surface current model that does not include tidal components in a coastal region greatly affected by tides. This would introduce significant error when determining the area to be searched. This is an obvious example, however, there may be more nuances to EDS current selection process applicable to the WFS. Since SAR case concentration is extremely high on the WFS, over 5% of national SAR cases occur in this area, an in depth evaluation of SAR planning tools is vitally important. Through a series of surface drifter deployments, this study evaluates the effectiveness of present EDS products and makes recommendations for operational use.
1.3 Research Questions

In an effort to improve the SAR mission success on the WFS this study seeks to find answers to the following questions:

- Is HF Radar an effective surface current product for operational SAR case planning on the WFS?
  - What are the limitations of the High Frequency (HF) Radar observations?
  - What are the special considerations for SAR Planners using HF Radar in a low energy environment?

- Do any non-USCG EDS surface current products perform better than the models already in use, and if so, should they be added to EDS?
  - What are the impacts of local vs deep forcing to the models?
  - Do the models have different performance levels on inner and outer shelf? If so, should additional guidance be provided to SAR Planners?

Based on these primary research questions a secondary question is:

- What can be done to improve SAR planning on the WFS?

1.4 Methods for Conducting Research

To answer these questions a baseline set of observations were gathered using satellite-tracked surface drifters called Self Locating Data Marker Buoys (SLDMBS) deployed along a 60 NM transect extending seaward from the mouth of Tampa Bay. This transect was chosen to capture observations within a high concentration SAR case.
area that coincides with HF Radar coverage (CODAR) and the domains of several USCG EDS current model domains as well as the West Florida Coastal Ocean Model (WFCOM), presently not a part of the EDS suite (Zheng and Weisberg, 2012; Weisberg et al., 2016a). The deployment transect is depicted by the red line in Figure 1.2.

SLDMB deployments were conducted in three seasons: Summer (August 2015), Fall (October 2015) and Winter (January 2016). A planned spring deployment was not conducted due to lack of resources.

**Figure 1.2:** Depiction of experiment SLDMB deployment transect in relation to HF Radar (CODAR and WERA) idealized coverage and Acoustic Doppler Current Profile moorings on WFS.

The data obtained from the drifters are compared with Eulerian and Lagrangian analyses of hindcast surface current products and CODAR HF Radar observations. In the Eulerian sense, velocity components, \( u \) (east-west) and \( v \) (north-south), are derived from drifter location differences and compared to modeled velocity fields. An in-depth analysis of this comparison is contained in Chapter 3. In the Lagrangian sense,
previous studies (e.g. O’Donnell et al., 2006; Bernstein, 2009; Rypina et al., 2013) used separation distance over time to evaluate the effectiveness of HF Radar predictions. Liu and Weisberg (2011) showed that separation distance alone can be misleading when trying to compare areas/times with different current speeds. They used a normalized cumulative separation distance to determine the relative skill of a model. This method provides a more meaningful analysis when comparing drifter to model skill in different underlying current magnitudes. This skill score has been used in evaluating trajectory models (e.g. Röhrs et al., 2012; Halliwell et al., 2014; Liu et al., 2014b; Sayol et al., 2014; Sorgente et al., 2016; Sotillo et al., 2016), including a recent assessment of HF radar data in SAR applications (Roarty et al., 2016). An in-depth analysis of this comparison is provided in Chapter 4.

1.5 Significance of the Study

1.5.1 Economic Impact

As previously stated, 5% of all Coast Guard SAR cases occur within the Coast Guard Sector St. Petersburg AOR which coincides with a large portion of the WFS of the GOM. Many of the SAR cases on the WFS result from recreational boaters; a 2011 U.S. Fish and Wildlife survey identified Florida as having 2.4 million saltwater anglers making it the highest concentration of salt water anglers in the country (“Value of saltwater fishing in Florida,” 2014). In FY 13/14 alone, 1,612,102 recreational saltwater fishing licenses were sold generating over $35 million in revenue for the state. Additionally the saltwater fishing industry supports over a 100,000 jobs and is a $7.6 billion dollar industry. The National Marine Manufacturers Association reports that over
900,000 recreational boats were registered in Florida in 2010 (NMMA, 2011). Ensuring the safety of the recreational fishing fleet is vital to the economy of the state.

In addition to the fishing industry revenue, the U.S. Office of Management and Budget values a human life anywhere from $7 million to $9 million (Partnoy, 2012). These numbers are generated by economists factoring in earning potential based on average income and remaining working years while factoring in interest and inflation, hence the range of values. Applying those figures to FY 13 SAR figure shows that the USCG saved 247 lives on the WFS, or $1.7 billion to 2.2 billion worth of human value. Conversely during that same year, 14 lives were lost or unaccounted for, totaling a loss of approximately $112 million. Saving lives is inherently noble, but it also has a net positive economic impact on the nation.

1.5.2 Impact to Search and Rescue

The WFS is unique in that it is a relatively wide section of continental shelf that has varying impacts from Loop Current interactions, fresh water inputs, and seasonal variations in wind and surface buoyancy fluxes. Additionally, the WFS is a relatively low wave energy environment. The often small sea state allows small vessels to travel further offshore than they would in other parts of the country. Furthermore, the warm temperatures of the GOM increase the amount of time a person in distress could survive before succumbing to the elements. The warm water temperatures combined with the high likelihood of recreational boat being far from shore often results in multi-day searches for relatively small search objects (such as people in the water or small vessels). With operation costs of USCG assets ranging from $2,000 an hour for a
Response Boat Small (RBS) to $20,000 an hour for a C-130 fixed wing aircraft, the cost of a multi-day search effort can easily total millions of dollars. Again using FY 13 as an example, over 36,000 hours of resource hours (vessels and aircraft) were utilized in the execution of SAR cases on the WFS. A reduction of aircraft search time by 1% could save the USCG over $7 million per year.

1.6 Hypothesis

A detailed evaluation of surface current models and HF Radar observations in one of the country’s highest SAR case concentration areas will provide a better understanding of ocean dynamics to SAR planners. Armed with the knowledge of relative skills, model limitations, and sources of potential errors, planners will be better equipped to execute SAR missions. Additionally, future resource allocation decisions in relation to infrastructure and ocean observing system improvements will be more appropriately carried out as a result of this study.

1.7 Organization of Study

This study is organized as follows:

Chapter 1 provides the introduction to Coast Guard SAR and the purpose of this study. The research questions are presented with the significance. Finally, a brief description of the study methods is presented to include the area of interest, data collection and data analysis.

Chapter 2 contains the literature review with an in depth look at current Coast Guard resources and operations (SAROPS, EDS, SLDMBS). Previous studies of HF
Radar systems and the WFS reviewed. Additionally inner and outer shelf dynamics on the WFS are discussed.

Chapter 3 describes the experiment conducted to answer the first research question regarding the effectiveness of CODAR HF Radar for SAR application on the WFS. Data processing and quality control measures are discussed for SLDMB and HF Radar data, HF Radar coverage areas are compared to SAR case locations, and as statistical comparison of Eulerian surface currents is made. Finally, results are discussed along with limitations of the HF Radar array.

Chapter 4 describes the experiment conducted to answer the second research question regarding the relative skill of the ocean current models (OCMs) used for SAR application. The OCMs are discussed, the normalized Lagrangian separation skill scores are presented, and an objective analysis of HF Radar surface currents is applied and included for comparison. Finally, the results are discussed with recommendations for SAR application.

Chapter 5 includes the discussion of the findings. The research questions are answered in relation to results found. Finally limitations are discussed, improvements to the SAR system are presented, and recommendations for future research are suggested.

1.8 Chapter Summary

The USCG is the nation’s oldest maritime service and SAR is one of its highest priority mission sets. Millions of dollars of assets are dedicated to SAR operations every year, and continuous efforts are made to increase the effectiveness of the SAR
planning system. This study looks to improve the effectiveness of SAR operations on in one of the highest SAR case concentration areas along the US coastline, the WFS, by evaluating relative skill of surface current models used for SAR planning using SAROPS. The underlying hypothesis is that doing so will increase the efficiency of SAR missions to achieve USCG mission goals and save more lives at reduced cost.
2.1 Coast Guard Search and Rescue System

The National SAR Plan assigns SAR responsibilities for waters where the United States has jurisdiction to the USCG. The USCG Addendum to the National SAR Plan states that “the mission and the purpose of the USCG’s SAR program is to prevent death or injury to persons and loss or damage to property in the maritime environment.” The USCG accomplishes this mission by maintaining distress communication capabilities, infrastructure, assets, and trained personnel along all coasts of the United States and its territories. The four key areas of USCG SAR are distress monitoring/communications, search planning, search coordination, and SAR operations (US Coast Guard, 2013). Search communications are conducted by monitoring all international distress communication frequencies to include VHF, HF and 406 MHz. Once a distress communication is received, the SAR system is activated to include Awareness, Initial actions, Planning, Operations and mission Conclusion (AIPOC). The Planning phase of SAR operations is carried out by Regional Coordination Centers (RCCs) which provide direction to the SAR Units (SRUs) which conduct the mission. SRUs are strategically stationed along the coast to respond to any SAR case within 90 minutes of notification (assuming launch within 30 minutes and 60 minutes of transit time).
2.1.1 Search and Rescue Optimal Planning System (SAROPS)

Through the efforts of the USCG Research and Development Center with cooperation from the Integrated Ocean Observing System, the USCG SAR mission planning has become much more sophisticated than it once was. Historically, SAR planners would use manual methods derived from the International Aeronautical and Maritime Search and Rescue (IAMSAR) Manual, Volume II, to calculate search areas. In the early 2000’s computer simulations were developed with environmental inputs and ultimately SAROPS was developed. SAROPS was fully implemented nationwide in 2007 and now it is an international tool for SAR planning (US Coast Guard, 2013). A comprehensive review of the SAROPS software can be found in Kratzke et al. (2010).

The SAROPS system includes an upload function for wind and current data, a simulation function, and a search asset planning interface.

SAROPS is an ARCGIS based system that uses gridded wind and current data from a USCG managed EDS to run a Monte Carlo simulation of thousands of estimated particle trajectories to develop a dynamic optimal search area based on high probability grids. Individual SAR Units can access SAROPS/EDS servers to simulate real time drifts of a multitude of search objects and assign search assets (surface or air units) to determine the best possible search pattern given speed and time constraints of the search asset.

SAROPS has four basic components: EDS, a simulator, a planner and a user interface. The simulator uses EDSs product for currents (and wind) to determine the drift (and leeway) of an object to create a search area at a desired time. SAROPS allows the planner to select the number of simulated particles to be drifted, 2500, 5000
or 10,000. Each particle is driven by the $u$ and $v$ components of the gridded EDS product that is selected at each time step. The simulator takes the three closest grid points and applies a weighted average (inversely proportional to distance) to determine total velocity at that time. If the gridded surface current product is missing values for a specific time, $u$ and $v$ speed are interpolated from closest times. Finally a random effect is computed using a random draw from normal distribution, and the $u$ and $v$ velocity components are perturbed by the random effect at each time step. Subsequent perturbations for each particle are correlated to the first random draw as a function of time (Kratzke et al., 2010). The decorrelation, $\rho(\Delta T)$, is defined as:

$$\rho(\Delta T) = e^{-\alpha \Delta T}$$  \hspace{1cm} (2.1)

where $\alpha$ is chosen so $e^{-\alpha \Delta 60} = \frac{1}{2}$, and $T$ is time in minutes.

Applying this method accounts for the velocity of the current, $V_{curr}$, with associated error, but Hackett (2006) defines the total drift velocity of a floating object, $V_{drift}$, as:

$$V_{drift} = V_{curr} + V_{rel}$$  \hspace{1cm} (2.2)

Where $V_{curr}$ is the ocean current velocity and $V_{rel}$ is the drift velocity of the object relative to ambient water. The ocean current velocity includes Ekman drift, baroclinic motion, tidal and inertial currents, and Stokes drift. In other words it is the surface current obtained from a numerical ocean circulation model with Stokes drift from a wave model linearly added. The relative current, $V_{rel}$, is the result of wind and waves acting on the object. When the length scale of the search object is smaller than the wavelength, as is the case in most SAR cases, the additional wave effects on the search object are small (Hodgins and Hodgins, 1998). Therefore the effects of the waves can be ignored and
\( V_{rel} \) is only the effects of wind, or leeway. Leeway calculations are more complicated and are partially dependent on surface area above the waterline. The wind forces on the above waterline portion of the search object are countered by water drag on the underwater portion. The result is a linear relationship between leeway speed \( (V_{leew}) \) and wind speed \( (W) \) defined by:

\[
\begin{align*}
V_{leew} &= bW + c, \text{ if } W \geq 6 \text{ knots} \\
V_{leew} &= (b + \frac{c}{6})W, \text{ if } W \leq 6 \text{ knots}
\end{align*}
\]

The slope \( (b) \) and intercept \( (c) \) are determined by linear regression by Allen and Plourde (1999) through a review of 26 leeway field studies where numerous objects were tested. The leeway tables are presented in Appendix H of US Coast Guard Addendum to the National SAR Plan (USCG, 2013). Equation 2.4 ensures that zero wind speed produces zero leeway. The overall leeway is composed of a downwind component and a cross wind component. The cross wind component is calculated using a divergence angle (USCG, 2013). The divergence angle, \( \alpha \), is applied because the asymmetrical shape of the search object results in a leeway drift offset from the observed wind direction due to the Relative Wind Direction (RWD).

Figure 2.1, adapted from Allen and Plourde (1999), shows the relationship between the RWD and the \( \alpha \), specifically demonstrating how the \( \alpha \) can be positive or negative based on the search object’s orientation to the wind. In SAROPS each particle is assigned a positive or negative \( \alpha \), as the search object orientation to the wind is unknown. The result of the simulation is a plume of particles forecasted to a set time. Additionally a large \( \alpha \) could cause a large cross wind component of leeway resulting in two plumes of particles.
A SAR planner can access the results of the simulated drift (accounting for winds and currents) through the user interface of the SAROPS system. The user interface allows the planner to view high concentrations of simulated particles on a color-coded grid superimposed on an ARCGIS mapping system. The planner can then manually plot a search pattern over the high concentration area, or the planning software can be employed to automatically select an optimized search pattern based on the type of search asset (boat or aircraft) and the amount of time the asset can stay on scene. The search optimization function will chart a course (or search pattern) for the search asset.
to follow in which the maximum number of simulated particles could be visually detected by the search asset. The probability of detecting a particle is based on a number of variables including the particle’s proximity to the track line, weather, search asset height of eye, size of search object, etc. The ability to detect a search object can be thought of in terms of perpendicular distance to either side of the search asset’s course in which a search object could be observed. This in turn determines the sweep width and track spacing of the search asset. If all of the simulated particles were static the search pattern would analogous to a lawn mower cutting every blade of grass in a yard, or a search asset detecting every particle in the drift. However, the simulated particles in the SAROPS system continue to drift in a dynamic environment as the search asset moves through its pattern. The system counts the particles that are detected and calculates a Probability of Success (POS) based on the product of the Probability of Detection (POD) (asset’s ability to see the search object) and Probability of Containment (POC)

**Figure 2.2:** Depiction of probability grid search area in Tampa Bay with search pattern using SAROPS. Created at US Coast Guard Sector St Petersburg.
(probability that the search object is within the search area). Increasing the search patterns track spacing to increase the overall area of the pattern would increase the POC, however POD would decrease. If the user plans a subsequent search in the area, the system will use information from the previous search to prioritize the particles that were not detected during the first search effort and a new POS would be calculated using the information from both search efforts (Kratzke et al., 2010).

Figure 2.2 shows an example of a drift simulation in Tampa Bay in June of 2016. The dark green circle represents the area where the simulated particles originated. The colored squares represent a grid color coded by concentrations of simulated particles falling within each grid cell. The black line represents the optimized search pattern created by SAROPS based on the search asset type and the amount of time on scene.

2.1.2 Environmental Data Server (EDS)

In 2008 the USCG completed a comprehensive analysis of 212 available atmospheric and oceanic models and made recommendations for implementation into the EDS system (Turner et al, 2008). The study identified a grading matrix based on desirable attributes, like Operational Status, Access, and Domain resolution, and many products were not implemented due to factors such as lack of technical support and redundant systems. In 2009 a study was completed to verify the effectiveness of the EDS products based on four regions along the Atlantic coast of North America to include the Caribbean and GOM (Bernstein, 2009). As a result, an operational decision guide was created to assist SAR Planners in choosing the most appropriate EDS product for the search area. For the continental shelf of the GOM the surface current
products recommended for operational use are listed here in order of preference (Allen, 2015):

- **HF Radar Data.** Shore-based HF radars can measure surface currents by the Doppler shift induced by the surface waves propagating with the surface currents. The Doppler shift defines the component of the current along the radial direction from a transmitter at a coastal site as detected by receivers. Overlapping radials from a set of HF radars allow for the estimation of surface velocity vectors. The HF radars on the WFS coasts are maintained through the Coastal Ocean Monitoring and Prediction System (COMPS) program at the College of Marine Science, University of South Florida (USF) (e.g., Merz et al., 2012). Currently, two types of HF radars are operating on the WFS: the Coastal Ocean Dynamics Applications Radar (CODAR) and the Wellen Radar (WERA). The three long-range (4.9 MHz) CODAR SeaSonde radars are located at Redington Shores, Venice and Naples, respectively. The two medium-range (12.7 MHz) WERA systems are located at Ft. De Soto and Venice, respectively. The CODAR and WERA systems measure currents at an effective depth of 2.4 m and 0.9 m, respectively, below the sea surface (Liu et al., 2010, 2014a). HF radar data are preferably used by the USCG for SAR purpose if search area is within HF radar coverage area.

- **Aggregated ADCIRC, Global RTOFS (NCEP).** Among the models, the USCG EDS currently prefers the aggregated ADCIRC (Luetrich and Westerink, 1991) - Global Real-Time Ocean Forecast System (RTOFS) product provided by the
National Centers for Environmental Prediction (NCEP). Since the Global RTOFS does not contain tides and ADCIRC is strictly tidal currents, these two are combined together to add tides to global RTOFS (NCEP) currents.

- Global HYCOM (Navy). The Navy global Hybrid Coordinates Ocean Model (HYCOM; Chassignet et al., 2007) is an eddy resolving 1/12° global model run once a day and produces 2-day nowcasts and 6-day forecasts. The model is initialized daily from the 3D Navy’s multi-variate data assimilation of a wide variety of sources in-situ and remotely sensed. Navy global HYCOM model is forced by the Navy NAVGEM 3-hourly winds, radiation and precipitation.

- Global RTOFS (NCEP). The NCEP global RTOFS model (Mehra and Rivin, 2010) is an eddy resolving 1/12° model based on HYCOM (Chassignet et al., 2009) run once a day and produces 2-day nowcasts and 6-day forecasts. The model is initialized daily from the 3D Navy’s multi-variate data assimilation of a wide variety of sources in-situ and remotely sensed. The global RTOFS model is forced by the NOAA GFS 3-hourly winds, radiation and precipitation. At the present time, The RTOFS does not include tides or tidal forcing.

- Northwest Atlantic (NCSU). The Northwest Atlantic Marine Environmental Prediction model is run by North Carolina State University (NCSU). The Northwest Atlantic (NCSU) is a fully coupled ocean (ROMS) /atmospheric (WRF) /wave (SWAN) modeling system that is run daily and produces forecasts out to 72 hours (Hyun and He, 2010). It has a regular grid of 7 km in the horizontal and 36 terrain-following vertical layers so thickness of the ocean surface layers varies from 10 cm in the shallows to ~1 meter along the outer deep water edge of the
model. The Northwest Atlantic (NCSU) coupled modeling system takes boundary conditions from the Navy global HYCOM model (for ROMS), NCEP GFS atmospheric model (for WRF), and NOAA WWIII global wave model (for SWAN). Tidal forcing includes 7 tidal harmonics.

2.1.3 Self-Locating Data Marker Buoys (SLDMBS)

SLDMBs are 7/10th scale Coastal Ocean Dynamics (CODE)/Davis Style surface drifters with drogue vanes that measure between 30 and 100 cm below the surface, depicted in Figure 2.3 (US Coast Guard, 2013). They can be deployed from vessels or aircraft and they “self-deploy” once in contact with the water. They report GPS position through the Argos Satellite network every 15 minutes for the first 2 hours deployed followed by 30 minute intervals thereafter. Most SLDBMs report positions for 14 to 30 days after deployment depending on initial battery health and stamina. SLDMB floats have minimal surface area above the sea surface and therefore have minimal impact from wind. SLDMBs were used in rapid response to the Deepwater Horizon Oil Spill in the eastern GOM (e.g., Liu et al., 2011a).

USCG policy mandates the use of SLDMBs during all significant SAR case operations or when EDS data is not available or the quality of the EDS data is suspected to be low quality. Additionally SAR planner should direct search assets to deploy SLDMBs when they suspect a case may result in a prolonged search effort. The purpose of deploying the drifter is to subjectively evaluate the EDS products as the case progresses. A SAR planner also has the option to preemptively deploy SLDMBs when they believe there will be a high likelihood of SAR cases (e.g. a fishing tournament or
holiday weekend). The number and location of drifters deployed is decided by the planner and is determined by factors such as the size of the search area and proximity to known current features (e.g. the boundary of the Gulf Stream). Deployment strategies are corners of a polygon, a transect, or an “X” shape and normally spaced 3 to 6 NM apart, depending on proximity to shore, or influence of tidal currents (USCG, 2013). SLDMBs are a valuable tool when other data is lacking, however limitations such as failure rates, single point data, and delay in receiving usually prohibit their use as a sole SAR planning tool. As previously stated SLDMBs are normally used in conjunction with EDS products validate the ocean current models in real time during a SAR case.

Figure 2.3: Schematic of Metaocean SLDMB currently in operational use by the USCG (left), above surface photo of deployed SLDMB (right). (US Coast Guard, 2014)
2.2 West Florida Shelf

The WFS is defined as the continental shelf on the eastern edge of the GOM extending from the Florida Keys to the Mississippi River. The shelf has a wide, gently sloping feature that extends approximately 200 km offshore of Tampa Bay before a sharp drop-off defined by narrowly spaced isobaths beyond the shelf break, known as the shelf slope and the Florida Escarpment. A prominent feature in the shelf is the Desoto Canyon, which lies perpendicular to the Florida Panhandle. To the west of the Desoto Canyon the shelf narrows near the Mississippi River delta. This study will focus on the WFS between the Florida Keys and the Desoto Canyon as it coincides the Sector St Petersburg SAR AOR.

The structure of the WFS creates an interesting coastal ocean environment for study. It is bounded seaward by the shelf break beyond which the circulation is dominated by the GOM Loop Current (LC) and its eddies, it has a large and seasonally varying freshwater inputs from the Mississippi River, plus additional inputs from Florida Rivers and the Everglades, and it is also driven by seasonally varying winds. Weisberg and He (2003) describe the WFS dynamics as being subject to both deep-ocean forcing and local (wind) forcing that change on inter-annual, seasonal and synoptic time scales. Weisberg et al. (2005) expanded on this and analyzed force balances at different points of the shelf. The study describes the three dimensional dynamics across the shelf as defined by an inner shelf (shoreward of 50 m isobaths), an outer shelf where deep-ocean processes penetrate onto the shelf, and the mid-shelf in between the two.

The dynamics of the inner shelf are of particular importance to SAR application, as the majority of cases occur in this region. Inner shelf dynamics have been the focus
of numerous studies (e.g. Mitchum and Clark, 1986; Lentz, 1995; Li and Weisberg, 1999ab; Weisberg et al., 2009ab). Mitchum and Clark (1986) use a simplified model (unbounded coastline) to describe the “blocking” of Ekman flux caused by the interaction between surface and bottom Ekman layers. Lentz (1995) used a two-dimensional model to examine the sensitivity of inner-shelf circulation to the vertical turbulent mixing applied and found little impact to along shelf transport, but larger impact to across shelf where direct stress on the surface is transmitted to the bottom, causing divergence of Ekman transport. Both Mitchum and Clark (1986) and Lentz (1995) concluded with similar definitions of the inner shelf, area where surface and bottom Ekman layers overlap.

Li and Weisberg (1999ab) applied a different technique to describe the dynamics on the WFS. They used a three dimensional, time-dependent, primitive equation model to analyze force balances under quasi-steady state after upwelling favoring (along-shore and across-shelf) winds were applied. The model accounted for coastal boundaries (Florida Keys) and unique isobaths that led to results contrasting previous studies, but showed the similar sensitivity to vertical friction parameterization. The definition of the inner shelf was developed by analyzing vertically integrated momentum balances, and ultimately defined the inner shelf as the transition region between Ekman and Ekman-geostrophic balances, where the geostrophic portion is a consequence of sea surface slope induced by surface Ekman layer divergence (Li and Weisberg, 1999b). Weisberg et al. (2001) extended these concepts to a stratified shelf where the surface and bottom Ekman layers may be separated by a geostrophic interior region. The same principle applies nonetheless. Where the surface and bottom Ekman layers
interact through divergence defines the inner shelf. Off of Sarasota, the model found the inner shelf to extend to a depth of approximately 50 meters with the center at about 25 m, where Coriolis and bottom stress terms were of equal magnitude. Following the 50 meter isobaths to the north, the WFS inner shelf widens through Florida’s Big Bend region, before narrowing at the Desoto Canyon. Dominant dynamics of the inner shelf was also confirmed through analyses of the terms in the momentum balance using velocity and other measurements from moored instrumentation at selected sites (Liu and Weisberg, 2005a, 2007).

In contrast to the dynamics of the inner shelf, which are controlled by surface and bottom Ekman layer interactions, the outer shelf is the region where direct forcing through interactions with the adjacent deep ocean currents are important (e.g., Weisberg and He, 2003, Weisberg et al., 2014a; Liu et al., 2016a). This outer shelf region generally extends shoreward from the shelf break by an internal Rossby radius of deformation (e.g., Kelly and Chapman, 1988; Brink, 1998), which for the WFS is about 30 km (He and Weisberg, 2003). There, without the stronger dissipating influences of bottom friction as occurs over the inner shelf, the outer shelf is characterized by eddy-like motions due to across isobath flows inducing relative vorticity (e.g. Weisberg et al, 2001). Being that the shelf is so narrow in the vicinity of the DeSoto Canyon, the inner and outer shelf regions there may overlap, this blurs the dynamical distinctions between the inner and outer shelf. Another similarly special place where this phenomenon occurs is the Dry Tortugas region, which is sometimes called the “pressure point” of the WFS (Liu et al., 2016a). If the GOM LC system impinges on this portion of the WFS, by contacting the shallow isobaths, the pressure perturbation from offshore forcing could
set the entire WFS into motion (Weisberg and He, 2003; Weisberg et al., 2014a, Liu et al., 2016a).

The current patterns on the inner WFS and their variability have been described in a series of studies using the long-term moored ADCP data (Liu and Weisberg, 2005b, 2012; Weisberg et al., 2009). The long-term mean currents on the WFS are generally southeastward down the shelf (Weisberg et al., 2009). The currents on the inner WFS exhibit seasonal variation: stronger and southeastward in fall, winter and spring, weaker and northwestward in summer (Liu and Weisberg, 2012). However, on the outer WFS, the seasonal variation of the currents is less pronounced (Liu and Weisberg, 2012), mainly due to the episodic impacts of the deep ocean through the GOM LC and its eddy interactions (e.g., Weisberg and He, 2003; Weisberg et al., 2014a, Liu et al., 2016a). Note that this deep ocean system does not have strong seasonal variation (Liu et al., 2016b).

On synoptic weather time scales, the WFS currents could switch from upwelling to downwelling patterns in days, mainly in response to local wind forcing (Weisberg et al., 2001; Liu and Weisberg, 2005b, 2007). Asymmetries are found between upwelling and downwelling current patterns: (1) surface currents are southeastward and stronger in upwelling patterns while the surface currents are northwestward and relatively weaker in downwelling patterns; (2) The southeastward coastal jet is located more offshore (around 25 – 30 m isobaths) in upwelling patterns, while the northwestward coastal jet is closer to the coast in downwelling regimes (Li and Weisberg, 1999; Liu and Weisberg, 2005b, 2007). These coastal oceanographic findings have important implications for using marine environmental data for SAR applications.
2.3 The West Florida Coastal Ocean Model (WFCOM)

In addition to the surface current models listed section 2.2, this study looks to evaluate all available surface current models. Most notably, the WFCOM (Zheng and Weisberg, 2012; Weisberg et al., 2016a), run by the USF College of Marine Science that is not presently a part of the USCG EDS, will therefore be included for comparison. The WFCOM is unique compared to the other models because it downscales deep ocean processes across the WFS by nesting the Finite Volume Coastal Ocean Model (FVCOM, e.g. Chen et al., 2003) into the Global HYCOM. The unstructured grid of the FVCOM allows for high resolution (150m) along the coast and estuaries expanding out to 12 km along the open boundary. The original version included 8 tidal constituents and 21 non-uniform vertical (sigma) layers. WFCOM is forced with NOAA NCEP NAM reanalyzed winds combined with in situ data using optimal interpolation. Zheng and Weisberg (2012) demonstrated the effectiveness of the model by comparing it to 2007 mooring observations. Liu et al. (2014b) further confirmed that the WFCOM performed better than the other models (the GOM & the Global HYCOMs) over the inner shelf region when their Lagrangian trajectory simulations were compared with the satellite-tracked surface drifter trajectories collected in summer 2010. The WFCOM proved useful for practical ecological studies addressing red tide absences in 2010 (Weisberg et al., 2014a) and tracking subsurface Deepwater Horizon oil (Weisberg et al. 2016b). In 2014, while addressing gag grouper larvae pathways, the WFCOM domain was expanded to include the Mississippi River delta, a newer version of FVCOM was used that included 31 vertical layers, and the model was nested in the GOM HYCOM instead of the Global HYCOM (Weisberg et al., 2014b). Beginning in 2014, the GOM HYCOM
also includes tides, negating the former requirement to add these along the open boundary of the WFCOM.

2.4 HF Radar Observation System

HF Radars are designed to capture high resolution surface current data where other observations such as mooring and drifters may be limited. HF radars operate between 3 and 30 MHz and use radio wave backscatter to map surface currents. Systems operating in the 12-25 MHz range can detect currents out to 60 km with a resolution of 1 – 3 km (Paduan and Rosenfeld, 1996; Graber et al., 1997). Lower frequencies, such as the 5 MHz CODAR SeaSonde Radars on the WFS, have a nominal range of 200 km with resolutions of 5 – 10 km and measure and have an effective depth of ~ 2 m (Steward and Joy, 1974; Paduan and Graber, 1997; Ramp et al., 2008). Harlan et al. (2010) describe the physics of HF Sea Scattering and national applications of this technology.

HF current mapping relies on the presence of surface gravity waves and conductive surface water. The presence of high volumes of fresh water (less conductive than sea water) can significantly reduce HF Radar observations (Long et al., 2006). Through Bragg Scattering, the radar can only detect waves with wavelength, \( \lambda_0 \), half the radar wavelength, \( \lambda \). Therefore the frequency of the radar determines the wavelength of the ocean waves to be detected, and the relative waves speed is the sum of the phase speed plus and the underlying current (toward or away from the radar). Subtracting the phase speed (for deep or shallow waves) leaves only the radial velocity (Harlan et al., 2010).
Since radial velocities only measure the portion of the current that is towards or away from an HF Radar antenna, radial velocities from two or more sites must be combined to determine a total velocity current. The polar coordinates grids of radial velocities are combined to create a Cartesian coordinate mapped data using a number of techniques, but all result in variations of data density, signal strength, and geometric dilution of precision (GDOP) (Chapman, 1997). Therefore a quality control measures must be implemented prior to using HF Radar surface current data for practical application. Currently HF Radar data is being used on a national scale for missions such as USCG SAR, oil spill response, tracking marine populations and coastal water quality, to name a few (Harlan et al., 2010).

Since the USCG identifies HF Radar as the preferred surface currents to apply for SAR planning purposes, evaluating these observations for SAR application is paramount. Multiple HF Radar validation studies have been completed to assess the viability of using HF Radar to accurately observe surface currents. HF Radar comparisons with surface drifters have been completed in areas such as the Soya Warm Current (Ebuchi et al., 2006) and in the offshore area of New England (Ullman et al., 2006; Abascal et al., 2009; Kuang et al., 2012; Rypina et al., 2014). The techniques of comparison vary, but common approaches include deriving Eulerian velocities from changes in drifter positions, and comparing root mean square of velocities in zonal and meridional directions (or down wind and cross wind). The problems with drifter analysis include poor spatial sampling, relatively short time scales, and typically experiments include a small number of drifters that limits statistical analysis. Another approach is to compare HF radars to current observations from moorings or vessels. While many HF
Radar validations have been completed in different regions of the world, on the WFS specifically, two such comparisons were completed recently (Liu et al., 2010, 2014a). The studies assess the surface currents derived from two HF Radar arrays, the 4.9 MHz CODAR and the 12.7 MHz WERA, to Acoustic Doppler Current profilers (ADCPs). The study found that the WFS’s low-energy environment and unfavorable surface wave directions limit the HF Radar observations, however, when data is acquired it agrees well with ADCP observations. RMS differences of 6 to 10 cm s⁻¹ between HF Radar and ADCP surface currents for hourly observations and RMSE decreased when a 36 hour low pass filter was applied.

Another study conducted in the Middle Atlantic Bight, off the coast of New York and New Jersey, simultaneously assessed surface currents from a coastal ocean model and HF Radar using surface drifters. Kuang et al. (2012) used data from 3 surface drifters to evaluate the New York Harbor Observing and Prediction System (HYHOPS) and HF Radar derived surface currents. The study identified areas were the RMS difference of the model and HF observations varied greatly (e.g. the mouths of rivers and estuaries) and ultimately found the RMS differences between the HF Radars and drifters was the same as the RMS difference between the model and drifters, both were approximately 10 cm s⁻¹. The HF Radar validation results were similar to those previously conducted in the area (e.g. Ullman et al., 2006). Additionally spatial and temporal discrepancies were identified in both the model and HF Radar’s skill in predicting surface trajectories. This type of analysis is useful to those using the products. An assessment of skill, identification of limitations, and an understanding of local constraints is useful information for the SAR planner to have when using a surface
current model to execute a mission. Recently, Roarty et al. (2016) evaluated the environmental data that are used by the USCG in the northeast US coast for the SAR purpose. They quantitatively assessed their HF radar data using the skill score proposed by Liu and Weisberg (2011).

2.5 Chapter Summary

The USCG SAR program is comprehensive in its organization and procedures. Assets are strategically staged along the coast to respond to any SAR case within a reasonable time. Every search cases is planned using computerized SAR planning software called SAROPS. The SAROPS system allows the user to select the most appropriate ocean current model to simulate a drift using a Monte Carlo approach. In addition to SAROPS, and its ocean current model inputs, a SAR planner can deploy a SLDMBs within the search area to subjectively validate the simulated drifts in real time. Additional tools available on the WFS are the WFCOM ocean current model and the CODAR HF Radar array. WFCOM is currently not available to SAR Planners, but the HF Radar data is, although it is not utilized often. In addition to the tools SAR tools, the planner must also have firm grasp of the physical ocean dynamics in the area in which they are operating. This chapter also summarizes the dynamics on the WFS to include areas where different forcing mechanisms are present to include descriptions of the inner and outer shelf regions.
CHAPTER 3:
EVALUATION OF HF RADAR

3.1 Abstract

The viability of using HF Radar observations for SAR planning is explored using data from three sets of drifter deployments and historical SAR data. It is determined that HF Radar velocity data must provide adequate coverage and accurate velocity estimates in order for it to be a useful tool for SAR operations. The coverage of HF Radar derived velocities, quality controlled for near-real time operations, is considered on temporal and spatial scales. A spatial comparison is conducted to determine where high percentage areas of HF Radar coverage are in relation to high probability SAR case areas. It is found that only 7.6 percent of SAR cases occur with areas that have at least HF Radar derived surface current observations 50% of the time over a three year period. Temporal analysis shows that HF Radar data has diurnal, semiannual and annual variability while SAR data shows diurnal, weekly, and annual variability. On an annual basis the variabilities of the two data sets are out of phase, however both have diurnal variations with maximum amplitudes in afternoon hours. The accuracy of the HF Radar velocities is assessed using drifters deployed in three separate experiments. Drifters were placed along a transect off the mouth of Tampa Bay and velocities were recorded during the summer, fall and winter between August of 2015 and February 2016. Statistical analysis shows varying errors and correlations between the three
Additional differences in results and causes of error are discussed in this Chapter.

3.2 Data

3.2.1 SLDMB Deployments

The CODE/Davis style (Davis, 1985) SLDMBs for this study were provided by the USCG Office of Search and Rescue. The SLDMBs were deployed along a 60 NM transect extending from the mouth of Tampa Bay. Drifters were deployed along the transect in August 2015, October 2015, and January 2016. This transect was chosen to capture observations within a high concentration SAR case area that coincides with HF Radar coverage (CODAR and WERA) and the domains of several USCG EDS current model domains as well as the WFCOM. The number of drifters available for each deployment was dependent USCG availability and operational demand, therefore each deployment had a different number of drifters deployed. Five SLDMBs were deployed in August of 2015, 10 were deployed in October of 2015 and 12 were deployed in January of 2016. The SLDMBs were deployed from Coast Guard Vessels of opportunity transiting to scheduled patrols. Deployment procedures were conducted in accordance with Coast Guard policy; hand deployed off the aft quarter of vessel transiting at 10 kts. All deployments experienced some failure rate: one SLDMB failed to report positions in August 2015, four failed in October 2015, and four failed in January of 2016. Of the 18 SLDMBs that did report positions, 1 only reported for only one day, while the rest all preformed in accordance with published specifications. Table 1 summarizes the data received from the drifters.
<table>
<thead>
<tr>
<th>Deployment Month</th>
<th>SLDMB #</th>
<th>Drift Start Date/Time</th>
<th>Drift Start Position</th>
<th>Drift End Date/Time</th>
<th>Drift End Position</th>
<th>Days of Drift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug-15</td>
<td>43359</td>
<td>04-AUG-2015 1800</td>
<td>27.544N 083.52W</td>
<td>03-SEP-2015 1600</td>
<td>27.022N 084.113W</td>
<td>29.96</td>
</tr>
<tr>
<td></td>
<td>43365</td>
<td>04-AUG-2015 1800</td>
<td>27.545N 083.713W</td>
<td>09-SEP-2015 1200</td>
<td>26.422N 084.026W</td>
<td>35.8</td>
</tr>
<tr>
<td></td>
<td>38723</td>
<td>14-OCT-2015 1600</td>
<td>27.539N 083.277W</td>
<td>04-DEC-2015 0000</td>
<td>29.987N 087.729W</td>
<td>50.38</td>
</tr>
<tr>
<td>Jan-16</td>
<td>43141</td>
<td>12-JAN-2016 1800</td>
<td>27.523N 082.894W</td>
<td>11-FEB-2016 1600</td>
<td>26.255N 082.958W</td>
<td>29.95</td>
</tr>
<tr>
<td></td>
<td>38779</td>
<td>12-JAN-2016 1900</td>
<td>27.529N 083.178W</td>
<td>11-FEB-2016 1900</td>
<td>25.889N 083.101W</td>
<td>30.04</td>
</tr>
<tr>
<td></td>
<td>38833</td>
<td>12-JAN-2016 2100</td>
<td>27.526N 083.369W</td>
<td>11-FEB-2016 2100</td>
<td>26.034N 082.885W</td>
<td>30.08</td>
</tr>
</tbody>
</table>
Figure 3.1 displays the SLDMB drifter data from the August 2015 deployment. Green triangles represent start positions and red squares are end positions.

Figure 3.1: Drifter tracks from August 2015 SLDMB deployment. Green triangles represent start positions and red squares are end positions.

Drifter #43475 was deployed 40 km west of the mouth of Tampa Bay. Drifters #43360, #43359, and #43365 are spaced at approximately 20 km extending to the west with #43365 placed 100 km offshore. A fifth drifter was placed at 20 km offshore, however it failed to report any positions. These drifters were deployed in August to capture the flow field of a “low energy” environment (Weisberg et al., 2012). Liu et al. (2010) conducted a monthly mean climatology from ADCP data on the WFS and found May, June, July, and August to have the lowest wind speeds, currents, wave energy and significant wave heights. Consequently, HF Radar radial returns are lower as well.
The implications of this for HF Radar to drifter comparison will be discussed in the Results and Discussion of this Chapter.

Figure 3.2 displays the drifter tracks recorded in the October 2015 SLDMB deployment. The deployment strategy and transect were the same as the August 2015 deployment, except 10 drifters were utilized. Therefore the spacing was reduced to 10 km. Four drifters failed to report any positions and #43122 (not pictured) reported for only 1.5 days. Additionally, #38647 did not report any positions for the first two days, and #43358 did not report for the first 4 days. Only three drifters (#43374, #38647, and #38723) recorded data within the CODAR footprint. All drifters displayed a similar drift pattern, with an initial offshore flow followed by a northwestward, along isobath, flow. After approximately two weeks, #43374 and #38647 drifted into the Florida Middle Grounds and slowed, while the others drifted past the De Soto Canyon before diverging.

The final experiment was conducted in January of 2016. The winter months

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**Figure 3.2:** Drifter tracks from October 2015 SLDMB deployment. Green triangles represent start positions and red squares are end positions.
(December, January, and February), on climatological average, experience the highest wind speeds and wave energy (Liu et al., 2010). Again the deployment strategy was the same as the previous two experiments, except 12 SLDMB drifters were deployed with 10 km spacing. The drift trajectories are displayed in Figure 3.3. Four drifters failed to report any positions, and the remaining eight drifted within the CODAR footprint.

Figure 3.3: Drifter tracks from January 2016 SLDMB deployment. Green triangles represent start positions and red squares are end positions.
for approximately 30 days. The velocities for the drifters were estimated by dividing the distance the drifters traveled by the time between reports. Since the drifters report GPS positions every half hour, the east-west, $u$, and north-south, $v$, estimated velocity components were recorded every half hour with the assigned position centered on the two reports. SLDMB drifter data can be erratic and some erroneous were reported, some positions were 100s of kms away from previous position. To exclude outliers, a quality control measure was implemented to remove any position that produced a velocity greater than 2 m/s. Velocities resulting from the quality control measure produced estimated velocities based on time separation of an hour, versus 30 minutes. The remaining data were interpolated to an hourly data set for comparison to hourly CODAR HF Radar data.

3.2.2 HF Radar Data

The HF radars on the WFS coast are maintained through the Coastal Ocean Monitoring and Prediction System (COMPS) program at the College of Marine Science, University of South Florida (e.g., Merz et al., 2012). The three long-range (4.9 MHz) CODAR SeaSonde radars are located at Redington Shores, Venice and Naples. In an effort to obtain the most practical data for SAR application the HF Radar data for this study was obtained from the Coastal Observing Research and Development Center (CORDC) (http://hfrnet.ucsd.edu/thredds/catalog.html). CORDC acquires surface ocean radial velocities from the coastal waters of the United States and applies near-real time quality control metrics to produce surface current maps for operational use. The data is available hourly and converted into Cartesian coordinates.
The HF Radar velocity data used in CORDC surface maps are quality controlled in three stages. The first stage is at the point of origin; the internal software of the CODAR radar determines whether spectra are acceptable and of suitable quality for velocity estimates based on factors such as signal to noise ratio. The second stage of quality control is conducted upon acquisition of radial data by the HF-Radar Network (HFRNet). This stage ensures appropriate formatting and disregards any data that does not fall into time or range specifications. The final quality control ensures all radial velocities are under a maximum magnitude threshold (3 m/s on East Coast) and over water (radials within ½ km from land are removed).

Velocities are mapped onto regional grids using a least squares fit (Gurgel, 1994) with the CODAR data on the WFS having a resolution of 6 km. Radials must come from at least two sites and there must be three radials with the search radius (30% greater than resolution) to produce velocity data at that point. After the least squares fit is applied to produce a total velocity from the radials, a maximum velocity threshold (3 m/s) and geometric dilution of precision (GDOP) threshold are applied. The GDOP is coefficient of uncertainty expressed as a ratio of the velocity component errors and the root mean square differences of the current estimates, with the velocity component errors being inversely proportional to the angle of intersecting beams (Trujillo et al., 2004). Lower angles of intersecting beams result in higher GDOP. To ensure quality control of data, a GDOP threshold of 10 is applied and higher are discarded (CORDC, 2016). There are many active developments in radial quality control, and CORDC is continuing work in this area. Since this study is focused on tools available to SAR planners, this data and the quality control process employed by CORDC was
determined to be practical for near real time availability of HF Radar derived surface currents.

3.2.3 USCG SAR Data

The USCG maintains all mission data in Maritime Information for Safety and Law Enforcement (MISLE) database. Every SAR case executed by the USCG is entered in near real time into this system. SAR data is stored in the USCG Business Intelligence system which can only be accessed through a USCG Portal on official workstations. SAR data can be obtained by submitting a request to the Freedom of Information Act (FOIA) Officer at any USCG Unit. This study utilizes SAR case information from USCG Sector St. Petersburg from FY 13-15 (or October 2012 to September 2015). The information includes a case number, date, time, location, assets utilized, search effort, and results (to include amount of lives and property saved).

3.3 Experiment Design

Research Question: Is HF Radar an effective surface current product for operational SAR case planning on the WFS?

Sub Questions:

- What are the limitations of the HF Radar observations?
- What are the special considerations for SAR Planners using HF Radar in a low energy environment?

To answer the first research question the performance of the HF Radar on the WFS must be evaluated. Performance can be thought of as the radar's ability to
produce data in terms of spatial or temporal coverage, or it can be thought of as the
ability to accurately observe the surface currents where data are available. To be useful
for SAR application the performance would have to have both ample coverage and
reliable accuracy.

To evaluate the coverage of the radar, the gridded data from the quality
controlled CORDC data are examined. Liu et al. (2010) demonstrated that there are
significant temporal variations in the spatial coverage, or number for radial velocities
recorded, on both diurnal and seasonal time scales. On the diurnal time scale,
corresponding variations in significant wave height and wind speeds were not found,
therefore the variations can be attributed to other factors, such as ionosphere effects
and background radio noise (Davies, 1990). The occurrence of SAR cases on the WFS
also displays temporal and spatial variations.

To determine if HF Radar coverage is useful for SAR planners:

1. Total data returns per hour of CORDC CODAR velocity data over a
   three year period (2013 to 2015) are analyzed for variations on daily
   and seasonal scales.

2. A similar analysis is done on three years of SAR data on the WFS.

3. A spatial analysis is conducted to determine if HF Radar derived
   surface currents are being observed in areas where SAR cases occur.

To analyze the accuracy of the HF Radar surface currents, a statistical
comparison of the observed drifters is conducted. A common measure of agreement
between scalar time series is the root-mean-square-deviation or root-mean-square error
(RMSE) defined by Oke et al. (2002). The equation is as follows:
\[ RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^{N} [V_{HF}(n) - V_{Drifter}(n)]^2} \]  

(3.1)

where \( V_{HF} \) is the velocity component derived from HF Radar, and \( V_{Drifter} \) is the velocity component derived by the SLDMB and \( N \) is the number of comparisons.

Additionally a correlation coefficient, \( r \), is calculated to measure the covariance of the HF Radar velocities and the drifter velocity components. The correlation coefficient is defined as:

\[ r(V_{HF}, V_{Drifter}) = \frac{\text{cov}(V_{HF}, V_{Drifter})}{\sigma_{HF} \sigma_{Drifter}} \]  

(3.2)

where the covariance of the HF Radar velocities and the SLMDB velocity components are normalized by their standard deviations, \( \sigma \), to produce a non-dimensional variable. The RMSEs and correlation coefficients are evaluated for each drifter as it drifts through the HF Radar footprint of observations.

Since the resolution of HF Radar data is 6 km in the radial direction, and the hourly returns are gappy and lacking in spatial coverage consistency, objective mapping, or optimal interpolation (OI) was done to compensate. A Gauss-Markov smoothing technique is used to accomplish this. Two assumptions are made prior to objectively mapping the HF radar data. First, the data is assumed to be homogeneous, meaning the statistical characteristics are same throughout the velocity field. And second, the covariance function is isotropic, or the same in all directions. Applying both assumptions results in the covariance becoming only a function of distance between the data observations (HF Radar) and the new grid on which the OI will be completed.

To accomplish this, the velocity components of the HF Radar velocity fields (east-west, \( u \), and north-south, \( v \)) were evaluated separately. A grid was created over the area of interest (from 25.5\(^\circ\)N to 28.0\(^\circ\)N and from 84.5\(^\circ\)W to 82.0\(^\circ\)W) at a resolution
of 0.06 degrees. An array of distances was calculated between HF Radar observation points, as well as an array between the interpolation grid and observation points. An error variance and decorrelation scale were chosen a priori and were 0.003 and 0.3 respectively.

The first step is creating a covariance matrix between the observation points.

\[ \mathbf{a} = \sigma_{err} + e^{-x^2/d^2} \]  

(3.3)

Where \( \mathbf{a} \) is the data-data covariance matrix, \( x \) is the array of distances between observation points, and \( d \) is the decorrelation scale. The matrix is calculated using the Gaussian covariance function. The data-data covariance matrix is augmented on the diagonal by the error variance, \( \sigma_{err} \). The covariance matrix between the observation points and interpolation grid, \( \mathbf{c} \), is:

\[ \mathbf{c} = e^{-x^2/d^2}. \]  

(3.4)

An Objective mean is calculated by summing the product of the observed HF Radar velocity components with the inverse of the data-data covariance matrix, \( \mathbf{a} \), and dividing by the sum of \( \mathbf{a} \). The mean is then removed from the observed velocities. The resulting residuals are multiplied by the covariance matrix of observation and interpolation points, \( \mathbf{c} \), and the inverse of \( \mathbf{a} \). Adding the mean back in results in the best linear unbiased estimator (BLUE) of interpolated HF Radar velocity components given by ordinary least squares. The standard deviation at each grid is calculated and multiplied by 100 to represent a percent error.

Figure 3.4 represents an example of an OI grid where gaps in the data were filled; the 10% error contour is represented with a red line, errors higher than 10% were not used for velocity comparison. The OI method successfully filled gaps in data while
maintaining low errors, however, by the nature of the calculation, extending beyond the coverage footprint of the radars produced high errors and the data could not be used for drifter comparison.

![Figure 3.4: Examples of HF Radar with gaps filled by OI method described above. Data is CORDC total velocity data from January 14th, 2016, at 1100. Blue vectors (left) depict original data set, Green vectors (right) are objectively mapped on 6 km grid. Red contour (right) shows the 10% error.](image)

Rather than further interpolating the OI grid to the positions of the drifters for each time step, a separate OI was conducted at each time step corresponding to the positions of the drifters. Only interpolated velocity components with a percent error of less than 10 were used for the velocity comparison. If the error was larger than 10% the drifter was deemed to be outside of the HF Radar footprint and no statistical comparison could be made. Velocity components for drifters and HF Radar derived surface currents
were compared using the RMSE and correlation coefficients to the 95% confidence interval.

Therefore, in order to assess the accuracy of the HF Radar velocities:

1. An OI is conducted on the HF Radar hourly velocity fields.
2. The resulting OI field is compared to surface drifter derived velocities by computing RMSEs and correlation coefficients for the two data sets.

3.4 Results

A spatial comparison of SAR case locations and CODAR HF Radar coverage is depicted in Figure 3.5. The figure shows only offshore cases (excluding Tampa Bay, Charlotte Harbor and the rivers) occurring in FY 13, 14 and 15. The shaded green area shows the area where total velocities were calculated, using CORDC’s quality control method, at least 50 percent of the time.

**Figure 3.5:** SAR cases from FY13-15 falling within area where quality controlled CODAR HF Radar velocities were recorded at least 50% of the time over the three year period. Red dots represent initial locations of SAR cases in USCG Sector St Petersburg AOR, Green area is 50% coverage area and black dots are SAR case initial locations falling within 50% coverage area.
It should be noted that the CORDC data only records a velocity when at least three radials from two sites are within the search area of 10 km around each 6 km grid point. This means that individual radial velocities were ignored if corresponding radial velocities from an adjacent site could not be used to calculate a total velocity. Additionally, SAR cases that fell outside of the USCG Sector St Petersburg AOR (in vicinity of the Florida Keys and West of the Florida Panhandle) are not depicted.

In the offshore area of Sector St Petersburg AOR on the WFS 2081 SAR cases were reported over the three year period, averaging 1.9 SAR case per day. Of those cases, 159 SAR cases fell within the 50 percent CODAR HF Radar coverage area. Therefore, only 7.6% of the offshore SAR cases fell within an area where CODAR HF Radar observations were available at least half of the time.

Figure 3.6: Histogram of SAR Case per hour (UTC) from FY13-15 (blue bars). Average CORDC CODAR HF Radar velocities (Red line) recorded per hour on WFS.
To observe temporal variations in CODAR HF Radar coverage and occurrence of SAR cases two data sets are compared: the number of CORDC total velocity vectors recorded per hour and the report times of SAR data for FY 13-15. Exploring the data sets on different time scales proves useful for the analysis. Both show strong diurnal variations; Figure 3.6 displays a histogram of SAR cases binned by “Incident Start Time” compared to the average number of CORDC HF radar derived velocities recorded per time of day. One outlier in the SAR data recorded at 00:00 UTC; if no time is recorded for a SAR case, the MISLE system default time is to 00:00 UTC. It is unknown if the high number of SAR cases at 00:00 UTC in Figure 3.6 is a result of data input error, or if a large number of cases actually occurred at this time. Both data sets show a diurnal variation with higher values between 15:00 and 23:00 UTC. Based on the daily data there is a correlation of 0.59 (99% confidence based on 22 effective Degrees of Freedom or DOF). Therefore, CODAR HF Radar data peaks on a diurnal cycle with the occurrence of SAR case in this area. Meaning the HF radar observation would be useful to SAR planners if a case occurred within the HF radar footprint, and the case duration did not extend into a period of time when HF radar coverage is lower than average.

A similar analysis on a monthly time scale is shown in Figure 3.7. The total number of SAR case recorded per month is averaged over the three years and compared to the average number of HF Radar velocities calculated during the same time frame. The SAR cases show a clear seasonal signal with summer month values almost doubling when compared to the winter months. The HF Radar velocities appear to have peaks in the spring (March – May) and again in the late fall (November).
On longer time scales the average number of HF Radar data recorded per day is compared to the number of SAR cases per day. To reduce the noise, a 30 day low pass filter is applied to both data sets. Figure 3.8 displays the 30 day low passed, scaled data of SAR case and HF radar returns per day over the three year period. There is a weak, yet still statistically significant (at 95% confidence) anti-correlation of -0.32 between the two data sets. Both show annual variability, however they appear to be out of phase, with the SAR cases peaking in the summer months and the HF Radar data peaking in the winter months. The HF Radar data appears to have semi-annual signal as well.

The power spectra of the number of SAR cases per day is compared to the spectra of HF Radar coverage (number of HF Radar velocities) per day for the 3-year period between FY 12 and FY 15. For comparison, both data sets were scaled by their
standard deviations. Auto-spectra was estimated using a Hamming windowed Fast Fourier Transform (FFT) using 5 adjacent frequency bands for averaging (with 22 DOF). Figure 3.9 displays the distribution of variance as a function of frequency for the two data sets. The SAR data shows a well resolved peak at the 7 day period. This coincides with a well-known increase of SAR cases on the weekends due to increased boating activity. There is no corresponding peak in variance of the HF Radar velocity estimates per day at the weekly frequency. At frequencies lower than weekly, the HF variance is higher than the SAR, conversely, SAR variance is higher at higher frequencies. Reducing the number of adjacent frequency bands to be averaged results in SAR peaks at annual and weekly frequencies and HF peaks at seasonal frequencies.

**Figure 3.8:** 30 day low pass filtered SAR (blue) and HF Radar data (red). For comparison, both are scaled by the maximum number of data recorded during the period from FY13-15.
however the DOF is significantly reduced and therefore not statistically significant. A longer time series would need to be evaluated to resolve these lower frequencies.

![Figure 3.9: Auto-spectra of number of SAR cases per day (blue) and number of HF Radar estimated velocities per day (red). Both data sets are scaled by their standard deviations and are represented as $n^2/\text{cpd}$ on the y-axis. The x-axis is frequency (cpd) and the period (days) is included for reference at the top of the figure.](image)

To assess the HF Radar accuracy the data are spatially interpolated using the process described in Section 3.3 and compared to drifter velocity components recorded at corresponding times. The output interpolation positions match those of the drifters at each hourly time step as they drift through the CODAR footprint. A temporal interpolation was not applied. Velocity components are only compared for times when HF Radar derived surface currents are recorded. Additionally, HF Radar velocities with percent errors greater than 10% are excluded.

Figure 3.10 shows an overview of the data used for comparison. The percent of time that HF Radar surface current velocities were recorded is depicted and hourly drifter positions for all drifters are connected with black lines to show the tracks of the
drifters relative to the CODAR array footprint. An overall 3 year average of the CODAR array footprint is included in Figure 3.10(a) for comparison to the footprints recorded during the experiment timeframes. The August to September 2015 experiment recorded the lowest number of HF Radar velocities for comparison, with only a small

![Figure 3.10: Comparison of drifters and HF Radar coverage.](image)

**Figure 3.10**: Comparison of drifters and HF Radar coverage. (a) Three year average of percent coverage of HF Radar, (b) HF Radar coverage during August 2015 deployment of SLDMB drifters (black lines), (c) HF Radar coverage during October 2015 deployment of SLDMB drifters (black lines), (d) HF Radar coverage during January 2016 deployment of SLDMB drifters (black lines).
area recording velocities more than 50% of the time. This is partially attributed to the seasonal variation in HF radar returns and partially due to a lightning strike to the Naples CODAR Seasonde HF Radar, disabling the system from June 24th, 2015 to August 20th, 2015. A larger field of HF Radar velocities was recorded from October to November, 2015, however the drifters moved offshore out of the footprint within 10 days of deployment. Only three drifters provided data for HF velocity comparison. The January 2016 deployment provided the best data set for comparison. All drifters stayed with the footprint and provided approximately 30 days of velocity data for comparison.

Figure 3.11 displays the results of the August 2015 experiment. The August experiment was designed to be lowest energy environment out of the three drift sets. The data supported this hypothesis with the drifters recording average absolute value velocities of 9.41 cm/s and 8.9 cm, for \( u \) and \( v \) components respectively. The HF Radar observed average absolute velocities of 6.3 cm/s (\( u \)) and 7.92 cm/s (\( v \)). The HF Radar derived data underestimated the \( u \) velocity (\( v \) velocity) by 49% (23%). The average RMSE for the \( u \) component (\( v \) component) of velocity was 10.43 (13.06) cm/s, with a range of 10.02 – 11.13 (11.86 – 15.16) cm/s. The average correlation coefficients were 0.68 and 0.49, for the \( u \) and \( v \) components respectively. Figure 3.12 displays the results of the October SLDMB deployment. Again data was only available for comparison during the first 10 days because the SLDMBs drifted out of the area of interest. However, during those ten days the average absolute value of velocities recorded from the drifters were 12.05 cm/s (\( u \)) and 11.27 (\( v \)). The HF radar underestimated the average \( u \) component of velocity by 40%, and overestimated the \( v \) component by 4.45%. The average RMSE values for \( u \) (\( v \)) were 9.77 (12.24) cm/s, with
Figure 3.11: East-West ($u$) and North-South ($v$) velocity comparisons for drifter derived velocities (blue) and HF Radar spatial OI velocity (red) for experiment beginning on 04 August, 2015. RMSE (cm/s) and correlation coefficients (lower and upper bounds for the 95% confidence interval) are annotated on each panel.
A range of 8.52 – 10.46 (10.43 – 13.38) cm/s. The average correlation coefficients were 0.71 (u) and 0.75 (v).

The January SLDMB deployment provided the most robust data set for comparison out of the three experiments. The results of the velocity component comparison of drifters and HF Radar velocities are in Figure 3.13 and 3.14. The WFS also experienced the highest velocity currents, as multiple cold fronts passed through

Figure 3.12: East-West (u) and North-South (v) velocity comparisons for drifter derived velocities (blue) and HF Radar spatial OI velocity (red) for experiment beginning on 14 October, 2015. RMSE (cm/s) and correlation coefficients (lower and upper bounds for the 95% confidence interval) are annotated on each panel.
Figure 3.13: East-West ($u$) and North-South ($v$) velocity comparisons for drifter derived velocities (blue) and HF Radar spatial OI velocity (red) for experiment beginning on 12 January, 2016. RMSE (cm/s) and correlation coefficients (lower and upper bounds for the 95% confidence interval) are annotated on each panel.
Figure 3.14: East-West (u) and North-South (v) velocity comparisons for drifter derived velocities (blue) and HF Radar spatial OI velocity (red) for experiment beginning on 12 January, 2016. RMSE (cm/s) and correlation coefficients (lower and upper bounds for the 95% confidence interval) are annotated on each panel.
the area during the observed time frame. The average absolute values of velocity components were 9.45 cm/s \((u)\) and 16.17 cm/s \((v)\). Again the HF Radar recorded slower velocity components and underestimated drifters by 54\% \((u)\) and 12\% \((v)\). The RMSE values for \(u\) \((v)\) were 8.23 (11.43) cm/s with a range of 6.8 – 11.24 (9.36 – 13.87) cm/s. The correlation coefficients were 0.70 and 0.82 for the \(u\) and \(v\) components respectively.

In addition to the vector component analysis, a vector correlation was computed using the method proposed by Kundu (1976). The vector correlation analysis results in a complex correlation coefficient,\(\gamma\), and a complex phase angle, \(\alpha\). The complex correlation coefficient is defined by:

\[
\gamma = \frac{\langle u_{HF} u_{Drifter} + v_{HF} v_{Drifter} \rangle + \langle u_{HF} v_{Drifter} + v_{HF} u_{Drifter} \rangle}{\sqrt{\langle u_{HF}^2 + v_{HF}^2 \rangle} \sqrt{\langle u_{Drifter}^2 + v_{Drifter}^2 \rangle}}
\] (3.5)

The complex phase angle is defined by:

\[
\alpha = \tan^{-1} \frac{\langle u_{HF} v_{Drifter} - v_{HF} u_{Drifter} \rangle}{\langle u_{HF} u_{Drifter} + v_{HF} v_{Drifter} \rangle}
\] (3.6)

where \(u_{HF}\), \(v_{HF}\), \(u_{Drifter}\), and \(v_{Drifter}\) are the velocity components of HF Radar and SLDMB drifters and \(\langle ... \rangle\) represents an average. The phase angle represents the average angle of the HF Radar velocity was offset in relation to the observed drifter velocity with a positive angle representing counter-clockwise rotation. For the August experiment the complex correlation between HF Radar drifter velocities ranged between 0.58 and 0.63 with an average of 0.62. The velocities of the HF Radar were rotated in a counter-clockwise direction in relation to the velocities of the drifters. The October experiment saw a higher average correlation \((\gamma = 0.76)\) with HF velocities rotated in a clock-wise direction. The highest complex correlations were in recorded in the January experiment.
(average $\gamma = 0.81$) and the phase angle varied widely amongst all of the drifters ($\alpha$ ranged from -16 to 2).

**Table 2:** Summary of HF / Drift Statistics

<table>
<thead>
<tr>
<th>SLDMB Number</th>
<th>$\text{RMSE}(u)$ (cm/s)</th>
<th>$\text{RMSE}(v)$ (cm/s)</th>
<th>$r$ (u)</th>
<th>$r$ (v)</th>
<th>$\gamma$</th>
<th>$\alpha$ (º)</th>
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<tr>
<td>43475</td>
<td>10.18</td>
<td>11.86</td>
<td>0.68</td>
<td>0.61</td>
<td>0.63</td>
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<td>10.02</td>
<td>12.78</td>
<td>0.71</td>
<td>0.49</td>
<td>0.61</td>
<td>12</td>
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<td>43359</td>
<td>11.13</td>
<td>15.16</td>
<td>0.70</td>
<td>0.33</td>
<td>0.65</td>
<td>18</td>
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<tr>
<td>43365</td>
<td>10.40</td>
<td>12.43</td>
<td>0.63</td>
<td>0.54</td>
<td>0.58</td>
<td>5</td>
</tr>
<tr>
<td>Average Aug 2015</td>
<td>10.43</td>
<td>13.06</td>
<td>0.68</td>
<td>0.49</td>
<td>0.62</td>
<td>12</td>
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<tr>
<td>43374</td>
<td>10.46</td>
<td>13.38</td>
<td>0.70</td>
<td>0.78</td>
<td>0.77</td>
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<tr>
<td>38647</td>
<td>10.34</td>
<td>12.91</td>
<td>0.70</td>
<td>0.75</td>
<td>0.75</td>
<td>-10</td>
</tr>
<tr>
<td>38723</td>
<td>8.52</td>
<td>10.43</td>
<td>0.74</td>
<td>0.73</td>
<td>0.76</td>
<td>-9</td>
</tr>
<tr>
<td>Average Oct 2015</td>
<td>9.77</td>
<td>12.24</td>
<td>0.71</td>
<td>0.75</td>
<td>0.76</td>
<td>-8</td>
</tr>
<tr>
<td>43141</td>
<td>6.86</td>
<td>11.39</td>
<td>0.79</td>
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<tr>
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<td>0.71</td>
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<td>0.74</td>
<td>0.83</td>
<td>0.80</td>
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</tr>
<tr>
<td>43115</td>
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<td>0.74</td>
<td>0.86</td>
<td>0.85</td>
<td>-5</td>
</tr>
<tr>
<td>38693</td>
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<td>0.61</td>
<td>0.88</td>
<td>0.86</td>
<td>-13</td>
</tr>
<tr>
<td>38785</td>
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<td>13.45</td>
<td>0.65</td>
<td>0.75</td>
<td>0.74</td>
<td>-15</td>
</tr>
<tr>
<td>43326</td>
<td>11.24</td>
<td>13.87</td>
<td>0.55</td>
<td>0.75</td>
<td>0.78</td>
<td>-16</td>
</tr>
<tr>
<td>Average Jan-Feb 2016</td>
<td>8.29</td>
<td>11.43</td>
<td>0.70</td>
<td>0.82</td>
<td>0.81</td>
<td>-7</td>
</tr>
</tbody>
</table>

Table 2 summarizes the results of the three drifts. The SLDMBs Numbers in the first column are arranged in order of their offshore release distance for each experiment (ranging from closest to shoreline to furthest from shoreline). Columns 2 through 5 of Table 2 present the results of the vector component analysis, and columns 6 and 7 are the results of the velocity analysis. When looking at the component analysis, all three experiments produced lower RMSE values for the $u$ component of velocity than the $v$ component. Additionally the $u$ component of velocity was significantly underestimated by the HF Radar in each deployment. Interestingly the October and January
deployments showed lower RMSE values for the $u$ component while having lower correlations (when compared the $v$ component). Conversely, the RMSE values for the $v$ component of velocity were higher during these two drifts, while the correlations were stronger. Larger RMSE values (10 – 15 m/s) are expected for the summer experiments due to the limitations of CODAR SeaSonde current mapping (Liu et al., 2010). The smaller RMSE values (7 – 14 cm/s) obtained in the fall and winter experiments are slightly larger than the RMSE values between the CODAR radial currents and the moored ADCP velocity data (Liu et al., 2010, 2012, 2014a).

The vector analysis shows complex correlations consistent with the vector component analysis. The highest complex correlations were observed in the January experiment and the lowest were in the August experiment. Additionally, the HF Radar velocities were generally counter-clockwise from the drifter velocities in August, while they were generally clockwise in the other two experiments. The January experiment provided the best results for cross-shelf comparison. Although the drifters did not maintain their relative distance from shore throughout the experiment, the drifters released closer to shore had higher complex correlations and lower complex phase angles. The drifters released further offshore (near the western edge of the CODAR footprint) had lower correlations and larger, more clockwise, phase angles.

3.5 Discussion

The experiment is designed to evaluate the spatial coverage, temporal coverage and accuracy of HF Radar surface currents for SAR planning application. A perfect SAR surface current observation tool would provide continuous coverage over an area
where maritime distress incidents occur. From this stand point, there are obvious shortcomings of using CODAR HF Radar data for SAR planning. First, the last three years of SAR data spatially represented in Figure 3.6 shows a clear concentration of SAR cases near the coast with decreasing density as the distance from shore increases. Due to the geometry of the CODAR HF Radar array and frequency of operation, radial velocities from adjacent radars cannot be combined at small angles without imposing large errors, due to the geometric criterion of calculating velocities. Where higher frequency WERA Radars (12.7 MHz) that are located closer together can observe near shore currents, only two such radars (shown in Figure 1.2) are in operation on the WFS, and are therefore not included in this study. Second, the idealized nominal range of the 5 MHz SeaSonde CODAR radar is approximately 200 km, however the last three years of data show that coverage declines significantly at 150 km. While SAR cases further than 150 km from shore are less likely, there were SAR cases reported seaward of HF radar range. Finally, the limited array on the WFS (three radars: Redington Shores, Venice and Naples) only provides minimal coverage in regards to SAR occurrences. Popular recreational boating area where high volumes of SAR cases transpire (along Florida’s “Nature Coast” north of Redington Shores, and boating routes to the Florida Keys south of Naples) are not included in the HF Radar footprint. With only 7.6% of SAR cases corresponding with areas where HF Radar derived surface currents are observed, the spatial coverage is inadequate for the vast majority of the WFS.

In regards to the temporal coverage, the data did show a correlation between the time of day when boaters report distress, and the highest number of radar velocities.
This is useful for SAR cases that have short search durations, however, due to ionospheric effects, radar coverage significantly declines between the hours of 23:00 and 11:00 UTC. This would be problematic if a search effort extended into these hours of the day. On longer time scales, the data showed a weak anti-correlation. SAR cases peaked in summer months, while HF data peaked in the spring and late fall, with the lowest averages of velocity observations in the summer months. One anomaly was a lightning strike in the summer of 2015 that caused the complete failure of one of the three antennas, however a similar observation was made by Liu et al. (2010) where relatively low numbers of radial velocities were recorded in summer months corresponding with lower wind speeds, ADCP current speeds, significant wave height and wave energy. The anti-correlation of temporal HF Radar coverage and SAR cases would make HF Radar surface currents a less than ideal tool for SAR planners in summer months than other times of year when coverage is more robust.

The OI technique used for this study proved to be useful for filling the gaps of HF Radar data for drifter velocity comparison, however, due to the short duration of the experiments (~approximately 30 days) and the limitations imposed by the assumptions (homogeneous and isotropic), correlation scales were not calculated based on spatially averaged correlation coefficients of surface currents (e.g. Kim et al. 2007). Instead a Gaussian correlation function is used with an a priori correlation scale of 0.3 degrees for both the x and y Cartesian coordinates. It is recommended that future studies explore a more robust OI method that accounts for spatial and directional differences in correlation scales within the WFS HF Radar footprint. While the correlations scale of 0.3 degrees (for both coordinates) was chosen to maximize interpolation beyond the HF
Radar footprint, it’s possible that this technique may have resulted in over smoothing of the data.

Additionally, the magnitude of the absolute values of the averaged $u$ component of the HF Radar velocities were significantly lower than the observed drifter velocities. This result is consistent with a previous study comparing radial velocities to ADCPs on the WFS. Liu et al (2014a) compared tidal ellipses of major tidal constituents derived from ADCP and CODAR. The CODAR ellipses were smaller as the result of differences in observation methods between the two systems. Hourly CODAR radial velocities are calculated by averaging the cross-spectral data over a 4 hour sliding window, resulting in a reduction of amplitude, thus reducing its ability to resolve the relatively high frequencies of the tidal constituents.

Another useful analysis of this data would be to examine the skill of the HF Radar at various points throughout the footprint of coverage. While this study provides a limited sample size, all of the drifters in the January 2016 experiment drifted within the coverage footprint for the duration of their drift. Therefore, some observations regarding the January experiment can be explored. First, the two drifters deployed closest to the shore (#43141 at 10 km and #43401 at 30 km) maintained their relative distance from shore throughout the 30 day period. The average $u$ component ($v$ component) RMSE values for these drifters were 6.79 (11.43) cm/s, and the correlation coefficients were 0.79 (0.84). When comparing the velocities, the average complex correlation was 0.835 and the average complex phase angle was 1.5 (counter-clockwise). Contrastingly, the two drifters deployed furthest offshore (#38785 at 100 km and #43326 at 120 km) averaged $u$ ($v$) RMSE values of 9.93 (13.66) with correlation coefficients of 0.60 (0.75),
and average complex correlation was 0.76 with a complex phase angle of -15.5 (clockwise). While the relative distance from shore varied more with the two offshore drifters, they did drift within the offshore extent of the CODAR footprint. The results from this small sample size are consistent with the horizontal variability of RMSE documented by Graber et al (1998). The larger error offshore is attributed to larger radar cell area, defined by the azimuth angle from the radar and the increment. A further distance offshore would result in larger distances between radar beams and create less spatial resolution. Radial velocities averaged over this larger area results in errors when compared to the smaller radial cells closer to the radar.

Overall, when HF Radar coverage coincides with the drifters (temporally and spatially) the results indicate strong positive correlations with speed mismatches on the order of 10 cm/s (or 10 km/day). The speed mismatch is largely due to spatial and temporal averaging; spatial due to averaging over radial bins and temporal due to averaging over 4 hour sliding window. The speed mismatches are acceptable for SAR application considering the fact that the correlations are high. Thus given more radar coverage the CODAR HF Radar would be a more useful SAR tool.

3.6 Chapter Summary

This chapter presents data from CODAR HF Radar derived velocities quality controlled for near real time usage from CORDC and compares it to SAR case history data and drifter velocities from three deployments on the WFS. The viability of HF Radar velocities for SAR application is tested by evaluating spatial coverage, temporal coverage, and accuracy. The spatial coverage was limited when compared to SAR
data over the last three years. The peaks in temporal coverage did not correlate with peak times of SAR case occurrences when comparing the power spectra. However, over diurnal periods HF Radar velocities increased during the same time period SAR cases were reported. In an effort to increase HF Radar coverage for drifter comparison, an objective analysis mapping technique was applied. HF Radar velocities (components and vector) were compared to drifter velocities with RMSE values, correlation coefficients, complex correlation coefficients and complex phase angles. RMSE values decreased and correlation coefficients increased from the lower energy summer months to the higher energy winter months. Additionally the complex correlation coefficients increased in the winter months, and a decreased with as distance from shore increased. Also, in the January experiment, the complex phase angles increased, becoming more clockwise, as distance from shore increased.
CHAPTER 4:  
MODEL COMPARISON

4.1 Abstract

This chapter expands on the general concept of examining the utility of surface current tools available for SAR operations on the WFS. Whereas the previous chapter focused on HF Radar surface current observations, this chapter explores OCMs and assigns a relative skill based on a normalized Lagrangian separation calculation. Hindcasts of OCMs are compared to observations from the three drifter experiments in August 2015, October 2015 and December 2016. Drift trajectories of simulated particles are compared to observed drifts and a skill score is derived. Four types of OCMs are used for comparison: a global model with coarse (~8 km) spatial resolution and no tidal forcing (Global HYCOM), a regional model with higher (~4 km) spatial resolution and inclusive of tides (GOM HYCOM), a coastal ocean model with spatial resolution increasing toward the coast to as fine as 150 m in the estuaries by using an unstructured grid and also inclusive of tides (WFCOM), and a model based purely on observations (CODAR HF Radar). The results are discussed as they relate to impacts from local (wind) and remote (deep) forcing on the shelf. Also, skill scores are compared based on region (inner shelf, outer shelf, northern WFS in vicinity of De Soto Canyon, and southern WFS off the coast of Florida). The WFCOM had better skill on the inner shelf, when excluding the De Soto Canyon region. The GOM HYCOM
performed better on the outer shelf and the HF Radar performed best, with the caveats (as in Chapter 3) being that the HF Radar data with limited coverage was not available for all three experiments.

4.2 Models

The OCMs for this experiment were chosen to closely match the models used by USCG SAR planners identified in Chapter 2.1.2, with two exceptions. First, the USCG preferred OCM for the WFS is a blended model that combines Global HYCOM (NCEP) with ADCIRC. Since the Global HYCOM does not include tides, the ADCIRC (strictly tidal currents) is combined with the Global HYCOM and made available to SAROPS users through the USCG EDS. When a SAROPS user requests the blended product, a local computation is done on the EDS to reproduce the real time tidal currents, and is stored on the server for 30 days (Allen, 2015). Due to lack of access to this historical blended model, this model was not included. Instead a regional GOM HYCOM model was chosen as a suitable substitute as it includes tidal information.

The second exception is the exclusion of the Northwest Atlantic (NCSU) OCM from this experiment. An attempt to obtain data for the timeframes of this experiment revealed large gaps in data. Since the model started running on the East Coast domain in 2013, the “uptime” has been approximately 78% (personal communication with Dr. Zambon, 03 June 2016). Since the coupled model relies on other models for initial and boundary forcing conditions, when data is not received from outside entities, the model will not run. Additionally in the fall of 2015 a long term outage was recorded due to a drive failure at NCSU (personal communication with Dr. Zambon, 03 June 2016).
Therefore this study will compare skill scores from the Global HYCOM, GOM HYCOM, and the HF Radar (CODAR). Additionally a model not presently in use by USCG SAR planners, WFCOM, is added for comparison.

4.2.1 Global HYCOM

A description of Global HYCOM is provided by Chassignet et al. (2007). The model is a 1/12° eddy resolving, real-time global product. The hybrid nature of the model allows it to transition from isopycnal based vertical layers in the open ocean to \( \sigma \) layers (based on bathymetry) in the coastal regions and pressure-level coordinates in unstratified seas. The ability to optimally adjust vertical coordinate spacing allows for more sophisticated simulations of vertical mixing processes. Additionally, the system employs multi-variate data assimilation from a variety of in-situ data sources (wind, radiation and precipitation). While Global HYCOM is a practical tool for ocean basins, its 1/12° horizontal resolution and 15 \( \sigma \)-level vertical resolution on shelves only marginally resolves the coastal ocean (Chassignet et al., 2007). This is why Global HYCOM is used to provide boundary conditions for regional and coastal models (e.g., Barth et al., 2008; Zheng and Weisberg, 2012).

4.2.2 GOM HYCOM

One such model that is nested within the Global HYCOM is the GOM HYCOM. This is a regional HYCOM-HYCOM nested product with a 1/25° horizontal resolution and 40 coordinate surfaces in the vertical. Like the Global HYCOM, it allows for a dynamical transition from isopycnal vertical coordinate system in the deep stratified ocean to the bathymetry based \( \sigma \)-level system in the shallower coastal regions. Data is assimilated from satellite and in-situ sea surface temperature (SST), XBT and ARGO.
profiles, and moored buoys using the Navy Coupled Ocean Data Assimilation (NCODA) system. It uses atmospheric forcing from the Navy Operational Global Atmospheric Prediction System (NOGAPS). Additionally the model includes tidal forcing. Both the Global and the GOM HYCOMs were used in an ensemble trajectory simulation system in response to the Deepwater Horizon oil spill (Liu et al., 2011b,c).

4.2.3 WFCOM

The WFCOM model is described in Chapter 2.3. It consists of FVCOM nested in HYCOM over the coastal ocean region of the northeastern Gulf of Mexico. Unlike the previous models mentioned, the WFCOM has an unstructured grid allowing for spatial resolution comparable to the HYCOMs near the open boundary and downscaling to much higher spatial resolutions over the inner shelf and into the estuaries (Zheng and Weisberg, 2012). Improvements were made to the original WFCOM in 2012 such that it presently extends westward past the Mississippi River Delta (to include actual river inflows, versus climatology), nests into the GOM HYCOM (versus the Global HYCOM previously), and includes 31 $\sigma$ layers in the vertical (e.g., Weisberg et al., 2014 b, 2016a,b,c). This present version of WFCOM is used herein.

4.2.4 HF Radar (CODAR)

The final comparison is made with CODAR HF Radar observations. A velocity field was created over the area of interest using the OI method described in Chapter 3. Large temporal gaps in HF Radar observations prevented drifter comparisons for August 2015 and October 2015 drifter experiments, so only the January 2016 data is included. The data is hourly, including an area from 25.5°N – 28.0°N and 84.5°W - 82.0°W at an approximate resolution of 6 km. It should be noted that the hourly data
observations are the result of 4-hour running means observations per radial bin. The velocity fields are sub-sampled at 3-hourly time frames for model simulation.

4.3 Experiment Design

This experiment is designed to answer the second research question:

- Do any non-USCG EDS surface current products perform better than the models already in use, and if so, should they be added to EDS?
  - What are the impacts of local vs deep forcing to the models?
  - Do the models have different performance levels on inner and outer shelf? If so, should additional guidance be provided to SAR Planners?

To answer this research question simulated particle drifts using each of the models are compared to observed drifts from the three SLDMB deployments. Since the three deployments displayed seasonally variable flow fields encompassing both inner and outer regions of the WFS, a normalized Lagrangian separation skill score is used for comparison. This skill score technique is described in Liu and Weisberg (2011) and summarized here.

A simulated trajectory model is initiated for each SLDMB at the location of the observed drifter at 0000Z for each day of drift. A simulation time of 3 days is chosen realistically match the duration of long term SAR case in this region. It should be noted that local SAR Mission Coordinators use a variety of factors to determine search durations including estimated survivability times calculated using variables such as water temperatures, clothing, sea conditions and physical characteristics of the subject
(USCG, 2013). Warmer waters of the GOM often result in longer estimated survivability times and therefore longer search durations when compared to other US Coastal regions. This is why a 3 day drift duration was chosen for the GOM, but shorter durations may be more appropriate for other areas.

The surface velocity field for each model are interpolated (or sub-sampled) into 3-hourly time series. The velocity fields are used to simulate particle tracking for the three day period using a method similar to other Lagrangian-tracking methods (e.g. Edwards et al., 2006) using a fourth order Runge-Kutta scheme. The same trajectory model was used in the rapid response to the Deepwater Horizon oil spill incident (e.g., Liu et al., 2011b,c). The simulated particles are initiated at the location of the drifter each day at 0000 UTC.

At the conclusion of day of simulated drift the separation distance, $d$, between the simulated trajectory and the observed drifter is recorded. Previous evaluations of model skills (e.g. Bernstein, 2009) use $d$ as a measure of performance (lower $d$ would indicate better skill), however Liu and Weisberg (2011) showed how looking at $d$ alone can be misleading when comparing the relatively fast currents speeds of the Loop Current to the slower moving waters over the shelf region. Therefore they proposed normalizing the separation distance by the length of the observed trajectory. Figure 4.1 illustrates how the skill score index, $c$, is derived.

The skill score index is:

$$c = \frac{\sum_{i=1}^{N} d_i}{\sum_{i=1}^{N} l_{oi}}$$  (4.1)

Where $N$ is the total number of time steps, $d_i$ is the distance between the modeled and observed positions at each time step, and $l_{oi}$ is the length of observed trajectory.
between over the time interval. The skill score, $s$, of the model is determined by the skill score index by the following relation:

$$s = \begin{cases} 
1 - \frac{c}{n}, & (c \leq n) \\
0, & (c > n)
\end{cases}$$

(4.2)

Where $n$, is a tolerance threshold. The tolerance threshold is chosen by the researcher, and is implemented in an effort to match previous skill numerical conventions, defining

![Diagram](image)

**Figure 4.1:** Illustration of skill score components. Trajectory A-B represents modeled Lagrangian trajectory and A-C observed drifter. The separation distance at each time step is $d_i$ and the modeled and observed drift lengths are $l_m$ and $l_o$ respectfully. A normalized separation, $c$, is defined by the average separation distances weighted by the lengths of the observed drift distance per time step (Adapted from Liu and Weisberg, 2011)
skill on a scale from 0 to 1. The choice of \( n = 1 \) would mean that any modeled trajectory having a cumulative separation distance larger than the cumulative distance of the observed drifter would result in a skill of 0. Following the procedures in Liu and Weisberg (2011) and Liu et al. (2014b), a tolerance threshold of 1 was chosen, reducing (4.2) to:

\[
s = \begin{cases} 
1 - c, & (c \leq 1) \\
0, & (c > 1)
\end{cases}
\]  

(4.3)

Figure 4.2 shows an example of the plotted skills scores with observed and modeled trajectories for SLDMB # 43374 comparing the Global HYCOM to the GOM.

**Figure 4.2**: Example of after 3-day simulated drift, \( S_3 \). Observed trajectory of SLDMB # 43374 (red) is compared to 3 day modeled trajectories (white) of Global HYCOM (a) and GOM HYCOM (b). White markers on simulated trajectories indicate days intervals. Skill score (colored circles) are depicted on top of the drifter trajectory at 0000 UTC for each day of drift. Colors indicate level of skill compared to model during the next three days of drift; skill score levels are defined by color bar ranging from 0 -1.
HYCOM. The modeled 3-day drifts (white) deviate from the observed drifter (red) and cumulative daily (white markers) separation distances are used to calculate the skill score. The skill score is plotted in the corresponding latitude and longitude of the simulation start time. In panel (a) of Figure 4.2, the second through fourth days (counting from the release position off the mouth of Tampa Bay) recorded a skill of zero. With the white simulated trajectories depicted one can visually detect that the separation distance from the observed drifter is larger than drifter trajectory over the three days. Therefore the skill index (Equation 4.1) is greater than 1, resulting in a skill score of 0. As expected, the skill scores of the GOM HYCOM are better in the inner shelf region than the lower resolution Global HYCOM model and both models displayed comparable skill on the outer shelf.

This study evaluates the skills scores for each day of drift for each drifter during the three drift experiments (summer, fall, winter). The results are analyzed based on location, water depth, dominate forcing features, and deviations from expected results. Finally, conclusions are drawn regarding overall model performance and recommendations for SAR application are made.

4.4 Results

For clarity, the results of the skill score calculations are plotted without the modeled and observed trajectories. Only the color-coded skill scores are represented. Figure 4.3 displays the results of the August 2015 experiment. In this experiment four drifters successfully recorded data along a transect 27.5° N across the WFS extending to 100 km offshore. The two drifters deployed inside of the 40 m isobath (isobaths not
pictured) drifted inshore and to the north, while the two deployed seaward of the 40 m isobath drifted offshore and to the south. For the Global HYCOM case, the average separation distance at the end of each 3-day simulation was 29 km and the mean skill score was 0.30. The GOM HYCOM and WFCOM had lower separation distances, 21 km and 19 km respectively, and better skill scores, 0.51 and 0.52 respectively. All models displayed very poor skill in the area centered on 27.3° N 83.5° W. This can be attributed to the “stagnant water effect” in which cumulative distance of the observed trajectory is small creating a small denominator (Equation 4.1) resulting in a large skill score index. To account for stagnant water case a correction was made in which the minimum possible 3-day observed trajectory 10 km for calculation purposes. Even with the correction, the cumulative separation distance of the models was larger than 10 km in this area resulting in a skill of zero. In the WFCOM case, SLDMB # 43365 drifted beyond the western extent of the model domain, and therefore no skill is calculated.

Figure 4.3: Results of August 2015 drifter skill scores. (a) Global HYCOM, (b) GOM HYCOM, (c) WFCOM skill scores, $S_2$, for period from August 15th to September 6th, 2015. Skill ranges from 0 (no skill) to 1 (perfect skill).
The results of the October 2015 experiment are in Figure 4.4. Of the 10 drifters deployed, only five successfully recorded data for more than three days. Of the three models, the GOM HYCOM performed the best with a mean skill score of 0.56. The WFCOM had a mean skill score of 0.50 and the Global HYCOM was 0.44. What’s interesting about this experiment is the disparity of skills within a model on different regions of the WFS. While all models initially performed poorly (near the release point off the mouth of Tampa Bay), the WFCOM had substantially better skill scores as the...
drifters moved to the northwest before reaching the Desoto Canyon. In the Desoto Canyon region the WFCOM skill diminished while the two HYCOM models recorded better skill scores.

For the third experiment, eight drifters recorded data for approximately 30 days beginning January 12th, 2016. The results of the skill are depicted in Figure 4.5. The OI CODAR HF Radar model was included for this comparison. HF Radar data was too

Figure 4.5: Results of January 2016 drifter skill scores. (a) Global HYCOM, (b) GOM HYCOM, (c) CODAR HF Radar, (d) WFCOM skill scores, S3, for period from January 12th to February 14th, 2015. Skill ranges from 0 (no skill) to 1 (perfect skill).
sparse for inclusion in the previous experiments. The HF Radar model observed a mean skill score of 0.64, which is the highest out of all three experiments. Both HYCOM models displayed similar skill (~0.45), however there is a clear geographic separation of where high skill scores were observed. The Global HYCOM performed better offshore seaward of the 40 m isobath (not depicted) while the GOM HYCOM performed better shoreward of the 40 m isobath. The WFCOM had an overall mean skill score of 0.55, however there is a clear temporal outlier in the data. On the 15th day of drift (January 28th, 2016) the average skill for WFCOM dropped to 0.1. These temporal and spatial differences in skill will be explored in the discussion section of this Chapter.

Table 3 shows the skill scores of all three experiments individually and an overall skill for each model. Furthermore, the inner shelf and mid-outer shelf skill scores are included for comparison. The definition of inner shelf is adapted from Li and Weisberg (1999) where an analysis of the force balances, to determine where the Ekman surface and bottom layers interact, suggest that the inner shelf is defined by the 50 m isobath off of Sarasota, FL. This 50 m isobath demarcation is extended throughout the WFS and average value of skills was recorded shoreward of the line. The mid and outer shelf is defined by the area seaward of the inner shelf. Of the three models, WFCOM

Table 3: Summary of Skill Score Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Global HYCOM</th>
<th>GOM HYCOM</th>
<th>WFCOM</th>
<th>HF Radar CODAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2015</td>
<td>0.30</td>
<td>0.51</td>
<td>0.52</td>
<td>N/A</td>
</tr>
<tr>
<td>October 2015</td>
<td>0.44</td>
<td>0.56</td>
<td>0.50</td>
<td>N/A</td>
</tr>
<tr>
<td>January 2016</td>
<td>0.44</td>
<td>0.45</td>
<td>0.55</td>
<td>0.64</td>
</tr>
<tr>
<td>Inner Shelf</td>
<td>0.37</td>
<td>0.45</td>
<td>0.56</td>
<td>0.67</td>
</tr>
<tr>
<td>Mid - Outer Shelf</td>
<td>0.49</td>
<td>0.52</td>
<td>0.44</td>
<td>0.56</td>
</tr>
<tr>
<td>Overall</td>
<td>0.41</td>
<td>0.50</td>
<td>0.53</td>
<td>0.64</td>
</tr>
</tbody>
</table>
recorded the highest skill score (0.56) on the inner shelf, and GOM HYCOM recorded the highest skill (0.52) on the mid and outer shelf. When the HF Radar model is included, it recorded the highest score on the inner shelf (0.67) and the mid-outer shelf (0.56). However, due to the spatial limitations of the observation system, limited offshore HF Radar skill scores were available for comparison.

**Table 4:** Summary of Skill Scores and Separation Distances on in Sector AOR

<table>
<thead>
<tr>
<th>Model</th>
<th>Inner Shelf $s_3$</th>
<th>Inner Shelf $d_3$ (km)</th>
<th>Outer Shelf $s_3$</th>
<th>Outer Shelf $d_3$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global HYCOM</td>
<td>0.35</td>
<td>29</td>
<td>0.46</td>
<td>27</td>
</tr>
<tr>
<td>GOM HYCOM</td>
<td>0.51</td>
<td>20</td>
<td>0.40</td>
<td>31</td>
</tr>
<tr>
<td>WFCOM</td>
<td>0.58</td>
<td>17</td>
<td>0.44</td>
<td>27</td>
</tr>
<tr>
<td>HF Radar</td>
<td>0.67</td>
<td>13</td>
<td>0.64</td>
<td>17</td>
</tr>
</tbody>
</table>

Furthermore, this study sought out to evaluate the skills of models for SAR application because a large number of SAR cases occur within the AOR of the USCG Sector St. Petersburg (depicted in Figure 1.1). Table 4 shows the results of the skill scores while the drifters were within the boundaries of Sector St. Petersburg’s AOR. To clarify the results for comparison, the separation distance after three days of drift, $d_3$, is added. On the inner shelf region the Global HYCOM had the lowest $s_3$ and the highest $d_3$. Out of the three OCMs the WFCOM had the highest $s_3$ and lowest $d_3$ on the inner shelf. On the outer shelf all three OCMs had comparable skill and separation distances. The HF Radar had the best performance, and $d_3$ values less than half of Global HYCOM. The inclusion of the $d_3$ in Table 4 provides context to the skill scores. The visual detection range of a search object could range from 0.18 km (for a person in the water) to 74 km (for a large commercial vessel), however the most common search
object in this area is a 20 ft recreational vessel (detection of ~10 km) (USCG, 2013). With the Global HYCOM inner shelf $d_3$ value of 30 km almost three times that of the detection range of the most common search object, it is evident that the Global HYCOM would not be a choice of EDS. While it is difficult to estimate the increase in efficiency that would result from selecting one model over another, it is reasonable to assume that search efficiency would increase by using a model with a higher skill score.

4.5 Discussion

From a SAR planner perspective, the ideal result of this study would be a clear description of which model performs better for each region, while identifying any seasonal exceptions, and providing clear guidance on which model to use where and when. Unfortunately the results require a more complicated analysis. The overall result of the skill score comparison was not surprising. The model that was based solely on observations, the CODAR HF Radar, performed the best; however the availability of the observations was limited spatially and temporally. Also, the Global HYCOM recorded the lowest skill. This model also had lowest resolution, 1/12º, and only had model outputs every 24 hours. Therefore, the model had to be interpolated into 3-hourly time steps to run the simulations. The GOM HYCOM data was available hourly and had a smaller resolution, 1/25º. Since both models (HYCOM and GOM HYCOM) have a similar hybrid vertical coordinate scheme, and use the same data assimilation system, NCODA, they produced similar skill, with GOM HYOM performing better in the inner shelf regions. When examining the skill scores for each drifter deployment experiment it is useful to look at the potential deep forcing effects on the
Figure 4.6: (Top) Weekly snapshots of Loop Current (LC) during duration of August 2015 drift experiment from GOM HYCOM archive. (Middle) Daily wind data from Weather Underground historical metrological data recorded at Sarasota, FL station KRSQ. First panel is wind speeds and second panel is wind direction. (Bottom) GOM mean SST for the month of August 2015 from GOM HYCOM archived data. Data is from satellite and in situ (XBTs, ARGO floats and moored buoys).
shelf as well as the local forcing. Using snapshots of the GOM HYCOM throughout the experiment (retrieved from http://www7320.nrlssc.navy.mil/hycomGOM/glfmex.html) the LC is observed in the far north of the GOM. Weekly snapshots of the LC are in Figure 4.6. The LC sheds an eddy in the northern portion of the Gulf during the middle of August and re-joins the LC during the first week of September. The impact of the LC, or one of its eddies, on the WFS has been previously observed by Hamilton and Lee (2005) where an eddy can be trapped by the topography of the De Soto Canyon and make contact with the shelf slope. The anti-cyclonic rotation of the eddy interacting with the relatively shallow isobaths results in an eastward surface flow that moves water from the Mississippi onto the WFS. It also promotes upwelling on the shelf break. The sea surface temperature average from the month of August is shown in Figure 4.6. It shows an area of relatively cold water (1 – 2°C cooler than surrounding surface water) extending from the northern portion of the canyon along the 60 m isobath down to 26ºN with warmer water to the east. Figure 4.6 also shows local wind forcing (as recorded by Weather Underground https://www.wunderground.com/history/airport/KSRQ/) from the Sarasota Airport. The wind data shows low magnitude winds shifting from the WSW to ESE through the duration of the observed drifts. Figure 4.7 displays a progressive vector diagram of wind vectors recorded from

Figure 4.7: Progressive vector diagram of wind recorded at moored buoy, C12, at 50 m isobath on WFS. Timeframe is from August 4th through September 9th, 2015.
moored buoy C12 (location depicted in Figure 1.2). Under the assumption that the inner shelf is mostly driven by local forcing, a net drift to the north would be expected, and in fact this was observed by the two drifters closer to shore. The two drifters closer to shore observed a trajectory similar to that of the progressive vector diagram of the observed wind. The two drifters further offshore, however, observed a net drift to the south, inconsistent with local forcing. The resulting conclusion would be that the offshore drifters were influenced by deep forcing effects caused by the LC (and the LC eddy) interacting with the shelf slope.

Figure 4.8 is the average sea surface salinity for August 2015 modeled by GOM HYCOM. Recovered from model archive http://www7320.nrlssc.navy.mil/hycomGOMmean/glfmex.html

Figure 4.8: Average sea surface salinity for August 2015 modeled by GOM HYCOM. Recovered from model archive http://www7320.nrlssc.navy.mil/hycomGOMmean/glfmex.html

Figure 4.8 is the average sea surface salinity for the month of August 2015. The figure illustrates how fresh water from the Mississippi is transported onto the WFS as a result of the LC. Interestingly, a tongue of higher salinity water remains present along the inner shelf, while the fresher water from the Mississippi delta moves south onto the outer shelf. Additionally there are large fresh water inputs from the Florida Rivers (along
Florida coast between 28 ° N and 30 ° N) on the east side of the salinity tongue. This created opposing baroclinic pressure gradient forces in the surface layer on the east and west portions of the study area. This is consistent with the observations and stresses the importance of the model’s ability to address both deep and local forcing.

During the August experiment, the Global HYCOM recorded the lowest skill of 0.30. As previously stated, this result is expected due to the model design focusing on deep water application. The WFCOM had the highest skill (0.52) on the inner shelf region. WFCOM is designed to downscale deep forcing effects across the continental shelf and the higher resolution accounts for local forcing better than the Global HYCOM. The average of the GOM HYCOM on the inner shelf (0.51) was similar to the WFCOM (0.52), however visual inspection of the shows the GOM HYCOM was mixed with high and low skills, while WFCOM was more consistent. Similar skill scores for GOM HYCOM and WFCOM were also recorded near the western boundary of the WFCOM model domain. The offshore boundary of the WFCOM is forced by the GOM HYCOM with a one-way nesting scheme; therefore it is possible for errors in the GOM HYCOM to propagate into the WFS domain. It should be noted that all models recorded low, or zero, skill in the stagnant water case. This can be attributed to the limitation of the calculation, dividing by a small observed trajectory, and therefore inhibits the ability of this skill score to compare models during period of slow drift.

The October 2015 experiment was conducted under very different forcing conditions. The LC was positioned further to the western portion of the GOM and the winds were predominately out of the east (offshore directed) for the duration of the period. By the end of October, the LC shed an eddy, south of Louisiana and weaker
warm core and cold core eddies began to form in the De Soto Canyon toward the end of October into the beginning of November. The LC eddy rejoined the LC by the middle of November. Figure 4.9 shows weekly snapshots of the LC and wind data recorded from the Sarasota, FL airport. With no LC interaction with the shelf, the primary forcing for all of the drifters was by local winds for the first part of the experiment. When the drifters entered into the De Soto Canyon area in the beginning of November, eddies were interacting with the shelf.

When examining Figure 4.4 the first notable observation is that all three models recorded poor skill during the first days of drift. Wind data from moored buoy at 50 m isobath, C12, shows a very abrupt shift in winds between 0600 and 1600 UTC on October 15th, 2015. The winds shifted from due north, 000ºT, to east-north-east, 075ºT, and doubled in magnitude. The wind continued to veer to due east over the next day and remained constant (with higher gusts) over next ten days. The surface currents in all three models lagged behind (example in Figure 4.2) the wind shift, while the drifters adjusted trajectories more rapidly. Under constant nearly offshore directed winds, the drifters tracked along isobath flow to the northwest until the wind shifted more to the south at the end of November, at which point the two drifters move closer to shore and slowed, while the other three continued northwest to De Soto Canyon.

During the period of the study from October 19th – 26th while the drifters were transiting to the northwest, primarily under local forcing, the WFCOM displayed the best skill scores. However, once the drifters reached the De Soto Canyon area, the WFCOM skill dropped, and the GOM HYCOM skill recorded the best skill. Again, it is expected that the GOM HYCOM would perform better than the Global HYCOM, but the difference
between the GOM HYCOM and WFCOM requires further analysis. By defining the De Soto Canyon region of the WFS as all continental shelf area west of 86°W, the skill scores for this experiment are compared for this region only. WFCOM skill was lowest, 0.41, Global HYCOM was 0.48 and GOM was highest, 0.57. The result is surprising.

**Figure 4.9:** (Top) Weekly snapshots of Loop Current (LC) during duration of October 2015 drift experiment from GOM HYCOM archive. (Bottom) Daily wind data from Weather Underground historical metrological data recorded at Sarasota, FL station KRSQ. First panel is wind speeds and second panel is wind direction.
because WFCOM is forced at its open boundary by the GOM HYCOM and is designed to appropriately downscale deep ocean processes onto the shelf. If errors were induced by the GOM HYCOM at the nested boundary of the WFCOM, lower skill would be expected to be observed in both models in this region. The higher skill in the GOM HYCOM however, suggests that source of error is within the WFCOM model itself. This could be due the fact that the shelf is narrower and isobaths are tightly grouped allowing deep forcing, from eddies, to significantly impact the shelf. Previous studies (Zheng and Weisberg, 2012; Weisberg et al., 2014abc) have evaluated WFCOM with ADCP moorings on the western continental shelf of the GOM, however, similar studies have not been conducted in the De Soto Canyon region. Further study is recommended in this area.

The final experiment was conducted in January 2016. During the winter months, climatic wind data suggests that winds tend to be alongshore in an upwelling favoring environment (Weisberg et al., 1996). This was observed during the drift experiment. Again, looking at meteorological data from the Sarasota Airport, between January 12th and February 14th, 2016, six cold fronts passed through the study area causing high magnitude winds from northwest (alongshore). The periods in between the fronts saw lower magnitude winds from the south and higher surface pressure. The net trajectory observed with all drifters was southerly. Additionally the eastern edge of the LC is in contact with the WFS between at 26ºN during the beginning of the study timeframe, before shifting to the west at the end of January. Figure 4.10 shows weekly snapshots of the LC and meteorological data from the Sarasota Airport. Figure 4.11 is a snapshot of the WFCOM model with sea level and depth averaged velocity on January 14th,
Figure 4.10: (Top) WFCOM snapshot from January 12th, 2016 depicting LC impact on the shelf break area of WFS. Yellow and red colors represent higher sea surface, and vector arrows are depth-averaged velocities (lower resolution than actual WFCOM Model). (Bottom) WFCOM modeled near bottom currents and temperatures showing cross-isobath, toward coast, bottom flow associated with upwelling. Retrieved from http://ocgweb.marine.usf.edu/~zheng/research/WFCOM/index.html.

2016, the bottom panel of the figure is the bottom temperature and velocity. The Figure 4.11 shows how the LC is impacting the WFS at along the longitude line of 84ºW.
When this happens the higher seas surface on the outer shelf sets a pressure gradient directed to the east, and geostrophic flow in the interior is to the south. As a result of

Figure 4.11: (Top) WFCOM snapshot from January 12\textsuperscript{th}, 2016 depicting LC impact on the shelf break area of WFS. Yellow and red colors represent higher sea surface, and vector arrows are depth-averaged velocities (lower resolution than actual WFCOM Model). (Bottom) WFCOM modeled near bottom currents and temperatures showing cross-isobath, toward coast, bottom flow associated with upwelling. Retrieved from http://ocgweb.marine.usf.edu/~zheng/research/WFCOM/index.html.
the bottom Ekman layer diverting to the left (in the northern hemisphere) the bottom layer velocity is towards the coast, and cross-isobath flow is observed. The upwelling favoring winds combined with the impact of the LC a strong upwelling effect that is capable of supplying cold, nutrient rich water to the shelf. This process is described in numerous studies (e.g. Weisberg and He, 2003; Weisberg et al., 2005; Weisberg et al., 2014a,c; Weisberg et al., 2016).

In the January experiment the drifters further offshore behaved differently than the drifters closer to shore. The differences observed could be attributed to deep forcing caused by the LC impinging onto the shelf, the near shore drifter, however, were forced by local, or wind, forces. Li and Weisberg (1999b) described the WFS response to upwelling favorable wind forcing in both time dependent and quasi-steady states. When a wind force is applied in the alongshore (southeastward) direction, the wind accelerates the water in the alongshore direction (this takes place in the initial hours). After some time the bottom stress and alongshore pressure gradient build and the wind stress balances the bottom stress (after about a day). Over the course of days the Coriolis force, associated with the alongshore flow, acts in the across shelf direction resulting in a pressure gradient, due to the divergence caused by the coastal boundary. In the cross shelf direction, the pressure gradient force is balanced by the Coriolis force and both reach a maximum centered on the coastal jet. Li and Weisberg (1999b) modeled the coastal jet at the 30 m isobath off of Sarasota, FL. Over the inner shelf the primary momentum balance is between the cross shelf Coriolis force and the bottom stress, and the outer shelf balance is between the wind stress and Coriolis force (Ekman Balance). Furthermore Li and Weisberg (1999a) noted an offshore return flow
on the outer shelf due to the partial closer of their model on the southern end of the WFS by the Florida Keys. With a constant alongshore wind, after days of simulation, water piled up on the southern boundary, flowed offshore and became a counter-current flowing to the north on the outer shelf. Although constant upwelling winds were not observed during the January experiment, this phenomenon may have contributed to the discrepancy in trajectories between inner shelf drifters and outer shelf drifters.

When examining the skill of the models for the January drift, two results are clear. One, the CODAR HF Radar OI data-based trajectory model recorded the best skill, 0.64, and two, Global HYCOM recorded the worst, 0.44. As previously stated, this result is expected due to the HF Radar being based on observations, and the Global HYCOM’s poor resolution. On the 15th day of the drift (January 28th, 2016) the WFCOM skill dropped when the other models reported reasonable skill. Since both HYCOMs are forced with NOGAPS winds and WFCOM is forced with NCEP winds, it is suspected that an error in the wind forcing caused the low skill. Lack of sufficient wind data for assimilation into the NCEP wind model may have attributed to this error. This stresses the importance of sufficient observational systems for accurate modeling.

Additionally, low skills were observed in all models on the 18th day of the experiment. Closer examination of the data revealed that this was a stagnant water case. The winds in Figure 4.9 were light and variable throughout this three day period and the drifter velocities (reported in Chapter 3) were small. This is a limitation with the skill score tool; however it is not a significant issue for SAR application, if it is recognized. Stagnant water is ideal for SAR planning, as the search object would not travel far. Another similar result between the WFCOM and GOM HYCOM was the low
skill scores in the southwest quadrant of the study area. Due to the one-way nesting of the WFCOM in the GOM HYCOM, any errors near the boundary observed in the GOM HYCOM would also be expected in the WFCOM, therefore this result is expected as well.

4.6 Chapter Summary

This chapter presents the experiment design and results of the second research question. The models used in the experiment are explained and the method used to calculate skill is derived. A normalized Lagrangian separation skill score is applied based on three day drift simulations using each model. The separation distance is compared to the observed trajectory of the SLDMBs, and the skill score is calculated. The results are presented for each drift experiment. The discussion section presents local and deep forcing effects present during each experiment and discusses how well the models account for them.
CHAPTER 5:
DISCUSSION AND CONCLUSIONS

5.1 Statement of the Problem

The ultimate goal of this research is to provide amplifying guidance to SAR planners on the WFS. The WFS is unique in its physical make-up, in that it is a relatively wide shelf with dynamical differences in the inner, mid and outer shelf regions. The WFS is also an area where the USCG executes a large number of SAR cases. Averaging about 3 cases a day, in the coastal waters off of the west coast of Florida (excluding the Panhandle and the Florida Keys), this area is one of the highest SAR concentration areas in the country. Expanding the knowledge base regarding all of the available surface current products in this area is vital to continued USCG SAR operational success.

Currently the USCG uses a SAR planning software referred to as SAROPS. The SAROPS system allows the user to choose a surface current model from a list of available choices (available on the USCG EDS Server) at the beginning of every SAR case. The planner uses national SAR planning guidance when selecting the appropriate model, however, guidance is generalized and many SAR planners have limited knowledge fundamental physical oceanography principals. Additionally SAR Planners have the option to run a SAROPS simulated drift using HF Radar observations. Once a model (or HF Radar) is selected the SAROPS system executes a
Monte-Carlo simulation and the trajectories of thousands of simulated particles are presented in an ARC-GIS user interface for the SAR Planner to commence planning operations.

The appropriate choice of surface current forcing for the SAROPS program is critical. SAR cases are inherently very time sensitive evolutions where people’s lives are in danger. The selection of the wrong model could result in wasted time searching an inappropriate area. This study evaluates the models and HF Radar on the WFS for SAR application by answering the following research questions:

- Is HF Radar an effective surface current product for operational SAR case planning on the WFS?
  - What are the limitations of the HF Radar observations?
  - What are the special considerations for SAR Planners using HF Radar in a low energy environment?

- Do any non-USCG EDS surface current products perform better than the models already in use, and if so, should they be added to EDS?
  - What are the impacts of local vs deep forcing to the models?
  - Do the models have different performance levels on inner and outer shelf? If so, should additional guidance be provided to SAR Planners?

To develop a baseline of observations for comparison to the HF Radar and models, three sets of surface drifters, or SLDMBs, were deployed off of the mouth of Tampa Bay on a transect extending to 120 km offshore. The first set of drifters was deployed in the summer, August 2015, the second in the fall, October, 2015, and the third in the winter, January 2016. The transect was chosen in the center of USCG St
Petersburg AOR in the northern portion of the CODAR HF Radar array “footprint.” GPS positions were recorded from the drifters and velocities were derived. The velocities (and velocity components) of the drifters were compared to HF Radar observations, and the trajectories of the drifters were compared to simulated trajectories using four types of models. A statistical comparison of velocities (and velocity components) was made using HF Radar observations, and a normalized Lagrangian skill score is used to evaluate the relative skill of the models.

5.2 Review of Methods

5.2.1 HF Radar Velocity Comparison

The HF Radar raw data is recorded in polar coordinates centered on the HF antenna and velocities directed in the radial coordinate (toward or away from the antenna). Radial velocities from two or more antennas are needed to determine the total velocity. The HF Radar data obtained was spatially and temporally inconsistent with many outliers. The need to quality control the data and convert it to total velocities (in a gridded Cartesian coordinates) for SAR application excluded HF Radar raw data as a practical option for real-time application in SAR cases. Instead, quality controlled HF Radar from CORDC was chosen for this study. The longer range CODAR HF Radar data was chosen, vice WERA, because it includes a larger area of observation over the WFS. Currently only two WERA HF Radars in operation on the WFS and only provide minimal near-shore spatial coverage.

The near real-time quality controlled CODAR HF Radar data was still spatially inconsistent, and it immediately became clear that there were not enough observations
to make direct comparisons to drifter velocities. To address this issue an OI method was applied to expand the HF Radar observations to include areas where drifters were observed. Observed HF Radar velocities were interpolated to drifter positions at each hour throughout the drift for all drifters, and velocity components were compared using RMSE and correlations coefficients. Velocities were compared using a complex vector correlation and complex phase angle. The statistical comparison allowed the researcher to draw conclusions about the accuracy of the HF Radar data.

Additionally, the number of HF Radar velocities observed per hour was compared to the times SAR cases were reported over the past three years. A spatial analysis was done as well to compare locations of observed HF Radar velocities with historical SAR case data. With knowledge that HF Radar velocity observations are limited in a low energy environment and at certain times of the day due to ionospheric effects, the HF Radar derived velocities would not be useful to SAR Planner if they were not available at corresponding times when SAR cases occur, regardless of how accurate the observations were.

5.2.2 Model Skill Scores

Four models were evaluated against the observed trajectories of the surface drifters. The models included a 1/12º resolution Global model, Global HYCOM, a 1/25º regional model, GOM HYCOM, a coastal model with unstructured grid, WFCOM, and a model created with an OI of HF Radar observations. Three day simulations were conducted with each model commencing from the 00:00 UTC position of each day of drift, for each drifter. The separation distances between the observed trajectories and modeled trajectories were recorded at the end of each day of drift. The skill was
calculated using the cumulative separation distances normalized by the observed length of drift. A threshold of \( n = 1 \) was applied, meaning any drifter that had a separation distance larger than observed drift resulted in skill score of zero. Skills of each model were compared to one another based on season, region, and whether or not it was drifting over the inner shelf or mid-outer shelf. Finally a review of local (wind) or remote (deep) forcing was evaluated for each experiment to determine how well the models accounted for each.

5.3 Summary of Discussion and Results

In order for the HF Radar to be a useful tool for SAR application in must be both accurate and available. By being available, it is meant that the HF Radar must observe surface velocities in the areas where SAR cases occur, and at the times when SAR cases occur. The comparison of SAR case data and HF Radar surface currents on spatial and temporal time scales was not ideal. In spatial terms, the study found that only 7.6\% of SAR cases occur within an area where HF Radar surface currents were observed at least 50\% of the time. Additionally, on an annual cycle, SAR cases tended to peak in the summer month, while HF Radar observation were more widely available in the fall through spring. It should be noted, however, that SAR cases do still occur in the winter season. Summer SAR cases recorded at almost 120 cases per month, while the winter cases were at a rate of 60 cases per month, meaning HF Radar would be a useful tool SAR cases occurring during winter months. Additionally the results found on daily cycles, SAR case occurrence peaked between 1500 and 2300 UTC when average HF Radar returns are at their highest.
In regards to the accuracy of the HF Radar, the results showed results consistent with previous drifter studies, and RMSE results were only slightly higher than low-passed HF velocity comparisons to moored ADCPs in the same area. In general, the RMSE values were higher and correlations were lower in the summer experiment, and RMSE values were lower (with higher correlations) in the winter experiment. Also the results showed lower accuracy in the furthest offshore drifters, but sample size was too small to draw definitive conclusions.

The skill scores results for the models produced results consistent with expectations. Overall, the Global HYCOM recorded the lowest skill scores for all three experiments. The GOM HYCOM and WFCOM produced different results on the inner and mid-outer shelf regions. The WFCOM recorded better skill on the inner shelf, and the GOM HYCOM recorded better skill on the mid-outer shelf. Additionally the WFCOM performed well east of 86ºW, where the continental shelf is broad, and skill diminished to the west, in the De Soto Canyon region, where the shelf is much narrower. While the HF Radar was not available during the August and October experiment (August because of low returns, and October because drifters drifted out of the area) the HF Radar skill score for January was the best out of any of the models for all experiments.

5.4 Implications of this Study and Recommendations for Future Work

There are two main implications of this study: (1) the HF Radar could be a useful tool for SAR application if the radar infrastructure was expanded to include a larger coverage area, and (2) WFCOM would be useful addition to the USCG EDS for use on the inner shelf region of the WFS.
The HF Radar data was limited during the August and October, 2015, however when it was available in the January experiment, it provided accurate velocities and the highest skill scores. Coastal SAR cases occurring in the fall to spring would benefit from use of HF Radar during the SAR planning process. One major drawback of utilizing this tool for SAR application is that HF Radar derived surface velocity observations were only minimally spatially available in areas where SAR cases occur. This finding can be attributed to the fact that there are only three HF Radars are in operation on the west coast of Florida. Popular boating routes north and south of the current CODAR foot print (e.g. Fort Myers, FL to Key West and Clearwater, FL to Florida Middle Grounds) are well traveled in the winter months, and high concentrations of SAR cases are reported in these areas. Despite the fact that HF Radar was minimally available in the summer months, HF Radar could be a useful tool for SAR application in the other seasons if the antenna array was expanded to include a larger portion of the WFS.

Additionally, this study found that when a model is created using a basic OI method with an a priori correlation scale applied to the HF Radar data, it can outperform the other available models. Future work in developing a more sophisticated approach to interpolating HF Radar data would be useful. Using a uniform correlation scale in all directions and in all locations is not the best approach; however it did show the value in pursuing this line of research on the WFS.

Unfortunately, in its current state the HF Radar data would not be considered a likely first choice for a USCG Sector St Petersburg SAR planner. Even if a SAR case were to occur within the HF Radar range of observations, a SAR planner would be
hesitant to choose the EDS product if the case originated near boundary of HF Radar coverage (search object could drift into an area where no HF Radar currents are observed) or the SAR case occurred at a time when HF Radar data is sparse. Therefore the usefulness of HF Radar is questionable, however, the observations from HF Radar should be considered valuable and are currently underutilized for SAR operations. It is recommended that future work incorporate HF Radar velocities into OCMs through data assimilation on the WFS. The results from Chapter 4 regarding the relative skill scores suggest that this would worth perusing.

Finally, the skill score inside the 50 m isobath on the WFS was the highest for the WFCOM Model. If the De Soto Canyon region is excluded from the study the WFCOM model skill on the inner shelf increases to 0.59 (compared to GOM HYCOM skill of 0.51). This means the WFCOM could be a useful inner shelf SAR tool on the WFS east of 86°N. An analysis of SAR case locations shows that the density of SAR occurrences decrease as distance from the coast increases. A model that specifically performs well in this inner shelf region, where the majority of SAR cases occur, would be extremely useful to SAR planners. It should be noted that USCG also uses a blended model in this region that combines Global HYCOM with ADCIRC, referred to as Aggregated ADCIRC. The Aggregated ADCIRC model combines the mean flow of the Global HYCOM to the unstructured grid of the ADCIRC using a weighted average technique. In this study, the Global HYCOM consistently overestimated the current trajectories in shallower water resulting in low or zero skill scores. While a direct comparison was not made between WFCOM and the Aggregated ADCIRC model, it is hypothesized that the errors associated with the Global HYCOM over the inner shelf region would also
present in the Aggregated ADCIRC model. The WFCOM’s ability to appropriately downscale deep ocean processes across the shelf would likely produce better results. Further research is recommended in this area.

It is understood that perusing actions such as increasing the HF Radar array on the WFS, or including the WFCOM into the USCG EDS would require substantial investment. The decision on whether or not to make that investment would depend on the potential benefits. Adding HF Radars would increase the spatial coverage of the HF Radar velocities; however, it is likely that temporal gaps would continue to be an issue. The benefits of investing in the WFCOM however are clearer. This model had the best skill scores in the inner shelf region where the majority of SAR cases occur. Additionally, due to the high concentration of SAR cases near inlets and bays, a model capable of accurately resolving these areas would be useful. A comparative study of harmful algae bloom tracking methods (Weisberg et al., 2016b) demonstrated the WFCOM’s ability to successfully track drifters in and out of inlets and bays along the west coast of Florida. The WFCOM’s ability to model deep and local forcing, combined with improved resolution in high SAR case regions (inlets and bays) would likely justify its inclusion in the USCG EDS for SAROPS application.

The WFS is a region where the local economy depends on tourism and recreational boating. As a consequence, this area experiences over 1000 SAR cases a year, accounting for 5% of the total SAR cases in the country. Additionally the warm waters of the GOM often result longer survivability times for subjects, and longer, multi-day, searches. The high number of long duration searches would require a model that appropriately scales between deep and local forcing and performs well on the inner
shelf. If the WFCOM was adopted into the USCG EDS, it would be useful to add additional SAR guidance regarding which EDS product to choose when conducting operations in the inner shelf versus the outer shelf region.

Finally, it is recommended that the Coast Guard expands its training program to ensure SAR planners understand ocean forcing dynamics present in their AORs. The WFS, for example, has unique dynamical characteristics separating the inner and outer shelf that are not discussed in the USCG’s present SAR training process. This is partially due to the fact that SAR controllers receive standardized national training, and transfer duty stations often, meaning they operate in multiple areas throughout their career. The lack of ocean dynamic knowledge at the operational level can also be attributed to the fact that the USCG has very few subject matter experts (SMEs) in this field, and the SMEs that do exist all work at the Head Quarters level. While the SMEs do an exceptional job of providing operational guidance to the field units, the local knowledge of the SAR operators is still lacking. It is recommended that USCG makes an effort to expand the local knowledge of physical ocean processes by encouraging field level SAR planning units supplement local training programs with current with academic literature and engage local colleges or universities with physical oceanography programs. This type of local engagement would pay dividends to the effectiveness of the SAR program.

5.5 Chapter Summary

This chapter summarizes the discussions and conclusions of the study. The Statement of the Problem is reiterated. The methods for conducting the study are
reviewed to include the deployment strategy of the SLDMBs, the method for comparing velocities between HF Radar and observed drifters, and the method in which models were compared to the drifters by using a normalized Lagrangian skill score. The results were summarized. Temporal and spatial limitations of the HF Radar were discussed as well as the accuracy of the HF Radar when compared to surface drifters. Finally the results of the skill score experiment were discussed, concluding that the WFCOM model performed the best (of the OCMS) on the inner shelf portion of the WFS, and the HF Radar was overall best (when HF Radar data was available). The implications of the study were that HF Radar and WFCOM would be useful additions for SAR application with a few caveats. First the HF Radar array would have to be expanded or the current data would have to be interpolated or incorporated into model through data assimilation. Second, WFCOM did not show appreciable increase in skill over the mid-outer shelf, or in the De Soto Canyon region, but it did the inner shelf of the WFS and its mid-outer shelf skill was comparable to the GOM HYCOM. This would make the WFCOM model a better choice for an inner shelf search, or for a search that encompassed both inner and mid-outer shelf regions. Recommendations for future study included continued work on HF Radar interpolation (and model assimilation), and a comparison of skill between the WFCOM and the USCG’s Aggregated ADCIRC model.
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