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LAGRANGIAN SIMULATION OF OIL TRAJECTORIES IN THE FLORIDA STRAITS

By

Kimberley L. Drouin

A THESIS

Submitted to the Faculty of the University of Miami in partial fulfillment of the requirements for the degree of Master of Science

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LAGRANGIAN SIMULATION OF OIL TRAJECTORIES IN THE FLORIDA STRAITS

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A Lagrangian particle based oil transport and weathering model is developed to simulate a continuous surface oil spill in the Florida Straits. The model is initiated at 97 different locations, representative of past and likely future exploratory drilling locations around Cuba’s Economic Zone. Ten day oil trajectories are generated for different seasons, and a hurricane scenario, using leeway-corrected, observed winds, and ocean currents, as well as a multitude of climatologies, and a Markov Lagrangian Stochastic Model. A Monte-Carlo scheme based on an oil half-life of 100 hours is used to parameterize oil weathering processes collectively. Overall, we note a strong seasonal dependence, where Florida is affected most in the summer and Cuba in the winter. Drilling locations at the center of the Straits show the largest impact on Florida (20%-70%). Cuba is most affected by shoreline locations (30%-80%). A significant amount of oil reaches the Florida coastline within two to ten days. Cuba is potentially affected within hours. Many simulations project impacts in the Florida Keys, and South Florida, between Homestead and West Palm Beach. The north and northwest Cuban shores see the greatest impact. The hurricane simulation shows similar impact for Florida (30%-50%) and localized impact on Cuba.
Dedication

To the memories of

my Grandfather Sylvester G. Meys (1932-2007)

and

Dr. Kevin D. Leaman (1948-2015).
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Chapter 1

Introduction

1.1 Motivation

The devastating consequences an oil spill can have were most recently illustrated by the now infamous Deepwater Horizon (DWH) rig that exploded on April 20, 2010. Today, the explosion is considered one of the worst disasters ever experienced in the Gulf of Mexico (GoM) (Lanier, 2013). Over a period of almost three months, the well released an average of 2.5 million gallons of oil per day into the ocean (Lanier, 2013), which equates to an estimated total of 5 million barrels of oil (Joyce, 2015; Liu et al., 2011a). The spilled oil ended up contaminating a total area of 149,000 km$^2$ in the Gulf (Özgökmen et al., 2016), which is approximately equal to the size of Illinois. Speaking in monetary terms, the total damages caused by DWH to British Petroleum (BP), the U.S. Gulf states, and more generally, the GoM ecosystem, are assumed to be on the order of $37 billion (Smith et al., 2011). Of course, the detrimental environmental impact must not be underestimated either. The DWH spill endangered or resulted in the death of countless birds, marine mammals, sea turtles, corals, oysters, and many more. The exact environmental effects remain hard to quantify due to the lack of
access to benchmark data, and the fact that the spill affected the entire water column. Given its vast area it is almost impossible to collect enough samples to accurately assess the damages (Graham et al., 2011).

From an environmental management perspective, a spill in the Gulf of Mexico is and was a guaranteed disaster. As was later established, the oil spill response plan for the DWH well was designed by a contractor for BP, with little consideration for the environment of the actual drilling region. In other words, the plan included no specific analysis of the flora and fauna present in the Gulf of Mexico, or near the Maconda site, but rather general statements that were obtained from NOAA websites (Graham et al., 2011).

Fish and wildlife can be negatively impacted by a spill in a number of ways, including the inhaling and ingestion of oil, which may cause significant health issues and even death (NOAA, Affected Gulf Resources). Just to give a few examples of the complexity of the Gulf ecosystem, as stated by NOAA, the GoM is home to a diverse array of marine mammals, including whales, dolphins and the Florida manatee, seven of which are classified as endangered under the Endangered Species Act. It also serves as a habitat and foraging area to five different sea turtle species, and countless bird species (NOAA, Affected Gulf Resources).

While a multitude of oil drilling sites are located in the GoM, they are not the focus of this work. Instead, motivated by DWH and other spills, we choose to examine the impact of a potential oil spill in the Cuban Exclusive Economic Zone (EEZ), an area which has more recently been the subject of attention. Cuban petroleum exploration itself dates back over a century to the discovery of the Montembo oil field in 1881, and the eventual establishment of two oil-rich provinces: the Northern and Southern Cuban Province (Echevarria-Rodriguez et al., 1991). Today, the Cuban government has divided part of its EEZ in the Florida Straits into 59 leasing blocks, some of which have been acquired by foreign companies from countries such as India, China, Spain,
Russia, and Brazil (e.g Genaw, 2010). While the drilling for oil has historically been localized to areas around Havana and the Matanzas Province, most recently, drilling sites in and around the Florida Straits have also been targeted (Lanier, 2013). In 2012, Repsol, Statoil, and ONGC India, for example, all conducted exploratory drilling operations at a site in the Florida Straits.

So far, no commercial quantities of petroleum have been located in the Straits. However, oil-bearing prospects in those areas are likely to lead to more drilling operations, and attract foreign investors (Lanier, 2013). This is supported by the fact that the first Cuba Oil & Gas Summit was just recently held in Havana, Cuba between February 7-9, 2017. The key points on the summit’s agenda [available at: http://www.cubaoilgassummit.com] clearly illustrate the continuous and current interest in Cuban offshore drilling operations: (1) How to get involved in Cuban hydrocarbon industry, (2) Challenges within Cuban Exclusive Economic Zone, (3) Current investment opportunities, and (4) Latest technology and required infrastructure. Even though concrete information about future drilling sites is not readily available, many companies, such as France’s Total and Australia’s Melbana Energy Limited, have voiced interest in pursuing exploratory drilling missions along with Cuba’s oil union CUPET.

A map of the Florida Straits and the locations of several Cuban leasing blocks is shown in Figure 1.1. The primary oceanic features that are important in this region are the Florida Current, which passes through the narrow Florida Straits, and forms the beginning of the Gulf Stream, as well as the downstream end of the Loop Current. Both are very dynamical features that exhibit seasonality, and contribute to mesoscale variability through the shedding of oceanic eddies. For a more extensive discussion of the oceanographic characteristics of this area, the reader is referred to Chapter 2.3.1. As is clearly shown in Figure 1.1, some of the drilling sites are located well within the Florida Straits. Consequently a spill from that general region has the
potential to affect not only the Cuban shore, but also the Florida Keys, and the east coast of Florida. In terms of first response to a potential spill in this area, a further complication arises. Until very recently, U.S.-Cuban interactions were very limited. As such, it is no surprise that the U.S. has no influence on environmental regulations in Cuba, which tend to be less strictly enforced, or not defined at all (Genaw, 2010).

Figure 1.1: The location of different Cuban leasing blocks and the dynamic features that define the Florida Straits. The color coding does not reflect the most recent state of oil leases (2012 set-up).

As became clear in the aftermath of DWH, it is essential to be aware of the surrounding ecosystems of any potential drilling site. Florida was in a sense “lucky” during the DWH, as an anticyclonic eddy interrupted the Loop Current (LC) pathway to the Florida Straits (Liu et al., 2011c). The close proximity of the Cuban drilling sites to Florida make it an even more vulnerable target in the event of a spill. Specifically, the Florida Keys and the shallow waters of southern Florida come to mind. They are home to the Florida Reef Tract (FRT), which is composed of count-
less individual coral communities including Fowey Rocks, Triumph Reef, and Sand Key Reef, to name a few (Murdoch and Aronson, 1999). The FRT formed between 4,000 - 8,000 years ago and, unfortunately, has experienced a number of harmful disturbances in the past few decades (Vega-Rodriguez et al., 2015).

The effect of petroleum on different types of corals has been the subject of many scientific papers. For instance, Loya and Rinkevich (1980) conducted an extensive review of the topic, and concluded that oil pollution can damage the reproductive system of corals, lead to lower life-expectancy, or even cause a complete halt in new coral colonization. Coral reefs are often referred to as the rain forests of the oceans due to their high biodiversity and immense complexity. It only follows that damage to the reef system also affects the floral and faunal community that depend on it for survival (e.g. Knowlton, 2001). Most studies associated with the DWH blowout have looked at the effects of oil on deep water corals. Etnoyer et al. (2016), for example, observed a ten-fold increase in coral injuries at sites close to the Maconda Well. Naturally, the FRT is not the only vulnerable ecosystem in the Straits. Florida is also home to many diverse mangrove and sea grass communities, as well as wetlands, the most famous of which are the Everglades. All of which could potentially be negatively impacted by oil. Economically speaking, an oil spill affecting Florida could disrupt commercial fisheries and shrimping industries, or even the tourism industry, which is a big source of income to Florida.

Unfortunately, the DWH explosion is not the only oil-spill the GoM has seen in recent history. The following are excerpts of what NOAA’s Emergency Response Division of the Office of Response and Restoration considers the most significant oil spills in the region. In 1979, an exploratory well Ixtoc I, located in the southwestern GoM, underwent a blowout that leaked an estimated total of 113 million to 300 million gallons of oil into the GoM over a period of nine months. In 1993, the collision of two barges and one freighter released over 300,000 gallons of oil into Tampa Bay
affecting sea grass, mangrove, and oyster communities. In 2005, Hurricane Katrina was responsible for polluting countless marshes, sand beaches, and shallow coastal areas with an estimated total of eight million gallons of oil (NOAA, *Other significant oil spills in the Gulf of Mexico*)

In light of such impacts one can easily understand the importance of modeling and studying the behavior of oil. Having access to prediction models can be of great help, not only post-spill, but perhaps even more importantly, pre-spill. By modeling different scenarios, contingency planners are able to better craft oil spill response reports, that have the potential to mitigate the disastrous effects of a spill (Reed et al., 1999). More specifically, models can help identify areas that are especially susceptible to oil landfall, and areas that are considered vulnerable in a biological sense, such as coral reefs, mangrove communities, or commercial fisheries. Post-spill the ability to track surface oil and predict its path is of immense value to first responders in terms of mitigation efforts, pollution control, ship survey guidance, and efficient allocation of scarce resources (Liu et al., 2011b; Huntley et al., 2011). Areas that are most likely to be impacted can be targeted first in order to lessen potential damage. The day after the DWH spill NOAA started generating oil spill trajectories, which, for example, helped determine when and where fisheries should be closed (Graham et al., 2011).

### 1.2 Objectives and Scope of the Study

Keeping in mind the continuous interest in the Florida Straits as an oil drilling site, we set out to develop an oil transport and weathering model that simulates a surface oil spill around Cuba’s Exclusive Economic Zone. The primary goals that guide this study are summarized as the following two objectives:
Objective I:
Identifying areas in Florida and Cuba that are most likely to be impacted by a spill originating from one of the proposed drilling sites.

Objective II:
Determining which individual drilling sites represent the greatest threat to Florida and Cuba in the event of a spill.

This model is Lagrangian in nature and uses realistic winds and ocean currents from observations and models as input data. Two-dimensional Lagrangian particles are used to represent a finite volume of oil. The main goal of this model is to answer these objectives for typical or climatological conditions in the Florida Straits. That is, this model is developed for pre-spill planning purposes, and one should keep in mind that in the event of an actual spill the prevailing oceanographic and atmospheric conditions may be very different from the climatological ones. Average environmental conditions are defined for different seasons and, additionally, a hurricane wind force scenario is considered.

Objective I is evaluated by considering the distribution of particles after ten days, as well as considering a worst-case impact scenario for Florida. Objective II is addressed by estimating the percentage of particles that enter shallow water (<10m depth) and make landfall. This study also includes an analysis of the time it would take for oil to reach locations along the Florida shore. It should be noted that the terms “oil” and “Lagrangian particles”, as well as the terms “launch locations” and “drilling sites,” are used interchangeably throughout this work.

Following the Literature Review (Section 1.3), the remainder of this thesis is organized into two chapters. Chapter 2 is further divided into a multitude of sections, as follows. Section 2.1 introduces the reader to the use of Lagrangian Stochastic Models in oceanography. Section 2.2 describes the methodology and parameters of
the oil transport model, as well as the oil weathering model. Section 2.3 introduces the data sets that are used to advect the oil particles. Section 2.4 outlines the initial sensitivity tests that are conducted to fine-tune the model. Section 2.5 discusses the seasonal and hurricane simulation results, Section 2.6 compares the results against drifter trajectories and a NOAA operational model. Finally, Chapter 3 summarizes the findings and discusses future opportunities.

1.3 Literature Review

The simulation of oil spills dates back decades to the 1960s, when a series of spills triggered increasing interest in the understanding and modeling of oil behavior (Simecek-Beatty and Lehr, 2016). Examples of early works include Fallah and Stark (1976), who looked into modeling the evaporation of oil at sea, and Stolzenbach et al. (1977) that, as cited in Simecek-Beatty and Lehr (2016), provide a detailed overview of the advection and weathering of oil in the ocean. Throughout history, this trend continues and significant advances in modeling are correlated with the occurrence of new spills (Simecek-Beatty and Lehr, 2016). Comprehensive overviews and reviews of earlier and more recent models can be found in Spaulding (1988), Reed et al. (1999), and Spaulding (2017), for example.

The modeling of oil spills, while important, is a difficult task for many reasons. First, one must choose between the implementation of an operational model that uses forecast circulation models, and a statistical model that relies on hindcast simulations (Liu et al., 2011a). For either, it is essential to remember that forecast errors grow in time, which will make the prediction more uncertain (Liu et al., 2011a). Then, one has to consider whether an oil surface model is to contain subsurface components or oil plume dynamics. Of course, the modeler must also acquire model fields and observations that accurately represent and resolve local ocean and wind dynamics.
Of equal importance is the correct initialization of the model using release parameters specific to the oil spill in question. The data for the initial conditions can, for example, be obtained from satellite data (Liu et al., 2011b), but may not always be readily available (Barker, 2011). Such data includes the release locations, the spill rate, and the start and end times of the spill (Spaulding, 1988). Finally, the implementation of an effective weathering scheme that accounts for the decay of oil is also not a trivial task, and will be addressed shortly. Most oil spill models are of the forecast type, and are designed to aid first responders or develop contingency plans. However, French-McCay (2004), for example, developed a multidimensional model that examines the effects of oil on wildlife and different aquatic organisms. Hindcast models can be employed when the source of the spill is unknown, but oil has been located onshore, or an oiled bird has been found (Simecek-Beatty and Lehr, 2016).

While the scope and capability of oil models vary greatly (Reed et al., 1999), many agree on the fact that the motion and transport of oil at the ocean surface is best approximated by employing a combination of wind drift, ocean surface currents, and large scale turbulence (Huang, 1983; Reed et al., 1999; Barker, 2011). The oil transport scheme is then combined with a weathering model to effectively approximate the behavior of oil. The oil itself is commonly modeled as a discrete Lagrangian element (LE), or Lagrangian particle (LP) that is tracked in time and space (Spaulding, 2017). Some models choose to further characterize the oil by assigning it a specific density, thickness, or chemical composition. This becomes especially important when the effects of oil weathering are modeled explicitly, as is discussed shortly.

From experimental and observational evidence it is known that the effects of wind on oil transport can be approximated as some percentage of the 10-m wind speed. Depending on oil type and other factors, these percentages range from 0-6% (French-McCay, 2004; Barker, 2011; NOAA Trajectory Analysis Handbook). For modeling purposes, some choose to vary the wind drift at randomly at every time-step, but most
modelers use a common rule known as \textit{3-4\% of the 10-m wind speed} to parameterize the wind drift (e.g. Reed et al., 1987; Sebastiao and Soares, 1995; Özgökmen et al., 2016). Commonly employed wind data products include winds from offshore buoys (Spaulding, 2017), or winds from operational weather and prediction models.

The ocean surface currents that advect the LPs are typically obtained from numerical circulation models, or high-frequency radar measurements (Spaulding, 2017). Liu et al. (2011b) compared six different numerical ocean circulation models and their performance in tracking the DWH spill. They concluded that an ensemble of different models provides the best results.

The effects of large scale horizontal turbulence or mixing are important to the dispersion of oil at the ocean surface, and are often approximated by employing a random-walk model, with a prescribed diffusion coefficient (e.g. Beegle-Kraus, 2001; French-McCay, 2004). This step is crucial, as it allows for the inclusion of sub-grid scale processes that may not be fully resolved in the large-scale ocean current inputs (Spaulding, 2017). The General NOAA Operational Modeling Environment (GNOME), which is NOAA’s operational model for oil spills, for example, uses this technique (Beegle-Kraus, 2001). The alternative is to use a higher order Lagrangian method, that, apart from the random dispersion, assumes that the velocities are correlated in time, such as the Markov model employed by Mariano et al. (2011). For a more detailed discussion of Lagrangian Stochastic Models (LSM) in oceanography, the reader is referred to \textit{Section 2.1}.

The most challenging part of oil spill modeling perhaps is the fact that oil is a non-conservative tracer (Mariano et al., 2011). This means that the behavior of oil readily changes as its composition is affected by numerous biological, chemical, and physical factors. Some processes that lead to these changes include evaporation, biodegradation, oxidation, dissolution, emulsification, and sedimentation (e.g Lehr, 2001; Passow and Hetland, 2016). These mechanisms are collectively referred to as
oil weathering processes (OWP). The OWP have highly variable time scales of days to months, making some of these processes irrelevant to some applications to begin with. Biodegradation, for example, only sets in after a few months, while evaporation already sets in after a few hours (Sebastiao and Soares, 1995). Furthermore, the OWP are dependent on the density, viscosity, and age of the oil (Lehr, 2001), as well as the location of the spill, and numerous other factors.

Apart from the OWP, mechanical oil removal processes, such as burning, skimming, or the addition of dispersant, also change the oil’s composition and behavior (e.g. Liu et al., 2011b; Özgökmen et al., 2016), and have to be taken into consideration. Numerous methods have been proposed for the modeling of OWP. For example, some modelers simply treat oil as a passive tracer (e.g. Huntley et al., 2011), while others choose to model each of the OWP explicitly. The latter is a difficult undertaking, as the OWP represent complex phenomena whose interactions are, for the most part, still poorly understood (Sebastiao and Soares, 1995; Özgökmen et al., 2016). To parameterize different aspects of oil weathering independently, modelers often revert back to the use of empirically or analytically determined parameters and algorithms (e.g. Sebastiao and Soares, 1995; Mishra and Kumar, 2015; Spaulding, 2017). As pointed out by Lehr (2001), many models adopt equations for the evaporation and emulsification of oil, proposed by Stiver and Mackay (1984) and Mackay et al. (1980), respectively. For the model used in this study, a Monte-Carlo approach used in Mariano et al. (2011) is adopted to parameterize the effects of oil weathering collectively, which is detailed in Section 2.2.

The potential impact of an oil spill close to the Cuban shore has been investigated by several research groups in the past, two of which are introduced next. The Mineral Management Service (MMS), which is now known as the Bureau of Ocean Energy Management (BOEM), performed several model runs that looked at the impact of an oil spill from three potential drilling sites in Cuban waters (personal communi-
Bradford Benggio, NOAA Scientific Support Coordinator, District 7). The simulations were run for a total of ten days, and showed that it would take at least three days for Florida to see an impact. Conditional probabilities of shoreline impact after ten days varied between 11-22%, with highest values projected for the northeastern Florida Keys, and Port Everglades (personal communication Bradford Benggio, NOAA Scientific Support Coordinator, District 7). Applied Science Associates, Inc. (ASA) South America were contracted by Repsol to model oil spills from the Jagüey well, which is located approximately 25km off the Cuban coast, at 23°22’29.6”N and 82°29’33.9”W. The information about ASA’s model, as well as the model results are detailed in their associated 2011 technical report.

ASA South America ran a total of 200 surface spill simulations using spill rates between 500-75,000 barrels per day. The oil was continuously released over a period of 30 days, and the total simulation length was 70 days. The Princeton Ocean Model (POM) and the Parallel Ocean Program (POP) were used to represent the local ocean circulation, and a numerical atmospheric model from NOAA was used as the wind input. The model predicted that a blowout could cause oil to spread towards the northeast and southeast Florida coast, as well as the northern Cuban coast.

Out of the 200 simulations that were performed, between 5-7% (depending on spill rate) predicted an impact somewhere along the Florida shore, and 92-95% along the Cuban shore. The simulations that did predict impact along Florida or Cuba, showed that the probability of oil reaching any part of the Florida and Cuban coasts is approximately 90%-100%. The average time to shore was calculated to be on the order of six days for Florida, and three days for Cuba. The worst-case scenarios predicted an impact to Florida after five days, and within a few hours for Cuba (ASA Technical Report, 2011).

Similarly to our model, these two studies are meant to evaluate the potential impacts of an oil blowout pre-spill for preparation and planning purposes. During
the event of an actual spill, oil prediction models have to be run in real-time, ideally, assimilating data at each time step to reduce prediction errors (Liu et al., 2011a), and incorporate multiple time and space scales. NOAA’s GNOME is an example of such an operational model, and is introduced in Chapter 2.6 as a part of the model validation.
Chapter 2

Lagrangian Simulations

2.1 Background

The following section provides a brief background on the use of Lagrangian Stochastic Models (LSMs) in oceanography. For a detailed introduction to oil spill modeling and the development of the Cuban offshore drilling industry the reader is referred to Chapter 1.

Lagrangian Stochastic Models have been used in the context of atmospheric science for several decades dating back to the work of Thompson (1986, 1987). The use of LSMs to study the dispersion of particles in the ocean has gained increasing popularity in recent history, as well. Griffa (1996), provides a comprehensive overview of three different Markov models of increasing complexity and their applications in oceanography. Dutkiewicz et al. (1993), for example, used stochastic modeling to look at the dispersion of large tracer particles and study the turbulent mixing of Gulf Stream meanders. Falco et al. (2000) used this method to predict the motion of drifters. Lagrangian Stochastic Models may also be used indirectly as a diagnostic tool to extract statistical information from Lagrangian data sets (Griffa, 1996).
Overall, in most oceanographic applications, LSMs are used to approximate the turbulent velocity component of a flow field and to parameterize chaotic ocean dynamics (e.g. Mariano and Ryan, 2007; Piterbarg et al., 2007). That is, they are needed when the Eulerian dynamics are not readily available or fully resolved, to represent the statistics of particles in a turbulent regime (e.g. Pasquero et al., 2007).

Lagrangian Stochastic Models are defined by the number of time scales they take into account; a property which is known as their order (e.g. Rupolo, 2007). The lowest order of LSMs is more commonly known as the random-walk process, and assumes that the flow is uncorrelated in time (e.g. Pasquero et al., 2007). This means that it neglects the idea that a velocity field may contain a “memory” (Reynolds, 2002). This Markov-0 model is introduced in Equation 2.1 and follows the notation of Rupolo (2007). In this model, a random component \( \left( \frac{dw}{dt} \right) \) taken from a Gaussian distribution is weighted by the appropriate diffusion coefficient \( (K) \), and added to the mean velocity component \( (U) \) to obtain the total velocity \( \left( \frac{dx}{dt} \right) \) (e.g. Pasquero et al., 2007; Rupolo, 2007).

\[
\frac{dx}{dt} = U + \sqrt{2K} \frac{dw}{dt}
\]  

(2.1)

As pointed out in Chapter 1, this random-walk model is often used in the context oil spill modeling. However, when representing the oceanic mesoscale, the assumptions associated with a Markov-0 model are typically not valid (Pasquero et al., 2007). This is especially true in very energetic regions that contain coherent vortices, loops, and are exposed to strong wave motion (e.g. Berloff and McWilliams, 2002; Mariano et al., 2002; Piterbarg et al., 2007). The Florida Straits, our model domain, are one such region. More advanced schemes, such as the Markov random flight model (e.g. Griffa, 1996; Mariano et al., 2002; Piterbarg et al., 2007) are needed in that case. One example, that accounts for the temporal correlation of the fluid field, is a first-order Markov LSM, which is employed in this model (Section 2.2). A Markov-1 LSM (Equation 2.2, following the notation of Rupolo (2007)), can be thought of as
consisting of two terms: the decaying memory term, which describes the variable at a previous time step, and the random term, which parameterizes velocity fluctuations (Pasquero et al., 2007). Here, the memory of the previous time-step is closely linked to the Lagrangian integral time scale (T).

\[
\frac{dx}{dt} = U + u \quad (2.2a)
\]

\[
\frac{du}{dt} = -\frac{u}{T} + \sqrt{\frac{2\sigma^2}{T^2}} \frac{dw}{dt} \quad (2.2b)
\]

### 2.2 Methodology

#### 2.2.1 Particle Trajectory Model

**Advection Scheme**

The Lagrangian advection model formulated for this study is classified as a two-dimensional model, that is the particles are advected at the surface only, and sub-surface components are not considered. The movement of oil at the ocean surface (Figure 2.1) is commonly approximated by a combination of wind drift, ocean surface currents, and large scale turbulence, a procedure which is adopted in this model, as well (e.g. Huang, 1983; Reed et al., 1999; Barker, 2011).
The different input wind products that are used are (1) a series of un-smoothed buoy wind data from the National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Center (NDBC) and the Citizen Weather Observer Program (CWOP), (2) the Scatterometer Climatology of Ocean Winds (SCOW), and (3) a blended model analysis of Hurricane Andrew ’92. The surface currents are represented either by (1) a new drifter-based ocean current climatology developed by Laurindo et al. (2017), or (2) the Hybrid Coordinate Ocean Model (HYCOM). The effects of large scale diffusion are parameterized using a first-order Lagrangian Stochastic Model (LSM). A detailed introduction to the individual data sets is given in Section 2.3.

For the basic framework of the oil transport model (Equation 2.3), we follow the notation of Mariano et al. (2011), and separate the horizontal ocean and wind velocity fields into a deterministic component $u_{(w,o)}(x, y, t)$, $v_{(w,o)}(x, y, t)$ and a stochastic
component $u'_{(w,o)}(r, t), v'_{(w,o)}(r, t)$ (e.g., Griffa, 1996). The deterministic state $\bar{u}_{(w,o)}(x, y, t)$ is approximated by the different ocean and wind data sets named above, while the deterministic state $u'_{(w,o)}(r, t)$ is modeled by a LSM (Equation 2.4).

\begin{align*}
  u(x, y, t)_{o,w} &= \bar{u}(x, y, t)_{o,w} + u'(x, y, t)_{o,w} \quad (2.3a) \\
  v(x, y, t)_{o,w} &= \bar{v}(x, y, t)_{o,w} + v'(x, y, t)_{o,w} \quad (2.3b)
\end{align*}

**Lagrangian Stochastic Model**

As mentioned in Section 2.1, it is common practice in oceanography to parameterize the diffusive term of the advection equation with the help of a stochastic model, in part, to account for model error (Huntley et al., 2011). The LSM chosen here, follows Mariano et al. (2011), and is defined in Equation 2.4. It is used in conjunction with the drifter-based climatology and the HYCOM velocity fields. As mentioned in Section 2.1, its dependence on the previous time step classifies it as a first-order Markov process (Huang, 1983; Mariano et al., 2011). The choice of a higher order Markov-Model to represent the stochastic velocity component is a more realistic alternative to the more traditional random-walk model, as it is generally assumed that both wind and velocity data are correlated if the time step between successive measurements is relatively short (Huang, 1983). The same LSM is used for the stochastic ocean and wind state by adjusting the parameters, which are summarized in Table 2.1.

\begin{equation}
  \bar{U}'(r, t)_{o,w} = \left(1 - \frac{\Delta t}{T}\right) \bar{U}'(r, t - 1)_{o,w} + \left(\sigma \varepsilon \sqrt{\frac{2\Delta t}{T}}\right) \quad (2.4)
\end{equation}

The LSM parameters for the ocean (Table 2.1) are adapted from Mariano et al. (2011), who based these parameters on values derived by Ohlmann and Niiler (2005). Typical values for the Lagrangian integral time scale are on the order of one day in
coastal regions, and on the order of five days in strong currents. For this simulation we justify the use of an average value of three days by noting that our model transcends these two regions, and the particles are exposed to both dynamical regimes. The LSM parameters for the wind were calculated by Mariano et al. (2011).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>LSM values</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Lagrangian Integral Time Scale</td>
</tr>
<tr>
<td>σ</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>Δt</td>
<td>Advection Time Step</td>
</tr>
<tr>
<td>ε</td>
<td>White Noise</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of the Lagrangian Stochastic Model parameters used in Equation 2.4.

Weathering Model

Chapter 1 described that the chemical and physical properties of oil change as it is exposed to the marine environment. Processes that contribute to these changes include evaporation, biodegradation, oxidation, dissolution, emulsification, and sedimentation (e.g. Lehr, 2001; Passow and Hetland, 2016). These mechanisms are collectively referred to as oil weathering processes (OWP). For the purpose of this model, however, the most important aspect is the fact that oil does decay; the individual processes that contribute to the weathering are of lesser interest. Thus, in terms of oil weathering, this work focuses on including a reliable estimate of the oil half-life to collectively simulate all OWP and mechanical removal processes. According to Mariano et al. (2011), the minimum weathering rate should be chosen such that the oil has a half-life of no more than one week. We employ a Monte-Carlo scheme to parameterize the effects of different oil removal processes (Mariano et al., 2011). The intent is to randomly remove particles at each time step using a set weathering rate, expressed as a percentage, and a random number generator. If the random number
\( \epsilon \sim N(0, 1) \) is larger than the weathering rate \((r)\) the particle is kept. If \( \epsilon \) is less than \( r \), the particle is removed from the simulation. The mean weathering rate is set to \( r = 0.005 \), which translates to an average of 0.5\% particles being removed at each time step, or a half life of 100 hours (approximately four days). Several sensitivity runs examine the effects of no weathering \( r = 0 \), halving the weathering rate \( r = 0.0025 \), doubling the weathering rate \( r = 0.01 \), and quadrupling the weathering rate \( r = 0.02 \) (refer to Section 2.4).

### 2.2.2 Simulation Details

The boundaries of our model domain are defined by \( 77^\circ W < x < 86^\circ W \) and \( 22^\circ N < y < 32^\circ N \). A map of the area of interest is shown in Figure 2.2. Each simulation is run for a total of ten days with a time step of \( \Delta t = 1 \) hour, following the finite predictability imposed by the Lagrangian nature of this model, which is given by its integral time scale. More specifically, the prediction of Lagrangian particle trajectories is limited to a time equal to twice the integral time scale of the velocity field (e.g. Mariano and Ryan, 2007; Piterbarg et al., 2007), after which the velocities become independent. Here, the upper limit of a five day integral time scale is used, to yield a simulation period of ten days.

The initial particle locations \((x_o, y_o)\) are chosen based on likely or proposed future drilling sites, located around Cuba’s 59 leasing blocks. Test runs are performed at a subset of five locations Figure 2.2 to assess the sensitivity of the model with respect to the spill rate \((s)\), the weathering rate \((r)\), the length of the simulation, and other parameters. Methods of evaluation include a number of bar plots, time series, and particle trajectories.

The final trajectory simulations are launched on a uniform grid composed of 97 individual sites, as shown in Figure 2.2. To simulate the effects of oil spilling from a tanker or a similar gushing source (Liu et al., 2011b), the Lagrangian particles are
released continuously at a spill rate of \( s = 100 \) particles/hour for a period of ten days. Here, it is emphasized that the spill duration as well as the simulation time period are both ten days. This means that the first 100 trajectories are projected for ten days, but the next 100 trajectories are only projected for nine days and 23 hours and so on. Sensitivity tests include runs with \( s = 1000 \) particles/hour to test the robustness of the results.

**Figure 2.2:** A map of the model domain (shaded in light blue) and its surrounding region. The location of the NDBC and CWOP buoy stations are indicated by black dots and triangles, respectively. The launch locations are shown as rectangles. The test locations refer to locations that were used in the sensitivity runs.
Table 2.2 provides a summary of the different simulation experiments along with the wind and ocean input data sets that are used. Simulation [S00] and [H00] denote the sensitivity simulations that are outlined in Section 2.4. These include calculations for all four seasons [S00], as well as different hurricane wind scenarios [H00]. The final particle trajectories are calculated for only two seasonal cases [S01-S04], and two hurricane wind scenarios [H01-H02]. For the seasonal runs, the months of January and July are chosen to represent the winter and summer seasons, respectively. For each of the six final simulations [S01-S04,H01-H02], a total of 24,000 particles are released over a period of ten days from each of the 97 launch sites (Figure 2.2). All simulations [S00-S04,H00-H02] include a Monte-Carlo scheme that parameterizes the effects oil weathering, and are coupled with two Lagrangian Stochastic Models, one for the ocean, and one for the wind. The interested reader is referred to Appendix A for a short discussion on the fall and spring simulation runs on the final grid.

The results from the oil trajectory simulations are evaluated by grouping the Lagrangian particles into two categories: (1) shallow water particles and (2) beached particles. Group (1) includes all particles located in water shallower than, or equal to 10-m in depth, and Group (2) includes all particles located onshore. Here, the term onshore is defined by the 0-m isobath of the General Bathymetric Chart of the Oceans (GEBCO), which is described in Section 2.2.5. The shallow water depth is chosen to take into account areas of high biological activity, such as coral reefs.

To address Objective (II), we generate probability maps based on the two particle groups. The probability maps indicate the percentage of particles that enter shallow water or make landfall in either Florida or Cuba from any given drilling location. Distribution maps showing the location of particles after ten days are constructed to assess which specific geographical regions could see the greatest impact (Objective (I)). These distribution maps are constructed by converting to a Eulerian representation. Specifically, the model domain is divided into a discrete grid
of $\frac{16}{4}$ resolution, after which the number of particles in each box at a given time is counted. We also discuss a worst-case scenario for Florida, which is initialized at the launch location that shows the highest percentage of shallow water particles. Such maps are typically of high interest to first responders for training and contingency planning purposes.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Ocean Input</th>
<th>Wind Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seasonal 00</td>
<td>annual drifter-based climatology</td>
<td>buoy winds</td>
</tr>
<tr>
<td>Seasonal 01</td>
<td>seasonal drifter-based climatology</td>
<td>buoy winds</td>
</tr>
<tr>
<td>Seasonal 02</td>
<td>seasonal drifter-based climatology</td>
<td>SCOW based on QuickSCAT</td>
</tr>
<tr>
<td>Seasonal 03</td>
<td>HYCOM</td>
<td>SCOW based on QuickSCAT</td>
</tr>
<tr>
<td>Seasonal 04</td>
<td>HYCOM</td>
<td>buoy winds</td>
</tr>
<tr>
<td>Hurricane 00</td>
<td>annual drifter-based climatology</td>
<td>Hurricane Andrew 92’ re-analysis winds</td>
</tr>
<tr>
<td>Hurricane 01</td>
<td>seasonal drifter-based climatology</td>
<td>Hurricane Andrew 92’ re-analysis winds</td>
</tr>
<tr>
<td>Hurricane 02</td>
<td>seasonal drifter-based climatology</td>
<td>shifted Hurricane Andrew 92’ re-analysis winds</td>
</tr>
</tbody>
</table>

**Table 2.2:** Summary of the different simulations and their respective ocean and wind data input sources. This table is to be used throughout this work as a reference. Simulations termed “S” each consist of a summer and winter scenario. For H02, “shifted” means that the hurricane wind field was shifted south by 3°. The reason behind this is explained in *Section 2.4.*
2.3 Data

2.3.1 Ocean Current Data

As was briefly mentioned in Chapter 1, the main oceanic features that are important in terms of oil transport in our region are the end of the Loop Current (LC), as well as the Florida Current (FC). This section introduces and compares the drifter-based climatology to the temporally and spatially varying HYCOM fields (Figure 2.3).

Drifter-based climatology

The annual and seasonal climatologies of ocean surface currents used in [S00-S02] were developed by Laurindo et al. (2017). The data set consists of 24 global fields of the zonal and meridional velocity components mapped to a $0.125^\circ \times 0.125^\circ$ spatial grid with a temporal resolution of approximately 15 days. The climatology is constructed from $\sim$36 years of slip-corrected velocity observations from 15-m drogued and undrogued drifters from the Global Drifter Program (GDP) (Laurindo et al., 2017). It is based on a new method for the decomposition of Lagrangian data that reduces the spatial smearing and smoothing effects of previous techniques. The GDP is part of the Global Surface Drifting Buoy Array from NOAA’s Global Ocean Observing System and a project of the Data Buoy Cooperation Panel (NOAA, The Global Drifter Program). The first drifters were deployed in 1979, followed by large-scale deployments in 1988, which focused on the tropical Pacific Ocean (Lumpkin and Pazos, 2007). In 1992 and 1994, the program was extended to include other parts of the Pacific, the North Atlantic, Southern and Indian Oceans (Niiler, 2001), and since 2004, also includes the tropical and South Atlantic (Lumpkin and Garzoli, 2005). Its goal is to maintain a global ocean observing system that provides information about in-situ measurements of mixed-layer currents, sea surface temperature, salinity, and more (NOAA, The Global Drifter Program).
Figure 2.3: Comparison of the deterministic ocean input data. The seasonal drifter-based climatology is shown on the left-most panel, and the seasonal HYCOM is shown on the three right panels. The top row shows the summer data, and the bottom shows the winter data. Three snapshots of the HYCOM fields are shown at the start, middle and end of the simulation period.

The summer (July 1-15) and winter (January 1-15) surface velocity climatologies that are used for the seasonal runs are shown in Figure 2.3 (left panel). The magnitude of the current is shown in color, while its direction is indicated by vectors. The well established seasonal cycle of the Florida Current (FC) (e.g. Leaman et al. (1987)) is apparent on the drifter record. It was first described by Montgomery (1938), who identified a seasonal maximum in July and a seasonal minimum in October. In this drifter-based climatology, the FC core velocities vary from a maximum value of 1.63 ms\(^{-1}\) in the winter, to a maximum value of 1.87 ms\(^{-1}\) in the summer, clearly capturing the well-established July seasonal maximum. The seasonality of the FC plays a role contributes to the noticeable variations of the results (Section 2.5). It should be noted that some historically well known features of the Florida Straits, such as the recirculation along the east coast of Florida, are not as well resolved in this climatology, presumably due to a lack of available drifter data in the region.
The hurricane simulation features the drifter-based climatology from August 15-31, which is chosen to better represent conditions during Hurricane Andrew that passed through the Florida Straits between August 23-25, 1992. This climatology closely resembles Figure 2.3(a) in magnitude, shape, and pattern, and reaches a maximum in the FC core of 1.78 ms\(^{-1}\). The gridded ocean surface fields are interpolated in space to the positions of each particle, at each time step, using a bicubic spline on a 5 x 5 point stencil. An explicit fourth-order Runge-Kutta scheme (RK-4) is used to advect the particles (e.g. Mariano et al., 2011).

**HYbrid Coordinate Ocean Model**

To account for the lack of variability inherently present in the drifter climatology, we perform two additional simulations [S03-S04] that use the HYCOM surface velocity fields at 1km spatial resolution, and three hour temporal resolution. The time period chosen for this simulation is identical to the buoy wind period (winter: January 1-10, 2014; summer: July 1-10, 2014). Three snapshots of the summer and winter HYCOM fields at the beginning, in the middle, and at the end of the simulation period are presented in Figure 2.3 for qualitative comparison to the drifter climatology.

We first note that the core location, width, and general shape of the Florida Current is a lot more variable in the HYCOM simulation, than the drifter-based climatology. The HYCOM fields clearly identify the downstream end of the Loop Current as it merges into the FC. The LC velocities are approximately 0.5 m/s larger in the summer as compared to the winter. The drifter-based climatology captures the direction of the LC, but fails to resolve its higher velocities in the summer. The dynamics and configuration of the LC play an important role in determining the particle trajectories, especially for drilling sites located near the western end of Cuba. We further observe the existence of several eddies in the HYCOM flow field. An anticyclonic eddy is located in the southwestern corner of the domain during the
summer and winter period, and a cyclonic eddy, centered around 24°N and 82.5°W, can be identified in the Florida Straits during most of the summer period. One further difference between the drifter-based climatology and the HYCOM fields is the direction of the circulation in the eastern most GoM. The HYCOM fields show a mean current field that either flows northward or southward during most of the examined time period. However, the drifter-based climatology shows no distinct flow direction and is much more variable.

To account for a lack of data close to the shore (white patches in Figure 2.3), the HYCOM velocity fields are extrapolated by fitting local splines on smaller stencils in coastal regions. This step is necessary for future data analysis, as it allows the particles to reach areas of shallow water.

While HYCOM generates velocity fields with a much higher resolution than the drifter-based climatology, it still does not fully resolve coastal dynamics and tides. Further, there is little guarantee that the mesoscale eddies that are resolved in the HYCOM fields are in the correct location. As is shown in Section 2.5 the existence of mesoscale features can significantly impact the distribution and trajectories of particles. Finally, the FC is known to reach peak velocities of up to 2 m/s off the Florida coast, which are still not resolved in some parts of the HYCOM fields. Hence, it is still advantageous to add a LSM to the HYCOM simulation. To allow for the best possible comparison to the drifter-based climatology simulations, the same LSM parameters (Table 2.1) are used for the drifter-based climatology and the HYCOM velocity fields. The adjustment of the LSM to smaller scales for the higher resolved HYCOM fields is beyond the scope of this work.

2.3.2 Wind Data

As is shown in Figure 2.1, wind drift is one of the components that contributes to the movement of oil at the ocean surface. More specifically, the wind exerts a drag force
on the oil and pushes it through the water (Allen, 2005). This process is also referred to as leeway drift, and is often expressed as a percentage of the 10-m wind speed (e.g. Mínguez et al., 2012). Since the 1990s it has been established that the leeway drift not only acts in the downwind direction (i.e. the direction of the wind), but rather shows a divergence to the left and right of the downwind direction (Allen, 2005). This divergence is caused by the crosswind component of leeway, which is perpendicular to the wind (Allen, 2005). To fully account for the leeway behavior, both of these components have to be taken into account. While the downwind component is always positive, the crosswind component is both positive and negative, causing a deflection to the right and left of the wind, respectively (Allen, 2005). It has been suggested that the crosswind sign may change at a certain hourly rate, however, not much is known about the specifics (Allen, 2005). In this model, each simulation is run twice; once with a positive crosswind component, and once with a negative crosswind component. The presented results are an average of the two different runs. For a more mathematical derivation of the use of the leeway vector in Lagrangian modeling applications the reader is referred to Mínguez et al. (2012).

Observational and experimental evidence has shown that the windage of oil typically varies between 0 – 6%, depending on oil type and other factors (e.g. French-McCay, 2004; Barker, 2011; NOAA Trajectory Analysis Handbook). For modeling purposes, the wind drift of oil is commonly approximated at ~ 3% of the 10-m wind speed, (e.g. Sebastiao and Soares, 1995; Barker, 2011; Ö zgökmen et al., 2016). **Appendix B** introduces a few simulations that are run using a value of 4%. The importance of leeway correction from a modeling perspective was confirmed during the DWH spill, where non-drift inclusive models predicted a much different outcome (Ö zgökmen et al., 2016). What follows is a detailed description of the individual wind data sets.
National Data Buoy Center and the Citizen Weather Observer Program

The first set of wind advection velocities is calculated from unsmoothed data from NOAA’s NDBC. This data set is archived by station ID and available at [http://www.nmdbc.noaa.gov/]. Different buoy stations are chosen in the Florida Keys and along the east coast of Florida to represent typical wind speeds in a specific space and time frame. The data used in Varadero, Cuba (MUVR) is obtained from the CWOP [available at: http://weather.gladstonefamily.net/site/MUVR].

Each seasonal run has a slightly different composition of stations, which are chosen based on data availability. The summer run employs ten consecutive days of hourly data between July 1-10, 2014. The stations that are chosen for the summer run are: Varadero, Cuba (MUVR), Sand Key, FL (sanf1), Long Key, FL (lonf1), Molasses Reef, FL (mlrf1), Fowey Rock, FL (fwyf1), the Bahamas (spgf1), and Trident Pier, FL (trdf1). The winter run uses ten days of hourly data between January 1-10, 2014 from Varadero, Cuba (MUVR), Vaca Key, FL (vcaf1), Molasses Reef, FL (mlrf1), Fowey Rock, FL (fwyf1), the Bahamas (spgf1), and Cape Canaveral, FL (41009). The geographical locations of these stations are shown in Figure 2.2. The buoy winds are interpolated to the position of each particle, at each time step, using Inverse Distance Weighting (IDW) (Equation 2.5). This method allows the buoy closest to the particle to contribute the most to the interpolated wind velocities.

\[
\bar{U}(x, y) = \frac{\bar{U}_1 d_2 + \bar{U}_2 d_1}{d_1 + d_2} \tag{2.5}
\]

where \(\bar{U}(x, y) = \bar{U}(u(x, y), v(x, y))\) is the interpolated wind speed, \(\bar{U}_1\) is the wind speed at buoy one, \(\bar{U}_2\) is the wind speed at buoy two, \(d_1\) is the distance between the particle \((x, y)\) and buoy one, and \(d_2\) is the distance between the particle \((x, y)\) and buoy two.
Scatterometer Climatology of Ocean Winds

The second wind data set employed in this model is obtained from the Cooperative Institute for Oceanographic Satellite Studies (CIOSS) at Oregon State University [available at http://cioss.coas.oregonstate.edu/scow/]. The SCOW fields are derived from 122 months (September 1999 - October 2009) of QuickSCAT scatterometer measurements by Risien and Chelton (2008). Specifically, zonal and meridional wind velocity maps with a spatial resolution of 0.25° x 0.25° from the months of January and July are used for the winter and summer runs, respectively. Missing values near coastal regions in the original data set are accounted for with an extrapolation scheme. This step is necessary to allow for the advection of particles to coastal and shore regions. The finalized (a) summer and (b) winter wind fields are shown in Figure 2.4.

The magnitude and direction from which the wind is blowing are shown by vectors. The summer field is dominated by southeasterly winds close to the southeast coast of Florida, which turn more southerly in northern Florida. Strong easterly winds prevail around northern Cuba (Figure 2.4 (a)). The magnitude of the summer field is largest in the southeastern part of the domain with values of \( \sim 5-6 \) ms\(^{-1}\), and becomes weaker towards the north, and along the east coast of Florida. The winter field features northeasterly winds throughout most of the domain, which are strongest off the north and east coasts of Cuba (Figure 2.4 (b)). Winds off the east coast of Florida are slightly weaker compared to the summer climatology. The northern domain (\( \geq 29^\circ\)N) is dominated by northwesterly winds. The QuickSCAT wind fields are interpolated, at each time step, to each particle location using a bicubic spline. It should be highlighted that, unlike the buoy winds, the QuickSCAT wind fields are seasonal climatological averages and, therefore, do not account for temporal variability.
Hurricane Andrew '92

Florida’s geographical location makes it a susceptible target for Atlantic Tropical Cyclones, especially between the period of June 1 - November 30, which is commonly defined as prime Atlantic hurricane season. Malmstadt et al. (2009) estimated that the likelihood of Florida being hit by at least one hurricane every year is as high as 46%. In the past 100 years, for example, the state of Florida has been affected by over 300 hurricanes. It is for that reason that this Lagrangian Simulation includes a hurricane scenario featuring the track and wind velocities of Hurricane Andrew '92 (Figure 2.5). Andrew was classified as a Category 5 hurricane when it made landfall in Homestead, Florida on August 24, 1992.

The wind velocity field for the hurricane run was constructed from a blended model analysis of environmental re-analysis winds, aircraft data, and best track winds from Hurricane Andrew '92 by Dr. Brandon Kerns at the Rosenstiel School of Marine and Atmospheric Sciences. The 10-m winds from the European Center for Medium-
Range Weather Forecasts (ECMWF) Interim Reanalysis (Dee et al. (2011)), which are available at a resolution of 0.7° x 0.7° every six hours, are used as the first-guess background winds. The vortex winds are reconstructed using the center and maximum winds from the National Hurricane Center (NHC) best track winds, and the radius of maximum winds (RMW) from NOAA’s Atlantic Oceanographic and Meteorological Laboratory (AOML) aircraft data. The RMW estimates from 141 individual aircraft transects were interpolated hourly, smoothed in time to eliminate fluctuations, and fitted to a Rankine vortex profile. Finally, the first guess re-analysis and storm winds are merged using a linear weighting ranging from the RMW, to six times the RMW. Beyond six times the RMW, the winds are equivalent to the first guess field. The merged wind field has a temporal resolution of Δt = 1 hour, and a spatial resolution of Δx, Δy = 0.05°.

![Figure 2.5: Hurricane Andrew '92 windfields (a) before and (b) after making landfall in Florida.](image)

**Figure 2.5** shows two snapshots of the wind field on (a) August 24, 1992 at 00:00:01 UTC and (b) 16:00:00 UTC. Strong northeasterly winds prevail downstream of the hurricane, while southeasterly winds dominate on the hurricane’s backside. In an attempt to account for the unpredictable and diverse nature of tropical cyclones,
the latitudinal and longitudinal landfall position of Hurricane Andrew is varied. For this, the constructed wind fields shown in Figure 2.5 are displaced north and south by a few degrees (between $\pm 3.0^\circ$). The impact that the different tracks could have on the amount of beached or stranded particles is assessed through a series of sensitivity runs in Section 2.4. The hurricane wind field is interpolated similarly to the SCOW winds to the location of each particle, at each time step, using a bicubic spline on a 3 x 3 point stencil. The hurricane run is initialized on August 16, 1992 and run for a period of ten days, akin to the seasonal scenarios.

2.3.3 Bathymetry

As described in Section 2.2.2, the Lagrangian particles are sorted into (1) shallow water particles and (2) beached particles. To determine the water depth at the location of each particle, the global 30 arc-second bathymetry grid product (2008 version) from the General Bathymetric Chart of the Oceans (GEBCO) is used (Figure 2.6). The updated 2014 version is available for download at [http://www.gebco.net/data-and_products/gridded_bathymetry_data/].

The bathymetry of the model domain can also help further motivate the development of this Lagrangian simulation (Figure 2.6). The colored contours depict the bathymetry, with darker colors representing deeper waters, and lighter colors referring to shallower depth. The 10-m depth contour, which is defined as shallow water in our study, is depicted in the lightest shade of blue. As can be seen, northwestern Cuba, northeastern Cuba, the Florida Keys, southeastern Florida, and the western Bahamas are surrounded by very shallow waters. These areas are home to a diverse array of ecosystems, and important from an economical standpoint. The topographical feature centered around 23.7°N, 80°W in the Florida Straits is known as Cay Sal Bank. This island forms the westernmost part of the Bahama Banks and its central location makes it a vulnerable target to the impacts of an oil spill.
Figure 2.6: Bathymetry map of the model domain. The colored contours represent the bathymetry, with blue colors indicating the presence of water. The lightest shade of blue contours the -10m isobath.

2.4 Sensitivity Tests

Seasonality [S00]

Several sensitivity checks [S00] are performed at a subset of five initial locations to fine-tune the model and test its robustness. The five test locations (TL) are shown in Figure 2.7 and represent different sections of the previously introduced drilling domain (Figure 2.2). For purposes of brevity, only an excerpt of these sensitivity results is presented next.
Figure 2.7: A map showing the five test launch locations (black) and the grid launch locations (grey).

Most importantly, the preliminary results reveal a significant seasonality (Table 2.3). For Florida, we observe a maximum in the summer, while for Cuba, we observe a maximum in the winter (highlighted cells in (Table 2.3)). The spring and fall test simulations fall in between the summer and winter maxima, in terms of percentage of particles in shallow water and on land. More specifically, for Florida, percentages decrease from summer values of $O(0 - 30\%)$, to spring values of $O(0 - 22\%)$, to fall values of $O(0 - 7\%)$, and to $O(0 - 8\%)$ in the winter. For Cuba, the percentages of particles reaching shallow water decreases from a maximum of $O(4 - 40\%)$ in the winter, to fall values of $O(1 - 28\%)$, to spring values of $O(2 - 16\%)$, and finally, summer values of $O(1 - 16\%)$. The percentages are given as ranges to account for the variability dictated by the different launch locations (Table 2.3). At the same time, however, Florida has the lowest values in winter (except at TL 05), and Cuba the lowest values in the summer (except at TL 02). Consequently only the seasonal
maximum cases, i.e. summer and winter runs, are the focus of this work. The large range of predicted percentages and the seasonal exceptions, suggest, that the distribution of particles is a strong function of the initial spill location.

<table>
<thead>
<tr>
<th>Location</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPRING</td>
</tr>
<tr>
<td>TL 01</td>
<td></td>
</tr>
<tr>
<td>CUBA</td>
<td>1.51%</td>
</tr>
<tr>
<td>FLORIDA</td>
<td>0.00%</td>
</tr>
<tr>
<td>TL 02</td>
<td></td>
</tr>
<tr>
<td>CUBA</td>
<td>16.77%</td>
</tr>
<tr>
<td>FLORIDA</td>
<td>0.01%</td>
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<tr>
<td>TL 03</td>
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<tr>
<td>CUBA</td>
<td>0.62%</td>
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<tr>
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<td>7.69%</td>
</tr>
<tr>
<td>TL 04</td>
<td></td>
</tr>
<tr>
<td>CUBA</td>
<td>16.12%</td>
</tr>
<tr>
<td>FLORIDA</td>
<td>1.51%</td>
</tr>
<tr>
<td>TL 05</td>
<td></td>
</tr>
<tr>
<td>CUBA</td>
<td>0.31%</td>
</tr>
<tr>
<td>FLORIDA</td>
<td>22.05%</td>
</tr>
</tbody>
</table>

Table 2.3: Summary of the preliminary results with respect to the percentage of shallow water particles. The first row of each location presents the percentage of particles near Cuba, the second row presents the percentage of particles near Florida

Oil Weathering and Spill Rate

To establish an appropriate weathering scheme, we next consider the preliminary results for five different weathering rates (Figure 2.8 (a)). To take into account the seasonal differences and the different launch locations, the weathering rates are tested in the summer and winter, at TLs 04 and 05, respectively. From left to right, these weathering rates correspond to half-lives of 200 hours, 100 hours, 50 hours and 25 hours, respectively. As expected, the higher the weathering rate, the smaller the percentage of total beached particles. Based on these results, the “normal” weathering rate is set to \( r = 0.005 \), or a half-life of \( \approx 100 \) hours. It should be noted that the “half” and “double” weathering rates also fall within the range of realistic half-life. While first-responders or modelers may choose to run a model without weathering, such
as GNOME during the DWH spill (MacFadyen et al., 2011), in theory, it is not representative of the physical world. In fact, the “no weathering” case would tend to overestimate the particle percentages (Mariano et al., 2011).

Since all Lagrangian particle based methods are sensitive to the number of particles used in the simulation (Spaulding, 2017), we include a comparison of two spill rates next. **Figure 2.8 (b)** compares two spill rates ($s = 100$ particles/hour vs. $s = 1000$ particles/hour) at three different launch locations for summer and winter runs, in “normal” and “no weathering” cases. The percentage results are virtually identical (difference of $O[1\%]$), indicating that a spill rate of $s = 100$ particles/hour is a good representative value. While our spill rate is much larger than commonly used values of operational models, such as GNOME (4 particles/hour), or the Oil Spill Risk Analysis Model, OSRA (1 particle/hour) (Barker, 2011), these models are typically run and averaged numerous times, whereas the simulations performed for this model are run only once, for each scenario. For all final runs we use the smaller rate (100 particles/hour), in part to reduce computational cost.

**Figure 2.8:** Excerpt from the sensitivity simulations [S00]. Panel (a) shows the effect of varying the weathering rate on the percentage of beached particles. Panel (b) compares two hourly spill rates at different locations and for different seasons.
Simulation Length

The length of time that a Lagrangian model can reliably predict the trajectories of particles is limited by its Lagrangian integral time scale. As explained in Section 2.2.1, for this particular model, a simulation length of ten days is chosen. However, to see whether this timescale is long enough to observe particles beaching themselves in Florida or Cuba, the preliminary analysis includes an array of time series, which are discussed next (Figure 2.9). The time series show the percentage of particles reaching the Florida and Cuban coasts each day at the five test locations (Figure 2.7).

Figure 2.9: Time series of the preliminary summer (top) and winter (bottom) [S00] results, indicating the time it takes in days for particles to reach shallow Florida waters (left) and shallow Cuban waters (right).
Overall particles start reaching shallow Cuban waters earlier, than shallow Florida waters. For Florida, test locations further east (TLs 03-05) typically show higher percentages throughout the summer and winter test simulations than locations further west (TLs 01-02). For Cuba, we can make no such distinction. Several maxima can be identified, the most common of which is around day ten. Other maxima are prevalent around days seven and eight for Cuba, and days four through six for Florida. As previously, the overall percentages of particles reaching Florida are higher in the summer, than in the winter, and reaching Cuba are higher in the winter than summer. Interestingly, for the seasonal maxima cases (Cuba in the winter, and Florida in the summer) we observe roughly 4% of the particles reaching shallow water on day four. While we observe a number of particles reaching shallow water on or around day ten, cumulatively more particles reach shallow water during the previous days. Additionally, the main geographical focus of this investigation are Northern Cuba and Southern Florida, which both see an impact in the earlier days of the simulation. We conclude that ten days is long enough to accumulate particles off the South Florida and North Cuban shore, and get a good sense of the particle distribution.

**Hurricane Andrew 1992 [H00]**

The effect of changing the landfall position of Hurricane Andrew is analyzed to account for the unpredictable and unique nature of many tropical cyclones. The original re-analysis fields are modified by moving them latitudinally by up to ±3.0°. Figure 2.10 (a) shows the results obtained at TL 05 where “0” denotes the original hurricane track. From this exploratory analysis, it seems that landfall positions further south increase the impact on Florida (i.e. −3.0°, O[25%]), whereas northern tracks generally decrease the impact. A likely contributing factor are the strong south-easterly hurricane winds. As shown in Figure 2.10 (b) only a small difference in the percentage of particles reaching Florida is observed for the ±0.5°, +2.0°, and −1.0° cases. The
+3.0° case, (black line in Figure 2.10 (a)) results in the least impact on Florida, as the particles are likely caught in strong westerly/northwesterly hurricane winds. The maximum case of this exploratory analysis (track moved by 3.0°S) at TL5 is further explored in Section 2.5.2, and is the simulation termed H02.

![Figure 2.10](image)

**Figure 2.10:** Sensitivity simulations examining the effect of different Hurricane Andrew ’92 track positions. Panel (a) shows the hurricane tracks, and panel (b) shows the corresponding percentages of particles reaching shallow Florida in the matching color.

### 2.5 Results

This section is divided into the results from the seasonal simulations (S runs), and the results from the hurricane simulations (H runs). We differentiate between results obtained from the drifter-based climatology (S01-S02), and results obtained using HYCOM (S03-S04). Throughout this section, the reader should keep in mind that the S01 and S02 simulations use a seasonal climatology as their ocean input, whereas simulations S03 and S04 are run using HYCOM model fields from an actual summer (July 2014) and winter (January 2014) case. For a more detailed summary of the different simulations the reader is referred back to Table 2.2. In each subsection, we
present a series of contour maps, which show the probability of any of the 97 launch location yielding particles in shallow Florida or Cuba water, as well as the probability of particles making landfall in either region. These maps are designed to address **Objective (II)** of this study. We further evaluate a series of distribution maps that show the location of particles from all 97 launch locations after ten days. These maps are used to evaluate **Objective (I)**. Several time series from the individual runs are shown to assess how fast oil could potentially reach the Florida shoreline, and quantify the response time. Finally, we highlight the worst-case scenario for Florida, which is defined by the launch location that yields the highest percentage of shallow and beached particles in the S01 and S02 runs.

### 2.5.1 Seasonal Simulations [S01-S04]

**Evaluation of Launch Locations**

**Drifter-based ocean climatology [S01-S02]**  
**Figures 2.11 and 2.12** show the interpolated probabilities of particles reaching any shallow Florida waters, and making landfall anywhere in Florida for each launch location, respectively. Summer I/Winter I refer to the buoy runs [S01], and Summer II/Winter II refer to the QuickSCAT runs [S02]. The reader is referred back to **Table 2.2** for a summary of the data sets involved in the different S simulations. The colored contours indicate the likelihood of particles reaching Florida or making landfall, with darker colors indicating a higher probability. For instance, a value of 20% in **Figure 2.12** indicates that if particles are initialized at that location, they have a 20% chance of reaching the Florida shore within ten days. As is anticipated, drilling sites located further offshore, in the northeastern launch domain, have the highest probability of impacting Florida. The individual particle trajectories (**Appendix C**) reveal that particles departing from those locations tend to get trapped in the Florida Current and transported northwards. This is especially true during the summer (**Figures 2.11(a)**), when the current exhibits a stronger
core (Figure 2.3). The probabilities of a Florida impact decrease substantially, as one moves towards the western launch domain. The interested reader is referred to Appendix C for a set of sample trajectories from the four seasonal simulations S01-S04.

Overall, we observe good agreement in the percentages between the S01 runs (Figures 2.11(a,c) and 2.12(a,c)) and S02 runs (Figures 2.11(b,d) and 2.12(b,d)). The S01 runs predict slightly larger maximum values for Florida in the summer (O[40%]), than the S02 runs (O[30%]). Given that the same ocean climatology is used for these runs, these differences exist due to the fact that the buoy winds are un-smoothed, and therefore slightly larger in magnitude. At Fowey Rocks, FL, for example, the July 1-10, 2014 mean is 5.24 ms\(^{-1}\), whereas the SCOW value at Fowey Rocks, FL is only 2.93 ms\(^{-1}\). Appendix D provides a more comprehensive discussion of the differences between the buoy and SCOW fields. We further notice that, for each individual simulation (compare Figures 2.11 and 2.12 column by column), the summer values are generally slightly larger than the winter values. This observation is in good agreement with the preliminary results. Naturally, the percentages of particles in shallow water are consistently higher than the percentages of beached particles, regardless of the season. Specifically, their mean rates vary by O[2%], while their maxima differ by O[5 – 15%].

<table>
<thead>
<tr>
<th></th>
<th>Florida</th>
<th></th>
<th>Cuba</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>summer</td>
<td>winter</td>
<td>summer</td>
<td>winter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHALLOW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S01</td>
<td>9.48 %</td>
<td>8.16%</td>
<td>8.08%</td>
<td>18.51%</td>
</tr>
<tr>
<td>S02</td>
<td>7.16%</td>
<td>6.82%</td>
<td>7.07%</td>
<td>16.31%</td>
</tr>
<tr>
<td>BEACHED</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S01</td>
<td>7.02%</td>
<td>6.58%</td>
<td>6.13%</td>
<td>15.87%</td>
</tr>
<tr>
<td>S02</td>
<td>4.59%</td>
<td>4.90%</td>
<td>5.08%</td>
<td>13.72%</td>
</tr>
</tbody>
</table>

Table 2.4: Mean probabilities of particles reaching Florida and Cuba for the seasonal S01-S02 simulations - supplement to Figures 2.11 and 2.12.
Figure 2.11: The probability of particles reaching shallow water in Florida, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S01, and panels (b) and (d) from S02.

Figure 2.12: The probability of particles making landfall on Florida, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S01, and panels (b) and (d) from S02.
Figures 2.13 and 2.14 show the same contour maps for Cuba. As previously stated, the roman numerals refer to the different simulations summarized in Table 2.2. We notice that the percentage distribution for Cuba looks very different from the percentage distribution for Florida. In fact, to a first approximation, launch locations that are barely affecting Florida, heavily affect Cuba, especially in the southern and southeastern launch domain. Potential drilling sites closest to the Cuban coast (especially around the Matanzas Province) show the largest impact on Cuba. The probabilities for both shallow and beached particles decrease as one moves further away from the Cuban coast. Again, we observe good agreement in terms of percentages between the S01 and S02 runs (compare Figures 2.13 and 2.14 row by row).

Similarly to the Florida case, the S01 simulations predict slightly larger values than the S02 simulations. Overall, we observe the highest percentages of particles reaching shallow water, or beaching themselves in Cuba, partly due to the close proximity of the launch locations to the Cuban shore (Table 2.4).

The seasonal variation pointed out for Florida is even more apparent for Cuba, where percentages for the winter runs are consistently larger than the summer by a factor of two (Table 2.4). In the winter we observe many launch locations in the western domain yielding percentages up to O[10-30%] (compare bottom panels of Figures 2.13 and 2.13), which show values of O[0-10%] in the summer. The prevailing wind regimes (Figure 2.4) play a significant role in these seasonal variations. In the summer, the strong south easterlies that dominate northern Cuba, manage to push many of the particles offshore, reducing the impact on Cuba, and increasing the effects on Florida. In the winter, strong north easterlies push particles towards the Cuban coast and away from Florida. Given that the Florida Current continuously advects particles towards the north throughout the simulation, it is not surprising that the seasonal variation observed for Florida is not as distinctive.
Figure 2.13: The probability of particles reaching shallow water in Cuba, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S01, and panels (b) and (d) from S02.

Figure 2.14: The probability of particles making landfall on Cuba, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S01, and panels (b) and (d) from S02.
HYCOM [S03-S04]  Figure 2.15 shows the interpolated probabilities of particles reaching shallow Florida waters for the summer and winter simulations of S03 and S04. While we compare these results to Figures 2.11, caution should be taken in making location by location comparisons due to differences in the ocean input data. The reader is referred back to Section 2.3 for a discussion of these variations.

![Figure 2.15: The probability of particles reaching shallow water in Florida, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S03, and panels (b) and (d) from S04.](image)

The most striking differences to the previous runs are the significantly higher percentage values of the S03 and S04 summer simulations, whose highest values reach 50-70% and 40-60% (compare Figures 2.11 (a-b) and 2.15 (a-b)). Further, launch locations towards the center of the Florida Straits pose less of a risk to Florida than before. Much of these variations can be explained, if we reconsider the dynamics of the Florida Current during the simulation time periods (winter: January 1-10, 2014; summer: July 1-10, 2014). We notice an eddy located right at the center of the Florida Straits, and mark the southern position of the FC core, which pulls particles
towards the Florida coast, even from more southern launch locations. The eddy causes particles that previously traveled towards the Florida shore, to be trapped in the Florida Straits instead. The magnitude of the S03 and S04 winter runs (Figure 2.15 (c-d)) is in very good agreement with previous estimates from the S01 and S02 simulations. Again, the shift of the maximum percentages further south can be attributed to vortices located in the area. For this set of simulations, the S04 runs yield slightly higher values for the summer only. While we would expect S04 to show higher percentages than S03 for the winter as well (due to the un-smoothed buoy wind input), we can explain the discrepancy as follows. Particles spent most of their time trapped in and around the eddy, which is a region of sparse buoy data, making the interpolated wind velocities in that specific region less accurate.

Figure 2.16 shows the contour maps associated with shallow Cuban waters for the S03-S04 simulations. The percentage values for the summer S03 and S04 runs are much lower than the S01 and S02 simulations in most of the drilling domain. For the winter, the values are in good agreement close to the Cuban shore, but vary by a factor of two or more towards the center of the domain. Again, we point out the presence of two eddies that significantly affect the behavior of particles. In the summer, the eddy located at the center of the Florida Straits mitigates the effects on Cuba by directing the particles offshore. In the winter, the eddy located in the western launch domain also prevents particles from reaching shallow Cuban waters. We also note that a significant amount of particles re-enter the Gulf of Mexico, instead of spreading towards Cuba. The last point will become more apparent in the next section, as we discuss the distribution of particles. The seasonality of the results is also apparent in the S03 and S04 simulation (Table 2.5), though now it is less distinct for Cuba due to the presence of eddies in the region.
Figure 2.16: The probability of particles reaching shallow water in Cuba, given as a percentage value, for each launch location. Panels (a) and (c) are the results from S03, and panels (b) and (d) from S04.

The similarity between S03 and S04 runs (and previously the S01 and S02 runs) themselves, could hint to the fact that overall, local ocean dynamics play more of a role than the local wind dynamics in the transport of oil at the ocean surface. The differences between the results of the drifter-based climatology runs [S01-S02] and the HYCOM runs [S03-S04] illustrate the importance of considering the local eddy and meander dynamics. Even though Figure 2.3 shows that the drifter-based climatology and HYCOM fields are broadly similar, the results indicate that even small variations in the eddy field at any particular point in time can produce very different outcomes. At the time of any oil spill, it is therefore important to use the best available knowledge of the state of the Florida Straits at that specific time, for an effective prediction.
Table 2.5: Mean probabilities of particles reaching Florida and Cuba for the seasonal S03-S04 simulations - supplement to Figures 2.15 and 2.16.

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<th>Florida</th>
<th>Cuba</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>summer</td>
<td>winter</td>
</tr>
<tr>
<td>S03</td>
<td>7.13%</td>
<td>4.46%</td>
</tr>
<tr>
<td>S04</td>
<td>7.72%</td>
<td>7.54%</td>
</tr>
</tbody>
</table>

Distribution of Particles after Ten Days

Drifter-based ocean climatology [S01-S02] The maps in Figure 2.17 and Figure 2.18 show the particle distribution after ten days for S01 and S02, respectively. The distribution maps show the combined effects of all 97 launch locations. Based on the analysis of the probability maps, we expect to see slight variations between the two seasonal cases. It should be noted that it appears as the S01 runs (Figure 2.17) do not extend as far north as the S02 runs (Figure 2.18). This is due to a lack of wind buoy data after Cape Canaveral and Trident Pier (Figure 2.2). Quantitative comparisons are therefore only made until latitude 28°N.

In the previous section we point out that the buoy runs [S01] tend to produce higher probabilities for Florida than the SCOW runs [S02]. Figure 2.17 and Figure 2.18 seem to indicate the opposite, as more particles seem to accumulate off the Florida coast in the SCOW runs [S02] (Figure 2.18), as opposed to the buoy runs [S01] (Figure 2.17). However, that is because the probability maps (Figures 2.11 and 2.12) only take into account particles located in shallow water, whereas the distribution maps include a larger geographical area. Further, the probability maps take into account the whole ten day time period, whereas the distribution maps show the location of particles on day ten.
Figure 2.17: Distribution maps of particles after ten days for S01 in the (a) summer and (b) winter. The boxes indicate the amount of particles in the respective boxes.

Figure 2.18: Distribution maps of particles after ten days for S02 in the (a) summer and (b) winter. The boxes indicate the amount of particles in the respective boxes.
We first note the two different seasonal maxima that are described in the previous section: for both S01 and S02, the Florida shore is potentially exposed to more oil during the summer (O11% [S01], O17% [S02]), and Cuba is more affected in the winter (O11% [S01], O17% [S02]). Additionally, the percentage concentrations of oil extend further up the Florida shore during the summer, than during the winter. Specifically for the summer, we see particles spreading from the Upper Florida Keys to Jupiter, with a large cluster near Key Largo. For the winter, we observe the same maxima near Key Largo, but the particles only extend to Miami-Dade County.

Overall, the summer runs are more dispersive than the winter runs. For instance, for S02, the particles contaminate an area of 332,500 km\(^2\) in the summer, and 254,100 km\(^2\) in the winter after ten days. Part of the reason are the dominant wind regimes of the summer and winter (Figure 2.4). It should be noted that these areas are not affected with equal likelihood.

Due to the well-defined Florida Current and trade winds, the Bahamas remain largely unaffected in the summer and winter. However, the S02 simulations (Figure 2.17 and Figure 2.18 (b)) suggest that the Grand Bahama Island, close to the city of Freeport, as well as the eastern part of Andros, are exposed to \(\sim 1\%\) of the particles after ten days. While the elongated feature shown in Figure 2.18 (b) around 24.5\(^\circ\)N and 79\(^\circ\)W may seem unusual, observational evidence from actual oil spill has suggested that oil does form similar features; in the literature, these shapes are referred to as “fingers” or “tiger tails” (e.g. Sebastiao and Soares, 1995; Özlükmen et al., 2016).

**HYCOM [S03-S04]** The distribution of particles after ten days for S03 and S04 is illustrated in Figures 2.19 and 2.20, respectively. Similarly to Figures 2.17 and 2.18, a significant amount of particles can be found in the Florida Keys [S03 only], and the particles extend further north during the summer simulations. As before,
the Bahamas remain largely unaffected and the summer simulation is more dispersed than the winter simulation. We observe less particles located around the Cuban shore than previously. Instead, particles accumulate in the center of the Florida Straits, and northwest of the Cuban coast. Both these areas coincide with the location of eddies (compare to Figure 2.3). We further point out the fact that we see a significant amount of particles that re-circulate into the GoM, which was not predicted in the S01 and S02 simulations. The Florida coast is, again, more affected in the summer (O9%[S03], O10%[S04]), than in the winter (O9%[S03], O 3%[S04]). However, the seasonality of the impact on Cuba is not as extreme as previously shown, which can also be attributed to the coherent vortices that trap the oil particles and keep them away from the Cuban shore. The distributions of S03 and S04 are both in very good agreement with each other.

![Figure 2.19: Distribution maps of particles after ten days for S03 in the (a) summer and (b) winter. The boxes indicate the amount of particles in the respective boxes.](image-url)
Figure 2.20: Distribution maps of particles after ten days for S04 in the (a) summer and (b) winter. The boxes indicate the amount of particles in the respective boxes.

Florida Worst-Case Scenario

Distribution maps that represent the worst possible outcome are often of high interest to oil spill responders, as they craft potential contingency and response plans, or even run practice response scenarios. Based on simulations S01 and S02 the worst-case scenario for Florida would be a spill from a launch location in the north east of the domain. A daily evolution of the particle distribution is shown in Figure 2.21. The launch site is marked by a black X, and the colored contours indicate the percentage of particles per grid box. Within one day, the oil starts to spread towards the east and northeast and has the potential to impact the Lower Florida Keys. On day two, the oil has reached the Upper Florida Keys, and by day four oil extends along the shore of Miami-Dade and Broward Counties. This trend continues, and at the end of ten days, the particles have spread up along the Florida east coast, approximately to the latitude of the Florida state line.
Figure 2.21: Daily distribution of particles for the Florida “worst-case” scenario, which is based on the results from S01 and S02.
2.5.2 Hurricane Simulations [H01-H02]

Evaluation of Launch Locations

Figure 2.22 shows the probabilities of particles reaching shallow Florida or Cuban waters from the hurricane simulations (H01 and H02). Seeing as the ocean climatology employed for H01 and H02 closely resembles the summer runs of S01 and S02, we expect to see at least some similarities between the results. Indeed, the contour maps for Florida (Figure 2.22(a,c)) are most similar to Figure 2.11(a).

For H01 the percentage of particles impacting Florida increases from 30% to 40% for the northeastern launch locations (Figure 2.22(a)), as a result of the strong cyclonic winds. Simulation H02 predicts a similar order of magnitude as S01 and S02. Cuba is significantly less affected in both runs (H01 and H02) when compared to the seasonal simulations (S01 and S02). As is illustrated by varying the two re-analysis
fields, the percentage impact on Florida and Cuba is a strong function of the local winds. Moving the hurricane field by only a few degrees produces outcomes that vary by as much O[10%]. The mean values of particles reaching Florida and Cuba are summarized in Table 2.6. This suggests that accurately determining the trajectory of oil during a hurricane would be extremely difficult, due to huge uncertainties associated with both systems. From the preliminary runs we expected that a more southerly hurricane track [S04] would result in higher percentages for Florida. However, we cannot confirm this preliminary finding after the grid simulations. Possible explanations include the fact that only a small subset of TLs was tested, and that the predicted probabilities are a strong function of when the hurricane hits the domain.

<table>
<thead>
<tr>
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<th>Cuba</th>
<th>Florida</th>
<th>Cuba</th>
</tr>
</thead>
<tbody>
<tr>
<td>H01</td>
<td>12.07%</td>
<td>5.46%</td>
<td>9.11%</td>
<td>4.29%</td>
</tr>
<tr>
<td>H02</td>
<td>8.70%</td>
<td>4.90%</td>
<td>6.10%</td>
<td>3.20%</td>
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</tbody>
</table>

Table 2.6: Mean probabilities of particles reaching Florida and Cuba for the hurricane H01-H02 simulations - supplement to Figure 2.22.

Distribution of Particles after Ten Days

The distribution of particles after ten days for H01 and H02 is illustrated in Figure 2.23. At first glance, the distribution resembles the S01 and S02 cases closely, however, small differences are observed in the percentage of particles reaching Florida, and in the areas that contain a significant number of particles. For instance, contrary to the summer S02 simulation, the majority of the particles extend to the Upper Florida Keys. One explanation is that the cyclonic winds of the hurricane push particles offshore, instead of onshore. In both runs, Cuba sees less of an impact than Florida. The main difference between H01 and H02, is the extent to which the particles enter the GoM. We point out, however, that in the H01 simulation the Central Florida Keys seem to be affected more than in previous runs. The northern track
from H01 allows particles to be caught in southwesterly winds on the backside of the hurricane, and be pushed into the GoM. For H02 more particles accumulate off the Florida shore than for H01.

One caveat of this hurricane simulation is the fact that one might expect to see higher weathering rates if the oil were to be exposed to hurricane force winds. To keep the model parameters consistent, the weathering rate for the Hurricane Andrew simulation is not changed in this model. Figure 2.8 (a) showed the impacts of changing the weathering rate on the percentage of particles beaching themselves. Using this figure, the values for the hurricane model results may be extrapolated for a higher weathering rate.

\[ \text{Figure 2.23: Distribution maps of particles after ten days for (a) H01 and (b) H02. The boxes indicate the amount of particles in the respective boxes.} \]
2.5.3 Time Series for all Simulations

One of the most important metrics from an oil spill response perspective is the time until oil impact. That is because knowing when oil will reach which parts of the coast is essential to efficient allocation of scarce resources, and the mitigation of the potentially disastrous effects of an oil spill. The time it takes for particles to reach shallow Florida waters for all simulations is evaluated in this section, with a set of time series. Figures 2.24-2.26 show the mean (blue line), ±1 standard deviation (light blue shading), and range (black lines) of the cumulative percentages of particles reaching the Florida coast each day. Overall, the four seasonal cumulative time series from S01 and S02 are relatively similar (Figures 2.24). The highest cumulative percentage (mean O(10%)) at the end of day ten is observed for the summer (Figures 2.24 (a)). For S01, the summer simulation sees particles starting to reach the Florida shore around days two and three, while the winter simulation particles reach the shore slightly later between days three and four. No such distinction can be made for the S02 simulation.

![Cumulative Percentage (CP) time series for S01 and S02.](image)

**Figure 2.24:** Cumulative Percentage (CP) time series for S01 and S02.
Figure 2.25: Cumulative Percentage (CP) time series for S03 and S04.

The most apparent difference between S01, S02, and S03 (Figures 2.25), is that particles start to reach shallow Florida water as early as day one in the summer. In the winter, particles start to reach Florida slightly earlier as well, around day two. The same observations are made from the S04 runs. The maximum CP (black line) for the summer is predicted by S03 to be approximately 75%, and for the winter by

Figure 2.26: Cumulative Percentage (CP) time series for H01 and H02.
S04 to be around 40%. Similarly to S03 and S04, both hurricane simulation (H01 and H02) predict a Florida impact as early as days one and two, with maximum cumulative impact of 40% to 50% (Figure 2.26).

A more significant comparison can be made when considering the individual means of the simulations, which are summarized in Figure 2.27. While we see that the summer means (S01-S04) are relatively close to one another, we note significant difference in the range of values between the different simulations (Figures 2.24-2.25). This could be the result of a specific set of particles being caught in a mesoscale feature, away from the mean current, for example, producing larger ranges. The particles from the summer S03 and S04 reach Florida first (day one), followed by H01 and H02 around day two. Figure 2.27 (b) shows that while some winter runs see impact starting around day two, more particles begin to reach Florida starting around day four. Overall, the S01 runs reach the shore a few hours earlier than the S02 simulations. Depending on the run, the cumulative means on day ten reach between 7% and 9% in the summer, and 4% to 7% in the winter, with a maximum value of around 12% predicted by H01.

**Figure 2.27:** Cumulative time series showing the mean for all simulations.
2.6 Model Validation

Ideally, the performance of any oil spill model is assessed by comparing its results to real-life observations (Spaulding, 2017). Since no such data is available in our region of interest, we choose to validate our results against the motion of undrogued drifters, and model output generated by NOAA’s Trajectory Analysis Planner (TAP).

Undrogued Global Drifter Program drifters

Previous studies have suggested that the motion of undrogued drifters may be used as a proxy for the behavior of oil and in the verification of oil trajectory models (Reed et al., 1987; Lumpkin et al., 2017). In fact, the slip coefficient of undrogued drifters is estimated to be around 1% of the wind speed (e.g. Poulain et al., 2009), which is closer to the windage of oil ($\sim 3.0\%$). Reed et al. (1987) established that the comparison between undrogued drifters and oil is especially applicable under calm conditions, with little wave-breaking and wind speeds less than 6 ms$^{-1}$, which is the case in large portions of the model domain (Figure 2.4). The undrogued drifters used for the model comparison are obtained from the GDP data set between February 14, 1999 and December 12, 2015. Only drifters that pass through the launch location box, defined by the outer limits of the 97 launch locations ($85^\circ W \leq x \leq 81^\circ W; 22^\circ N \leq y \leq 24^\circ N$) are chosen. For the drifter distribution map, the model domain is divided into a discrete grid of boxes of $\frac{1}{4}^\circ$ resolution. This is the same grid that was used to construct the distribution maps.

In Figure 2.28 (a) the ten day trajectory of 59 undrogued GDP drifters are shown. The trajectory start points are located within the launch site box (light blue background shading). Surface drifters that pass through water less than or equal to 10-m in depth at any point in their life time are shown in blue. In total, 18.6% of the GDP drifters pass through shallow water. Caution should be taken when making statistical comparisons to the model results, due to a small number of sample points
(59 drifters). However, the number of drifters reaching shallow water does, at the very least not, contradict the model results. The trajectories mapped out by the drifters are also in good visual agreement with our results. Most drifters are trapped in the FC and move north up the east coast of Florida, eventually joining the Gulf Stream. Some drifters, however, remain in the launch location area and approach the Cuban coast. A few drifters also re-circulate into the Gulf of Mexico. Yet others exhibit a looping motion and reside in the waters northwest of Cuba. Figure 2.28 (b) shows the distribution of (37 remaining) GDP drifters after ten days. We observe a cluster of drifters off the Florida coast around 26° N, several drifters spread out through the Florida Keys, and a few are located close to the Cuban shore. Again, the distribution pattern is in qualitative agreement with the model results.

**Figure 2.28:** (a) Ten day un-drogued GDP drifter trajectories and (b) distribution of un-drogued GDP drifters ten days after leaving the launch location box

**Trajectory Analysis Planner**

NOAA’s TAP uses six years (1992-1998) of model output from GNOME to generate valuable statistics on oil spills (NOAA, *Trajectory Analysis Planner (TAP) User’s Manual Florida Straits edition*). The planner was originally developed to help the U.S. Coast Guard and other first responders with contingency planning. Some of the
statistics calculated by TAP include areas that are most likely to be impacted by a spill, how much oil could reach those sites, and when oil would hit specific parts of the coastline (NOAA, *Trajectory Analysis Planner (TAP) User’s Manual Florida Straits edition*). GNOME is a Eulerian/Lagrangian model that calculates oil trajectories by careful consideration of ocean surface currents and winds (Beegle-Kraus, 2001). The *Florida Straits Edition* employs the Princeton University Hydrodynamic Model of the Gulf of Mexico, and calculates winds from observational and model data (NOAA, *Trajectory Analysis Planner (TAP) User’s Manual Florida Straits edition*). GNOME also takes into account the bathymetry and coastal configuration of the model locations, along with oil weathering processes. The oil trajectories are initialized at 20 different locations north and northwest of Cuba for random start dates to capture as much variability as possible (Barker, 2011). It should be noted that TAP combines all the trajectory simulations for its analysis, and therefore, does not capture seasonal variability.

When generating output from TAP, the user can choose between different release rates and levels of concerns, which are expressed in terms of barrels or gallons per day, and per cell, respectively. Since it is relatively difficult to convert between a quantity given in barrels per day and a certain number of particles released per hour, we explain these quantities in terms of percentages. For the comparison we choose a release rate of 50,000 barrels per day and a level of concern of 500 barrels per cell. Expressed in terms of percentages, this means grid cells that show more than 0.1% of the oil are taken into account in the analysis. For example, in Figure 2.29 a value of 100 % (red) indicates that all of the GNOME simulations observed a concentration of at least 0.1 % in that cell. Thus, we note that the TAP colored contoured maps indicate the most likely position of oil after a release period of ten days, regardless of the season. Our distribution map contours indicate where most of the oil is located after ten days for two seasonal climatologies (S01-S02), and two specific summers and
winters (S03-S04). While these are two different metrics they essentially provide the same information to the reader, and a comparison between the two models is thus valid for qualitative purposes. This specific drilling site is chosen as it is relatively close the available TAP sites, and predicts significant impact for Florida.

![Figure 2.29:](image)

**Figure 2.29:** The most likely distribution of oil after a continuous ten day spill as generated by NOAA’s TAP.

**Figure 2.30** shows the distribution of particles after ten days from launch location 71 for all four seasonal simulations (S01-S04). The grid size was adjusted to match the grid choice of TAP to allow for the best possible comparison. We note that the same drilling site gives rise to an array of different particle distributions, which are driven by the local ocean dynamics, as well as the local wind forcing. At first glance, the summer S02 simulation (**Figure 2.30 (c)**) resembles the TAP distribution most closely. For the best comparison to TAP, we imagine a combination of all eight different outcomes. When combining **Figure 2.30 (a-h)**, we note that we recover the highest concentrations at the drilling site, and to the northeast of it. We observe a similar pattern in the TAP map. Our maximum extent also corresponds well with the maximum extent predicted by TAP (Northern Florida). Approximately 0%-20% of the TAP trajectories predict oil spreading west of the drilling site, a pattern that
is featured in the S03 and S04 simulations (Figure 2.30 (e-h)). The fact that this distribution pattern is considered to be less likely by TAP (Figure 2.29) is in good agreement with our results, that only showed this specific pattern due to the vortex located in that area (Figure 2.30 (e-h)).

**Figure 2.30**: The distribution of particles after ten days from launch location 71, as generated by the different seasonal simulations S01-S04.

**Figure 2.31** shows the response time in days as predicted by TAP, from the same drilling site as Figure 2.29. As previously noted, the response time indicates the number of days it will take the oil to reach a certain location. We use these results from TAP to validate our findings from the time series Section 2.5.3. Similarly to our results, the oil is relatively localized during the first day of the spill, but starts
reaching shallow Florida waters within a few days. The response time for the Lower Florida Keys is on the order of three to five days, but takes about five to ten days for the oil to spread further along the east coast of Florida.

Figure 2.31: A map of the response time in days for Florida from the indicated drilling site.
Chapter 3

Conclusion

3.1 Summary

In light of continuous interest in the Florida Straits as a potential source for petroleum, this work focused on the development and analysis of a Lagrangian particle advection model that simulates an oil spill from the proposed drilling locations. The two-dimensional particles were initialized on a grid of 97 different launch sites located around Cuba’s leasing blocks. The model was run continuously for a ten day period in a seasonal and hurricane mode. The effects of oil weathering were approximated with a Monte-Carlo scheme using a half-life of 100 hours. Wind data was obtained from NOAA and CWOP buoys, SCOW based on QuickSCAT data, and a blended-model analysis of Hurricane Andrew. Ocean input data was taken from a drifter based ocean current climatology and HYCOM fields at 1km spatial resolution. The effects of large scale turbulence and diffusion were parameterized by a Lagrangian Stochastic Model.

Figure 3.1 provides a summary of the findings of this work in terms of the original objectives (Chapter 1). Light blue rectangles indicate the launch locations that show
the most impact for Florida, and dark blue rectangles indicate which launch locations show the greatest impact on Cuba. The shoreline regions in Florida, Cuba, and the Bahamas that are most likely to be affected are outlined in black.

Figure 3.1: A map of the area of interest summarizing the findings for the study objectives. Potentially affected areas are highlighted in dark green. Launch locations most likely to affect Cuba are marked in dark blue, launch locations most likely to affect Florida are marked in light blue.

For the drifter-based ocean runs [S01-S02], overall, we found good quantitative and qualitative agreement between the buoy [S01] and climatology simulations [S02], with mean values differing by $\sim 2.0\%$ and maximum percentages varying $O(5.0\% - 10.0\%).$
The results revealed a strong seasonal dependence. More particles end up in shallow water and beach themselves in Florida, in the summer, as compared to the winter. The opposite is true for Cuba, where higher percentages are observed in the winter. The seasonal variation is strongest for Cuba. Satisfactory quantitative and qualitative agreement is also seen between drifter-based runs [S01-S02], and the HYCOM based runs [S03-S04]. For [S03-S04], the local ocean dynamics are responsible for predicting higher probabilities of impact for Florida. The differences between the drifter-based climatology runs and the HYCOM runs highlight the importance of having access to real-time observations when predicting the behavior of an actual oil spill. The presence of mesoscale features, such as meanders and eddies, has the ability to significantly impact the distribution of particles.

The probability maps reveal that a spill from the drilling locations along the Cuban shoreline would most likely affect large parts of the north Cuban coast, with probabilities being larger in the winter, relative to the summer. A spill at the center of the Straits would tend to carry oil towards the Florida Keys and the east coast of South Florida. This is especially true during the summer season. Drilling locations at the center of the domain will favor the advection towards the northeast in the summer, and south in the winter. A spill at the drilling locations furthest west will drive particles into the GoM, and towards the west Cuban shoreline. In terms of **Objective II**; independent from the season, Florida could be most affected by northeastern and central drilling sites, whereas Cuba has the highest potential of being affected from locations in the southeast, or southwest of the domain (*Figure 3.1*).

The distribution maps reveal that the summer simulations are more dispersive than the winter, and show large clusters in the Florida Straits, the Florida Keys, off the South Florida coast, and northwest of the Cuban coast. Variations are seen between the individual simulations. Coherent vortices have the ability to trap particles
and change their distribution and impact. The winter distribution is more localized and has the potential to affect the northern shoreline of Cuba, as well as the Lower Florida Keys. Surprisingly, only a few percent of particles arrive near the western edge of the Bahamas, which remain largely unaffected. The maximum latitudinal extent of the simulations suggests that particles could reach the Florida/Georgia state line within ten days of a spill. In terms of Objective I; we conclude that the areas most likely to be impacted by a spill are the Upper and Lower Florida Keys, the east coast of South Florida, and the waters north and northwest of the Matanzas Province in Cuba (Figure 3.1).

The hurricane scenario resembles the regular summer seasonal cases the most, presenting similar outcomes at the same launch locations. Launch locations in the northeast launch domain affect Florida the most, and locations in the southwest of the domain affect Northern Cuba. Overall, we see an increased impact on Florida, and a decreased impact on Cuba. Sensitivity results suggest that the effects of hurricane force winds on the dispersion of oil is still poorly understood, as small changes in the hurricane velocity fields contribute to significant differences in particle distribution.

The results of the time series analysis reveal that oil particles generally reach the Florida shore slightly sooner in the summer (days one to two), than the winter (day three). The hurricane simulation shows impact after approximately two days. Cuba sees an impact from the closest launch locations within hours of the spill, regardless of the season. After a period of ten days, mean cumulative percentages of shallow water particles for Florida are on the order of 5%-10%. Particles continuously reach shallow water throughout the model simulation period. The response time calculated in this model is in good agreement with previous estimates (Chapter 1), and other model outputs (NOAA’s TAP).

To validate the model against real-life observations we considered all available undrogued GDP drifters in the region, and mapped their trajectories and distribution
after ten days. Approximately 20% of the drifters reach shallow water, a number that falls well within the model results. Due to a lack of additional drifter data, we are careful in making statistical comparisons between the two results, and conclude that the drifter data does, at the very least, not contradict our findings.

From a modeling perspective a few important aspects were confirmed. The behavior of the oil is a strong function of initial spill location, and initial spill parameters. The large-scale oceanic currents and the wind field both play a significant role in the distribution of oil at the sea surface. However, the discrepancies between the S01/S02 and S03/S04 results, suggests that the local ocean dynamics may have be important to the distribution of oil at the ocean surface. Further investigation into this topic is needed to make a clear statement.

3.2 Suggestions for Future Work

In light of this work the following is a list of suggestions for future work, some of which involve the improvement of this model, and others which involve the enhancement of the existing model. Most suggestions evolved from issues encountered throughout this research study.

(1) The improvement of the oil weathering scheme As was noted in Chapter 1 of this thesis, the current generation of oil spill models often attempts to model different oil weathering processes independently. Since this model parameterizes all natural and mechanical weathering effects through the use of a generalized half-life, there is still room for improvement. As a first step, algorithms for the natural processes, such as evaporation, could be added to the model while retaining the Monte-Carlo scheme as a way of parameterizing mechanical removal of oil.

(2) Comparison to spring and fall seasonal cases From the preliminary results it was concluded that the fall and spring seasonal cases generate results that
fall in between the summer and winter simulations. For a more complete picture of the model analysis, the spring and fall seasonal cases from all model runs should be added to the discussion.

(3) **Investigate the Importance of Mesoscale features** As was pointed out in the *Data Section*, we added a Lagrangian Stochastic Model to the HYCOM velocity field, even though it features a higher resolution than the drifter-based ocean current climatology. To investigate the importance of this, comparative runs using only the HYCOM velocity fields should be performed.

(4) **Adjustment of the LSM to smaller scales** To investigate how smaller scale features could affect the dispersion of oil, the addition of a Lagrangian Stochastic Model that parameterizes such scales could be added to the ocean input data sets. The LSM employed in this model could easily be adapted for this purpose by changing its Lagrangian integral time scale and velocity standard deviation.

(5) **Additional summer and winter simulations on different dates** Throughout this model we employ the months of January and July as representatives of the summer and winter seasons. To get an even better idea of the seasonal differences, wind and ocean data from different months and dates should be added as well. The resulting simulations should be averaged seasonally and annually. This would not only allow for a better comparison to existing models such as TAP, but also the drifter-based climatology runs. Using a larger array of input data would also allow us to quantify how different ocean dynamics influence the distribution of oil. For instance, the eddy we observed in the HYCOM velocity field may be located elsewhere later in the season, resulting in a different outcome.

(6) **Modifications to the Hurricane Andrew ’92 simulations** In the discussion of the Hurricane Andrew ’92 results we hint at the fact that the predictability and behavior of oil during hurricane-force winds is likely much different from regular
conditions. Improvements can be made to more accurately model the behavior of oil during the event of a hurricane, by implementing a higher weathering rate and adding subsurface components to the model.
Appendix A

Spring and Fall Simulations

As described in Section 2.4, the preliminary runs [S00] reveal that the spring and fall simulations yield results that fall in between the summer and winter simulations for both Cuba and Florida. Specifically, S00 shows that maximum values for Florida are expected in the summer, and for Cuba in the winter. For comparison and validation, this appendix explores the S01 simulation on the final grid for the spring and fall seasons. Table A.1 provides a summary of the data sets used for these simulations.

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<th>RESOLUTION</th>
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</tr>
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</table>

Table A.1: Summary of the wind and ocean input data used for the spring and fall simulations of S01.
Before considering the probability maps featuring the individual launch locations, we compare the frequency distribution of the percentage of shallow water particles for all four seasons (Figure A.1 and Figure A.2). A value of 60, for example, indicates that 60 launch locations predict an impact of the given percentage range for Florida or Cuba. For Florida (Figure A.1) we note, that there is less seasonal variability, but that the summer simulation predicts the highest probability of impact. The winter calculation has the highest frequency of launch locations yielding low impact (0%-10%). The spring and summer have comparable values for impact above 20%.

![Figure A.1: Frequency of launch locations per shallow particle percentage range for Florida.](image)

For Cuba (Figure A.2), we observe considerably more seasonal variation, with the winter consistently showing the highest frequencies of higher impact probabilities.
The spring and summer both show high frequencies at low percentage ranges. All four seasons show a few launch locations with an impact probability of higher than 90%, which are the drilling sites located closest to the Cuban shore.

**Figure A.2:** Frequency of launch locations per shallow particle percentage range for Cuba.

**Figures A.3-A.6** show the probability maps for the spring, summer, fall, and winter for both Florida and Cuba in shallow water and on land. The summer and winter maps are identical to the ones shown in Section 2.5, and are repeated here to ease the comparison to the other two seasonal cases for the reader. **Figure A.3** indicates that, as suggested by the preliminary results and the frequency plots, Florida sees maximum percentages in the summer, with comparable probabilities in the spring and fall, and least impact predicted in the winter. While this is true for most launch locations, we note that the maximum values are shifted slightly east in
the winter, and the central eastern launch locations predict slightly larger probability of impact in the spring and fall, than in the summer. We observe a similar pattern for the percentage of beached particles Figure A.4. While the spring and summer predict comparable percentage values, the affected launch locations vary slightly, with the spring sowing greater impact for central southern locations.

For Cuba (Figures A.5 and A.6), the final grid results are in excellent agreement with the preliminary runs. Most impact is predicted for the winter, followed by the spring and fall, with least impact predicted for the summer. Regardless of the season, we see a significant amount of particles reaching shallow water and making landfall for the locations closest to the Cuban shore, especially in the southeastern launch domain, which was previously noted in the frequency bar plot. The seasonal variation for Cuba is most pronounced in the center and western launch domain, where values vary between 30-40% in the winter, to 0-10% in the summer.

From this additional set of runs we draw and confirm the following conclusions: The seasonality of the results is most prevalent for potential impact on Cuba, with slight variations also predicted for Florida. For Cuba, the minimum and maximum impact cases coincide with the winter and summer seasons, respectively. For Florida, the distinction is less clear, and large potential impact is predicted throughout the spring and fall. However, due to the similarity in the results between the spring and summer for Florida, we do reconfirm that the summer simulation used for S02-S04 is a good proxy to predict potential impact.
Figure A.3: The probability of particles reaching shallow water in Florida for all seasons as calculated by S01, given as a percentage value, for each launch location.

Figure A.4: The probability of particles making landfall in Florida for all seasons as calculated by S01, given as a percentage value, for each launch location.
Figure A.5: The probability of particles reaching shallow water in Cuba for all seasons as calculated by S01, given as a percentage value, for each launch location.

Figure A.6: The probability of particles making landfall in Cuba for all seasons as calculated by S01, given as a percentage value, for each launch location.
Appendix B

Four Percent Wind Drift

In Section 2.3 we explain that, for the purpose of modeling, the effect of wind drift on oil is commonly approximated by using 3% of the 10-m wind speed. However, some have argued that a value of 3.5% or 4% may be better suited (e.g. Reed et al., 1987; Spaulding, 1988; Özgökmen et al., 2016). In accordance, this appendix explores results of the S02 run (Table 2.2) using a value of 4% of the 10-m wind speed.

Figure B.1 shows the probability of particles reaching shallow waters or making landfall in Florida and Cuba, respectively, during the summer. These maps are the equivalent of panels (b) in Figures 2.11 -2.14 but using a windage of 4% instead of 3%. At first glance, the two simulations agree well with each other; both show the same pattern and approximate percentages for the individual launch locations. As a consequence of the increased windage, we observe slightly higher values throughout the launch domain for the 4% run. For an even better comparison of the two S02 simulations, Figure B.2 presents a difference map, where the S02 [4%] run is subtracted from the S02 [3%] run. The colored contours depict the percentage difference between the two simulations, where blue indicates a negative, and red a positive difference. Red colors thus signify that the S02 [4%] run predicted larger percentages, and blue colors signify that the S02 [3%] run calculated higher percentages.
Figure B.1: The probability of particles reaching shallow waters, or making landfall in Florida or Cuba, given as a percentage value, for each launch location. Panels (a) and (b) are the Florida results, and panels (c) and (d) the Cuba results.

Figure B.2: The difference in probability predictions of the two S02 simulations. Panels (a) and (b) are the Florida results, and panels (c) and (d) the Cuba results.
For Florida (Figure B.2 (a-b)) the predicted percentages are within 2% of each other throughout most of the domain. We observe the most difference in regions of maximum percentages at the northern boundary of the launch domain, and even in areas of maximum variability, the predicted percentages vary by 5% at most. For Cuba (Figure B.2 (a-b)), the agreement between the two simulations varies by only 1% in most of the domain, with slightly higher variation along the north coast of Cuba. Overall the calculated differences are not larger than differences that were previously observed between individual runs, or individual simulations [S01-S04].

We next consider the distribution of Lagrangian particles after ten days, as shown in Figure B.3, which is the equivalent of Figure 2.18. For the S02 [4%] simulation we observe a similar distribution as for S02 [2%], especially in the Florida Straits, where the higher concentrations area clustered closer to the Cuban coast, to the northwest of the Cuban shore, and around the Upper Florida Keys. We do not observe a larger percentage of particles spreading up the east coast of Florida, in that sense the S02 [4%] simulation is more similar to the S01 run (Figure 2.17 (a)). The slightly larger particle windage seems to contribute to an increased spreading in particles, but overall the two calculations correspond well to one another.

To summarize, the probability and distribution maps for this summer simulation (S02) suggest that for the purpose of this model, the prominent rule of 3% of the wind speed is enough to approximate the windage of oil. We observe a variation of no more than 5% in isolated areas, that coincide with areas of maximum predicted percentages. These variations are, however, no larger than variations that are predicted by the use of different input data sets. To obtain an average picture of which parts of the coast might be impacted, and which launch locations might yield the worst impact, the simple windage approximation is sufficient. When trying to predict the exact future location of oil in the event of an actual spill, a more complex approximation, such as varying the windage randomly at every time step, may be more appropriate.
Figure B.3: Distribution maps of particles after ten days for S02 at four percent for the summer. The boxes indicate the percentage of particles located within that box after a period of ten days.
Appendix C

Sample Particle Trajectories

The following appendix introduces the reader to a diverse array of sample trajectories from the seasonal S01-S04 simulations. The trajectories and launch locations are picked at random for each set of simulations. Each trajectory map shows 100 different particle trajectories. Figure C.1 serves as a reminder and reference for the location of the different launch sites.

![Figure C.1: Numbered launch sites to be used as a reference for the particle trajectory Figures.](image_url)
Figure C.2: Sample trajectories from the S01 simulation. The left panel is from the S01 summer simulation, and the right panel is from the S01 winter simulation. From top to bottom the launch sites are 34, 67, and 72.
Figure C.3: Sample trajectories from the S02 simulation. The left panel is from the S02 summer simulation, and the right panel is from the S02 winter simulation. From top to bottom the launch sites are 24, 46, and 56.
Figure C.4: Sample trajectories from the S03 simulation. The left panel is from the S03 summer simulation, and the right panel is from the S03 winter simulation. From top to bottom the launch sites are 42, 54, and 86.
Figure C.5: Sample trajectories from the S04 simulation. The left panel is from the S04 summer simulation, and the right panel is from the S04 winter simulation. From top to bottom the launch sites are 08, 28, and 68.
Appendix D

Comparison of Wind Input Data

In the results section, we point out that the difference in magnitude between the S01 and S02 runs, as well as the S03 and S04 runs, can partially be explained by the use of un-smoothed buoy winds versus the use of SCOW fields. This appendix provides the reader with a comparison of the two data sets at several buoy stations. The geographical locations of the individual buoy stations are shown in Figure 2.2. The SCOW fields are interpolated to the locations of the buoy stations using a bicubic spline.

Figure D.1 shows the comparison of the wind input data sets for the summer, and Figure D.2 for the winter. As can be seen in Figure D.1, the buoy mean is consistently higher at the three sample stations (Fowey Rock, Molasses Reef, and Sand Key) in the summer period. During the winter (Figure D.2), the discrepancy is even more significant at Cape Canaveral and Fowey Rock, where the two means vary by at least a factor of two. At Vaca Key, FL the two winter means are approximately the same. Seeing that the SCOW fields seem to underestimate the magnitude of the wind speed for significant periods of time during the simulation, the fact that we do observe higher percentage for most of the buoy runs [S01 and S04] is plausible.
Figure D.1: A comparison of the two wind input data sets at different buoy stations. The thin black line shows the instantaneous wind speed as recorded at the buoy stations. The thick black line indicates the ten day average of the buoy data (July 1-10, 2014) and the thick red line shows the climatological wind speed as calculated from the SCOW fields.
Figure D.2: A comparison of the two wind input data sets at different buoy stations. The thin black line shows the instantaneous wind speed as recorded at the buoy stations. The thick black line indicates the ten day average of the buoy data (January 1-10, 2014) and the thick red line shows the climatological wind speed as calculated from the SCOW fields.
Bibliography


