Oil Spill Risk Management
Gulf of Mexico satellite sea surface temperature (SST) images (upper left: May 28, 2010; lower left: April 20, 1984) and sample DieCAST ocean circulation model SST plots (upper right: day 180; lower right: day 1220 (from Dietrich et al., 1997, see Ch 10).

The similarity between observations and model results published many years before is remarkable. The same DieCAST model was coupled to the authors’ oil spill dispersal model to hind-cast the oil spread from the 2010 Deepwater Horizon blowout (see cover picture and described in detail in Ch. 5).

1 http://eddy.colorado.edu/ccar/data_viewer/index
2 http://podaac.jpl.nasa.gov/dataset/JPL-L4UHfnd-GLOB-MUR
This book is dedicated to Dr. Verne E. Dietrich, the father of the first author. Dr. Dietrich Sr. was a mathematician who understood the nature of science, and who emphasized that it is as important to understand the reasoning behind science as it is to know science. His favorite hymn, “In the Garden” relates closely to the inspirational poem “Footprints”, which explains any successes that I [David E. Dietrich] have had in science.
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Preface

The Deepwater Horizon oil spill accident (variously referred to as the BP oil spill/disaster or the Macondo blowout) commenced on April 20th, 2010 on the BP-operated Macondo Prospect drilling platform. The ensuing fire aboard the drilling platform claimed eleven lives. Following the explosion and sinking of the floating oil rig, a sea-floor oil gusher flowed for 87 days, until it was capped on July 15th, 2010. The total discharge has been estimated at 4.9 million barrels (780,000 m³), and the event was considered by some authorities to be the largest accidental marine oil spill in the history of the petroleum industry. ¹

Gulf fisheries, tourism, nearshore and wetlands environments were also severely damaged by the blowout [1]. Much of the released material was less dense than the Gulf surface waters, so its buoyancy caused it to rise to the surface and accumulate in a spreading surface patch. Some of the surface material was quickly blown ashore by winds. Some floating residues were entrained into Gulf of Mexico mesoscale eddies and into the Loop Current that are dominant features of the central and eastern Gulf. The combined action of winds and underlying Gulf currents apparently kept the surface material from escaping from the Gulf through the Florida Strait.² A small amount of subsurface suspended denser material may have escaped undetected, either eastward through the Florida Strait or southward through the Yucatan Strait between Cuba and Mexico.

In this book, we attempt to address several important questions:

i. During the period of the Deepwater Horizon gusher, how did the major ocean circulation features transport and disperse oil fractions, both at the surface and at depth?

ii. Based on the oceanography of the Gulf, where might deep-suspended and coated bottom sediments be concentrated and where might they remain concentrated over many years?

¹http://en.wikipedia.org/wiki/Deepwater_Horizon_oil_spill
²http://en.wikipedia.org/wiki/Deepwater_Horizon_oil_spill
iii. How much remaining oil residue, if any, might be possibly churned up by future extreme weather events and subsequently made available to be blown ashore?

**Organization of the Book**

In Chapter 1 we compare the 2010 DWH event to the 2002 Prestige supertanker event; the ship broke up near the northwest corner of Spain and sank to about 3,500 m depth. This is of interest as both events leaked huge amounts of oil material near an open coast. In Spain and Portugal it gravely damaged fisheries and deposited tar-balls on beaches, damaging sensitive ecosystems and negatively impacting tourism. We also raise the question of how much of the DWH spilled oil remains in deep waters of the Gulf and the role of ocean models in explaining what happened.

In Chapter 2 we describe the dominant physical properties of the Gulf and its circulation patterns with a focus on those that affected the transport and fate of the DWH well blowout material. We describe exchanges of water and material at the lateral and surface boundaries, the spectacular Loop Current eddies, properties of the water column pycnocline and close with a brief discussion of the possible fate of the well blowout material.

In Chapter 3 we introduce basic concepts of geophysical fluid dynamics and how the motion and mixing of the Gulf’s waters influenced the transport and fate of spilled materials near surface, in the water column and near the bottom.

In Chapter 4 we discuss the coupling of the DieCAST ocean model to the Korotenko Oil Transport Module to create the Gulf of Mexico Oil Spill Model (GOSM) and the modeling approach to investigate the spreading, diffusion, transformation and evaporation of the spilled materials. The numerical approach is described along with the complexities of modeling near-equatorial circulation dynamics. We discuss major Gulf flow features that affect the fate of material leaked during the DWH event, plus the challenges inherent in running very long (multi-century) simulations.

In Chapter 5 we present the results obtained using the coupled GOSM to predict the transport pathways and fate of the various oil fractions released during the DWH accident.

Advanced Topics: Finally, in a series of appendices, we present a variety of advanced modeling topics for the expert modeler, with a focus on applications to the Gulf of Mexico.
It is hoped that our studies will provide useful information about how natural oceanographic and atmospheric processes can be successfully modeled using modern numerical methods in order to shed light on how these processes effect the transport and dispersion of hydrocarbons accidently released into the sea.

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Reference

Part I

Applied Oil Spill Modeling (with applications to the Deepwater Horizon oil spill)
The 2010 Deep Water Horizon and 2002 Supertanker Prestige Accidents

1.1 Introduction

The Gulf of Mexico is a marginal sea forming the southern coast of the United States, bounded on the northeast, north and northwest by the Gulf Coast of the United States, on the southwest and south by Mexico, and on the southeast by Cuba. The Gulf has a surface area of ~ 1.6 million km² with almost half of the basin being shallow continental shelf waters. However, in the Sigsbee Deep, an irregular trough more than 550 km long, the maximum depth is almost 4,400 m deep.¹ The dominant circulation feature is the Loop Current, which flows into the Gulf from the Caribbean Sea through the Yucatan Channel between Mexico’s Yucatan Peninsula and Cuba. The Loop Current subsequently feeds the Gulf Stream as it flows through the Florida Strait that lies between Florida, Cuba and the Bahamas.

The Gulf is a tropical and sub-tropical ocean basin boasting beautiful beaches, coral reefs, productive recreational and commercial fisheries,

¹ http://en.wikipedia.org/wiki/Gulf_of_Mexico
recreational boating, a unique Cajun heritage and extensive coastal wetlands supporting healthy ecosystems. The Gulf is considered by southern states to be an international treasure as well as a major economic resource for the southeastern United States.

There are about 3,850 oil rigs active in the Gulf, supporting over 50,000 drilling wells. The major environmental threats to the Gulf are agricultural runoff and oil drilling accidents. There are also more than 600 natural oil petroleum seeps that are estimated to leak between 80 to 200,000 tonnes yr$^{-1}$. The Gulf contains a large, elongated hypoxic zone south of the Mississippi River delta that runs east-west along the Texas-Louisiana

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2 Courtesy of the Colorado Center for Astrodynamics Research. http://eddy.colorado.edu/ccar/data_viewer/index
4 http://en.wikipedia.org/wiki/Petroleum_seep
5 http://books.nap.edu/openbook.php?record_id=10388&page=70
coastline\(^6\). There are frequent “red tide” algae blooms that kill fish and marine mammals and cause respiratory problems in humans and some domestic animals when the blooms reach close to shore. In recent years, these have been plaguing the southwest and southern Florida coast, from the Florida Keys to north of Pasco County, Florida.

1.2 The Oil Spills Described

Between the 10th of April and the 15th July, 2010, it is estimated that the Deepwater Horizon/Macondo well released about 780,000 cubic meters of blowout material into the Gulf. The volume of Macondo crude oil that was suspended at depth greater than the Florida Straits\(^7\) sill depth may be the most important factor in the end, because the residence time\(^8\) of deep Gulf waters is estimated to be about 250 years \([1, 2]\). Deep Water Horizon oil material residues that are denser than the surface water but less dense than underlying bottom water migrate vertically, due to buoyancy forces, until they reach water having their same material density. This may be called the residue’s equilibrium depth, because water density increases with increasing depth and has much smaller horizontal variability (which also would have little effect because gravitational acceleration totally dominates total acceleration). Details of such vertical migration are not important except during the short migration time; the pressure forces acting on the water are the same as the forces acting on the residue material; thus, after such equilibrium depth is reached, the material simply goes with the flow (of the ambient water) to within exceptionally good approximation. Thus, the suspended oil material deep residues, like their ambient water, has a residence time of up to 250 years unless it is ingested into the deep ecosystem or geochemically modified. The ambient waters experience typically only a few meters vertical displacement, except during short lived, localized violent churning under hurricane eye walls.

Further warning is implied by an event involving the supertanker Prestige running aground off the coast Spain. The ship subsequently sank off the northwest coast of Spain\(^9\). It leaked only one tenth of the oil spilled from the BP/Macondo well; yet tar-balls from the Prestige spill were still deposited on

\(^6\) http://en.wikipedia.org/wiki/Dead_zone_(ecology)  
\(^7\) http://en.wikipedia.org/wiki/Straits_of_Florida  
\(^8\) http://en.wikipedia.org/wiki/Residence_time  
\(^9\) http://en.wikipedia.org/wiki/Prestige_oil_spill
far-away beaches. This led to a serious decline in tourism along the Bay of Biscay coast (in both Spain and France). It also gravely damaged local fisheries.

However, unlike the Gulf of Mexico, the Bay of Biscay has no deep basin that can trap suspended materials. Rather, the Bay is open to the Atlantic Ocean. Thus, spilled Prestige oil could eventually be dispersed throughout a significant portion of the world’s oceans.

The Deep Water Horizon oil spill in the Gulf of Mexico in 2010 and the sinking of the Prestige supertanker event off the coast of Galatia, northwestern Spain in 2002 both released large amounts of crude oil into the ocean at great depths. Spilled oil fractions surfaced and polluted coastal regions including Gulf wetlands, open shorelands and Bay of Biscay beaches. Both seriously affected fishing and tourism industries. First responders were not adequately prepared to deal with such deep-water disasters as hundreds of workers painstakingly removed beached oil deposits and tar-balls.

The 2010 Deepwater Horizon and the 2002 Prestige supertanker accidents differed in important ways. For example, in the Deep Horizon accident, about 10 times more hydrocarbon source material was leaked into the ambient ocean as compared to the Prestige event. Chemical dispersants were added to the plume in the Deepwater accident; none was added in the Prestige case.

The deep Gulf water and material residence times are estimated to be ~250 years [2, 3]. Unlike the Prestige oil spill, the Deep horizon waters and materials may be confined to the deep Gulf region (up to 3,500 deep) but probably of areal extent ~100 times less than the North Atlantic Ocean basin. Thus, much fewer opportunities are expected to exist for dispersal and dilution in the Gulf deep basins as compared with the North Atlantic Ocean. Eventually, the deep material will slowly decay by biogeochemical processes, or, as mentioned above, be mixed up to the surface by extreme weather events such as hurricanes.

### 1.3 How Much Material Remains in the Gulf?

Much of the subsurface well material that was not blown ashore or evaporated into the air may still be trapped in subsurface waters within the Gulf. Material suspended at depths greater than the ~700 m Florida Strait sill could possibly remain in the Gulf for centuries [1, 2], unless its density is altered by biogeoophysical processes. On the other hand, future hurricanes

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may churn up deeply suspended materials (often in the form of tar-balls) to the surface and blow these ashore or out of the Gulf through the Florida Strait, as did 2012 Hurricane Isaac\textsuperscript{12}.

Even a weak category 1 hurricane can churn material deeper than a few hundred meters to the surface, as did typhoon Kai-Tak\textsuperscript{13} [3]. Thus, it is not surprising that category 1 Hurricane Isaac churned up tar-balls and blew them ashore. Stronger hurricanes could churn deeper water to the surface, so the effects of Hurricane Isaac suggest that future hurricanes may lead to more damage from tar-balls, impacting Gulf beaches and wetlands. This would be especially apparent at locations where hurricane eye-wall winds blow toward the coast.

In summary, a hurricane in the Gulf of Mexico may churn up deep cold water and mix it with warmer upper level Gulf waters, thus allowing these waters, with its suspended material, to escape through the Florida Straits and into the western Atlantic Ocean. However, some suspended oil materials do not mix readily with water (see Chapter 5), and thus may re-sink and settle to a new equilibrium depth closer to its depth before the hurricane.

1.4 The Role of Ocean Models to Explain what Happened

Economically important and environmentally sensitive questions can partly be addressed by well-tested and validated circulation and oil spill simulation models. Our contribution is to apply the DieCAST ocean model\textsuperscript{14} coupled with the Korotenko oil dispersion model (Korotenko \textit{et al.}, 2013) to shed light on probable transport, transformation and fates of oil residues released during the Deepwater Horizon (hereafter DWH) oil platform accident. We name the coupled model GOSM (Gulf Oil Spill Model). We use the DieCAST model to simulate Gulf circulation dynamics and vertical mixing processes and apply this information to investigate what possibly happened to the well blowout material. We also discuss the role of hurricanes over the long-term in churning up deep deposits and flinging them onto coastlines.

Winds, waves, currents, water density and temperature fields all determine the paths of elements of material leaked from the well site. These in

\textsuperscript{12} http://en.wikipedia.org/wiki/Hurricane_Isaac_(2012)
\textsuperscript{13} http://en.wikipedia.org/wiki/Typhoon_Kai-tak_(2012)
\textsuperscript{14} http://efdl.as.ntu.edu.tw/research/diecast/
turn affect the biogeochemical processes in the evolving element material properties. The Korotenko oil transport model features a Lagrangian particle-tracking method that is a cost-effective approach for the simulation of various events including oil spills [4].

References

2 Gulf of Mexico Circulation

2.1 General Characteristics

The Gulf of Mexico circulation is dominated by strong currents possessing considerable variability. Driven by the Trade Winds, tropical North Atlantic Ocean waters flow into the Caribbean Sea\(^1\) between the Lesser Antilles islands\(^2\). The currents then flow through and out of the Caribbean Sea and into the Gulf of Mexico through the Yucatan Strait\(^3\) as the so-called Loop Current. These currents are the source of nearly all water that enters the Gulf [1]. The Loop Current, as its name implies, loops around the central Gulf and exits through the Florida Strait\(^4\). It then flows northward along the southeastern United States coast as the Gulf Stream\(^5\).

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\(^2\) [http://en.wikipedia.org/wiki/Lesser_Antilles](http://en.wikipedia.org/wiki/Lesser_Antilles)
\(^3\) [http://en.wikipedia.org/wiki/Yucat%C3%A1n_Channel](http://en.wikipedia.org/wiki/Yucat%C3%A1n_Channel)
After leaving the Gulf, the Gulf Stream flows northward as an intense western boundary current in deep waters offshore from the southern States of Florida, Georgia, South Carolina and North Carolina. It then separates from the coastal region near Cape Hatteras, North Carolina, and flows further offshore from the eastern seaboard as the continental shelf widens. It then continues across the North Atlantic Ocean as the Gulf Stream Extension. The Gulf Stream with its source, trajectory, dynamical properties and eventual interactions with the oceans of the northeastern Atlantic and continental Europe is one of the most majestic and most studied of all oceanographic phenomena.

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6 Courtesy of the Colorado Center for Astrodynamics Research. http://eddy.colorado.edu/ccar/data_viewer/index
7 http://en.wikipedia.org/wiki/Boundary_current
2.2 Exchanges at Lateral and Surface Boundaries

Discharges from rivers, particularly the Mississippi River, are many orders of magnitude smaller than the transport of the Loop Current, but help maintain the Gulf salt balance and are especially important locally near the Gulf coast. They tend to be loaded with sediments and nutrients, affecting Gulf ecosystems and creating harmful algal blooms associated with toxic red tides \(^8\) that occur almost every year.

Heat exchange with the atmosphere is important, especially when the Loop Current penetrates far northward during winter. In winter, cooled surface water near the shelf break, sometimes slightly modified by near-surface river plumes, mixes downward, creating a deep, cooler upper mixed layer. When the Loop Current collides with this coastal water mass, strong upper level fronts form at its northern edge. As the Loop Current is by nature surface-intensified, the associated potential energy may easily

\(^8\) http://en.wikipedia.org/wiki/Red_tide
be converted into kinetic energy leading to baroclinic instability and the formation of unstable meanders.

2.3 Loop Current Eddies

Mesoscale Loop Current anticyclonic eddies\(^9\) (~ 300 km in diameter) are formed within the Gulf of Mexico as huge bulges in the Loop Current (Figs. 2.1 and 2.2). They grow and pinch off at approximately nine-month intervals with clockwise rotational flows sometimes exceeding 1 m s\(^{-1}\) (2 knots). The eddies then drift westward under the influence of the Earth’s rotation (Coriolis effect) until they collide with the western boundary of the Gulf; then split into rotating fragments which can flow both northwards and southwards along the edge of the western continental shelf, lasting for years. These spectacular phenomena of the large-scale circulation of the Gulf possess large amounts of angular momentum and are persistent enough to last for years as well as being largely independent of local wind and oceanographic conditions.

Loop Current frontal eddies facilitate the separation and dispersion of Loop Current energy, in large Loop Current eddies that propagate westward and smaller ones that disperse its energy into the northeastern Gulf. Eddies of various shapes and sizes ventilate the western Gulf with tropical North Atlantic and Caribbean Sea water (see Chapter 10 for further details). They also affect Gulf ecosystems including HABs (Harmful Algal Blooms)\(^{10}\) associated with deleterious red tides that occur almost every year along the northeastern Gulf coast.

The Gulf’s currents, fronts and eddies can concentrate and transport oil spill residues over large distances. Although winds obviously play a very important in the near-surface mixed layer, the underlying powerful Loop Current and its daughter mesoscale and frontal eddies become relatively more important with increasing depth and horizontal distances from continental-shelf-based well sites.

The Gulf of Mexico eddies are especially vigorous during those winters in which the Loop Current penetrates further northward than usual. As mentioned above, such eddies can significantly fuel harmful algal blooms and red tides that occur along the Gulf coast of Florida. However, because of the inherent randomness, they may not be predictable in detail beyond a few months.

\(^9\) [http://en.wikipedia.org/wiki/Eddy_(fluid_dynamics)]
\(^{10}\) [http://en.wikipedia.org/wiki/Algal_bloom]