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An Improved Method to Estimate the Probability of Oil Spill Contact to Environmental Resources in the Gulf of Mexico

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Abstract: The oil spill risk analysis (OSRA) model is a tool used by the Bureau of Ocean Energy Management (BOEM) to evaluate oil spill risks to biological, physical, and socioeconomic resources that could be exposed to oil spill contact from oil and gas leasing, exploration, or development on the U.S. Outer Continental Shelf (OCS). Using long-term hindcast winds and ocean currents, the OSRA model generates hundreds of thousands of trajectories from hypothetical oil spill locations and derives the probability of contact to these environmental resources in the U.S. OCS. This study generates probability of oil spill contact maps by initiating trajectories from hypothetical oil spill points over the entire planning areas in the U.S. Gulf of Mexico (GOM) OCS and tabulating the contacts over the entire waters in the GOM. Therefore, a probability of oil spill contact database that stores information of the spill points and contacts can be created for a given set of wind and current data such that the probability of oil spill contact to any environmental resources from future leasing areas can be estimated without a rerun of the OSRA model. The method can be applied to other OCS regions and help improve BOEM's decision-making process.

Keywords: trajectory model; oil spill model; oil spill response; oil spill risk analysis; Gulf of Mexico; Outer Continental Shelf; environmental resources; risk modelling; Princeton Ocean Model; trajectory analysis

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1. Introduction

The Gulf of Mexico (GOM), a semi-enclosed sea bordering the western Atlantic Ocean in the east and connected with the Caribbean Sea to the south, remains an important ecosystem that provides the Gulf Coast communities and nations with abundant fisheries and energy resources. Offshore oil production in the U.S. GOM Outer Continental Shelf (OCS) generally has increased over the past several decades, partly due to advancing technology. Today, the GOM OCS remains a significant source of oil and gas for the nation's energy needs. As of December 2017, OCS leases in the GOM produce 17 percent of domestic oil and 5 percent of domestic gas, and oil and gas production in the GOM OCS is forecasted to increase through 2024 [1].

According to the Outer Continental Shelf Lands Act (OCS Lands Act), established in 1953, the U.S. Department of the Interior (USDOI) has jurisdiction over OCS lands—submerged lands located generally 3 miles from state coastlines. Under the OCS Lands Act, the Bureau of Ocean Energy Management (BOEM) within the USDOI is responsible for managing the oil and gas resources in the OCS, with a goal of balancing the benefits derived from development of these resources with environmental protection. Prior to any offshore oil and gas leasing or approval of exploration and development plans, BOEM is required to prepare environmental analyses such as Environmental

Impact Statements (EISs) under the National Environmental Policy Act (NEPA). One of the key components in BOEM's EIS documents is the estimation of the likelihood of oil spill contact with biological, physical, social, and economic resources in the OCS. These resources are referred to as 'environmental resources' herein, with details discussed in Section 2.4.

The oil spill risk analysis (OSRA) model was developed by the USDOI in 1975 to evaluate the oil spill risks associated with the offshore oil and gas leasing and related activities to the environmental resources. A variety of environmental resources are considered in BOEM's OSRA model, including coastlines; water quality; archaeological and culture resources; recreation, tourism, and visual resources; environmental sensitive areas that represent concentrations of wildlife, habitat, or subsurface habitat; and national and state parks, refuges, and protected areas. The first application of OSRA was conducted in 1976 for the North Atlantic OCS Lease Area [2], and the first detailed documentation of the OSRA model was written by Smith et al. in 1982 [3]. The OSRA model has been verified with several oil spill incidents including the Argo Merchant incident off Nantucket Island in 1976 [4] and the Santa Barbara Channel blowout in 1969 [5], and the spill trajectories simulated by the OSRA model closely resembled the observed movements of the spill oils during these incidents.

As shown in Figure 1, the OSRA model delivers three products: conditional probability, oil spill occurrence, and combined probability. The calculation of the conditional probability begins with the construction of the oil spill trajectory. The trajectories are initiated every day and calculated every hour using long-term (decades) hindcast wind and current data. The conditional probability of contact to an environmental resource is calculated by dividing the number of contacts (i.e., number of times a trajectory reaches a location occupied by the environmental resource) in a given time by the total number of trajectories initiated within each hypothetical oil spill area. Only spills greater than or equal to 1000 barrels (referred to as 'large oil spills') undergo trajectory simulation in the OSRA model because smaller spills would not persist on water long enough for such analysis. The term 'conditional' is used to reflect the assumption (condition) that an accidental large oil spill occurs at hypothetical oil spill location. The OSRA model estimates the probability of large oil spills occurring from the prospective production sites and transportation routes of a specific volume over the lifetime of the scenario. The estimate of large spill occurrence at the production sites or transportation routes is based on the projected oil production volume, transportation scenarios, and historical spill occurrence in the U.S. OCS [6–8]. Finally, the OSRA model uses the conditional probability and estimated oil spill occurrence relative to the production volume and transport scenarios to derive the combined probability. The 'combined' probability is the overall probability of one or more large oil spill occurring and contacting the environmental resources over the lifetime of the scenario.

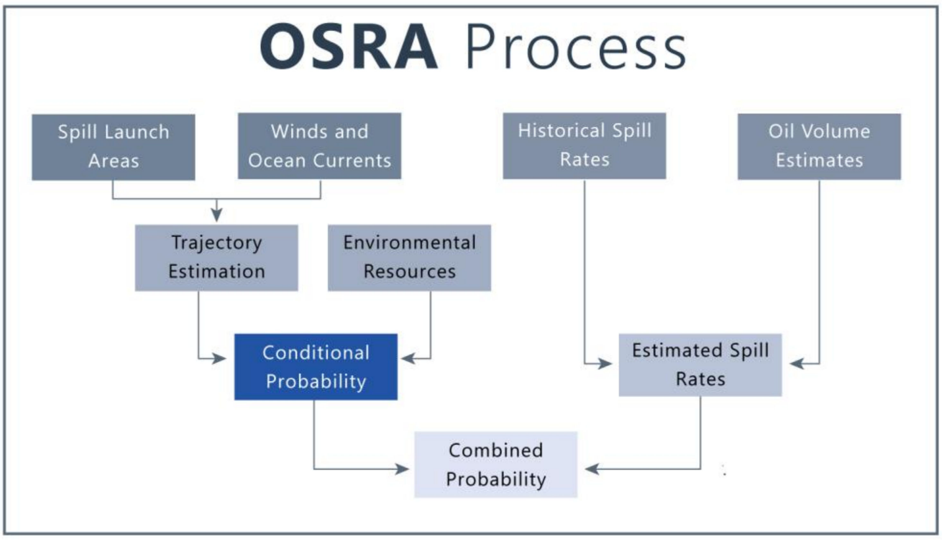


Figure 1. Schematic diagram of the OSRA model process.

BOEM has committed to continuous improvement of the OSRA model over years [9–16]. A more recent overview of the OSRA model is given by Price et al. (2003) [9]. The sensitivity analysis in Price et al. (2004) [10] showed that a time integration step of 1 h with a fourth-order Runge–Kutta scheme and a daily release of the hypothetical oil spills are sufficient to apply the OSRA model to the GOM using the selected wind and current data sets. Guillen et al. (2004) [11] suggested utilizing a 'multivariate statistical method called cluster analysis' to group areas that 'pose similar risk to specific targets or groups of targets'. This method was used in the spill risk analysis for the recent lease sales in the GOM OCS [12]. Johnson et al. (2005) [13] examined the statistics of length of coastline in the GOM contacted by the hypothetical oil spills by varying the number of spillets (adding a random component to both components of velocity at each OSRA model integration time step to represent the spreading of oil spills), the number of the trajectories, and level of concern.

The OSRA model results have been compared with the surface drifter data in the GOM to evaluate the accuracy of the model. Comparison of the estimated landing probabilities on the GOM coastline from the historical (1955–1987) surface drifter data (mostly cards and bottles) with the OSRA model results by Lugo-Fernández et al. (2001) [14] demonstrated that the probabilities were within an order of magnitude. The correlation coefficients were from 0.44 to 0.49 for the total, winter, and nonwinter seasons in their spatial distributions. The OSRA model trajectories were compared statistically against 97 trajectories of 'oil-spill-simulating' drifters (freely moving, satellite-tracked, surface floats) deployed over the northeastern GOM continental shelf during five hydrographic surveys from 1997 through 1999 in Price et al. (2006) [15]. The discrepancies found were largely due to the integration of the imperfect wind and ocean current fields, the empirically derived wind-drift factor, and inability of the ocean model in resolving the smaller-scale processes.

Though the OSRA model was designed to study the surface oil spills, it was shown to statistically capture the pattern of surface oiling from the Deepwater Horizon oil spill of 2010, as detailed in Ji et al. (2011) [16]. For a deepwater oil spill trajectory model, BOEM uses the Clarkson Deepwater Oil and Gas Blowout Model [17–19], which was funded by BOEM in collaboration with 11 industry partners [20,21] and simulates the transport of oil and natural gas from a blowout or a pipeline rupture in deepwater.

Although most of the oil spill models are designed for use in real-time forecast mode, such as the National Oceanic and Atmospheric Administration's (NOAA's) General NOAA Operational Modeling Environment (GNOME) [22,23], the OSRA model was specifically developed to inform the decision-making process for OCS oil and gas lease sales. It was designed to estimate the long-term (decades) risk associated with the OCS lease sales. The model characterizes an entire lease sale area by simulating hundreds of thousands of trajectories under decade-long, historical wind and current conditions to derive the climatology of spill contact probabilities, without having to make assumptions on the exact locations of the leases, numbers of wells drilled, and the oil properties. As such, the OSRA model adopts a conservative approach without considering the oil weathering process. The specifics of one or more appropriate oils for weathering estimates are described in the EIS using the oil weathering model from SINTEF (*Stiftelsen for INdustriell of TEknisk Forskning ved NTH*—Foundation for Industrial and Technical Research) [24]. The use of a stand-alone weathering modelling allows BOEM the flexibility of examining the weathering characteristics of different types of crude oils rather than a single oil type for multiple different reservoirs.

BOEM's NEPA documents for lease sales are governed by a number of environment laws, regulations, and executive orders, including Clean Air Act, Clean Water Act, Coastal Zone Management, Endangered Species Act, Magnuson–Stevens Fishery Conservation and Management Act, Marine Mammal Protection Act, Migratory Bird Treaty Act, Tribal Consultation and Environmental Justice. To comply with these laws and regulations, the OSRA model compiles a large list of environmental resources that include broad categories of onshore and offshore resources [12] and estimates the likelihood (probability) of oil spill contact to the resources. The impact of oil spill on all considered resources is analyzed separately in the EIS that are prepared prior to conducting any leasing sales, and therefore factors in measures such as weathering and the effects of cleanup activities.

The existing OSRA model estimates the conditional probability of contact from a specific launch area to an environmental resource mapped to OSRA model grid at three time intervals—3, 10, and 30 days. The environmental resources, typically on the order of hundreds of resources, are treated as inputs to the existing OSRA model; as such, a rerun of the OSRA model is needed if additional environmental resources are considered later. In this study, a method is developed to calculate the conditional probability by treating entire waters in the GOM as a multitude of environmental resources consisting of ocean grid cells. The number of contacts to each ocean grid cell from hypothetical oil spill trajectories initiated over entire planning areas of the U.S. GOM OCS is tracked and tabulated. For a given wind and current data set, this information can be loaded into a database and statistics on any launch areas within GOM OCS planning areas can be retrieved later for use in the estimates of conditional probability of future lease sales. Using this method, conditional probability maps can be generated, thus allowing a quantitative evaluation of the effects of hindcast surface winds and ocean currents on conditional probability estimates. Instead of estimating conditional probability of contact at three fixed time intervals, this study calculates these probabilities each day from day 1 to day 30.

The conditional probabilities are calculated in this study using two sets of relatively high resolution hindcast surface wind (six-hourly) and ocean current (three-hourly) data from two time periods, 1993–1999 and 2000–2007. Both sets of surface ocean current data were generated by the Princeton Regional Ocean Forecast System (PROFS), which is described in detail by Oey and Lee (2002) [25], Oey et al. (2003) [26], Oey (2005) [27], and Chang et al. (2011) [28]. The model results were used to study the Loop Current, eddies, and related circulation in the GOM, and they were extensively verified with a variety of surface and subsurface observations including in situ and shipboard acoustic Doppler current profiler measurements, National Data Buoy Center data, and satellite and drifter data [29–40]. Chang et al. (2011) [28] demonstrated that trajectories generated by a long-term hindcast current data (2000–2007) from the PROFS can reasonably simulate the spread of the Deepwater Horizon oil spill in 2010. An in-depth description of these data sets is in Section 2.3. These data sets were chosen to match that used in the recent OSRA application in BOEM's Eastern Planning Area in the GOM [12]. BOEM also provided these data sets to NOAA for use in its analysis of long-term outlook of oil spill transport during the Deepwater Horizon oil spill incident [41].

Similar approach was used in the European Commission's NEREIDs project for assessing shoreline and offshore susceptibility to the hypothetical large oil spills around Suez Canal and nearby oil and gas fields in the Eastern Mediterranean Sea [42–44]. The model in NEREIDs project considers various factors that mitigate the impacts of oil spills and is designed for use in a small confined marine basin that needs a rapid response. The method proposed in this study aims for use in open sea with the focus on long-term contingency planning.

This paper begins with descriptions of the OSRA model domain and components, followed by comparisons of annual and monthly conditional probability calculated from two time periods, and an application of the new method to estimate probability of spill contact to a subset of environmental resources in the GOM OCS. The discussion focuses on the advantage of this method and explains how this method will improve BOEM's decision-making process in the future.

2. Methods

2.1. Study Area

As shown in Figure 2, the study area for OSRA extends from 98° W to 78° W and 18° N to 31° N, which includes portion of the western Atlantic Ocean. The study area was chosen to be large enough to allow hypothetical oil spill trajectories to develop without contacting the boundary at the east within 30 days (the maximum elapsed time considered). The OSRA model has a resolution of 0.1° latitude by 0.1° longitude and a total of 28,564 grid cells in the study area. The hypothetical oil spill locations, also referred to as the launch points, are shown as blue dots in Figure 2. There are 6044 launch points spaced at a resolution of 0.1° latitude by 0.1° longitude. These launch points are selected to represent the Western GOM, Central GOM, and Eastern GOM Planning Areas as displayed in Figure 3. Note that the launch points are located in the OCS waters, which are generally about three miles from the shore, except for the launch points off the western Florida Shelf and Texas coastline, which are about nine miles offshore. As of 3 December 2018, the GOM OCS planning areas comprised a total of 29,100 leasing blocks and 159,381,023 acres. The number of active leases was 2557, covering 13,540,330 acres of leased areas. About 86% of active leases are in the Central GOM Planning Area, and very few are in the Eastern GOM Planning Area.

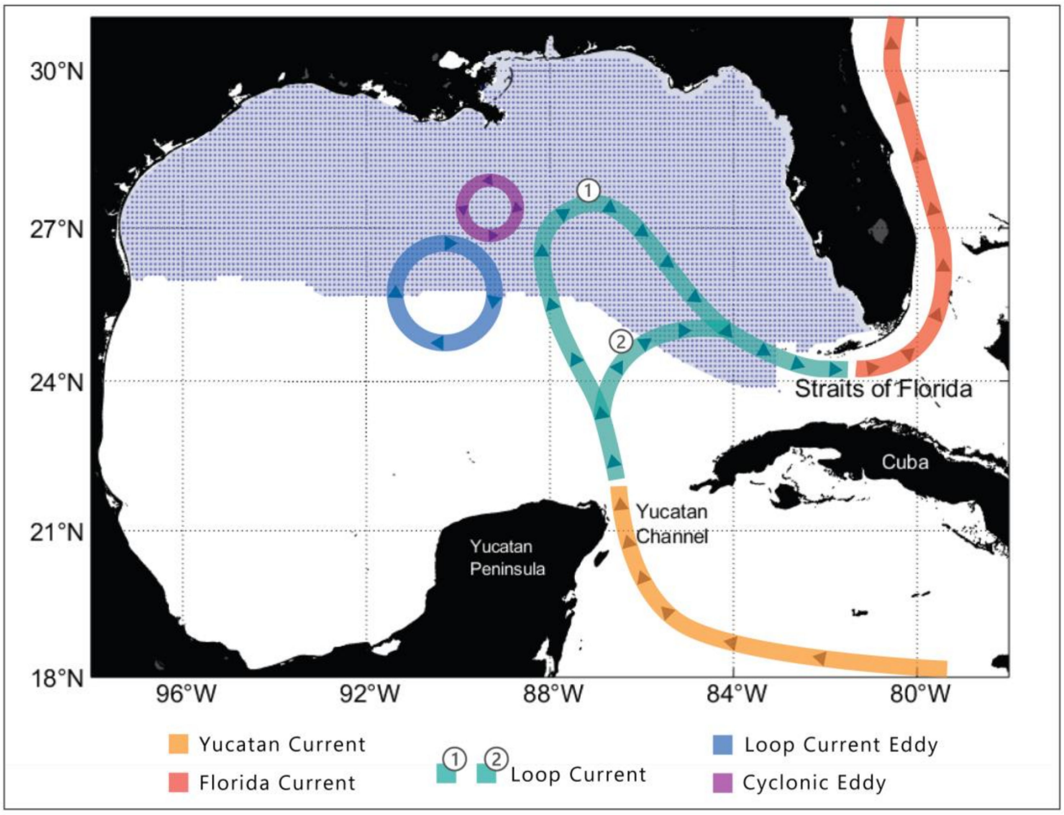
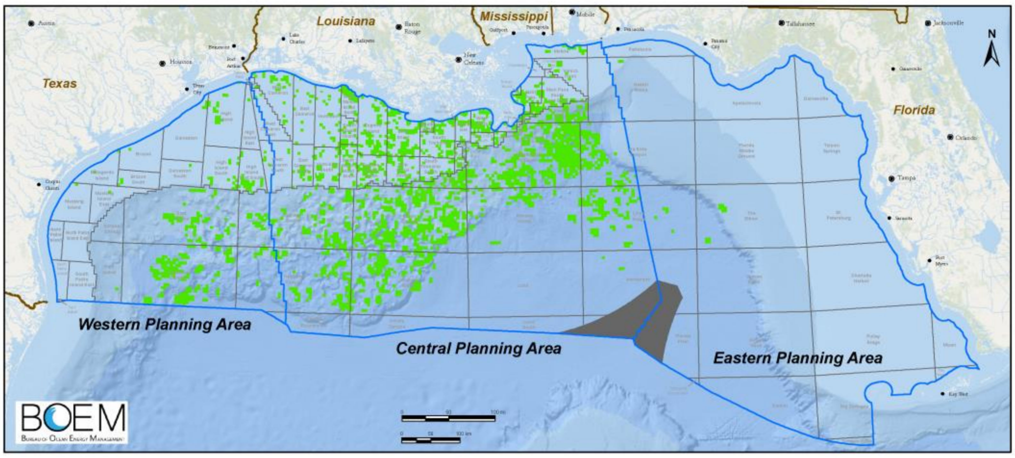


Figure 2. Map of the GOM used for the OSRA model simulation with schematic drawings showing the Loop Current and Loop Current Eddy. Blue dots denote hypothetical oil spill locations.

The dominant circulation features in the GOM are the Loop Current and Loop Current eddies (Figure 2). The Loop Current originates from the Yucatan Channel and loops inside the GOM before forming the Florida Current at the Straits of Florida around the Florida Peninsula. As part of the Gulf Stream System, the Florida Current flows from the Straits of Florida to Cape Hatteras along the U.S. southeastern coast. The Loop Current can reach a speed of 1.7 ms^{-1} inside the GOM [45] and extends deep into the GOM. The Loop Current exhibits a range of variations, which can be measured by how much farther north it penetrates into the GOM. The Loop Current eddies are large anti-cyclonic rings separating from the Loop Current when it becomes unstable as it extends farther north into the GOM, and these eddies subsequently drift to the west after separation [46]. The time interval of the separation events varies from 3 to 17 months with an average of about 9.5 months [46]. Cyclonic eddies, also referred to as the Loop Current Frontal eddies, are much smaller than the Loop Current eddies, and they originate from the boundary of the Loop Current and Loop Current eddies. These powerful currents can influence biological production, pollutant transport such as oil spills, design and operation of oil and gas facilities, fishery management in the GOM, and other processes and resources [47].



Planning Areas	Total Blocks	Total Acres	Number of Leases	Acres Leased
Western	5,240	28,576,813	344	1,964,366
Central	12,409	66,446,351	2,195	11,472,284
Eastern	11,537	64,357,859	18	103,680
Sub-Totals	29,186	159,381,023	2,557	13,540,330
CPA / EPA Shared Blocks*	(86)		0	
Totals	**29,100**	**159,381,023**	**2,557**	**13,540,330**

Active Lease
Exclusive Economic Zone
Northern Portion of the Eastern Gap
Planning Area Boundary

* CPA and EPA contain 86 shared blocks. These blocks are given both a CPA and EPA designation in the data which may account for a higher block total.

Figure 3. Active leases in the GOM planning areas (Western, Central, and Eastern) as of 3 December 2018.

2.2. Trajectory Simulations

One of the key components of the OSRA model is trajectory simulation. The path that a hypothetical oil spill moves under the forces of surface currents and winds is the modeled trajectory. The hypothetical oil spill trajectories are constructed using vector addition of a temporally and spatially varying ocean current field and an empirical wind-induced drift of the hypothetical oil spills [48]. The wind-drift factor was estimated to be 0.035, with a variable drift angle ranging from 0° to 25° clockwise that is inversely related to wind speed. The drift angle is computed as a function of wind speed according to the formula in Samuels et al. (1982) [48]. Collectively, the trajectories represent a statistical ensemble of simulated oil spill displacements produced by the fields of winds and ocean currents from numerical models with observations assimilated.

The existing OSRA model initiates the trajectories every day at the same time from hypothetical spill locations in areas of prospective drilling and production and along projected pipeline and tanker routes. The trajectories are advected every hour using the instantaneous surface current and wind data and are allowed to continue for as long as 30 days. The maximum travel time of 30 days is chosen because a typical GOM oil slick of 1000 barrels (bbl) or greater, when exposed to typical winds and currents, would not persist on the water surface beyond 30 days [49]. Considering the diurnal cycle of surface winds, initiating trajectories at random time during the day would be a better approach and will be pursued in the future.

It is worth noting that the trajectories simulated by the OSRA model represent only hypothetical pathways of oil slicks, and they do not consider cleanup, dispersion, or weathering processes that could alter the quantity or properties of oil that might eventually contact the environmental resources. However, an implicit analysis of weathering and decay can be considered by choosing a travel time that represents the likely persistence of the oil slick on the water surface.

2.3. Surface Wind and Ocean Current Data

The trajectory simulations in this study used two sets of six-hourly surface wind and three-hourly ocean current data, one from 1993 to 1999 and the other from 2000 to 2007. These wind and current data were further interpolated in the OSRA model to an hourly interval to calculate the trajectories, and seasonal statistics on conditional probability were derived from a huge ensemble (millions) of individual trajectories simulated on an hourly basis. These data were chosen because they were used in the recent OSRA report for lease sales in the Eastern GOM Planning Area [12], and therefore the results generated from this study can be validated before applying this method to BOEM's lease sales.

Surface wind data for 1993–1999 are taken from the European Centre for Medium-Range Weather Forecasts [27]. Surface wind data for 2000–2007 are from the National Centers for Environmental Prediction (NCEP) QuikSCAT blended (https://rda.ucar.edu/datasets/ds744.4/) [50]. Both sets of data are at six-hourly time intervals. The NCEP QuikSCAT blended wind data are derived from merging of high-resolution satellite data (SeaWinds instrument on the QuikSCAT satellite) and NCEP reanalysis. The NCEP–QuikSCAT blended winds were corrected using high-resolution wind fields from NOAA's Hurricane Research Division, which includes hurricane strength winds [39].

Surface winds are primarily northeasterly in the winter, becoming easterly or southeasterly in the summer. During the spring and fall time, the surface winds are mostly easterly or southeasterly. Winds at the west Florida shelf are primarily offshore, where strong winds (northeasterly in winter, easterly in spring and southeasterly to easterly in fall) push the particles offshore. The weak onshore winds tend to occur in the summer months.

As mentioned earlier, PROFS produced the ocean current data at three-hourly time intervals. PROFS is a version of Princeton Ocean Model (POM), which is a three-dimensional, time-dependent, primitive equation model using orthogonal curvilinear coordinates in the horizontal dimension and a topographically conformal coordinate in the vertical dimension [51]. These coordinates more realistically represent coastline and bottom topography in the model simulation. There are some similarities and differences in model configuration for these two time periods. Both simulations cover a large domain that includes the northwest Atlantic Ocean, extending to 55° W in the east, 50° N in the north, and the Caribbean Sea in the south. Monthly climatology of temperature and salinity is obtained from the World Ocean Atlas at NOAA's National Oceanographic Data Center and is used for initial conditions and boundary conditions for eastern boundary in the Atlantic Ocean [28]. The model simulation incorporates daily river discharges from 34 rivers in the northern GOM obtained from the U.S. Geological Survey [28]. Both simulations assimilate satellite-derived sea surface height and sea surface temperature. Major differences between these two runs are data assimilation scheme and resolution. The 2000–2007 simulation uses a nested grid in the GOM with a resolution of 3.5 km and adopts a more advanced Ensemble Kalman Filter data assimilation scheme. Simulation for 1993–1999 uses an optimal interpolation and has a resolution of 5 km. The temporal and spatial resolution of the PROFS is typical of the state-of-the-art ocean model used in the GOM for oil spill modelling. For example, during the Deepwater Horizon oil spill, MacFadyen et al. (2011) [23] applied ocean current output from six hydrodynamic models with spatial resolution ranging from ~3 to 14 km to NOAA's GNOME ensemble forecasting (daily 72 h) of surface oil transport.

The model simulations were extensively verified with many observations, from satellite-borne instrument to in situ measurements including moored current meters and drifters in the GOM [29,31–35,39,40]. These extensive observations afford a rigorous assessment of the POM's ability to reproduce ocean transport and prominent features in the GOM, such as the Loop Current and large, energetic eddies that spin off from the Loop Current. The POM reproduced realistic surface currents both on and off the continental shelf.

2.4. Environmental Resources

The environmental resources consist of biological, physical, and socioeconomic resources located in any onshore and offshore areas that could be potentially affected by OCS oil spills. BOEM analysts defined these resources in the GOM region with additional input from the National Marine Fisheries Service and the U.S. Fish and Wildlife Service. BOEM analysts also used information from the results of the Bureau's funded research projects, literature reviews, and consultations with other scientists to define resources. Typically, the OSRA model for the GOM OCS incorporates 184 offshore and 102 onshore environmental resources [12]. Those resources are not limited to environmental sensitive areas such as fish habitats; they also include the state offshore waters that are defined by each of five costal states (Texas, Louisiana, Mississippi, Alabama, and Florida) that border the GOM and seafloors of nearshore, shelf, and deepwater. Moreover, international waters of Cayman Islands, Bahamas, and Jamaica are considered. The onshore environmental resources include the U.S. coastline (grouped into counties or parishes, resource habitats, recreational beaches) and coastline of Mexico, Belize (country), and Cuba. For a comprehensive list of these resources, see Ji et al. (2013) [12].

The geographic locations of environmental resources are displayed as maps that can be digitalized onto the OSRA model grid. Each environmental resource has a seasonal vulnerability, defined as a time period when resources are present or susceptible to damage from an oil spill. The offshore environmental resources—the focus of this study—are delineated as the areas of surface waters overlying their locations.

In the existing OSRA model, the environmental resources are treated as inputs to the OSRA model. The spatially and temporally varying environmental resources are digitalized and hard-coded onto the OSRA model grid prior to OSRA model simulation. If the environmental resources are changed later, a new OSRA model run has to be performed. The new method proposed in this study tabulates the trajectory contacts to every ocean grid cell in the OSRA model and archives the number of counts to compute the conditional probability to a specific environmental resource later without re-running the OSRA model.

The OSRA model does not assess the susceptibility of these environment resources to oil spill, such as the 'Environmental Susceptibility Index' defined in Adler and Inbar (2007) [52]. The details of how and why these resources could be negatively impacted by oil spills due to BOEM's leasing activities are discussed thoroughly in the EIS.

2.5. Conditional Probability

The OSRA model geographically tracks the contacts of each hypothetical spill trajectory to the environmental resources. A contact occurs when a trajectory touches an environmental resource. At every hour, the OSRA model calculates the locations of the simulated spills and counts the number of oil spill contacts to the environmental resources. The OSRA model only tabulates the counts during the months when the environmental resources are vulnerable. For a given hypothetical launch point, the OSRA model divides the total number of contacts to the environmental resources by the total number of hypothetical spills initiated in the model after specific periods of time. These ratios are the estimated conditional probabilities of oil spill contact from a given hypothetical launch point at designated oil spill travel times, which are 3, 10, and 30 days in the GOM OCS.

2.6. Conditional Probability from Two Launch Points in 1998

Two launch points of the same latitude are selected to demonstrate how conditional probability is calculated using the new method. One launch point is east of Mississippi delta at 91.9° W, 29° N and the other launch point is west of Mississippi delta at 88.1° W, 29° N. The trajectories were launched from each launch point every day for year 1998 and were driven by the corresponding six-hourly surface winds and three-hourly ocean currents. Price et al. (2006) [15] compared the OSRA model generated trajectories using the 1993–1999 wind and current data described earlier with drifter data collected during five hydrographic survey from 1997 through 1999 and found that the cumulated errors in the input fields led to an average discrepancy of 78 km after 3 days. Nevertheless, this wind and current data were shown to be able to reproduce the similar oil spill patterns when used in the ORSA model to simulate the 2010 Deepwater Horizon oil spill [16].

The trajectories are calculated every hour and are allowed to continue for 30 days. The model tabulated contacts of trajectories to each ocean grid cell and estimated the conditional probability of contact at each ocean grid cell using the number of contacts divided by the total number of trajectories launched, i.e., 365. Figures 4 and 5 show the conditional probability of contact from these two launch points at 3, 10, and 30 days.

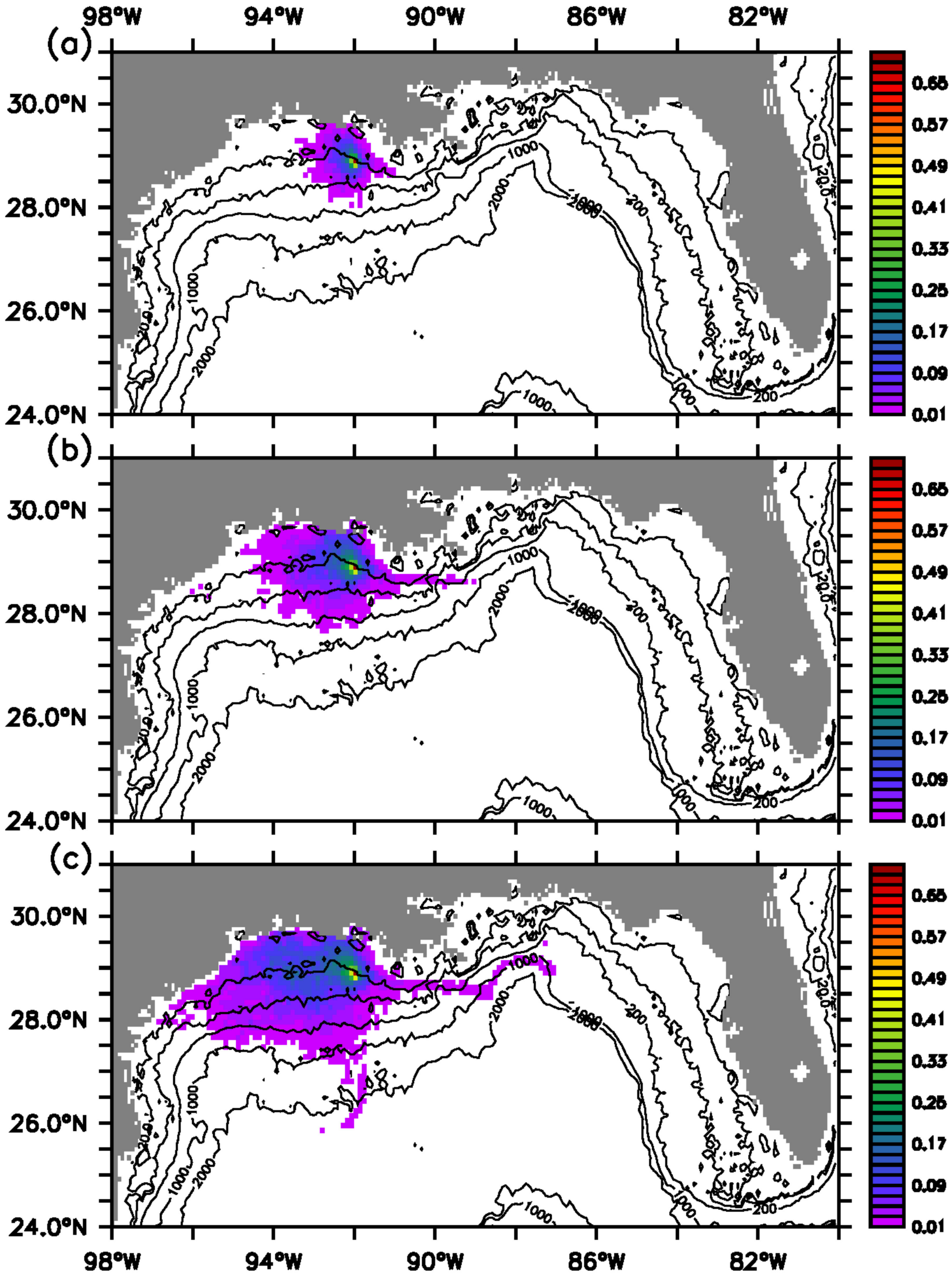


Figure 4. Conditional probability of contact from the launch point at 91.9° W, 29° N for year 1998: (**a**) 3 days; (**b**) 10 days; (**c**) 30 days. Isobaths of 20, 50, 200, 1000, and 2000 m are shown.

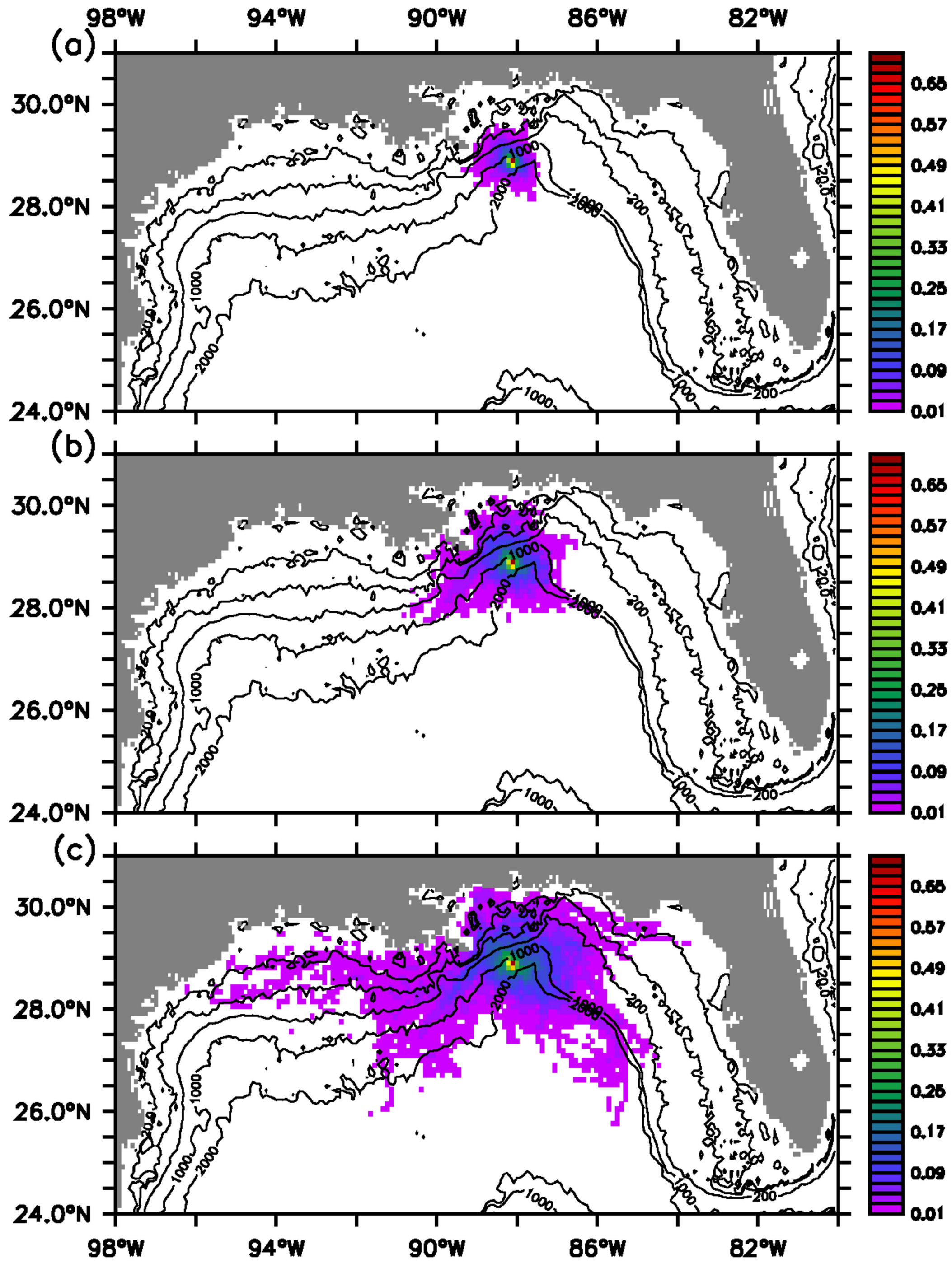


Figure 5. Conditional probability of contact from the launch point at 88.1° W, 29° N for year 1998: (**a**) 3 days; (**b**) 10 days; (**c**) 30 days. Isobaths of 20, 50, 200, 1000, and 2000 m are shown.

Conditional probability maps for two launch points that are separated by the Mississippi River (MR) Delta show a completely different behavior. For the launch point west of the MR Delta, the conditional probability of contact remains mostly in areas west of the MR Delta; for the launch point east of the MR Delta, the conditional probability of contact spreads both westward and eastward.

2.7. Sensitivity Studies

Significant amounts of computer time are required to calculate the trajectories from over 6000 launch points on an hourly basis and tabulate contacts to each of 20,615 ocean grid cells on a daily basis for 30 days. Since trajectories are initiated every day over a combined time period of 13 years, over 28.6 million trajectories are generated. A sensitivity test was performed by reducing the number of launch points to 3022, i.e., every other point in Figure 2, to assess the differences in conditional probability fields between these two simulations. No significant differences were found in the conditional probability at day 30 when reducing the number of launch points by half. With the reduced number of launch points, over 1.1 million trajectories are initialized each year.

3. Results

3.1. Annual Conditional Probability

Annual conditional probability refers to the conditional probability calculated over an entire year for the environmental resources that are vulnerable all year round. Each year OSRA model launches over 1.1 million trajectories for estimating the annual conditional probability, as each launch point initiates one trajectory every day for a period of 365 days. Two sets of wind and current data, i.e., 1993–1999 and 2000–2007, are used to estimate annual conditional probability on a daily basis from day 1 to day 30. Because the OSRA model simulates the trajectories for 30 days, a trajectory launched at 31 December 1998 (or 31 December 2006) will need the first 30 days of data from year 1999 (or 2007) to complete a 30-day trajectory analysis. Thus, the annual conditional probability calculated is from 1993 to 1998 and from 2000 to 2006. Figure 6 through Figure 7 show the annual conditional probability at day 30 for each year for these time periods. The annual conditional probability displays a strong variability from year to year, with different spatial distributions. The distribution of the annual conditional probability reflects the convergence of the trajectory paths, which depends on convergence of surface ocean currents and drifting effects of surface winds.

Areas of highest annual conditional probability tend to occur near the Loop Current and Loop Current eddies. From 1993 to 1998, areas of highest annual conditional probability appear around the Loop Current near the western entrance of Florida Strait. Annual conditional probability in the Loop Current–Florida Current in 1997 and 1998 stands out as the highest among all. Another area of relatively high annual conditional probability for 1993–1998 is at the Texas shelf. A relatively high annual conditional probability occurs near the Texas shelf at the 20- to 50-m isobaths in 1994.

For 2000–2006, areas of large annual conditional probability are located in the interior of the GOM, where cyclonic and anti-cyclonic eddies dominate. It is not surprising that locations of largest annual conditional probability coincide with the most energetic portion of circulation in the GOM. The distribution pattern varies, with highest annual conditional probability occurring in 2001, 2003, and 2005.

The west Florida shelf remains one of the areas with lowest probability of contact despite the fact there are launch points adjacent to it. The low annual conditional probability in the west Florida shelf coincides with the so-called 'Forbidden Zone' described by Yang et al. (1999) [53]. In this zone, drifters do not enter the shallow waters off the coast of southwest Florida and Florida Bay (i.e., south of Tampa Bay and west of Florida Bay); it suggests that currents, winds, bathymetry, or all three combined, keep the drifters offshore. The drifters presented by Yang et al. (1999) [53] were launched by the Surface Current and Lagrangian-Drift Program (SCULP) II during February 1996 to June 1997 [54]. Over 300 passive drifters were launched at various locations in the northeastern GOM, from the Mississippi-Alabama border on the east to Cedar Key in Florida on the west; drifters were tracked via satellite throughout the GOM and along the Florida Current. Although drifters in the SCULP II were deployed mostly north of the Tampa Bay at 28°N, the launch points in this study were located inside the Forbidden Zone, but the trajectories initiated from these launch points were mostly driven away from the shore by the combination effects of currents, winds, and bathymetry.

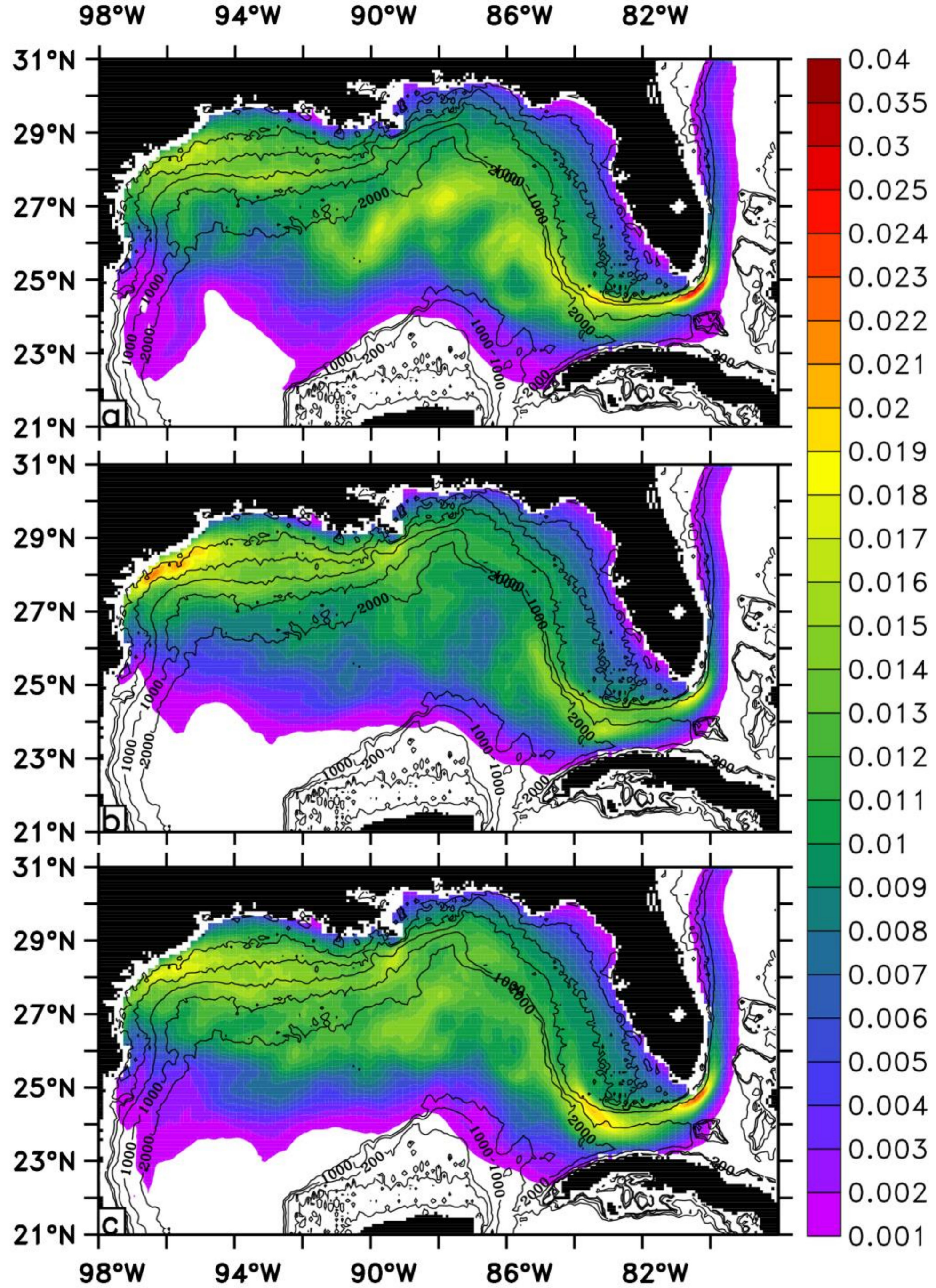


Figure 6. *Cont.*

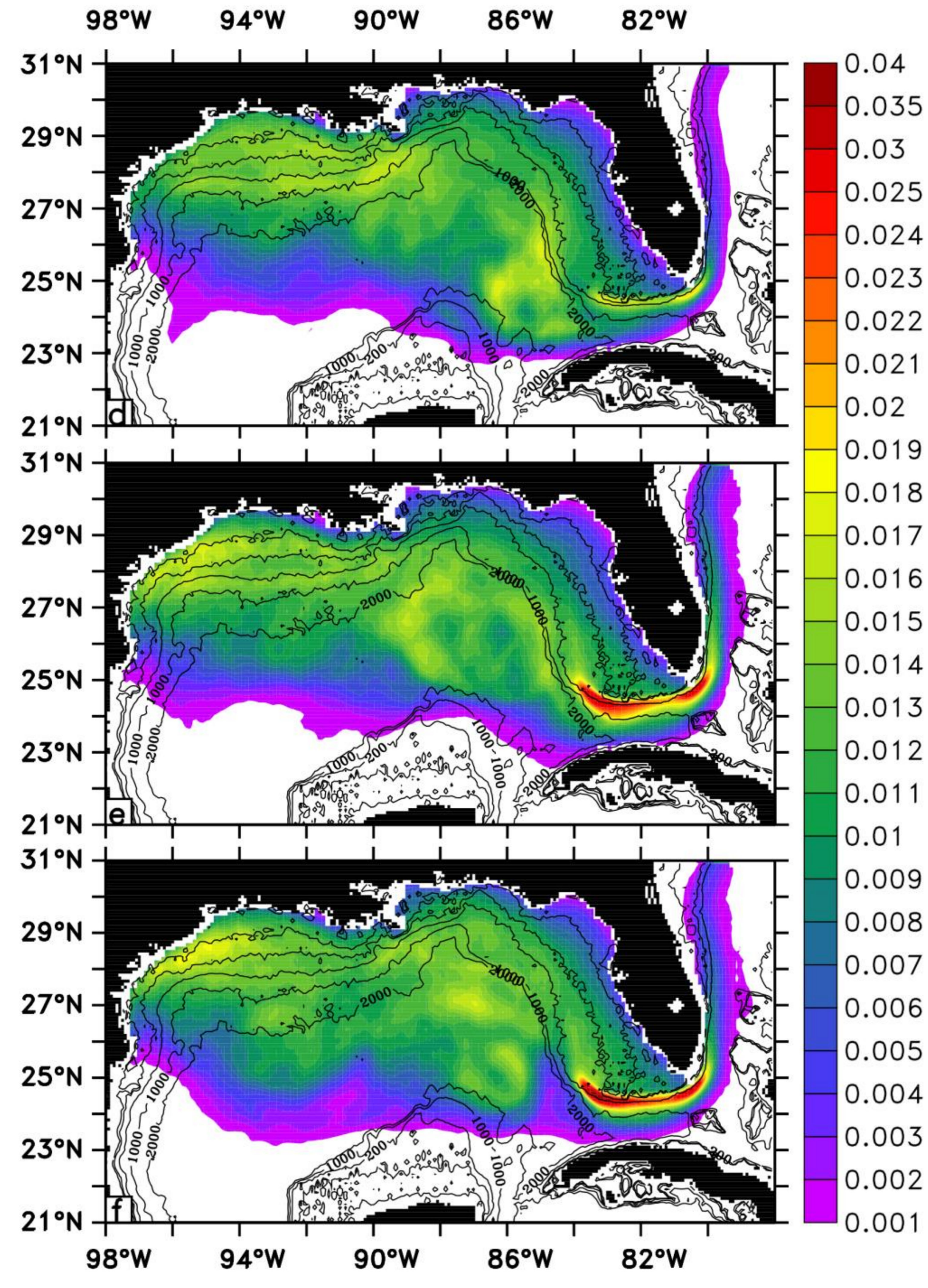


Figure 6. Annual conditional probability at day 30 for year: (**a**) 1993; (**b**) 1994; (**c**) 1995; (**d**) 1996; (**e**) 1997; (**f**) 1998. The color bar has an interval of 0.001 from 0.001 to 0.025 and an interval of 0.005 from 0.025 to 0.004. Isobaths of 20, 50, 200, 1000, and 2000 m are shown as black lines.

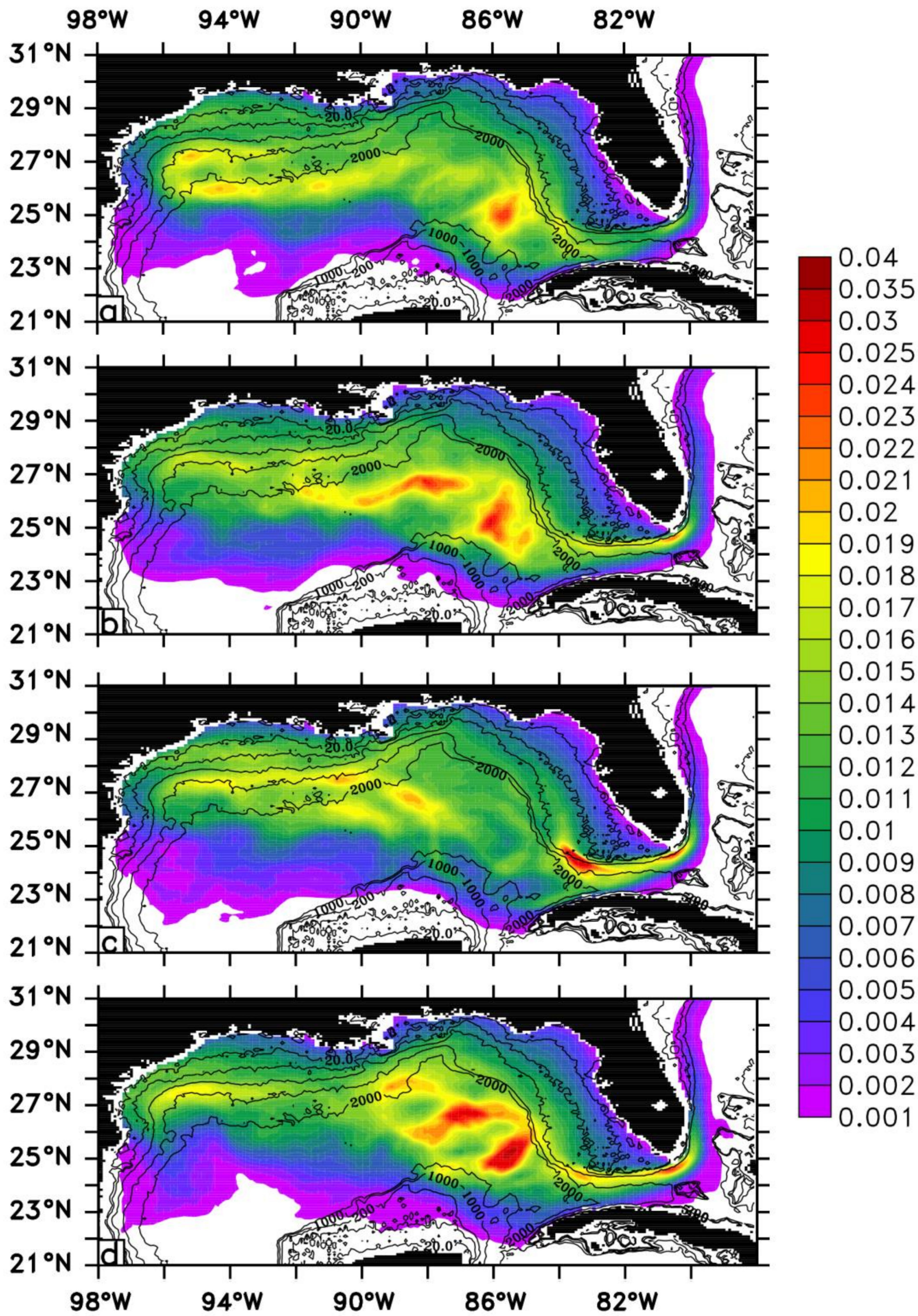


Figure 7. *Cont.*

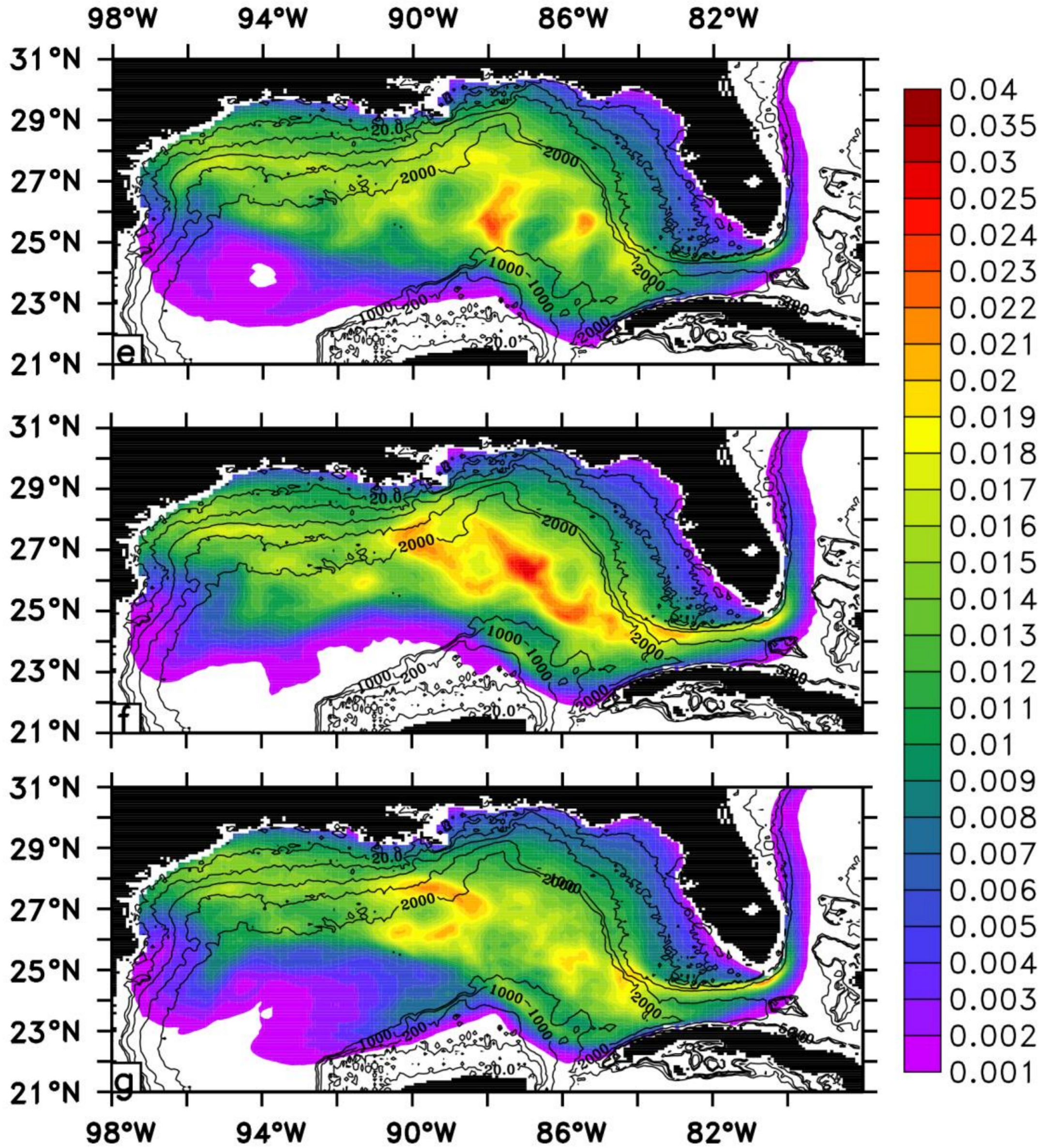


Figure 7. Annual conditional probability at day 30 for year: (**a**) 2000; (**b**) 2001; (**c**) 2002; (**d**) 2003; (**e**) 2004; (**f**) 2005; (**g**) 2006. The color bar has an interval of 0.001 from 0.001 to 0.025 and an interval of 0.005 from 0.025 to 0.004. Isobaths of 20, 50, 200, 1000, and 2000 m are shown as black lines.

3.2. Multi-Year Mean Annual Conditional Probability

This section analyzes multi-year mean annual conditional probability and standard deviations for these two time periods. The OSRA model launches 6,527,520 trajectories for 1993–1998, and 7,615,440 trajectories for 2000–2006. The model tabulates the contacts of these trajectories to each of 20,615 ocean grid cells to estimate the multi-year mean annual conditional probability and the standard deviations of annual conditional probability. These are calculated every day from day 1 to day 30.

As shown in Figure 8, maps of multi-year mean annual conditional probability at day 30 for these two time periods show different patterns. For 2000–2006, the multi-year mean annual conditional probability reaches a maximum value in areas of Loop Current eddies and has relatively large values in areas of Loop Current eddies; for 1993–1998, its counterpart has relatively large value in the Loop Current. For 1993–1998, the multi-year mean annual conditional probability is relatively larger near the Texas shelf, ranging from 0.016 to 0.018. Areas of maximum variations in the annual conditional probability coincide with the most energetic part of the circulation in the GOM as indicated by large standard deviations.

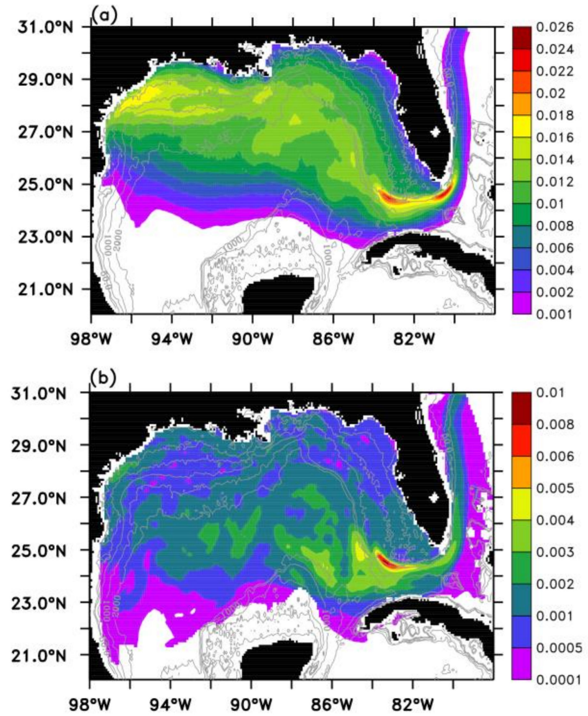


Figure 8. (**a**) Multi-year mean of annual conditional probability for 1993–1998 at day 30; (**b**) Standard deviation of annual conditional probability for 1993–1998 at day 30; (**c**) Multi-year mean conditional probability for 2000–2006 at day 30; (**d**) Standard deviation of annual conditional probability for 2000–2006 at day 30. Isobaths of 20, 50, 200, 1000, and 2000 m are shown as grey lines.

3.3. Monthly Conditional Probability

The monthly conditional probability at day 30 is calculated every month from January to December for each year from 1993 to 1998, and a multi-year averaged conditional probability for each month is generated. Figure 9 shows the monthly conditional probability averaged from 1993 to 1998 at day 30 in January, March, May, July, September, and November. Relatively low monthly conditional probability occurs at the Texas shelf from May to August, and the monthly conditional probability starts to increase during the fall and winter months, as would be expected from the seasonal difference in the Texas–Louisiana coastal circulation [55].

Figure 10 shows the monthly conditional probability averaged from 2000 to 2006 at day 30 in January, March, May, July, September, and November. Very high monthly conditional probability occurs at the Loop Current in January and November. The monthly conditional probability at Loop Current–Florida Current near the Florida Strait in January and March is among the highest of all months for this time period. The monthly conditional probability in May remains the lowest of all months. Compared to 1993–1998, the monthly conditional probability for 2000–2006 is much higher in areas around the Loop Current and Loop Current eddies, reflecting the presence of stronger Loop Current and Loop Current eddies for this time period.

Standard deviations of monthly conditional probability for these two time periods are calculated (not shown). Generally speaking, large variability tends to occur in the Florida Current in 1993–1998, versus in areas of Loop Current and Loop Current eddies in 2000–2006. For 1993–1998, largest standard deviation occurs in May and July near the Loop Current centered at about 83.5° W and overlaid on top of the 200-m isobaths. For 2000–2006, largest standard deviation occurs in September and November in regions dominated by the Loop Current and Loop Current eddies.

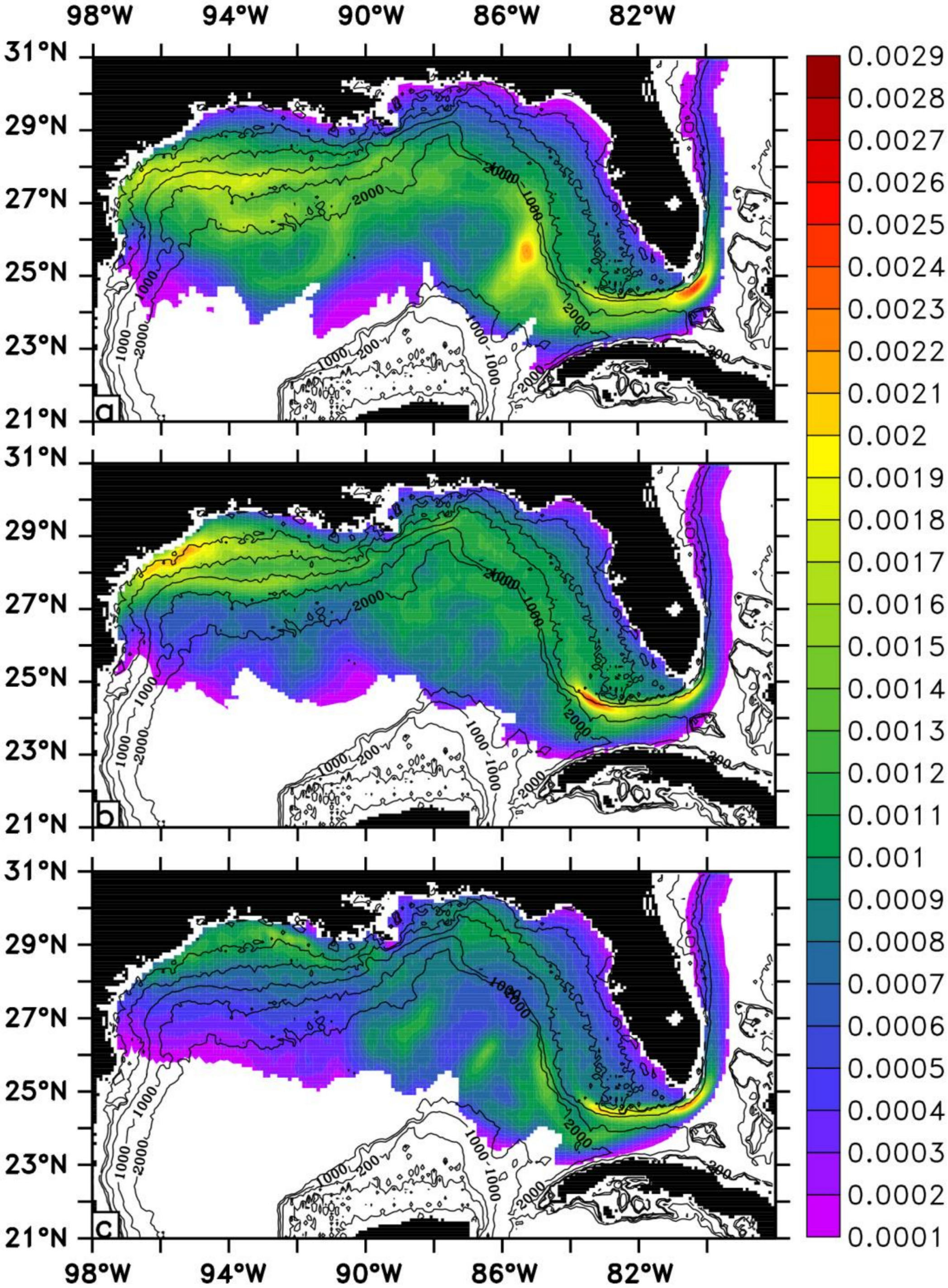


Figure 9. *Cont.*

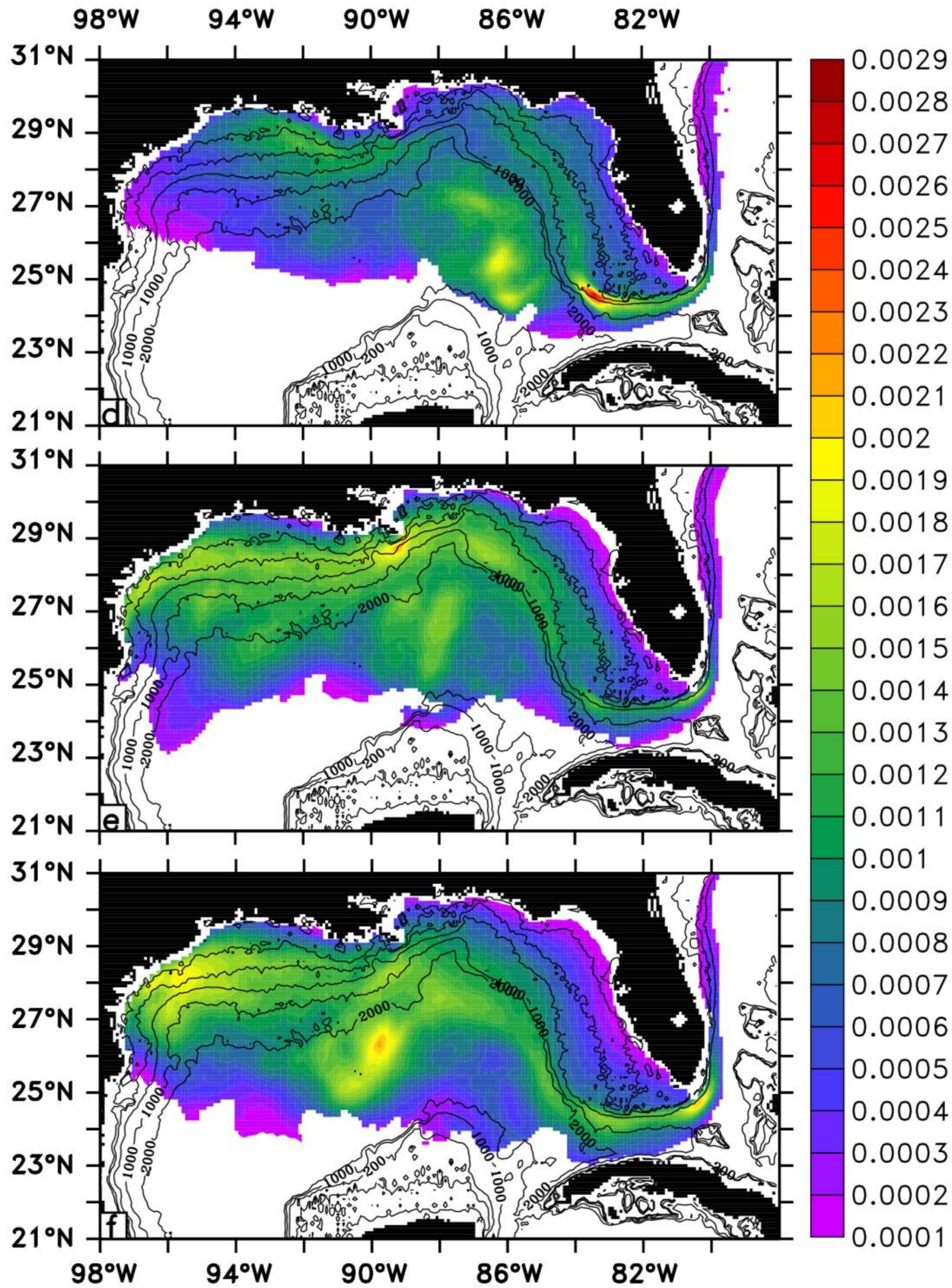


Figure 9. Monthly conditional probability averaged from 1993 to 1998 at day 30 in (**a**) January; (**b**) March; (**c**) May; (**d**) July; (**e**) September; (**f**) November. Isobaths of 20, 50, 200, 1000, and 2000 m are shown as black lines.

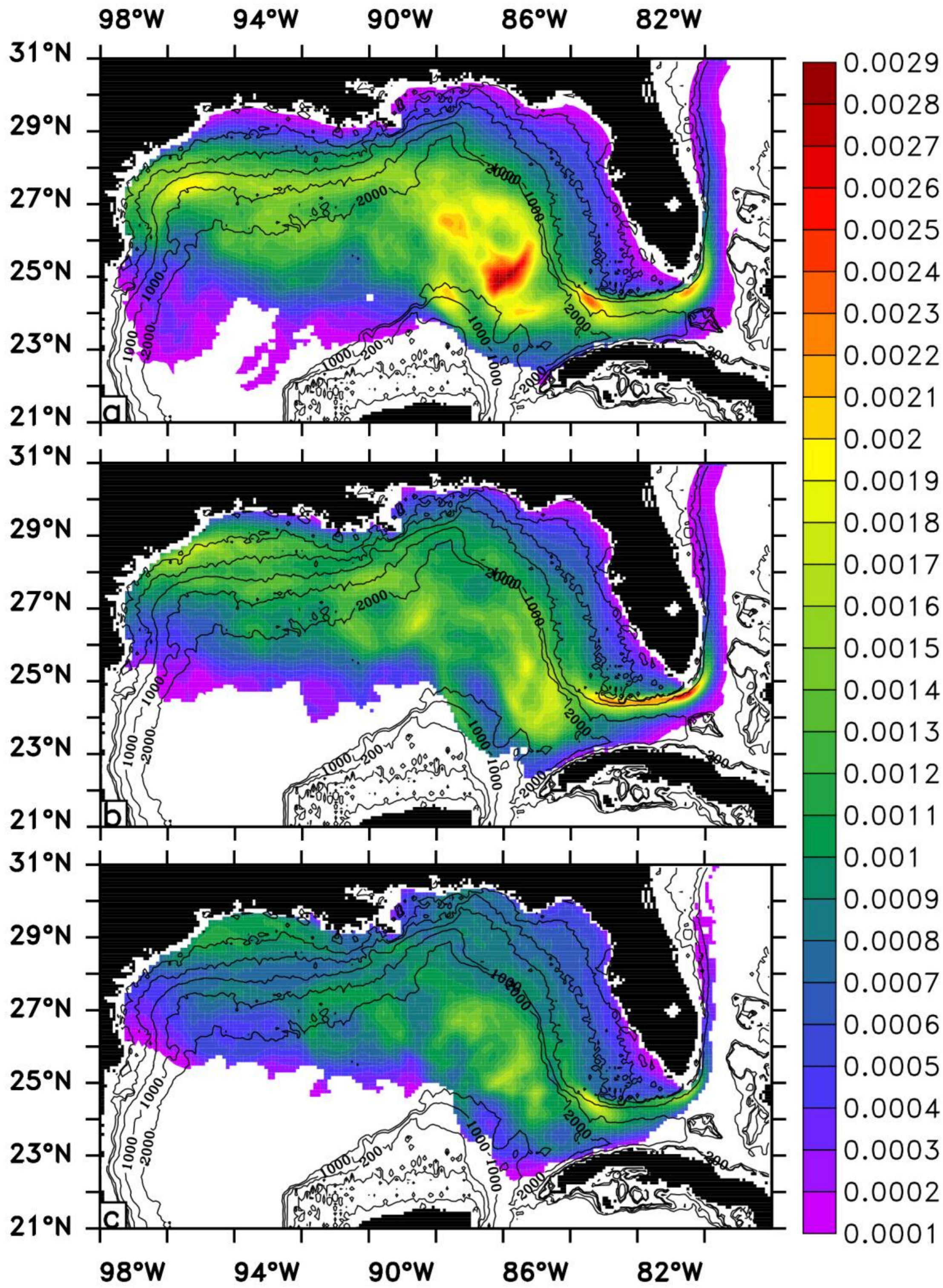


Figure 10. *Cont.*

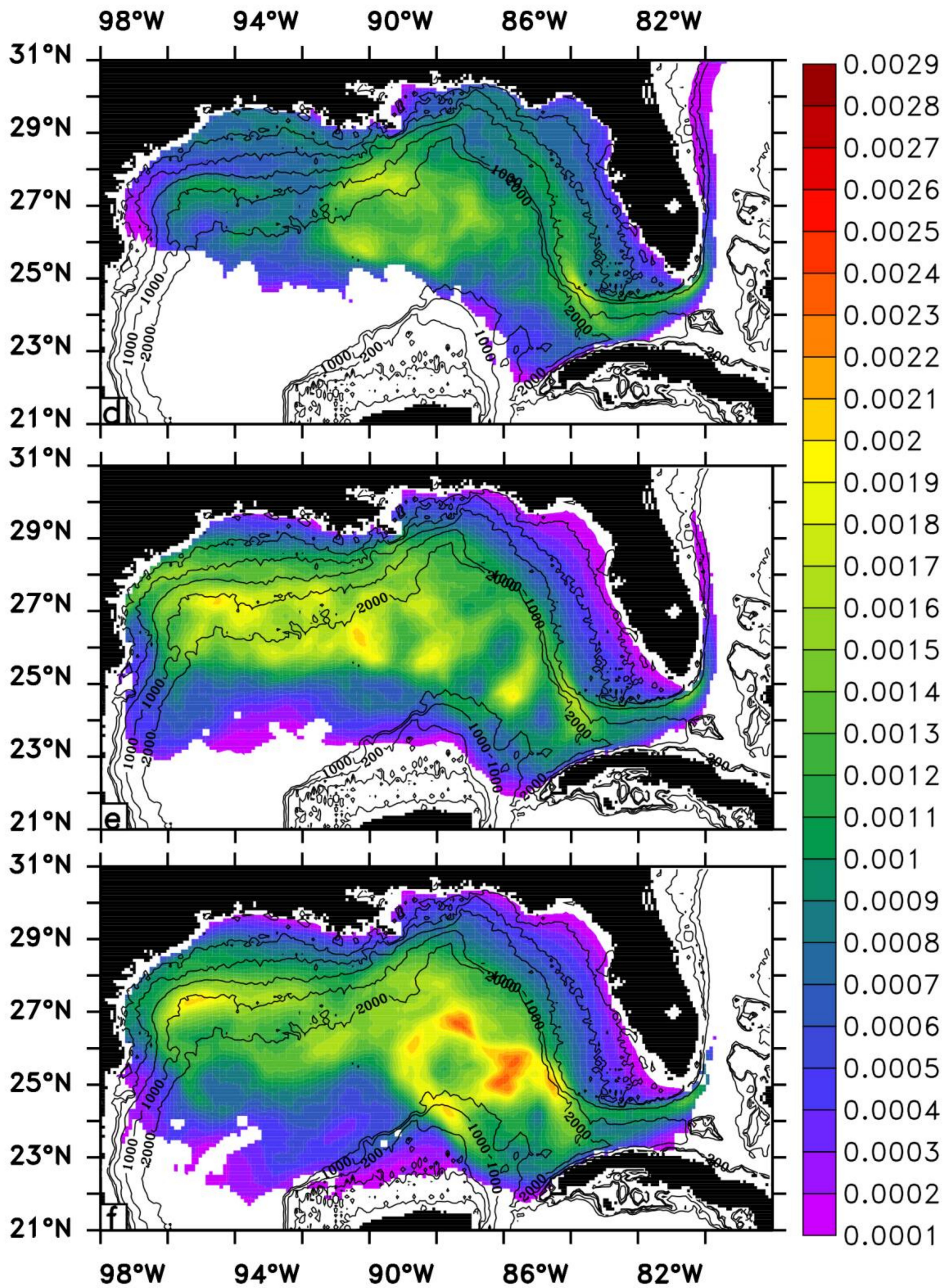


Figure 10. Monthly conditional probability averaged from 2000 to 2006 at day 30 in (**a**) January; (**b**) March; (**c**) May; (**d**) July; (**e**) September; (**f**) November. Isobaths of 20, 50, 200, 1000, and 2000 m are shown as black lines.

3.4. Estimation of Annual Conditional Probability for a Subset of Environmental Resources

To demonstrate the advantage of the new method, the annual conditional probability of a few selected offshore environmental resources in the GOM OCS is estimated. Note that these estimates are for demonstration purpose only; the hypothetical oil spills are assumed to occur over the entire planning areas, and therefore these estimates do not represent real lease sales. Because annual and monthly conditional probability are estimated from each launch point in the planning areas to every ocean grid cell in the OSRA model and are estimated on a daily basis from 1 to 30 days, a database could be created to archive these results. For any future lease sales, conditional probability for any offshore environmental resources can be calculated later from the database without re-running the OSRA model, and they can be estimated at any designated oil spill travel time from 1 to 30 days if wind and current data remain the same.

The resources shown in Figure 11 are examples of offshore environmental resources included in the EISs prior to a lease sale in the GOM. These particular resources are part of the group of resources described as Habitat Areas of Particular Concern (HAPC). HAPCs are defined by the NOAA's National Marine Fisheries Service, and regional Fishery Management Councils identify habitats that fall within HAPCs. These areas provide important ecological functions and/or are especially vulnerable to degradation. HAPCs are discreet subsets of Essential Fish Habitat (EFH). HAPCs are considered high priority areas for conservation, management, or research because they are rare, sensitive, stressed by development, or important to ecosystem function. The HAPC designation does not necessarily mean additional protections or restrictions are placed upon an area, but it helps to prioritize and focus on conservation efforts. Although these habitats are particularly important for healthy fish populations, other EFH areas that provide suitable habitat functions are also necessary to support and maintain sustainable fisheries and a healthy ecosystem. Most of the resources areas in this group are topographic features, meaning that the ocean water over the feature is shallower than much of the surrounding sea floor. These areas are frequently habitats for a variety of fish species, including commercial, recreational, and non-commercial fish.

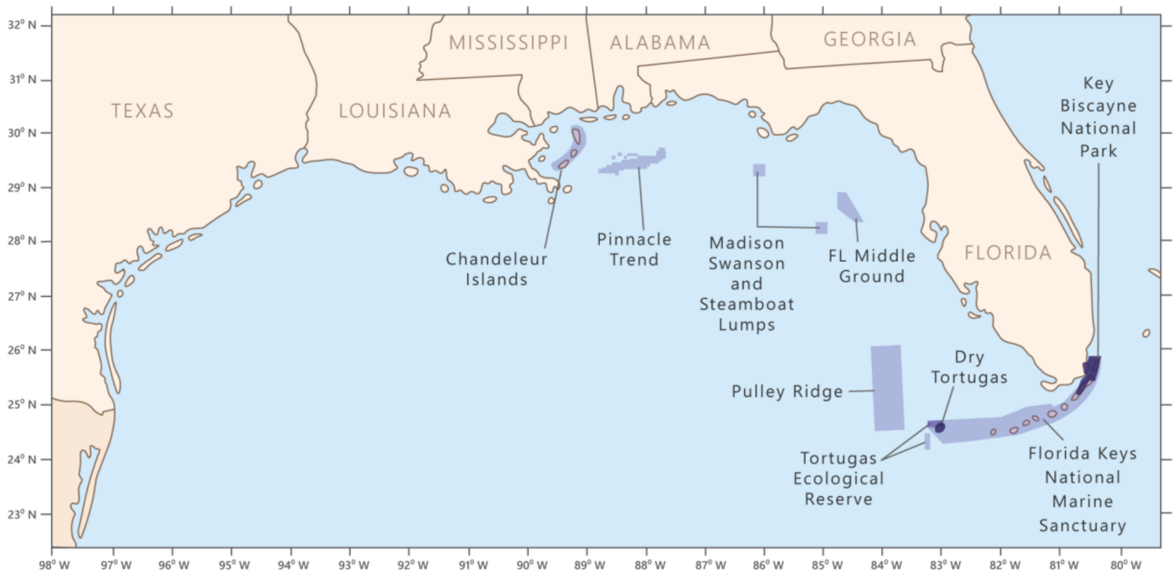


Figure 11. Locations of selected offshore environmental resources in the GOM OCS.

Table 1 lists the estimated mean annual conditional probability and standard deviations for selected environmental resources at day 30, which are calculated from OSRA model output shown in Figures 6 and 7. The environmental resources located near the western edge of the Florida Current, such as the North and South Tortugas Ecological Reserve, have relatively high annual conditional probability and are often associated with high standard deviations due to the interannual and seasonality variability of Loop Current positions. The mean annual conditional probability is slightly higher for 1993–1998 for all selected environmental resources than that of 2000–2006.

Table 1. Mean and standard deviations (SD) of annual conditional probability for a few selected environmental resources in the GOM OCS at day 30 calculated from two data sets.

Environmental Resource	1993–1998		2000–2006	
	Mean	**SD**	**Mean**	**SD**
Chandeleur Islands	0.0061	0.0009	0.0054	0.0010
Madison Swanson and Steamboat Lumps Marine Reserve	0.0100	0.0009	0.0084	0.0005
Florida Middle Ground	0.0084	0.0008	0.0072	0.0007
Pulley Ridge	0.0123	0.0022	0.0118	0.0017
Pinnacle Trend	0.0107	0.0008	0.0098	0.0013
Tortugas Ecological Reserve (North & South)	0.0178	0.0050	0.0143	0.0031
Key Biscayne National Park	0.0088	0.0018	0.0061	0.0011
Dry Tortugas	0.0100	0.0009	0.0090	0.0011
Florida Keys National Marine Sanctuary	0.0112	0.0015	0.0093	0.0014 [1]

[1] Note that these estimates are based on the assumption that the hypothetical oil spills occur in the entire planning areas and do not represent a real leasing scenario. They are for demonstration purposes only with a very small subset of environmental resources considered.

4. Discussion

The OSRA model plays an important role in BOEM's decision-making process as it provides critical information for BOEM's NEPA documents and oil spill response planning. BOEM continues to improve the OSRA model on several fronts, including updating ocean circulation model on a recurring schedule, improving the pre-processing and post-processing of OSRA model input and output files, and developing tools for visualization of OSRA results.

However, utilizing the OSRA model to meet the needs for NEPA analyses still proves to be a challenge, especially when a lease sale is announced without adequate time to perform an updated OSRA model run. This study attempts to provide a solution that will speed up the OSRA process by 'extracting' conditional probability from an existing database without re-running the model. For each leasing scenario, the conditional probability field for the hypothetical oil spills at a specific travel time can be generated for BOEM's contingency planning. Typically, BOEM updates the ocean model hindcast data every five to seven years depending on the availability of funds from BOEM's Environmental Study Program. With this method, the conditional probability can be derived from conditional probability database and used in NEPA analyses for any lease sales, as long as the wind and current data are not updated within the five- to seven-year time frame.

There are many other applications for this method. Because the OSRA model typically uses a long-term, hindcast wind and current data to generate a large ensemble of trajectories for statistical analyses, the variations in conditional probability can be estimated by calculating the standard deviations to reflect the annual and seasonal variability in the forcing fields. Second, this method can be used to analyze the environmental resources that are not distributed evenly in the area represented by the polygon. For this type of environmental resource, a spatial- and/or temporal-dependent density function can be created, and this function can be used in combination with the number of counts tabulated to generate a more accurate estimate of conditional probability. Third, because the database will store the information of the hypothetical oil spill locations, the 'source of pollution' may be identified from convergence of the conditional probability. This is equivalent to running the OSRA model in a reverse mode. These locations can be presented in the form of probability map showing the hypothetical oil spill locations with a certain travel time. Fourth, this method can be used to answer questions; for example, what is the likelihood of the potential oil spills from proposed leasing areas exiting the GOM via the Florida Straits and into the Atlantic Ocean, and at what travel time?

It is important to note that the OSRA model is not designed for use as an oil spill response tool. It was developed for assessing the spill risk prior to a lease sale, without knowing the oil properties. The trajectories are calculated without any approximations of weathering or intervention. It is a conservative approach specifically for the pre-sale process. The use of the term 'contact' to the environmental resources was chosen by USDOI before 1982 to allow a calculation of the probabilities while leaving out the estimation of the 'impact' of the possible oiling. The impact estimation was based on the probability of contact, with the subject matter expert on the particular resource making the assessment. Barker (2011) [41] discussed the similarities and differences between the OSRA model and GNOME when used for longer-term planning purposes, such as the Deepwater Horizon oil spill. The OSRA model is capable of considering the probability that a spill may occur, while NOAA's GNOME and Trajectory Analysis Planner approaches do not have this capability. The OSRA model only considers the surface release of the oil spills because much of the oil released at depth was shown to surface within a few hours and at a radius of a few kilometers [56]. Though the OSRA model includes the sub-surface environmental resources, the model only calculates the probability of contact at the surface and the subject matter experts will use the OSRA model results to assess the impacts to these resources in BOEM's EIS documents.

This method can be improved by conducting more sensitivity tests to derive an optimal number of launch points and model resolutions corresponding to a specific set of wind and current data. Spacing between the launch points may depend on the geographic areas, whether mesoscale or sub-mesoscale eddies dominate. It is constrained by the Rossby radius of deformation, which varies from 10 km in the shelf to 40 km in the interior of the GOM [57]. This study identifies the 'least contacted areas' (i.e., the west Florida shelf, east coast of Florida), and the 'most contacted areas' (i.e., Loop Current and eddies) in the GOM on seasonal and interannual time scales, based on the assumptions that there are hypothetical spills from BOEM's entire planning areas. The analysis can be further grouped into each planning area, such as the Western GOM, Central GOM, and Eastern GOM Planning Areas, with field of conditional probability generated for each planning area. Other OCS regions can use this method to speed up the spill risk assessment process.

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References

1. Zeringue, B.A.; Yu, C.W.; Riches, T.J., Jr.; De Cort, T.M.; Maclay, D.M.; Wilson, M.G. *U.S. Outer Continental Shelf Gulf of Mexico Region Oil and Gas Production Forecast: 2018–2027*; OCS Report BOEM 2017–082; Department of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico OCS Region: New Orleans, LA, USA, 2017; p. 32.
2. Smith, R.A.; Slack, J.R.; Davis, R.K. *An Oil Spill Risk Analysis for the North Atlantic Outer Continental Shelf Lease Area*; Geological Survey Open-File Report 76-620; U.S. Geological Survey: Reston, VA, USA, 1976; p. 38.
3. Smith, R.A.; Slack, J.R.; Wyant, T.; Lanfear, K.J. *The Oilspill Risk Analysis Model of the U.S. Geological Survey*; Geological Survey Professional Paper 1227; United States Government Printing Office: Washington, DC, USA, 1982; p. 40.
4. LaBelle, R.P.; Samuels, W.B.; Amstutz, D.E. An Examination of the Argo Merchant Oil Spill Incident Using a Probabilistic Oil Spill Model. Presented at the 47th Annual Meeting of the American Society of Limnology and Oceanography, Vancouver, BC, Canada, 11–14 June 1984.

5. Johnson, W.R.; Marshall, C.F.; Lear, E.M. *Oil-Spill Risk Analysis: Pacific Outer Continental Shelf Program, Minerals Management Service*; OCS Report 2000-057; OCS Report: Herndon, VA, USA, 2000; p. 290.
6. Anderson, C.M.; LaBelle, R.P. Comparative Occurrence Rates for Offshore Oil Spills. *Spill Sci. Technol. Bull.* **1994**, *1*, 131–141. [CrossRef]
7. Anderson, C.M.; LaBelle, R.P. Update of Comparative Occurrence Rates for Offshore Oil Spills. *Spill Sci. Technol. Bull.* **2000**, *6*, 303–321. [CrossRef]
8. Anderson, C.M.; Mayes, M.; LaBelle, R.P. *Update of Occurrence Rates for Offshore Oil Spills*; OCS Report 2012-069; Bureau of Ocean Energy Management Division of Environmental Assessment, and Bureau of Safety and Environmental Enforcement: Herndon, VA, USA, 2012. Available online: http://www.boem.gov/uploadedFiles/BOEM/Environmental_Stewardship/Environmental_Assessment/Oil_Spill_Modeling/AndersonMayesLabelle2012.pdf (accessed on 21 December 2018).
9. Price, J.M.; Johnson, W.R.; Marshall, C.F.; Ji, Z.-G.; Rainey, G.B. Overview of the Oil Spill Risk Analysis (OSRA) Model for Environmental Impact Assessment. *Spill Sci. Technol. Bull.* **2003**, *8*, 529–533. [CrossRef]
10. Price, J.M.; Johnson, W.R.; Ji, Z.-G.; Marshall, C.F.; Rainey, G.B. Sensitivity Testing for Improved Efficiency of a Statistical Oil-Spill Risk Analysis Model. *Environ. Model. Softw.* **2004**, *19*, 671–679. [CrossRef]
11. Guillen, G.; Rainey, G.; Morin, M. A Simple Rapid Approach Using Coupled Multivariate Statistical Methods, GIS and Trajectory Models to Delineate Areas of Common Oil Spill Risk. *J. Mar. Syst.* **2004**, *45*, 221–235. [CrossRef]
12. Ji, Z.-G.; Johnson, W.R.; Li, Z.; Green, R.E.; O'Reilly, S.E.; Gravois, M.P. *Oil-Spill Risk Analysis: Gulf of Mexico Outer Continental Shelf (OCS) Lease Sales, Eastern Planning Area, 2012–2017, and Eastern Planning Area OCS Program, 2012–2051*; OCS Report BOEM 2013–0110; Department of the Interior, Bureau of Ocean Energy Management: Herndon, VA, USA, 2013; p. 61.
13. Johnson, W.R.; Ji, Z.-G.; Marshall, C.F. Statistical Estimates of Shoreline Oil Contact in the Gulf of Mexico. In Proceedings of the International Oil Spill Conference, Miami Beach, FL, USA, 15–19 May 2005; pp. 547–551.
14. Lugo-Fernandez, A.; Morin, M.V.; Ebesmeyer, C.C.; Marshall, C.F. Gulf of Mexico Historic (1955–1987) Surface Drifter Data Analysis. *J. Coast. Res.* **2001**, *17*, 1–6.
15. Price, J.M.; Reed, M.; Howard, M.K.; Johnson, W.R.; Ji, Z.-G.; Marshall, C.F.; Guinasso, C.N., Jr.; Rainey, G.B. Preliminary Assessment of an Oil-Spill Trajectory Model using Satellite-Tracked, Oil-Spill-Simulating Drifters. *Environ. Model. Softw.* **2006**, *21*, 258–270. [CrossRef]
16. Ji, Z.-G.; Johnson, W.R.; Li, Z. Oil Spill Risk Analysis Model and its Application to the Deepwater Horizon Oil Spill Using Historical Current and Wind data. In *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise*; Liu, Y., MacFadyen, A., Ji, Z.-G., Weisberg, R.H., Eds.; American Geophysical Union: Washington, DC, USA, 2011; pp. 227–236.
17. Zheng, L.; Yapa, P.D.; Chen, F.H. A Model for Simulating Deepwater Oil and Gas Blowouts—Part I: Theory and Model Formulation. *J. Hydraul. Res.* **2003**, *41*, 339–351. [CrossRef]
18. Chen, F.; Yapa, P.D. A Model for Simulating Deep Water Oil and Gas Blowouts—Part II: Comparison of Numerical Simulations with "Deepspill" Field Experiments. *J. Hydraul. Res.* **2003**, *41*, 353–365. [CrossRef]
19. Yapa, P.D.; Chen, F.H. Behavior of Oil and Gas from Deepwater Blowouts. *J. Hydraul. Res.* **2004**, *130*, 540–553. [CrossRef]
20. LaBelle, R.P.; Lane, J.S. Meeting the Challenge of Deepwater Spill Response. In Proceedings of the International Oil Spill Conference, Tampa, FL, USA, 26–29 March 2001; pp. 705–708.
21. LaBelle, R.P. Overview of US Minerals Management Service Activities in Deepwater Research. *Mar. Pollut. Bull.* **2001**, *43*, 256–261. [CrossRef]
22. Beegle-Krause, C.J. General NOAA Oil Modeling Environment (GNOME): A New Spill Trajectory Model. In Proceedings of the International Oil Spill Conference, Tampa, FL, USA, 26–29 March 2001; pp. 865–871.
23. MacFadyen, A.; Watabayashi, G.Y.; Barker, C.H.; Beegle-Krause, C.J. Tactical Modeling of Surface Oil Transport during the Deepwater Horizon Spill Response. In *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise*; Liu, Y., MacFadyen, A., Ji, Z.-G., Weisberg, R.H., Eds.; American Geophysical Union: Washington, DC, USA, 2011; pp. 167–178.
24. Reed, M.; Singsaas, I.; Daling, P.S.; Faksness, L.-G.; Brakstad, O.G.; Hetland, B.A.; Hokstad, J.N. Modeling the Water-accommodated Fraction in OSCAR2000. In Proceedings of the International Oil Spill Conference, Tampa, FL, USA, 26–29 March 2001; pp. 1083–1091.

25. Oey, L.-Y.; Lee, H.-C. Deep Eddy Energy and Topographic Rossby Waves in the Gulf of Mexico. *J. Phys. Oceanogr.* **2002**, *32*, 3499–3527. [CrossRef]
26. Oey, L.-Y.; Lee, H.-C.; Schmitz, W.J., Jr. Effects of Winds and Caribbean Eddies on the Frequency of Loop Current Eddy Shedding: A Numerical Model Study. *J. Geophys. Res.* **2003**, *108*, 3324. [CrossRef]
27. Oey, L.-Y. *Circulation Model of the Gulf of Mexico and the Caribbean Sea: Development of the Princeton Regional Ocean Forecast (& Hindcast) System–PROFS, and Hindcast Experiment for 1992–1999*; OCS Study MMS 2005–049, Final Report; Department of the Interior, Minerals Management Service: Herndon, VA, USA, 2005; p. 174.
28. Chang, Y.-L.; Oey, L.; Xu, F.-H.; Lu, H.-F.; Fujisaki, A. Oil spill: Trajectory Projections Based on Ensemble Drifter Analyses. *Ocean Dyn.* **2011**, *61*, 829–839. [CrossRef]
29. Wang, D.-P.; Oey, L.-Y.; Ezer, T.; Hamilton, P. Near-Surface Currents in DeSoto Canyon (1997–1999): Comparison of Current Meters, Satellite Observations, and Model Simulation. *J. Phys. Oceanogr.* **2003**, *33*, 313–326. [CrossRef]
30. Ezer, T.; Oey, L.-Y.; Lee, H.-C.; Sturges, W. The Variability of Currents in the Yucatan Channel: Analysis of Results from a Numerical Ocean Model. *J. Geophys. Res.* **2003**. [CrossRef]
31. Fan, S.J.; Oey, L.-Y.; Hamilton, P. Assimilation of Drifter and Satellite Data in a Model of the Northeastern Gulf of Mexico. *Cont. Shelf Res.* **2004**, *24*, 1001–1013. [CrossRef]
32. Oey, L.-Y.; Ezer, T.; Lee, H.-C. Loop Current, Rings and Related Circulation in the Gulf of Mexico: A Review of Numerical Models and Future Challenges. In *Circulation in the Gulf of Mexico: Observations and Models*; Geophysical Union Geophysical Monograph Series; Wiley: Hoboken, NJ, USA, 2005; Volume 161, pp. 32–56.
33. Oey, L.-Y.; Ezer, T.; Forristall, G.; Cooper, C.; DiMarco, S.; Fan, S. An Exercise in Forecasting Loop Current and Eddy Frontal Positions in the Gulf of Mexico. *Geophys. Res. Lett.* **2005**, *32*, L12611. [CrossRef]
34. Oey, L.-Y.; Ezer, T.; Wang, D.-P.; Fan, S.; Yin, X.-Q. Loop Current Warming by Hurricane Wilma. *Geophys. Res. Lett.* **2006**, *33*, L08613. [CrossRef]
35. Oey, L.-Y.; Ezer, T.; Wang, D.-P.; Yin, X.-Q.; Fan, S.-J. Hurricane-induced Motions and Interaction with Ocean Currents. *Cont. Shelf Res.* **2007**, *27*, 1249–1263. [CrossRef]
36. Oey, L.-Y.; Inoue, M.; Lai, R.; Lin, X.-H.; Welsh, S.; Rouse, L., Jr. Stalling of Near-inertial Waves in a Cyclone. *Geophys. Res Lett.* **2008**, *35*, L12604. [CrossRef]
37. Oey, L.-Y. Loop Current and Deep Eddies. *J. Phys. Oceanogr.* **2008**, *38*, 1426–1449. [CrossRef]
38. Oey, L.-Y.; Chang, Y.-L.; Sun, Z.-B.; Lin, X.-H. Topocaustics. *Ocean Model.* **2009**, *29*, 277–286. [CrossRef]
39. Yin, X.-Q.; Oey, L.-Y. Bred-ensemble Ocean Forecast of Loop Current and Rings. *Ocean Model.* **2007**. [CrossRef]
40. Lin, X.-H.; Oey, L.-Y.; Wang, D.-P. Altimetry and Drifter Data Assimilations of Loop Current and Eddies. *J. Geophys. Res.* **2007**, *112*, C05046. [CrossRef]
41. Barker, C.H. A Statistical Outlook for the *Deepwater Horizon* Oil Spill. In *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise*; Liu, Y., MacFadyen, A., Ji, Z.-G., Weisberg, R.H., Eds.; American Geophysical Union: Washington, DC, USA, 2011; pp. 237–244.
42. Alves, T.M.; Kokinou, E.; Zodiatis, G.A. Three-step Model to Assess Shoreline and Offshore Susceptibility to Oil Spills: The South Aegean (Crete) as an Analogue for Confined Marine Basins. *Mar. Pollut. Bull.* **2014**, *86*, 443–457. [CrossRef] [PubMed]
43. Alves, T.M.; Kokinou, E.; Zodiatis, G.A.; Lardner, R.; Panagiotakis, C.; Radhakrishnan, H. Modelling of Oil Spills in Confined Maritime Basins: The Case for Early Response in the Eastern Mediterranean Sea. *Environ. Pollut.* **2015**, *206*, 390–399. [CrossRef]
44. Alves, T.M.; Kokinou, E.; Zodiatis, G.A.; Radhakrishnan, H.; Panagiotakis, C.; Lardner, R. Multidisciplinary Oil Spill Modeling to Protect Coastal Communities and the Environment of the Eastern Mediterranean Sea. *Sci. Rep.* **2016**, *6*. [CrossRef]
45. Forristal, G.Z.; Schaudt, K.J.; Cooper, C.K. Evolution and Kinematics of a Loop Current Eddy in the Gulf of Mexico during 1985. *J. Geophys. Res.* **1992**, *97*, 2173–2184. [CrossRef]
46. Sturges, W.; Leben, R. Frequency of Ring Separations from the Loop Current in the Gulf of Mexico: A Revised Estimate. *J. Phys. Oceanogr.* **2000**, *30*, 1814–1819. [CrossRef]
47. Sturges, W.; Lugo-Fernandez, A. (Eds.) *Circulation in the Gulf of Mexico: Observations and Models*; Geophysical Monograph Series; American Geophysical Union: Washington, DC, USA, 2005; Volume 161, p. 347.
48. Samuels, W.B.; Huang, N.E.; Amstutz, D.E. An Oilspill Trajectory Analysis Model with a Variable Wind Deflection Angle. *Ocean Eng.* **1982**, *9*, 347–360. [CrossRef]

49. Department of the Interior, Bureau of Ocean Energy Management. *Gulf of Mexico OCS oil and Gas Lease Sales: 2014 and 2016; Eastern Planning Area Lease Sales 225 and 226—Final Environmental Impact Statement*; OCS EIS/EA BOEM 2013-200; Department of the Interior, Bureau of Ocean Energy Management, Gulf of Mexico Region: New Orleans, LA, USA, 2013; Volume 1.
50. Oey, L.-Y. Extended Hindcast Calculation of Gulf of Mexico Circulation: Model Development, Comparison with Observations, and Application to the 2010 Oil Spill. Unpublished work.
51. Mellor, G.L. *User Guide for a Three-Dimensional, Primitive Equation, Numerical Ocean Model (Jul/2002 Version)*; Program in Atmospheric and Oceanic Sciences, Princeton University: Princeton, NJ, USA, 2002; p. 42. Available online: http://www.ccpo.odu.edu/POMWEB/UG.10-2002.pdf (accessed on 21 December 2018).
52. Adler, E.; Inbar, M. Shoreline Sensitivity to Oil Spills, the Mediterranean Coast of Israel:Assessment and Analysis. *Ocean Coast. Manag.* **2007**, *50*, 24–34. [CrossRef]
53. Yang, H.; Weisberg, R.H.; Niiler, P.P.; Sturges, W.; Johnson, W. Lagrangian Circulation and Forbidden Zone on the West Florida Shelf. *Cont. Shelf Res.* **1999**, *19*, 1221–1245. [CrossRef]
54. Sturges, W.; Niiler, P.P.; Weisberg, R.H. *Northeastern Gulf of Mexico Inner Shelf Circulation Study*; Final Report, MMS Cooperative Agreement 14-35-0001-30787, OCS Report MMS 2001–103; US Minerals Management Service: Herndon, VA, USA, 2001; p. 90.
55. Nowlin, W.D., Jr.; Jochens, A.E.; DiMarco, S.F.; Reid, R.O.; Howard, M.K. Low-frequency Circulation over the Texas-Louisiana Continental Shelf. In *Circulation in the Gulf of Mexico: Observations and Models*; Geophysical Monograph Series; Sturges, W., Lugo-Fernandez, A., Eds.; American Geophysical Union: Washington, DC, USA, 2005; Volume 161, pp. 219–240.
56. Johansen, O.; Rye, H.; Cooper, C. DeepSpill—Field Study of a Simulated Oil and Gas Blowout in Deep Water. *Spill Sci. Technol. Bull.* **2003**, *8*, 433–443. [CrossRef]
57. Chelton, D.B.; de Szoeke, R.A.; Schlax, M.G.; El Naggar, K.; Siwertz, N. Geographical Variability of the First Baroclinic Rossby Radius of Deformation. *J. Phys. Oceanogr.* **1998**, *28*, 433–460. [CrossRef]