Chapter 3
Environmental Impact and Modeling of Petroleum Spills

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3.1 Introduction

The risks associated with a release of oil posed by potentially polluting wrecks (PPW) span a wide range of probabilities and potential magnitudes for environmental consequences. Even a lay reader will be well aware that following a release of oil, there is great potential for environmental damage and mortality of birds, mammals, and fish. Fisheries and beach closures and localised evacuations may occur to limit the exposure of humans to potential contaminants. The range of socio-economic and ecological impacts can be quite large between releases with the geographic extent and magnitude of effects being extremely variable between releases. In addition, the duration of these effects and changes to populations and ecosystems can range from a few days to years or even decades in some circumstances. This variability necessitates the quantitative assessment of the range of environmental impacts to understand where a release may occur, the environmental conditions at the time of the release, the geographic extent over which it may be transported, and the receptors of interest (e.g., species of concern, shorelines, populated areas) that may be impacted. Computational oil spill models were developed to characterise the movement and behavior of released oil in the environment, while also quantifying the duration of exposure to levels of contamination and their potential for both lethal and sublethal effects.

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3.2 Background

Countless ships have been lost at sea. A portion of these may contain petroleum products that have the potential to result in environmental impacts. The National Oceanic and Atmospheric Administration (NOAA) maintains a large database of shipwrecks, dumpsites, navigational obstructions, underwater archaeological sites, and other underwater cultural resources. This internal database, Resources and Undersea Threats (RUST), has over 30,000 targets, including approximately 20,000 shipwrecks in US waters (Overfield, 2004; Zelo et al., 2005). However, only a small fraction of these wrecks is likely to contain oil. Many vessels came to a violent end, breaking apart in storms, collisions, or in battle. Shallower wrecks were frequently salvaged or intentionally destroyed, as they posed risks to navigation. The remaining wrecks are therefore located at depth and have likely suffered from corrosion and the passage of time. However, reviews of historical information have identified thousands of sunken vessels along the U.S. coast, which have identified many with significant volumes of oil remaining on-board (French McCay et al., 2012, 2014; NOAA, 2013). In 2005, it was estimated that there are at least 8500 potentially polluting sunken wrecks of tankers and large vessels (at least 400 gross tons) worldwide (Michel et al., 2005). Unless located and remediated, these largely forgotten wrecks will begin to leak, often becoming the source of 'mystery spills' until the source is identified. Concerns lie with the potential for effects following a release with contaminants in the water column, on the water surface, and along nearby shorelines.

The RUST database (and those like it) is important from an environmental impact and modeling perspective as it provides risk assessors with a more complete understanding of where wrecks are located and what they likely contain. The range of locations enables the risk assessor to consider local environmental conditions (e.g., currents, tides, winds), key geographic features, and water depth, which will impact the potential transport of released oil and its potential to impact specific locations and/or receptors. As an example, an oil spill from a wreck that is located near the Gulf Stream off the coast of North Carolina has a greater potential for current transport, when compared to a wreck that may be in more stagnant waters and may affect amenity beaches along the coast. The range of product types and potential release volumes contained on each vessel enables the determination of trajectory and fate based upon known physical and chemical transport and fates processes. As an example, a large amount of marine diesel may evaporate, dissolve, and degrade quickly, and also be readily entrained in the water column, leading to a relatively small area for potential effects. A comparably smaller release of a heavier crude oil or fuel oil may be much more persistent and be transported greater distances, with a greater potential to impact beaches. The chemical composition of each oil will also impact its level of toxicity and potential to impact aquatic life. It is clear that there are numerous variables that must be considered when simulating the potential environmental consequences following a release.

3.3 Previous Work

The U.S. Coast Guard and the Regional Response Teams (RRTs), as well as NOAA, are responsible for the development of regional and area contingency plans. In 2010, the U.S. Congress appropriated $1 million to identify the most ecologically and economically significant potentially polluting wrecks (PPW) in U.S. Waters. NOAA worked closely with the U.S. Coast Guard Office of Marine Environmental Response Policy in implementing this mandate. The Remediation of Underwater Legacy Environmental Threats (RULET) effort supported the prioritisation of potential threats to coastal resources, while at the same time assessing the historical and cultural significance of these nonrenewable cultural resources (Symons et al., 2014). Similarly, there was an initiative using a slightly different screening approach to develop for the Mediterranean Sea with the Development of European Guideline for Potentially Polluting Shipwrecks (DEEPP), categorised with respect to Volume Class (estimated volume of oil on board) and Distance Class (proximity to shore) which are used to determine a risk factor (Alcaro et al., 2007). The RULET project narrowed the list of 20,000 vessels from RUST to 107 wrecks within the U.S. Exclusive Economic Zone (U.S. EEZ) that could pose a substantial pollution threat, which was further refined to 36 high priority worst case discharge (WCD) scenarios. From that, NOAA developed a total of 87 risk assessment packages for consideration by the U.S. Coast Guard Federal On-Scene Coordinators (FOSCs).

While each of the RUST, RULET, and DEEPP projects were sizeable investments, they operated under the premise that it would be impossible (from a financial and time perspective) to proactively respond to all wrecks immediately. Rather, the intent was to focus attention and limited resources on specific regions of interest that had the highest potential risk (likelihood and magnitude of potential consequences). Oil spill modeling was used to assess releases from numerous identified wrecks to begin to understand the range of potential consequences. The highest risk wrecks were then identified as focus points for oil spill response preparedness, surveillance, and potential mitigation efforts.

The components of an oil spill risk assessment for PPWs are essentially like that for other potential spill sources (Etkin et al., 2017; Etkin, 2019). Improvements have been made in the assessment of leakage probabilities, specifically in the VRAKA model (Landquist et al., 2014). However, given enough time, the probability of any specific wreck releasing oil will increase due to the continued corrosion of the hulls in the marine environment. The remainder of this chapter will focus on the assumption that oil has been released.

3.4 Released Oil

The environmental consequence following any release of oil depends on a number of factors, the two most obvious of which include the type (e.g., gasoline, diesel, crude oil, heavy fuel oil, etc.) and volume of oil. Oil is a complex mixture of many thousands of different hydrocarbon compounds derived from naturally occurring geological formations. Each of these compounds has its own molecular weight, density, viscosity, solubility, volatility, and toxicity. Therefore, the unique mixture of each oil has physical and chemical properties that reflect its unique composition, as well as its state of weathering from fresh oil along the continuum of weathering, which will affect its transport and fate, once discharged into the environment (NRC, 2003). In addition, these physical and chemical properties of each chemical compound within the oil impacts the ultimate toxicity of the oil, which will influence the magnitude of potential consequences following a release (e.g., mortality). The next most important factor influencing the potential consequence is the environmental conditions at the time of release for that specific release location. Environmental forcing parameters such as winds, currents, and tides will transport (i.e., advect) the oil, while other environmental parameters such as waves, temperature, and sunlight may change the dispersion, behavior, and/or weathering of the oil. Ultimately, the potential effects are dependent on both the concentration of contaminants and the duration of exposure to receptors (French-McCay, 2002) that may be sessile or mobile. Therefore, release rate of the product (amount of oil entering the environment over a period of time) will also play an important role in influencing the potential transport, fate, and resulting consequences.

To develop a robust understanding of the potential risks and the variability of effects from oil spills from PPWs, computational oil spill models may be used to assess the range of potential movement, behavior, and resulting consequences of a range of specific releases under a range of geographic locations and environmental release conditions. These tools can then be used to quantify the range of potential releases and resulting effects, which can be quite variable.

3.5 Computational Spill Models

Computational oil spill models such as OILMAP and SIMAP have been in development for over 40 years. The models are validated against real-world release and used extensively in the United States and internationally to meet regulatory requirements and to develop recommendations and guidelines. They are frequently used by industry, government, and academia. SIMAP was derived from the Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) (French et al., 1996), which was developed for the U.S. Department of the Interior as the basis of the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Natural Resource Damage Assessment regulations (as amended) for Type A. These comprehensive oil spill modeling tools have been developed to predict the trajectory (i.e., movement) and fate (i.e., behavior and weathering) of released hydrocarbons into water. The state-of-the-art capability of the oil fate and impact assessment model SIMAP is ideally suited to simulate spill scenarios from PPWs (French et al., 1996; French McCay & Rowe, 2004; French McCay et al., 2004). For wrecks known or suspected to contain chemical hazards, the CHEMMAP model can be applied to simulate spills and measure impacts in a similar fashion to the oil spill modeling but for chemicals which have different behaviors once released into the environment (French McCay, 2001). Using the data from the trajectory, fate, and effects modeling in SIMAP and CHEMMAP, with the addition of the appropriate spill response within the model simulation, the costs and damages from the resulting oil and chemical spills are then calculated. This methodology has been applied in several studies (Etkin et al., 2003, 2006; Etkin & Welch, 2005; French McCay et al., 2005). In addition to the RULET study, oil spill modeling tools have been used to assess the risk from PPW, specifically, and helped to prioritise oil removal operations (Etkin et al., 2009; Etkin, 2019).

Oil spill modeling tools incorporate site-specific and season-specific geographic and environmental variables (e.g., winds, currents, tides, waves, habitat data, bathymetry, temperature, salinity, etc.), as well as the product-specific chemical and physical characteristics of the hydrocarbons to effectively predict its movement and behavior in the environment (Fig. 3.1). They use wind data, current data, and transport and weathering algorithms to calculate the mass of oil components in various environmental compartments (water surface, shoreline, water column, atmosphere, sediments, etc.), oil trajectory over time, surface oil distribution, and concentrations of the oil components in water and sediments. SIMAP also contains physical fate and biological effects models, which estimate exposure and impact on each habitat and wildlife species (or species group) in the area of the spill. Environmental, geographical, physical-chemical, and biological databases supply required information to the model for computation of fates and effects. Seasonal and spatial variations in wildlife populations, particularly migratory birds (which may or may not be present at specific points throughout the year), are incorporated into the modeling databases when available. SIMAP and CHEMMAP can therefore be used to determine the potential biological effects (i.e., acute mortality) that may result following a release of oil and/or chemicals.

3.6 Acute Biological Effects

Biological effects of oil spills can be assessed using the predicted trajectory and fate of hydrocarbon contamination to use the spatially and time-varying concentrations and duration of exposure to determine acute mortality following a release. In the SIMAP model, aquatic biota (e.g., fish, invertebrates) are affected by dissolved hydrocarbon concentrations in the water or sediment. This rationale is supported by the fact that soluble aromatics are the most toxic constituents of oil

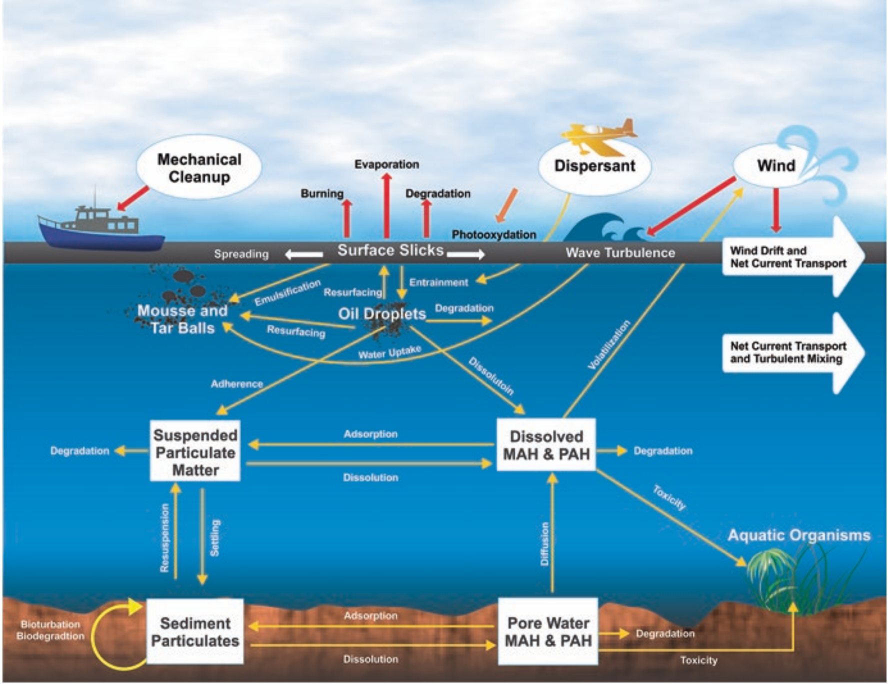


Fig. 3.1 Diagram depicting the transport, fate, and select response processes that may be relevant for subsurface releases from PPW that are simulated in OILMAP and SIMAP

(Neff et al., 1976; Rice et al., 1977; Tatem et al., 1978; Neff & Anderson, 1981; Malins & Hodgins, 1981; National Research Council (NRC), 1985, 2003; Anderson, 1985; French-McCay, 2002). Soluble aromatics refer to low molecular weight compounds that are composed of aromatic rings (six-carbon rings) and can dissolve in water, including compounds such as benzene, toluene, ethylbenzene, and xylene (BTEX), mono-cyclic aromatic hydrocarbons (MAHs) that have 8–10 carbon atoms, and to some extent some smaller poly-cyclic aromatic hydrocarbons (PAHs) that have 10–12 carbon atoms. Exposures in the water column are short, and effects are the result of acute toxicity. In the sediments, exposure can be both acute and chronic, as the concentrations may remain elevated for longer periods of time.

French-McCay (2002) provides estimates of $LC50_\infty$ (which is the infinite time exposure) for MAH and PAH mixtures in fuel and crude oils for spills under different environmental conditions. Figure 3.2 plots LC50 values for total dissolved PAHs for species of average sensitivity under turbulent conditions ($LC50_\infty = 50$ µg/L) for a range of exposure durations and temperatures. The $LC50_\infty$ for 95% of species fall in the range 5–400 µg/L. This oil toxicity model has been validated using laboratory oil bioassay data (French-McCay, 2002). In SIMAP, $LC50_\infty$ for the dissolved hydrocarbon mixture of the spilled oil is input to the model. For each aquatic biota

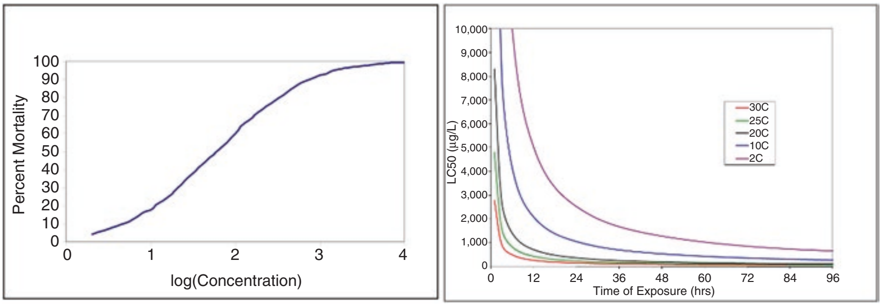


Fig. 3.2 Illustration of percent mortality as a function of concentration (left). The LC50 is at the center of the log-normal function, aligning with 50% mortality. The LC50 of dissolved oil PAH mixtures as a function of exposure duration and temperature (right)

behavior group, the model evaluates exposure duration and corrects the LC50 for time of exposure and temperature to calculate mortality (Fig. 3.2). The oil toxicity model is described in the next section, and in detail in French-McCay (2002). However, it is important to note that an $LC50_{\infty} = 50$ µg/L does *not* correlate to 50% mortality at a concentration of 50 µg/L if the exposure is for less than several days (unlikely in real world offshore releases). Narcosis from hydrocarbons is generally disruptive to cellular function, but sublethal effects range widely including impairment, decreased growth rate and reproduction, developmental delays, observable structural (deformation), genetic, biochemical, physiological, and behavioral changes. The SIMAP model accounts for the duration of exposure and scales the predicted mortality to lower values for shorter durations of exposure (e.g., hours), which would be more typical in open ocean environments.

The SIMAP biological exposure model estimates the volume and area of water affected by surface oil, concentrations of oil components in the water, and sediment contamination. The exposure model takes into account the time and temperature of exposure. Time of exposure is evaluated by tracking movements of organisms' relative concentrations greater than the concentration lethal to 1% of exposed organisms (LC1, approximated as 1% of $LC50_{\infty}$, which is the infinite time exposure). Stationary or moving Lagrangian tracers that represent organisms record the concentrations of exposure over time and the dose (summed concentration times duration) to an organism represented by that behavior. Then, the SIMAP biological effects model estimates losses resulting from acute exposure after a spill (i.e., losses at the time of the spill and while acutely toxic concentrations remain in the environment) in terms of direct mortality. Exposure time is the total time concentration exceeds LC1. The concentration is the average over that time, or total dose divided by exposure time. The percentage mortality is then calculated using the log-normal function centered on the LC50 at any specific point in time. The end result is a predicted percent mortality at each point in space and for each representative type of organism and behavior group.

3.7 Seasonal Considerations

As noted above, there are many variables that may impact the magnitude of potential consequences following a release, including: the number of wrecks, their locations, the fuel types and volumes contained, as well as the largest unknown being the specific point in time that a release takes place. One clear example of the point in time of a release impacting the potential for effects is for wrecks within the Great Lakes. Should a release occur in August, the oil would most likely rise to the surface and be transported by winds and currents to adjacent shorelines, with a portion of the oil evaporating to the atmosphere and a smaller portion dissolving into the water column. However, if that same release were to occur in February, the oil may become trapped beneath the layer of ice at the water surface, which would enable much larger portions of the oil to dissolve into the water column as the evaporation of lighter ends would be capped by the ice. In addition, the areal extent of effects may be smaller during the winter, as the oil would become trapped beneath the ice and not transported by surface winds. This would decrease the overall footprint or extent of effects but may increase the magnitude of contaminants and duration of exposure to local organisms, thereby increasing the potential for effects (e.g., acute mortality) to nearby aquatic species. Similar variability can occur in the offshore marine environment, where metocean (i.e., meteorological and oceanic) conditions can be extremely variable in any given time period, even on hourly timescales or below. Therefore, it is important to have an understanding of not only the conditions that may be present at the time of release, but throughout any given year and over many years to have a more complete understanding of the variability in potential transport and fate of any given release. Stochastic assessments will be discussed below to address this environmental variability and the resulting likelihood that releases may impact certain areas.

3.8 Validation Studies

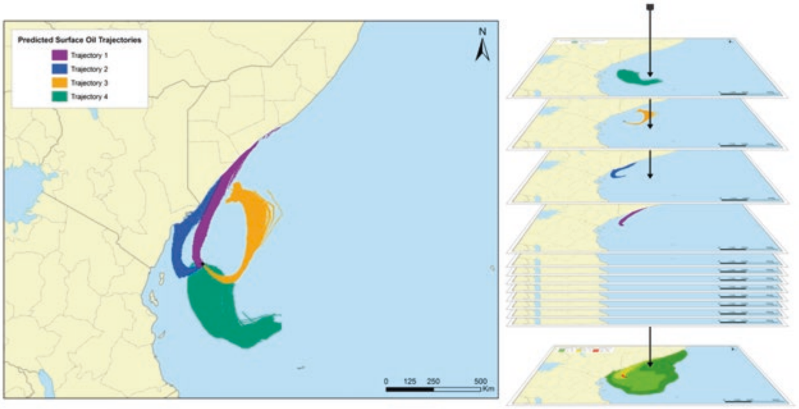
The SIMAP transport model has been validated with more than 20 case studies, including the Exxon Valdez and other large spills such as *Deepwater Horizon* in the Gulf of Mexico (French-McCay, 2003, 2004; French McCay & Rowe, 2004; French-McCay et al., 2018a, b, c, 2021a, b, c). In addition, the models have been further refined and validated using test spills designed to verify the model's transport algorithms (French & Rines 1997, French-McCay et al. 2007) as well as numerous laboratory studies. The oil toxicity model was validated using laboratory oil bioassay data for both fresh and salt-water organisms (French-McCay, 2002) and for lobster mortality in the case of the North Cape spill (French-McCay, 2003). The underlying toxicity data used to develop the model is based on bioassays for freshwater and marine fish, invertebrate, and algal species at a variety of life stages. Below is a summary of the oil toxicity analysis by French-McCay (2001, 2002).

These computational spill modeling tools have been used extensively throughout the world to meet and exceed regulatory requirements for offshore exploration, development, operations, transport, and risk assessment. These tools, and SIMAP specifically, have been used in numerous Natural Resource Damage Assessments (NRDA) for the U.S. government, including notable releases such as the *Deepwater Horizon* oil spill in the Gulf of Mexico beginning on April 20, 2010 (USDOI, 2023).

The *Deepwater Horizon* was a particularly notable release, not only for its magnitude, but because of the large amount of attention that was focused on the release. While the well was still releasing oil, BP dedicated approximately $500 million to be spent over 10 years 'to fund an independent research program designed to study the impact of the oil spill and its associated response on the environment and public health in the Gulf of Mexico.' This investment spawned the Gulf of Mexico Research Initiative, or GOMRI, which is governed by an independent, academic research board of 20 science, public health, and research administration experts and independent of BP's influence. In addition, hundreds of millions of dollars were spent on the scientific study of the response itself by both academia and industry. One result of this was a tremendous focus on improving the understanding of trajectory, fate, and effects modeling. Numerous improvements were made to underlying model algorithms including entrainment, emulsification, weathering, degradation, and other processes that serve move the oil within the environment or alter its chemical and physical state. This spawned numerous studies and improvements in computational oil spill modeling, including several associated with characterising the mass balance of the release, the state of the oil, and the validation of the trajectory, fate, and ultimate effects (French-McCay et al., 2018a, b, c, 2021a, b, c).

3.9 Stochastic Assessments

One of the largest challenges with assessing the risk (and specifically consequence) of a release from a PPW is that the exact time of the release, and the corresponding environmental conditions at that time, are not known. A stochastic approach can be used to determine the footprint and probability of areas that are at increased risk of oil exposure based upon the variability of meteorological and hydrodynamic conditions that might prevail during and after a release. A stochastic scenario is a statistical analysis of results generated from many (e.g., >100 simulations) different individual trajectories of the same release scenario, with each trajectory beginning at a different point in time, selected from a relatively long-term window of time (e.g., 10 years). Stochastic simulations therefore provide insight into the probable behavior of potential oil spills in response to spatially and temporally varying meteorological and oceanographic conditions around a release location (Fig. 3.3). This stochastic approach therefore allows for the same type of release to be analyzed under varying environmental conditions (e.g., summer vs. winter, calm vs. windy, or low vs. high current from 1 year to the next). The results provide the probable behavior of the potential releases based upon this environmental variability.



Examples of four individual spill trajectories predicted by OILMAP for a particular spill scenario. The frequency of contact with given locations is used to calculate the probability of impacts during a spill. Essentially, all 100+ model runs are overlain (shown as the stacked runs on the right) and the number of times that trajectory reaches a given location is used to calculate the probability in that location.

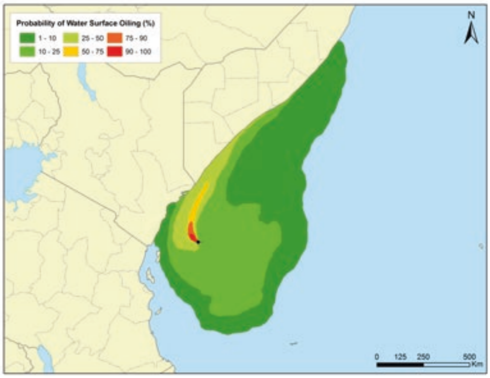


Fig. 3.3 Stochastic modeling approach used to generate probability of surface oil exceeding a given threshold for an example release. The example in the top left highlights four individual release trajectories predicted by SIMAP for a single generic release scenario at a generic location simulated with different start dates and therefore environmental conditions. In a stochastic analysis, over 100 individual trajectories are overlaid (shown as the stacked simulations on the right) and the frequency of threshold exceedance at each location is used to calculate the predicted probability following a release (bottom)

The stochastic model computes surface and subsurface trajectories for an ensemble of hundreds of individual cases for each release, thus sampling the variability in regional and seasonal wind and current forcings by starting the simulation at different dates and times within the timeframe of interest. The stochastic analysis provides two types of information: (1) the footprint of areas that might be oiled and the associated probability of oiling, and (2) the shortest time required for oil to reach any point within the areas predicted to be oiled. The areas, probabilities, and minimum timing of oiling are generated by a statistical analysis of all the individual stochastic runs. The left panel of Fig. 3.3 depicts four individual trajectories predicted by SIMAP for a generic example scenario. Because these trajectories were started on different dates and times, they experienced varying environmental conditions, and thus traveled in different directions. To compute the stochastic results, hundreds of individual trajectories like the four depicted here were overlaid upon one another and the number of times that each given location throughout the modeled domain was intersected by the different trajectories was used to calculate the probability of oil exposure for each specific location. This process is illustrated by the stacked runs in the right panel of Fig. 3.3. The predicted footprint is the cumulative oil-exposed area for all of hundreds of individual releases combined. The colour-coding represents a statistical analysis of all the individual trajectories to predict the probability of oil at each point in space, based upon the environmental variability.

It is important to note that although large footprints of oil would be depicted by a stochastic analysis, they are not the expected distribution of oil from any single discharge. These maps do not provide any information on the quantity of oil in a given area. They simply denote the probability or minimum time of oil exceeding the specific threshold passing through each grid cell location in the model domain at any point over the entire model duration, based on the entire ensemble of simulations. The footprint of any single release of oil, be it modelled or real, would be much smaller than the cumulative footprint of all the runs used in the stochastic analysis. Similarly, the footprint of oil from any individual release at a single time step (snapshot in time) would be even smaller than the cumulative swept area depicted here.

3.10 Conclusions

While the use of computational oil spill modeling tools in the realm of PPW is not new, there have been numerous improvements in recent years that refine our understanding of not only the likelihood of releases, but also the potential movement, behavior, and resulting effects that may follow any specific release. These refinements do affect the predicted trajectory, fate, and effects following a release. When conducting risk assessments, it is necessary to understand both the likelihood of a release as well as the resulting consequence. Computational oil spill modeling can be used to quantify the range of potential consequences, while also informing potential response strategies. Specifically, oil spill models may be used to identify locations where oil may be transported and the range of time for oil to reach those locations, based upon site-specific and season-specific conditions. This will identify key locations of concern (e.g., populated areas, fisheries, sensitive receptors, etc.) that have the potential to be impacted, as well as the associated time of first arrival and duration of exposure to contaminants. Continued focus on modeling of PPW and specific wrecks of interest can help prioritise which wrecks to remediate first

(Brennan et al., 2023). In addition to forecast predictions of any potential future release, the oil spill modeling tools themselves can and have been used in ‘reverse’ to provide hindcast predictions of the origin location of any observed slicks that may be on the water surface (French McCay, 2001). In essence, winds and currents are reversed to ascertain where a slick may have come from. Therefore, following any observation of oil, oil spill modeling tools can be used to determine whether a known wreck had the potential to be the source of a release. The application of oil spill modeling tools is great in determining the range of potential risk and location of oil contamination, as well as range of potential consequence following a release.

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