Supplementary Material S2

# Modeling of oil spills scenarios

A spill scenario is a statistical and probabilistic assembly of hundreds or thousands of individual spill simulations under different oceanographic and atmospheric conditions (*e. g*., currents, winds, temperature). The spill scenarios were generated using the CIC-OIL model, which is an integrated spill modeling system that contemplates multiple processes of weathering and dispersion of oil in the three spatial dimensions. CIC-OIL is composed of a near-field model ([Texas A&M](https://github.com/socolofs/tamoc) Oil Spill Calculator (TAMOC): <https://github.com/socolofs/tamocOilspill>, Socolofsky et al. 2015) that simulates the blowout and produces the initial conditions for the far-field model. The far-field is the Lagrangian OpenDrift model, in its version for oil called OpenOil (Dagestad et al. 2018; Röhrs et al. 2018). This model was improved for the CIGoM project and the modified version includes a specially designed interface to automatically communicate results from the TAMOC plume model to the far-field model OpenDrift, in addition to new parameterizations of oil degradation processes such as evaporation, dissolution and biodegradation. This enhanced model, CIC-OIL, provides the total mass of the spill indicating the mass of oil associated with each degradation process (*e.g*., evaporation, emulsion, wave entrainment) and each spatial dimension (*i.e*., surface, water column, and atmosphere), and generates oil trajectories and concentration maps.

The scenarios were constructed using the same initial conditions of a blowout for all individual spills: oil flow of 40 kg/s (a flow in between the *Ixtoc-I* and the *Deepwater Horizon* accidents), outlet diameter of 0.15 m, outlet temperature of 35°C, vertical release angle, and duration of 15 days. These initial conditions were estimated based on the *Ixtoc-1* and *Deepwater Horizon* oil spills, both of which occurred in the Gulf of Mexico in 1979 and 2010, respectively. A generic heavy oil (Maya: API=21.3) based on the physical properties of oil of Mexican origin found in the NOAA database. Twenty years (1993–2012) of simulations of the oceanographic and atmospheric conditions of the Gulf of Mexico were used. Marine currents and seawater properties were simulated with the hydrodynamic model NEMO (<https://www.nemo-ocean.eu)> and winds with the atmospheric model DFS5.2 (Dussin et al. 2016), with the open boundary conditions given by the GLORYS2V3 reanalysis (<https://www.mercator-ocean.eu/en/ocean-science/glorys/)>. Each oil spill simulation began on the first day of each month; therefore, each scenario was built from 240 individual spills which had each very different hydrodynamical conditions, and hence a different spatial evolution of the fate of the oil.

The CIC-OIL model uses the droplet size distribution model of Johansen et al. (2013), which estimates the mean droplet size (droplet size such that 50% of the oil volume has broken into smaller drops and the other 50% into larger drops). Subsequently, the complete droplet size distribution is derived from the Rosin-Rammler probability distribution with a constant spreading factor. The far-field model uses a specific number of particles, considering separately the particles that are on the surface (spillets) and those that are submerged (droplets). Each particle has a set of initial properties (diameter, mass, density, thickness) and is tracked independently, as their properties can change over time due to environmental processes at the surface (weathering) or when they are trapped in the water column because of waves (dispersion), dissolution and biodegradation. The oil weathering processes included in CIC-OIL are evaporation, emulsification and dissolution, as well as the physical processes of horizontal spreading and transport by ocean currents, wind drag and wave drift, droplet buoyancy, and vertical dispersion (wave entrainment). Wave entrainment is a process by which particles on the surface can be submerged by the action of waves, breaking into finer droplets that are dispersed by turbulence and, eventually, float up again to the surface. This vertical movement has the net effect that the oil is less exposed to the action of evaporation, wind drag, and wave drift, than would be the case if only a two-dimensional surface layer model were used (*e.g.,* Röhrs et al. 2018; Kotzakoulakis and Simon 2021).

Evaporation is the most effective weathering process, with up to 40% of oil extracted from the sea surface within the first hours/days of the spill, followed by dissolution, which acts at a slower rate. There are other weathering processes that were not included, but all act at much slower and at longer time scales (such as biodegradation and photo-oxidation), and in any case would result in reducing the amount of oil in the water, so one could claim the results here presented are a worst case scenario. On the other hand, the processes which most determine the horizontal spreading of the oil in the surface layer, and hence its geographical location over time, are transport by the ocean flow, wind drag and wave drift, wave entrainment, oil droplet size, and vertical dispersion. The ocean currents have the largest effect on the oil trajectory (Kotzakoulakis and Simon 2021), while the rest are complex processes that are parameterized, and which are nearly impossible to evaluate under all possible conditions present in the field. Nevertheless, Röhrs et al. (2018) showed that the parameterizations used in OpenDrift/OpenOil enabled the model to simulate the horizontal spreading and transport of observed oil slicks in the North Sea.

The winds used are a reanalysis product, hence they have reduced the uncertainties by combining models with all available observations (DFS5.2; Dussin et al. 2016). The currents are obtained from free-runs of the ocean circulation model, hence they have not incorporated data and are subject to errors due to subgrid parameterizations, as well as errors introduced at the open boundaries. Nevertheless, the main aspects of the mean surface flow and its variability are fairly well reproduced, as evaluated using altimetry (Jouanno et al. 2016; Damien et al. 2021) and surface drifters density distributions (Gough et al. 2019), allowing to study processes such as the formation of Loop Current frontal eddies, the effect Loop Current eddies have in the biological productivity of the gulf, and the existence of persistent transport barriers in the northwestern gulf, respectively. So the collection of hydrodynamical conditions used to generate the statistical oil spill scenarios do represent the observed variability of the ocean surface flow and winds in the region. In short, modeling oil spills is extremely difficult since oil is one of the most complex organic compounds in nature, subject to a large set of processes which act at different time scales and many of which are yet poorly understood under controlled conditions. This certainly poses a great challenge in predicting the fate of a given spill were it to happen, hence using a statistical approach based on a large set of hydrodynamical conditions, in which the variability of the winds and currents are well represented, allows to get a low order approach that allows to plan ahead an accident and make a first attempt to analyze its possible consequences.

The plume (near-field model) showed that most of the oil accumulated in the top 20 m of the water column, with less than 5% of the oil spilling below that depth. Therefore, the analysis focuses on the surface layer of the water column. The spatial distribution of oil near the surface (in the first 20 m of the water column) was followed for 60 days. From each individual spill, the oil mass was obtained for each cell of 0.25º x 0.25º for each day of the simulation, and the mass fraction was calculated by dividing the daily oil mass by the total mass released during the 15 days that the spill lasted.

The metric used was the maximum average mass fraction (*Pmax*). This is calculated as follows: first, the average of the daily mass fraction over all individual spills is calculated, and the maximum value over the 60 days of the spill duration is *Pmax*. The contour delimited by *Pmax* = 0.1% was defined as the area where the largest amount of mass is expected to be found for any individual oil spill. This contour delimits an area where the greatest amount of mass of any particular spill is expected to be found. It was shown that, for the scenarios of the three wells, it is true that more than 80% of the individual events have more than 70% of the total oil spilled inside the contour (Pérez-Brunius et al. (2020). The full description of the construction of the oil spill scenarios can be consulted in Pérez-Brunius et al. (2020) and a summary as supplementary material in Romo-Curiel et al. (2022).

*Pmax* values ranged from 0.00014 to 0.07620. The cells within the affected area were categorized using the 25th and 75th percentiles; thus, *Pl* (low amounts of oil) includes cells with *Pmax* values < first quantile, *Pm* (medium amounts of oil) cells with values in the interquartile range, and *P*h (high amounts of oil) for cells with values > third quantile.

Imagen que contiene Diagrama

Descripción generada automáticamente

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