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Numerical simulation of oil spill dispersion along Morocco's Northern Atlantic coast using OpenOil: A case study near Asilah

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ABSTRACT

Accidental petroleum discharges pose considerable hazards to marine biomes and coastal economies, particularly in vulnerable and heavily-trafficked maritime corridors such as Morocco's northern Atlantic coastline. This investigation utilizes the OpenOil module within the OpenDrift framework to quantitatively simulate the dispersion and degradation of a theoretical 100-ton oil discharge in proximity to Asilah over a seven-day interval. The simulation incorporates real-time meteorological and oceanographic information from NOAA-GFS and CMEMS, encapsulating essential physical and biochemical phenomena including advection, diffusion, evaporation, emulsification, and biodegradation. The outcomes elucidate a predominant northeastward movement of the slick, with approximately 68% of the oil mass either dispersed in the aquatic column (37%) or subjected to evaporation and biodegradation (16% each). Approximately 3421 out of 5000 particles were beached along the Asilah-Tangier shoreline, emphasizing high-risk ecological areas such as estuaries, rocky coastlines, and fishing zones. Lagrangian dispersion coefficients were computed to evaluate horizontal spreading dynamics, while droplet size distributions corroborated the impact of wave activity and oil characteristics on emulsification behavior. These results accentuate the pivotal function of numerical modeling in oil spill prediction, emergency preparedness, and ecological risk alleviation. The study represents the inaugural high-resolution application of OpenOil to Moroccan waters, providing actionable insights for national oil spill response frameworks and reinforcing the significance of incorporating real-time simulation instruments into coastal monitoring systems.

Keywords: oil spill modeling, OpenOil, OpenDrift, oil budget analysis, hydrodynamic simulation, Moroccan Atlantic coast, marine pollution, numerical prediction, emergency response.

INTRODUCTION

Oil spills constitute a major ecological and socio-economic threat to marine and coastal environments, with both immediate and long-term consequences. The ocean's wildlife, especially various fish, birds that live at sea, and marine mammals, have shown serious biological reactions from substances derived from oil, particularly polycyclic aromatic hydrocarbons (PAHs), leading to injuries and issues with reproduction. (Priede, 2023; Reddy et al., 2023; Ukpene et al., 2024). Additionally, primary producers such as phytoplankton are adversely affected, disrupting trophic dynamics (Ukpene et al., 2024). Sensitive ecosystems such as mangroves and coral reefs are particularly vulnerable, often experiencing long-lasting degradation following contamination (Sharma et al., 2024; Sekiguchi et al., 2024).

Beyond environmental damage, oil spills can also lead to substantial economic losses, especially in regions dependent on fisheries and tourism (Thakur and Koul, 2022; Priede, 2023). Cleanup operations are complex and costly, involving advanced technologies, trained personnel, and significant logistical support (Zhang and Sun, 2024; Aşan, 2024). Recent advances, including remote sensing and autonomous systems, have improved detection and response capacity (Yusup, 2024), while international regulations, such as the MARPOL Convention, have contributed to a notable decline in spill incidents over the past decade (Riadh, 2024).

Despite these improvements, effective forecasting and simulation of oil dispersion remain challenging. The success of response strategies depends on accurate modeling that incorporates physical, chemical, and biological processes. Hydrodynamic factors such as wind, current patterns, temperature, and salinity significantly influence oil transport (Niu et al., 2013; Zheng and Yapa, 1998). Advanced numerical approaches, including Lagrangian particle tracking, cellular automata, and neural networks, have enhanced the accuracy of spill simulations in diverse marine environments (Zhang et al., 2015; Zanier, 2015). Nonetheless, many of these tools require substantial computational resources and calibration with observational data (Zheng and Yapa, 1998; Niu et al., 2013).

While OpenOil and similar models offer important predictive capabilities, few studies have applied them to the Moroccan Atlantic coast, particularly near Asilah, an area with significant maritime traffic and ecological sensitivity (Lourenço et al., 2020). In this context, numerical modeling can help identify high-risk areas and support mitigation planning.

This study addresses this gap by implementing the OpenOil module within the OpenDrift framework – an open-source Lagrangian modeling system developed by the Norwegian Meteorological Institute (Dagestad et al., 2018). OpenOil simulates oil dispersion by integrating wind fields from NOAA-GFS and ocean currents from CMEMS, along with key processes such as advection, diffusion, emulsification, and biodegradation (Prasad et al., 2020; Ren et al., 2025). The model's parameterization is based on NOAA's ADIOS database and validated against real-case scenarios (Rohrs et al., 2018; Pärt et al., 2023).

The main objective is to simulate a hypothetical spill of 100 tonnes of oil off the coast of Asilah using 5000 particles over a 7-day period, a timeframe that balances physical realism with forecast reliability (Brekke et al., 2021; Pärt et al., 2023). We hypothesize that combining real-time met-ocean data with oil weathering processes can yield accurate, operationally relevant predictions. The results are expected to contribute to improved preparedness and response strategies for future oil spill events along Morocco's northern Atlantic coastline.

STUDY AREA

The investigative zone is placed in the northern Atlantic waters, adjacent to Morocco's coast, specifically 40 km west of Asilah (coordinates: 6.48° W, 35.65° N). This maritime sector lies along a critical transit route for international shipping, particularly oil transportation, significantly increasing the risk of accidental hydrocarbon spills. The coastal region situated between Larache and Tangier along the northwestern shoreline of Morocco is unequivocally distinguished by substantial ecological diversity.

This area is abundant in marine biodiversity, with upwelling phenomena exerting a profound influence on species distribution and community structure. Such conditions foster a distinctive habitat that sustains a wide array of marine organisms, including novel species documented for Morocco (Lourenço et al., 2020).

This region is strategically important due to its high maritime traffic, especially for petroleum transport, making it highly vulnerable to environmental risks associated with maritime accidents. It is situated near the Strait of Gibraltar, one of the busiest shipping lanes in the world, where the high density of vessel movements raises the potential for collisions, groundings, or mechanical failures that could lead to accidental oil spills. The scarlet dashed line marks the key tanker navigational route inside the defined geographical zone, as verified by MarineTraffic (https://www.marinetraffic.com), which uses the Automatic Identification System (AIS) for the instant tracking of maritime vessel paths (Fig.1).

A numerical simulation was carried out to assess the dispersion behavior of a 100-ton oil spill of the Generic Banker variety (971.1 kg/m³), released from the designated reference point. The simulation incorporated local hydrodynamic conditions, including wind, ocean currents, and tidal dynamics, to realistically replicate the transport and transformation of oil particles in this coastal setting. This analysis aims to characterize the spatial extent of the potential spill, identify vulnerable ecological zones, and support the refinement of local contingency planning and response measures.

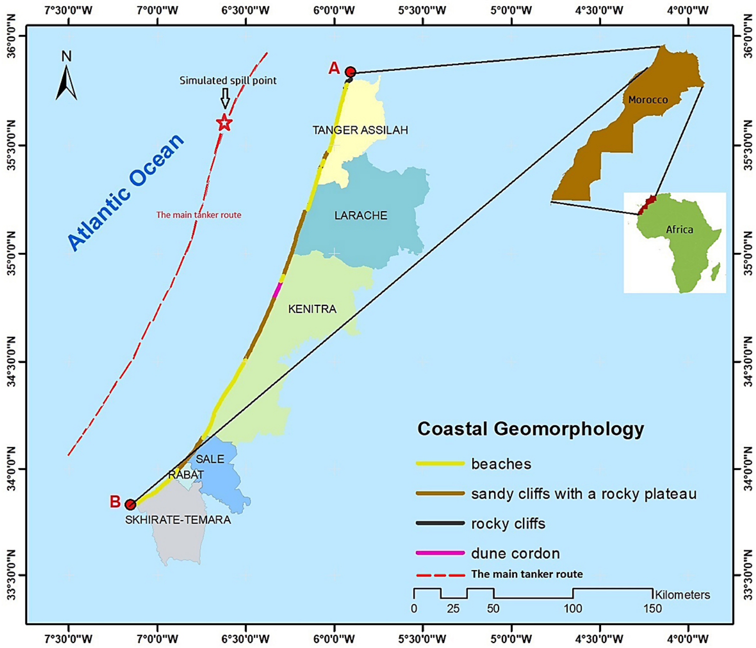

Figure 1. Geospatial positioning and the morphological characteristics of the research region

MATERIALS AND METHODS

OpenOil model

The simulation was conducted using OpenOil, a module within the OpenDrift modeling framework (Dagestad et al., 2018; Dagestad et al., 2024). OpenDrift applies Lagrangian particle-tracking methods governed by advection-diffusion equations, using oceanographic and atmospheric forcing data. The model supports various environmental processes, including evaporation, emulsification, biodegradation, vertical mixing, and surface drifting, allowing it to realistically simulate oil slick behavior.

For this case study, the OpenOil module was configured with an initial spill volume of 100 metric tons, a simulation duration of 7 days, and 5000 Lagrangian particles. The selected oil volume represents a moderate-scale release scenario that aligns with historical maritime incidents in the region, providing a realistic estimate of potential accidental discharges near tanker navigation routes. While the released volume could be scaled up to 10.000 or even 100.000 metric tons, such variations would have negligible influence on the spatial dispersion results, as the model primarily tracks relative particle behavior rather than absolute mass. In contrast, the number of particles used in the simulation is a critical parameter that significantly affects the resolution and accuracy of the results.

The choice of 5000 particles is supported by sensitivity analyses conducted by (Pärt et al., 2023; Brekke et al., 2021), which demonstrated that simulations with fewer than 3000 particles tend to underrepresent spatial heterogeneity in oil drift and weathering behavior. Conversely, increasing the number of particles beyond 5000 offers limited improvements in predictive performance while substantially increasing computational demand. These findings indicate that a particle count of 5000 provides an optimal trade-off between accuracy and computational efficiency, particularly for medium-scale spill events.

The 7-day simulation window corresponds to the standard operational timeframe used in oil spill forecasting, as it captures the key weathering processes – evaporation, dispersion, emulsification, and stranding – while remaining within the range of reliable metocean forecast data. This configuration ensures that the model outputs are both scientifically robust and practically useful for emergency preparedness and response planning.

Oil weathering processes are parameterized using the NOAA ADIOS database, which defines rates of evaporation, dispersion, and emulsification for different oil types under varying environmental conditions (Rohrs et al., 2018). The model accounts for Stokes drift (wave-induced transport) and current–wind interactions, providing a more realistic representation of oil particle trajectories.

The consolidation of the OpenOil module with OpenDrift substantially enhances the forecasting capabilities pertaining to oil spill trajectories through the application of advanced modeling techniques and the incorporation of real-time data. OpenOil, which is an extension of the OpenDrift framework, amalgamates a plethora of physical phenomena alongside current met-ocean forecasts to proficiently replicate the transport dynamics and eventual outcomes of oil spills (Dagestad et al., 2024). The synthesis of these elements facilitates the generation of predictions that are not only more precise but also timely, which is imperative for the development of effective strategies for emergency response and mitigation. The ensuing sections articulate how this integration improves the predictive precision of oil spill trajectories.

OpenOil represents an open-source endeavor that utilizes real-time met-ocean forecasts sourced from esteemed organizations such as NOAA-GFS and CMEMS, which provide essential data regarding oceanic currents and atmospheric phenomena. The assimilation of real-time data facilitates continuous model updates, thus improving the accuracy of oil spill trajectory forecasts by incorporating prevailing environmental factors (Keramea et al., 2022).

The utilization of high-resolution oceanic current data and surface wind metrics obtained from ocean circulation models significantly bolsters the accuracy of trajectory predictions, enabling the model to adapt to variable environmental conditions and yield more reliable forecasts (Prasad et al., 2020).

OpenOil employs sophisticated algorithms that replicate a variety of physical phenomena, including oil entrainment, vertical mixing, resurfacing, and emulsification. These phenomena are essential for comprehending the dynamics of oil spills in marine ecosystems and are incorporated into the OpenDrift framework to augment predictive precision (Keramea et al., 2022).

Furthermore, the model is enhanced through the utilization of advanced deep learning methodologies, such as adversarial temporal convolutional networks (ATCN), which rectify numerically projected sea surface dynamic fields. This rectification facilitates a closer alignment with reanalysis data, thereby enhancing the model's efficacy in accurately forecasting oil spill trajectories (Ren et al., 2025).

In our ongoing research, the current version (1.11.13) of OpenDrift was used. OpenDrift is a publicly accessible software framework developed in the Python programming language at the Norwegian Meteorological Institute, specifically engineered to simulate the trajectories and eventual fate of objects or substances adrift in the marine environment. Figure 2 illustrates the series of processes involved in OpenOil simulations.

Once OpenDrift is adequately installed or its scripts directory has been incorporated into the system's PATH environment variable, the graphical user interface can be initiated utilizing the command $ python opendrift_gui.py, executed from within the scripts directory. On Windows, the script opendrift_gui.py can alternatively be initiated employing the Miniforge application.

The initial step in the simulation procedure entails selecting the preferred model from the dropdown menu at the apex of the interface. When OpenOil is chosen, a secondary menu permits the user to select an oil type from the NOAA OilLibrary. In this investigation, the chosen oil type is Generic Banker C. Users must subsequently delineate the initialization parameters for the particle release (seeding). The latitude and longitude of the commencement location must be provided in decimal degrees, with negative

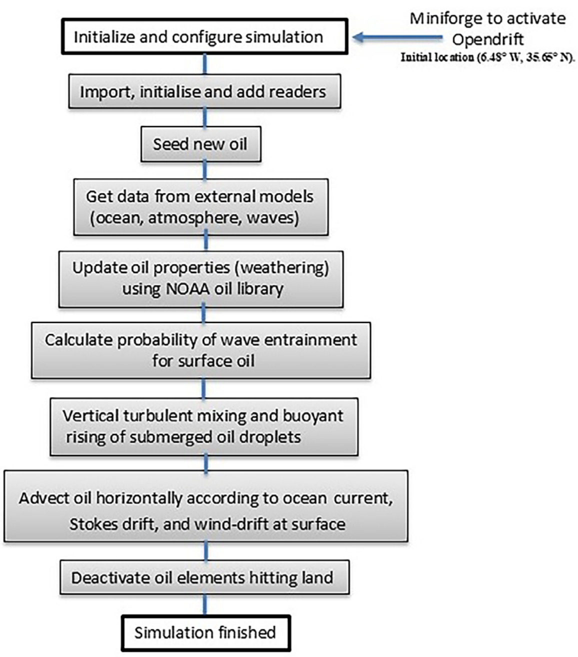

Figure 2. Flowchart illustrating the sequence of processes involved in OpenOil simulations

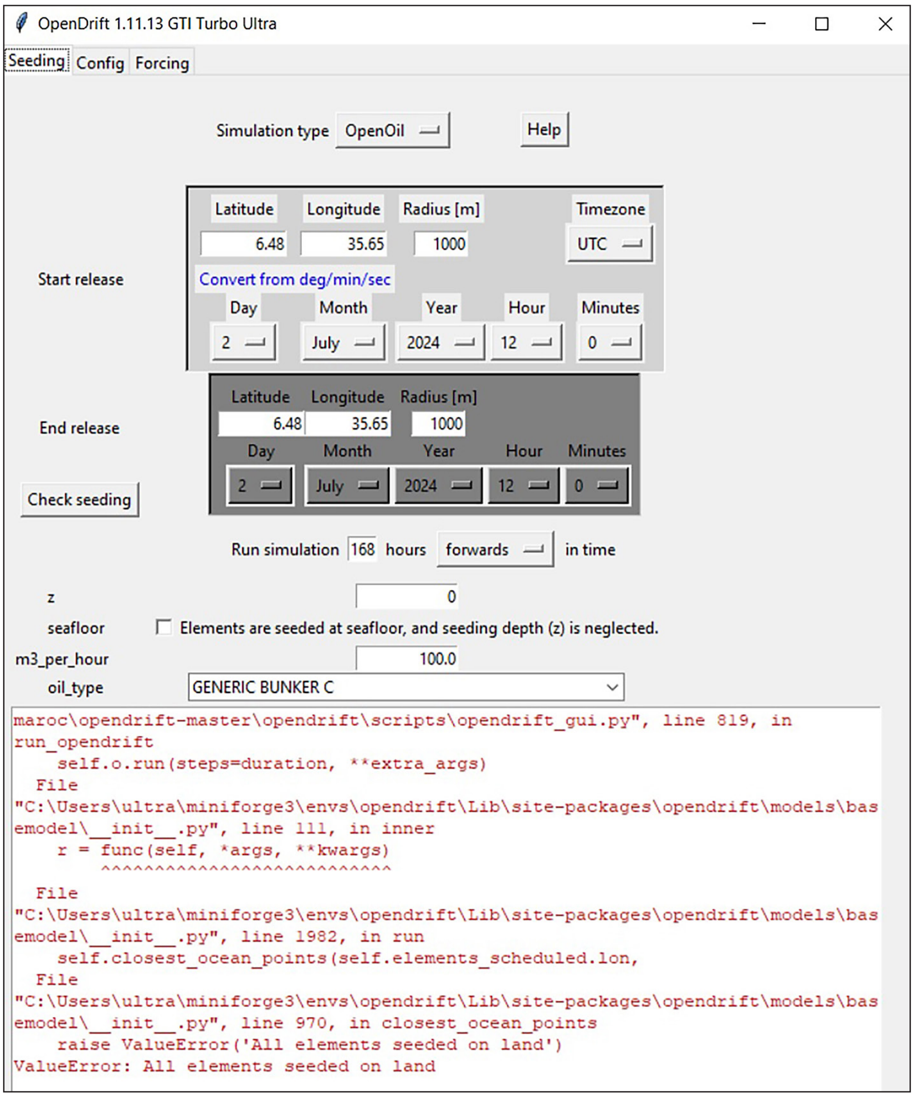

Figure 3. Screen capture of graphical user interface used in this study (v1.11.13)

longitude values signifying positions west of the Greenwich meridian. The radius delineates the standard deviation of uncertainty (in meters) surrounding the specified location, within which all 5000 particles will be randomly seeded.

Simulations can be configured to proceed forward or in reverse (backtracking) to ascertain the potential origin of the spill. In this investigation, the simulation is executed in forward mode.

The simulation duration is specified in hours. It is salient to note that simulations surpassing 100 hours may necessitate considerable computational time (often exceeding 10 minutes), particularly for oil drift simulations. In this instance, the simulation was configured to operate for 168 hours (equivalent to 7 days) (Fig. 3). The simulation is commenced by clicking the Start button situated at the bottom of the user interface.

Subsequent to the completion of the simulation, the resultant data may be evaluated through the interface options located at the lower section:

- animation: a graphical representation of the simulation is either displayed or stored in a file format;
- oil budget (oil drift exclusively): the chronological record of the oil budget is either presented or preserved in a file format.

Simulation setup

In the present investigation, a particular scenario was examined: the release of crude oil into the vast expanse of Assilah. The temporal scope for this simulation spanned a duration of 7 days, initiating on 02 July 2024 at 12:00 and culminating on 08 July 2024 at 12:00. The type of crude oil utilized in this study was designated as

GENERIC BANKER, which is characterized by a density of 971.1 kg/m³ and a viscosity of 650 centipoise. Initially, an estimated 5000 oil particles were released, with the initial radius of the spill established at 1000 meters. The development of the OpenOil framework required integrating wind data that coexists from the NCEP/NCAR Reanalysis, representing the National Centers for Environmental Prediction and the National Center for Atmospheric Research, in addition to perspectives derived from the NOAA Global Forecast System, abbreviated as GFS (Johansen et al., 2015; Li et al., 2017).

Moreover, OpenOil integrated hydrodynamic datasets obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) database. In particular, the hydrodynamic parameters and oceanic currents were derived from CMEMS, with a specific focus on the dataset pertaining to the Mediterranean Sea Physics Analysis and Forecast (MEDSEA_ANALYSISFORECAST_PHY_006_013). The initial conditions pertinent to the test case are illustrated in (Table 1).

Model results post-processing

Throughout the intricate and comprehensive simulation process, the various trajectories exhibited by the particles that were introduced into the surface of the sea were meticulously monitored with great attention to detail, and subsequent analyses were conducted to evaluate the relative influence and impact of each individual physical and weathering process that could potentially affect these particles. Additionally, a thorough report was generated regarding the physico-chemical transformations that occurred within the properties of the oil, and an extensive discussion was undertaken concerning the oil budget, particularly at the conclusion of the simulation period, highlighting significant findings and implications. In order to enhance our understanding of the complex horizontal dispersion patterns of the particles, we meticulously computed the total dispersion coefficient (K) along with the longitudinal dispersion coefficient (designated as Kx, which reflects dispersion along the flow direction) and the transverse dispersion coefficient (denoted as Ky, representing dispersion across the flow direction), all of which were calculated over the entirety of the simulated tidal cycles. These dispersion coefficients were then articulated as the Lagrangian effective dispersion coefficients, which serve as a function of the ensemble variance (s^2) associated with the coordinates of the particles at each discrete time step throughout the simulation process, thereby providing a detailed quantitative framework for analyzing particle movement (Sentchev et al. 2005).

Table 1. The primary parameters of the simulation

Parameters	Simulation case
Longitude, Latitude	6.48° W, 35.65° N
Number of particles used	5000
Start time of simulation used	02 July 2024
End time of simulation	08 July 2024
Duration used	7 days
Oil type used	Generic Banker
Wind data reader	NOAA GFS
Hydrodynamic data reader	CMEMS

$$K(t) = 1/2 \times (Kx(t) + Ky(t) = = 1/4 \times [(sx^2(t+T) - sx^2(T)) / T + + (sy^2(t+T) - sy^2(T))/T] \quad (1)$$

where: *sx* and *sy* indicate the longitudinal and transverse standard deviations associated with the spatial arrangement of particles concerning the center of mass of the particle system at a specific time *t*, and *T* denotes the tidal period (s).

Oil droplet size distribution

Two principal methodologies are utilized to elucidate the distribution of oil droplet dimensions. The first methodology, founded upon the research conducted by Delvigne and Sweeney (1988), proposes a power-law distribution that exhibits a propensity for smaller droplets, with dimensions ranging from 1 μm to 1 mm. The subsequent methodology, as articulated by Li et al. (2017), incorporates the variables of oil viscosity and oil-water interfacial tension to produce a log-normal distribution, whereby the droplet volume is predominantly concentrated around 100 μm.

The median diameter D50 is determined through a computational formula that is contingent upon the Weber (We) and Ohnesorge (Oh) numbers, which encapsulate the interplay of inertial, viscous, and surface tension forces.

In the course of each wave-breaking occurrence, droplet sizes are allocated in accordance with these distributions and undergo dynamic evolution as a consequence of weathering and re-emulsification phenomena.

RESULTS AND DISCUSSION

Oil slick trajectory

The dispersion and temporal evolution of an oil slick off the northwestern coast of Morocco, particularly in the region between Larache, Tangier, and Asilah. It illustrates the spatial dynamics of marine pollution over a seven-day period (Day 1 to Day 7), suggesting a numerical modeling of the drift and behavior of hydrocarbons at sea. The slick initially moves northeast, influenced by dominant winds and ocean currents.

Impacted coastal zones

(Figure 5) illustrates the cumulative state of oil dispersion and coastal stranding as simulated by the OpenOil module within the OpenDrift framework, specifically at the final stage of the seven-day simulation (Day 7, i.e., July 8, 2024, at 12:00 UTC). Unlike the stepwise temporal progression presented in Figure 4 (Day 1 to Day

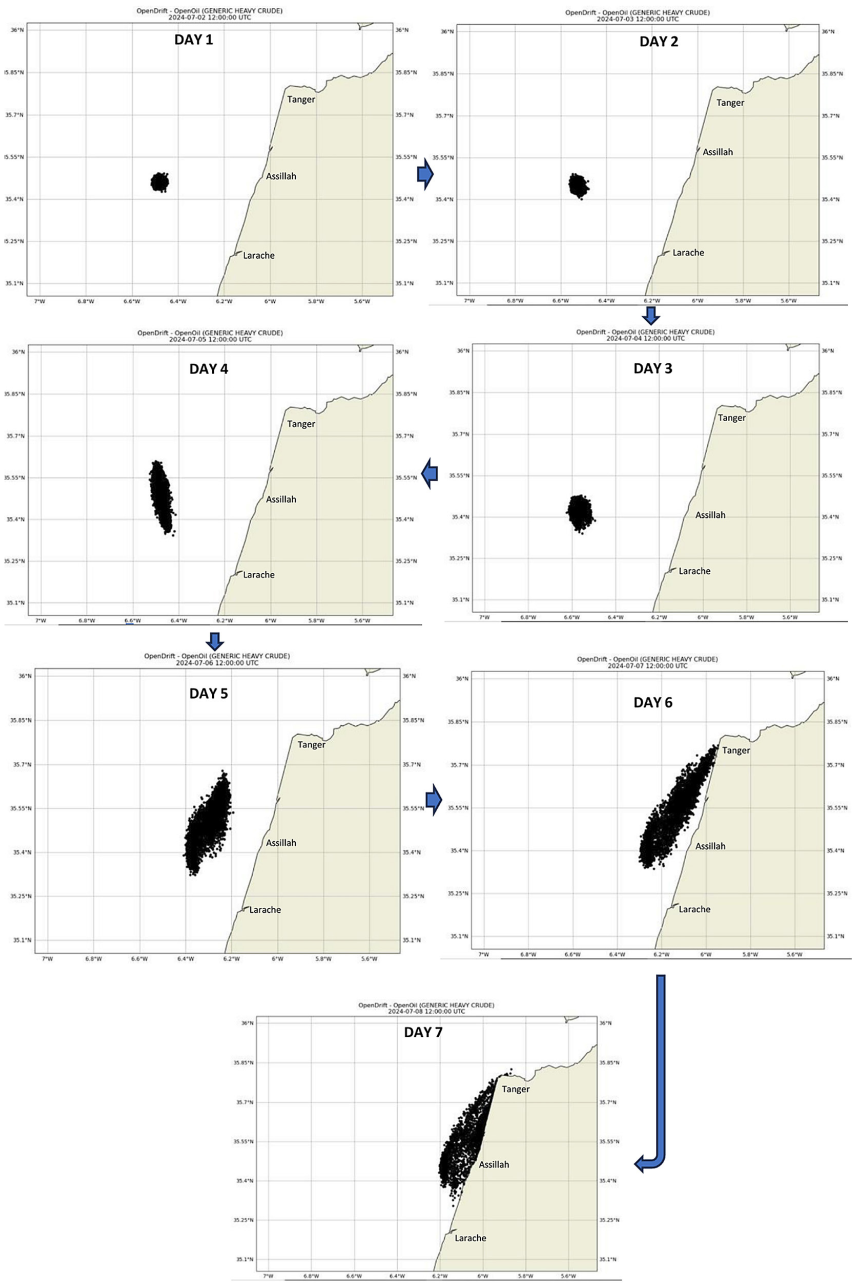

Figure 4. Daily progression of the oil slick

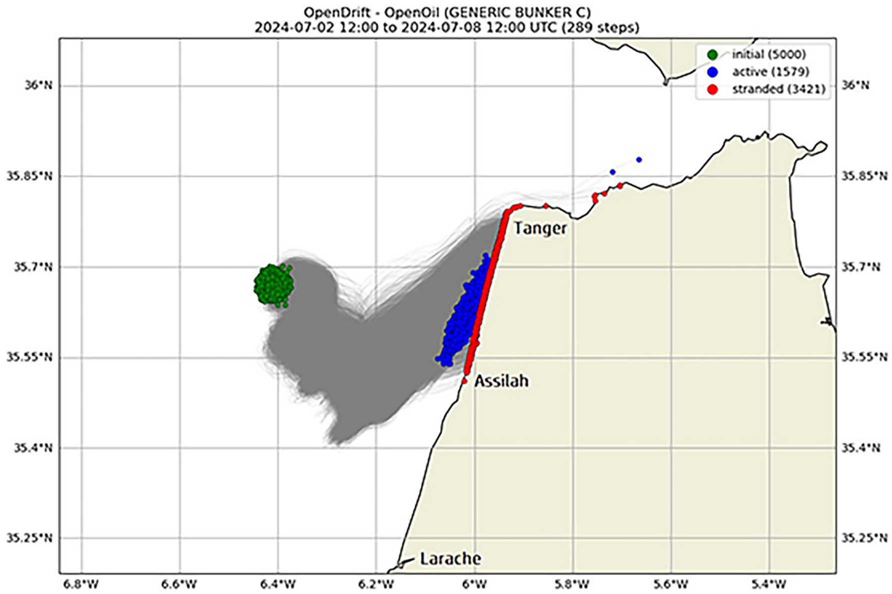

Figure 5. Simulation of oil spill dispersion using the OpenOil

7), which shows the daily evolution of the oil slick, Figure 5 offers an integrated spatial visualization of the overall extent of dispersion and shoreline impact.

The simulation scenario assumes no mitigation or cleanup intervention by emergency response teams. This modeling choice represents a worst-case scenario designed to evaluate the natural drift behavior and environmental exposure of coastal zones in the absence of containment or remediation efforts. Such an approach allows for identifying high-risk areas and informing the development of proactive oil spill contingency planning. The oil particles are color-coded as follows: green for the initial release positions, blue for particles remaining adrift at sea (1579), and red for particles that have stranded onshore (3421), predominantly along the Asilah-Tangier coastline.

Analysis of impacted areas

The trajectory of the oil slick shows a general dispersion towards the northeast, influenced by ocean currents and prevailing winds. A significant portion of the oil reaches the coastline between Asilah and Tangier, where a large number of stranded particles (red dots) indicate substantial environmental impact along this section of the shore. Numerous natural ecosystems will be particularly influenced in the occurrence of a protracted reaction and the deferral of essential interventions:

- Jbel Moussa Natural Park and Wetlands: indispensable for migratory avifauna, significantly affected by pollution.
- Tahaddart Estuaries: pivotal breeding and foraging habitats for marine fauna, endangered by contamination.
- Rocky shores and cliffs (Achakar, Sidi Kacem, Hercules Cave): vulnerable to petroleum sedimentation, impacting both the ecosystem and tourism.
- Fishing areas and coral reefs of the allians (Cap Spartel, Southern Coast of Tangier): integral for marine biodiversity and fishing endeavors, at peril of contamination.
- Key consequences: disruption of coastal ecosystems and pollution of marine organisms. Economic detriments for the fishing and tourism sectors. Degradation of natural habitats, complicating regeneration initiatives.

Oil budget anlysis

Figure 6 presents the oil budget evolution over time for the simulated spill of Bunker C (971.1 kg/m³) using the OpenOil model within OpenDrift. The simulation spans from July 2, 2024, at 12:00 UTC to July 8, 2024, at 12:00 UTC, focusing on the northern Atlantic coastline of Morocco between Larache, Asilah, and Tangier.

This graph (Fig. 6a) illustrates how the spilled oil is distributed across different categories over time – surface (light blue) – the fraction of oil remaining on the sea surface. Submerged (dark

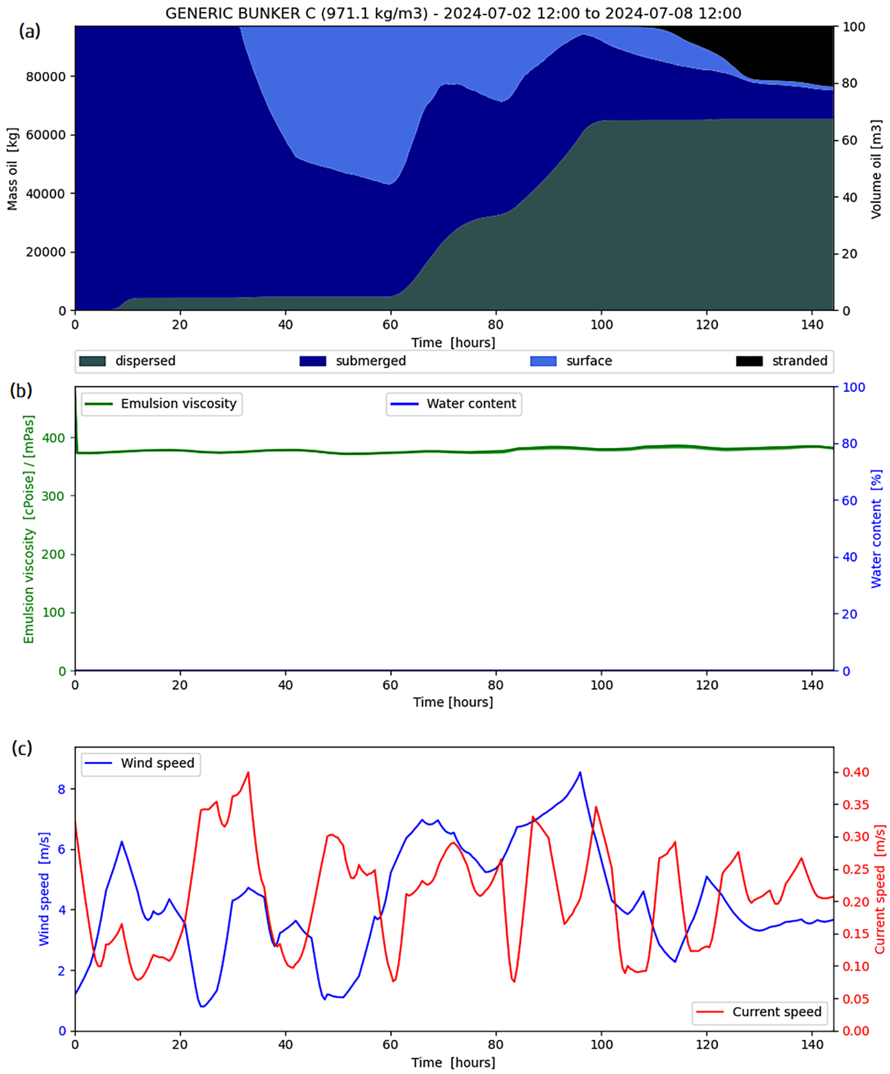

Figure 6. Oil budget evolution over time for the simulated spill

blue) – the fraction of oil that has sunk below the surface. Dispersed (dark green) – oil mixed into the water column due to turbulence and oceanic conditions. Stranded (black) – the portion of oil that has reached the coastline.

At the beginning of the simulation, most of the oil remains on the surface. Between 60–80 hours, the submerged and dispersed fractions increase, indicating that oceanic and meteorological conditions are affecting the oil's mixing behavior. After 100 hours, a significant portion of the oil is stranded along the coast (black area), confirming the impact of the spill on the shoreline.

The graph (Fig. 6b) tracks two important factors influencing oil behavior – emulsion viscosity (green, left axis) – it remains relatively stable (~400 cP/mPa.s), indicating limited alteration of the oil's physical properties. Water content (blue, right axis, %) – represents the amount of water absorbed by the oil, affecting its density and dispersion behavior. The values hover around 80%, indicating a high level of emulsification.

As illustrated in (Figure 6c), the evolution of wind and current speeds occurs throughout the seven-day simulation. The NOAA-GFS atmospheric forecast data showed that wind speeds ranged from 2 to 9 m/s, illustrating the standard summer meteorological situations in the study region. This spectrum of wind speeds was observed to facilitate realistic forcing conditions, as such velocities are frequently recorded along the Moroccan Atlantic coastline during the warm season. The influence of wind is crucial in the dynamics of surface oil drift, as it significantly enhances both horizontal advection and the dissemination of the slick. Particularly, the elevated wind speeds (> 6 m/s) documented during Days 4 to 6 played a substantial role in the northeastward dispersion

Table 2. The quantity of oil that undergoes evaporation, dispersion, and biodegradation

Time (hours)	0	20	40	60	80	100	120	140
Evaporation (%)	5	7	9	10	12	13	15	16
Dispersion (%)	10	15	20	25	30	32	35	37
Biodegradation (%)	2	4	6	8	10	12	14	16

and coastal stranding observed in the concluding stage of the simulation. Conversely, current velocities generally remained below 0.3 m/s, suggesting a comparatively minor influence in relation to wind forcing on the dynamics of surface transport.

Table 2 presents the percentage of evaporated, dispersed, and biodegraded oil mass over a 140-hour period, with measurements taken every 20 hours.

Evaporation: The proportion of evaporated hydrocarbons gradually increases, reaching 16% after 140 hours, indicating moderate oil volatilization. Dispersion: The proportion of oil that is distributed within the water column demonstrates a notable augmentation, escalating from 10% to 37%, thereby indicating a substantial impact of oceanic and atmospheric conditions. Biodegradation: Although slower, biodegradation steadily increases from 2% to 16%, reflecting the role of microbial processes in breaking down hydrocarbons.

The temporal progression of results generated by the OpenOil model pertains to (a) the oil budget along with the relative influence exerted by each physical and biochemical mechanism; (b) the characteristics of the oil, specifically the mean and standard deviation of mass density and viscosity; (c) the dominant wind patterns and surface current velocities observed throughout the seven-day simulation interval.

The dispersion of hydrocarbons in the offshore region of Asilah is significantly influenced by wind and temperature, as these factors affect the behavior and spread of gas clouds and oil spills. The way hydrocarbons are moved and scattered is greatly affected by wind strength and direction, with heat conditions also impacting their distribution and evaporation rates (Fig. 7, Fig. 8).

Wind speed and direction are critical in determining the spread of hydrocarbon plumes. High wind speeds can increase the dispersion area of flammable gas clouds, as seen in studies where a 35% greater platform area was covered by gas clouds at higher wind speeds (Asogan et al., 2022).

The graph (Fig. 7) depicts the mean wave direction recorded at the simulation Point over the same period. The wave direction fluctuates between approximately 50° and 350°, indicating significant variability in wave propagation.

The most prevalent wave directions appear to be oriented towards the northeast, suggesting a dominant wave influence from the Atlantic. Wave dynamics play a crucial role in oil dispersion, as they enhance surface advection, vertical mixing, and shoreline stranding.

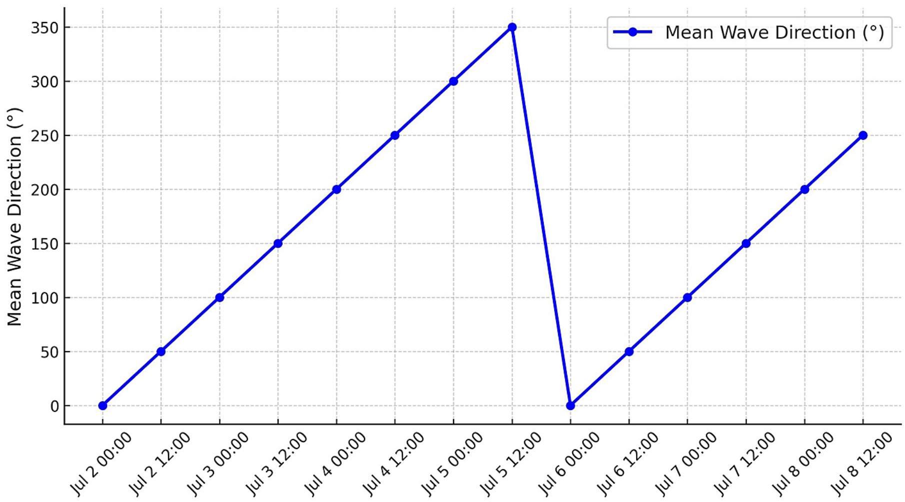

Figure 7. Mean wave evolution over time for the simulated spill

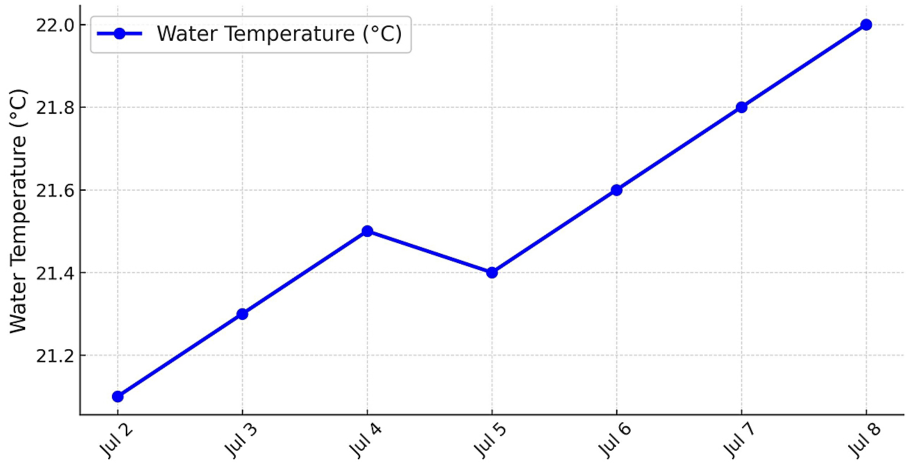

Figure 8. Water température evolution over time for the simulated spill

The observed fluctuations in wave direction suggest a dynamic hydrodynamic environment, which must be accounted for in oil spill simulations to improve prediction accuracy. The diagram (Fig. 8) delineates the temporal progression of marine water temperature at the simulation point, situated off the northern Atlantic seaboard of Morocco, in proximity to Asilah, between July 2 and July 8, 2024. The temperature measurement ranges between 21.1 °C and 22.0 °C, demonstrating a gradual rise across the research timeframe. The temperature variability is modulated by regional atmospheric phenomena, seasonal thermal increase, and oceanic circulation patterns. These shifts in temperature are pivotal for oil spill assessments, given their direct influence on the viscosity, rate of evaporation, and the dispersal patterns of the released hydrocarbons.

Elevated water temperatures generally diminish oil viscosity, facilitating expedited spreading and enhanced emulsification, which may impact the trajectory of the oil slick and its degradation processes. The graph (Fig. 9) shows sea surface salinity at simulation zone gradually increasing from 36.4475 PSU to 36.4600 PSU between July 2 and July 8, 2024, indicating stable ocean conditions.

Higher salinity increases seawater density, enhancing hydrocarbon buoyancy and keeping oil slicks at the surface. It stabilizes oil-water emulsions, complicating cleanup. Salinity variations can affect microbial biodegradation processes and create fronts, influencing the transport and distribution of hydrocarbons at sea.

Model limitations include the assumption of constant spill release, simplification of shoreline

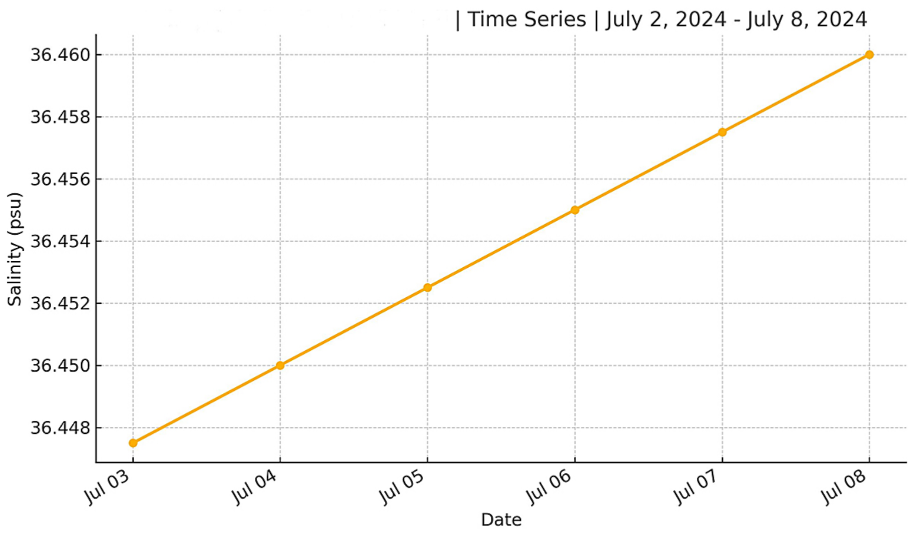

Figure 9. Salinity variation over time for the simulated point

interactions. However, these are balanced by the model's flexibility, real-time forcing capabilities, and open-source adaptability, making it a reliable tool for risk mapping and response planning in unmonitored areas like the Moroccan Atlantic coast. Model performance has been validated by the OpenDrift development team using in situ experiments in the Baltic Sea (Pärt et al., 2023), where wind drift factors and particle trajectories showed strong correlation with observed data (skill score > 0.7).

CONCLUSIONS

This study successfully achieved its objective of simulating the dispersion of a hypothetical 100-ton oil spill near the city of Asilah on Morocco's northern Atlantic coast using the OpenOil module within the OpenDrift framework. The results demonstrate the model's ability to provide high-resolution, time-sensitive forecasts of oil slick trajectories, weathering processes, and shoreline impacts over a 7-day period, driven by real-time metocean data.

The simulation revealed a predominant northeastward drift, with significant stranding of oil particles along the Asilah–Tangier coastline. Oil budget analysis indicated that 37% of the oil dispersed into the water column, 16% evaporated, and another 16% biodegraded. These figures reflect the interplay of physical and biochemical degradation mechanisms under realistic marine conditions. The model's outputs also identified key ecological and economic zones at risk, including natural parks, estuaries, rocky coasts, and fishing grounds.

This work contributes a novel application of OpenOil to Moroccan waters – a region previously lacking such simulation studies. It fills a critical knowledge gap by providing the first detailed assessment of oil spill behavior specific to this high-risk maritime corridor. The study demonstrates how Lagrangian modeling tools can support national oil spill preparedness by identifying vulnerable zones and enabling proactive risk mitigation.

In future applications, integrating OpenOil into real-time coastal monitoring systems could significantly enhance Morocco's capacity for emergency response and environmental protection. The findings offer a scientific foundation for establishing an operational forecasting system and may inform the development of a national spill response strategy grounded in predictive modeling.

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