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Simulation of oil spill trajectories using Opendrift: case study on Canary Islands

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1. Introduction	1
2. Objectives	5
3. Material and methods	6
3.1 Study area	6
3.1.1 Ecological Importance	6
3.1.2 Social Importance	7
3.1.3 Economic Importance	7
3.2. Historical oil spill events	7
3.2.1. The Castillo de Bellver, 1983	7
3.2.2. The Aegean Sea, 1993	8
3.2.3. The New Flame, 2007	8
3.3 OpenOil	8
3.4 Data Sources	9
3.5. Oil Concentration map.	12
3.6 Risk Assessment	12
4. Results	15
4.1 Hypothetical oil spills	15
4.1.2 February 2023 daily set	16
4.1.2. April 2023 daily set	17
4.1.3 July 2023 daily set	18
4.1.4 October 2023 daily set	19
4.2 Oil budget plots	20
4.2.1 February 2023 daily set	20
4.2.2 April 2023 daily set	22
4.2.3 July 2023 daily set	23
4.2.4 October 2023 daily set	24
4.3 Potential Risk Assessment Scenario	25
4.3.1. February scenario	25
4.3.2. April scenario	25
4.3.3. July scenario	25
4.3.4. October scenario	26
5. Discussion	28
5.1 Potential Spill Scenarios	28
5.2 Oil weathering process	29
5.3 Potential risk assessment	29
5.4. Evaluation of applicability and reality	30

6. Conclusion	32
7. References	34
Annexe I	38
Annexe II	39

Figures

Figure 1: Study area at Canary Islands (a) and high-risk zone for oil discharges based on regional oil tankers traffic (b) (Source: Marine Traffic: Global Ship Tracking Intelligence AIS Marine Traffic)	6
Figure 2: General concept of Operational oil-spill modelling, involving in the OpenOil simulation (Keramea, <i>et al.</i> , 2023).	10
Figure 3: Diagram provided of the explanation of the risk assessment.	13
Figure 4: Scenarios of an oil spill in eastern Canary Island generated in February 2023	16
Figure 5: Scenarios of an oil spill in eastern Canary Island generated in April 2023	17
Figure 6: Scenarios of an oil spill in eastern Canary Island generated in July 2023	18
Figure 7: Scenarios of an oil spill in eastern Canary Island generated in October 2023	19
Figure 8. Oil weathering simulation of oil spill on Canary Islands in February 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s ⁻¹).	21
Figure 9. Oil weathering simulation of oil spill on Canary Islands in April 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s ⁻¹).	22
Figure 10. Oil weathering simulation of oil spill on Canary Islands in July 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s ⁻¹).	23
Figure 11. Oil weathering simulation of oil spill on Canary Islands in October 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s ⁻¹).	24
Figure 12. Oil risk simulation of oil spill on Canary Islands in February (a), April (b), July (c) and October (d) 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13. Risk value between 0 and 0.25.	26
Figure 13. Areas of high-risk simulation of oil spill on Canary Islands using Opendrift model and ISO31000 framework. Risk value between 0 and 10 (see Table 3).	27

Tables

Table 1: Datasets used in the development of the oil spill simulations.	11
Table 2. Configuration features of the two oil spill simulations performed in the east area of Canary Islands with OpenOil	12
Table 3: Risk Index adapted from the ISO 31000 framework.	14

ABSTRACT

This study examines the simulation of oil spills in the eastern part of the Canary Islands using a modelling system called OpenOil, integrated into the open-source OpenDrift trajectory framework. These simulations focus on tracking the trajectories and assessing the weathering processes of oil spills under specific wind, wave, and ocean current conditions. We simulated four incidents that occurred in February, April, July, and October of 2023 involving a set of crude oil spilled onto the sea surface. Results showed that oil trajectories and slicks were influenced mainly by wind drift and ocean currents, directing the spilled oil towards Lanzarote and Fuerteventura coastlines in February and October, and toward Marocco and Sahara coastlines in April and July. Oil weathering effects, such as evaporation and water content were also simulated throughout the year. This process gradually increased the water fraction, potentially leading to the formation of tar balls along affected coastlines within the simulated areas. Wind speed emerged as a critical factor, accelerating the evaporation of spilled oil in the warm waters of the Canary Islands Sea. The application of OpenOil in predicting oil spills and weathering processes in the Canary Islands has proven to be a valuable tool, offering insights to enhance planning control measures for potential oil spills. Future simulations could benefit from higher spatial and temporal resolution databases to further improve the accuracy and effectiveness of the results.

Key words: *Oil spill, modelling, oil weathering, OpenOil, Canary Islands, environmental risks.*

RESUMEN

Este estudio examina la simulación de vertidos de petróleo en la parte oriental de las Islas Canarias utilizando el software de modelado OpenOil, el cual está integrado en el código abierto OpenDrift para la evaluación de vertidos de petróleo. Las simulaciones se orientaron a rastrear las trayectorias y evaluar los procesos de degradación de un posible vertido de petróleo en condiciones específicas. Se simularon cuatro posibles incidentes en febrero, abril, julio y octubre de 2023 a partir de una cantidad potencial de petróleo crudo vertido sobre la superficie del mar. Los resultados mostraron que las trayectorias y las manchas de petróleo estaban influenciadas principalmente por la deriva producida por el viento y por las corrientes oceánicas, dirigiendo el petróleo hacia las costas de Lanzarote y Fuerteventura en febrero y octubre, y hacia las costas de Marruecos y el Sahara en abril y julio. También se simularon a lo largo de las simulaciones los efectos de la degradación del petróleo. Este proceso aumentó gradualmente la fracción de agua, lo que podría conducir a la formación de agregados de alquitrán a lo largo de las costas afectadas dentro de las áreas donde se realizó la simulación. La aplicación de OpenOil en la predicción del comportamiento de los vertidos de petróleo y en los procesos de degradación en las Islas Canarias ha demostrado ser una herramienta valiosa, que ofrece información para mejorar la planificación de diferentes medidas de control ante posibles derrames de petróleo.

Palabras clave: *Vertido de petróleo, modelización, OpenOil, degradación de petróleo, Islas Canarias*

1. Introduction

Liquid fossil hydrocarbons, commonly referred to as oils, play a crucial role in energy and chemical production. The impacts of producing, transporting, and using various hydrocarbon products on the marine environment are well-documented (Chilvers *et al.*, 2021, Farrington *et al.*, 2014, Hampton, *et al.*, 2003, Lindgren *et al.*, 2020, Olita A. *et al.*, 2012). There are different sources of oil pollution such as those related to natural oil and gas seeps, oil extraction, transportation, and consumption. In recent year, the number of large oil spills has declined (NAS, 2022), despite nearly 30% of global trade compromises oil and its derivate products (Yan *et al.*, 2020). However, most sea-based oil pollution arises from shipping activities (e.g., accidental collision, or sinking of oil tankers), or offshore platforms operations (e.g., oil drilling, failure in pipelines and oil rigs, which can be accidental or deliberate (NAS, 2022).

Oil spills represent a significant environmental threat, causing widespread ecological damage and posing serious challenges to marine ecosystems, coastal communities, and industries dependent on marine resources (Keramea *et al.*, 2021). These spills, whether resulting from accidents during oil extraction, transportation, or other industrial activities, release vast quantities of hydrocarbons into marine environments, leading to contamination of water, sediment, and wildlife and can last for decades (Singh *et al.*, 2020). The behaviour of an oil spill in the marine environment is influenced by various physical, chemical, and biological processes. These processes are primarily determined by the properties of the spilled oil, hydrometeorological conditions (such as waves, winds, currents, solar radiation, and seawater properties), and the specific characteristics of the release into the aquatic environment (Keramea *et al.*, 2023). Additionally, the quality of the oil (density, viscosity, etc.) vary as it spreads across seawater. Those changes are known as oil weathering, and they include the physical, chemical, and biological processes that alter oil composition once it is released in sea environment (Torres *et al.*, 2020). In general, weathering processes can be studied in two time-response frames. The spreading, evaporation, dissolution, dispersion, and emulsification processes, for example, occur immediately (within hours) and affect the oil spill right away. Sedimentation, biodegradation, and photooxidation are the longer-term mechanisms which break down compounds in the environment. It all happens slower—within months. Ocean currents, waves, and winds play a major role in the horizontal transport of oil spilled at sea (Mishra and Kumar, 2015).

Efforts to mitigate and clean up oil spills are complex and often require coordinated responses involving government agencies, industry stakeholders, environmental organizations, and local communities. Prevention through stringent regulations, improved technology, and emergency preparedness measures remains paramount in minimizing the occurrence and severity of oil spills and

safeguarding marine ecosystems for future generations. Detecting and monitoring oil spills are crucial for effective contingency planning. In recent decades, aerial and remote sensing tools are used for oil spill detection and monitoring (Al-Ruzouq *et al.*, 2020). Following the detection of a significant oil spill, one primary concern in response activities is predicting the trajectory of oil spills and its spatial distribution. Numerous operational models worldwide simulate and forecast the movement and evolution of oil spills, including MEDSLIK-II (De Dominicis *et al.*, 2013), GNOME (Elizaryev *et al.*, 2018), OSCAR (Barreto *et al.*, 2021), and OpenDrift (Dagestad *et al.*, 2018).

Oil spill models are used to forecast the trajectory and outcomes of hydrocarbon spills in both surface and underwater environments. Oil spill modelling refers to the use of computer simulations and mathematical algorithms to predict the trajectory, behaviour, and potential impact of oil spills in marine environments (Keramea *et al.*, 2023). These models are essential tools to effectively forecast the course and outcome of oil spills that happen at the surface of the ocean as well as the processes that occur during oil degradation. This makes possible to enhance the pollution response teams during real-time response planning during crisis management, risk assessment, and decision-making during oil spill events. There are several types of oil spill models, each with its own set of assumptions, parameters, and capabilities. Some common types include Lagrangian Models, Eulerian Models, Hydrodynamic Models, Fate and Transport Models (Barker *et al.*, 2020). Those models integrate information of oil type, initial spill location, and meteorological and oceanographic factors (e.g., three-dimensional flow patterns, sea conditions atmospheric winds, and ocean floor topography). In Spain, the most developed and widely used operational oil drift modeling system is the Operational Ocean Forecast Python Engine (OOFe) and the oil spill model General NOAA Operational Modelling Environment (GNOME) (Carracedo *et al.*, 2006; Marta-Almeida *et al.*, 2013). As an alternative, we have chosen to use OpenDrift.

OpenDrift is a multidimensional oil spill distribution and destiny simulator that utilizes an open-source, Python-based Lagrangian's particle path analysis methodology (Dagestad *et al.*, 2018). OpenDrift was developed and currently used operationally at the Norwegian Meteorological Institute (MET Norway) (Jones *et al.*, 2016; Dagestad *et al.*, 2018). It has also been used in studies at the Mediterranean Sea (Keramea *et al.*, 2021). OpenDrift is designed for simulating the drift and dispersion of particles in the ocean. It is specifically developed for applications such as oil spill modelling, search and rescue operations, marine pollution studies, and tracking of floating objects like marine litter or drifting buoys. OpenDrift is designed with a modular architecture, allowing users to easily customize and extend its functionality to suit their specific modelling needs. It provides a flexible framework for integrating different physical processes, environmental data sources, and numerical algorithms. This model employs a Lagrangian approach to simulate the movement of particles or

"tracers" in the ocean. It accounts various parameters and settings, including the initial release location of particles, release rates, particle properties (e.g., buoyancy, size), environmental forcings (e.g., wind, currents), and simulation duration. OpenDrift also provides built-in tools for visualizing simulation results, including maps of particle trajectories, concentration fields, and dispersion patterns. It also offers tools for analysing model outputs, such as calculating arrival times, tracking particle behaviour, and assessing environmental impacts. This work uses OpenOil, a recently built submodule for oil spill transport and outcome, which is a part of OpenDrift. Currently it is used as a resource for the prediction of behaviour and trajectories of an oil spill (Brekke *et al.*, 2021). One of the most significant applications of this computational model is the fact OpenOil can accurately predict the trajectory of an oil spill, providing authorities and appropriate agencies with the necessary data to rapidly determine how best to optimize search, rescue, and cleanup efforts. Becoming a fundamental aspect of the response measures and management of the authorities for the minimization of impact to the social economic and biological aspects comprehensive and integrated strategies are being employed aiming to mitigate impacts and safeguard ecosystems in the face of catastrophic event. OpenOil includes the ADIOS Oil Library, which registers physical properties of around 1000 different types of oil globally (Lehr *et al.*, 2002). Regarding the degradation and oil transportation processes, the simulation incorporates all fundamental processes—such as advection, spreading, evaporation, dispersion, entrainment, diffusion, evaporation, biodegradation, and emulsification—over timescales ranging from hours to days. Weathering process is based on the NOAA ERR-ERD Oil Library package (Thrift-Viveros *et al.*, 2015).

The pristine waters surrounding the Canary Islands, a Spanish archipelago off the northwest coast of Africa, are under high risk of oil spills originating from cargo ship traffic and offshore oil extraction. Due to its unique geographical, climatological, and oceanographic characteristics, it is highly sensitive to environmental impacts from human activities. Similar to other parts of the world's oceans and seas, potentially polluting wrecks are an emerging problem (Lindgren *et al.*, 2020). Oil spills pose a severe environmental threat to the delicate marine ecosystems of the Canaries, known for their rich biodiversity and marine life, and potentially may affect several protected areas, including the UNESCO World Heritage Site of Lanzarote, and Fuerteventura Biosphere Reserve (Kunkel, 2012). In this area some oil spill incidents have been reported in the past (Benjamin *et al.*, 2015) regarding the environmental and socioeconomic impacts. The response to these types of environmental disasters involved contingency operations designed to massive cleanup effort by local authorities, volunteers, and environmental organizations, employing various techniques such as booms, skimmers, and dispersants to contain and remove the oil slick. However, the impact on the environment and local communities may be significant, highlighting the vulnerability of coastal regions

to maritime accidents and the urgent need for stricter regulations and preventive measures in maritime transport (Barron *et al.*, 2020). The use of numerical models could be improved the prevention of oil spill and operational actions.

2. Objectives

This work aims to present the setup of the OpenDrift framework, integrated with local hydrodynamical and wave models, for modelling oil spills in the sea area around the Canary Islands. The structure of this TFG was divided in three specific objectives:

1. Investigate the effectiveness of Opendrift simulation in predicting the trajectory and weathering of oil spills in the marine environment surrounding the Canary Islands, providing insights into potential spill scenarios.
2. Assess the areas of high vulnerability to environmental impact as consequences of hypothetical oil spill incidents in the Canary Islands region through comprehensive analysis of Opendrift-simulated scenarios.
3. Evaluate the applicability and reliability of Opendrift as a decision-support tool for emergency response planning in the Canary Islands, aiming to enhance the region's capacity to effectively manage and mitigate the risks associated with oil spills in its coastal waters.

phytobenthic including significant populations of seagrasses which are crucial for carbon sequestration and serve as breeding grounds for marine life these ecosystems are not only vital for maintaining biodiversity but also play a crucial role in protecting the shoreline from erosion and in carbon dioxide absorption mitigating climate change impacts.

3.1.2 Social Importance

The sea is essential to the local communities of the Canary Islands. The importance of fishing to the culture and economy of these communities cannot be underestimated as it helps in sustaining many families on the islands. In addition, the coast is important to them culturally and traditionally in terms of heritage with respect to numerous festivals and community activities that are ocean related. Moreover, recreational activities in swimming, diving or sailing by the sea contribute immensely towards improving quality of life. These marine areas need protection not just because they represent the unique Canary Islands culture but also due to this reason that it maintains social coexistence within a community. Additionally these coastal zones have rich cultural heritage characterized by traditional methods of fishing artisan crafts among others such as coastal fortifications or lighthouses which remind people about maritime history and legacy in the area.

3.1.3 Economic Importance

The economy of Canary Islands relies heavily on the ocean and nearby coastal regions, mainly driven by tourist activity as well as fishery. The islands possess magnificent beaches that captivate millions of tourists each year for their rich marine biodiversity and recreational fishing opportunities. This branch of the economy is an imperative generator of income and employment in local societies, with a range of sub-service industries. Commercial fishing is also mainstay to the area's economy. The fishing grounds within this archipelago are so rich that important catches are made here which are used both locally and exported to other European and international countries. Maritime transportation is also one of the pillars sustaining this locality's economy since ports in Canary Islands are vital hubs across Europe, Africa, and America trade routes. These strategic locations make them very critical maritime points for logistics purposes where these goods can be offloaded or taken by route to their destinations.

3.2. Historical oil spill events

The Canary Islands have faced several oil spill incidents over the years, with varying degrees of impact on the local environment and economy. Here are some notable historical events:

3.2.1. The Castillo de Bellver, 1983

One of the most significant oil spills in the Canary Islands took place on the 20 July 1983 (located at 9.493° N, 75.776° W, Fig. S1) when the Spanish tanker "Castillo de Bellver" ran aground near the island of Lanzarote, spilling approximately 78,000 metric tons of crude oil into the Atlantic Ocean. The spill resulted in extensive environmental damage to the coastline, affecting marine life, beaches, and local fisheries. Cleanup efforts were launched to mitigate the impact, but the incident highlighted the vulnerability of the region to large-scale oil pollution.

3.2.2. *The Aegean Sea, 1993*

In 1993, the Greek oil tanker "Aegean Sea" sank off the coast of Gran Canaria, releasing thousands of metric tons of crude oil into the surrounding waters. The spill caused significant pollution along the coastline of Gran Canaria, threatening marine ecosystems, coastal habitats, and tourism-dependent industries. Cleanup operations were initiated to contain the spread of oil and minimize environmental damage, underscoring the risks posed by maritime accidents to the Canary Islands' delicate ecosystems.

3.2.3. *The New Flame, 2007*

The oil tanker "New Flame" collided with a cargo vessel near the coast of Gibraltar in 2007, resulting in a maritime accident that led to the spillage of fuel oil into the waters surrounding the Canary Islands. While the majority of the spill occurred outside the territorial waters of the islands, there were concerns about potential oil slicks reaching the coastline of Fuerteventura and Lanzarote, prompting authorities to monitor the situation closely and implement preventive measures to protect the islands' marine environment.

3.3 OpenOil

OpenOil is an advanced oil spill simulation tool designed to predict the flow and fate of oil released into marine environments. OpenOil is a component of the OpenDrift framework, which offers a modular and adaptable architecture suited to many kinds of oceanic drift and dispersion simulations ("OpenDrift - SINTEF Ocean", Dagestad *et al.*, 2018). OpenDrift was developed by SINTEF (*Stiftelsen for industriell og teknisk forskning*, The Foundation for Industrial and Technical Research), one of the biggest independent research institutions in Europe. OpenOil simulates the intricate processes involved in oil dispersion using complex algorithms. It considers variables like wind, waves, and ocean currents, all of which are crucial in determining how oil behaves after it spills (Dagestad *et al.*, 2018).

OpenOil represents a comprehensive oil drift model that comprises sub-models for independent physical processes, including wave stimulation of oil (Li *et al.*, 2017), vertical mixing

resulting from marine turbulence (Rohrs *et al.*, 2018), buoyancy-induced resurfacing of oil (Tklich and Chan, 2002), and emulsification and evaporation considering oil properties (Lehr *et al.*, 2002) (Fig. 2). The main forcing parameters including in the current study, which was aimed at replicating the trajectories of oil spills on the surface, were winds, waves, and currents. Thus, to guarantee accurate assessment of the destiny and trajectories of oil slicks, the inclusion of high-resolution ocean current, meteorological, and wave models was essential to simulate numerical models of oil spill.

3.4 Data Sources

Copernicus Marine Environment Monitoring Services (CMEMS, <https://marine.copernicus.eu/>) is a key component of the European Union's Earth observation program, providing open access to maritime data and services. Numerous applications are supported by CMEMS, such as marine safety, oceanic research, and environmental monitoring. The service provides extensive and up-to-date datasets, which are essential for effectively modelling and comprehending marine dynamics under a range of atmospheric and marine circumstances. The-ocean conditions (i.e., currents, wind, and waves), represent the fundamental components influencing the spreading of oil in the marine environment (Keramea *et al.*, 2023).

Hydrodynamic ocean models

The framework used on this study for simulating the behaviour of oil spills in OpenOil involves the data set using on hydrodynamic ocean models (Table 1). The ocean-circulation models were obtained from Mercator Ocean / CMEMS model. This model provides an evaluation of the ocean currents, water properties over the water column, and waves at a specific time and location (Table 1).

Meteorological datasets

Meteorological models provide information on properties such as surface winds and direction that transport and affect the oil particles (Keramea *et al.*, 2023). Meteorological datasets are essential for forecasting the surface drift of oil spills in OpenOil simulations. Usually derived from high-resolution atmospheric models, and meteorological data linked into OpenOil, allows the simulation to dynamically include changing weather conditions, improving the model's predictive power in real-time response situations (Table 1). For meteorological input, the Royal Netherlands Meteorological Institute (KNMI) was used to obtain weather monitoring data, which provides a $0.125^\circ \times 0.125^\circ$ wind speed and direction at hourly intervals (<https://www.knmi.nl/producten-en-diensten>).

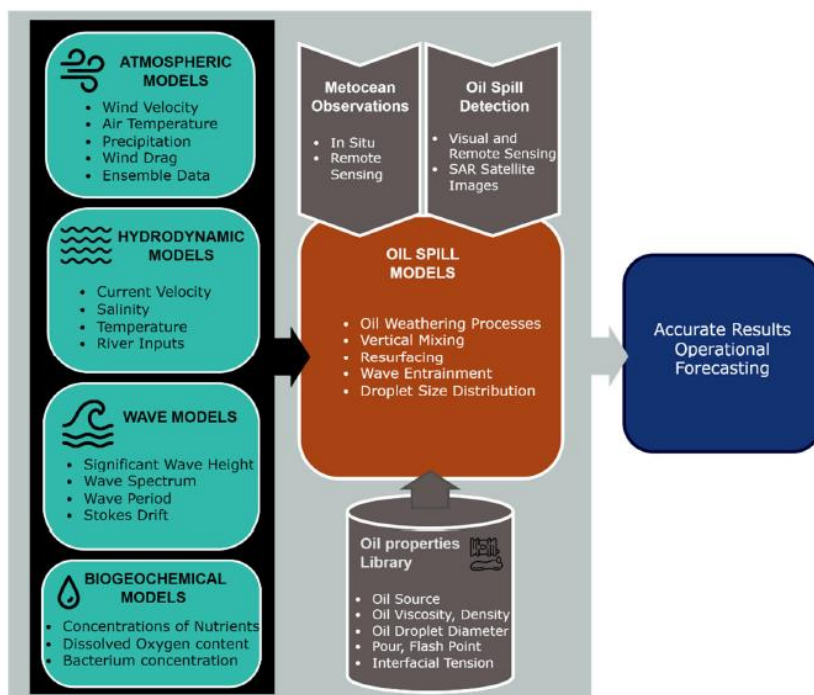


Figure 2: General concept of Operational oil-spill modelling, involving in the OpenOil simulation (Keramea, *et al.*, 2023).

Waves

Parallel to Meteorological datasets, wave models offer details on the velocity, stokes drift fields, and significant wave height that influence vertical mixing, oil dispersion, and wave turbulence in the water column. In addition, characteristics from oceanic models—like the salinity of the seawater and the thickness of the ocean mixed layer—affect how oil is transported after it reaches the sea environment (Table 1). The Mercator Océan International model (<https://www.mercator-ocean.eu/en/>) offers a wind-based wave model covering open oceans and coastal regions. The model has been widely used to simulate and describe the wave condition in different areas. The model was implemented with a $0.083^\circ \times 0.083^\circ$ spatial resolution and hourly time scale.

Table 1: Datasets used in the development of the oil spill simulations (own elaboration).

Dataset	Organizer	Spatial resolution	Temporal resolution	Source
Hydrodynamic (current)	Mercator Océan International	$0.083^\circ \times 0.083^\circ$ (~9 km)	Hourly	Numerical models
Meteorological	KNMI (The Netherlands)	$0.125^\circ \times 0.125^\circ$ (~27 km).	Hourly	Numerical models & Satellite observations
Wave	Mercator Océan International	$0.083^\circ \times 0.083^\circ$	Hourly	Numerical models
Oceanic	Mercator Océan International	$0.083^\circ \times 0.083^\circ$	Hourly	Numerical models

OpenOil model calibration

The model selected to simulate oil spill trajectories was OpenOil (https://opendrift.github.io/_modules/opendrift/models/openoil/openoil.html), and it was focused on assessing potential oil spill scenarios in a zone marked by high-density ship transport route (see Fig. 1, coordinates 12.75°W, 29°N). OpenDrift offers flexibility in using various configurations for environmental input data. In this study, it was considered that oil particles were transported horizontally by ocean currents provided by global ocean physical forecasting products (Table 1, ~9 km) at time resolution of hourly steps. Simulations began with 1000 oil elements (super particles) seeded at the ocean surface in the specified area. These elements had properties of Generic Light Crude Oil (Simanzhenkov and Idem, 2003), similar to the average characteristics of crudes traded globally. The super particles were seeded at the sea surface ($z=0$). Table 2 summarizes the configuration features and initial metocean conditions for each experiment.

Table 2. Configuration features of the two oil spill simulations performed in the east area of Canary Islands with OpenOil (own elaboration).

Configuration features	Study cases
Initial date and time	February, April, July and October 2023
Oil Source Coordinates	12.75°W, 29°N
Duration of the simulation before all particles stranded	Seven days
Number of particles and oil spill radius	1000 particles, 800 m
Oil type	Generic light crude
Initial wind	Speed < 3 m s ⁻¹ with N/NE direction
Initial Stoke drift	< 3 cm s ⁻¹
Initial currents	< 0.1 m s ⁻¹

3.5. Oil Concentration map.

OpenOil modelling was used to map the oil concentration in the study area. First, the data were verified for quality and compatibility with MATLAB through processes of cleaning and normalization (Casado Fernández, 2018). Then, a grid was constructed over the study area, subdividing into smaller segments to facilitate detailed analysis. Then the quantity of oil within each grid cell was determined based on the simulation data. To reduce the effects of environmental changes in daily maps, seven models were generated for each scenario, with each model representing a day's difference. An average was taken across these seven models and were merged to form a strong dataset for visualizing oil spills and assessing risks. As a result, a contour plots were used to illustrate the distribution of the oil concentration and the oil mass budget over time during the simulated spill. The oil mass weathering was divided into different components: dispersed, submerged, surface, stranded, and evaporated (Tarr *et al.*, 2016).

3.6 Risk Assessment

The ISO 31000 (2009) defines the concepts and procedures for risk management. It was released by the International Standardization Organization (ISO), including those risks related to oil spill (Neves *et al.*, 2015). In oil spill simulations, risk assessment is essential to determining the potential impacts on the social, economic, and environmental areas. In this approach, the probability of oil spill impacts into sensitive areas were analyzed using a comprehensive risk assessment using MATLAB in conjunction with OpenOil simulations (Fig. 3) considering fifteen different factors (Table

3). Those factors included ecological, economic, and social implications. Each component was given an estimated risk score based on its significance and potential impact (Olita *et al.*, 2012).

Finally, the places that need protection and mitigation were identified (Amir-Heidari *et al.*, 2019), including assessing coastline vulnerable areas to oil pollution due to fragility of biological resources, and socio-economic features.

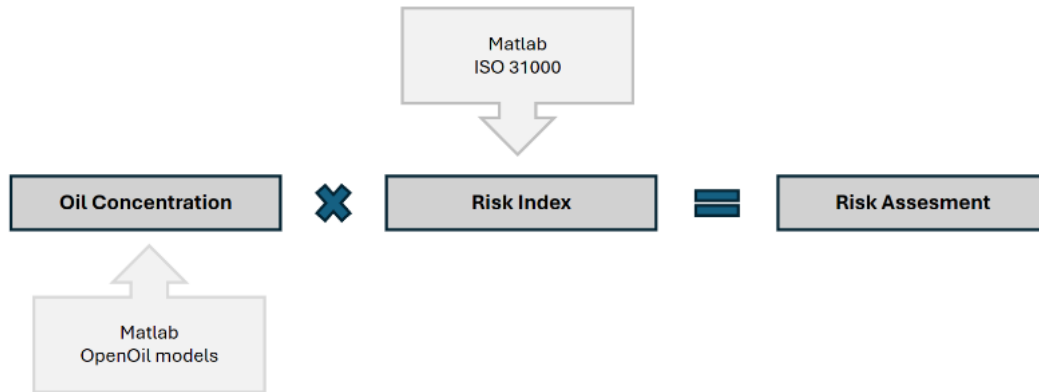


Figure 3: Diagram provided of the explanation of the risk assessment (own elaboration).

Table 3: Risk Index adapted from the ISO 31000 framework (own elaboration).

Risk Factor	Impact Type	Risk Score (1-10)	Rationale
Vulnerability of Protected Marine Areas	Ecological	10	High vulnerability due to the unique biodiversity and protected status of marine ecosystems.
Long-term Environmental Damage	Ecological	10	Considering potential long-term degradation of marine and coastal ecosystems.
Impact on Endemic Species	Ecological	10	Critical due to the potential irreversible damage to species found only in this region.
Impact on Fisheries	Economic	9	Significant due to the importance of fisheries for the local economy and food supply.
Oil Reach to Coastal Beaches	Ecological	9	High impact due to potential damage to coastal habitats and recreational areas.
Socio-economic Impact on Local Populations	Social	8	Includes potential health impacts and disruption to daily life and economic activities.
Effect on Nearshore Nursery Habitats	Ecological	8	Nearshore habitats serve as nurseries for many marine species; their loss has cascading effects.
Tourism Disruption	Economic	8	Major impact on the tourism sector, crucial for the Canary Islands' economy.
Disruption of Coastal Erosion Processes	Environmental	7	Oil can interfere with natural erosion processes, leading to changes in coastline dynamics.
Disruption of Desalination Plants	Economic	7	Oil contamination can affect desalination plants, jeopardizing water supply in coastal areas.
Disruption of Marine Research Activities	Social	7	Oil spills can impede marine research efforts, affecting scientific understanding and management.
Clean-up and Recovery Costs	Economic	7	Significant costs involved in cleanup operations and ecological restoration.
Damage to Cultural Heritage	Social	6	Underwater archaeological sites and artifacts are at risk of damage or destruction from oil spills.
Disruption of Marine Traffic	Economic	6	Affects shipping and logistics, though with potentially less direct impact than other factors.
Public Perception in Authorities	Social	5	Important for managing the social response and trust in environmental stewardship.

4. Results

4.1 Hypothetical oil spills

For hypothetical oil spills accident scenarios, one area with a significant potential for oil spills was selected (Fig. 1) involving surface spill resulting from a potential shipwreck. The hypothetical spill was simulated at four seasons (February, April, July, and October of 2023, at 00:00 UTC) and lasted seven days. Each of these periods was chosen to represent different meteorological and oceanographic conditions that affect the behaviours of spilled oil particles. This method offers a thorough picture of the particles produced under various seasonal conditions by enabling the measurement of short-term dispersion and behavioural understanding and reducing the impact of daily environmental fluctuation figures 4, 5, 6, and 7 display the outcomes of the hypothetical oil spills, together with the particle dispersion.

4.1.1 February 2023 daily set

The simulations from February 2023 showed that oil particles were mainly drifting westward towards areas in the Canary Islands leading to the particles getting stuck along the shores of Fuerteventura and Lanzarote (Fig. 4). Early in the modelling process, the trajectory of the oil moved westward in line with the orientation of main seasonal winds (Annexe 1, Supplementary material). Some of the scenarios concluded with oil particles reaching the shoreline (stranded particles), and eventually some of the oil travelled southwest until it reached the eastern shore of the Lanzarote and Fuerteventura islands. It's interesting to note that the impact of wind and waves seemed to have effect in situations resulting in some cases where the particles did not get stuck during the observation period. However, there was a pattern suggesting particle stranding along the coastlines of these islands. In scenarios where particles get stuck included the Playa Blanca, Corralejo and Isla de Lobos (Lanzarote) and Puerto Laja and Parque Holandes (Fuerteventura). Scenarios 6 and 7 showed a movement upwards with some particles ending up at Chinijo Natural Park (north of Lanzarote Island). The impact of trade winds on particle drift, in these scenarios appeared to be diminished.

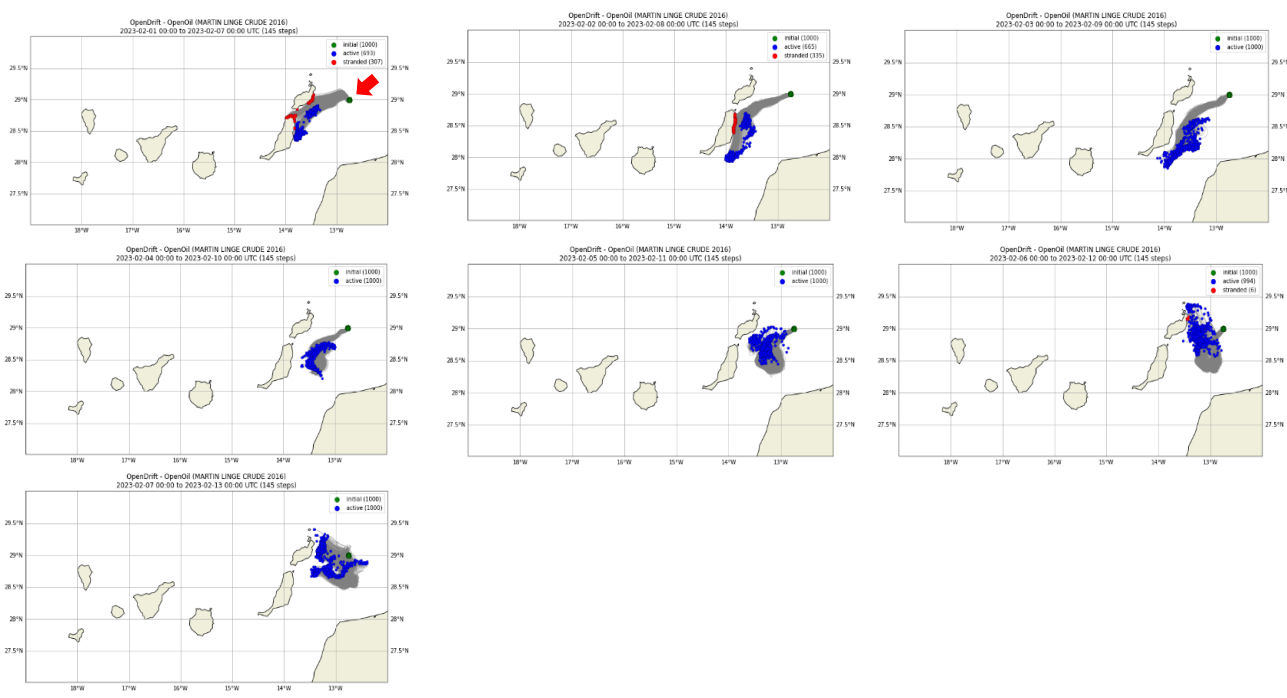


Figure 4: Scenarios of an oil spill in eastern Canary Island generated in February 2023 (own elaboration).

4.1.2. April 2023 daily set

During the simulations carried out for the OpenOil project in April, it was observed that oil particles were more affected by wind and waves than ocean currents. The currents remained relatively stable on this season (Fig. 5, Fig. All, Supplementary Material), showing lower sensitivity to atmospheric conditions. Throughout the whole simulation, the spill trajectory moved southward until it reached the Moroccan coast, where it ended up stranded. In some scenarios this resulted in oil particles getting stranded along the coast near Tarfaya and Fom el Oued (Morocco). There was no evidence of particle stranding within the expected timeframe with particles drifting towards southern regions beyond the main study area. Importantly there was no deposition of oil particles on the Canary Archipelago during the simulation period. Additionally, it was noted that despite strong inertial drag from the Trade winds, the oil slick's region stayed mostly unchanged during the modelling.

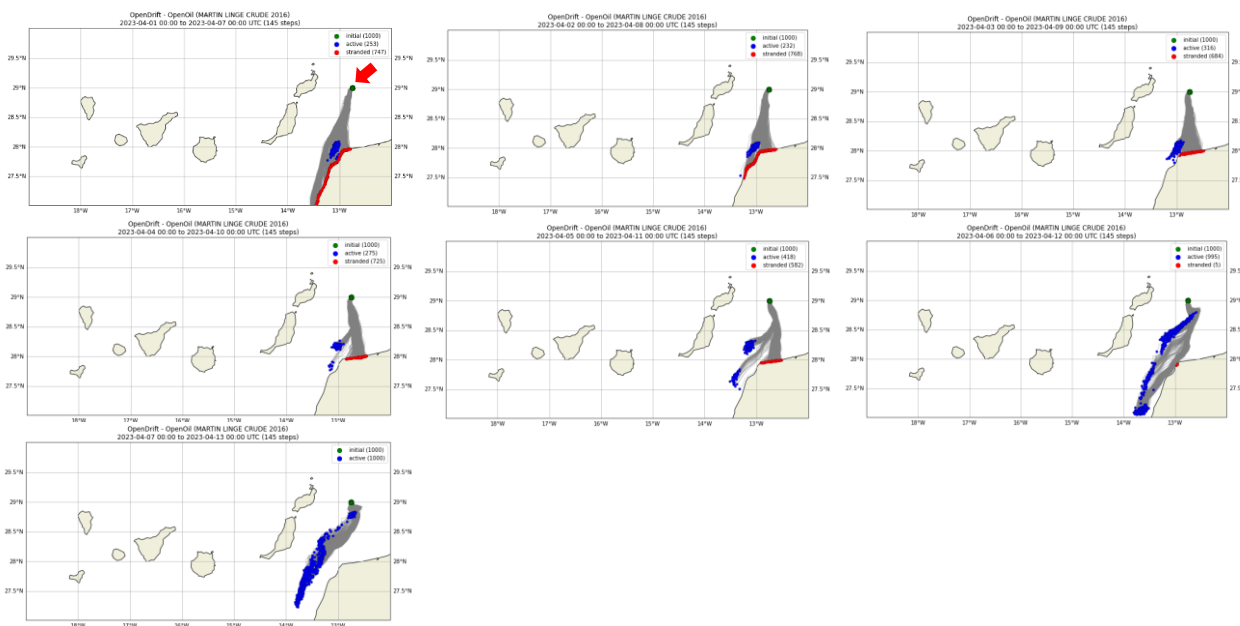


Figure 5: Scenarios of an oil spill in eastern Canary Island generated in April 2023 (own elaboration).

4.1.3 July 2023 daily set

In the July 2023 charts, we observed an occurrence of Trade winds and wave impacts showing a flow pattern suggesting particles were moving towards the southern parts of the Morocco coast (Fig. 6). The study zones boundaries revealed low levels of particle accumulation in Morocco, although it reached the coasts of western Sahara out of the Canary Island area.

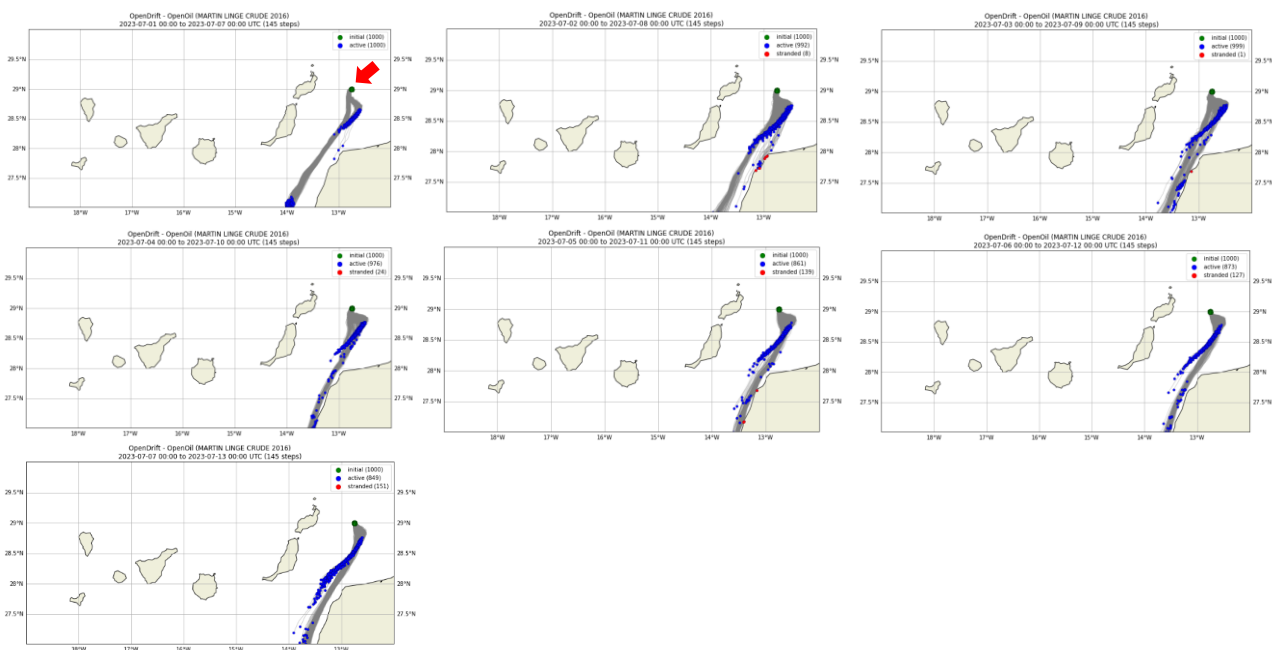


Figure 6: Scenarios of an oil spill in eastern Canary Island generated in July 2023 (own elaboration).

4.1.4 October 2023 daily set

On this season, the trajectory of the oil moved towards the south during the first days of the simulation coincident with the direction of seasonal winds and current (Fig. 7). Oil particles then started to move towards the west reaching the channel between Lanzarote and Fuerteventura, where all the oil slick reached the coastline (stranded particles). Notably oil particles affected the capital of Lanzarote (as seen in scenario one) at Corralejo and Playa Blanca. This concordance underscored how the movement and settling of particles during winter and autumn in this area can be significantly influenced by wind intensity.

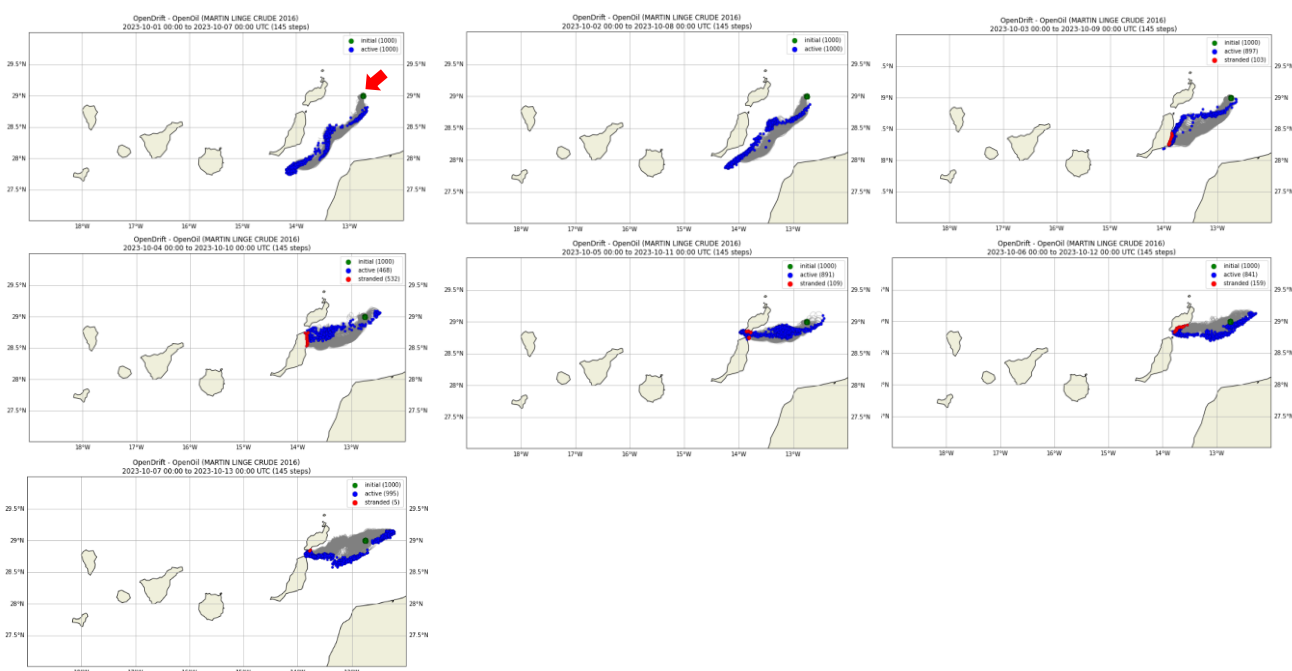


Figure 7: Scenarios of an oil spill in eastern Canary Island generated in October 2023 (own elaboration).

4.2 Oil budget plots

The weathering of oil spills models is presented in Fig. 8,9,10 and 11 including the total, dispersed, submerged, surface, stranded and evaporated oil mass (kg) and oil volume (m³), as well as the emulsion viscosity and water content. The resulting simulations were analysed in detail by evaluating the spatial and temporal evolution of oil weathering over the four distinct time frames: February, April, July, and October 2023.

4.2.1 February 2023 daily set

The simulations showed that at 80 hours after the oil spill, still nearly 65% of the hydrocarbon was in the surface (Fig. 8). As the oil slick continued moving towards the coast, dispersed fraction increase rapidly, driven by wind velocities. The remaining oil transitioned into dispersed, submerged, and surface states, with minimal stranding. High wind speeds, particularly those above 6 m s⁻¹, significantly enhance the weathering process. High evaporation values played an important role in the occurrence of emulsification, impacting oil viscosity. The emulsion viscosity increased sharply initially and stabilized as the water content in the emulsion rose to about 75%. The simulation also showed that the hydrocarbon spilled reached up to 80% water content as the oil evaporated (140 hours). This is consistent with the typical behaviour of oil emulsification, forming stable emulsions with high water content, referred to as "chocolate mousse." These emulsions eventually break into pieces, forming semisolid tar balls. Wind speeds fluctuated between 4 and 12 m/s, with current speeds peaking at around 0.25 m/s.

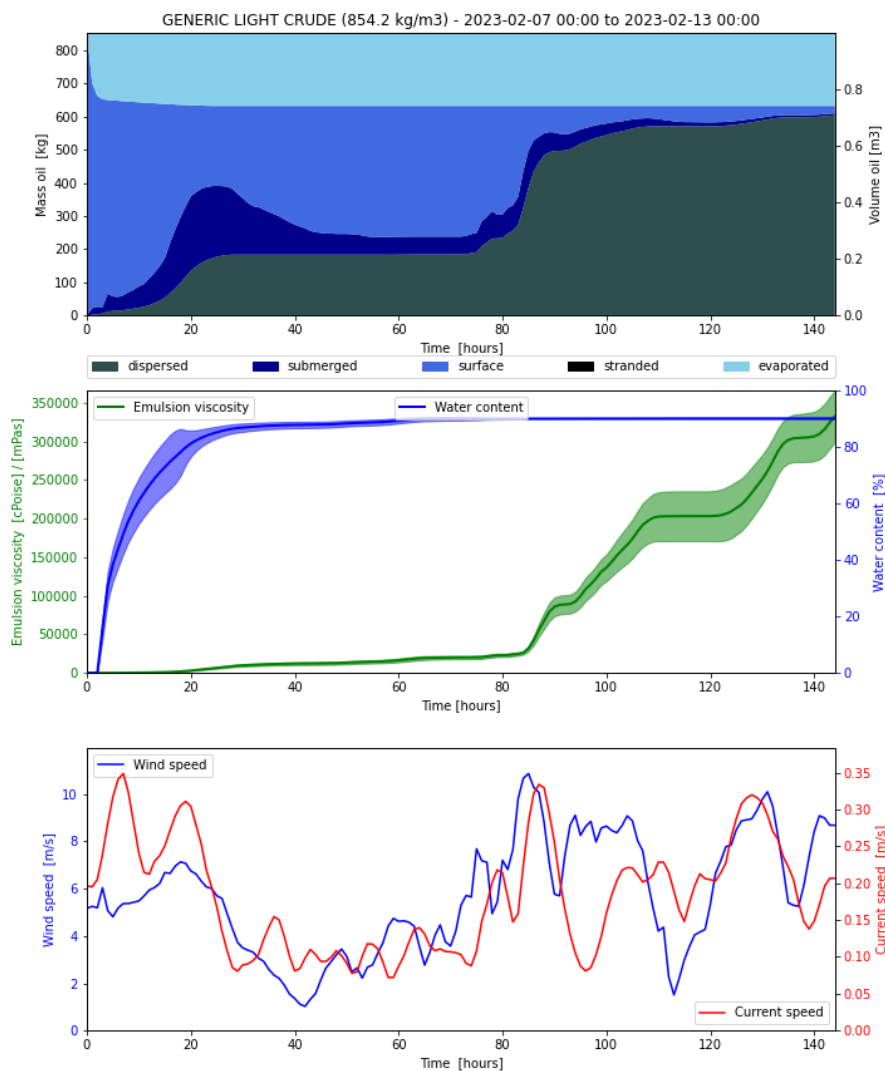


Figure 8. Oil weathering simulation of oil spill on Canary Islands in February 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s^{-1}) (own elaboration).

4.2.2 April 2023 daily set

In April, the weathering simulation showed a different pattern, with higher values of submerged oil just after spill and an increasing value of dispersed oil, nearly 100% after 100 hours (Fig. 9). The remaining oil remained on the surface. Lower wind speeds, particularly those under 6 m s^{-1} , reduce the evaporation values. The emulsion viscosity increased sharply initially and stabilized as the water content in the emulsion rose after 80 hours. The simulation also showed that the hydrocarbon spilled reached up to 80% water content as the oil evaporated (140 hours). Wind speeds fluctuated between 4 and 10 m s^{-1} , with current speeds showing variability and peaks reaching approximately 0.35 m s^{-1} .

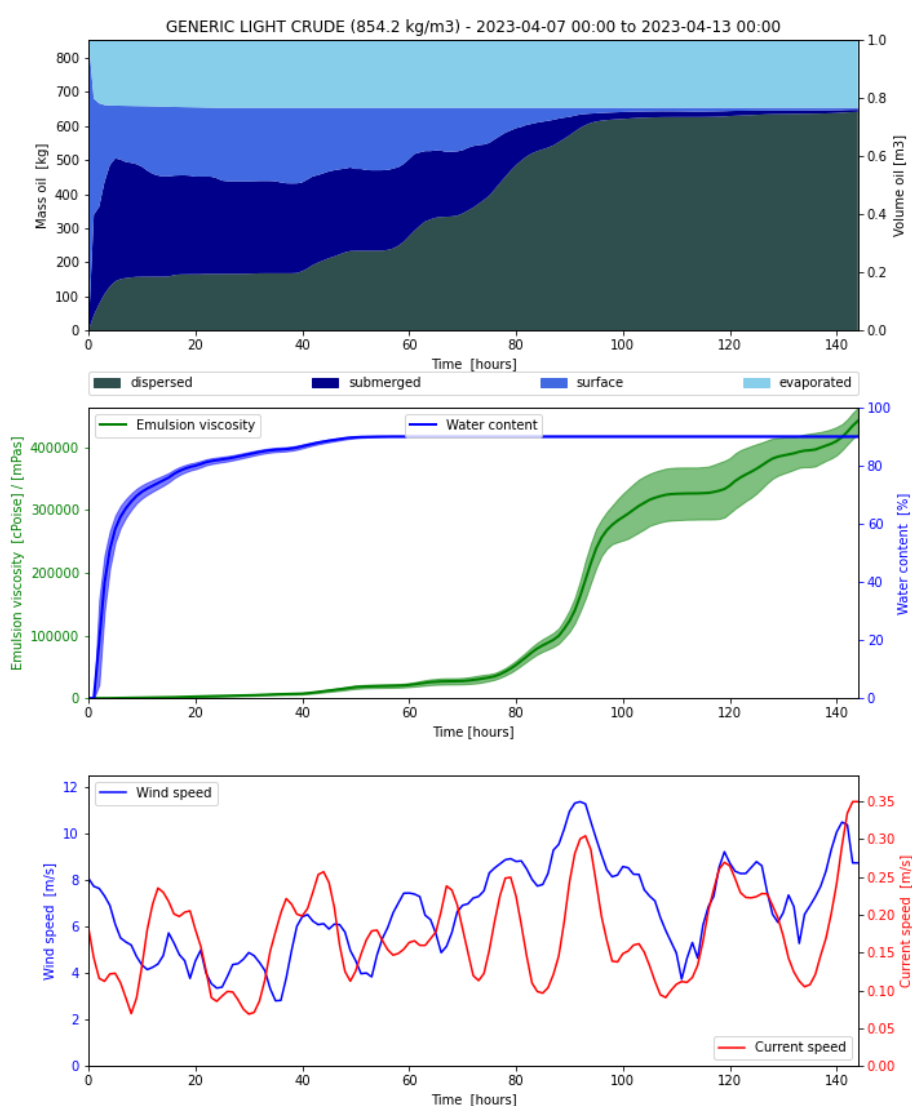


Figure 9. Oil weathering simulation of oil spill on Canary Islands in April 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPa·s) and water content (%); (down) the current and wind speed (m s^{-1}) (own elaboration).

4.2.3 July 2023 daily set

The July simulations displayed a rapid initial loss of oil mass due to high dispersion values which reached around 100% after 50 hours, followed by a steady distribution (Fig. 10). Emulsion viscosity increased sharply and stabilized, with the water content in the emulsion reaching around 100% at 100 hours. Environmental conditions showed wind speeds fluctuating between 8 and 10 m s⁻¹, and current speeds exhibited variability, peaking at around 0.15 m s⁻¹.

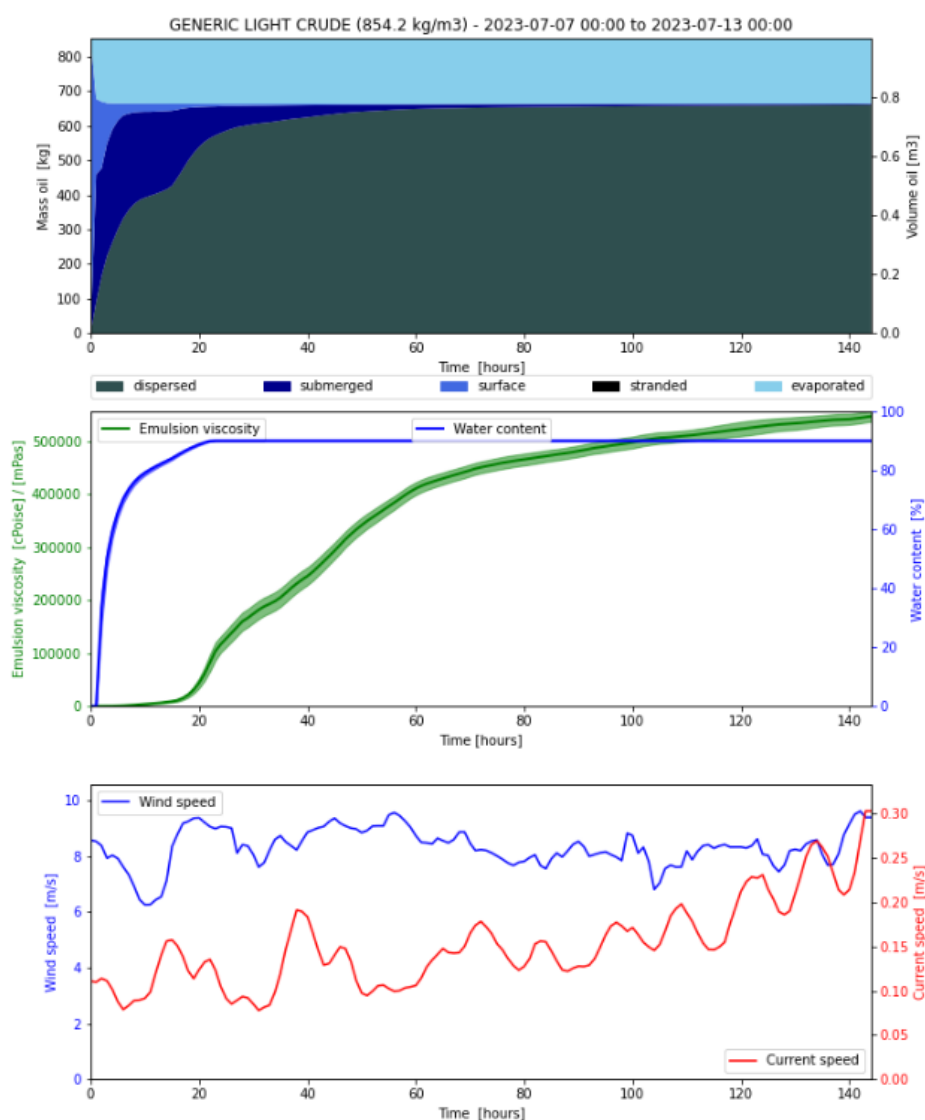


Figure 10. Oil weathering simulation of oil spill on Canary Islands in July 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s⁻¹) (own elaboration).

4.2.4 October 2023 daily set

In October, the simulations indicated a similar response than in July, with a rapid initial dispersion and submerged rates of the oil, followed by stabilization of the remaining oil in the dispersion state, and low surface proportion. Emulsion viscosity rose sharply initially and then stabilized, with water content in the emulsion increasing steadily to nearly 80% after 60 hours. Wind speeds fluctuated between 4 and 8 m s⁻¹, with current speeds varying with peaks around 0.35 m s⁻¹.

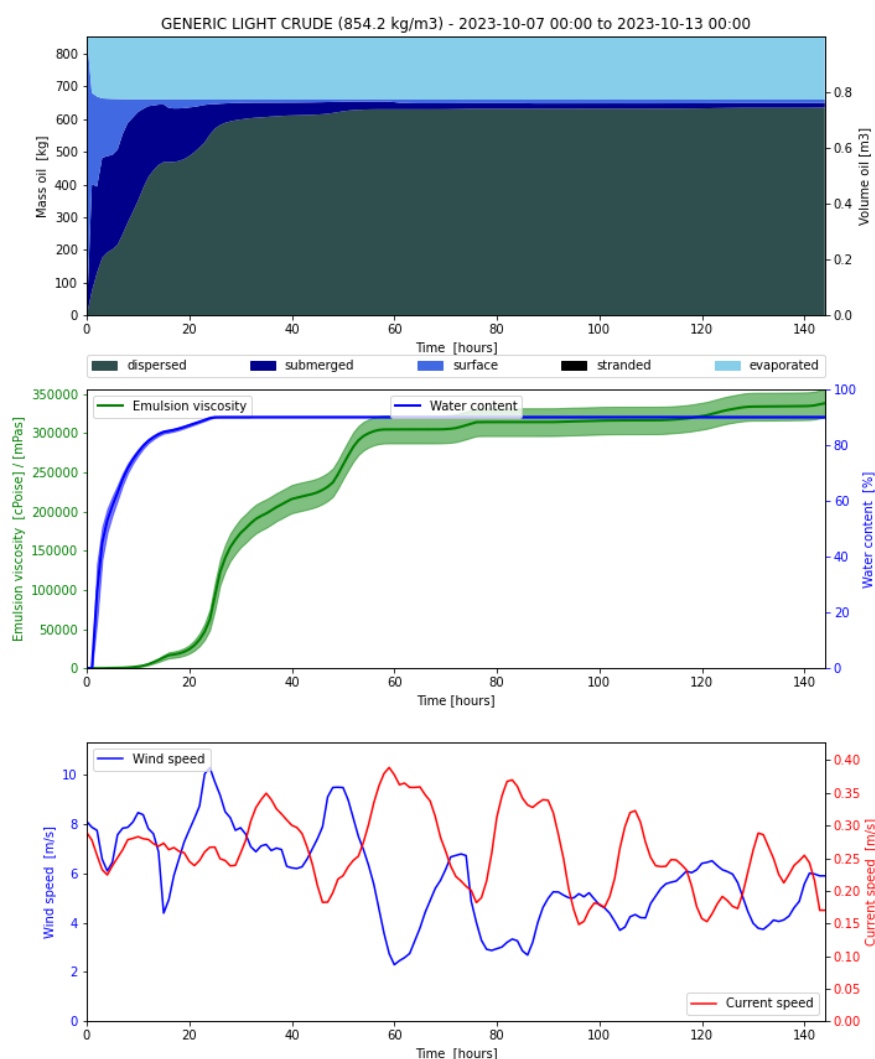


Figure 11. Oil weathering simulation of oil spill on Canary Islands in October 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13 February. (up) the total, dispersed, evaporated, and submerged mass (kg); (middle) the emulsion viscosity (mPas) and water content (%); (down) the current and wind speed (m s⁻¹) (own elaboration).

Overall, the simulations for each month showed two consistent trends in the behaviour of oil. During February and April, oil showed a lower dispersion rate and more presence of oil in the surface up to 80 hours after oil spill. On the other hand, in July and October there was a very rapid dispersion process with very low presence of oil in the surface. Evaporation showed similar values on the four seasons, with slightly higher values in February. The evaporation of volatile fractions was a critical process, leading to the formation of stable water-in-oil emulsions. These emulsions significantly impacted the viscosity and stability of the remaining oil.

4.3 Potential Risk Assessment Scenario

The simulations of OpenOil offered a comprehensive risk simulation for four potential oil spill scenarios during February, April, July and October 2023 (Fig. 12). Those scenarios demonstrated the different oil spill impacts upon the marine and coastal areas of Canary Islands and how the seasonal changes affected the potential outcomes of oil spills.

4.3.1. February scenario

February simulation presented a worrying concentration of oil particles encroaching on densely populated communities and natural reserves on Lanzarote and Fuerteventura (Fig. 12 a). High values of risk (>0.15) were observed at the eastern shore of the Lanzarote and Fuerteventura islands, in particular in the Playa Blanca, Corralejo and Isla de Lobos (Lanzarote) and Puerto Laja and Parque Holandes (Fuerteventura, with some particles ending up at Chinijo Natural Park (north of Lanzarote Island).

4.3.2. April scenario

April's scenario illustrated a less immediate impact from direct oil particle contamination on Canary Islands but underscores a significant indirect effect on regional oceanography (Fig. 12b). Throughout the whole simulation, the higher risk areas (<0.10) area located in the south at the Moroccan coast (Tarfaya and Fom el Oued). There was no risk within the Canary Island coastlines during this simulation period.

4.3.3. July scenario

Like April, July scenario suggested significant indirect effects rather than direct contamination on Canary Island. Higher risk areas (<0.15) were located towards the southern parts of the Morocco coast (Fig. 12c). The study zones boundaries revealed middle risk levels in Morocco and the coasts of western Sahara out of the Canary Island area.

4.3.4. October scenario

In October, the simulation indicated a significant oil spill risk impact on Canary Island costs, where oil particles reached crucial environmental and economic zones, including major shipping routes near Fuerteventura and Lanzarote (Fig. 12d). Oil particles reached the channel between Lanzarote and Fuerteventura and the coastline. Notably there was a risk over the coastline of Fuerteventura (as seen in scenario one). This concordance underscored how the movement and settling of particles during winter and autumn in this area can be significantly influenced by wind intensity.

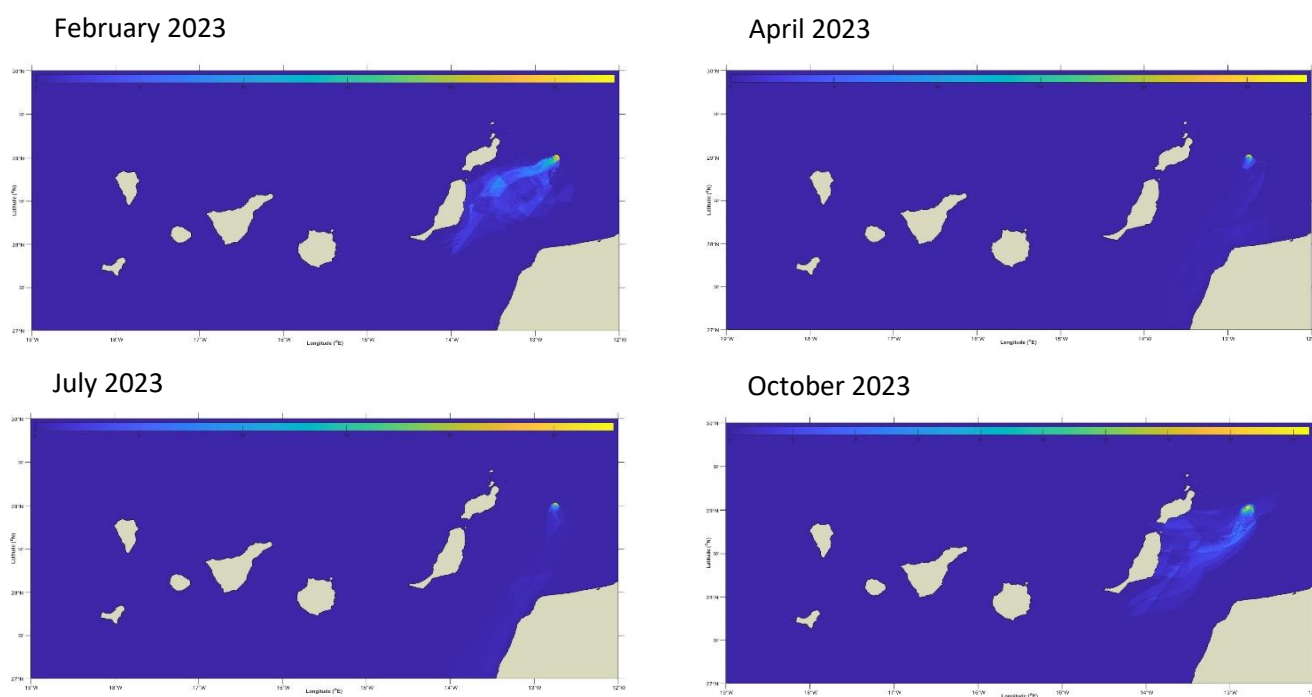


Figure 12. Oil risk simulation of oil spill on Canary Islands in February (a), April (b), July (c) and October (d) 2023. Composed results of four different temporal simulations: 1-7, 3-9, 5-11, and 7-13. Risk value between 0 and 0.25 (own elaboration).

A detail risk evaluation maps adapted from the ISO 31000 framework are presented (Fig. 13). Those maps illustrate a risk index for the Canary Islands and surrounding regions, with values ranging from 1 to 10. This risk index comprehensively integrates environmental, economic, and social factors to assess the relative importance of different areas. The analysis revealed a spatial risk distribution, with certain regions exhibiting higher risk values:

High-Risk Areas: The highest risk values, approaching 10, are concentrated in the eastern parts of the Canary Islands, particularly around the island of Lanzarote. This area is highlighted in yellow and light green, indicating significant risk factors that could be environmental, economic, or social in nature.

Moderate-Risk Zones: The central areas of the Canary Islands, including parts of Tenerife and Gran Canaria, display moderate risk values ranging from 5 to 7. These regions, shaded in shades of green and blue, suggest a balanced yet notable presence of risk factors.

Low-Risk Regions: Western islands such as El Hierro, La Palma, and La Gomera predominantly show lower risk values, in the range of 1 to 3. These areas, depicted in darker blue, indicate minimal risk when considering the combined factors.

Transitional Zones: There are noticeable gradient zones where risk values transition from high to low, particularly between the eastern and central islands. This gradient is critical in understanding how risk factors diffuse and affect adjoining regions.

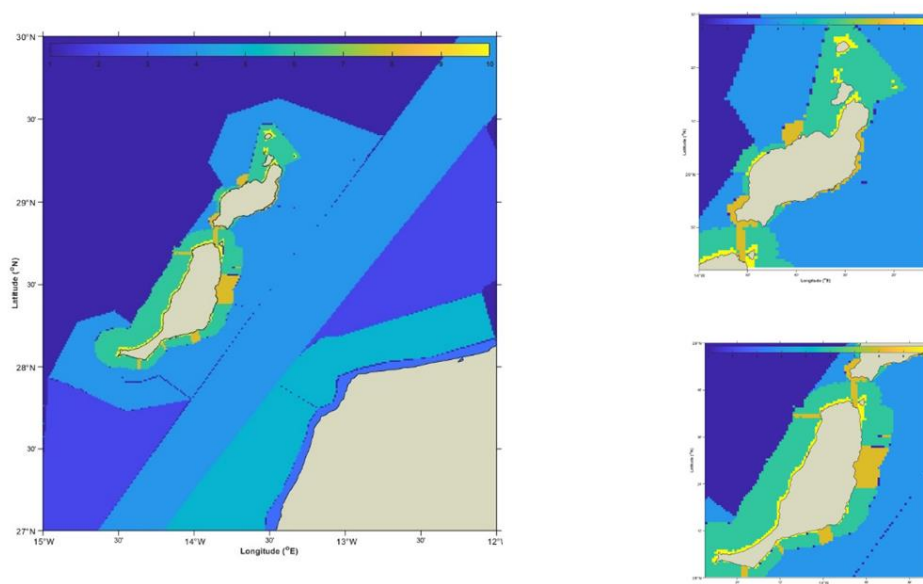


Figure 13. Areas of high-risk simulation of oil spill on Canary Islands using Opendrift model and ISO31000 framework. Risk value between 0 and 10 (see Table 3) (own elaboration).

5. Discussion

The Canary Islands, situated off the northwest coast of Africa, boast a diverse marine ecosystem that is both ecologically valuable and economically significant. However, this region faces the risk of oil spills due to its proximity to major shipping routes and oil extraction activities. To mitigate potential environmental disasters, the predictive modelling Opendrift has been employed to forecast oil spill trajectories and assess their potential impact on the marine environment of the trajectories of oil spills in several sea regions. On this study, model results allow a better interpretation and comparison of the simulated trajectories of drift patterns in an eventual oil spill in Canary Island which can be used to mitigate potential environmental disasters by forecasting oil spill trajectories and assess their potential impact on the marine environment of this high environmental and economical rich region.

5.1 Potential Spill Scenarios

Opendrift utilizes numerical modelling techniques to simulate the movement and fate of spilled oil in marine environments (Kotzakoulakis and George, 2021). By incorporating data on ocean currents, wind patterns, and other environmental factors, Opendrift can generate predictive simulations of oil spill trajectories. One of the key benefits of Opendrift simulation is its ability to provide insights into various spill scenarios (Dagestad *et al.*, 2018). By running simulations under different conditions, such as varying spill volumes, locations, and environmental factors, researchers can assess the potential range and severity of oil spill events in the Canary Islands. This allows stakeholders to anticipate and prepare for different scenarios, enhancing emergency response preparedness (Walker *et al.*, 2015).

In this study, Opendrift was used to simulate an oil spill in the context of the Canary Islands, where the complex oceanographic and ship traffic conditions play a crucial role in oil spill risks. Results of simulation agreed with previous findings for similar studies (Benjamin Ivorra *et al.*, 2015, Padron *et al.*, 2015, Calvilla *et al.*, 2017). The differences observed among seasons was related to wind, stokes drift and different dynamics of hydrometeorological conditions increasing its reliance on currents and resulting in different trajectories. In our modelling setup, we used data from NEMO-EST05 (currents), SWAN-EST (waves) and ECMWF (winds) at seasonal scales which enabled a coherent and synchronized with large data series of ocean conditions, and their impact on drift trajectories (Pärt *et al.*, 2023). Observed oil trajectories aligned closely with trade winds and current conditions reported (Semedo, 2018). Marine wind fields along the Canary Island are defined by the Mediterranean water, into the North Atlantic basin, and the Azores current closer to the surface. These conditions, together with the prevalent trade winds during the winter and autumn, creates a southwest flow action along the east

coast of Lanzarote and Fuerteventura. On the other hand, in spring (April) and summer (July), wind fields conditions change to south component, moving oil spill to the Morocco and Sahara coastline (Semedo, 2018)

5.2 Oil weathering process

Oil mass undergo weathering processes over time, which can alter its behaviour and make it more challenging to contain and recover (Tarr *et al.*, 2016). The prolonged presence of the spill heightens the likelihood of oil reaching shorelines, thereby impacting the ecological and economic values. The present research examined how oil weathered over the course of seven days, during which spreading, evaporation, dissolution, dispersion, and emulsification happened gradually. Results analysed the spatial and temporal evolution of oil evaporation and the water fraction on February, April, July, and October 2023.

The simulations showed that during February and April ,oil showed a lower dispersion rate and more presence of oil in the surface up to 80 hours after oil spill. On the other hand, in July and October there was a very rapid dispersion process with very low presence of oil in the surface. Evaporation showed similar values on the four seasons, at the end of the study period (140 hours) 80% of the hydrocarbon was evaporated, driven by wind velocities. Ocean currents, waves, winds, and weather conditions all have a significant influence on these events (Robertson and Campbell, 2020). High wind speeds, particularly those above 5 m s^{-1} , significantly enhance the weathering process (Tarr *et al.*, 2016). High evaporation values play an important role in the occurrence of emulsification, impacting oil viscosity (Tarr *et al.*, 2016). In our simulations, the hydrocarbon spilled in various months showed that the slick reached up to 80% water content as the oil evaporated. This is consistent with the typical behaviour of oil emulsification, forming stable emulsions with high water content, referred to as "chocolate mousse" (Farrington, 2014). These emulsions eventually break into pieces, forming semisolid tar balls.

5.3 Potential risk assessment

Potential risk assessment of simulated oil spills is crucial to recognize their potential environmental and economic impacts. Those outcomes are influenced by the specific location, environmental conditions during the simulation, and the properties of the oil being modelled (Chang *et al.*, 2014). The relatively rapid dispersion observed in the simulated spill scenarios of this study underscores the importance of immediate response actions to mitigate environmental damage in Canary Island. Swift responses enhance the effectiveness of containment and cleanup efforts, thereby reducing harm to marine ecosystems, wildlife, plants, and sensitive habitats. Moreover, addressing oil

spills in open sea locations is generally easier and less costly compared to dealing with shoreline contamination (Ventikos *et al.*, 2004).

In particular, the conditions in February and October exhibited the highest proportion of oil stranding to high value ecological areas in Lanzarote and Fuerteventura islands, highlighting the significance of the risk spill reaching the coast. Given the short distance of potential spill sites to the coastline of Lanzarote and Fuerteventura, there is an elevated risk of oil reaching sensitive coastal areas (Playa Blanca, Corralejo and Isla de Lobos at Lanzarote; and Puerto Laja and Parque Holandes at Fuerteventura). Therefore, rapid response measures are essential to prevent or minimize oil contamination on the shore. Assessing the environmental impact and potential socio-economic consequences of hypothetical oil spill incidents in the Canary Islands region through comprehensive analysis of Opendrift-simulated scenarios aids in developing effective response strategies and mitigation measures. The spill scenario in April and July demonstrated a different risk behaviour. Only a small amount of oil surfaced may reach Canary Island, affecting more to Morocco and Sahara coastline.

It is important to recognize that spills from shipwrecks often involve continuous leakage rather than single events like in this simulation. Prolonged oil leakage presents unique challenges for spill response and mitigation efforts (Barron *et al.*, 2020). This ongoing contamination increases the cumulative impact on marine ecosystems, wildlife, and coastal areas (Hampton *et al.*, 2003). Continuous spills necessitate sustained monitoring and response measures to minimize the spread of oil, mitigate environmental damage, and protect sensitive habitats. Furthermore, the persistent nature of these spills can impact the effectiveness of containment and cleanup operations. Through Opendrift simulations, areas of high vulnerability to oil spills can be identified with greater precision (Brude *et al.*, 2021). By analyzing the simulated trajectories, researchers can pinpoint sensitive ecological areas, important fishing grounds, and coastal communities that may be at risk of contamination in the event of a spill. This information is crucial for prioritizing risk mitigation measures and implementing strategies to protect vulnerable ecosystems and livelihoods.

5.4. Evaluation of applicability and reality

The simulations obtained on this study indicated that under changing seasonal conditions, only a relatively small amount of oil remains on the water surface, while a significant portion disperses into the water column. This dispersion poses a considerable challenge for oil removal and mitigation efforts. Oil dispersed in the water column is more difficult to address and may lead to long-term ecological consequences. Opendrift simulation offers valuable insights into oil spill prediction, but accurate predictions rely heavily on the availability and quality of input data, including oceanographic

and meteorological data. Additionally, uncertainties in model parameters and assumptions can impact the reliability of simulation results. Continuous validation and refinement of the model are necessary to improve its predictive accuracy and robustness. Thus, evaluate the potential applicability and reliability of Opendrift as a decision-support tool for emergency response planning to oil spills in Canary Islands can enhance the region's capacity to effectively manage and mitigate the risks associated with oil spills in its coastal waters.

6. Conclusion

In conclusion, Opendrift simulation represents a valuable tool for predicting the trajectory and fate of spilled oil in the marine environment surrounding the Canary Islands. By providing insights into potential spill scenarios and identifying areas of high vulnerability, Opendrift supports informed decision-making and enhances the region's ability to respond effectively to oil spill incidents.

The primary objectives of this study were to evaluate the effectiveness of the OpenDrift simulation in predicting the trajectory and fate of oil spills in the marine environment surrounding the Canary Islands, and to identify areas of high vulnerability to inform decision-making processes. Our results demonstrate that OpenDrift is a valuable tool for simulating potential spill scenarios and assessing the associated risks to the Canary Islands' marine ecosystem. By replicating the trajectories of hypothetical oil spills under varying seasonal conditions, the study highlighted the influence of wind and currents on the dispersion and weathering processes of oil spills. These findings are crucial for developing effective response strategies tailored to specific environmental conditions. The research underscored the need of continuous improvement in data quality, model validation, and stakeholder engagement to enhance the predictive accuracy and applicability of the OpenDrift model. Additionally, the study emphasizes the importance of understanding crude oil behavior post-spill, given the significant environmental and socioeconomic risks associated with hydrocarbon transportation.

Overall, the insights gained from this study are to enhance the Canary Island capacity to manage and mitigate oil spill risks, thereby safeguarding the Canary Islands' marine ecosystem. Future efforts should focus on refining the model through higher resolution databases and ongoing validation to ensure robust and reliable predictions. However,

1. Ongoing efforts to improve data quality, model validation, and stakeholder engagement are essential to maximize the effectiveness of this predictive tool and its application to safeguard the Canary Islands' marine ecosystem.
2. It is needed to research the effectiveness of Opendrift simulation experiment in predicting the trajectory and fate of oil spills in the marine environment surrounding the Canary Islands, providing insights into potential spill scenarios and identifying areas of high vulnerability.
3. The study highlights the importance of understanding crude oil behaviour post-spill due to environmental and socioeconomic risks associated with hydrocarbon transportation.

4. Simulations using the OpenOil model in the eastern Canary Islands area demonstrated its suitability for predicting oil spill trajectories and weathering processes, offering valuable insights into spill evolution.

5. Wind and current effects were identified as primary factors influencing oil spill position changes, with wind playing a crucial role in both horizontal advection and physicochemical properties. This emphasizes the need for higher resolution databases for more accurate ocean model implementations.

6. Limitations encountered using OpenOil model are the quality of data source and options of validation.

7. References

- Al-Ruzouq, R., Gibril, M.B., Shanableh, A., Kais, A., Hamed, O., Al-Mansoori, S., Khalil, M.A., (2020). Sensors, features, and machine learning for oil spill detection and monitoring: a review. *Remote Sensing* 12, 1–42.
- Amir-Heidari, P., Arneborg, L., Lindgren, J.F., Lindhe, A., Rosén, L., Raie, M., Hassellöv, I.M. (2019). A state-of-the-art model for spatial and stochastic oil spill risk assessment: A case study of oil spill from a shipwreck. *Environment international* 126, 309-320.
- Barker, C.H., Kourafalou, V.H., Beegle-Krause, C.J., Boufadel, M., Bourassa, M. A., Buschang, G., Zheng, Y. (2020). Progress in operational modeling in support of oil spill response. *Journal of marine science and engineering* 8(9), 668.
- Barreto, F.T., Dammann, D.O., Tessarolo, L.F., Skancke, J., Keghouche, I., Innocentini, V., Winther-Kaland, N., Marton, L., (2021). Comparison of the coupled model for oil spill prediction (CMOP) and the oil spill contingency and response model (OSCAR) during the DeepSpill field experiment. *Ocean & Coastal Management*, 204, 105552.
- Barron, M.G., Vivian, D.N., Heintz, R.A., Yim, U.H. (2020). Long-term ecological impacts from oil spills: comparison of Exxon Valdez, Hebei Spirit, and Deepwater Horizon. *Environmental Science & Technology* 54(11), 6456-6467.
- Brekke, C., Espeseth, M. M., Dagestad, K. F., Röhrs, J., Hole, L. R., Reigber, A. (2021). Integrated Analysis of Multisensor Datasets and Oil Drift Simulations—A Free-Floating Oil Experiment in the Open Ocean. *Journal of Geophysical Research: Oceans* 126(1), e2020JC016499.
- Brude, O. W., Jakobsen, V., Rinaldo, Ø., Tvedt, H.B., Rudberg, A., Gravir, G., Olsen, K.E. (2021). EnviRisk—Automated Environmental Risk Assessment for Ship Traffic in Norwegian Waters. In *International Oil Spill Conference* (Vol. 2021, No. 1, p. 688603).
- Calvilla, J.M., Bergueiro, J.R., González, J. . (2017). Oil Spill Model and Response Tools: Analysis of Oil Spill Risks Due Exploration and Oil Prospecting Near The Coast of The Canary Islands. *Journal of Maritime Research* 14(2), 32-40.
- Carracedo, P., Torres-López, S., Barreiro, M., Montero, P., Balseiro, C.F., Penabad, E., Pérez-Muñuzuri, V. (2006). Improvement of pollutant drift forecast system applied to the Prestige oil spills in Galicia Coast (NW of Spain): Development of an operational system. *Marine Pollution Bulletin* 53(5-7), 350-360.

Casado Fernández, C 2018 *Manual básico de MatLab*, Universidad Complutense, Servicio de Publicaciones, Madrid

Chang, S.E., Stone, J., Demes, K., Piscitelli, M. (2014). Consequences of oil spills: a review and framework for informing planning. *Ecology and Society* 19(2), 26.

Chilvers, B.L., Morgan, K.J., White, B.J. (2021). Sources and reporting of oil spills and impacts on wildlife 1970–2018. *Environmental Science and Pollution Research* 28(1), 754-762.

Dagestad, K.F., Röhrs, J., Breivik, Ø., Ådlandsvik, B. (2018). OpenDrift v1. 0: a generic framework for trajectory modelling. *Geoscientific Model Development*, 11(4), 1405-1420.

De Dominicis, M., Falchetti, S., Trotta, F., Pinardi, N., Giacomelli, L., Napolitano, E., Fazioli, L., Sorgente, R., Haley, P.J., Lermusiaux, P.F., Martins, F., Cocco, M., (2014). A relocatable ocean model in support of environmental emergencies. *Ocean Dynamic* 64, 667–688.

Elizaryev, A., Maniakova, G., Longobardi, A., Elizareva, E., Gabdulkhakov, R., Nurutdinov, A., Khakimov, R., (2018). Numerical simulation of oil spills based on the GNOME and ADIOS. *International Journal of Engineering and Technology* 7, 24–27.

Farrington, J. W. (2014). Oil pollution in the marine environment II: fates and effects of oil spills. *Environment: Science and Policy for Sustainable Development* 56(4), 16-31.

Hampton, S., Ford, R. G., CARTER, H. R., Abraham, C., Humple, D. (2003). Chronic oiling and seabird mortality from the sunken vessel SS Jacob Luckenbach in central California. *Marine Ornithology* 31, 35-41.

Jones, C.E., Dagestad, K.-F., Breivik, Ø., Holt, B., Röhrs, J., Christensen, K.H., Espeseth, M.M., Brekke, C., Skrunes, S. (2016). Measurement and modeling of oil slick transport. *Journal of Geophysical Research – Oceans* 121(10), 7759–7775.

Keramea, P., Kokkos, N., Zodiatis, G., Sylaios, G. (2023). Modes of Operation and Forcing in Oil Spill Modeling: State-of-Art, Deficiencies and Challenges. *Journal of Marine Science and Engineering* 11(6), 1165.

Keramea, P., Spanoudaki, K., Zodiatis, G., Gikas, G., Sylaios, G. (2021). Oil spill modeling: A critical review on current trends, perspectives, and challenges. *Journal of marine science and engineering* 9(2), 181.

Kotzakoulakis, K., George, S.C. (2021). Advanced oil spill modeling and simulation techniques. In *Oil Spill Occurrence, Simulation, and Behavior* (pp. 225-264). CRC Press.

Kunkel, G. (Ed.). (2012). *Biogeography and ecology in the Canary Islands*. Springer Science & Business Media.

Lehr, W., Jones, R., Evans, M., Simecek-Beatty, D., Overstreet, R. (2002). Revisions of the ADIOS oil spill model. *Environmental Modelling & Software* 17(2), 189-197.

Li, C.; Miller, J., Wang, J., Koley, S., Katz, J. (2017). Size distribution and dispersion of droplets generated by impingement of breaking waves on oil slicks. *Journal of Geophysical Research: Oceans* 122(10), 7938-7957.

Lindgren, J.F., Åberg, F., Johansson, J.R., (2020). Polluting shipwrecks in Swedish waters: investigations, risk assessment methodology and oil removal operations. In: 2020 International Oil Spill Conference, pp. 1–20.

Marta-Almeida, M., Ruiz-Villarreal, M., Pereira, J., Otero, P., Cirano, M., Zhang, X., Hetland, R. D. (2013). Efficient tools for marine operational forecast and oil spill tracking. *Marine pollution bulletin* 71(1-2), 139-151.

Mishra, A.K.; Kumar, G.S. (2015). Weathering of oil spill: Modelling and analysis, *Aquatic Procedia* 4, 435-442.

Benjamin Ivorra, S.; Gomez, A.M (2015) *Modeling and Forecasting the 2015 Oleg Noydenov Oil Spill near the Canary Islands*. Universidad de la Laguna, Tenerife.

NAS, 2022. Oil in the Sea: Inputs, Fates, and Effects, 1. The National Academies Press, Washington, DC.

Neves, A. S., Pinardi, N., Martins, F., Janeiro, J., Samaras, A., Zodiatis, G., De Dominicis, M. (2015). Towards a common oil spill risk assessment framework—adapting ISO 31000 and addressing uncertainties. *Journal of Environmental Management*, 159, 158-168.

Norma ISO 31000 versión 2009: *Gestión de Riesgos – Principios y Guías*. Traducción libre NO OFICIAL – NO Comercial, Solo con fines informativos Hoja No 1.

Olita, A., Cucco, A., Simeone, S., Ribotti, A., Fazioli, L., Sorgente, B., Sorgente, R. (2012). Oil spill hazard and risk assessment for the shorelines of a Mediterranean coastal archipelago. *Ocean & Coastal Management*, 57, 44-52.

Padron, F., Calvilla, J.M., González, J.A. (2015). Oil Spill Response Cost-Effectiveness Analytical Tool (Osreac): Application in The Canary Islands. *Journal of Maritime Research* 12(1), 61-64.

Pärt, S., Björkqvist, J. V., Alari, V., Maljutenko, I., Uiboupin, R. (2023). An ocean–wave–trajectory forecasting system for the eastern Baltic Sea: Validation against drifting buoys and implementation for oil spill modeling. *Marine Pollution Bulletin* 195, 115497.

Robertson, T., Campbell, L.K. (2020). *Oil Spill Occurrence Rates for Cook Inlet, Alaska Oil and Gas Exploration, Development, and Production. Anchorage (AK)*. US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM, 51, 78.

Röhrs, J., Dagestad, K. F., Asbjørnsen, H., Nordam, T., Skancke, J., Jones, C. E., Brekke, C. (2018). The effect of vertical mixing on the horizontal drift of oil spills. *Ocean Science* 14(6), 1581-1601.

Semedo, A. (2018). Seasonal variability of wind sea and swell waves climate along the canary current: The local wind effect. *Journal of Marine Science and Engineering* 6(1), 28.

Simanzhenkov, V., Idem, R. (2003). *Crude oil chemistry*. Crc Press, New York.

Singh, H., Bhardwaj, N., Arya, S.K., Khatri, M. (2020). Environmental impacts of oil spills and their remediation by magnetic nanomaterials. *Environmental nanotechnology, monitoring & management* 14, 100305.

Tarr, M. A., Zito, P., Overton, E.B., Olson, G.M., Adhikari, P.L., Reddy, C.M. (2016). Weathering of oil spilled in the marine environment. *Oceanography*, 29(3), 126-135.

Thrift-Viveros, D.L.; Jones, R.; Boufadel, M. (2015). Development of a new oil biodegradation algorithm for NOAA's oil spill modelling suite (GNOME/ADIOS). In Proceedings of the 38th AMOP Technical Seminar, Vancouver, BC, Canada, 2–4 June 2015; Environment Canada: Ottawa, ON, Canada, 2015; pp. 143–152.

Tkalich, P., Chan, E.S. (2002). Vertical mixing of oil droplets by breaking waves. *Marine Pollution Bulletin* 44(11), 1219-1229.

Torres, D. H. A., da Costa Dias, F., Bahiana, B.R., Haddad, A.N., Chinelli, C.K., Soares, C.A, (2020). Oil spill simulation and analysis of its behavior under the effect of weathering and chemical dispersant: A case study of the Bacia de Campos—Brazil. *Water, Air, & Soil Pollution* 231(10), 521.

Ventikos, N.P., Vergetis, E., Psaraftis, H.N., Triantafyllou, G. (2004). A high-level synthesis of oil spill response equipment and countermeasures. *Journal of hazardous materials*, 107(1-2), 51-58.

Walker, A. H., Pavia, R., Bostrom, A., Leschine, T.M., Starbird, K. (2015). Communication practices for oil spills: Stakeholder engagement during preparedness and response. *Human and Ecological Risk Assessment: An International Journal* 21(3), 667-690.

Yan, Z., Xiao, Y., Cheng, L., Chen, S., Zhou, X., Ruan, X., Ran, B. (2020). Analysis of global marine oil trade based on automatic identification system (AIS) data. *Journal of Transport Geography* 83, 102637.

Annexe II.- Current Map of the Canary Islands

