

Faculté des bioingénieurs

Vulnerability assessment of Seychelles' coastal assets to oil spills

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Abstract

Small island developing states (SIDS) are particularly vulnerable to oil pollution incidents, with little to no infrastructure available to detect, monitor or combat those spills. Seychelles archipelago is no exception to this rule as oil pollution could heavily impact its tourism industry, which accounts for about a 25% of its GDP. However, with a steady increase in maritime transport through the region as well as an increase in shipping incidents, its coastal assets vulnerability to oil spills remains largely unexplored. To tackle this deficiency, we developed a high resolution ocean circulation model of Seychelles plateau (SP) simulating ocean currents during three consecutive years (2018-2020). Those currents were used to simulate oil spill dispersal backward-in-time from six coastal areas of significant ecological and/or economical importance. That allowed us to identify which offshore areas pose the greatest threat to those sites. Our results show a clear seasonality of the offshore risk distribution that is driven by the seasonal changes in the atmospheric and oceanic circulations. We also show that the risk distribution can extend over most of the plateau during the year, which means that an oil spill coming from anywhere on the plateau could potentially impact a sensitive coastal location in less than five days. By overlaying the simulated risk distributions with areas with a high maritime traffic density, prone to shipping incidents (i.e. shallower than 10 m) and under oil exploration licences, we identified the major north-south shipping route as an area of particularly high risk to most sensitive coastal locations. We therefore advise that this particular route should be closely monitored by the local authorities.

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Acronyms

ADCP accoustic Doppler current profiler.

CMEMS Copernicus Marine Environment Monitoring Service.

DJF December to February period.

ECMWF European Centre for Medium-Range Weather Forecasts.

GDP Gross Domestic Product.

JJA June to August period.

MAE mean absolute error.

MAM March to May period.

NEMO Nucleus for European Modelling of the Ocean.

NOAA National Oceanic and Atmospheric Administration.

RMSE root mean square error.

SIDS small island developing state.

SLIM Second-generation Louvain-La-Neuve Ice-ocean Model.

SLOMO Seychelles Local Ocean Modeling and Observation program.

SON September to November period.

SP Seychelles' plateau.

Contents

1	Introduction	10
1.1	Challenges faced by small island developing states	10
1.2	Threats posed by oil spills to coastal ecosystems	11
1.3	The case of Seychelles archipelago	14
1.4	Objectives	18
2	Material and Methods	19
2.1	General approach	19
2.2	Hydrodynamic model	20
2.2.1	Study area	20
2.2.2	Model Description	22
2.2.3	Mesh generation	23
2.2.4	Model forcings	24
2.3	Oil spill dispersal model	24
2.3.1	<i>OpenOil</i> model	24
2.3.2	Oil particles release and input data	27
2.4	Oil pollution indicators	29
2.4.1	Oil spill probability and arrival time	29
2.4.2	Exposure to shipping and oil extraction	30
2.4.3	Monthly exposure time series	32
3	Results	33
3.1	Hydrodynamic model	33
3.1.1	Model validation	33
3.1.2	Ocean circulation over Seychelles' plateau	37
3.2	Minimum arrival time maps	38
3.3	Probability and exposure maps	40
3.4	Total exposure time series	45
4	Discussion	47
5	Conclusion	50
A	Hydrodynamic model validation (North of SP, January to April 2018)	57
B	Arrival time maps	58
C	Probability and exposure maps	61

List of Figures

1	Tourism as a share of GDP (%) in several SIDS (UN-OHRLLS, 2015)	11
2	Interactions between oil spills and the environment (Zhang et al., 2019)	12
3	Offshore oil spill cleanup methods (Chen et al., 2019)	13
4	Localisation of Seychelles and of Seychelles' plateau	14
5	Limits of Seychelles' plateau with the 3 main islands of Mahé, Praslin and La Digue	15
6	Tourists arrivals in the Seychelles, 2000 - 2020 (tourists/month), Data from Seychelles' National Bureau of Statistics ("Seychelles Tourist Arrivals 2021 Data 2022 Forecast 2000-2020 Historical Chart", n.d.)	16
7	Shipping density over Seychelles plateau ("MarineTraffic", 2007)	17
8	Studied coastal areas	19
9	Comparison between GEBCO and ETOPO bathymetry	20
10	Absolute error between (left) GEBCO and (right) ETOPO bathymetries and NOAA single beam data	21
11	Bathymetry considered on the SP	22
12	Mesh used for the simulations	24
13	Operations involved in the <i>OpenOil</i> model process (Hole et al., 2019)	25
14	Evolution of oil weathering, as simulated by <i>OpenOil</i> for the oil "MARINE DIESEL OIL, ESSO". The simulation has been carried out on the SP with an oil mass of 852.1kg and lasted 5 days.	26
15	Illustration of backtracking and forward-in-time oil drift simulation (Ciappa, 2021)	27
16	Oil release points for the zone of "Mahé North West Arrow, Bel Ombre"	27
17	5-days backward in time simulation initiated on 2018-01-10 for the tag of "Silhouette Marine Park".	28
18	Example of minimum arrival time map, obtained for season DJF and for the area of "Mahé North-West Arrow, Bel Ombre".	29
19	Example of probability map, obtained for season DJF and for the area of "Mahé North-West Arrow, Bel Ombre".	30
20	(a) Shipping and (b) petroleum extraction exposure areas	31
21	Example of Exposure map, obtained for season DJF and for the area of "Victoria Port, St-Anne Marine Park". It clearly shows that shipping routes east of Mahé are the most hazardous.	31
22	Validation data : SLOMO currents observation points (East of Mahé Island and North of the SP) and JCR tide gauge (North of Mahé Island).	33
23	Comparison between sea elevation simulated by SLIM2D and data observed by JCR tide gauge (WSL-925-Seychelles-Pt, 4.5°S, 55.5°E) between 2018-01-01 and 2018-04-01.	34

24	Current velocity profile (SLOMO East of Mahé observation) for the year 2018	34
25	(a) Current directions and (b) current amplitudes histogram comparison between SLIM and observation data	35
26	(a) Current's magnitude evolution according to SLOMO observations and SLIM simulations and currents velocity according to (b) SLOMO observations, (c) SLIM model and (d) the CMEMS Mercator model (SLOMO East of Mahé observation point) for the year 2018)	35
27	(a) SLOMO current velocities observations (East of Mahé island) and (b) SLIM2D simulated current velocities, only taking winds and tide forcings into account, from 2018-01-01 to 2018-04-01.	36
28	Seasonal variability of the residual ocean circulation over the SP as simulated by SLIM, averaged for each season and over the 3 years	37
29	Seasonal variability of the minimum arrival time of an oil spill reaching (left) "Mahé North-West Arrow, Bel Ombre" and (right) "Victoria Port, Saint-Anne Marine Park" coasts	38
30	Seasonal variability of the minimum arrival time of an oil spill reaching (left) "Silhouette Marine Park" and (right) "Praslin, La Digue and Curieuse Islands" coasts	39
31	Seasonal variability of the minimum arrival time of an oil spill reaching (left) "Bird Island" and (right) "Denis Island" coastlines	40
32	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Mahé North-West Arrow, Bel Ombre"	41
33	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Victoria Port, Saint-Anne Marine Park"	41
34	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Silhouette Marine Park"	42
35	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Praslin, Curieuse and La Digue Islands"	43
36	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Bird Island"	44
37	Seasonal variability of (left) probable origin of an oil spill and (right) exposure to shipping and petroleum extraction for "Denis Island"	44
38	Evolution of the vulnerability of each sensitive coastal area through a year . .	45
39	Evolution of the vulnerability of each sensitive coastal area to (up) shipping and (down) petroleum extraction through a year	46

List of Tables

1	Seychelles' protected areas (Clifton et al., 2012)	16
2	RMSE and MAE of the GEBCO and ETOPO bathymetries, compared to the NOAA observations	21
3	Oil particles releasing points and released oil particles per simulation depending on the concerned area	28
4	RMSE related to current magnitude ($RMSE_{norm}$) and to its latitudinal ($RMSE_v$) and longitudinal ($RMSE_u$) components for data provided by the SLIM simulation and by the CMEMS Mercator model.	36

1 Introduction

1.1 Challenges faced by small island developing states

Small island developing states (SIDS) are a group of small island countries that share common characteristics and problems. These include small size, low population despite a high population density, limited land resources, vulnerability to natural hazards, threatened biodiversity, high dependence on tourism and limited funds (Wong, 2011). SIDS were recognised by the United Nations as a special case both for their environment and development at the 1992 United Nations Conference on Environment and Development (United Nations, n.d.). There are nowadays 52 SIDS recognised by the United Nation Department of Economic and Social Affairs (de la Croix et al., 2013).

Economically speaking, while SIDS have the advantage to produce specialised goods and services like fisheries and tourism, they face many economic disadvantages either related to their smallness, remoteness or their economic scale (Adrianto and Matsuda, 2004). The remoteness of those states will induce transport and communication problems, hence higher transport cost and uncertainty of supply (Briguglio, 1995), monopolistic market problems and an important role of the service industry (Adrianto and Matsuda, 2004). The smallness of these countries will for its part induce problems such as limited natural resources, high import content (in relation to GDP), limited import-substitution possibilities and dependence of the export market (Adrianto and Matsuda, 2004). Moreover, the small amount of land and human resources restricts the ability of the state to diversify its exports and it then makes the country dependent on a narrow range of products and services (Briguglio, 1995). All those disadvantages tend to make SIDS economies more vulnerable to external shocks and to natural disasters.

In many of the SIDS, tourism has been the main growth sector over the past years, so much that out of the 10 most tourism-dependent countries in terms of tourism part in GDP, 9 of them are SIDS (Scheyvens and Momsen, 2008). The reason of that growth is the fact that it offers the best potential for small island. Indeed, it provides for example lower transport costs. Moreover, the geographic isolation, which is normally a disadvantage, may be in the case of tourism a advantage by making the those island states more attractive and exotic (Scheyvens and Momsen, 2008). Tourism has thus become a key component for economic development, but also for poverty reduction in those regions.

However, the tourism has the disadvantage of having a low resistance to external perturbations such as natural disasters, terrorism, diseases, oil spills, and so on. Countries are dependant on their attractiveness with international tourists, which can quickly change to other destinations. For example, an oil spill occurring near the coasts of a SIDS could then inhibit the tourist arrivals if it reaches touristic locations, which are usually located in coastal areas in these countries, which will consequently paralyse the economy of the country (Raghoo, 2021).

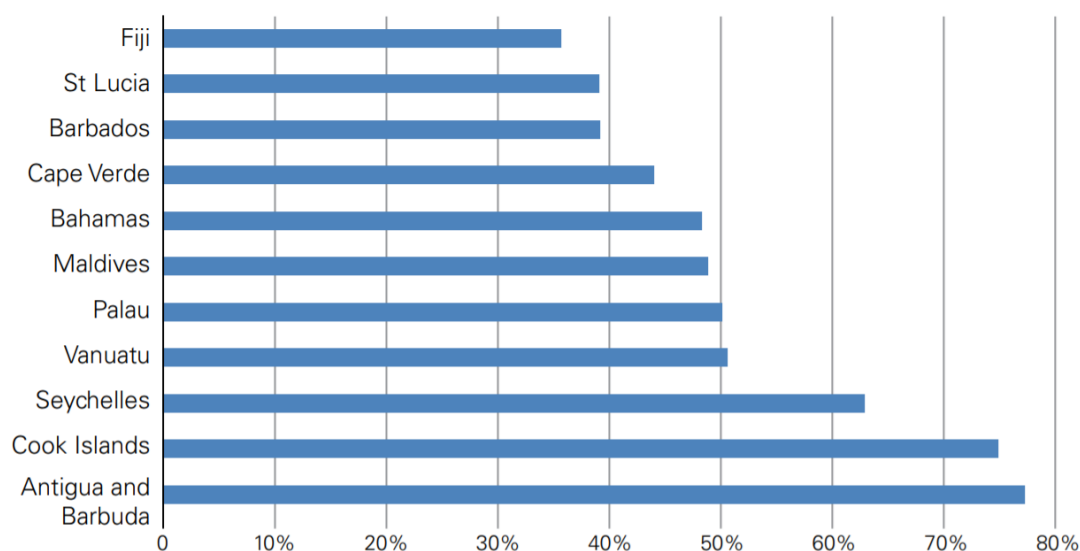


Figure 1: Tourism as a share of GDP (%) in several SIDS (UN-OHRLLS, 2015)

1.2 Threats posed by oil spills to coastal ecosystems

Oil spills can be defined as a release of a liquid petroleum hydrocarbon into the environment (especially marine areas) due to human activities or natural disasters (Li et al., 2016). They can have many sources, such as release of crude oil, spill of refined petroleum, spill of heavier fuels from ships and so on. The majority of oil spills (80%) are less than 1,000 tonnes, while only 5% of them are above 10,000 tonnes (Saadoun, 2015). Even if larger spills tend to be scarcer nowadays, still 6 million tonnes of oil enter the ocean each year (Zhang et al., 2019). The most of those spills are related to shipping and industrial activities (ITOPF, 2021).

After the oil has spilled in the sea, it starts spreading out on the sea surface as a thin layer and undergoes a series of physical and chemical processes known as weathering, which will either degrade oil or alter its properties. Some of these weathering processes take place at the sea surface and others within the water column. At the sea surface, we find processes such as evaporation, aerosolisation, photooxidation and emulsification. Evaporation is the fastest process to take place and has the greatest impact on the volume of the oil (Zhang et al., 2019). Photooxidation will transform poly-cyclic aromatic hydrocarbons into oxygenated products, which will be more resistant to biodegradation, more soluble and also more toxic (Lee, 2003). In the water column, the main processes are dissolution, sedimentation and natural dispersion. In addition to this, biodegradation can take place at the sea surface and in the water column and will depend on the chemical composition of the oil and its physical state, as well as on the state of the sea.

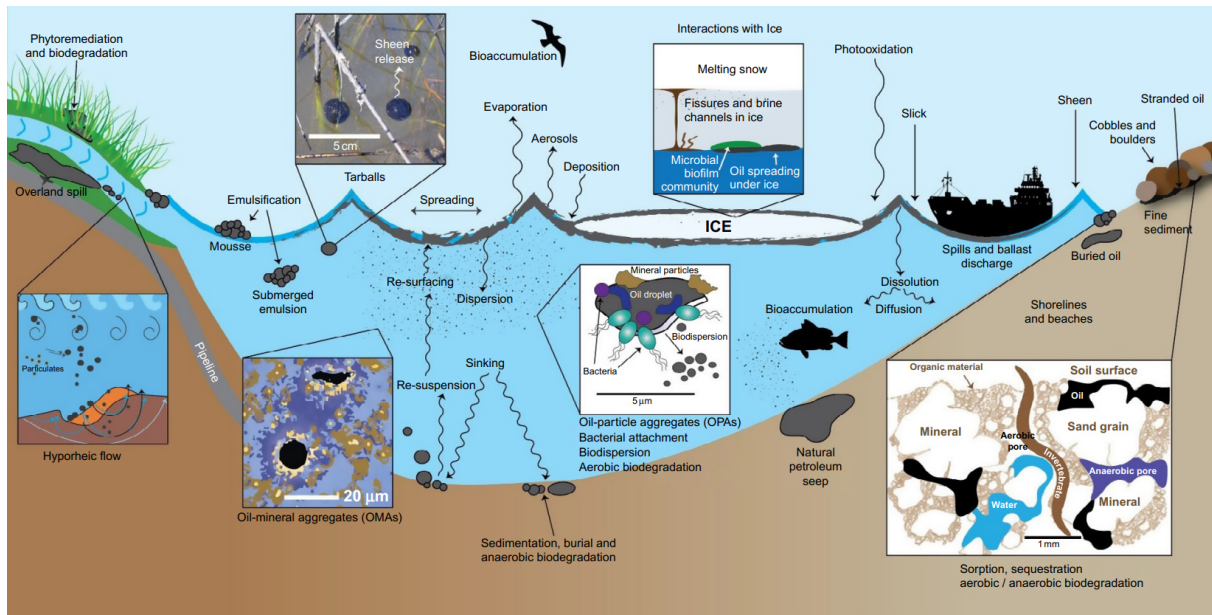


Figure 2: Interactions between oil spills and the environment (Zhang et al., 2019)

From an environmental point of view, oil spills' impacts are numerous, starting with zooplankton (at the base of the marine food chain), some of whose species ingest the oil present in the water in the form of droplets or contaminated food, which can cause the death of individuals or, for surviving individuals, abnormal development or reproductive problems (Saadoun, 2015). Seabirds are very vulnerable to oil as contact with it can reduce their flight and insulation abilities. In addition to this, frequent contact with the oil layer in an attempt to feed, contaminated food and inhalation of toxic fumes will lead to a high mortality rate among seabird species (Zhang et al., 2019). For example, during the 1989 Exxon Valdez oil spill in Alaska, which released 37,000 tonnes of oil into the sea, it is estimated that 250,000 seabirds were killed (Corn, 2010). Marine mammals are also threatened by oil spills due to the amount of contact they have with the water surface in order to breath, eat and swim. It has however been shown that physical contact with the oil can have negative, even lethal, effects on marine mammals, in addition to the ingestion of contaminated food (Zhang et al., 2019). Finally, coastal ecosystems are vulnerable to oil. Indeed, oil will settle on the soil surface and alter the chemistry and permeability of the soil. In addition, the oil will surround surfaces such as the breathing part of the roots, the stems, the seeds,... (Zhang et al., 2019) All this will lead to the death of the plant.

Economic impacts of oil spills can be of many different types : cleanup costs, environmental damages, research costs, and other costs (Li et al., 2016). In addition, there can be large losses on different industries such as tourism and fisheries, which could even face shutdown periods. For instance, fishermen have to deal with a decline of fish population. Fish raised in ponds cannot escape this oil and will hence also cause economic losses (Alvernia et al., 2021). The total cost of an oil spill will depend on several factors (spill size, location of the accident, characteristics of the state, type of the accident and the oil spilled, detection speed, cleanup methodology used, weather conditions, leakage rate of oil into the sea), but nowadays, experts agree that the predominant factor regarding this cost is the spill location (Ventikos and Sotiropoulos, 2014).

When an oil spill occurs, there are different options of cleanup shown on figure 3. Some of them can be used together in some cases.

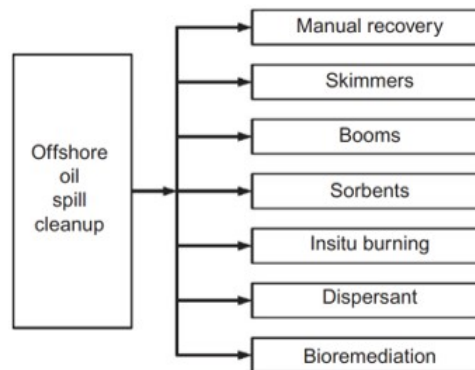


Figure 3: Offshore oil spill cleanup methods (Chen et al., 2019)

Manual recovery means that the oil will be physically removed from shorelines. Skimmers are machines able to separate the oil from the water surface without changing its physical or chemicals properties and move it to storage tanks, they are sometimes used with booms which are barriers that alleviate the spreading of the oil and so contain the oil to facilitate the cleanup. Sorbents are used to soak up the oil from the water, by mechanisms like absorption and adsorption. In Situ Burning involves a controlled burning of the oil at or near the spill. Dispersants are chemicals that will accelerate the formation of small oil droplets which will disperse throughout the the top layer of the water column. Finally, bioremediation is method that is used to increase the efficiency of natural biodegradation through the use of decomposers, green plants or their enzymes (Chen et al., 2019).

However, besides the existence of those cleanup methods, previous oil spills have shown that the responses to a spill have limitation. Indeed, a lack of specialised equipment or techniques and a lack of expertise and organisation, which are crucial in those cases, can be observed in the touched areas (Chen et al., 2019). It is then important to be able to predict, out of an area of interest or out of locations of interest, which locations will be the more at risk if an oil spill occurs so that either policies and regulations can be taken or response plans can be created in order to alleviate the potentiality of heavy impacts on those locations.

Unfortunately, SIDS, being by definition surrounded by the ocean, are highly exposed to the risk of oil spills. Indeed, the likelihood of an oil spill in the SIDS is increased by the fact that a large part of the transport takes place by ship. For example, in the Caribbean SIDS, it is estimated that 90-95% of imported goods are transported by ship (Singh et al., 2015). For instance, between 2006 and 2020, at least seven spills coming from non-tank vessels have been recorded inside SIDS territory (Hebbar and Dharmasiri, 2022). And, while large cruise ships (which may be numerous in SIDS as tourism represents an important part of their economy) can contain between 3,500 and 7,000 tonnes of oil and as large bulk carrier can have up to 7,000 tonnes of oil, the marine oil pollution in the majority of those countries remains nowadays largely unexamined (Hebbar and Dharmasiri, 2022).

Furthermore, the consequences for these states with an economy mainly based on fishing

and tourism are extremely important, as it has been seen with the Wakashio oil spill in Mauritius which occurred on August 06, 2020 (Rajendran et al., 2021) and where, at the end of the spill 125 km² of waterfront and 30 km of coastline had been touched. The numerous impacts included tainting of fishes, algal bloom in marine park, death of dolphins, loss of livelihood of fisheries, human health effects, fisheries closures and ban of recreational activities (Hebbar and Dharmasiri, 2022). However, SIDS remain largely unprotected to an oil spill risk, with generally little means of action and infrastructure to detect, monitor and combat those spills.

1.3 The case of Seychelles archipelago

The Seychelles is an independent SIDS located about 1200 km NE from Madagascar in the western Indian Ocean (Figure 4). The state is made up of 115 islands, equivalent to about 455 km² of land, of which only a third is actually inhabited (Podhorodecka, 2018). It has a population of around 87,000 people (McEwen, 2010), living mainly on the three main islands of Mahé, Praslin and La Digue.

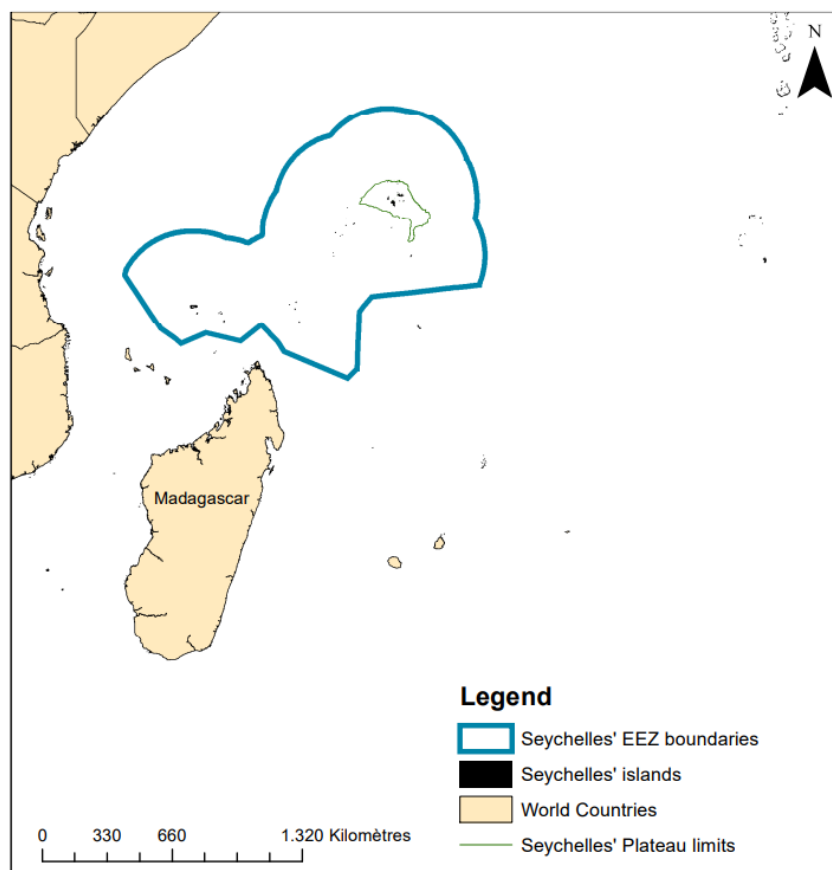


Figure 4: Localisation of Seychelles and of Seychelles' plateau

Part of these archipelago islands (including those 3 main ones) are located on a plateau (Figure 5) called the Mahé plateau or Seychelles Plateau (SP), which has an area of around 40,000 km² (Seychelles Fishing Authority, 2019) and extends for about 350 km in the latitudinal direction and about 150 km in the meridional direction (Castillo-Trujillo et al., 2021). This plateau

is rather shallow with an average depth of around 50m, which drops very quickly to depths greater than 2000m at its limits. (Castillo-Trujillo et al., 2021).

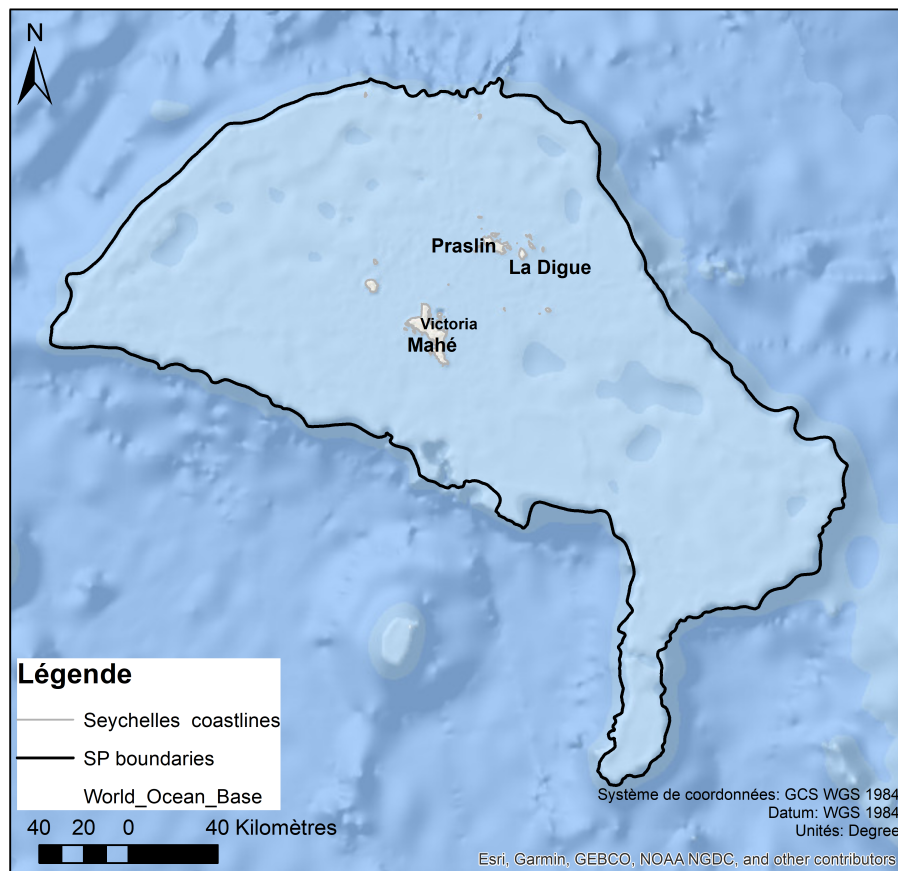


Figure 5: Limits of Seychelles' plateau with the 3 main islands of Mahé, Praslin and La Digue

The Seychelles archipelago is of great ecological interest. Indeed, due to their geographical isolation, these islands are very favourable to endemism. It is estimated that between 50 and 80% of animal species and 45% of plant species are endemic ("Bio-safety Unit | Main Details", n.d.). For example, there are 13 species and 17 subspecies of endemic birds ("Bio-safety Unit | Main Details", n.d.). A large part of the Seychelles islands are surrounded by coral reefs, which is also the habitat of many fish species (Techera, 2019).

The Seychelles' government has shown great interest in ecological conservation. The country was the first in East Africa to declare a marine protected area: St Anne Marine National Park in 1975 (Techera, 2019). Today, it has 16 protected areas (Clifton et al., 2012), representing 47% of the total area of the state, including 26,841 ha of land and 29,833 ha of marine area (Table 1), mainly owned by the government (Clifton et al., 2012).

Site	Marine area (ha)	Terrestrial area (ha)	Total Area (ha)
Sihouette	3045	1860	4905
Curieuse	1176	294	1470
St Anne	1073	380	1453
Port Launay	158	0	158
Baie Ternaie	80	0	80
Ile Coco	1	0	1
Aldabra	23,100	20,800	43,900
Cousin Island	1200	27	1227
Aride Island	0	70	70
La Digue Veuve	0	8	8
Morne Seychellois	0	3045	3045
Praslin	0	310	310
Moyenne	0	9	9
Vallée de Mai	0	20	20
6 sites: Ile Seche, Ile aux	0	15	15
Vaches Marines, Ile aux Fous, Les Mamelles, Boudeuse, Etoile			
African banks	0	3	3

Table 1: Seychelles' protected areas (Clifton et al., 2012)

Tourism has steadily increased since 1971 when the international airport of Mahé opened (Archer and Fletcher, 1996). Figure 6 shows an increase in monthly tourist arrivals each year until March 2020 (due to the cessation of international travel because of the global Covid-19 pandemic). In 2018, Seychelles had 361,844 tourist arrivals ("Tourism", n.d.).

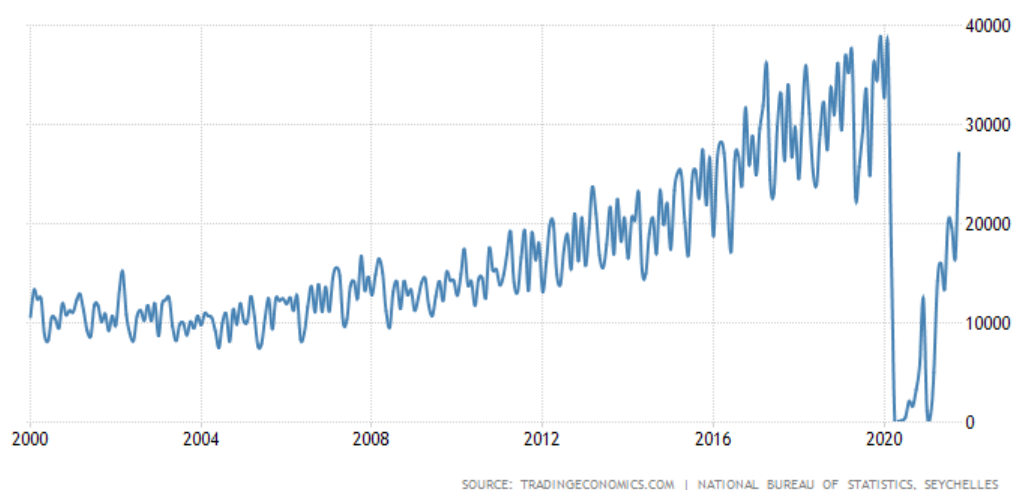


Figure 6: Tourists arrivals in the Seychelles, 2000 - 2020 (tourists/month), Data from Seychelles' National Bureau of Statistics ("Seychelles Tourist Arrivals | 2021 Data | 2022 Forecast | 2000-2020 Historical | Chart", n.d.)

Indeed, the Seychelles government's strategy is to achieve self-sustaining economic growth by securing a targeted increase in the number of tourists and money spent by each tourist. This

will be done by improving the quality of tourism offered in Seychelles, enhancing its position in international markets and involving the local population (McEwen, 2010).

Maritime traffic in the Seychelles is mainly on a North-South navigation axis crossing the SP (Figure 7). This axis passes through the port of Victoria, which is the main port of the archipelago. Ships bypass the island of Mahé from the north-east, which could make this side more threatened by a potential oil spill (“MarineTraffic”, 2007). There is also some shipping between the island of Mahé and those of Praslin and La Digue (“MarineTraffic”, 2007) as these are linked by catamarans for passenger transport. Although the port of Victoria is the main port of the state, it currently has too little capacity and is obliged to have boats berthed at its entrance. Since 1981, regulations prohibit any oil discharge into the Seychelles territorial waters (Mwebaza et al., 2009).

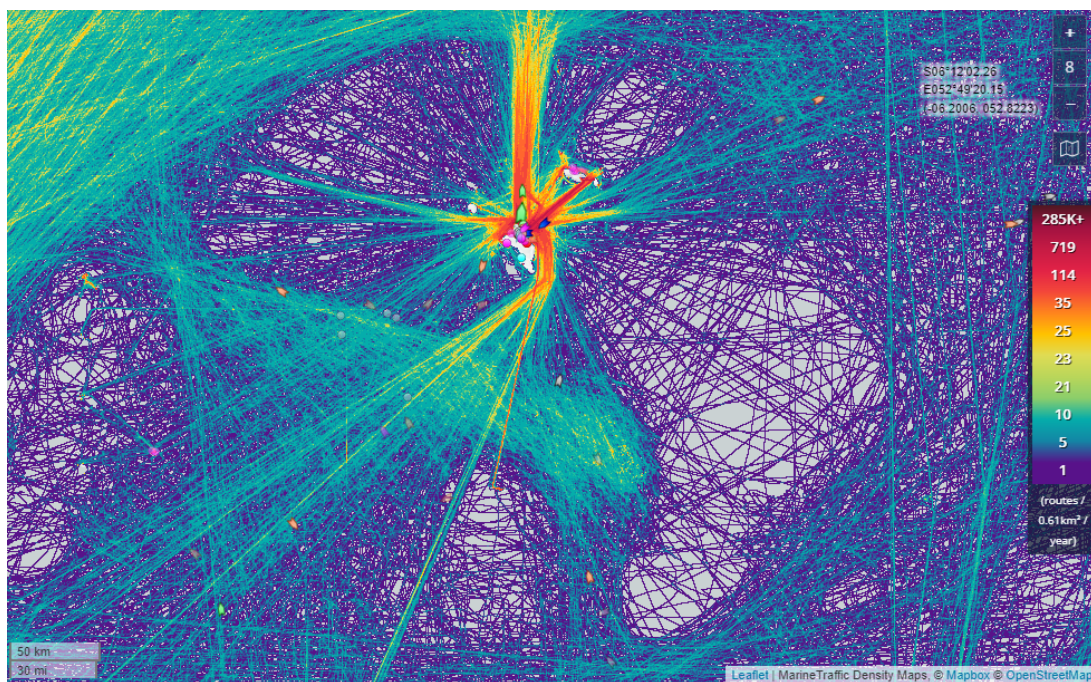


Figure 7: Shipping density over Seychelles plateau (“MarineTraffic”, 2007)

Regarding oil extraction, there is nowadays no real extraction activity running on the SP. However, two areas inside the plateau are currently under petroleum exploration licence and several wells have been made in the past, occasioning a risk of oil leakage on the plateau (“Currently Active Licenses”, n.d.). Furthermore, the Cabinet of Ministers has approved a new petroleum exploration contract in the South-East of the SP (Joubert-Lawen, 2022).

Seychelles does not have much experience nor infrastructure to manage oil spill incidents. Minor spills in the port are generally managed with dispersant (“Seychelles”, n.d.). However, tarballs are often being observed over the plateau (“Petroseychelles Technical Atlas”, n.d.), probably due to exploration well leakages. Seychelles authorities never had to deal with a major oil spill like the one that resulted from the Wakashio grounding in Mauritius in August 2020. It is however quite safe to assume that they would not be able to manage it better than Mauritian authorities.

1.4 Objectives

As said above, the Seychelles, due to ecological (high biodiversity found in the protected areas for instance), economical (high dependence on tourism industry) and geographical reasons, are, as many small island developing state, particularly vulnerable to oil spills. However, this state can only afford few infrastructure to detect, monitor or combat those spills. Hence, it is important to allocate the little resources available as efficiently as possible in order to contain oil spills as quickly as possible. The objective of this thesis is then to contribute to the development of an oil spill mitigation strategy for the Seychelles by assessing the vulnerability of Seychelles environmentally and economically sensitive coastlines to oil spills originating from shipping and petroleum extraction on the Seychelles' plateau.

To tackle this problem, the marine circulation on the SP will first be modelled over a period of three year (2018 to 2020) using the unstructured mesh ocean model SLIM. To analyse the risk of the target locations being affected by an oil spill, a reverse trajectory method will be followed by using the particle transport model *OpenDrift*, and in particular its module *OpenOil*, designed for oil spill dynamics.

2 Material and Methods

2.1 General approach

In order to investigate the vulnerability of Seychelles coastal assets to oil spill, a three-step modelling approach is used. The first step consists in modelling the hydrodynamics of the Seychelles plateau, while the second step consists in simulating the dispersion of oil particles backward in time from these sensitive areas. A last step is the computation of indicators to report the results. These different steps will be detailed in the following sections.

For this study, 6 coastal areas to asses, shown in Figure 8, have been defined according to their environmental and economic importance for the Seychelles. These include various marine parks, major tourism infrastructures and the port of Victoria, in the capital of the state.

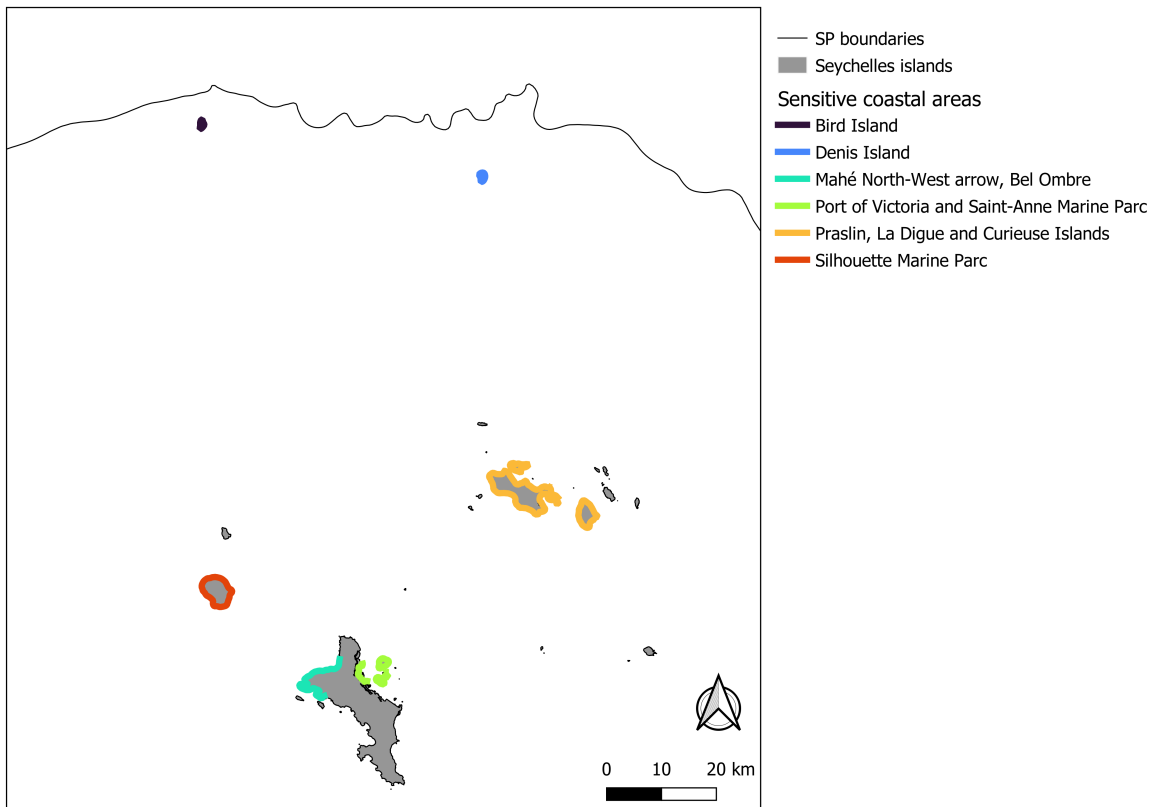


Figure 8: Studied coastal areas

The hydrodynamic modelling is performed with the SLIM¹ (Second-generation Louvain-La-Neuve Ice-ocean Model) model, and more precisely with its two-dimensional barotropic version, SLIM2D. This model numerically solves the ocean circulation governing equations with the discontinuous Galerkin finite element method on an unstructured mesh. This will allow us to obtain a better resolution in the critical areas and to limit computations in the areas of less interest by having a coarser resolution. The use of the 2D version of the model is justified by

¹<https://www.slim-ocean.be/>

the limited depth of the Seychelles plateau, which allows us to assume that the water column is relatively well mixed and that the current velocities are constant over depth.

In order to simulate oil drift dispersal, the open-source Lagrangian trajectory model OpenDrift², and more particularly its oil drift oriented module OpenOil, will be used (Dagestad et al., 2018). This model has been developed by the Norwegian Meteorological Institute and has been thoroughly parameterised and validated.

2.2 Hydrodynamic model

2.2.1 Study area

The study area extends over the Mahé plateau (SP), which has been delimited by the 400 meters isobath. The depth is around 50m over most of it.

To report the bathymetry, two data sources were available: ETOPO and GEBCO. The main advantage of the GEBCO database is that it offers a better resolution (1 arc second) than ETOPO (1 arc minute). However, GEBCO presents an area of up to 700 metres depth north of La Digue island which seems unrealistic, especially as it does not seem to have been referenced by other sources in the literature (Figure 9).

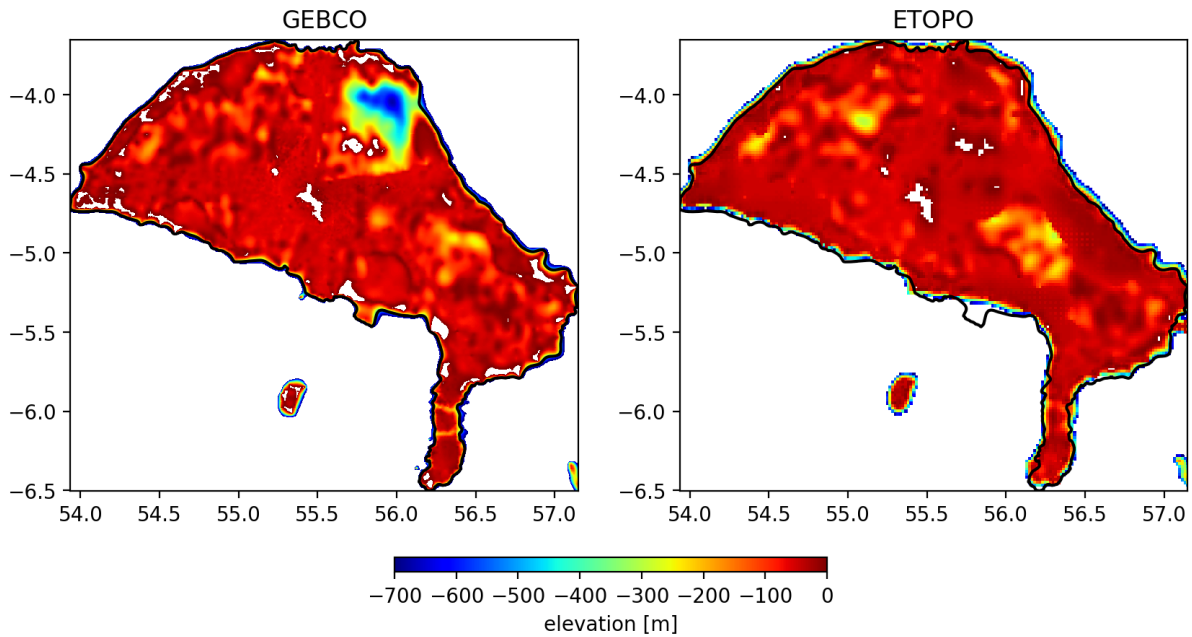


Figure 9: Comparison between GEBCO and ETOPO bathymetry

The two bathymetries have been compared using bathymetric single beam data provided by the National Oceanic and Atmospheric Administration (NOAA), which does not include data covering the 700m depth area (Figure 10). The RMSE and MAE have been computed (Table 2) and show a slightly better reliability of the GEBCO bathymetry. However, it is important to keep in mind that the reliability of the single beam data is not known. The high value of those

²<https://opendrift.github.io/>

statistics is due to the steep bathymetry gradient on the boundary of the SP.

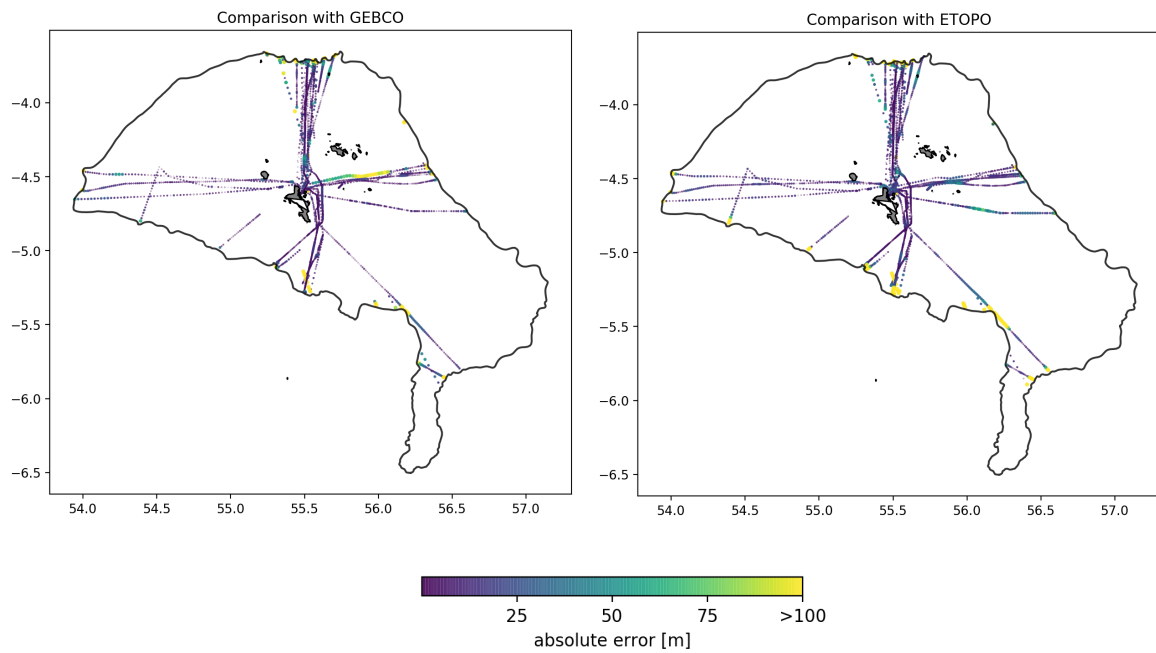


Figure 10: Absolute error between **(left)** GEBCO and **(right)** ETOPO bathymetries and NOAA single beam data

	RMSE (m)	MAE (m)
GEBCO	1092.34	389.41
ETOPO	1097.54	398.25

Table 2: RMSE and MAE of the GEBCO and ETOPO bathymetries, compared to the NOAA observations

In order to keep the bathymetry's resolution as fine as possible, we decided to use the GEBCO bathymetry over most of the area considered and use ETOPO bathymetry for the area where GEBCO provides unrealistically deep values (Figure 11).

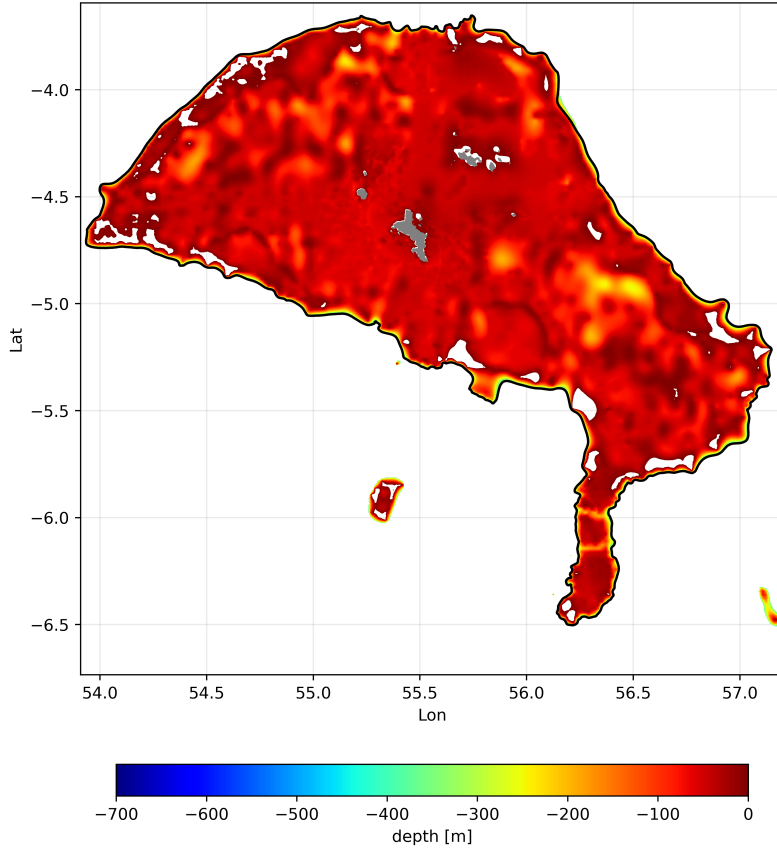


Figure 11: Bathymetry considered on the SP

2.2.2 Model Description

SLIM2D is used to solve the non-linear shallow water equations (1) and (2) for sea surface elevation (η) and horizontal current velocity ($\mathbf{u}$) :

$$\frac{\partial \eta}{\partial t} + \nabla \cdot (H\mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla (\mathbf{u}) = -f\mathbf{e}_z \times \mathbf{u} - g\nabla \eta - \frac{g\|\mathbf{u}\|\mathbf{u}}{C^2 H} - C_s \frac{|\mathbf{u} \cdot \nabla H|}{H} \cdot \mathbf{u} + \frac{\boldsymbol{\tau}}{\rho H} + \frac{1}{H} \nabla \cdot [H\nu(\nabla \mathbf{u})] \quad (2)$$

where $H = h + \eta$ is the water column depth, h the reference depth and η the variation from this reference depth. f is the Coriolis factor and $\mathbf{e}_z$ is a unit vector pointing upwards in the vertical direction. g is the gravitational acceleration, C_s is the numerical slope coefficient, $\boldsymbol{\tau}$ is the surface wind stress, ρ is the water density and ν is the horizontal viscosity.

C is the Chézy bottom stress and is defined by the Chézy-Manning formula $C = \frac{H^{1/6}}{n}$ (de Brye et al., 2010), where n is the Manning coefficient, which has been set to $0.025\text{m}^{-1/3}\text{s}$, corresponding to a sandy seabed. The surface wind stress $\boldsymbol{\tau}$ is defined as a function of the air density (ρ_{air}), a drag coefficient (C_D) and the wind speed (ms^{-1}) at 10m above sea surface ($\mathbf{u}_{10}$) following the equation (4) (Cushman-Roisin et al., 2011) :

$$\boldsymbol{\tau} = \rho_{air} C_D \|\mathbf{u}_{10}\| \mathbf{u}_{10} \quad (3)$$

The wind speed data used here come from the ERA5 (ECMWF Reanalysis 5th Generation) dataset released by ECMWF (European Centre for Medium-Range Weather Forecasts). The wind drag coefficient is parameterised in order to take into account the fact that stronger winds will induce rougher sea surfaces and increase the wind influence :

$$C_D = 10^{-3}(\alpha + \beta \|\mathbf{u}_{10}\|) \quad (4)$$

where $\alpha = 0.63$ and $\beta = 6.6 \cdot 10^{-2} \text{ m}^{-1}\text{s}$. Those values are acceptable for a range of wind speeds between 3 and 21 ms^{-1} (Geernaert, 1987).

Finally, the horizontal viscosity is computed following the Smagorinsky parametrisation (Smagorinsky, 1963) :

$$\nu = (\tilde{C}\Delta)^2 \sqrt{2 \left(\frac{\partial u}{\partial x} \right)^2 + 2 \left(\frac{\partial v}{\partial y} \right)^2 + \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2} \quad (5)$$

where Δ is the mesh element size, $\tilde{C}$ is the Smagorinsky coefficient, set to 0.1 (Lambrechts et al., 2008), (u, v) are the components of the depth integrated velocity $\mathbf{u}$ and (x, y) are the cartesian coordinates of the horizontal plan.

For this study, we used a timestep $\Delta t = 900\text{s}$ exported the results every hour. Since the shallow water equations can not be solved with a negative depth H , a minimum depth has been set to $h = 10\text{m}$ alongside the SP boundary, decreasing progressively to reach $h = 3\text{m}$ from 15km away from the SP boundary. It has been chosen to simulate the hydrodynamics from January 2018 to December 2020 (included). The model has been set to start 15 days before this period in order to let it some time adjusting itself.

2.2.3 Mesh generation

As mentionned above, the SLIM model allows the equations to be discretized on an unstructured mesh made of triangles. The mesh used to simulate the hydrodynamics over the SP has a resolution which depends on the distance to the coasts following the Equation (6) :

$$\Delta_c(d) = \begin{cases} l_0 & \text{if } d \leq d_0 \\ l_0 \frac{d_1-d}{d_1-d_0} + l_1 \frac{d-d_0}{d_1-d_0} & \text{if } d_0 < d < d_1 \\ l_1 & \text{otherwise} \end{cases} \quad (6)$$

With Δ_c the mesh size, d the distance to the coast, $l_0 = 200\text{m}$, $l_1 = 4.5\text{km}$, $d_0 = 3\text{km}$ and $d_1 = 75\text{km}$.

The resulting mesh can be seen on Figure 12. Close to the coast, the minimum resolution is 140m and it increases further away to reach 4.6km as maximum resolution.

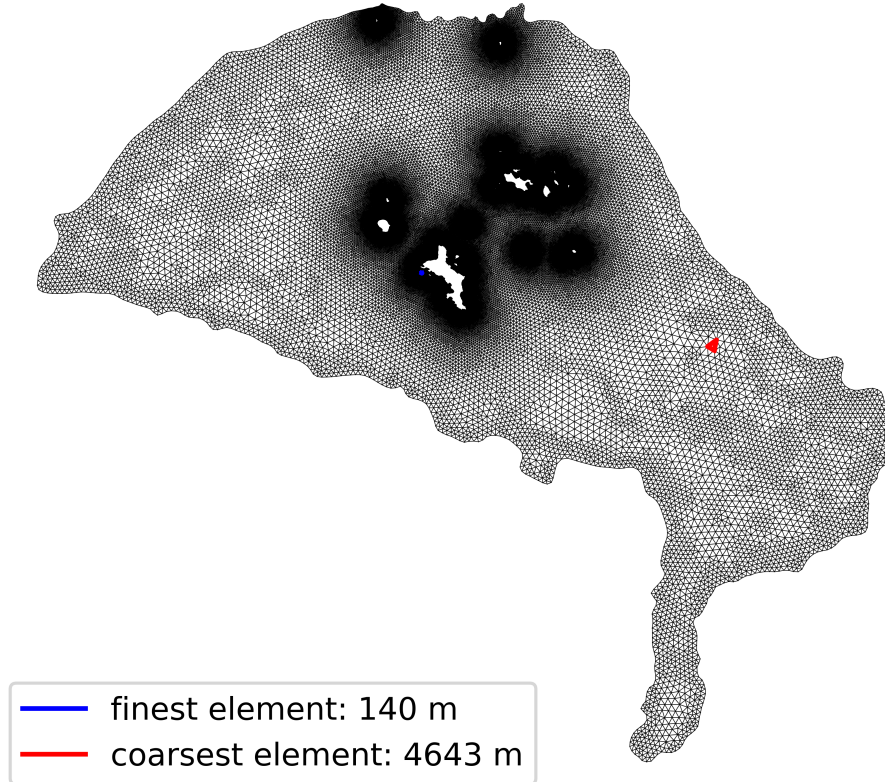


Figure 12: Mesh used for the simulations

2.2.4 Model forcings

The SLIM model needs three external forcings in order to have as realistic outputs as possible : winds, tides and large-scale currents at the boundaries of the SP. As said in Section 2.2, the wind data come from the ERA5 (ECMWF Reanalysis 5th Generation) dataset released by ECMWF, which has a spatial resolution of 30km. The tides data, tidal velocities and elevations have been provided by the baroclinic model TPXO9³ which has a spatial resolution of 1/30°.

The sea surface elevation and the 3D ocean velocity at the boundaries of the SP come from the Operational Mercator global ocean analysis and forecast system⁴, provided by the CMEMS (Copernicus Marine Environment Monitoring Service), which has a grid resolution of 1/12°. In order to keep SLIM modeled velocities close to the Mercator ones around the plateau boundary, a relaxation term is added to the model, with a maximum relaxation at the plateau limit. As the SP is of shallow depth, no relaxation inside it has been implemented, besides a 20km band around the boundary of the plateau.

2.3 Oil spill dispersal model

2.3.1 *OpenOil* model

As mentioned before (Section 2.1), the module *OpenOil* from the model *OpenDrift* has been used to simulate the drift of oil particles under the combined effect of currents, wind and waves.

³<https://www.tpxo.net/global/tpxo9-atlas>

⁴https://resources.marine.copernicus.eu/product-detail/GLOBAL_ANALYSIS_FORECAST_PHY_001_024/INFORMATION

This open-source model has a source-code written in python. It has been developed at the Norwegian Meteorological Institute. In this model, oil particles are considered as Lagrangian elements representing a certain volume of oil (Dagestad et al., 2018 ; Röhrs et al., 2018). The different steps involved in the *OpenOil* model process are shown in Figure 13.

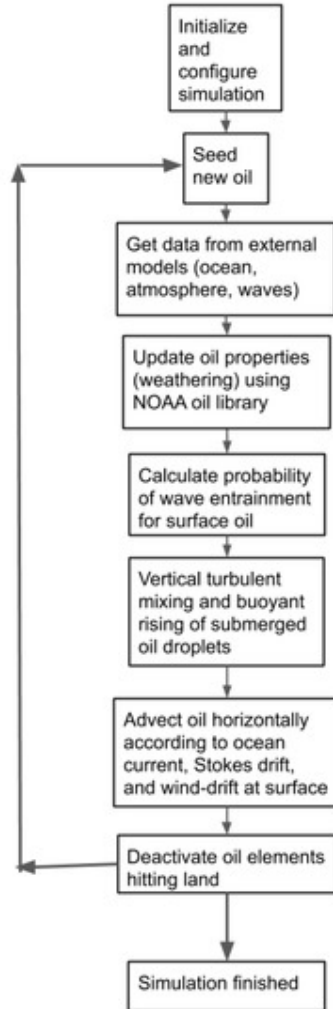


Figure 13: Operations involved in the *OpenOil* model process (Hole et al., 2019)

Concerning the horizontal transport of oil particles, three processes are taken into account: the ocean currents, the Stokes drift and the wind velocity (Hole et al., 2019). Firstly, oil droplets, either at the surface or submerged, are all drifted along with the ocean current. The particles are also driven by the surface wave propagation, taken into account with the Stokes drift, parameterised at 1.5% of the wind velocity at the surface of the water column and decreasing with depth (Breivik et al., 2016). The horizontal transport is finally characterised by a surface wind factor applied on elements at the surface of the water column and equal to 2% of the surface wind velocity. Hence, by adding the Stokes drift to the surface wind velocity, 3.5% of the surface wind velocity will be added to the ocean current (Ardhuin et al., 2009).

In terms of vertical transport, two processes are taken into account. The first process is the fact that oil particles at the surface can be entrained by breaking waves into the ocean (Hole et al., 2019), depending on wind and wave conditions. The occurrence of this phenomenon

is a probability depending on time (Jones et al., 2016). Another parameter important for the vertical transport is the buoyancy of the oil elements : this parameter is calculated with the physical properties of the oil (viscosity and density), seawater temperature, salinity and the size of the droplets (Tkalich and Chan, 2002).

As for the weathering of the oil, the type of the oil has to be taken into account in order to have a reliable model representing the degradation of the oil. *OpenOil* uses the NOAA oil database (NOAA, n.d.), which counts almost 1000 different oil types from around the world and their physical properties.

For this thesis, the oil type has been set to "MARINE DIESEL OIL, ESSO" (35° API) in order to have a representative oil type considering that, over the SP, the most probable origin of an oil spill would be from shipping. This oil type has a density of 852.067 kg/m^3 and a viscosity of $7.724 \times 10^{-6} \text{ mPa.s}$. Salinity has been set by default to 40 PSU, while for each month, temperature has been set to the average temperature of the month. The droplet size and the entrainment rate have been set to their default values (Dagestad et al., 2018).

The evolution of the oil and it's different weathered fractions through time after it's release can be seen on Figure 14. The surface oil decreases by half during the first few hours of the simulation due to phenomenon of evaporation, which is the fastest, and the most impacting on oil volume, weathering process.

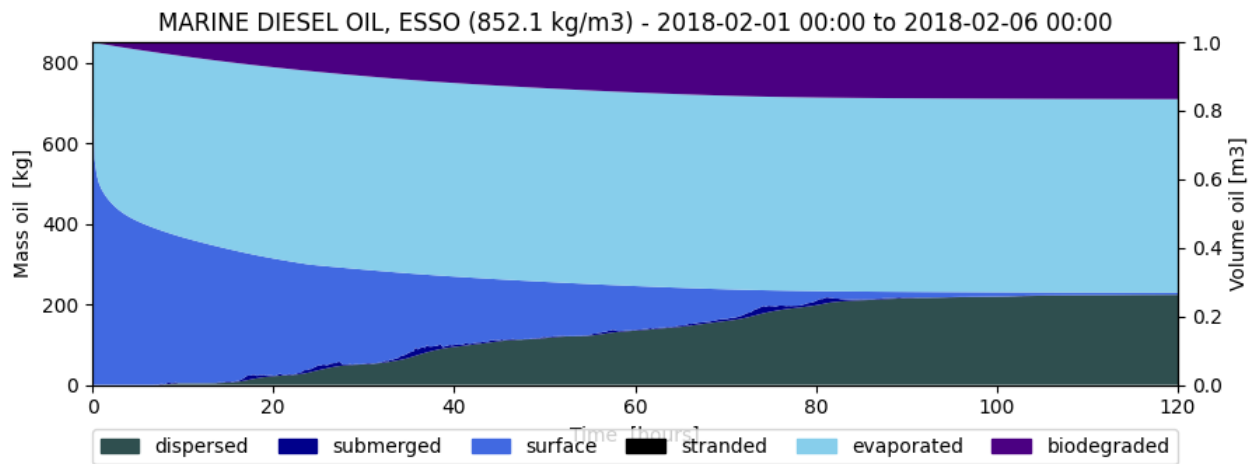


Figure 14: Evolution of oil weathering, as simulated by *OpenOil* for the oil "MARINE DIESEL OIL, ESSO". The simulation has been carried out on the SP with an oil mass of 852.1kg and lasted 5 days.

For this thesis it has been chosen to simulate the oil drift using backtracking method instead of forward in time tracking method. As can be seen on Figure 15, a forward-in-time tracking releases oil particles at a source and track those particles up to their destinations, while, with a backtracking simulation, elements are released at a destination point and are tracked backward in time in order to find a probable source of an oil spill reaching this destination point (Ciappa, 2021).

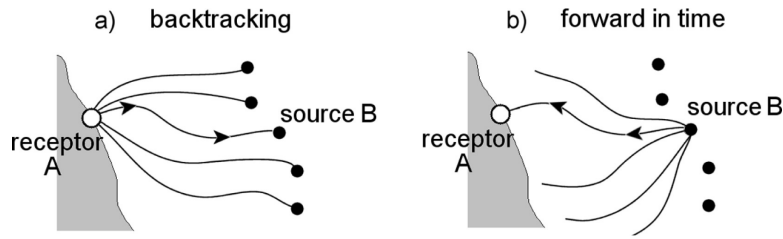


Figure 15: Illustration of backtracking and forward-in-time oil drift simulation (Ciappa, 2021)

The disadvantage to the forward-in-time method is that, since there is no specific area that would be the source of an oil spill, it would require a lot of particles, and therefore a lot of computational capacity, to obtain an acceptable result. This method is therefore not efficient in a case like this one (Anselain, 2021). The backtracking method will allow us to identify areas from which an oil spill could reach the sensitive area studied in this thesis and to estimate the time it would take for an oil spill originating from any source point to reach those areas.

However, the main inconvenient with the backtracking method is that weathering process applying on oil particles cannot be taken into account and so the mass of the oil particles remains constant. It is why the duration of each backtracking simulation is 5 days. It is assumed that, after this time laps, most of the oil has been weathered. This assumption is confirmed by Figure 14, where it can be seen that almost no surface oil remains at the end of the 5-days forward-in-time simulation.

2.3.2 Oil particles release and input data

As mentioned above (Section 2.1), Six environmentally and ecologically sensitive coastal areas have been defined in order to asses their vulnerability to oil spills. In order to run backtracking simulations, oil particles were released from points of 0.004 decimal degrees away from coastlines and 0.002 decimal degrees apart from each other, as it is illustrated for the "Mahé North West Arrow, Bel Ombre" area on Figure 16.

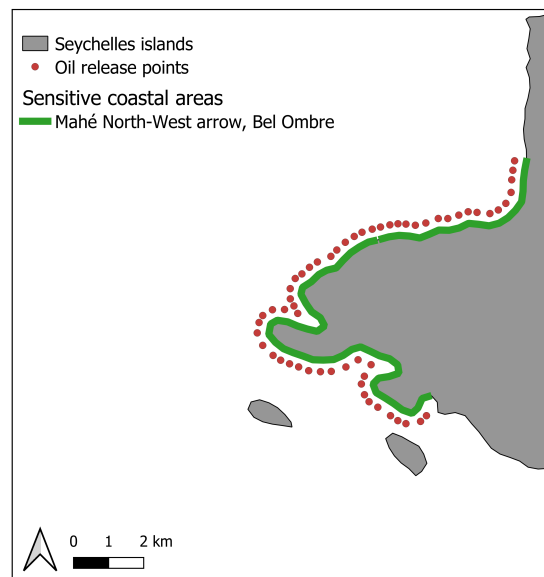


Figure 16: Oil release points for the zone of "Mahé North West Arrow, Bel Ombre"

For each release point and for each simulation, 15 oil particles were seeded. Table 3 summarises the number of particles released per location. For each studied area, a backward-in-time simulation was launched at each day of the year, simulating a period of 5 days (see Section 2.3.1).

Location	Release points	Particles released / simulation	total number of particles released over the 3 years
Mahé North West Arrow, Bel Ombre	58	870	939,600
Victoria port, St-Anne Marine Park	87	1305	1,409,400
Silhouette Marine Park	65	975	1,053,000
Praslin, La Digue and Curieuse Islands	228	340	367,200
Bird Island	21	315	340,200
Denis Island	22	320	345,600

Table 3: Oil particles releasing points and released oil particles per simulation depending on the concerned area

To be able to run properly, *OpenOil* needs current, wave and wind data over the SP. While current velocities come from the SLIM2D hydrodynamic model described above (Section 2.2), wind data come from the ERA5 dataset (see Section 2.2.4).

As mentioned above, a backward-in-time simulation has been carried out for each day of the 3 years studied for this thesis and for each sensitive coastal area. Starting from the releasing points along the coastlines, the oil particles are followed backward in time to deduct its trajectory. As an oil spill originating along one of the backward trajectories could also be a threat for the sensitive areas, it is important to evaluate oil particles all along their drifts. An example of a backward-in-time simulation output can be seen on Figure 17. The active points represent the position of still active oil particles at the end of the simulation, while the stranded points represent no-more active element positions. It is important to note that, as the SLIM simulation only takes place over the SP, oil particles reaching the Plateau's boundaries are deactivated (and referenced as 'stranded').

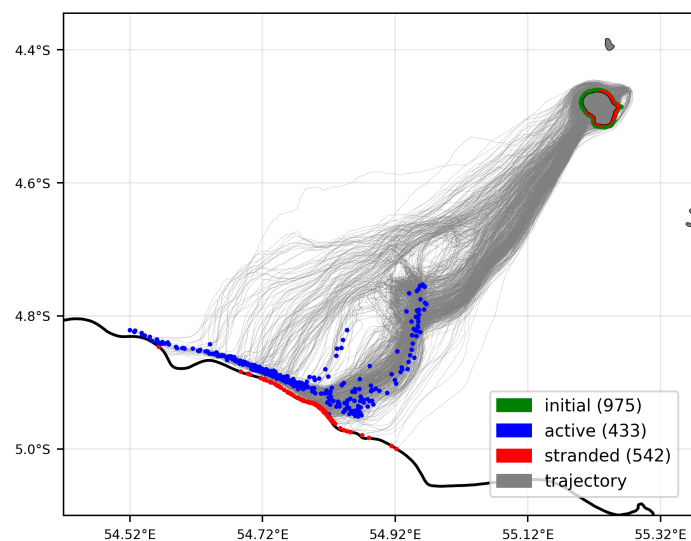


Figure 17: 5-days backward in time simulation initiated on 2018-01-10 for the tag of "Silhouette Marine Park".

2.4 Oil pollution indicators

2.4.1 Oil spill probability and arrival time

From the outputs of the backward-in-time simulations, two types of maps can be created : a minimum arrival time map and a map indicating the portion of oil released per pixel that will reach the sensitive coastal area (Ciappa, 2021). For those two types of map, the backtracking simulation results for each day of a given set of month (December to February period (DJF), March to May period (MAM), June to August period (JJA) or September to November period (SON)) and over the 3 simulated years have been combined in order to take into account as much variability in the input data as possible. The spacial resolution of those maps has been set to 0.005 decimal degree ($\sim 500\text{m}$).

As its name suggests, the minimum arrival time map shows the minimum time it would take an oil spill to reach the studied area and is, hence, a worst case scenario indicator. As the simulations are done backward in time, the shortest time for one of the trajectories to reach a pixel from the oil particle releasing points is assessed. This process is realised for each day of the set of months over 3-year period and the results are combined to have a single map representing the shortest time between the beginning of an oil spill in a pixel and the time it reaches sensitive coastlines. The results have been grouped into 5 categories in order to have an easier map to read : < 1 day , 1 to 2 days, 2 to 3 days, 3 to 4 days and 4 to 5 days. This procedure has been executed for each coastal area studied (Section 2.3.2). An example of minimal arrival time map is shown on Figure 18 (green entities represent the oil particle releasing points).

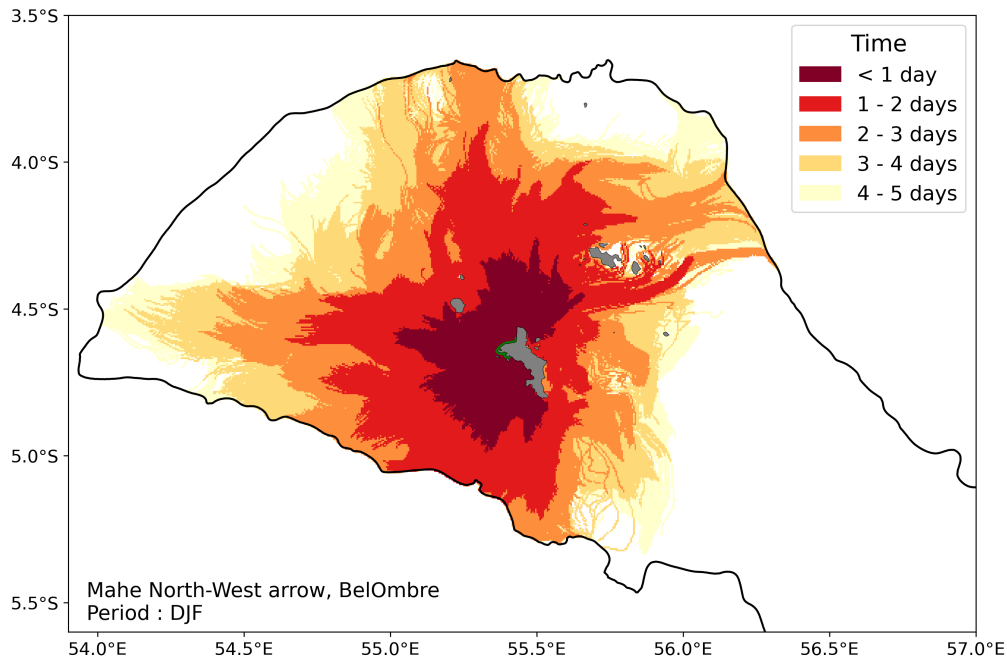


Figure 18: Example of minimum arrival time map, obtained for season DJF and for the area of "Mahé North-West Arrow, Bel Ombre".

The second vulnerability indicator map, called 'probability map', shows the fraction of all trajectories (in %) crossing a 0.005x0.005 decimal degree pixel during a 5-day backward-in-

time simulation. It hence highlights the offshore area from where an oil spill would be most likely to reach a sensitive coastal asset (Ciappa, 2021). The simulations starting at each day of the set of months assessed and over the 3 years are combined to include forcing variability, obtaining as final result a map highlighting areas most likely to be an oil spill source, knowing the location it reached, as can be seen on Figure 19.

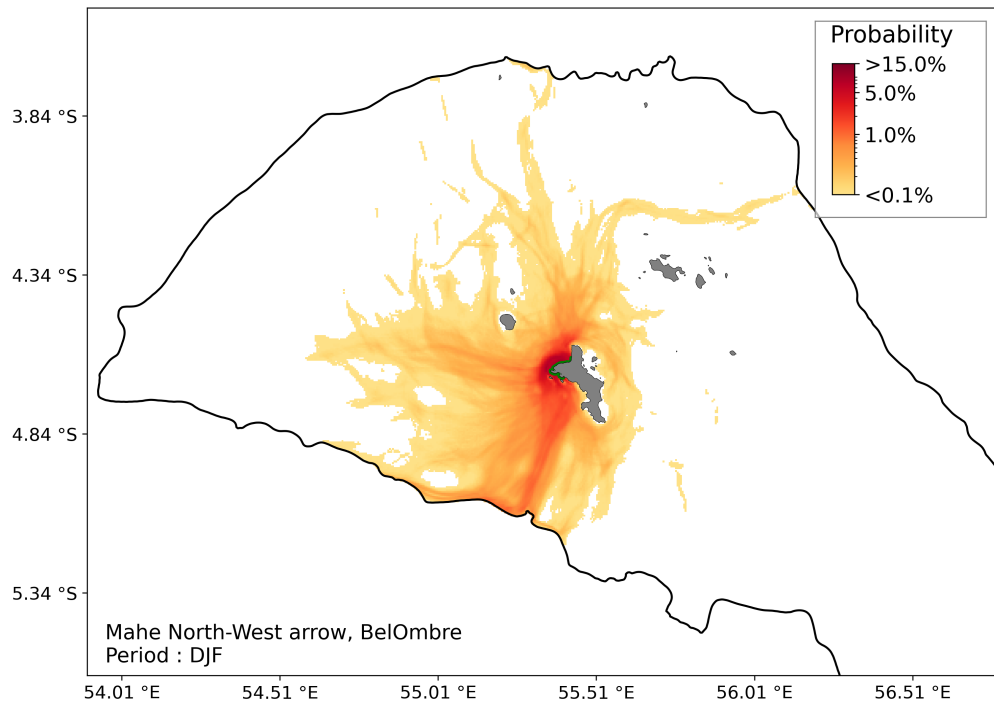


Figure 19: Example of probability map, obtained for season DJF and for the area of "Mahé North-West Arrow, Bel Ombre".

2.4.2 Exposure to shipping and oil extraction

On the Seychelles plateau, the most likely source of an oil spill is an intentional or unintentional release of fuel at sea from a ship. The density of shipping on the plateau follows a predominantly north-south axis passing by the port of Victoria, as well as a few shipping lanes linking the main islands together ("MarineTraffic", 2007). In addition, another likely source of oil spills is related to petroleum extraction on the plateau. As of today, there are no oil extraction platforms on the plateau, but 2 areas are currently under exploration licences and 3 boreholes have been drilled in the past, which may pose a risk of oil spills ("Currently Active Licenses", n.d.). In addition, a new oil investigation contract in the south-east of the plateau has recently been approved by the Cabinet of Ministers (Joubert-Lawen, 2022). Those exposure area considered can be seen on Figure 20 (a) and (b).

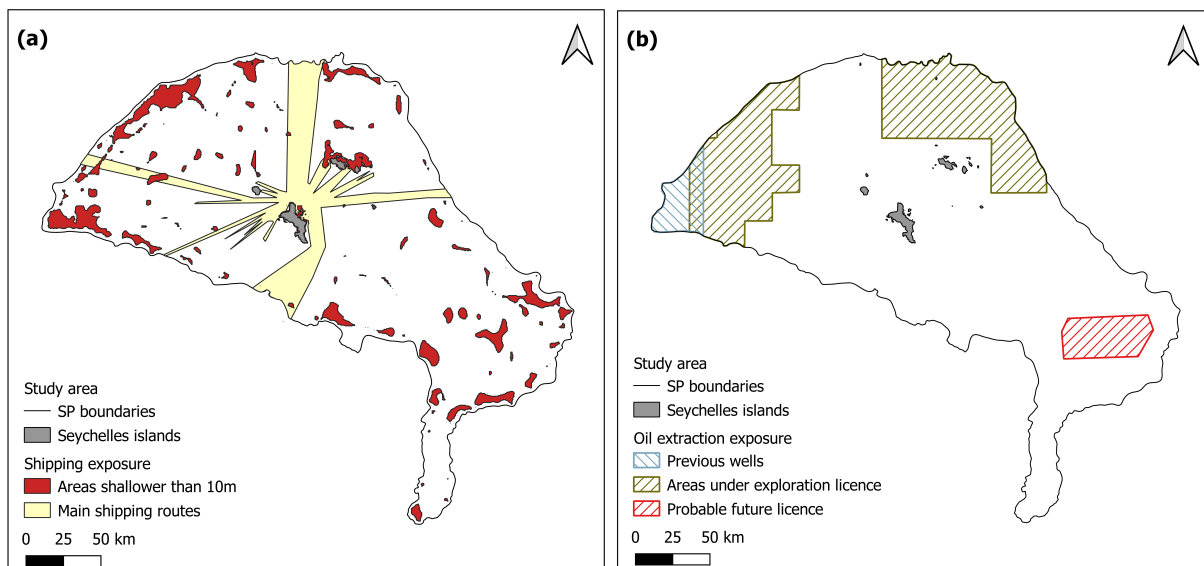


Figure 20: (a) Shipping and (b) petroleum extraction exposure areas

To take account of exposure to shipping, these areas of high shipping density, areas less than 10m deep and therefore more prone to boat groundings, areas of previous oil exploration and drilling and the likely future oil exploration area have been overlaid on the previous probability maps, resulting to 'exposure maps' (Figure 2.4.2) which indicate the areas that need to be monitored as priority to allow early detection of oil spills that could reach sensitive coastal assets.

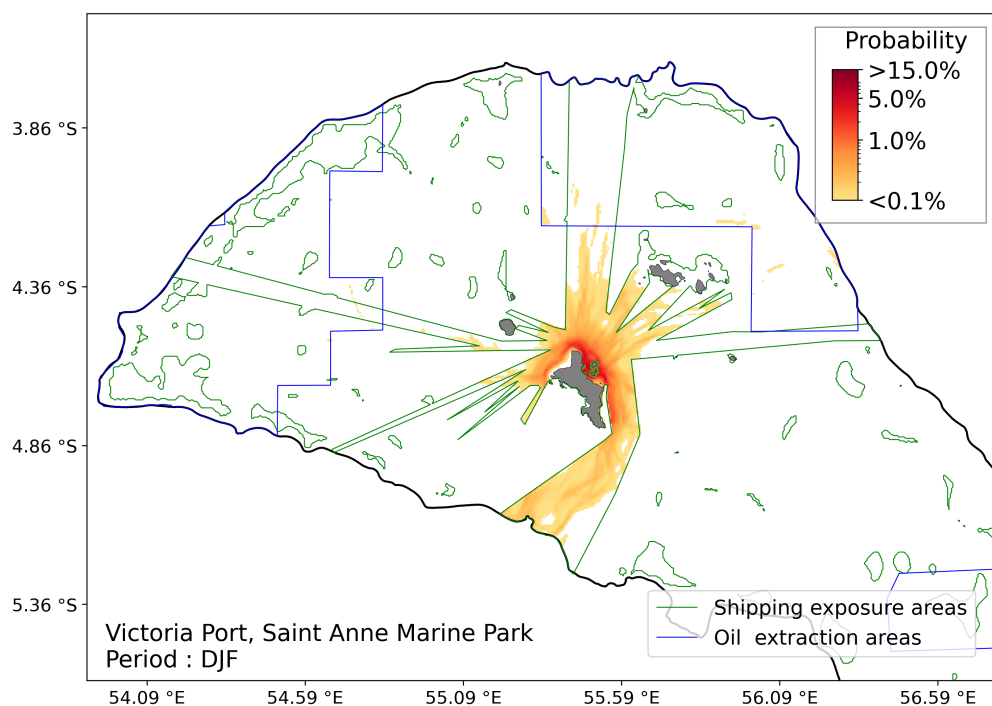


Figure 21: Example of Exposure map, obtained for season DJF and for the area of "Victoria Port, St-Anne Marine Park". It clearly shows that shipping routes east of Mahé are the most hazardous.

2.4.3 Monthly exposure time series

In order to assess each sensitive coastal area's vulnerability through time, values of each pixel from probability maps can be summed, resulting in a unique time-dependent indicator for each coastal area considered highlighting its exposure to oil spill. These time series have been averaged over 2018, 2019 and 2020. The same can be done to assess the exposure to oil extraction and shipping by only taking into account pixels within the respective exposure areas.

3 Results

This section is dedicated to the results obtained with the SLIM and *OpenOil* models. The different maps produce will show the spatial and temporal variability of sensitive coastal areas vulnerability to oil spill. Those maps have been produced by averaging indicators value over the 3 years studied in order to be as representative as possible. For the sake of clarity, the results have been gathered into 4 seasons: DJF, MAM, JJA, SON.

3.1 Hydrodynamic model

3.1.1 Model validation

While the hydrodynamic simulations have been carried out over 3 years, the model has only been validated for the year 2018, as more observation data were available for that year. Two types of data were used to validate the model : sea surface elevation observations from a tide gauge North of Mahé island and provided by the Space, Security and Migration directorate of the European Commission Joint Research Center (JRC) and current velocities observed by acoustic Doppler current profilers (ADCP) deployed by the Seychelles Local Ocean Modeling and Observation program (SLOMO) at the East of Mahé and at the North of the plateau(Castillo-Trujillo et al., 2021). Figure 22 shows the positions of these observation points.

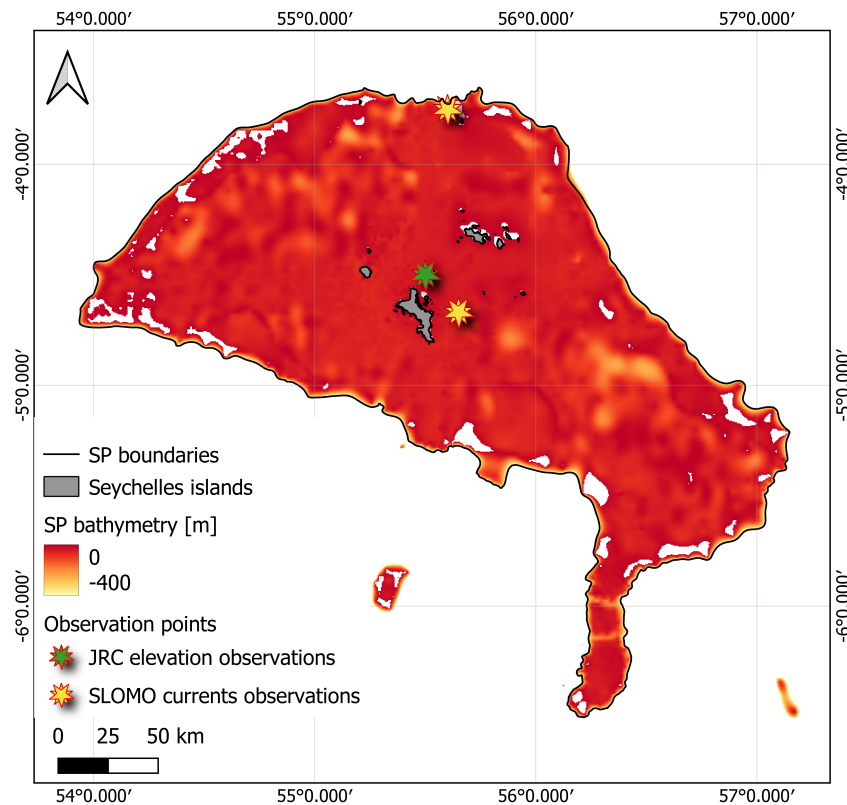


Figure 22: Validation data : SLOMO currents observation points (East of Mahé Island and North of the SP) and JCR tide gauge (North of Mahé Island).

Regarding the sea surface elevation, the model reproduces quite well what is observed at the JCR tide gauge, as it is shown on Figure 23 (representing 3 months of simulation (2018-01-01 to

2018-04-01), for the sake of clarity). It can however be seen that the the SLIM model generates a sea surface elevation with a slightly smaller amplitude than what is really observed. The RMSE obtained between simulated and observed values over the all year is of 7.5cm.

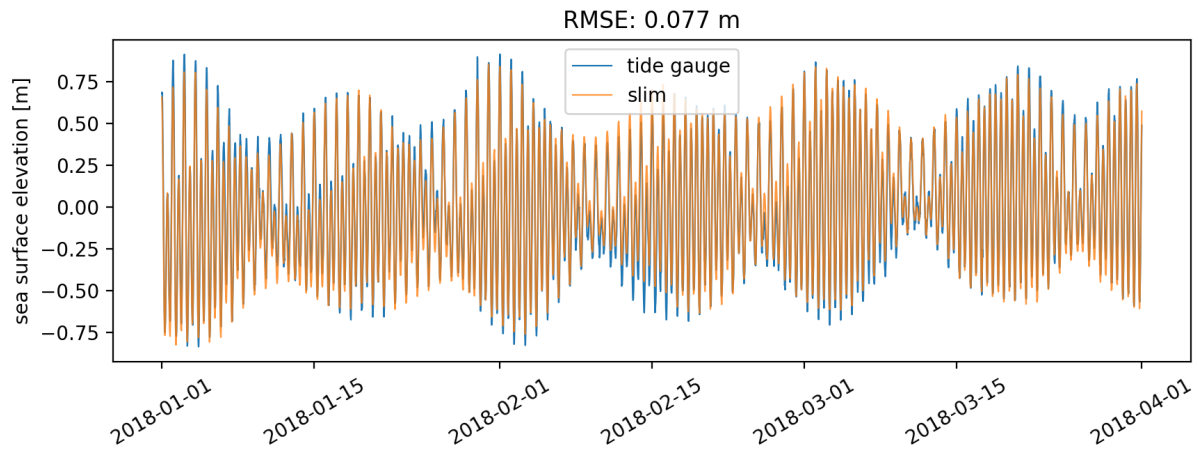


Figure 23: Comparison between see elevation simulated by SLIM2D and data observed by JCR tide gauge (WSL-925-Seychelles-Pt, 4.5°S, 55.5°E) between 2018-01-01 and 2018-04-01.

Regarding the current velocities, as the northern ADCP only recorded data from January to April 2018, this section focuses here on the data observed by the ADCP located East of Mahé Island. An interested reader can find the validation obtained with northern observations in Appendix A. It first can be seen with the observed data that the velocities are quite homogeneous in the water profile (Figure 24), which confirms that the use of the 2D version of SLIM is reasonable.

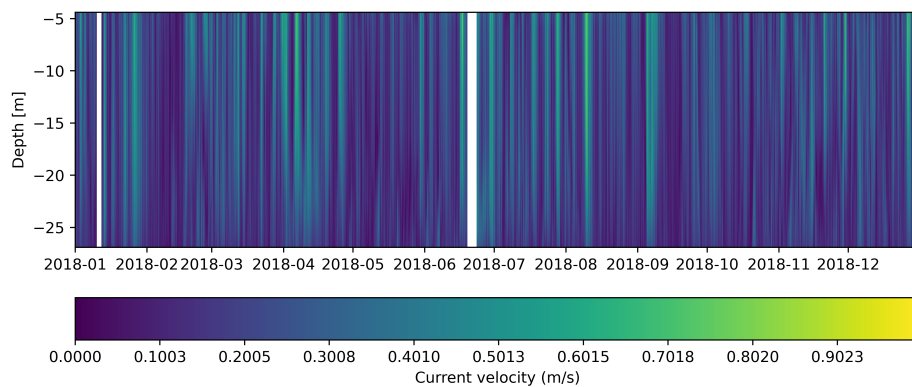


Figure 24: Current velocity profile (SLOMO East of Mahé observation) for the year 2018

Overall, the current velocity amplitudes simulated by SLIM remain in the same range as the observed values but the model tends to overestimate these values (Figure 25(a)), especially towards the beginning of the year (Figure 26(a)). In terms of the direction of the currents, the simulation seems less reliable (Figure 26(b) and (c)), predicting more northward currents than what is observed by the SLOMO ADCP (Figure 25(b)).

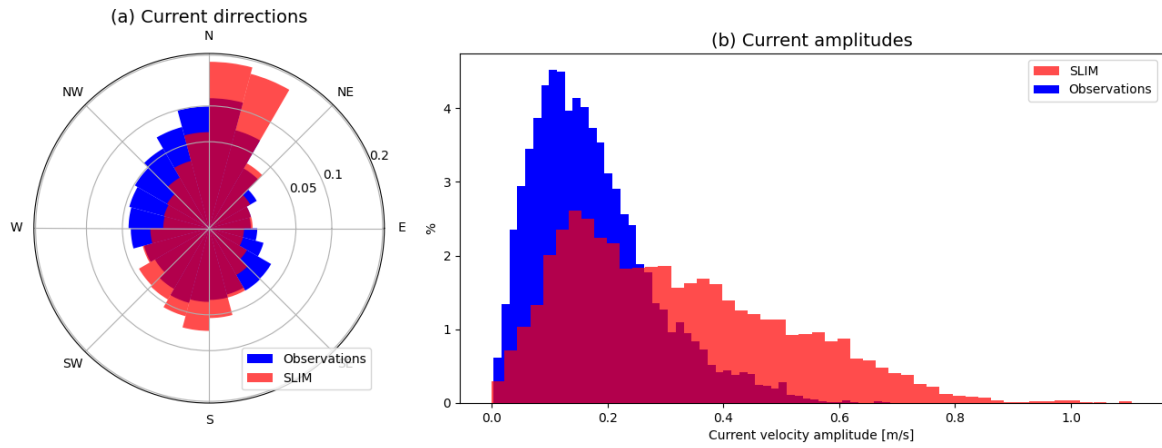


Figure 25: **(a)** Current directions and **(b)** current amplitudes histogram comparison between SLIM and observation data

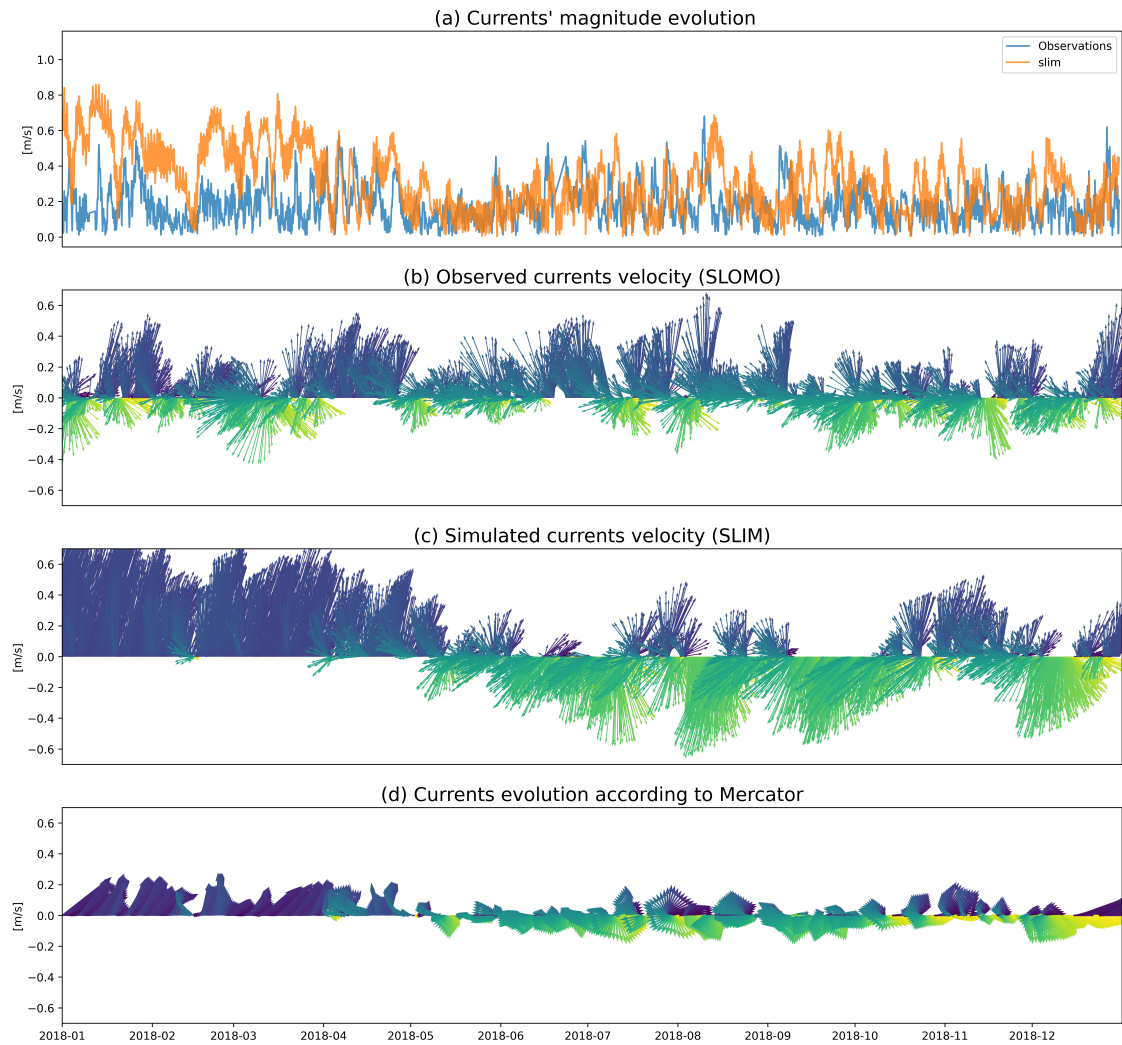


Figure 26: **(a)** Current's magnitude evolution according to SLOMO observations and SLIM simulations and currents velocity according to **(b)** SLOMO observations, **(c)** SLIM model and **(d)** the CMEMS Mercator model (SLOMO East of Mahé observation point) for the year 2018)

The differences between simulated and observed data can also be expressed numerically by the root mean square error (RMSE), which has been calculated for the all year for the SLIM simulation and for the CMEMS Mercator model, as it can be seen in Table 4. Those values highlight the fact that the slim simulation tends to overestimate the latitudinal component (v) of current velocities, as higher RMSE values are found for this component than for the longitudinal component.

	$RMSE_{norm}$ (m/s)	$RMSE_u$ (m/s)	$RMSE_v$ (m/s)
Mercator model	0.095	0.17	0.128
SLIM simulation	0.24	0.163	0.36

Table 4: RMSE related to current magnitude ($RMSE_{norm}$) and to its latitudinal ($RMSE_v$) and longitudinal ($RMSE_u$) components for data provided by the SLIM simulation and by the CMEMS Mercator model.

The results of the simulation seem to be highly dependent on the Mercator simulation (Figure 26(d)). Indeed, although also influenced by a tidal component as well as by the winds, the currents at the edge of the plateau appear to be the most influential factor for the currents simulated by the model. However, this large influence seems to be important to thoroughly reproduce the ocean circulation over the SP. Indeed, when simulating the hydrodynamics while only taking tidal and wind forcings into account (Figure 27), the outputs do not reproduce the seasonal variation of current directions nor current amplitudes that can be observed. Furthermore, current amplitudes seem to be strongly underestimated. This hydrodynamic simulation is therefore largely based on the reliability of the data provided by Mercator.

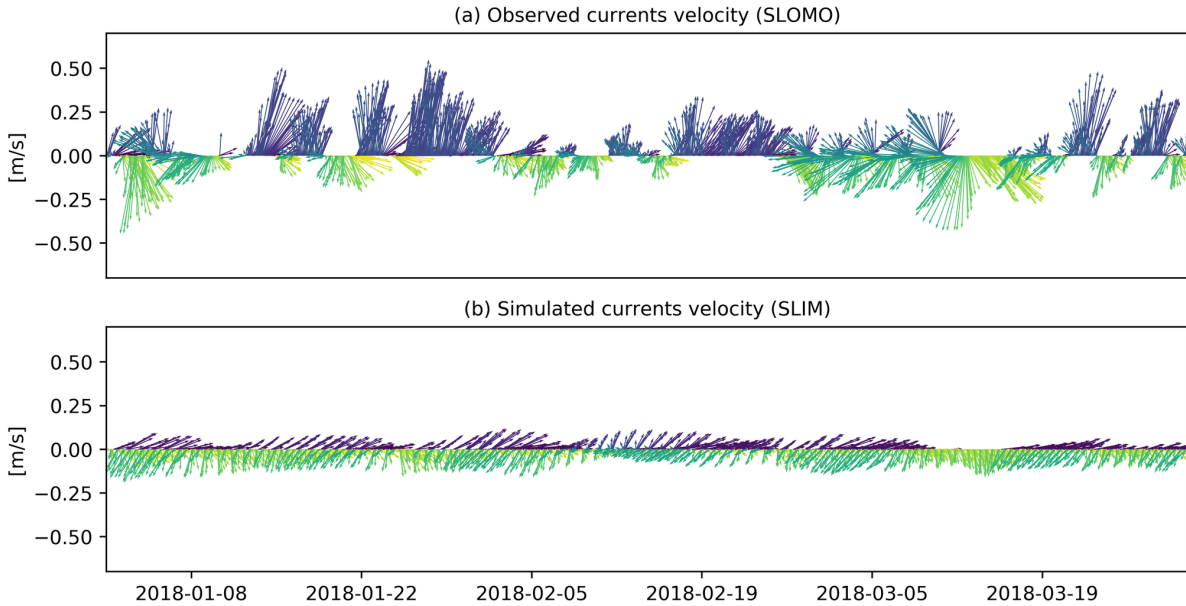


Figure 27: **(a)** SLOMO current velocities observations (East of Mahé island) and **(b)** SLIM2D simulated current velocities, only taking winds and tide forcings into account, from 2018-01-01 to 2018-04-01.

3.1.2 Ocean circulation over Seychelles' plateau

The ocean circulation over the SP is influenced by two monsoon seasons : the southeast monsoon during the austral winter (June to September), where winds blow in the northwesterly direction, and the northwest monsoon during the austral summer (December to March), where winds blow in the southeasterly direction. Between those two monsoon seasons, winds tend to be weaker and more variable (Castillo-Trujillo et al., 2021 ; Schott and McCreary, 2001). The SLIM model tends to simulate currents flowing in the northeasterly direction during the northwest monsoon, with current velocities up to between 0.6 and 0.8 m/s at the peak of the monsoon, and in the Southwesterly direction during the southeast monsoon, with velocities up to 0.5 m/s (Figure 28). During the inter-monsoon seasons, currents tend to be weaker and more variable than during the monsoon seasons.

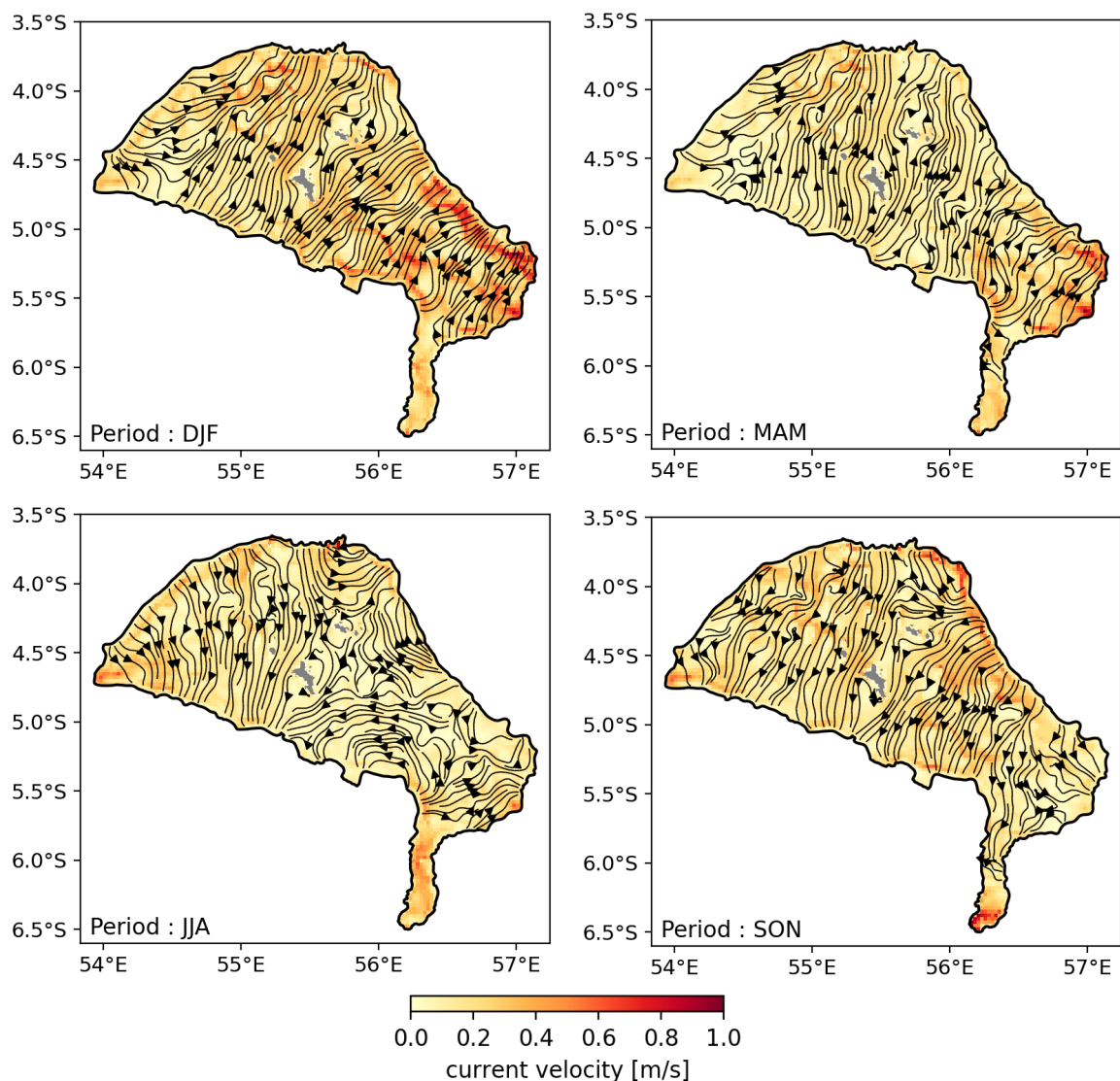


Figure 28: Seasonal variability of the residual ocean circulation over the SP as simulated by SLIM, averaged for each season and over the 3 years

3.2 Minimum arrival time maps

As described in Section 2.4.1, those maps represent the minimal time it would take for an oil spill originating from a certain offshore area to reach the sensitive coastal asset considered. In general, as the currents are quite strong on the plateau, the oil dispersion will be more influenced by the residual oceanic circulation than by the tidal component. It is indeed observed that an oil spill spreads more rapidly eastward during the austral summer and westward during the austral winter. However, it can be seen that, for each processed period and for each coastal area assessed, an oil spill could reach those coastal locations from a large part of the plateau within less than 5 days. For the sake of brevity, only the 2 extreme seasons, DJF (NW monsoon) and JJA (SE monsoon) are shown here. The interested reader is referred to appendices section to see the entire result for the four seasons.

Regarding "Mahé North-West Arrow, Bel Ombre" and "Victoria Port, Saint-Anne Marine Park" (Figure 29), those two coastal areas are geographically opposed on the island of Mahé and will present slightly different results. As expected, the first one tend to be more sheltered from an oil spill occurring east of the plateau, while the second one would be more protected from an oil spill originating from the west part of the SP. During the DJF season, an oil spill occurring at the western plateau boundary could reach "Mahé North-West Arrow, Bel Ombre" coasts in less than 2 days. In the JJA period, an oils spill starting at the eastern and the southwestern plateau boundaries could reach "Victoria Port, Saint-Anne Marine Park" coasts within 1 to 4 days.

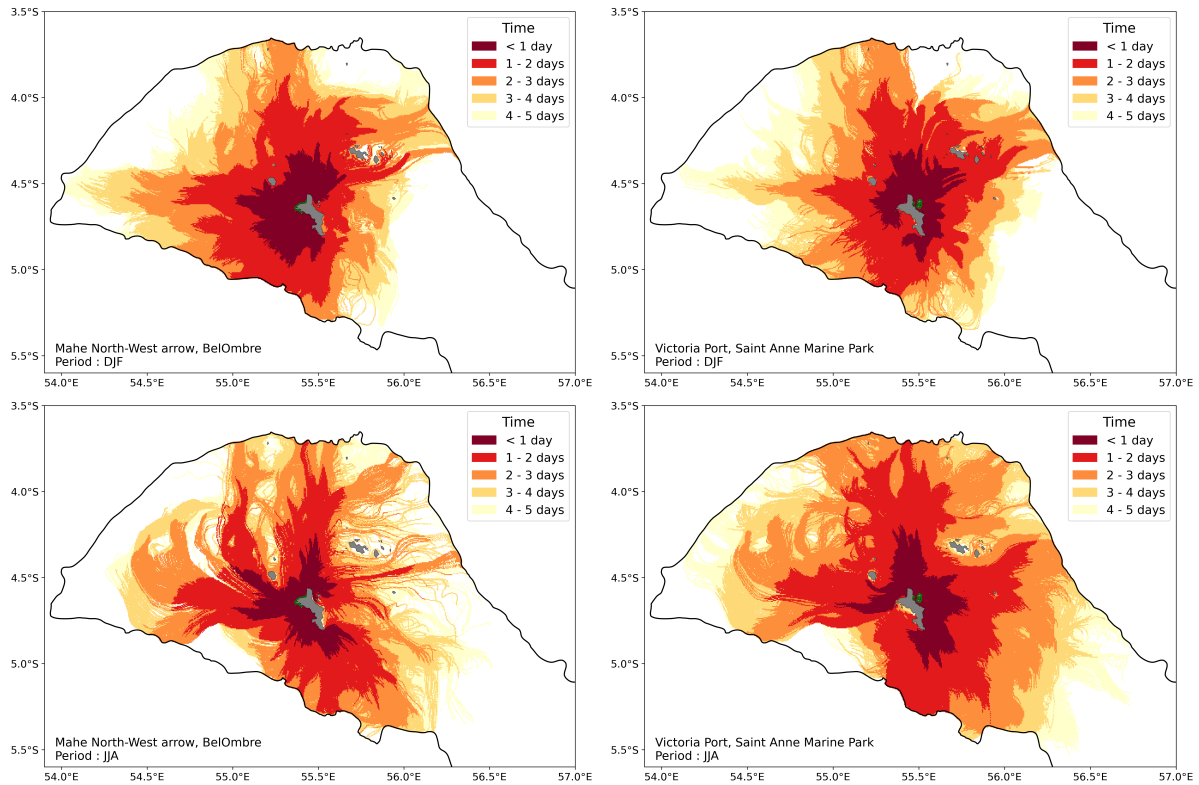


Figure 29: Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Mahé North-West Arrow, Bel Ombre" and **(right)** "Victoria Port, Saint-Anne Marine Park" coasts

"Silhouette Marine Park" and "Praslin, La Digue and Curieuse Islands" coasts (Figure 30) share the particularity to be geographically exposed from all sides. Their exposure will hence vary more with the ocean circulation. They will indeed be more exposed to spills coming from the western side of the plateau during the austral summer and from the eastern side during the austral summer. It can also be seen that for both studied areas, an oil spill occurring near the port of Victoria, which is the main port of the Seychelles state, could reach their coasts within between 2 and 4 days.

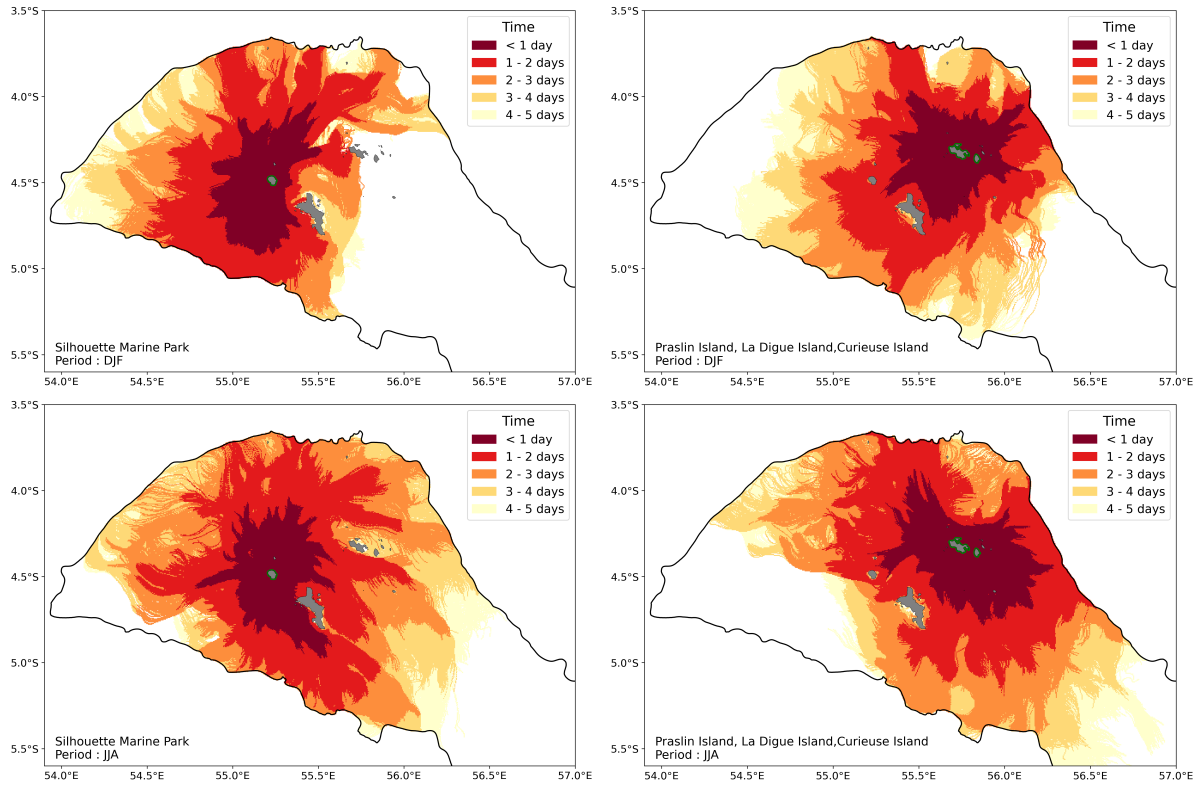


Figure 30: Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Silhouette Marine Park" and **(right)** "Praslin, La Digue and Curieuse Islands" coasts

Finally, concerning Bird and Denis islands' coastline (Figure 31), the same general pattern of oil dispersion as for the previous sensitive coastal areas can be seen. However, as those islands are located near the SP boundary, delimiting the oil drift model operating zone, a large proportion of oil particles backtracked leaves the plateau in less than one day of simulation.

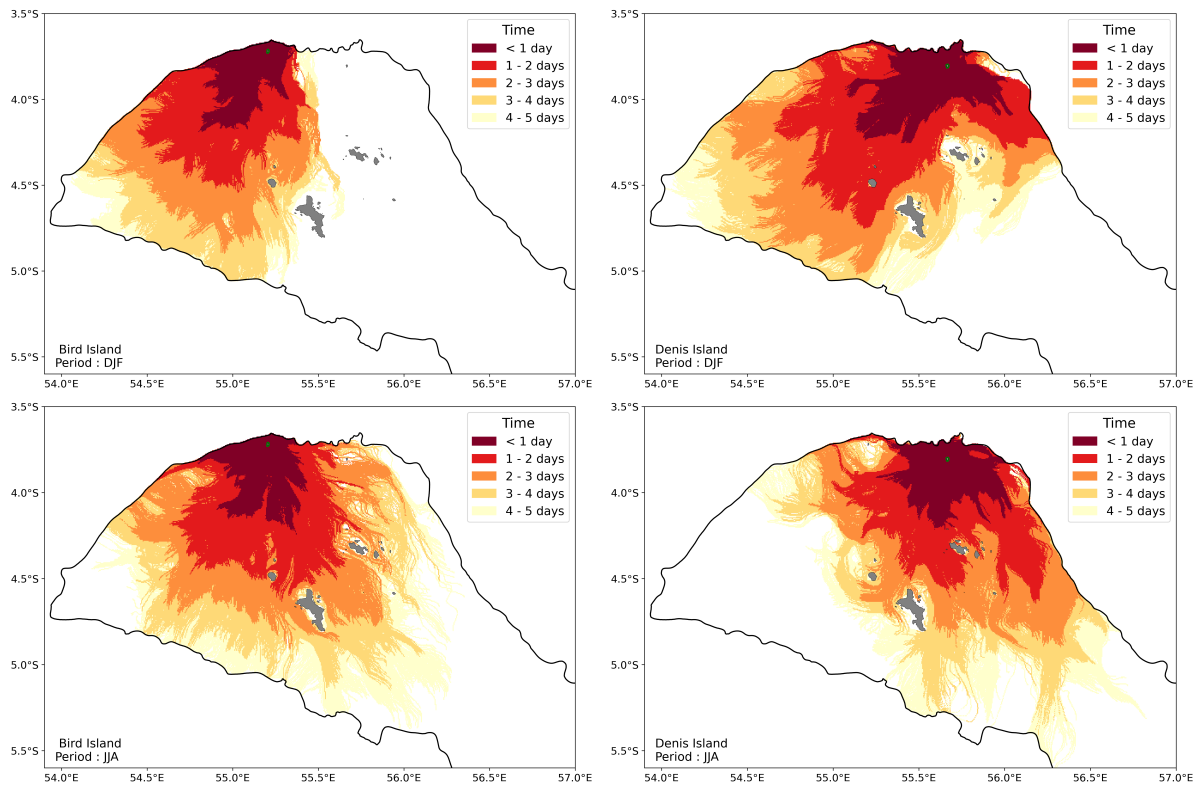


Figure 31: Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Bird Island" and **(right)** "Denis Island" coastlines

3.3 Probability and exposure maps

The probability maps represent the most probable locations from where an oil spill could reach the studied coastal areas (Section 2.4.1). Those maps can be overlaid with locations prone to shipping accidents and to oil extraction, resulting in exposure maps (Section 2.4.2).

Regarding the Northwest shore of Mahé and the coasts of Bel Ombre (Figure 32), the extent of the probability zone tends to be at its greatest during the austral summer (SE monsoon), which is characterised by north-easterly currents that will expose these coastal areas to oil spills from the western part of the plateau. This then decreases until the southern winter (NW monsoon), when these study areas are geographically sheltered from dispersed oil spills by south-westerly currents. For this area, oil spill exposure is mainly due to maritime traffic, as the probability area only marginally intersects with oil extraction areas throughout the year.

In contrast to the previous study area, Victoria Harbour and St Anne Marine Park (Figure 33, being located east of Mahé, will be more exposed during the southern winter to oil spills starting east of the SP, but it appears to remain more exposed during the southern summer than the previous area was during the southern winter. Although those coastal areas seem to be more exposed to oil exploration areas than the previous ones (especially during SON season), they remain more exposed to shipping routes. During the austral winter, a spill threatening area can be observed heading north along the north-to-south major shipping route.

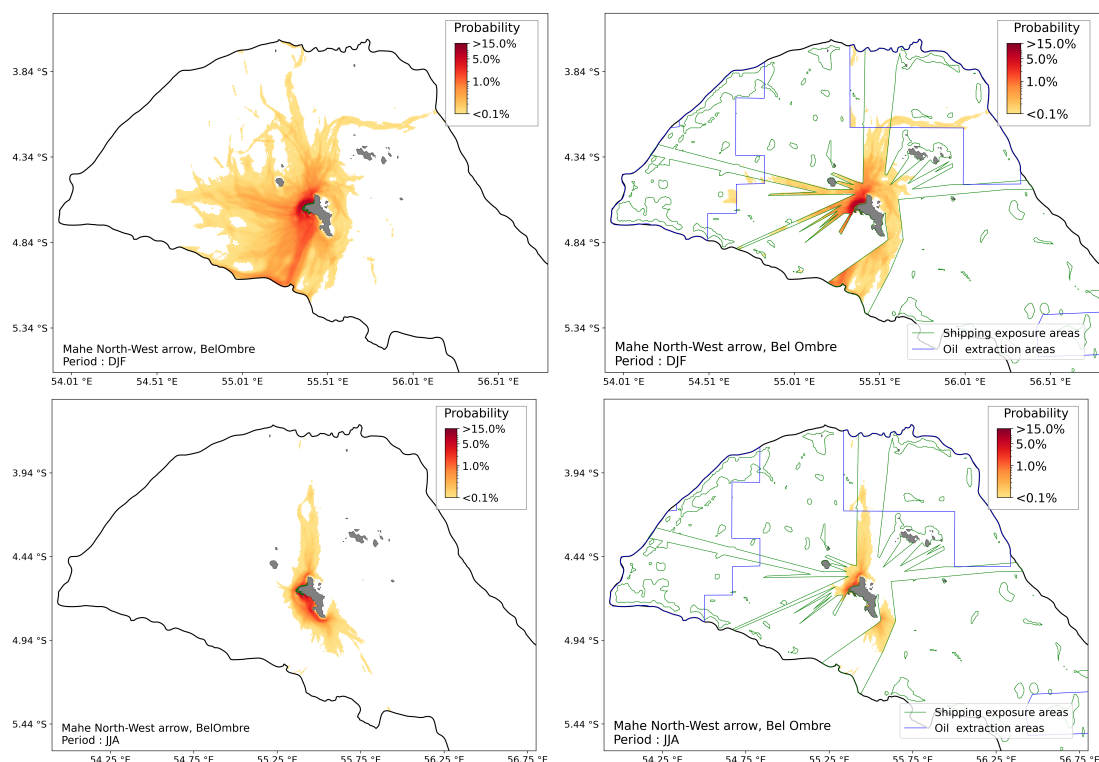


Figure 32: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Mahé North-West Arrow, Bel Ombre"

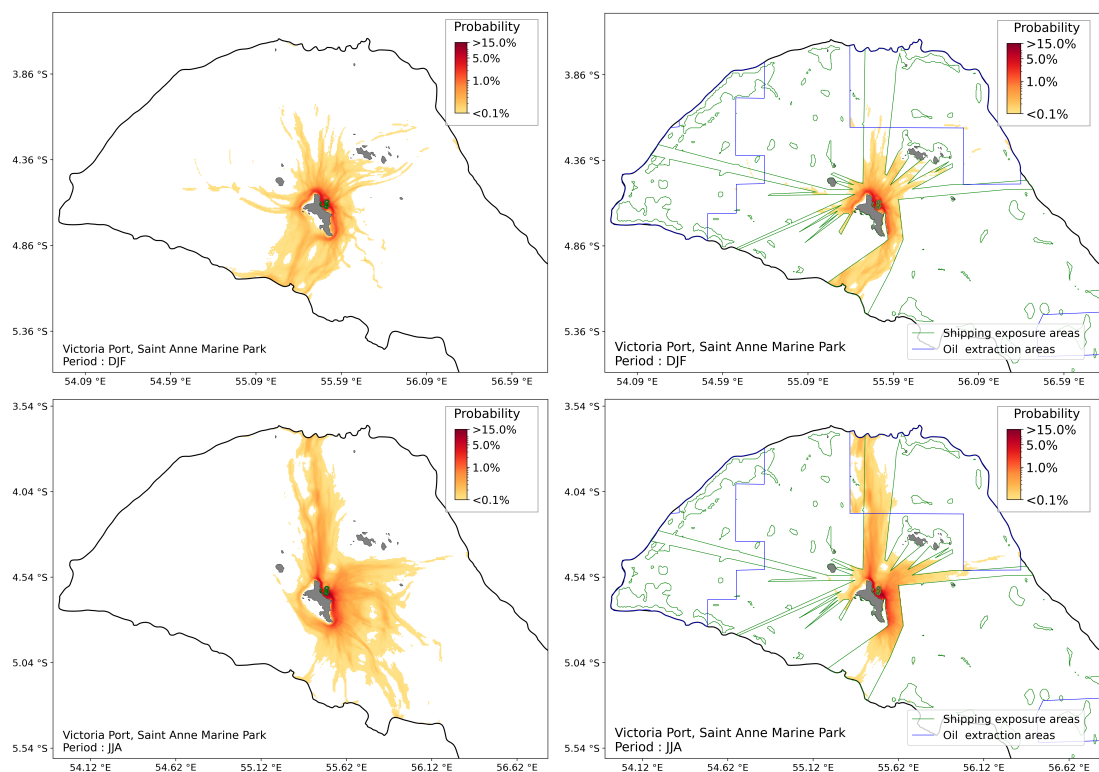


Figure 33: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Victoria Port, Saint-Anne Marine Park"

The Silhouette Marine Park (Figure 34) and the islands of Praslin, Curieuse and La Digue (Figure 35) are more exposed to oil spills from the west during the southern summer and from the east during the southern winter. Silhouette, for the first part of the year (DJF and MAM), is only minimally exposed, but this area is exposed to shipping and oil extraction during the rest of the year. Praslin, Curieuse and La Digue are exposed throughout the year to both types of exposure.

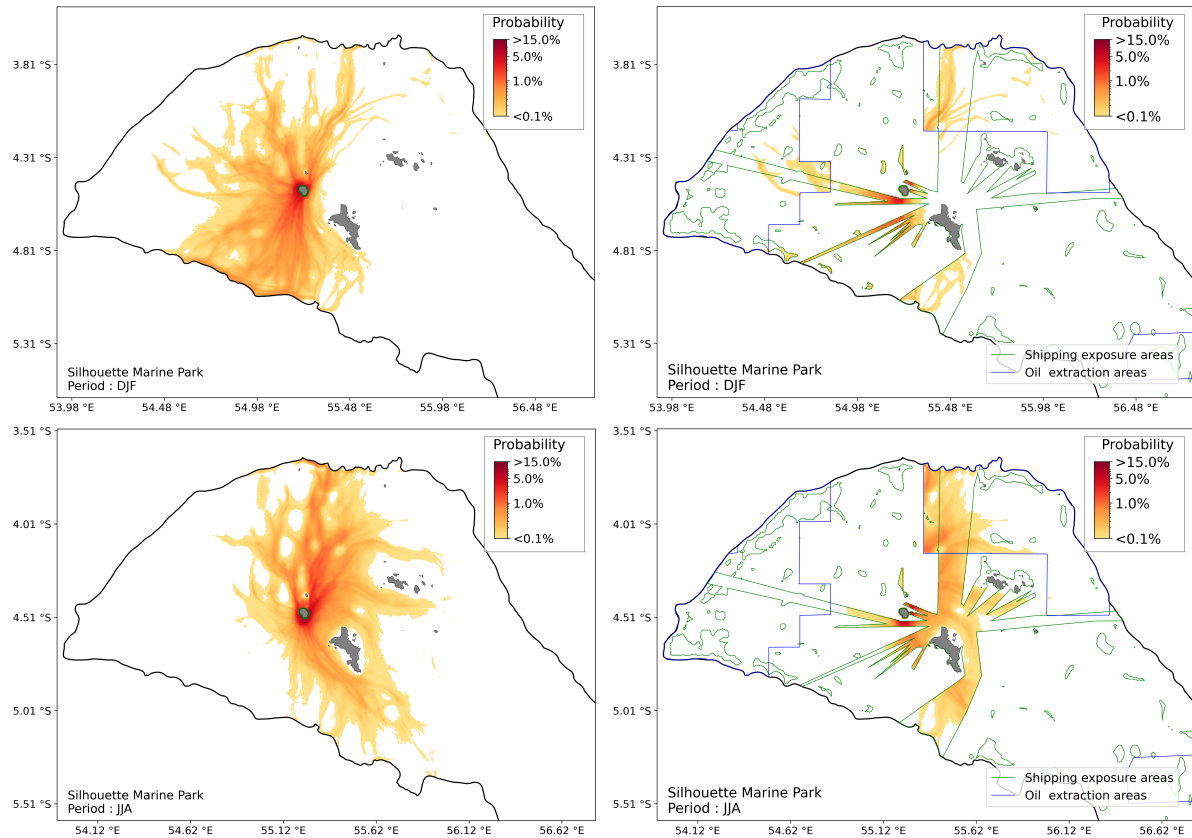


Figure 34: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Silhouette Marine Park"

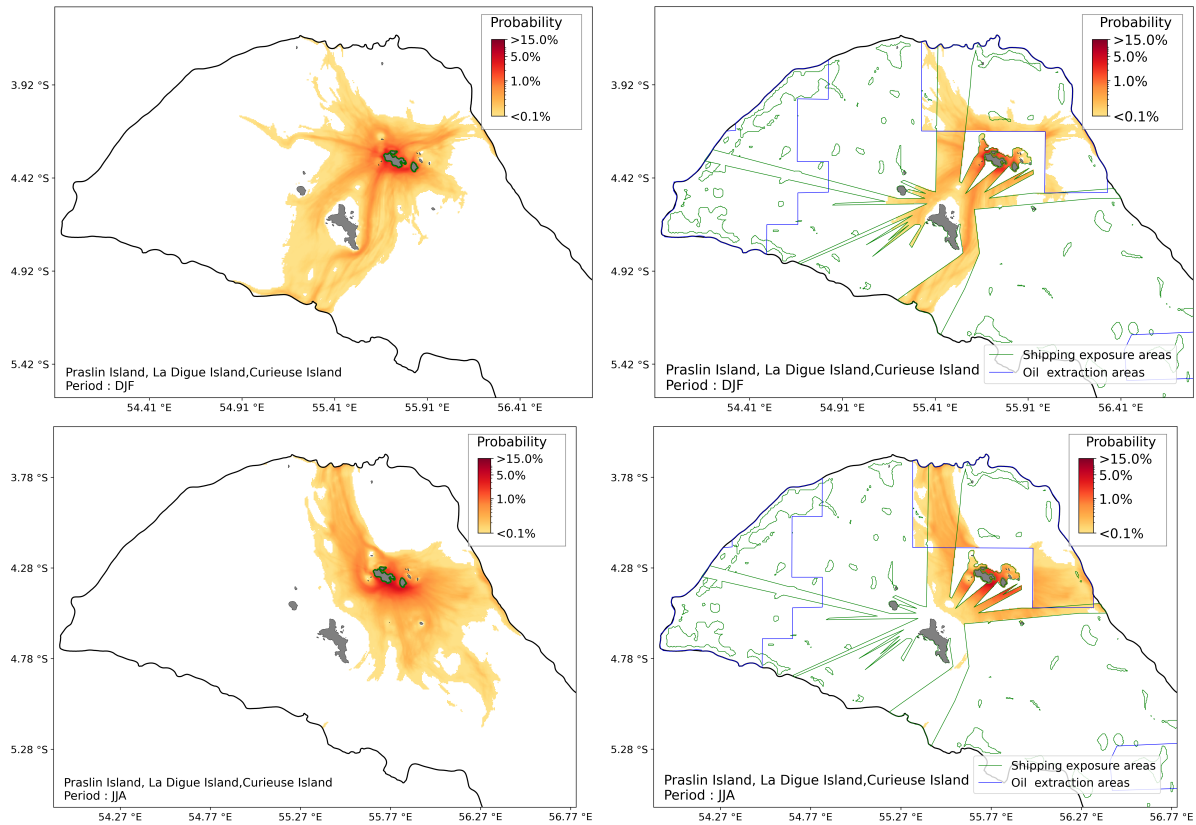


Figure 35: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Praslin, Curieuse and La Digue Islands"

Bird Island's coastline appears to have very little exposure to the various risk areas (Figure 36). It is mostly exposed to accidents on the shallow area around the island, which is less than 10 metres deep and therefore prone to boat accidents. Denis Island (Figure 37), on the other hand, is located within an oil exploration licence area and is therefore highly exposed to the risk of an oil spill due to oil extraction affecting its shores.

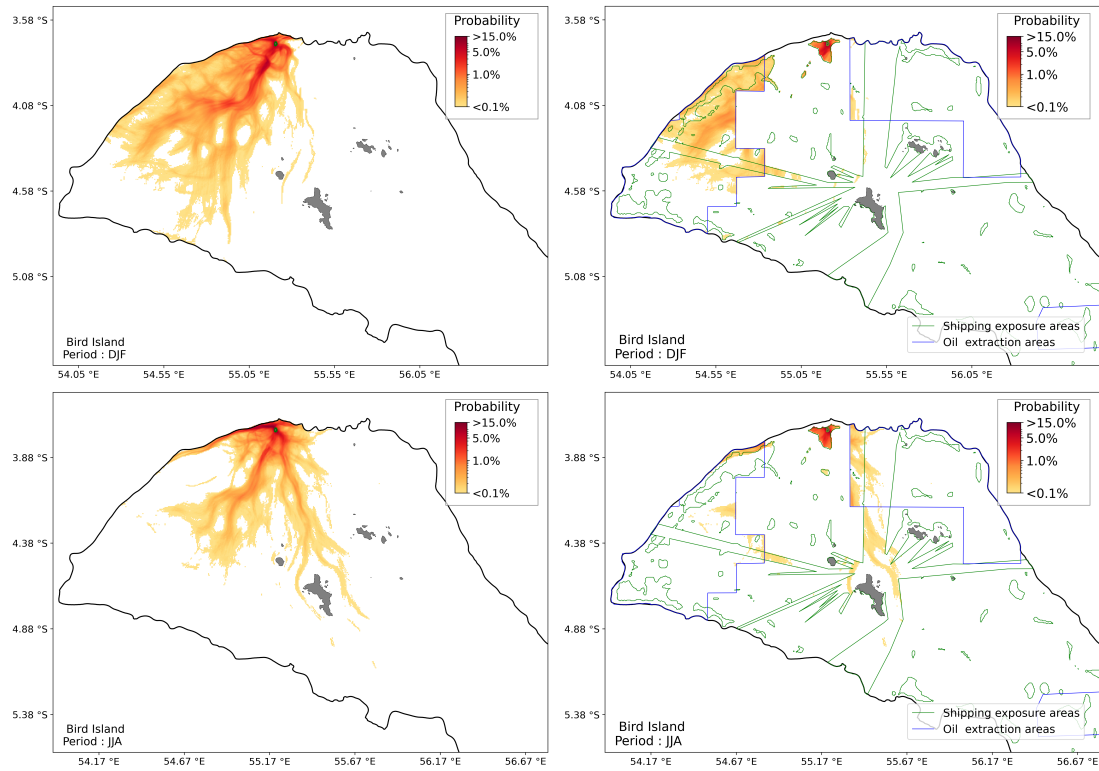


Figure 36: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Bird Island"

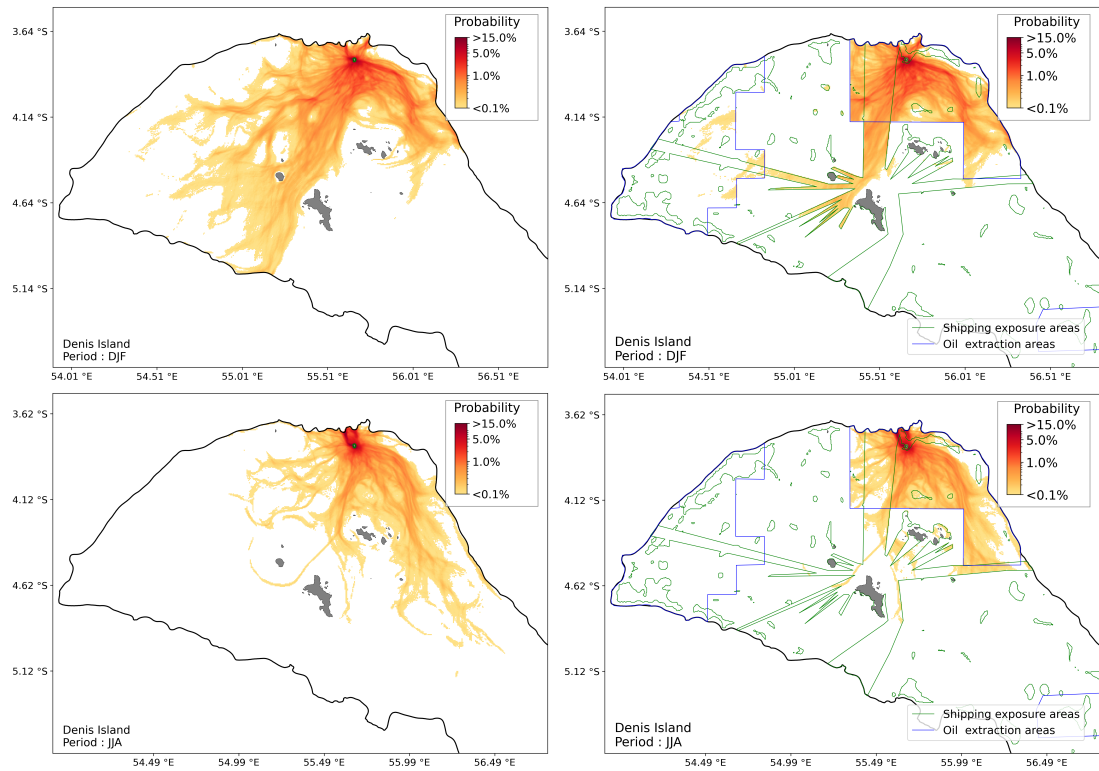


Figure 37: Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Denis Island"

3.4 Total exposure time series

The total exposure for each sensitive coastal area considered in this study and for each month has been computed and averaged over 3 years (2018-2020), as it can be seen on Figure 38.

For the two areas located on Mahé Island ("Mahé North-West arrow, Bel Ombre" and "Victoria port, Saint-Anne Marine Park"), their exposure evolution are the opposite to each other. West coasts are indeed more vulnerable during the austral summer (DJF) while the Victoria harbour and the Saint-Anne marine park are more vulnerable in the austral winter. This can be seen in the probability maps in previous section and is due to the geographical position of those two areas and the shift in the ocean circulation direction between the two monsoon seasons.

Regarding Bird and Dennis Islands, those two sensitive areas show an higher vulnerability during the austral summer, and much lower during the austral winter. As the currents during this period flow in the South-westerly direction, and as those island are located near the plateau boundaries, a large portion of the backtracked oil particles has been pushed outside of the plateau. This vulnerability may hence be underestimated.

The vulnerability of Silhouette Marine Park and of the islands of Praslin, La Digue and Curieuse remains quite constant through the year. This is due to the fact that those studied areas are exposed from all sides (since the all island coastlines are considered), in contrast to the the areas located on Mahé island, which are geographically protected during a part of the year.

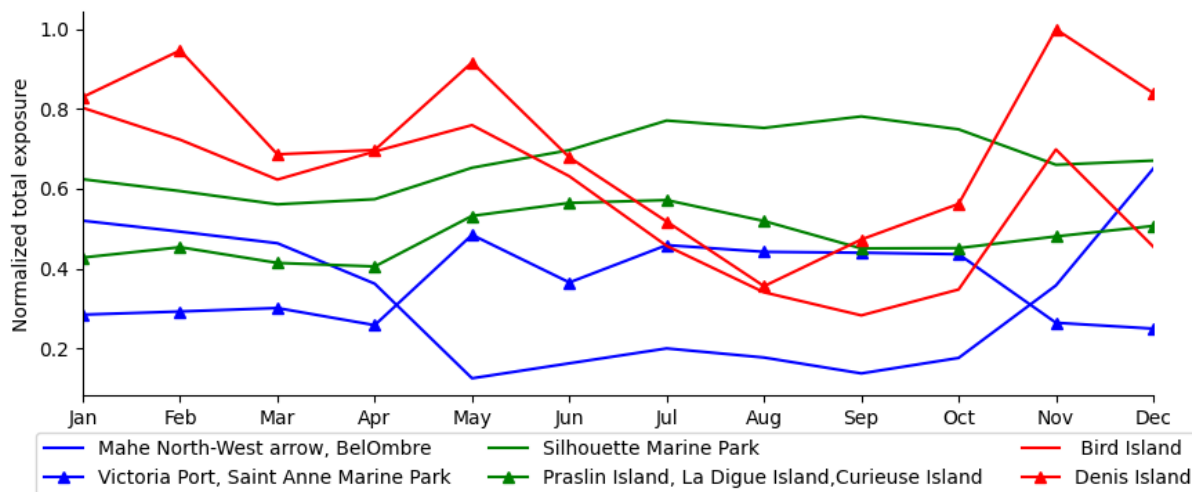


Figure 38: Evolution of the vulnerability of each sensitive coastal area through a year

The exposure to shipping and petroleum extraction can also be computed, obtaining a time series for each area studied. Each exposure has been normalised by its maximum value for all 6 sites over the entire time series. the resulting time series show the vulnerability evolution of each coastlines to petroleum extraction and to shipping through time.

Regarding the exposure to shipping (Figure 39), Mahé North-West arrow and Bel Ombre coastal

vulnerability remains much lower than the vulnerability of the Victoria harbour and the Saint-Anne marine park. This is due to the fact that large shipping routes pass east of Mahé (even crossing the Victoria harbour), and western coastal areas are hence sheltered from the pollution that would originate from this traffic, especially during the austral winter. Concerning the exposure to petroleum extraction, Denis Island coasts are the most vulnerable to the petroleum extraction (Figure 39) as this island is located inside of an area under petroleum exploration licence.

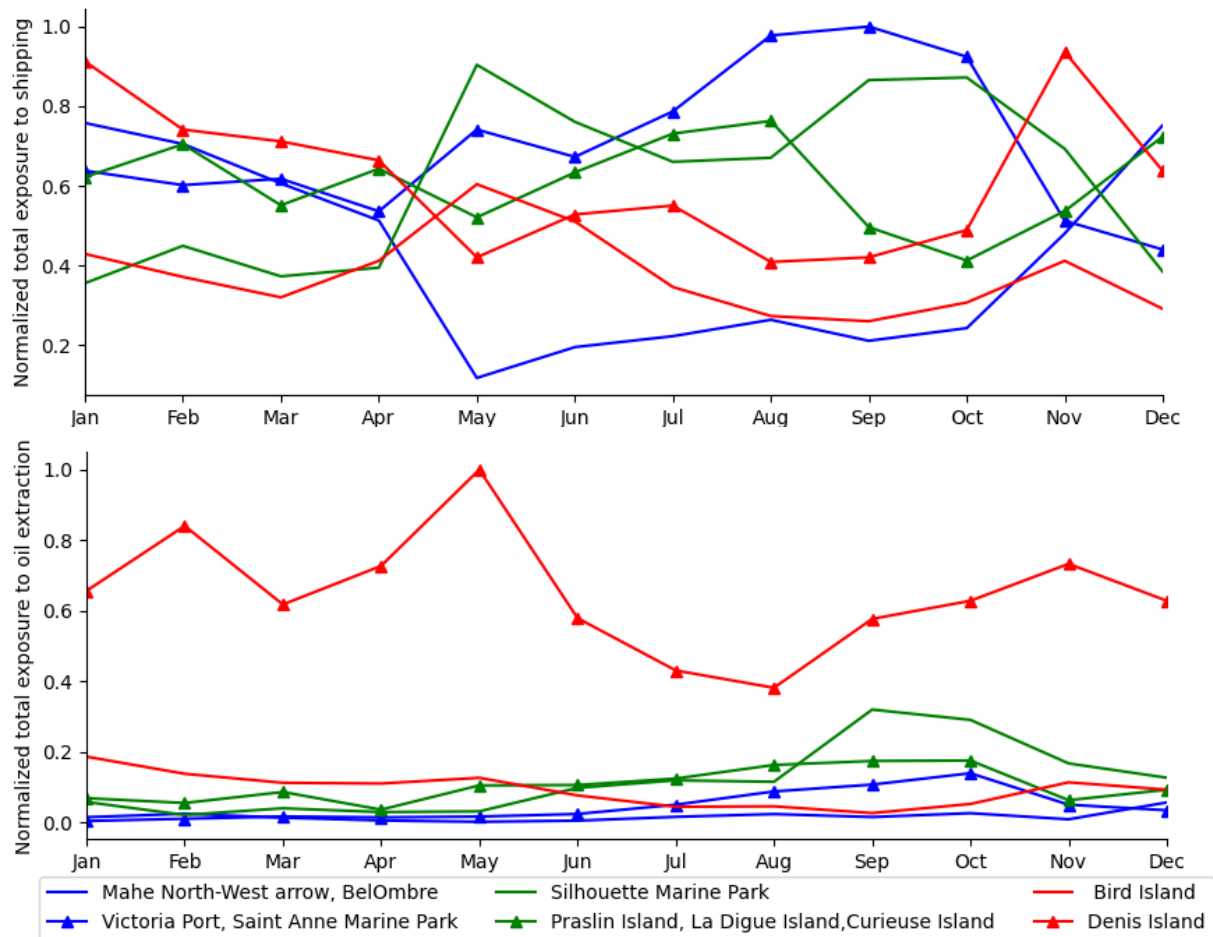


Figure 39: Evolution of the vulnerability of each sensitive coastal area to **(up)** shipping and **(down)** petroleum extraction through a year

4 Discussion

Our analysis suggests that the 6 sensitive coastal areas considered in this study present all a high vulnerability to oil spills. The offshore risk spatial distributions have a strong seasonality directly driven by the atmospheric and oceanic circulations over the Seychelles' plateau. Over one entire year, no part of the plateau can be assumed to be risk-free. Given its relatively limited size, any oil spill incident occurring on the plateau has the potential to reach a sensitive coastal area in less than 5 days. When combining the oil spill risk distribution with areas with high maritime traffic density, or prone to shipping accidents or under oil exploration licence, the main north-south shipping route appears to pose a significant risk to 5 of the 6 sensitive coastal areas for at least half of the year.

The offshore oil spill risk distributions show a strong seasonal variability as the oil spill dispersal is driven by the winds, the ocean currents and the waves, which all change during the year. Oil particles at the surface are directly impacted by winds, but also by the waves induced by the wind and contributing to this oil dispersal, which has been taken into account through the Stokes Drift. The combined effect of Stokes drift and direct wind effect on oil dispersal reaches an oil dispersal velocity of 3.5% of the actual wind velocity (Jones et al., 2016). In the water column, denser oil particles and particle brought by ocean vertical mixing become less influenced by wind with depth. All particle drifts are also influenced by ocean currents, which themselves are impacted by many different factors and which have been previously simulated. The wind influence on oil dispersal is not negligible as wind velocities are high over the SP, especially during the monsoon seasons. For instance, winds during the Southeast monsoon can blow up to 10 m/s, impacting of 0.35 m/s the oil dispersal, while the current velocities rarely exceed 0.5 m/s. During the inter-monsoon seasons, winds have a weaker impact on the oil dispersal and oil particle drifts are hence mainly driven by ocean circulation.

The strong variation of ocean circulation and winds through the year will induce important changes in the areas threatening the studied coastlines from oil spills. During the austral winter (Southeast monsoon), as the oceanic and atmospheric circulations flow respectively in the southwestern and the northwestern directions, oil spill threats generally come from the East. During the austral summer (Northwest monsoon), currents are usually oriented in the south-eastern direction, but are weaker than during the Southeast monsoon and hence have a weaker impact on the oil dispersal. Ocean circulation, on the other hand, flows in the north-eastern direction. The combination results in threatening areas usually located South-West of the studied areas. During the inter-seasons, winds weaken, having hence less influence on the spatial distribution of the spill threatening areas. This strong seasonal shift in ocean circulation due to the monsoon system has also been described in previous attempts to simulate ocean currents over the SP (Castillo-Trujillo et al., 2021).

An oil spill originating from the main upper part of the plateau could, in a worst-case scenario, reach sensitive coastal areas less than 5 days. Given this short duration, and the limited infrastructure available to combat an oil spill, it will be important to take extra care about a possible threat. As it has been seen with the Wakashio oil spill in Mauritius (2020), where around 1,000 tonnes of oil have been leaked through the ocean fifteen days after the ship grounded while authorities had already removed a part of the fuel from its tanks (Pilling, 2022), the authorities reaction time to implement mitigation measures for events such as those would be extremely short, especially with such short spill travel time to reach the coast.

The exposure to oil spill originating from shipping is mainly influenced by a north-south shipping connecting to the Port of Victoria. Five out of the six sensitive coastal areas are vulnerable to any oil pollution event along that route for at least two seasons for the year. This route is all the more threatening as it concentrates most of the shipping activity of the SP (Figure 7). It indeed links the Victoria port, which is the point of entry for 95% of the country's import ("Port of Victoria", 2018), to the main land (African continent). It would hence be essential to closely monitor this route to allow an early detection of a spill that could be heavily hazardous for several coastal assets. The coastal areas most vulnerable to accidental or deliberate oil discharge are the port of Victoria and the Saint-Anne Marine Park (Figure 33), which are both located next to this main shipping route. Bird Island's coastal area seems to be rarely exposed to the main shipping routes (Figure 36) but is strongly exposed to oil pollution that could result from ship grounding over its surrounding shallow seabed. The sensitive coastal areas on the western coast of Mahé (Figure 32) are also more sheltered from oil spills originating from shipping activities, which are mostly concentrated on the eastern side of the island.

Denis Island seems to be the coastal area most vulnerable to (potential) oil extraction activities (Figure 39), as it is located in one of them. As the exploration area extends outside of the plateau boundaries (and hence out of our model domain), Denis Island's vulnerability could still be underestimated. However, we do not have any information relating how this area is explored and hence the real risk it may represent for Denis Island.

As every model-based assessment, this study has several limitations, for example due to assumptions made or inherent in the different models used. Firstly, regarding the hydrodynamic simulations, only few observations were available to validate the model, inducing the fact there remain uncertainties concerning the quality of the simulations carried out. Moreover, as said before, those simulations are highly dependent on the quality of CMEMS Mercator model data used as forcing for external ocean circulation. However, the SLIM2D model seems to reproduce quite well the ocean circulation patterns observed over the SP and represent therefore a good basis for further studies.

As the SP is not limited by any physical boundary, the ocean circulation at the edge of the plateau will have a great influence on the circulation observed on the plateau, regulating circulation in and out of the plateau. The quality of our simulations with the multiscale coastal ocean model SLIM therefore depends on the quality of the external currents forcing, which is here provided by the CMEMS Mercator system that runs a global data-assimilated version of the ocean model NEMO. Although this large-scale model has been recently updated and is still actively developed, and although it tends to correctly represent the basin-scale circulation patterns and their variability, it still faces some biases and errors, including in mid-latitude and equatorial areas (Lellouche et al., 2018).

Another limitation of this study is the fact that it has only been carried out for 3 years of simulation. This may not be enough to capture all the interannual variability of the ocean circulation over the studied area. Even if the seasonal patterns keep appearing in the different years, local current velocities may vary from one year to the next, leading to slightly different oil spill risk distribution. A wider range of simulated years would lead to more robust risk estimates. The precise number of years that be necessary to fully represent the interannual variability of the oceanic and atmospheric circulation in that area remains to be determined.

As the 2D version of the SLIM model assumes a vertically-homogeneous water column, it cannot be used to realistically simulate the ocean circulation outside the the SP boundaries, since greater depths will lead to a vertical stratification of the water column. This is a major limitation for the study as, for the 6 different coastal areas considered here, the possibility to reach coasts within five days frequently extends outside the plateau boundaries. This is especially the case for the coasts of Bird and Denis islands, which are located at the edge of the SP. At first sight, those two islands seem to have a weaker total vulnerability (Figure 38) during the austral winter, while this could actually be related to more threats coming from outside of the plateau. Further studies could take the surroundings of the plateau into account by using a 3D baroclinic ocean model to simulate ocean circulation over a broader area.

Regarding the oil drift simulations carried out, these have been set to a maximum duration of five days backward-in-time. Depending on the type of oil and its characteristics, oil spills could, however, still represent a threat on longer time scales. It has here been assumed that, for oil spills reaching the coasts in more than 5 days, it would be easier to activate oil spill mitigation measures before the spill reaches the coasts.

It is also important to note that, as the oil spill dispersal simulations have been carried out backward-in-time, weathering processes have not been taken into account. Since some of those processes, namely evaporation and biodegradation, remove oil from the water column, the oil spill exposure of coastal areas could vary. The weathering rate of the oil depends on several factors, such as temperature and wave activity. Hence, higher temperatures and higher winds would induce more oil weathering and thus more oil removal from the water column. Another important factor regulating the weathering of the oil, and thus the exposure of coastal areas to oil spills, is the type of the oil spilling into the ocean. Indeed, oils of higher density will tend to evaporate less easily and hence stay longer in the water column. The oil spill threatening area would therefore change whether the spillage originates from a shipping incident (hence leaking refined oil of lower density) or from oil extraction activities (hence leaking heavier crude oil).

Finally, the lack of information about shipping and petroleum extraction is a real limitation to this study. Concerning the exposure to shipping, only high shipping density routes have been approximately drawn but no shipping density spatial distribution was available. For the petroleum extraction, besides the areas currently under exploration licence, no data was available regarding wells made by the company exploring those areas and their spatial distribution. That information could help further refine our study by having more precise information on the oil extraction area and hence potentially allow a more quantitative comparison between total exposures to shipping and petroleum extraction.

In addition to the vulnerability to oil spills assessment, this study could serve as a basis to works aiming to assess the vulnerability of Seychelles coastlines to drifting material staying relatively close to the ocean surface, not considered herein, which would hence also be transported under the combined influence of ocean currents, wind and waves. It is expected that the resulting offshore risk distribution would be close to those derived here. This could be for instance the case micro and macro plastics settling on the coasts, which is an issue that has already been observed at different locations of the Seychelles Archipelago (Dunlop et al., 2020).

5 Conclusion

SIDS are generally considered as particularly vulnerable to external disasters due to their geographical remoteness, their small size or even their fragile ecosystem hosting a large number of endemic species. An oil spill reaching their coasts could therefore have dramatic impacts on the marine environment of those island states, but also on their economy, mainly based on tourism and fisheries. As one of those states, the Seychelles Archipelago is not an exception to this. However the vulnerability of its coast to accidental or deliberate release of oil in the ocean remained largely unexplored. The objective of this thesis was to address this issue by identifying the offshore oil spill risk distribution for 6 sensitive coastal areas throughout the Seychelles Plateau and assess their seasonal variability.

This has been achieved following a three steps modelling sequence. The first step has been to simulate ocean circulation over the Seychelles' plateau, which has been the extend of this study, from year 2018 to year 2020. This ocean circulation has been simulated with the Second-generation Louvain-La-Neuve Ice-ocean Model (SLIM) model, based on an unstructured mesh discretisation, which allows a finer spatial resolution along the coastline and at the shelf break, and a coarser resolution in the open ocean. It has been chosen to carry out those simulations with the 2-dimensional version of the model, assuming a good vertical mixing of the water column, given the relatively shallow depth over the plateau ($\sim 50\text{m}$). The second step has been to simulate oil particles dispersal backward in time to predict their probable trajectories from the 6 sensitive coastal areas. With those simulations, the spatial distribution of the minimal time needed for an oil spill to reach those coastal areas has been computed, allowing us to evaluate the time available to put countermeasures in place. We also derived oil spill risk exposure maps for each sensitive coastal area. Combining these with a distribution of areas prone to oil pollution (high maritime traffic density or water depth less than 10 m), as well as areas currently under petroleum exploration licence, has highlighted the most threatening areas for the different sensitive coastal areas.

Through this analysis, we showed a strong seasonality of the risk distributions due to the monsoon climate occurring over the plateau. Coastal assets will indeed usually be more exposed to oil spills from the West during the austral summer as the Northwest monsoon is occurring (December to March), from the East during the austral winter as the Southeast monsoon takes place (June to September). Between the monsoon seasons, the SP facing weaker and more fluctuating conditions, oil dispersal is set to be more variable. The shore of Victoria Harbour and Saint-Anne Marine Park tend to be highly vulnerable to oil spills resulting from shipping activities as the Port of Victoria is the main harbour of the Seychelles state and all shipping routes therefore connect to this port. Denis Island is for its part highly vulnerable to spills caused by petroleum extraction activities as it stands inside one of the two areas under petroleum extraction licence.

Due to the strong seasonal variability of the oil spill threatening area for each coastal asset studied, it would be very difficult to establish an exclusive area to protect, Appart from the main north-to-south shipping routes, which represents a hotspot in terms of oil spill exposure. Moreover as an oil spill starting on a large proportion of the SP could reach sensitive coasts within less than 5 days, it will be extremely important to take extra care preventing events such as these from happening on the plateau and its surroundings, for instance by ensuring frequent ship controls and closely monitoring boat discharges on the plateau. As, when an

oil spill event occurs, the time authorities will have to react would be extremely short, and as very few infrastructures are available to combat those spills, it will be important to eliminate as many spillage risk as possible by directly reacting in case of any doubt. As preparedness is a key to the success of oil spill response measures, frequent oil spill response exercises should be put in place to ensure good experience and training for all agencies and people involved by the Seychelles oil spill contingency plan. More investments should also be made to improve and increase infrastructures dedicated to detecting and combating oil spills. Special considerations should be addressed to the north-to-south major shipping route, with a close monitoring allowing early oil spill detection.

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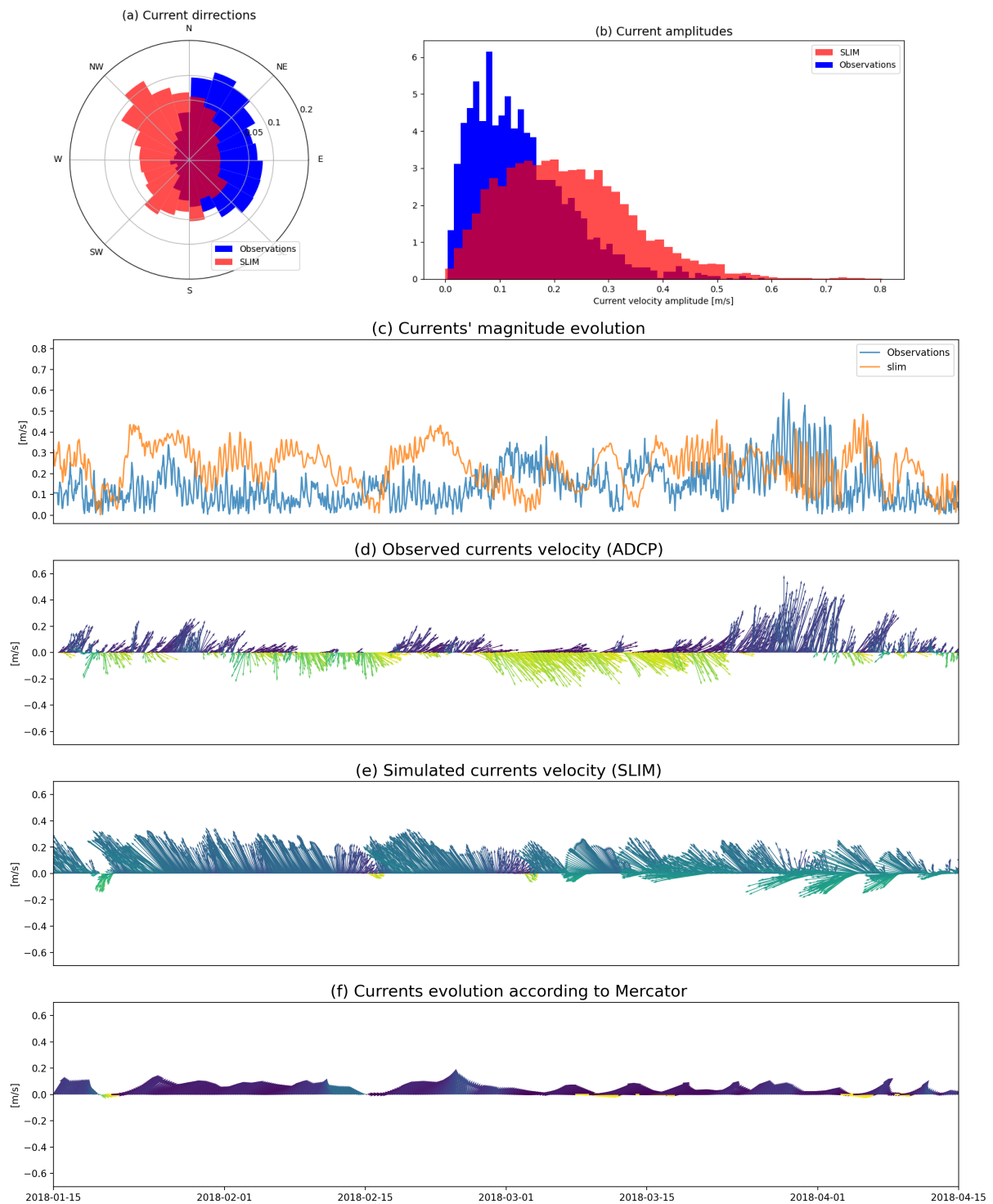
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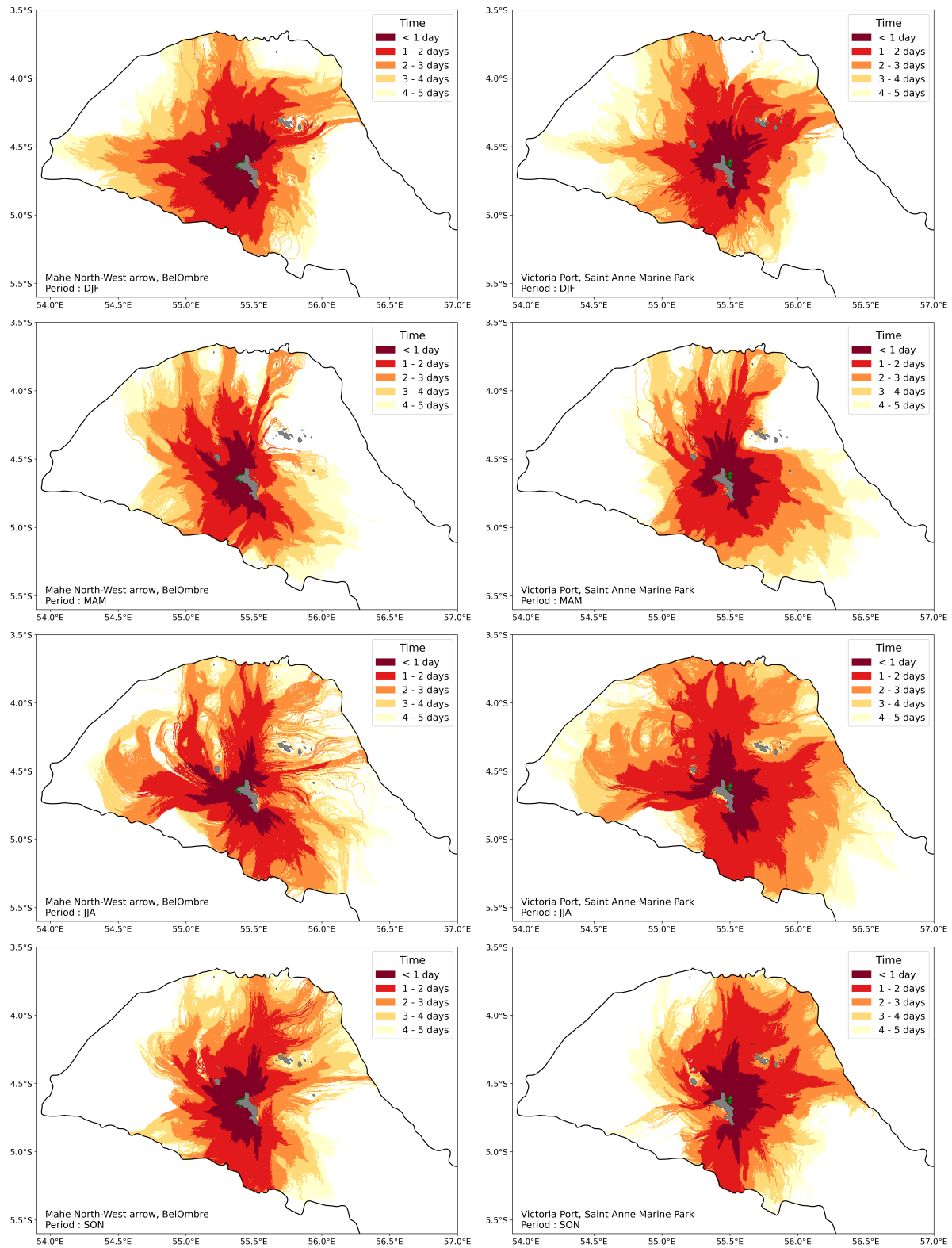
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Appendices

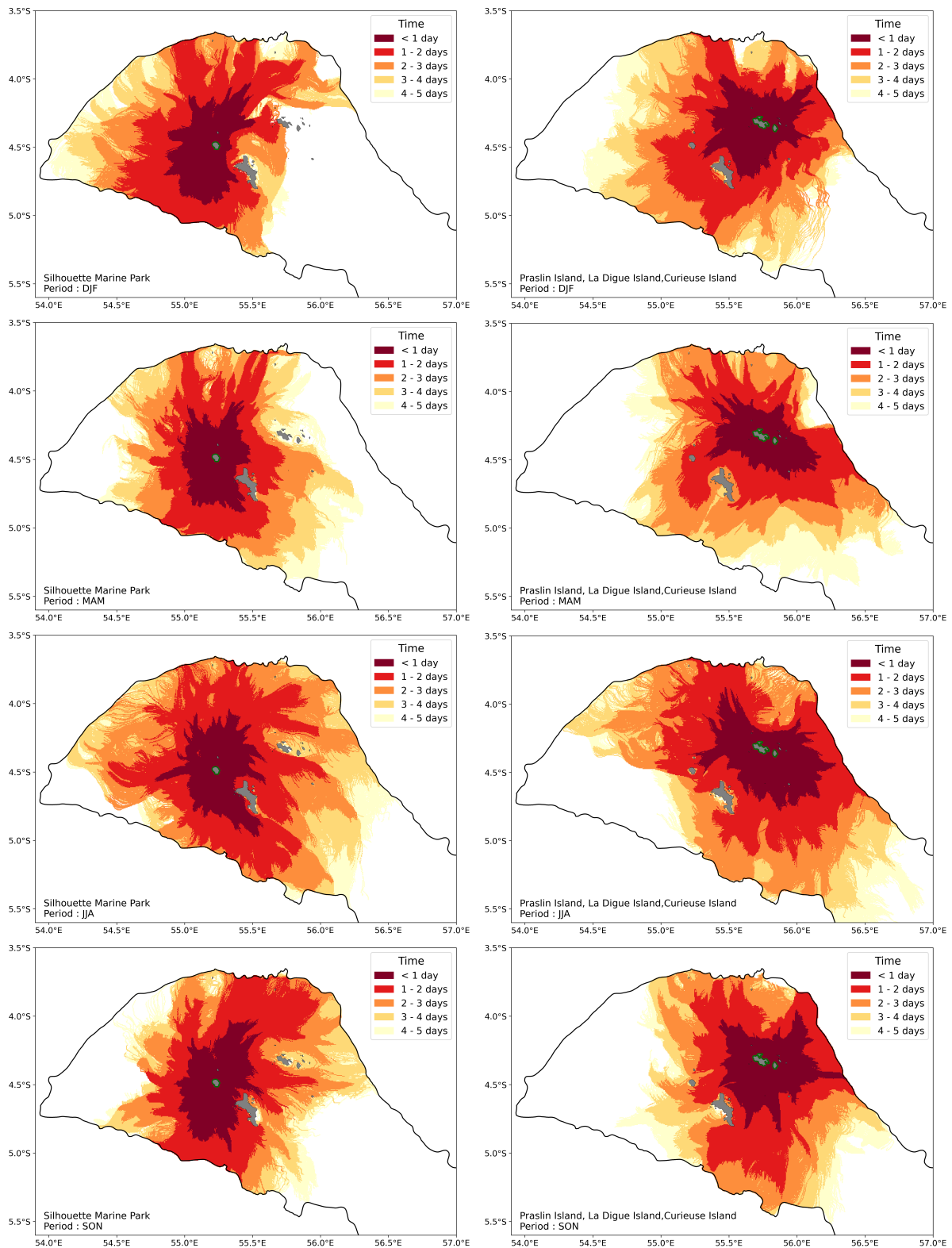
A Hydrodynamic model validation (North of SP, January to April 2018)



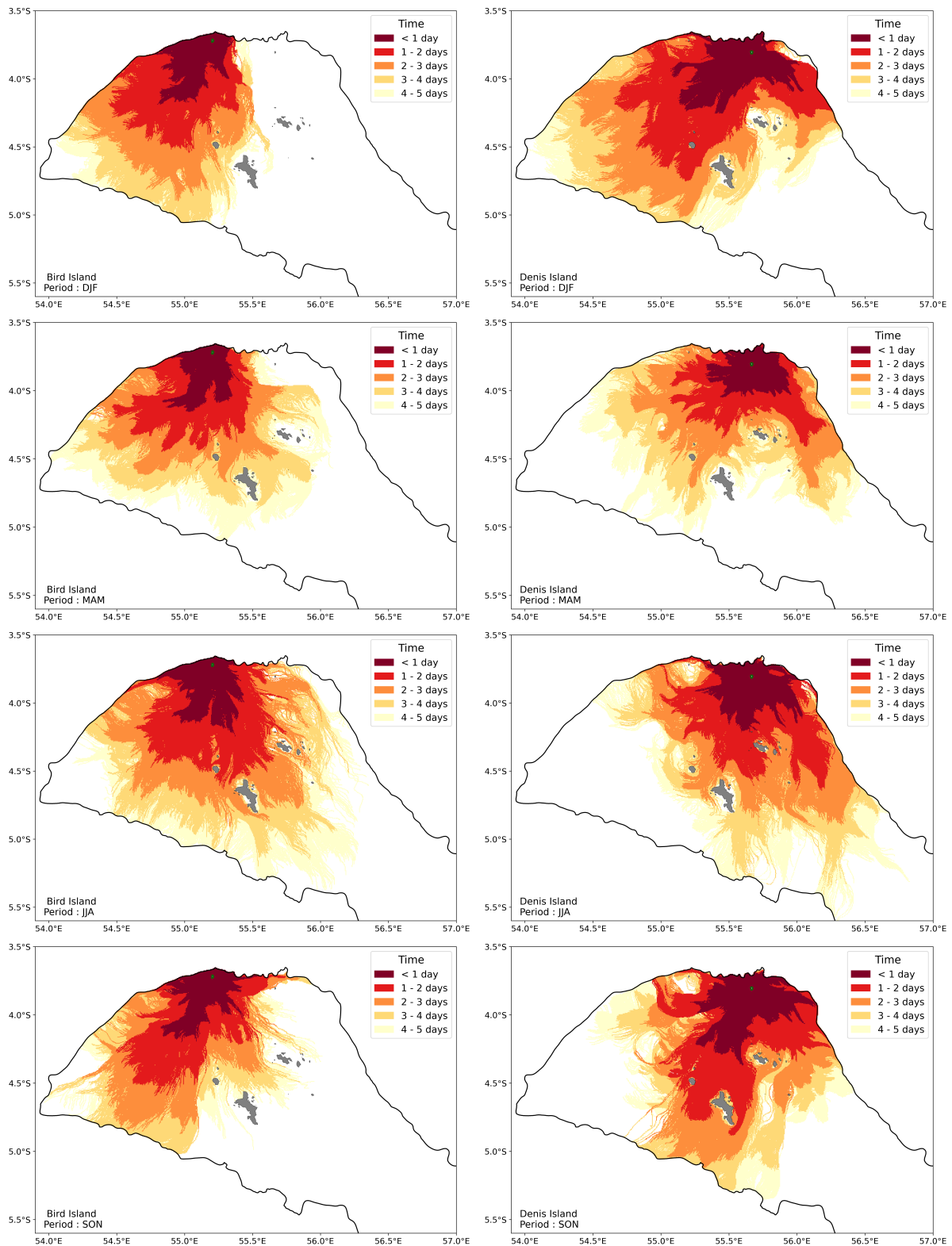
B Arrival time maps



Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Mahé North-West Arrow, Bel Ombre" and **(right)** "Victoria Port, Saint-Anne Marine Park" coasts

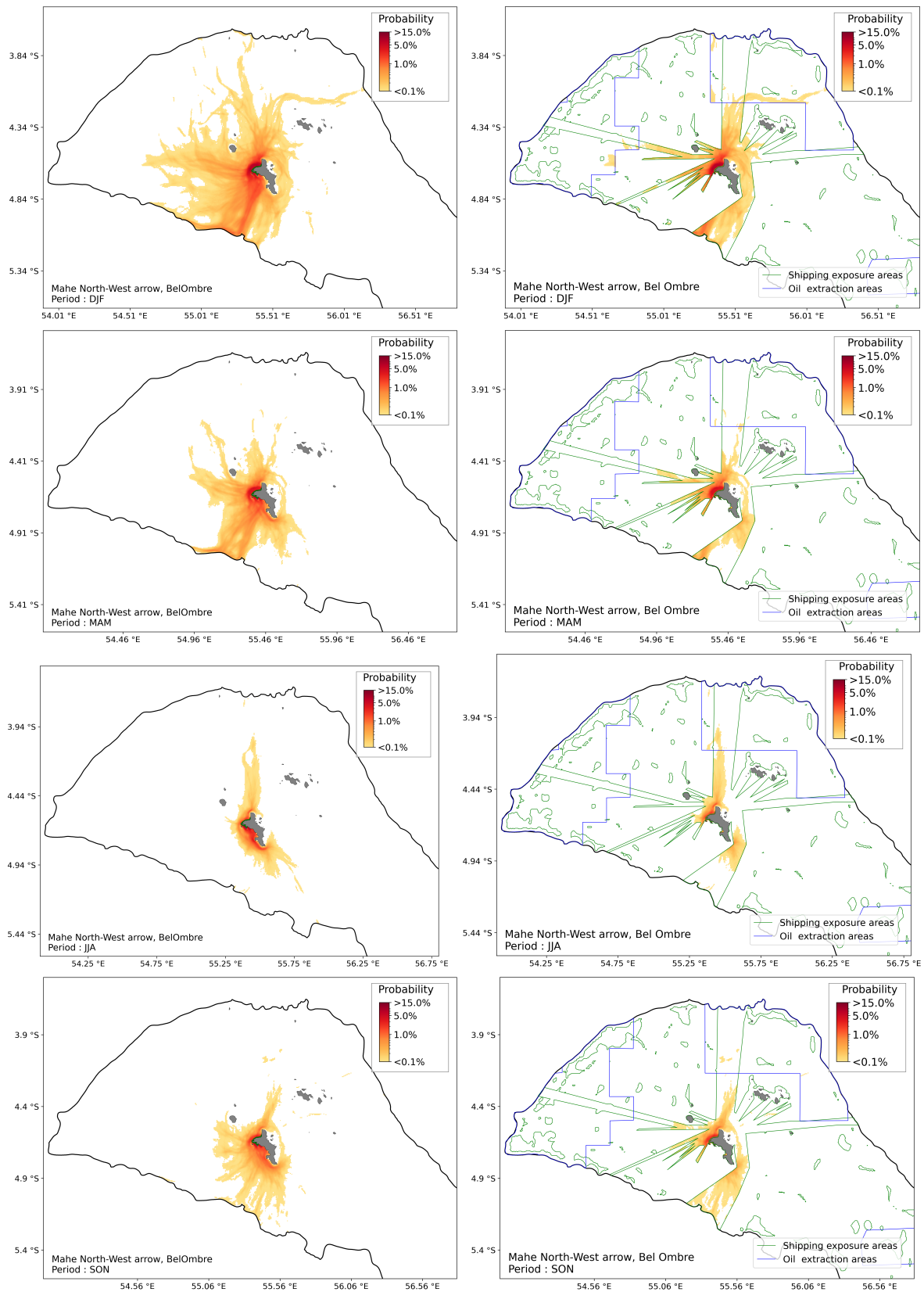


Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Silhouette Marine Park" and **(right)** "Praslin, Curieuse and La Digue Islands" coasts

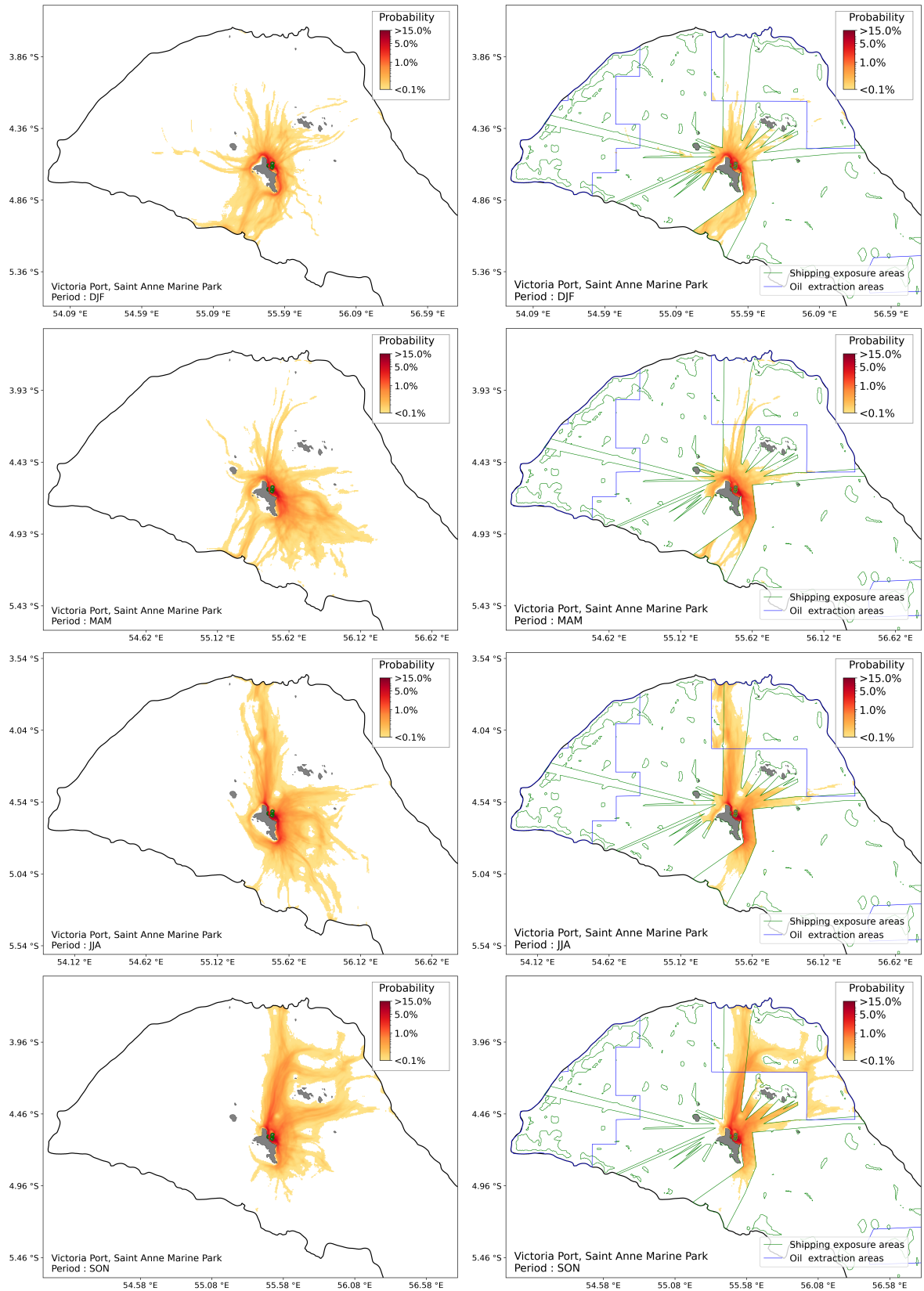


Seasonal variability of the minimum arrival time of an oil spill reaching **(left)** "Bird Island" and **(right)** "Denis Island" coasts

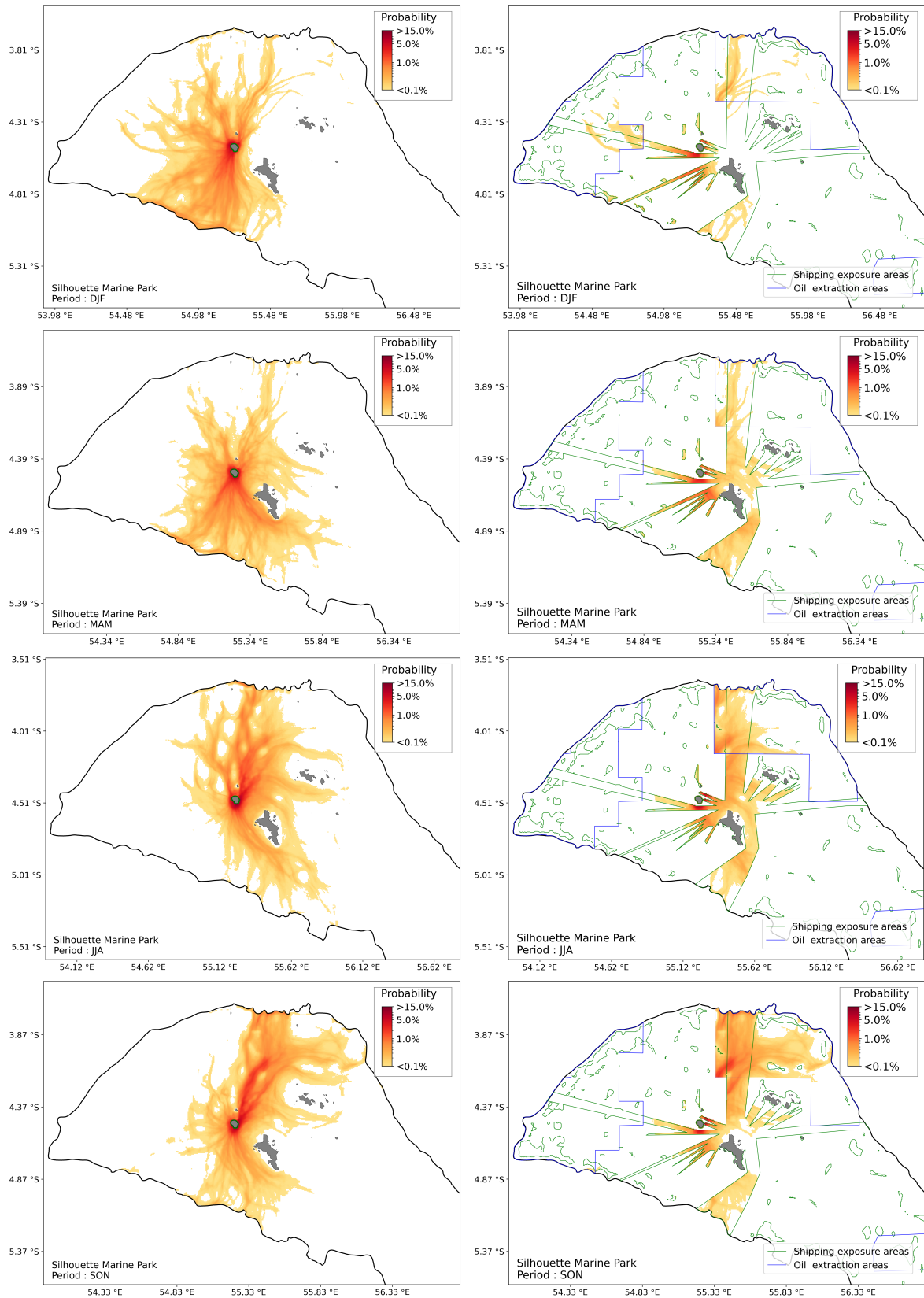
C Probability and exposure maps



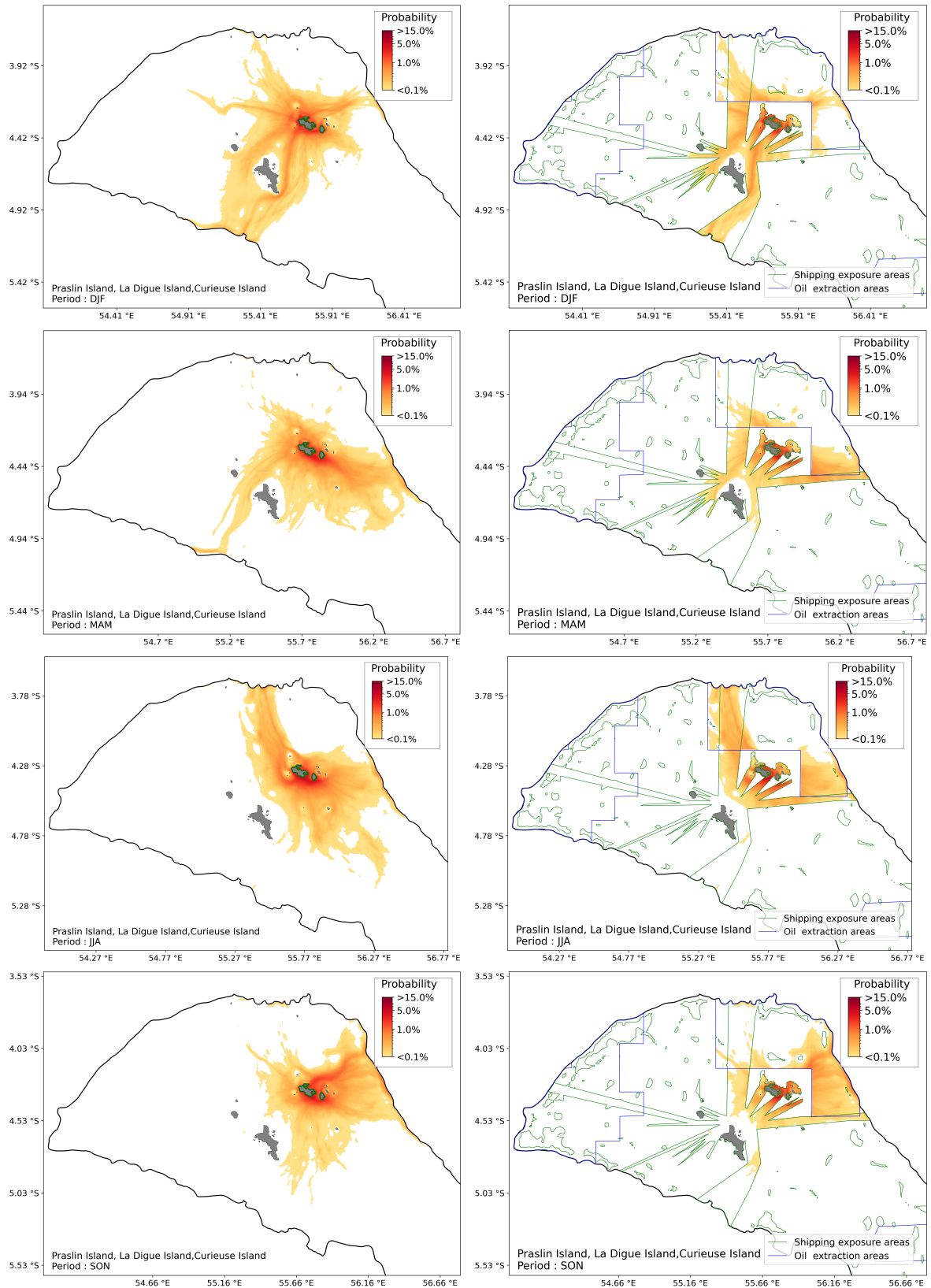
Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Mahé North-West Arrow, Bel Ombre"



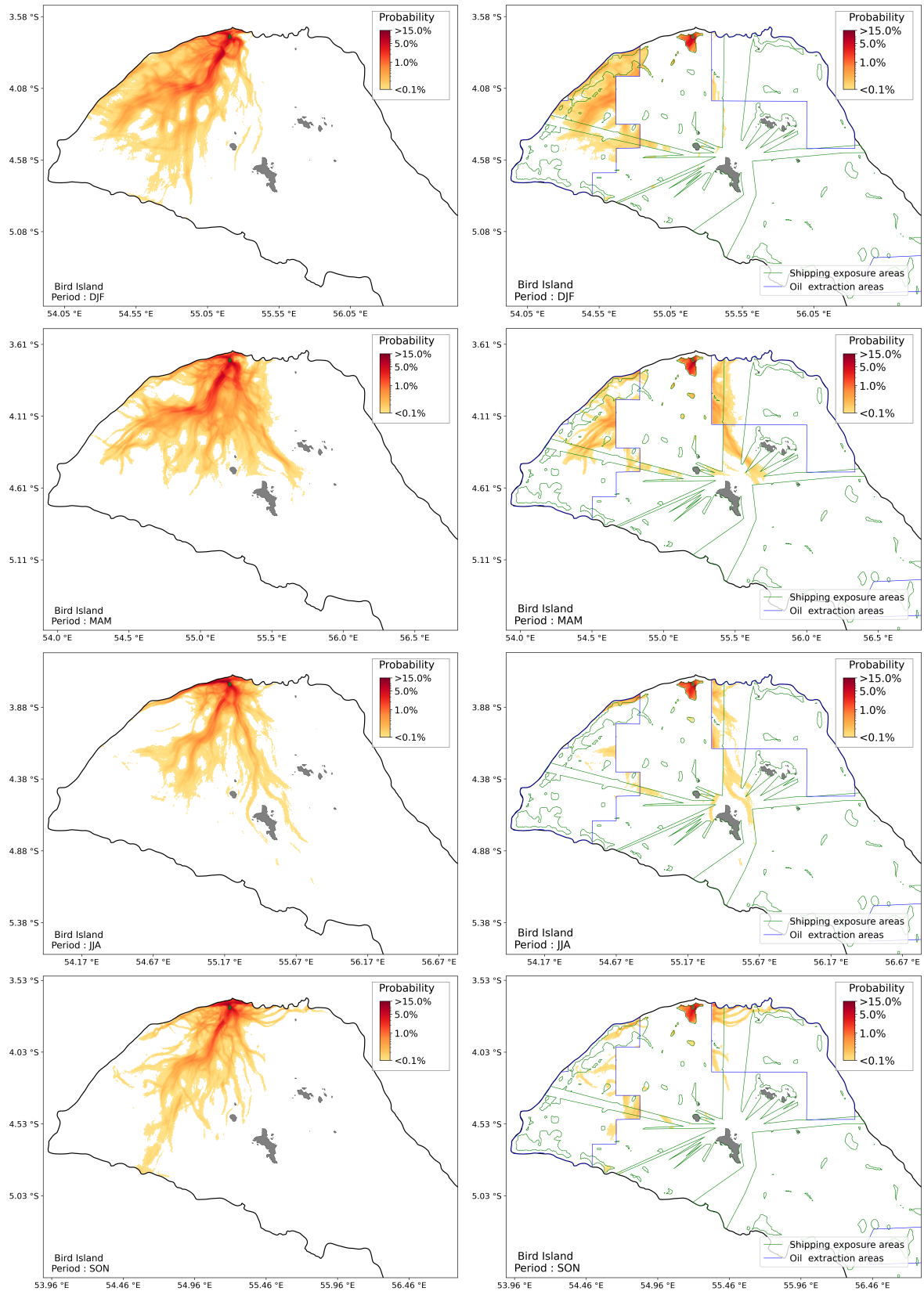
Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Victoria Port, Saint-Anne Marine Park"



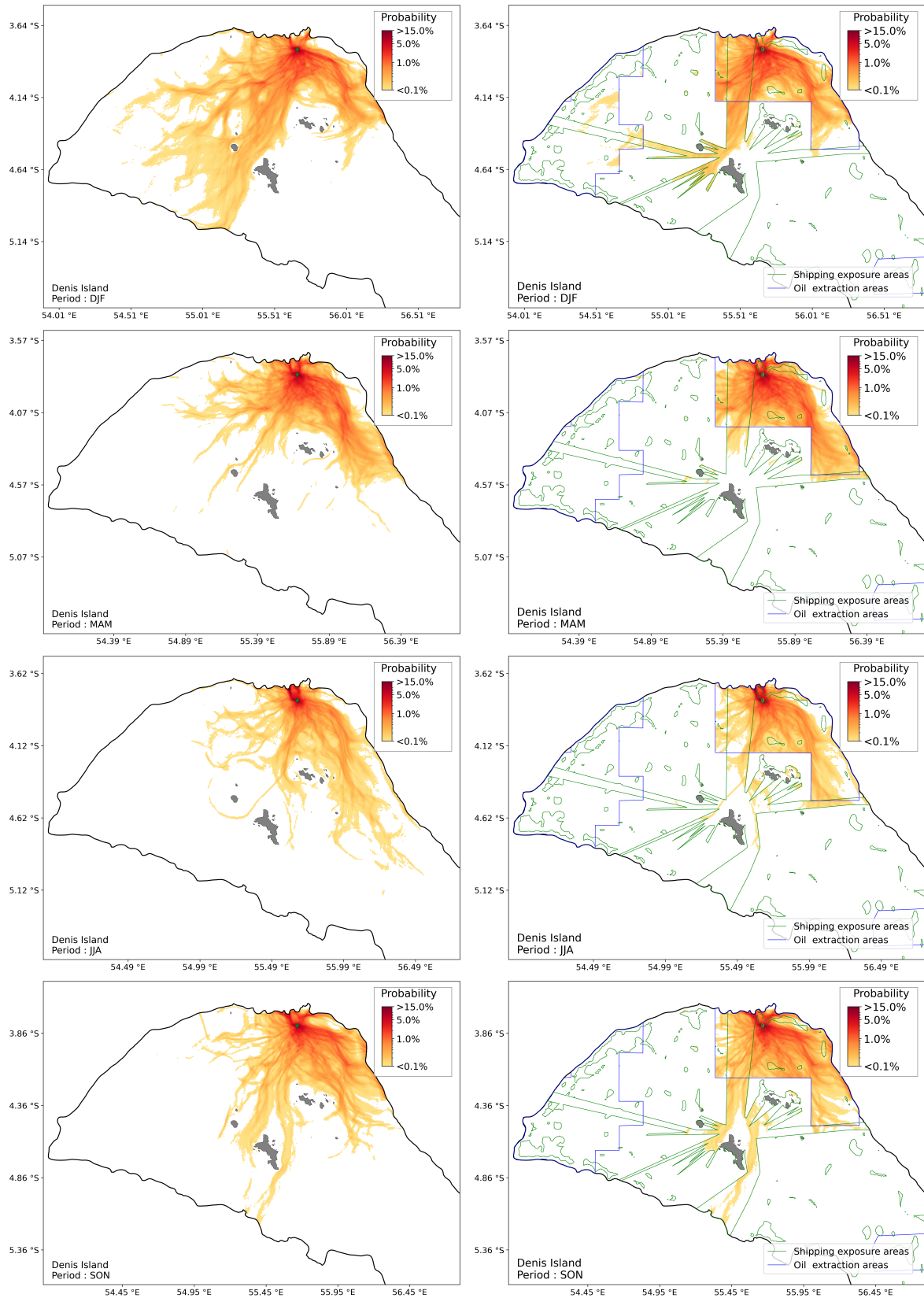
Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Silhouette Marine Park"



Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Praslin, La Digue and Curieuse Islands"



Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Bird Island"



Seasonal variability of **(left)** probable origin of an oil spill and **(right)** exposure to shipping and petroleum extraction for "Denis Island"

Vulnerability assessment of Seychelles' coastal assets to oil spills

Alex Verhofstede

Small island developing states (SIDS) are particularly vulnerable to oil pollution incidents, with little to no infrastructure available to detect, monitor or combat those spills. Seychelles archipelago is no exception to this rule as oil pollution could heavily impact its tourism industry, which accounts for about a 25% of its GDP. However, with a steady increase in maritime transport through the region as well as an increase in shipping incidents, its coastal assets vulnerability to oil spills remains largely unexplored. To tackle this deficiency, we developed a high resolution ocean circulation model of Seychelles plateau (SP) simulating ocean currents during three consecutive years (2018-2020). Those currents were used to simulate oil spill dispersal backward-in-time from six coastal areas of significant ecological and/or economical importance. That allowed us to identify which offshore areas pose the greatest threat to those sites. Our results show a clear seasonality of the offshore risk distribution that is driven by the seasonal changes in the atmospheric and oceanic circulations. We also show that the risk distribution can extend over most of the plateau during the year, which means that an oil spill coming from anywhere on the plateau could potentially impact a sensitive coastal location in less than five days. By overlaying the simulated risk distributions with areas with a high maritime traffic density, prone to shipping incidents (i.e. shallower than 10m) and under oil exploration licences, we identified the major north-south shipping route as an area of particularly high risk to most sensitive coastal locations. We therefore advise that this particular route should be closely monitored by the local authorities.