Seychelles Plateau's oil spill vulnerability

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Abstract

Small Island Developing States, such as Seychelles, are highly susceptible to oil pollution incidents, with limited infrastructure for detection and mitigation. While an oil spill could significantly impact Seychelle's tourism industry, contributing to $\sim$40% of its GDP, the archipelago's vulnerability remains largely unknown. Here, we developed a high-resolution ocean circulation model for Seychelles Plateau, simulating currents over three years (2018-2020) to model oil spill dispersal to six ecologically and economically significant coastal areas. Our findings reveal distinct seasonality in offshore risk distribution, driven by seasonal fluctuations in atmospheric and oceanic circulations. We show that an oil spill originating from any part of the plateau could potentially impact a sensitive coastal site in less than five days. By identifying high-risk areas, including the major north-south shipping route, we emphasize the importance of close satellite and airborne monitoring for early warnings to protect Seychelles' coastal ecosystems and tourism industry.

Keywords: Seychelles Plateau, multiscale coastal ocean model, oil spill risk, backtracking

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1. Introduction

Small Island Developing States (SIDS) are a unique group of nations that face distinct challenges due to their geographical, socio-economic, and environmental characteristics (Nurse et al., 2014). Comprising small land areas and isolated locations, SIDS are particularly susceptible to a wide range of vulnerabilities, including climate change, natural disasters, and limited resource availability (Betzold, 2015). Among these challenges, their heightened vulnerability to oil spills has emerged as a pressing concern with potential long-lasting consequences (Farbotko and Lazrus, 2012). Oil spills pose significant risks to SIDS, as their economies largely depend on coastal resources, particularly tourism and fisheries (Briguglio, 1995). Given the interconnectedness of marine ecosystems, oil spills can lead to the deterioration of coral reefs, mangroves, and seagrass beds, directly impacting the livelihoods of local communities (Nurse et al., 2014). Additionally, the tourism industry, which often serves as the economic backbone of these island states, can be severely affected by oil spills, resulting in reduced tourist arrivals and loss of revenue (Scheyvens and Momsen, 2008).

Due to their small size and limited resources, SIDS often lack the infrastructure and capacity to effectively respond to oil spills, further exacerbating the impacts on local ecosystems and economies (Campbell and Barnett, 2010). Strengthening their preparedness and response capabilities is crucial in order to mitigate the risks associated with oil spills. This may include the implementation of early warning systems, enhancement of regional collaboration, and the development of robust contingency plans (Farbotko and Lazrus, 2012). Addressing this challenge is essential for the sustainable development and resilience of SIDS in the face of

growing environmental threats (Nurse et al., 2014).

Seychelles, an archipelago in the Indian Ocean, is a typical example of a SIDS particularly vulnerable to oil spills (Campling and Rosalie, 2006). With tourism accounting for 42% of its gross domestic product (GDP) in 2019 (World Travel & Tourism Council, 2022). Seychelles' economy could be severely impacted by an oil spill. Although recent minor oil spills have been manageable through dispersant spraying (ITOPF, 2005), the country experienced a major incident in 1970 when the British tanker Ennerdale, carrying 41,500 tons of oil products, sank off the coast of Mahé (The New York Times, 1970). Another notable event occurred in 2020, when the MV Wakashio bulk carrier ran aground in Mauritius, resulting in the leakage of approximately 1000 tons of oil into the surrounding waters (Gurumoorthi et al., 2021). While not directly threatening Seychelles, this incident highlighted the vulnerability of Mauritius, a SIDS just south of Seychelles, to maritime pollution and the subsequent ecological and economic impacts.

While Seychelles has developed an oil spill mitigation strategy, which includes the Seychelles National Oil Spill Contingency Plan (NOSCP) to enhance preparedness and response capabilities (Government of Seychelles, 2018). There are several limitations that may hinder the effectiveness of these efforts. As a SIDS, Seychelles faces resource constraints in terms of financial, human, and technological capacity (Briguglio, 1995; Campling and Rosalie, 2006). This may affect its ability to invest in state-of-the-art equipment, infrastructure, and training required to efficiently manage and respond to oil spills. The archipelago's remote location also poses logistical challenges in accessing international support, resources, and expertise during an oil spill incident (Farbotko and Lazrus, 2012). Finally, the comprehensive monitoring of maritime traffic and potential oil spill

risks over a large sea area is very resource-intensive. Seychelles hence lacks the necessary infrastructure or technology, such as satellite and airborne synthetic-aperture radar, to continuously monitor its vast exclusive economic zone (EEZ) for potential threats.

The aim of this study is to enhance Seychelles' oil spill preparedness by pinpointing offshore regions posing the greatest risk to coastal areas of significant ecological or economic value in the event of an oil spill. To accomplish this, we employ a high-resolution ocean model to simulate ocean circulation over the Seychelles Plateau (SP) and utilize the generated currents to model oil spill dispersal across three consecutive years (2018-2020). The oil dispersal simulations produce monthly oil spill risk estimates, which are then integrated with shipping lanes and oil extraction maps for the SP to identify pollution exposure hotspots related to these activities. We recommend prioritizing monitoring resources in these identified areas.

2. Material and methods

To assess the vulnerability of Seychelles' coastal assets to oil spills, we simulate the dispersal of oil particles backward in time, starting from some selected sensitive coastal areas on SP. These simulations allow us to identify offshore areas from where an oil spill would have a high probability of reaching one of those sensitive areas, and to estimate the time needed for the spill to reach that area. The subsequent sections provides a detailed explanation of our methodology, beginning with a description of the study area.

2.1. Study area

The Seychelles archipelago is situated approximately 1200 km northeast of Madagascar in the western Indian Ocean (Fig. 1a). Comprising 115 islands that cover around 455 km^2 of land, only a third of them are inhabited (Podhorodecka, 2018). The nation's population of about 87,000 residents (McEwen and Bennett, 2010) primarily reside on the three main islands: Mahé, Praslin, and La Digue. These islands, along with others in the archipelago, are situated on the Mahé or Seychelles Plateau (SP, Fig. 1b), spanning approximately 40,000 km^2 (Seychelles Fishing Authority, 2019) and extending around 350 km latitudinally and 150 km meridionally (Castillo-Trujillo et al., 2021). The relatively shallow plateau, with an average depth of about 50 m, plunges to depths exceeding 2000 m at its edges (Castillo-Trujillo et al., 2021). The Seychelles archipelago holds significant ecological value. Due to its geographic isolation, the islands foster high levels of endemism. It is estimated that between 50 and 80% of animal species and 45% of plant species are endemic. Rocamora and Skerrett (2001) list 11 bird species that are endemic to Seychelles. Additionally, the coral reefs surrounding much of the Seychelles serve as habitats for numerous fish species (Techera, 2019).

Maritime traffic in the Seychelles primarily follows a North-South navigation axis across the SP (Fig. 1c). This axis leads through the port of Victoria, the archipelago's main port and point of entry for 95% of the country's imports (Agence Française de Développement, 2018). Ships navigate around the northeastern side of Mahé Island, potentially making this area more susceptible to oil spills (MarineTraffic, 2023). Additionally, there is shipping between Mahé, Praslin, and La Digue islands, as passenger transport catamarans connect them. Though Victoria is the primary port, its limited capacity often necessitates

berthing boats at the entrance. Currently, there is no active oil extraction on the SP. However, two areas within the plateau are under petroleum exploration licenses, and several wells have been drilled in the past, posing a risk of oil leakage on the plateau (Fig. 1d, PetroSeychelles, 2023). Moreover, the Cabinet of Ministers has approved a new petroleum exploration contract in the SP's southeast region (Zabasajja and Bhuckory, 2022).

For this study, we assessed the oil spill vulnerability of six coastal areas on SP that have a particularly high ecological and economic value (Fig. 1b). They include Seychelles' main marine national parks (MNP's) and protected areas such as Saint Anne MNP located east of Mahé, Port Launay and Baie Ternay on the northwest coast of Mahé, Silhouette MNP, Curieuse MNP, Denis Island and Bird Island. These protected areas play a crucial role in conserving the Seychelles' rich marine biodiversity and promoting sustainable tourism. We also considered the touristic islands of Praslin and La Digue, as well as the port of Victoria that plays a crucial role in Seychelles' economy as it is the main gateway for international trade, handling the majority of cargo traffic in and out of the country. It serves as a base for the country's fishing fleet and as a point of entry for cruise ships, yachts, and other vessels carrying tourists.

2.2. Oil dispersal model

We simulate oil spill dispersal using the open-source OpenOil model, developed by the Norwegian Meteorological Institute (Röhrs et al., 2018; Dagestad et al., 2017). OpenOil is a Lagrangian model that represents oil spills as ensembles of oil particles. The horizontal transport of oil particles is influenced by three processes: (1) ocean currents, (2) surface wind-generated waves through the Stokes drift, which is equal to 1.5% of the wind velocity at the surface and de-

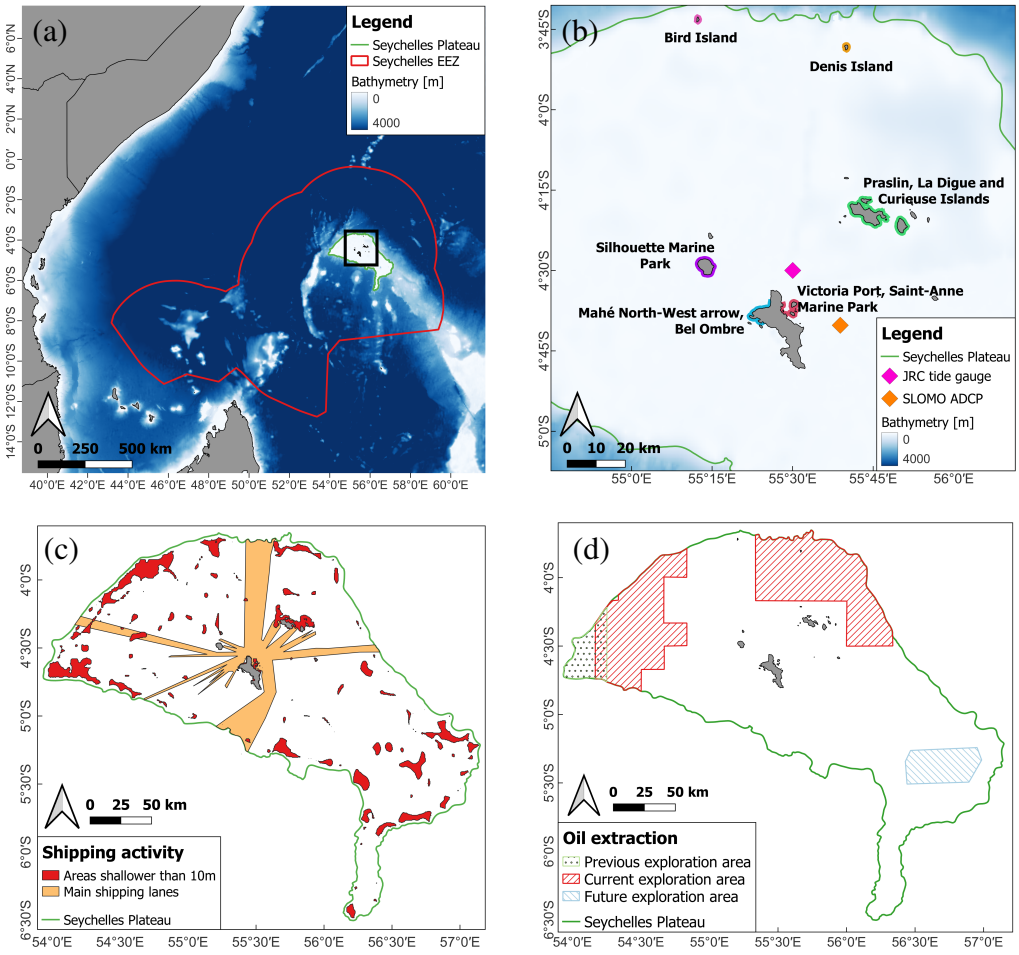

Figure 1: Overview of the area of interest with (a) the extent of Seychelles EEZ in the Indian Ocean, the bathymetry and the location of Seychelles Plateau (SP), (b) close-up view on SP corresponding to the black box in panel (a) with the locations of the 6 sensitive coastal areas, (c) the location of the main shipping lanes and accident-prone areas and (d) the location of past, present and future oil extraction areas.

creases with depth (Ardhuin et al., 2009; Jones et al., 2016; Breivik et al., 2016), and (3) wind, causing an additional surface velocity equal to 2% of the wind velocity. The oil spill vertical dynamics is influenced by several factors. First, breaking waves can entrain surface oil particles beneath the ocean surface (Jones et al., 2016). Second, oil particle buoyancy depends on oil viscosity, oil density, seawater temperature, salinity, and oil droplet size distribution (Tkalich and Chan, 2002). Finally, oil particles within the water column are subject to vertical turbulence, which depends on ocean stratification and shear stress. OpenOil accounts for these physical processes, which have been thoroughly parametrized and validated in multiple studies (Röhrs et al., 2018; Dagestad et al., 2017; Jones et al., 2016).

Oil spill transport simulations can be conducted forward and backward in time. The forward approach simulates the future movement of a spill from its release point to its final destination, estimating the area that will be affected by an oil spill from a specific location and time. This approach is typically used for operational forecasting and contingency planning (Zodiatis et al., 2016). In contrast, the backward approach simulates the spill's past evolution, starting from its final destination and moving backward in time to estimate the spill's origin (Batchelder, 2006). This method is most efficient when the impacted area is known but the pollution source remains unidentified. However, the backward approach does not consider oil weathering processes, which cause changes in the oil's chemical composition and physical characteristics. Consequently, the oil type has limited impact on the results, influencing only the vertical dynamics of oil particles through droplet size distribution, density, and viscosity. As Ciappa (2021) and Anselain et al. (2023), we set the duration for each backward simulation to 5 days. Within this timeframe,

the oil spill can typically travel a distance greater than the distance between the selected sensitive coastal areas and the boundaries of the SP, where our model is applied. The uncertainty regarding the spill's position increases with the duration of the simulation, due to both the diffusivity incorporated in OpenOil (set here to 2 m^2/s) to account for subgrid-scale processes, and the uncertainties in the oceanic and atmospheric forcings. Consequently, a 5-day duration has been chosen as an optimal balance between the accuracy and practicality of our results.

As the aim of this study is to assess the vulnerability of Seychelles' main coastal assets to oil spills, the backward approach is most suitable. We considered a distillate marine fuel of 35° API as this type of fuel is now steadily replacing the higher-viscosity and higher-sulfur heavy fuels that used to the standard shipping fuels. By choosing this type of fuel, we implicitly assume that the most likely source of pollution are shipping accidents and shipping operations such as ballast cleaning. Default values were used for droplet size and entrainment rate (Dagestad et al., 2017). Obviously, distillate oil is not representative of the crude oil extracted on SP. The precise oil type used in the simulation has however a limited impact on the backward oil spill modelling results, as it only influences the vertical oil distribution and not the oil weathering processes. We conducted a sensitivity analysis with other oil types and found very similar results. To initiate the backward simulations, oil particles were released from receptor points located 0.004° (≈ 400 m) away from the sensitive coastal areas and separated by 0.002° (≈ 200 m). The number of receptor points per coastal area depends on the length of the coastline. Bird and Denis Islands have the shortest coastline and hence the smallest number of receptor points (resp. 21 and 22). Praslin, La Digue and Curieuse Islands have together the longest coastline, which is represented by 228

receptor points. We released 15 oil particles from each receptor point every day of the 2018-2020 period at midnight. During the 3-year period, the transport of $\sim 7.79 \times 10^6$ particles was simulated.

The ocean currents that drive oil spill dispersal are simulated using the multi-scale ocean model SLIM[1]. SLIM solves the ocean circulation governing equations on an unstructured mesh, which allows for locally increased resolution to accurately capture variations in bathymetry and coastal topography. In this study, we focus on simulating the ocean circulation solely on the SP. Given its relatively shallow average depth of 50 m (Castillo-Trujillo et al., 2021), we employ the 2D barotropic version of SLIM. For the same computational cost, a 2D model can achieve a considerably higher horizontal resolution compared to a 3D model. In shallow areas like the SP, small-scale horizontal features are anticipated to have a more significant influence on large-scale oil dispersal patterns than vertical dynamics. The model mesh has a horizontal resolution reaching about 200 m along all the islands' coastlines on the SP. The resolution coarsens to about 4 km offshore. The model bathymetry is a combination of the GEBCO (General Bathymetric Chart of the Oceans) and ETOPO (Earth Topography) bathymetric data. Details on the bathymetry reconstruction are provided in Appendix A.

The SLIM model bottom stress is parametrized with a Chézy-Manning drag formulation and a Manning coefficient $n = 0.025$ m$^{-1/3}$s. The model is forced with wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis, which has a spatial resolution of 31 km and a temporal resolution of 1 hour. The same wind data is used in OpenOil as well. On

[1]SLIM: Second-generation Louvain-la-Neuve Ice-ocean Model, `www.slim-ocean.be`

the open boundary surrounding the SP, we impose a combination of the depth-averaged velocity provided by the Mercator global ocean analysis, produced by running the global data-assimilated ocean model NEMO on a 1/12° grid, and the tidal velocity obtained from the OSU TPXO9-atlas dataset (Egbert and Erofeeva, 2002). Although the Mercator global ocean analysis accurately reproduces the large-scale ocean circulation patterns in the Indian Ocean, we acknowledge that Vogt-Vincent and Johnson (2023) recently generated multidecadal simulations of the southwestern Indian Ocean with a finer horizontal resolution of 1/50°. However, these results were not available at the time we conducted this study. More details on the SLIM model formulation can be found in Lambrechts et al. (2008) and Hanert et al. (2023). SLIM has already been used to simulate flows on shallow submerged platforms or banks similar to SP such as the Great Bahama Bank (Lopez-Gamundi et al., 2022; Purkis et al., 2023) or shallow continental shelf areas such as the Great Barrier Reef (Australia, Lambrechts et al., 2008) and the Florida Reef Tract (Frys et al., 2020). More details on the model validation on the SP are provided in Appendix B.

2.3. Oil spill vulnerability indicators

The backward oil-dispersal simulations generate an ensemble of trajectories originating from receptor points around each sensitive coastal area on the SP and moving backward in time. We follow the approach of Ciappa (2021) to derive vulnerability indicators from the backward oil particles trajectories. By partitioning the sea surface with a 0.005° (≈ 500 m) resolution grid, we can calculate the number of trajectories intersecting each grid element during each month of the 2018-2020 period, as well as the travel time for the oil particles to move from the receptor points to the grid element. Dividing the number of trajectories crossing

each grid element during a specific month by the total number of trajectories originating from all the receptor points representing a sensitive coastal area during that time yields a probability map. This map indicates the probability of each grid element being a source of pollution that will reach the coastal area during that month. It can also be interpreted as the fraction of all oil released in that element during the month that would reach the sensitive coastal area.

Oil spill risk is formally defined as a combination of the probability of being affected by a spill and the resulting consequences. In this study, we assume that the consequences are comparable for all the selected coastal sites. Therefore, the risk indicator corresponds to the probability of an oil spill released within a 500 m grid element during a specific month reaching a particular coastal site. Monthly risk distribution maps have been averaged over the 2018-2020 period to account for interannual variability in the atmospheric and oceanic circulations on the SP. A time-of-arrival map can also be generated by considering the minimum time required for oil released in a grid element to reach the sensitive coastal area. Both probability and arrival-time maps were calculated for every month of the 2018-2020 period. We then averaged the data for each season (DJF, MAM, JJA, and SON) across the three years to obtain statistically reliable seasonal estimates.

Since the most likely source of oil pollution on the SP is currently maritime traffic, either through intentional or accidental releases, we can further refine the oil spill risk maps by combining them with the locations of the main shipping lanes and the most accident-prone areas, which we assume to correspond to areas shallower than 10 m (Fig. 1c). These areas include shallow sandbanks and coral reefs that present a higher risk of ship grounding and subsequent hull damage. We also considered offshore areas under oil exploration licence or where

oil extraction used to take place (Fig. 1d) as potential sources of pollution. By spatially integrating the oil spill risk distribution over the areas where an oil spill is most likely to occur, either because of shipping or oil extraction activities, we can estimate the total exposure of each sensitive coastal area to both sources of oil pollution and assess how this exposure varies during the year.

3. Results

Oil dispersal across the SP is primarily influenced by the residual ocean circulation and wind patterns. The ocean circulation exhibits distinct seasonality in response to the monsoon regime (refer to Appendix C for further details). Consequently, oil spills tend to spread more rapidly eastward during the austral summer and westward during the austral winter. To maintain conciseness, we present results for DJF (NW monsoon) and JJA (SE monsoon), as they best represent the seasonal variability observed on the SP. Comprehensive results for all sites and seasons are available as the supplementary online data.

3.1. Arrival time maps

The arrival time maps reveal the minimum duration needed for an oil spill originating from a specific offshore area to reach one of the sensitive coastal locations under study. "Mahé North-West Arrow, Bel Ombre" and "Victoria Port, Saint-Anne Marine Park" (Fig. 2a,a',b,b') are situated on opposite sides of Mahé Island, resulting in different arrival time patterns. The former is more protected from oil spills originating from the east of the plateau, while the latter is better sheltered from spills coming from the western part of the SP. During the DJF season, an oil spill released at the western plateau boundary could reach "Mahé

North-West Arrow, Bel Ombre" coasts in under two days (Fig. 2a). In the JJA period, spills starting at the eastern and southwestern plateau boundaries could reach "Victoria Port, Saint-Anne Marine Park" coasts within one to four days (Fig. 2b').

"Silhouette Marine Park" and "Praslin, La Digue, and Curieuse Islands" coasts (Fig. 2c,c',d,d') are geographically exposed from all directions. They face greater exposure to spills from the western side of the plateau during the austral summer and the eastern side during the austral winter. Moreover, an oil spill near Victoria Port, Seychelles' main port, could impact both studied areas within two to four days. Bird and Denis islands display the same general oil dispersal pattern as Silhouette and Praslin. However, since these islands are situated near the boundaries of the SP, which define the limits of the oil spill dispersal model, a significant portion of backtracked oil particles leave the plateau in under one day of simulation (see supplementary data).

3.2. Oil spill risk maps

The probability maps indicate the most likely locations from which an oil spill could impact SP's sensitive coastal areas. Since the consequences of an oil spill can be assumed to be similar for all coastal areas, these probability maps can be interpreted as the oil spill risk faced by the coastal areas. Offshore areas where an oil spill is most likely to occur can be superimposed over the risk maps to better highlight oil spill exposure to both both maritime traffic and oil extraction.

Regarding the northwest coast of Mahé and Bel Ombre, the extent of the risk distribution tends to peak during the austral summer (SE monsoon) when northeasterly currents expose these coastal areas to oil spills from the western part of the plateau (Fig. 3a). This exposure diminishes until the austral winter (NW monsoon), when these areas are geographically sheltered from dispersed oil spills

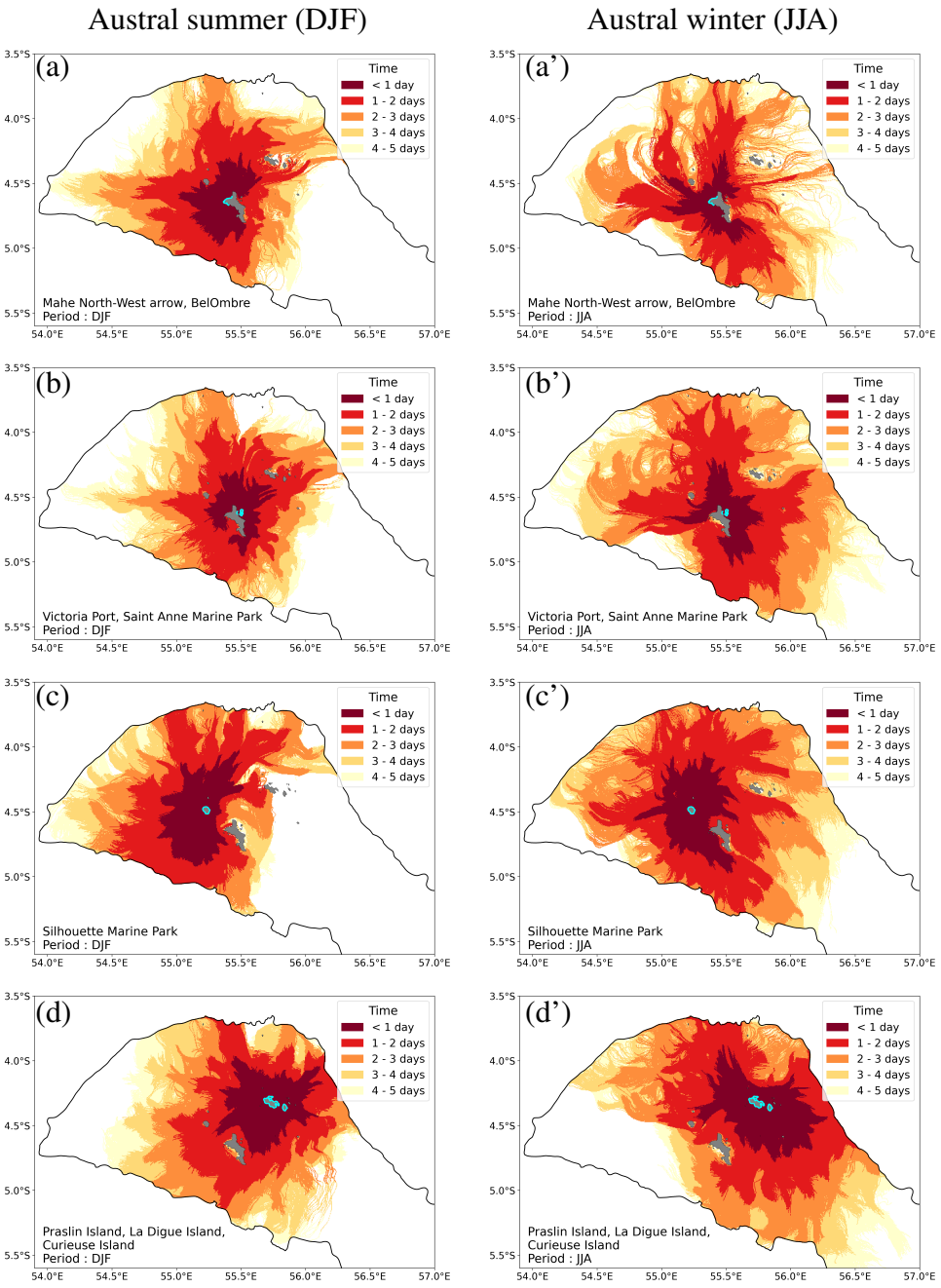

Figure 2: Seasonal variability of the minimum arrival time for an oil spill to reach the (a, a') "Mahé North-West Arrow, Bel Ombre", (b, b') "Victoria Port, Saint-Anne Marine Park", (c, c') "Silhouette Marine Park" and (d, d') "Praslin, La Digue and Curieuse Islands" coastlines. The sensitive coastal areas are highlighted in blue.

by south-westerly currents (Fig. 3a'). In this region, oil spill exposure primarily stems from maritime traffic, as the probability area only slightly intersects with oil extraction areas throughout the year.

In contrast, Victoria Harbour and St Anne Marine Park, located east of Mahé, are more at risk of being impacted during the austral winter by oil spills originating east of the SP (Fig. 3b'). However, these areas remain more exposed during the austral summer (Fig. 3b) compared to the exposure of the areas on the north-west coast of Mahé during the austral winter (Fig. 3a'). Although these coastal regions appear to have higher exposure to oil exploration areas than the previous ones (especially during the SON season, see suppl. data), they still face greater exposure to shipping routes. During the austral winter, a spill-threatening area can be observed heading north along the major north-south shipping route.

The Silhouette Marine Park (Fig. 3c,c') and the islands of Praslin, Curieuse, and La Digue (Fig. 3d,d') are more exposed to oil spills from the west during the austral summer and from the east during the austral winter. Silhouette experiences limited shipping and oil extraction exposure during the first part of the year (DJF and MAM), but this exposure increases during the remainder of the year. Praslin, Curieuse, and La Digue are exposed to both types of exposure throughout the year. Bird Island's coastline appears to have limited exposure to both potential sources of oil spills (Fig. 4a,a'). It is primarily exposed to accidents in the shallow area around the island, which is less than 10 m deep and therefore prone to boat accidents. Conversely, Denis Island (Fig. 4b,b') is situated within an oil exploration license area, making it highly susceptible to oil spill risks due to its proximity to oil extraction areas.

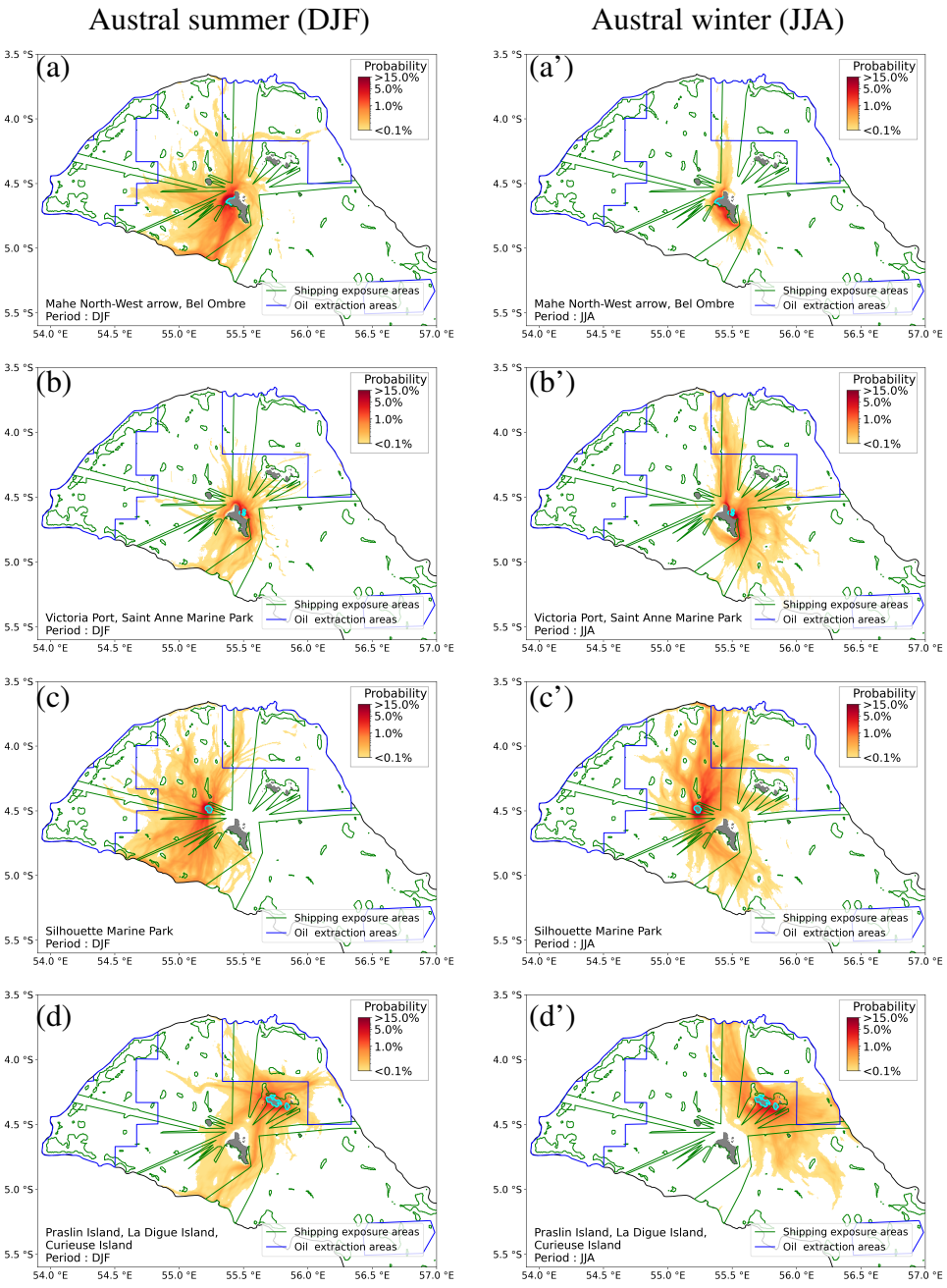

Figure 3: Seasonal variability of the risk distributions for an oil spill to reach the (a,a') "Mahé North-West Arrow, Bel Ombre", (b,b') "Victoria Port, Saint-Anne Marine Park", (c,c') "Silhouette Marine Park" and (d,d') "Praslin, La Digue and Curieuse Islands" coastlines. The sensitive coastal areas are highlighted in blue.

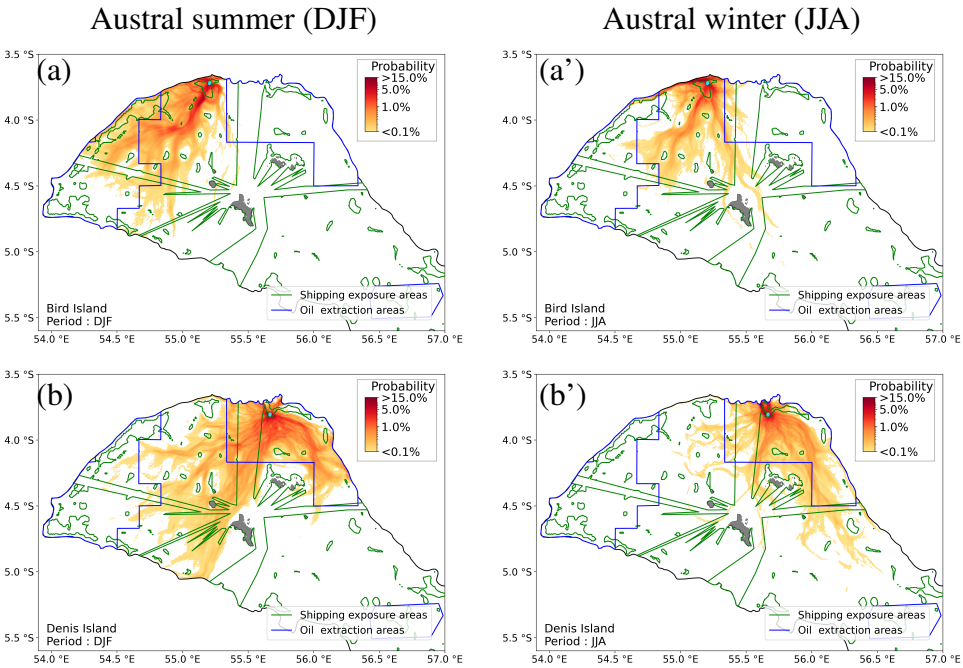

Figure 4: Same as Fig. 3 for (a,a') "Bird Island" and (b,b') "Denis Island" coastlines.

3.3. Total exposure to maritime shipping and oil extraction

The total exposure of each sensitive coastal area to pollution from both shipping and oil extraction has been calculated by spatially integrating the oil spill risk patterns over offshore areas with significant shipping traffic (Fig. 1c) and oil extraction (Fig. 1d) activities. These exposures to two different sources of pollution have then been monthly averaged over the years 2018-2020 and normalized with respect to the largest monthly value (Fig. 5). Overall, oil extraction pollution primarily affects Denis Island (Fig. 5a) since it is located within an oil exploration license area. The other sensitive sites, being farther from oil extraction areas, have considerably lower total exposure, which remains fairly stable throughout the year. The notable exception is Silhouette Marine Park, whose exposure increases during the austral spring (SON).

Shipping pollution exposure exhibits more variability (Fig. 5b). The total exposure time series of the two areas on Mahé Island ("Mahé North-West Arrow, Bel Ombre" and "Victoria Port, Saint-Anne Marine Park") are inversely related. The west coast faces greater vulnerability during the austral summer (DJF), while Victoria Harbor and Saint-Anne Marine Park are more vulnerable in the austral winter (JJA). This trend, evident in the risk maps from the previous section, results from the geographical positions of these areas and the change in the atmospheric and oceanic circulation patterns between the two monsoon seasons. The vulnerability of Mahé North-West Arrow and Bel Ombre coasts remains lower than that of Victoria Harbor and Saint-Anne Marine Park. This is because the main north-south shipping route passes east of Mahé (to reach Victoria Harbor), hence protecting the western coastal areas from pollution originating from this traffic, particularly during the austral winter.

The vulnerability of Silhouette Marine Park and the islands of Praslin, La Digue, and Curieuse to shipping pollution remains relatively constant throughout the year. This is because these areas are exposed from all sides (as all islands coastlines are considered), unlike the areas on Mahé Island, which are geographically protected for part of the year. As for Bird and Denis Islands, these sensitive areas display higher vulnerability during the austral summer and lower vulnerability during the austral winter. Due to south-westerly currents during this period and the islands' proximity to the plateau boundaries, a large portion of the backtracked oil particles are pushed outside the plateau. Consequently, this vulnerability may be underestimated.

4. Discussion and conclusions

The analysis of six sensitive coastal areas in the Seychelles Plateau (SP) reveals high vulnerability to oil spills, with strong seasonality driven by atmospheric and oceanic circulations. No part of the plateau can be considered risk-free, and any oil spill incident could potentially impact sensitive coastal areas in less than five days. The main north-south shipping route poses a significant risk to five of the six sensitive coastal areas for at least half of the year.

Offshore oil spill risk distributions exhibit considerable seasonal variability as they are influenced by winds, ocean currents, and waves, which change throughout the year. Surface oil particles are directly affected by winds and wind-induced waves, while denser oil particles and those in the water column become less influenced by wind with depth. Wind velocities are high over the SP, particularly during monsoon seasons, significantly impacting oil dispersal. The significant variation in ocean circulation and winds throughout the year results in substan-

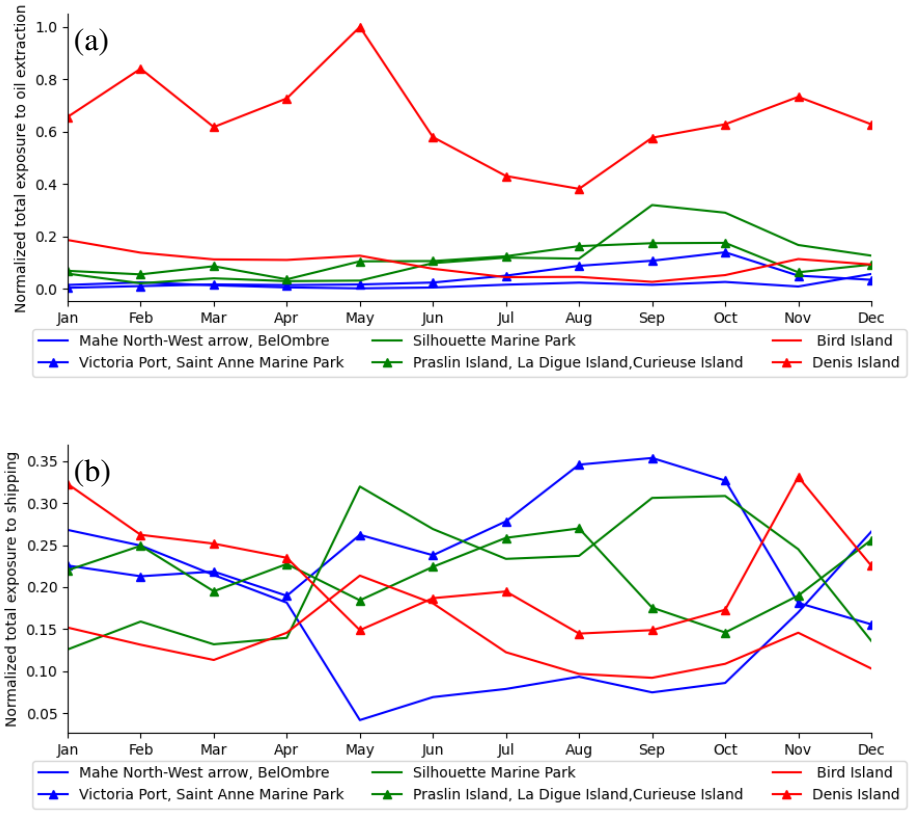

Figure 5: Monthly evolution of total (a) oil extraction and (b) shipping pollution exposure, defined as the spatial integral of the oil spill risk patterns over the offshore areas where those two activities take place, and normalized by the largest monthly value of both indicators.

tial changes in the areas threatening SP's coastlines. The strong seasonal shift in ocean circulation is due to the monsoon system. In a worst-case scenario, an oil spill originating from the northern part of the plateau could reach sensitive coastal areas in less than two days, necessitating an oil spill rapid response plan and efficient infrastructure to combat the spill.

Exposure to oil spills from shipping is primarily influenced by a north-south shipping route connecting to the Port of Victoria. Five out of six sensitive coastal areas are vulnerable to potential oil pollution events along this route for at least two seasons of the year. This route is especially threatening as it concentrates most of the shipping activity on the SP. Closely monitoring this route is essential for early detection of spills that could pose significant hazards to numerous coastal assets. Denis Island seems to be the coastal area most vulnerable to potential oil extraction activities, as it is located within one of these areas. However, the actual risk it may pose to Denis Island remains uncertain due to a lack of information regarding the exploration activities in the area, the number of wells that might be exploited in the future and their precise location.

Beyond assessing vulnerability to oil spills, this study could also contribute to the assessment of Seychelles coastlines' vulnerability to other drifting materials that remain relatively close to the ocean surface, and are transported under the combined influence of ocean currents, wind, and waves. The resulting offshore risk distribution is expected to be similar to those derived in this study. This could be the case, for example, with micro and macroplastics settling on coasts, an issue already observed in various locations throughout the Seychelles Archipelago (Dunlop et al., 2020). It could also be the case for jellyfishes, harmful algal blooms and sargassum.

This study has however some limitations due to assumptions made or inherent in the models used. First, the hydrodynamic simulations are limited by the availability of observational data for validation and heavily depend on the quality of the Mercator global ocean analysis for the external ocean circulation forcing, which might not be optimal (Lellouche et al., 2018). The SLIM model used in the study assumes a vertically homogeneous water column and is hence not suitable to simulate the circulation beyond the plateau boundaries. The vulnerability assessment could hence only be performed on the plateau and not over the entire Seychelles' EEZ. Furthermore, the study's three-year simulation may not capture the full interannual variability of ocean circulation in the area. To obtain more robust risk estimates, a broader range of simulated years might be necessary. The oil drift simulations are limited to a maximum duration of five days backward-in-time, while weathering processes, such as evaporation and biodegradation, have not been considered. Lastly, limited information about shipping and petroleum extraction poses a significant constraint to the study. Only high shipping density routes have been approximated, with no available spatial distribution of shipping density. For petroleum extraction, aside from areas currently under exploration licenses, there was no data on wells and their spatial distribution made by the company exploring those areas. Access to such information could help refine the study and enable a more quantitative comparison between total exposures to shipping and petroleum extraction.

Seychelles' oil spill vulnerability is shared by most SIDS. Given this vulnerability, it is crucial for SIDS to develop an oil spill monitoring and mitigation strategy. This may involve investing in infrastructure and technology to detect and respond to oil spills rapidly, as well as building capacity through training and

international collaboration. Given their limited resources, SIDS should prioritize their monitoring resources to the areas from where oil spills would pose the greatest threat to their coastal assets such as those identified here for Seychelles. Furthermore, integrating environmental risk assessments into development planning can help these nations better understand their vulnerabilities and adapt accordingly. By developing a robust oil spill monitoring and mitigation strategy, SIDS can better protect their unique ecosystems, economies, and communities from the devastating consequences of oil spills. Investing in these measures will enhance the resilience of these islands and ensure their long-term sustainable development.

CRediT authorship contribution statement

A. Verhofstede: Software, Investigation, Writing - review & editing. **T. Dobbelaere**: Software, Investigation, Writing - review & editing. **J. Harlay**: Conceptualization, Methodology, Writing - review & editing. **E. Hanert**: Conceptualization, Methodology, Writing - original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The oil spill arrival time and risk maps for the six selected sites, encompassing all four seasons, can be accessed at `https://doi.org/10.5281/zenodo.8414759`.

Code availability

The SLIM model source code can be found at `https://git.immc.ucl.ac.be/slim/slim`.

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Appendix A. Bathymetry reconstruction on Seychelles Plateau

We examined two bathymetric data sources for the SP: GEBCO (Fig. A.6a) and ETOPO (Fig. A.6b). GEBCO is usually preferred due to its higher resolution of 15 arc seconds compared to ETOPO's 1 arc minute resolution. However, we noted that GEBCO's bathymetric data depict an approximately 700-meter-deep trench in the northeastern part of the plateau (Fig. A.6a). This trench appears unrealistic on a shallow granitic plateau and, to our knowledge, has not been mentioned in any other studies.

To evaluate the accuracy of the GEBCO and ETOPO datasets, we compared them with single-beam bathymetric observations retrieved from the IHO DCDB[2], which is hosted by NOAA's National Centers for Environmental Information. Although no observations were collected directly in the area where the trench is

[2]International Hydrographic Organization's Data Centre for Digital Bathymetry, `https://www.ncei.noaa.gov/maps/iho_dcdb/`

located, those obtained in its immediate vicinity suggest that GEBCO is less accurate than ETOPO in that region (Fig. A.6c). Nevertheless, observations in other parts of the plateau indicate that GEBCO generally has higher accuracy than ETOPO (Fig. A.6d). Consequently, we decided to merge both datasets, utilizing ETOPO only in the region where the trench is situated and GEBCO for the rest of the plateau. The resulting bathymetry employed in the model is illustrated in Fig. A.7.

Appendix B. Hydrodynamic model validation

Although the hydrodynamic simulations span three years, the model has only been validated for 2018, as more observational data was available for that year. We validated the sea surface elevation using observations from a tide gauge situated north of Mahé island (WSL-925-Seychelles-Pt, 4.5°S, 55.5°E) , provided by the European Commission Joint Research Center's Space, Security, and Migration directorate, and the current velocities with Acoustic Doppler Current Profiler (ADCP) data from the Seychelles Local Ocean Modeling and Observation program (SLOMO), collected east of Mahé (Castillo-Trujillo et al., 2021, see location in Fig. 1b). The model accurately reproduces the tidal signal observed in the sea surface elevation time series (Fig. B.8). The root mean square error between the observed and simulated elevation over the entire year of 2018 is 7.5 cm.

ADCP velocity measurements east of Mahé suggest that the velocity field is relatively uniform in the vertical direction (Fig. B.9), which justifies the use of a 2D depth-averaged model for simulating oil dispersal over the SP. The simulated current velocity amplitude aligns with the observed values, although the model has a tendency to overestimate these values (Figure B.10a). Regarding the direction

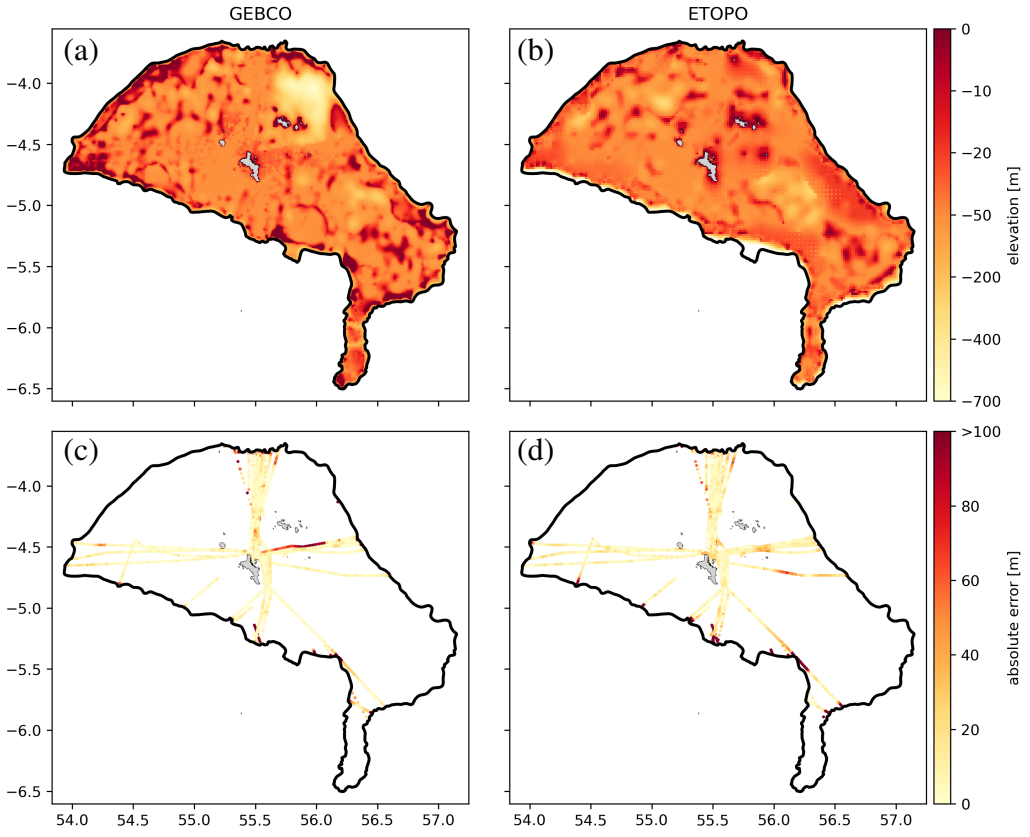

Figure A.6: Comparison between (a) the GEBCO and (b) ETOPO bathymetric data on the SP. The former exhibits a deep trench reaching about -700m in the northeastern part of the plateau that is not present in the latter. Both bathymetric data are compared with bathymetric single beam observations (c-d).

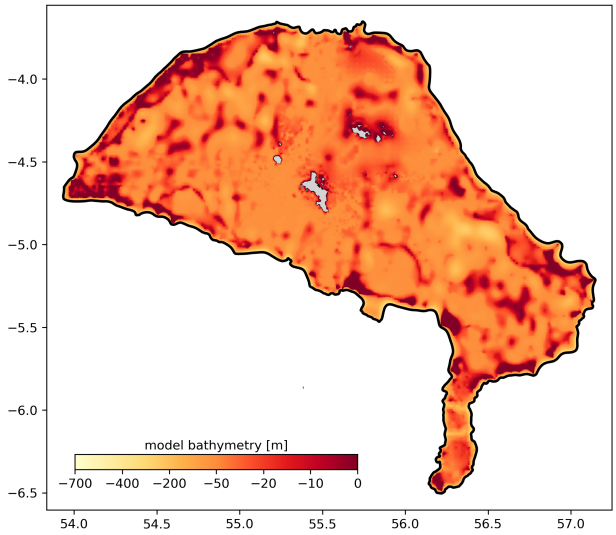

Figure A.7: Bathymetry used in the hydrodynamic model of SP. It has been obtained by merging the GEBCO and ETOPO bathymetric data.

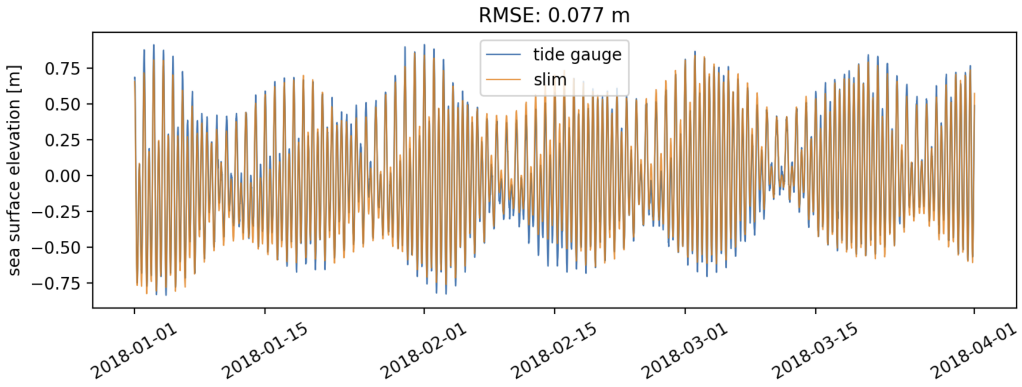

Figure B.8: Comparison of the observed and simulated sea surface elevation. The mean value of the time series was subtracted from all measures to obtain a signal with a zero mean in both cases.

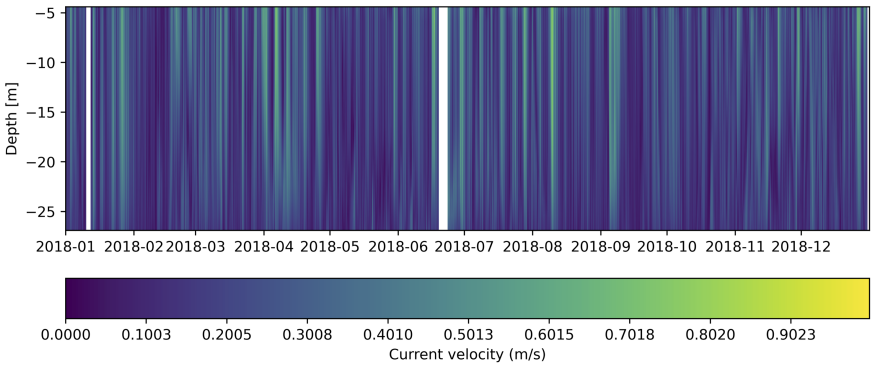

Figure B.9: Current velocity profile recorded by the SLOMO ADCP situated east of Mahé throughout 2018.

of the currents, the simulation often predicts more northward currents than those observed by the SLOMO ADCP (Fig. B.10b).

Appendix C. Seasonal circulation patterns 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), characterized by northwesterly winds, and the northwest monsoon during the austral summer (December to March), marked by southeasterly winds. In between these two monsoon seasons, the winds tend to be weaker and more variable (Castillo-Trujillo et al., 2021; Schott and McCreary, 2001). The SLIM model simulates northeasterly currents during the northwest monsoon, with peak current velocities ranging between 0.6 and 0.8 m/s, and southwesterly currents during the southeast monsoon, with velocities up to 0.5 m/s (Figure C.11). During the inter-monsoon seasons, the currents are generally weaker and more variable than during the monsoon seasons.

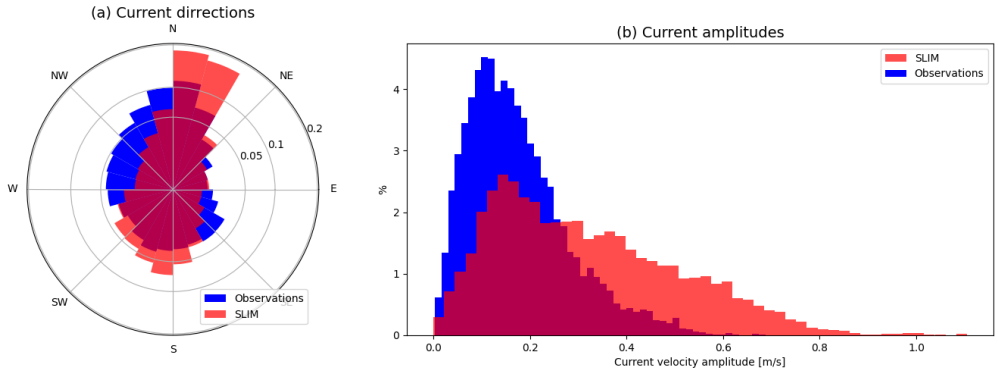

Figure B.10: Comparison of observed and simulated currents in terms of (a) current direction and (b) current amplitude for the entire year of 2018.

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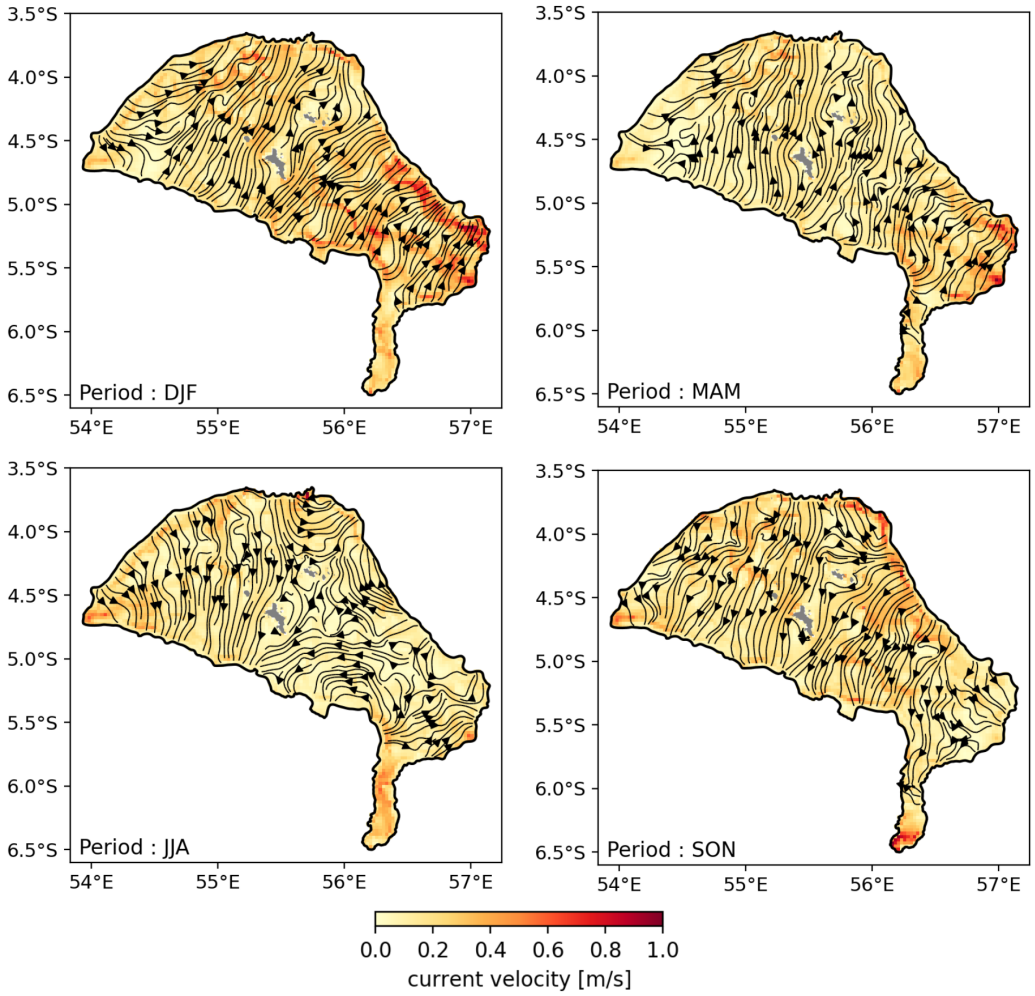

Figure C.11: Seasonal variations in the simulated residual ocean circulation over the Seychelles Plateau, as averaged seasonally from 2018 to 2020.

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