UCLouvain

École polytechnique de Louvain

Investigating the dispersal of hawksbill sea turtle hatchlings in the Arabian Gulf

From local-scale interactions with artificial structures to regional-scale distributions

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Preface

It has been quite a journey up until today to end these 5 years, or actually 6 years, of university with this thesis. 6 years because I first made the wrong choice before realizing that studying mathematics had always been the way it had to be. As a student in applied mathematics, I really wanted to take it a step further than only mathematics and apply all I've learned on some important real-life topic. In my mind, and I hope in yours as well, I have achieved my objective at the end of this thesis. Even though it might look silly, I have always been a big fan of nature and it is probably one of the first reasons why this topic attracted me so much. Despite doing the work only behind a computer screen and not being able to go on site to observe the turtles, I still enjoyed working on this a lot. I hope this work will open up a lot of possibilities for future research on the possible impact of artificial structures on sea turtle hatchlings.

First and foremost, I would like to thank Emmanuel Hanert for the amount of time he spent supervising my work during the whole year. Even outside of the weekly meetings he was always very available and ready to help. It was a real pleasure working with him and get to be a witness of his great teaching and leading skills. Thanks to him for all the guidelines and advises he gave me to write this thesis. Thank you also to Eric Deleersnijder for supporting the project. Thank you to Jean-Charles Delvenne from UCLouvain and Mark Chatting from Qatar University for agreeing to be the readers of this work. Thank you to Lauranne Alearts and Antoine Saint-Amand for the time they gladly spent helping me when I had specific questions. And to end this, I would like to address a very special thank you to Thomas Dobbelaere without whom I would never have been able to succeed in running all the experiments. I harassed him with questions and even though he had 3 other students to help as well as his own work, he never rejected helping me when I needed him.

Contents

Abstract

The lost years of sea turtles is a subject biologists are still very much investigating every day. Between the moment they hatch, battle to reach offshore water and then come back years later to lay their own eggs, very little is known about the journey of sea turtles. How to model the way they swim in order to get to safe places is one of the challenges that was faced. In this work, we will focus on Hawksbill sea turtles in the Arabian Gulf. How many leave the Gulf? Are they affected by the multiple artificial structures of Qatar? Thanks to the oceanic models SLIM and NEMO we will be able to simulate real life dispersal of the hatchlings. We will show that a small portion of hatchlings do in fact leave the Gulf and that they do not often interact with artificial structures such as Ras Laffan's LNG terminal or the Halul oil terminal. Artificial structures do not seem to disturb the hatchlings dispersal in a significant way. For the regional-scale analysis, we will observe that hatchlings seem to leave at speficic periods during the year and that there are certain areas in which they are more present than others in the Gulf. The results here seem to show that during their dispersal around the Gulf, turtles might, at certain periods, gather around certain areas such as the South Pars/North Dome gas condensate field. It also shows that, even though it is only a small fraction, some turtles might get trapped inside artificial structures and not be able to get out due to the currents. Perspective for future research on the topic is first to model the swimming of turtles in a more realistic way. Another improvement that could be made is to take a model that has better resolution near the coasts for the regional-scale analysis as the NEMO model is limited in that regard. Hopefully this is a step towards making sure of the well-being of sea turtles in the Gulf.

Chapter 1

Introduction

1.1 Disappearance of sea turtles

Most of the living creatures on earth are not prepared to suffer from fast changes in their living conditions. Over the two previous centuries, human activity and climate change has made it almost impossible for some species to survive. Sea turtles are one of these. Sea turtles are present around the whole planet, from the Carribean sea to the Coral triangle in Australia and to the Arabian Gulf for example.

Sea turtles are an endangered species due to five main factors [1]. The first of those threats is overfishing [2] and it has many consequences. Industrial fishing has been happening for centuries but it has developed a lot more since the start of the 20th century [3]. Fish help maintaining the coral reefs healthy. Corals reefs are one of the main food resources for turtles. Thus, less fish implies unhealthier coral reefs, which in turn implies that turtles have less food to catch. But more importantly, the development of longlines, gill nets, and trawls kill thousands of sea turtles each year. turtles get entangled into the fishing nets and cannot go to the surface to breath, but those fishing nets also destroy the turtles natural habitats like seagrass beds and coral reefs.

The second cause of the disappearance of sea turtles is overharvesting and illegal trade. They are killed for human consumption of their meat and eggs but also for some of their bodyparts and to make medicines, religious ceremonies, etc. Even though the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) [4] prohibits trade of all species of sea turtles and their parts, tens of thousands of sea turtles are killed every year due to that [5]. For example, in 2021, illegal fishing has devastated sea turtles in Kenya because there was less surveillance due to the COVID-19 crisis [6].

Thirdly, coastal development harms sea turtles in many ways. It not only destroys their nesting beaches, but also alters the seafloor due to dredging, traffic and construction [7]. Without their nesting beaches, turtles cannot survive. Another effect of coastal development is that the lights around the nesting beaches (coming from roads, buildings, etc.) can disorient hatchlings from the sea as they orient themselves thanks to the moonlight reflecting on the ocean. Traffic on the beaches makes it impossible for turtles to dig their nest because the sand is too compact.

Ocean pollution and marine debris are also impacting sea turtles. They can often mistake floating plastic debris for jellyfish and die choking because of that. They can get trapped in what is called "ghost gear", discarded or lost fishing gear which causes them to drown or to be unable to feed themselves. Trash that lies on the beach can also trap hatchlings while they try to reach the ocean. Water pollution by oil or other chemical pollutants also poisons the turtles, which causes their immune system to weaken and make them vulnerable to diseases [7].

Lastly, we can say that climate change may be the biggest threat to the sea turtles' survival. It affects all stages of a sea turtle's life. More extreme weather events [8] that causes the loss of nesting beaches, increases the temperature of the oceans which then causes the whole marine ecosystem to disfunction. The rise of the temperature even impacts the sex ratio of hatchlings as fewer male hatchlings are born [9].

1.2 Why sea turtles matter

Sea turtles play a key role in maintaining the balance of the ocean ecosystem. They have graced our oceans and contributed to its well-being for the past 100 million years. Some of the species help maintaining the health of seagrass beds by feeding on it [10] : they act as seagrass lawn mowers. Those seagrass beds are fundamental because they help fish, crustaceans and other marine species to feed [11] and to live which in turn feed other fish species, etc. Sea turtles help control the population of some marine species like jellyfish, sponges, etc. They[12] are also the preys of other species such as birds, crabs, mammals, and fishes that feed on turtle hatchlings [13] while adults are preys for sharks, orcas, etc.[13]. Less turtles would mean less food for all these species. An ecosystem is like a chain : lose one link and the others will follow.

Not only are sea turtles part of the marine ecosystem, but they also have great influence outside the water. Sea turtles play a great role in the beaches and dunes ecosystem [14]. Sand is very bad in holding nutrients which means very little vegetation can grow on the beaches and dunes. Sea turtles lay their eggs in the sand of beaches and lower dunes. For example, on a 30 km long beach, sea turtles lay more than 68 tons of eggs during the summer nesting season [15]. Not every nest will hatch, not every egg among every nest will hatch, and among those who do hatch, not all hatchlings will make it to the sea. Those dead hatchlings furnish crucial nutrients to the dunes and beaches ecosystem [14]. Even the empty shells from eggs that did hatch will furnish nutrients to the beaches and dunes [14]. This allows vegetation to grow stronger and improve the whole ecosystem. It will prevent the erosion of beaches and dunes.

Since turtles are a main part of two very important ecosystems, it is clear that marine turtle protection cannot be neglected. Sea turtles have been there for more than a 100 million years and can help to make people aware of the seriousness of the situation.

1.3 Lost years of sea turtles

Figure 1.1: Hatchlings reaching trying to reach the ocean.

Very little is known about the first few years of sea turtles before they come back to beaches as teenagers. This is period is often called the "lost years" of sea turtles [16]. During their adult life, sea turtles travel thousands and thousands of kilometers. But first, hatchlings have an enormous step to make if they want to get to the oceans when coming out of their eggs. Sea turtles lay their eggs in nests that they dig in the sand of beaches or dunes. Hatchlings come out of their eggs, "buried" in the sand, all at once. The reason for that is [17] that it has an anti-predator role. When these eggs hatch, hatchlings have to get out of their nest, travel from the beach to the ocean and then swim offshore to go into deeper waters in order to get away from predators like crabs, raccoons, boars, birds, coyotes depending on the region they live in [18].

1.4 Aim of the research

The aim of this thesis will be to investigate the dispersal patterns of Hawksbill turtle juveniles from the main nesting beaches in Qatar. Since sensors cannot be put on juveniles because they are too heavy, very little is known about what happens to them during the first few years of their life. The two main research questions we will try to answer to in this thesis are :

- What fraction of the Hawksbill turtle juveniles originating from Qatar nesting beaches could leave the Arabian Gulf?

- What is the effect of artificial structures, such as the industrial port of Ras Laffan , on the dispersal of Hawksbill turtle juveniles ?

In order to answer the first question, the NEMO Ocean model will be used with data that has already been processed. For the second question, it will be the SLIM ocean model that will be used and that allows to simulate some areas of the Gulf in greater detail.

Chapter 2

Context

2.1 Hawksbill sea turtle

2.1.1 Characteristics

Hawksbill sea turtles (*Eretmochelys imbricata*) are named after their narrow and pointed beak. It can be found in various places around the planet (Fig 2.1). Hawksbill sea turtles mainly live in tropical and sub-tropical waters near coral reefs. Hawksbills's lifespan is unknown but is estimated to be at least 50 years [19].

Hakwsbills are an omnivorous species that feed mainly on sponges that they find on coral reefs, for which their hawk-like beak is perfectly suited. They also have very distinct patterns on their shelves that look like snake scales and for which they are hunted for. Their shell is known as the "tortoise shell" [21] and is used for jewerly and trinkets. Hawksbill sea turtles are fundamental in the marine ecosystem as they maintain the health of coral reefs by eating sponges on the reefs which then allows reef fish to feed more easily [22]. Hawksbills are, as many other sea turtle species, a highly migratory species [23]. They can travel thousands of kilometers from nesting beaches to foraging sites [2].

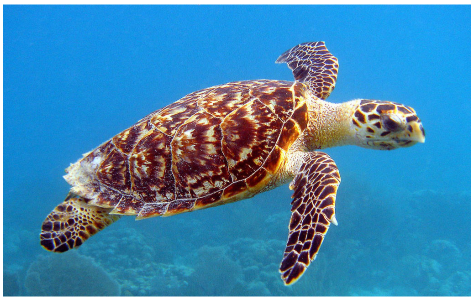


Figure 2.1: Picture of a Hawksbill sea turtle [20]

2.1.2 Reproduction

Even though the CITES (Convention on International Trade of Endangered Species, [25]) forbids any trade of turtle products (such as shell and meat), illegal hunting

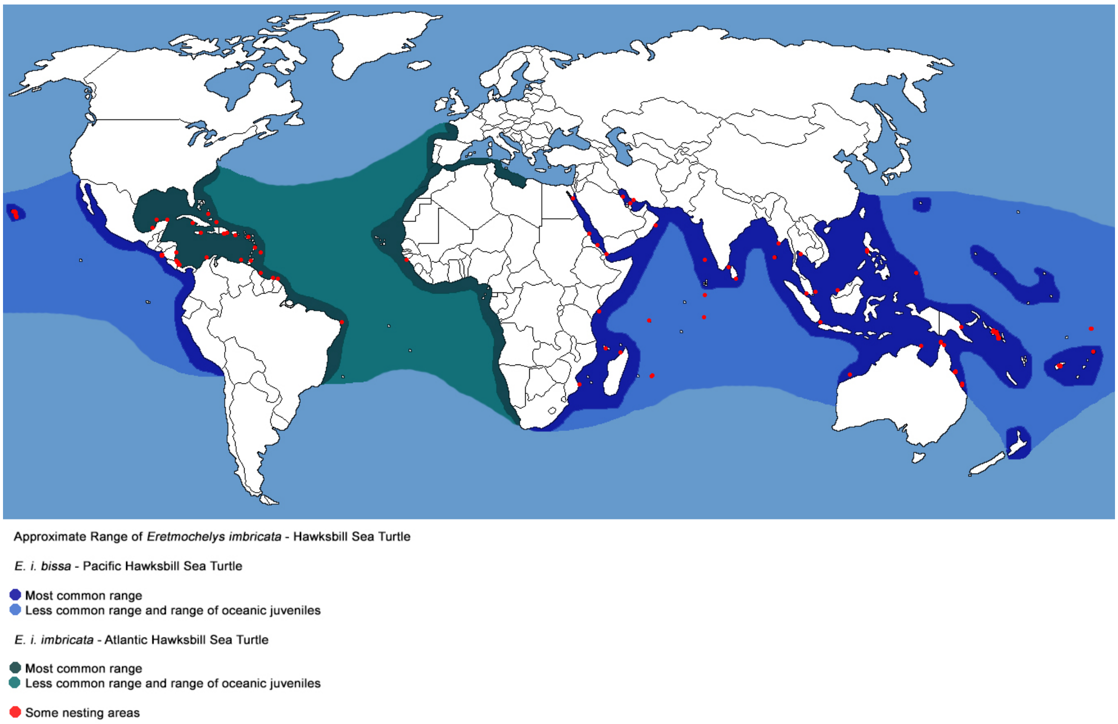


Figure 2.2: World map of Hawksbill sea turtles main living areas and nesting places [24]

still threatens this species around the world [2]. Over the last century, scientist estimate that the population of Hawksbill sea turtles has declined by 80 %.

Hawksbill sea turtle are very fertile. The nesting season lasts for approximately 6 months between April and November ([2]) and takes place every two years. During a nesting season, a turtle can come back to lay eggs up to 5 times with each nest containing approximately 70 eggs [26] (nests can contain up to 250 eggs [27]). Females always come back on the beach they were born to lay their eggs. To do so, they dig holes in the sand from 10cm to 100cm [28]. After their eggs are laid, it takes around 2 months of incubation for the eggs to hatch [28]. Once they get out of the shell of their egg, the hatchlings have to go through the beach to get to the ocean. During the crossing of the beach they are very vulnerable to predators like birds (waders for example), foxes and other land mammals [28]. Even after reaching the ocean, the adventures of the hatchlings aren't over. During their time in the shallow waters of the ocean, there are many birds and fishes, sharks and whales that hunt them.

2.1.3 Migratory Activity of hatchlings

Once sea turtles reach the ocean after battling to survive through the beach, their struggle isn't finished and they have to adopt the most efficient strategies to avoid predators. The main strategy of sea turtle hatchlings is to swim to deeper waters as fast as possible through what is called "the swimming frenzy", a continuous swimming gait (power stroking). This swimming frenzy can last up to several days. ([29]) . Surprisingly, this is not the method Hawksbill hatchlings adopt to have the most chance of survival [30]. Hawksbills adopt a relatively inactive survival method.

To measure the swimming speed of hatchlings, F.C. Chung et al. proceeded the following way :
To try and make the measurements as close to reality as possible, the experiences were made on the night at the scheduled hatchling emergence. Multiple nests were chosen, and among these a few hatchlings were picked for the experience. Light monofilament fishing lines of 2.0m were tied around the hatchling's shells and they were then released on the beach 1.0m from the water. Once they swum 1.0m in water (around $30 - 40$ cm water depth), hatchlings were held in place for some time and released again for a 2.0m distance. After measuring the time required to complete this movement, the experience was repeated 5 times for each hatchling. This process gave approximations of the swimming speed of hatchlings during their first days of swimming. The conclusions of this study were that the method used by Hawksbill hatchlings is to be relatively inactive during the first 7 days of swimming [30]. Hatchlings couple inactivity periods with less "active" swimming. Instead of using power stroking, the fastest swimming gait, they use drag-based swimming like "rear-flipper kicking" and "dogpaddling". The hypothesis is that it might make them less detectable by predators by doing so. They mimic dead leaves or other floating objects and let themselves drift at the surface. The reason for this particular survival strategy is unknown but some of the hypothesis are that since Hawksbill hatchlings are smaller than other sea turtles, they cannot swim as fast. This hypothesis has been proven wrong since studies [30] have found no link between size and swimming speed. An alternative hypothesis suggests the migratory strategy used is thus the cause of the slower swimming, and not its consequence [30]. After 5 to 6 days of "calm" swimming, Hawksbill hatchlings start to swim faster during a few hours a day, using fast swimming gait like power stroking more than drag based swimming gaits. This might be because they have now reached deep enough waters for them to be able to search for food and don't have to worry as much about predators anymore [30].

2.2 Arabian Gulf and Qatar

The Arabian Gulf, hereafter just called the Gulf, is located in the Middle East between latitudes 24 ° and 30 ° North [31] and between longitudes 48 ° 57 ° East. The countries surrounding the Gulf are Qatar, Bahrain, Saudi Arabia, Oman, the United Arab Emirates, Iran, Kuwait and Iraq.

Figure 2.3: Map of the Arabian Gulf

The Gulf is a large and shallow enclosed basin. It can be seen as an extension of the Indian Ocean. The area covered by the Gulf is approximately 230 000 km^2 [32]. Most of the countries surrounding the Gulf base their economy around oil [33] but the Gulf also has a big touristic activity thanks to its flora and fauna attractions. Even though it has extreme environmental conditions [34], the Gulf is a place with more biodiversity than one could expect. An example of the extreme conditions is that the water temperature of the Gulf can vary from 15 ° to 36 ° between winter and summer seasons [34].

Seagrass meadows (or seagrass beds) are an important marine biotope [35]. Sea turtles and other animal species feed on those seagrass beds. Seagrass is also helpful as a filter to some pollutants. They cover around 7000 km^2 [7] of the Gulf. The Gulf also shelters coral reefs, one of the most important ecosystems on earth. The coral reefs in the Gulf are the most thermally tolerant in the world [36]. Coral reefs are a multitask animal species : they provide food, maintain habitat and have economic benefits [37] as they attract tourists. Without them, very little flora would be able to survive. Unfortunately, coral reefs in the Gulf are threatened by human activity (dredging, pollution,...). Over 70% of the original coral reefs have been lost according to [7] and 27% of the remaining coral reefs are extremely endangered.

Inside the Gulf, a small peninsula is the home of a lot of sea turtles nesting beaches [38]. This peninsula is a country named Qatar. Qatar covers only 12000 km^2 of land but is a key place for sea turtles. Its beaches are widely used by sea turtles to lay their eggs. The 3 main places of nesting in Qatar are Fuwairit, Ras Laffan and the Halul island [38]. In 1996, the Industrial city of Ras Laffan was created and is now used for its natural gas resources. This has big environmental consequences not only on the sea turtles' nesting but also on the flora surrounding Ras Laffan. Ras Laffan's industrial city produces a lot of pollution which endangers the surrounding vegetation and animals.

2.3 Hawksbills in the Gulf

Marine turtles have been swimming in the Gulf's waters for more than 7 millenials [39]. In the recent years, marine turtles of the Gulf have been under pressure for survival due to the large shipping densities [40] and many other threats such as commercial and recreational fishing. As the main threats that endanger marine turtles have already been covered in previous sections, we will here focus specifically on the migratory activity and foraging areas of Hawksbills inside the Gulf and more specifically near the coasts of Qatar. The Gulf shelters different species of sea turtles such as green turtles, Hawksbill turtles, Olive ridley turtles and even, and on rarer occasions, loggerhead and leatherback turtles [41] [40].

Nesting sites of Hawksbills in the Gulf is a well known subject but little is known about their dispersal. According to the research [40] from Nicolas J. Pilcher (figure 2.5) we can observe the trajectory of 90 post-nesting turtles from the Gulf up to the Gulf of Oman. Hawksbill sea turtles are spread around the world but here we will focus only on the population of the Gulf and whose nesting beaches are in Qatar. According to [9], more than 100 female Hawksbill sea turtles nest on the Qatar beaches every year while according to [38] it is around 200 female that nest in Qatar every year. The main nesting sites in Qatar are displayed on

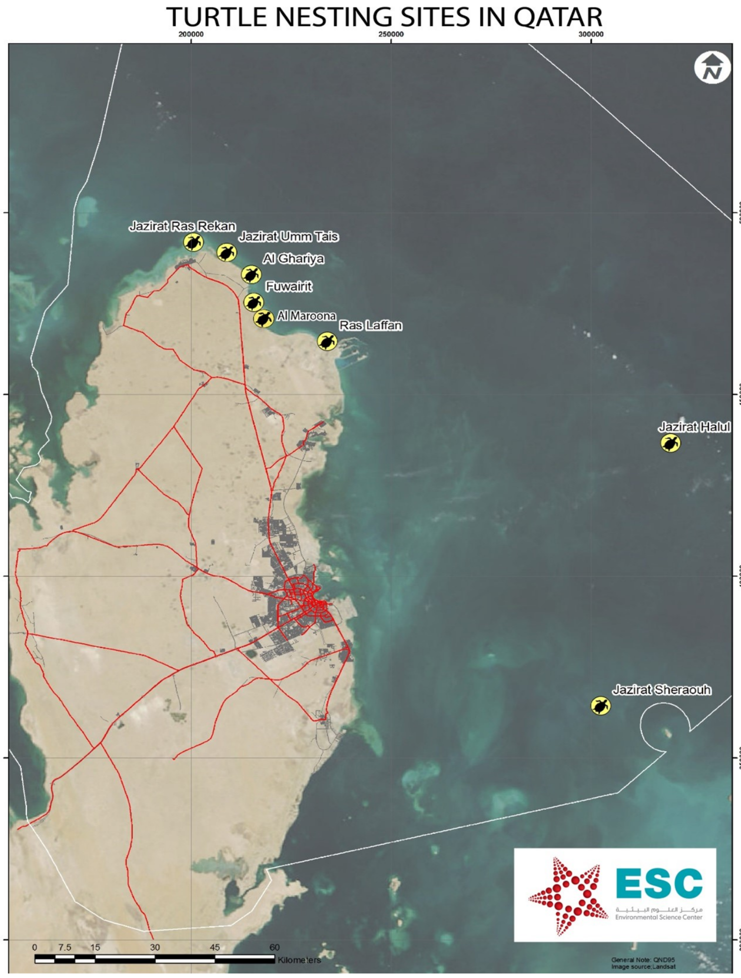


Figure 2.4: Main nesting sites of Hawksbills in Qatar [42]

figure 2.4 and these will be used for the simulations. To have a general idea of how the turtles could be moving inside the Gulf, we can look at figure 2.6 that displays the predominant surface water currents in the Gulf. As Hakwsbills are not fast-swimming turtles, their trajectory will be strongly influenced by the currents. This will appear clearly in the results.

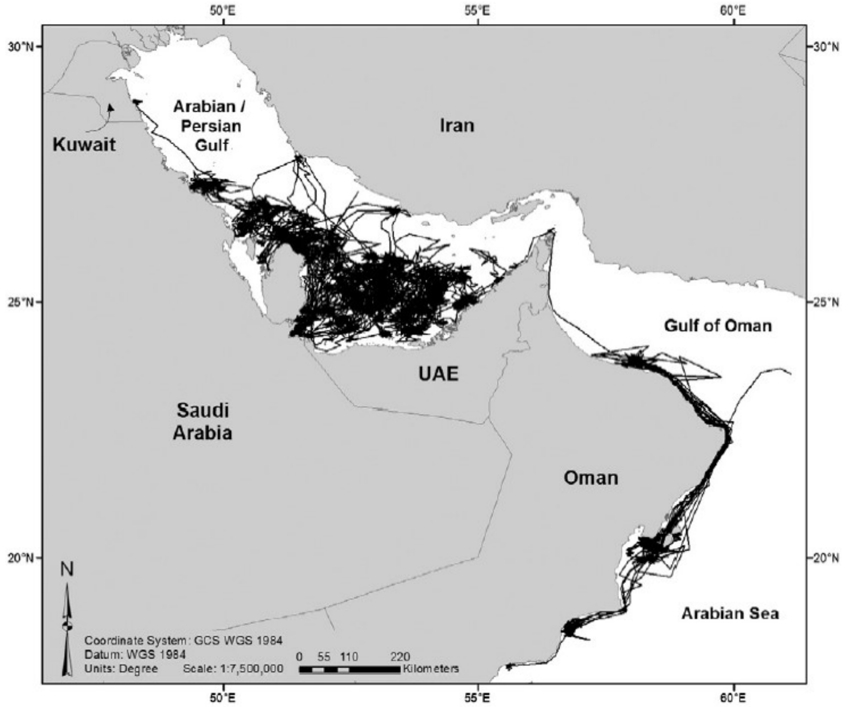


Figure 2.5: Post nesting trajectories of 90 turtles [40]

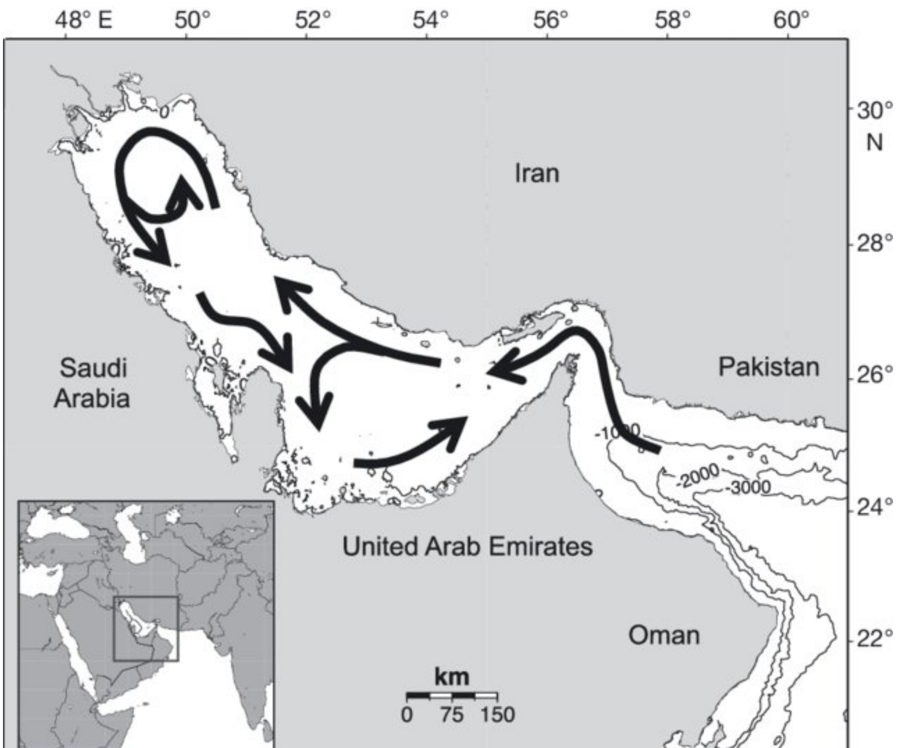


Figure 2.6: Plot of the predominant surface water currents in the Gulf [38]

Chapter 3

Material and methods

In this study, we follow a 3-step sequence to model the dispersal of Hawksbill turtle hatchlings in the Arabian Gulf and estimate their interactions with artificial structures as well as the fraction that leaves the Gulf. We first simulate the ocean circulation in the Gulf at both the local and regional scales. This is done by using two different models: SLIM for the local scale and NEMO for the regional scale. We then use those currents to simulate hatchlings dispersal with a biophysical model that represents different swimming behaviours. Finally, the biophysical model outputs are analysed with different indicators.

3.1 Local-scale ocean circulation model: SLIM

We used the multi-scale coastal ocean model SLIM[1] to simulate the fine-scale details of the ocean circulation around artificial structures. SLIM is a hydrodynamic model developed at UCLouvain that uses unstructured grids to solve the ocean circulation governing equations with the discontinuous Galerkin finite element method [43]. There are 1D, 2D and 3D versions of the model depending on the geometry of the area of interest and the main processes driving the flow. For this study, we use the 2D barotropic version, which solves the depth-averaged "shallow water" version of the full 3D ocean circulation equations that assumes a constant density and a small aspect ration. The model equations can be expressed as:

$$\frac{\partial \eta}{\partial t} + \nabla.(H\mathbf{u}) = 0, \tag{3.1}$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -f\mathbf{e}_z \times \mathbf{u} - g\nabla\eta - \frac{g\,\|\mathbf{u}\|\,\mathbf{u}}{C^2 H} - C_S\frac{|\mathbf{u}\cdot\nabla H|}{H}\cdot\mathbf{u} + \frac{\tau}{\rho H} + \frac{1}{H}\nabla\cdot(H\nu(\nabla\mathbf{u})), \tag{3.2}$$

[1]Second-generation Louvain-la-neuve Ice-ocean Model, `http://www.slim-ocean.be`

where h $[m]$ is the reference water depth, η $[m]$ is the sea-surface elevation such that $H = h + \eta$ $[m]$ represents the total water column height. $\mathbf{u} = (u_x, u_y)$ $[\frac{m}{s}]$ represents the 2-dimensional horizontal depth-averaged velocity vector, f is the Coriolis factor $[\frac{1}{s}]$, $\mathbf{e}_z$ is a vertical unit vector pointing upwards, g is the gravitational acceleration $[\frac{m}{s^2}]$, τ is the surface wind stress $[\frac{N}{m^2}]$, ρ is the water density $[\frac{kg}{m^3}]$, ν is the water horizontal kinematic viscosity $[\frac{m^2}{s}]$, C is the Chezy bottom-stress coefficient $[\frac{m}{s^2}]$ and C_S is the numerical slope stress coefficient $[\frac{m}{s^2}]$.

The Chezy bottom-stress coefficient is defined as : $C = \frac{H^{1/6}}{n}$ with n being the Manning coefficient and defined as : $n = 0.025[m^{-1/3}s]$ [44]. The surface wind stress τ is computed with the following formula :

$$\tau = \rho_{air} C_D \left\| \mathbf{u}_{10} \right\| \mathbf{u}_{10} \tag{3.3}$$

where ρ_{air} is the air density, $\mathbf{u}_{10}$ is the wind speed $[\frac{m}{s}]$ 10 meters above the sea surface and C_D is the drag coefficient which is computed thanks to the Smith and Banke formulation [45] :

$$C_D = 10^{-3}(\alpha + \beta \left\| \mathbf{u}_{10} \right\|) \tag{3.4}$$

with $\alpha = 0.63$ and $\beta = 6.610^{-2} \frac{s}{m}$. For the viscosity ν, SLIM uses the Smagorinsky parametrization [46]:

$$\nu = (\tilde{C}_S \Delta)^2 \sqrt{2(\frac{\partial u}{\partial x})^2 + 2(\frac{\partial v}{\partial y})^2 + (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2}, \tag{3.5}$$

where $\tilde{C}_S = 0.1$ is the Smagorinsky coefficient [47] and Δ is the local mesh size and (x, y).

The model bathymetry has been retrieved from the open-source GEBCO[2] [48] database. The bathymetry of the Gulf is generally quite shallow with most of the Gulf shallower than 100 m (Fig. 3.1). Qatar's territorial waters are even shallower as a large part of them have less than 20 m depth. It's important to note that the bathymetry around and within artificial is often dredged to allow the passage of large vessels. Information on the precise location of dredged channels and their depth is usually not public and hence not included in the GEBCO dataset. There might therefore be discrepancies between the model bathymetry and the actual water depth around the Port of Ras Laffan.

The model equations are forced with the large-scale atmospheric circulation, astronomical tides and the currents from the Gulf of Oman. Atmospheric variables such as the wind velocity and the at atmospheric pressure were taken from the ERA5 [49] dataset from the European Centre for Medium-range Weather Forecasts (ECMWF). The tidal velocity and elevation data come from the OSU TPXO9-atlas dataset [3], computed on a $\frac{1}{30}^\circ$ grid. The large-scale currents and sea elevation data

[2]General Bathymetric Chart of the Oceans

[3]https://www.tpxo.net/global/tpxo9-atlas

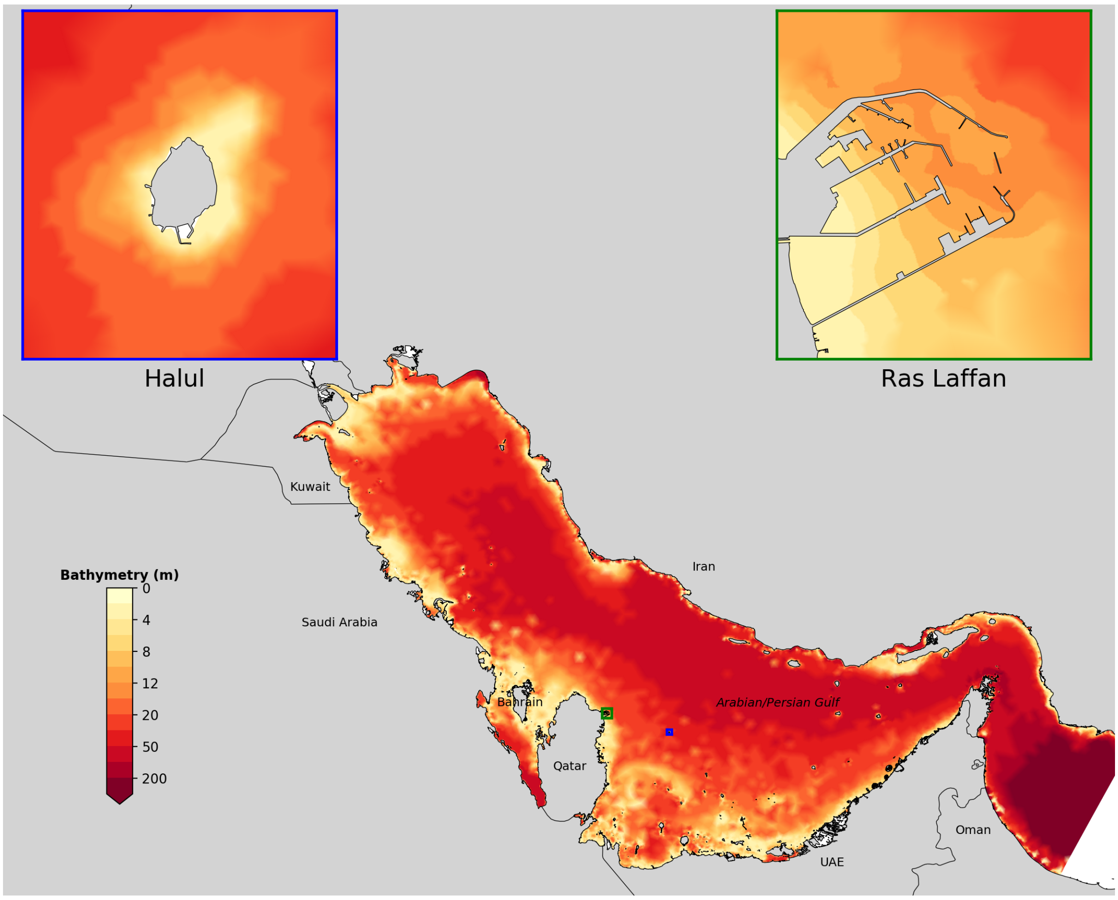


Figure 3.1: Bathymetry of the Gulf used for this study with close-up views on the LNG terminal of Ras Laffan and the oil terminal of Halul Island.

comes from the Copernicus Marine Environment Monitorings Service (CMEMS [4]).

3.1.1 Mesh generation

SLIM numerically solves the governing equations on an unstructured mesh generated with Gmsh [50]. That allows us to locally increase the model resolution in areas of particular interest, such as along the coastline and around artificial structures, while keeping it coarser elsewhere. As the region of interest includes the entire Arabian Gulf but with a particular interest on the area near the turtles nesting beaches in Qatar, we produced a mesh with a particularly fine resolution in the vicinity of those beaches and a coarser resolution elsewhere to optimize computational resources. To generate a mesh with Gmsh, we first have to provide a *.shp* shapefile

[4] https://marine. copernicus. eu

(generated with *QGIS* [5]) that defines the domain topography. That file contains all the boundaries of the domain as polyline. That boundary can be divided in different parts that will have a specific tag (e.g. "coast" for closed boundaries). We will then also assign a specific mesh resolution for all these tags. This allows us to fix a fine mesh resolution along the coastline and then let the mesh resolution smoothly decrease (hence becoming coarser) as we move away from the coast. This transition in the mesh resolution is obtained thanks to the following function :

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

In this work, we have considered 3 different coastal mesh resolutions :

- Default for all the coastlines : $l_0 = 2km$, $l_1 = 10km$, $d_0 = 5km$, $d_1 = 10km$
- For coastlines of Qatar : $l_0 = 250m$, $l_1 = 10km$, $d_0 = 2km$, $d_1 = 10km$
- Around Ras Laffan and Halul island : $l_0 = 50m$, $l_1 = 10km$, $d_0 = 1km$, $d_1 = 10km$

Fig. 3.2 shows the mesh of the entire Gulf with close-up views on the LNG terminal of Ras Laffan and on Halul Island. It can be seen that the mesh resolution is finer along the coastline than in the middle of the Gulf. The coastal resolution is further increased along Qatar's peninsula and and even further increased near the two aforementioned structures of interest.

3.2 Regional-scale ocean circulation model: NEMO

We model the regional circulation the Gulf by using the global ocean circulation model NEMO[6]. The physical ocean component of NEMO solves the 3D ocean circulation primitive equations for the velocity field, sea surface elevation, temperature and salinity. It uses a global curvilinear orthogonal grid in the horizontal direction and a mixture of z and s coordinates in the vertical. NEMO is well suited to regional and global ocean circulation problems down to kilometric scale.

NEMO model outputs are distributed by Mercator Ocean, the French center for analysis and forecasting of the global ocean. Mercator Ocean operates global forecasting systems and produces global and regional reanalysis, all based on NEMO ocean model, coupled to a data assimilation system. For this project, we used the

[5]https://www.qgis.org/fr/site/

[6]NEMO: Nucleus for European Modelling of the Ocean, `http://www.nemo-ocean.eu`

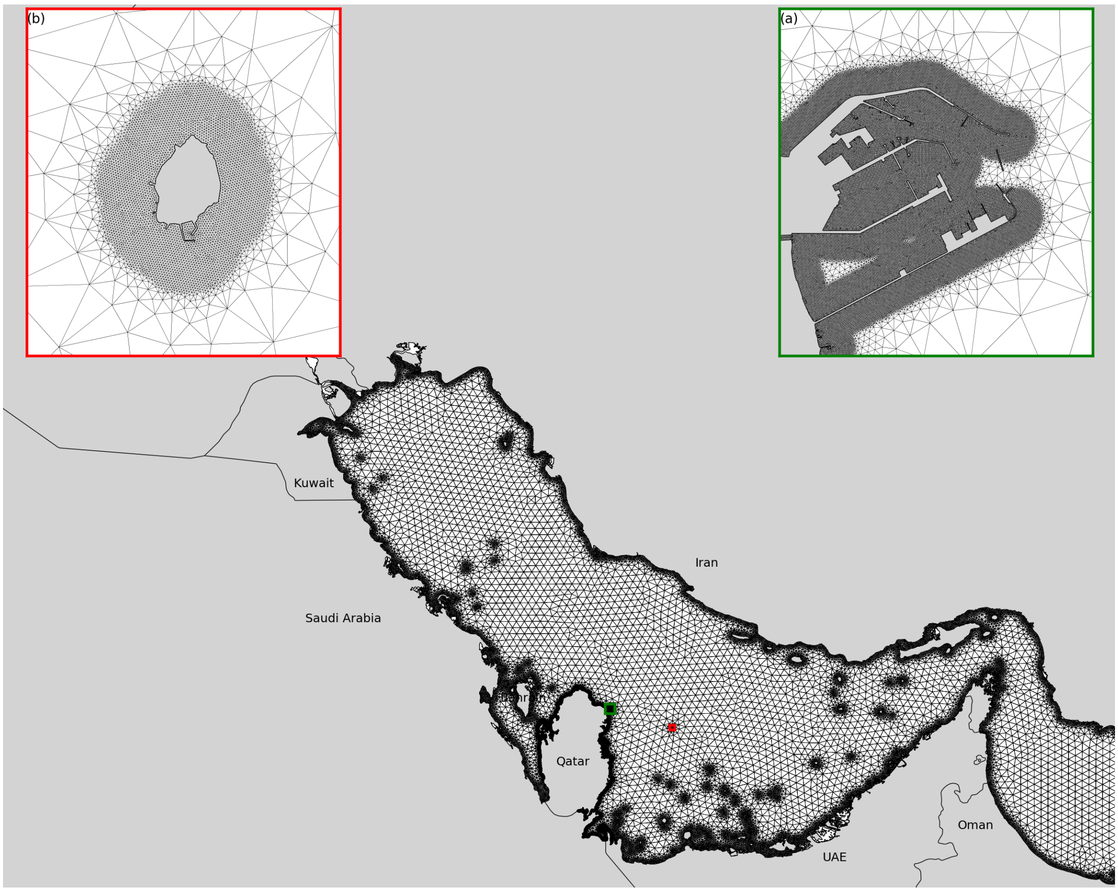


Figure 3.2: Unstructured mesh of the Gulf with a close-up view on Halul Island (upper left) and on Ras Laffan (upper right) where the mesh has been refined to reach a resolution of 50 m.

outputs of the global forecasting system, which are available on the Copernicus web interface [7]. They include hourly mean surface fields for sea level height, temperature and currents. The global ocean output files are displayed with a 1/12° horizontal resolution and 50 vertical levels ranging from 0 to 5500 meters.

For both the local and regional scale studies, around 340000 particles were released each year between June 15 and July 31. This lead to approximately 680000 being released over the 2 years.

[7] https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_PHY_001_024

3.3 Hatchlings dispersal biophysical model

To model the dispersal of turtle hatchlings from the different nesting beaches, we developed a biophysical model based on SLIM's Lagrangian Particle Tracker (hereafter called LPT). This 2D transport model is based on a random walk formulation that computes the new position $\mathbf{X}_{n+1}$ of a discrete particle (representing a turtle hatchling) at time t_{n+1} in term of its former position $\mathbf{X}_n$ at time $t_n = t_{n+1} - \Delta t$, the particle velocity $\mathbf{v}_n$ at time t_n and a diffusivity coefficient K that represents the effect of subgrid-scale turbulence:

$$\mathbf{X}_{n+1} = \mathbf{X}_n + \mathbf{v}_n \Delta t + \frac{\mathbf{R}_n}{\sqrt{r}} \sqrt{2K\Delta t} \tag{3.6}$$

where $\mathbf{R}_n$ is a random vector of zero-mean and variance r (thus $\frac{\mathbf{R}_n}{\sqrt{r}}$ has a unit variance). The diffusivity K has been calculated with the Okubo formulation [51]:

$$K = \alpha \Delta^{1.15}, \tag{3.7}$$

where $\alpha = 0.041[\frac{m^{0.85}}{s}]$ and $\Delta[m]$ is the local element size. When we will be using SLIM to assess the effect of artificial structures on the dispersal of turtle hatchlings, we will have a resolution parameter Δ that varies according to the mesh resolution. When we will be using NEMO to assess what fraction of the hatchlings originating from Qatar nesting beaches can leave the Gulf, Δ will remain constant and be equal to NEMO's uniform resolution of about 10^4 m.

The particle velocity $\mathbf{v}_n$ consists in the sum of the currents velocity (as simulated by SLIM or NEMO) and one or two corrective factors depending on whether we use a depth-averaged velocity (as with SLIM) or a surface velocity (as with NEMO). When using SLIM's depth averaged velocity, we have to add a correction depending on the gradient of the diffusivity and one depending on the gradient of the bathymetry. With NEMO, we only need the former. Hence we obtain:

$$\mathbf{v}_n^{SLIM} = \mathbf{u} + \nabla K + \frac{K}{H} \nabla H \tag{3.8}$$

$$\mathbf{v}_n^{NEMO} = \mathbf{u} + \nabla K \tag{3.9}$$

Model parameters

The precise location of the different nesting beaches was provided by Mr Mark Edward Chatting from the Environmental Science Center of Qatar University. They are shown in Fig. 2.4 and their coordinates are summarized in Table 3.1.

Hawksbill hatchlings biological traits were quantified thanks to observations collected by [30] in Malaysia and on data collected directly by researchers from Qatar

Location	Longitude	Latitude
Ras Laffan (tank farm)	$51.569238°E$	$25.919722°N$
Ras Laffan (mangrove area)	$51.526908°E$	$25.940398°N$
Ras Laffan (coast guard)	$51.508959°E$	$25.951690°N$
Al Maroona	$51.40047°E$	$26.004729°N$
Fuwairit	$51.375216°E$	$26.031106°N$
Al Ghariyah	$51.358141°E$	$26.087956°N$
Al Mafyar	$51.318119°E$	$26.127549°N$
Umm Tais	$51.266404°E$	$26.167378°N$
Ras Rakkan	$51.227057°E$	$26.179242°N$
Halul (0)	$52.40484°E$	$25.67466°N$
Halul (1)	$52.405023°E$	$25.675933°N$
Halul (2)	$52.405869°E$	$25.677426°N$
Halul (3)	$52.40694°E$	$25.67873°N$
Shraouh	$52.228887°E$	$25.030696°N$

Table 3.1: Coordinates of the nesting beaches in Qatar mainland and on Halul Island.

University near the nesting beaches of Qatar mainland. The average swimming speed of hatchlings in Qatar lies around $0.15[\frac{m}{s}]$ (Fig. 3.3), which coincides with the average swimming speeds measured on Malaysian Hawksbill hatchlings by Chung [30]. Other parameters, such as the duration of the active swimming period (also called the swimming frenzy) were directly taken from [30] and assumed to be valid for Qatar's hatchlings (Table 3.2).

Swimming speed	$0.15 \pm 0.05[\frac{m}{s}]$
Minimal swimming speed	$0.02[\frac{m}{s}]$
Initial seeding time	June 15
Final seeding time	July 31
Seeding location std [8]	100 [m]
Duration of active swimming	$48 \pm 12[h]$
Minimal duration of active swimming	$12[h]$

Table 3.2: Parameters chosen for the simulations

Swimming behaviour

The precise swimming behaviour of Hawksbill hatchlings is not precisely known. Chung et al. [30] have studied the swimming behavior of Hawksbill hachtlings in

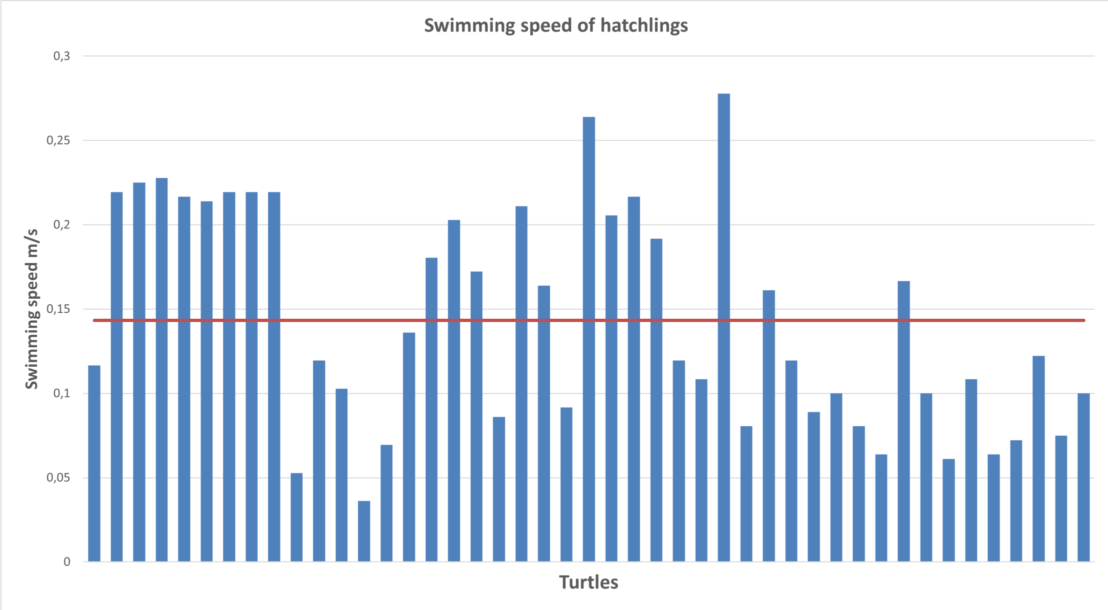


Figure 3.3: Observed swimming speeds of turtles in Qatar (blue) and average swimming speed (red). Each blue bar represent a specific turtle measurement.

Malaysia but they could not clearly quantify the way those hatchlings swam during their first days of life, how long they were able to sustain active swimming nor in which direction they were swimming. In this study, we have therefore considered three different *swimming modes*:

- *Perpendicular* : turtles swim perpendicularly to the coast in order to get offshore as quickly as possible during 48 ± 12 hours with a minimum of 12 hours.
- *Decreasing* : turtles swim perpendicularly for 4 hours, and in the direction of the current for the rest of the day, again during a total time of 48 ± 12 hours with a minimum of 12 hours.
- *Stokes* : turtles swim against the direction of the waves for 48 ± 12 hours with a minimum of 12 hours.

The *Perpendicular* swimming mode assumes that hatchlings try to move away from the coast as quickly as possible. It assumes that hatchlings can figure out that particular direction from sensory cues. A *Decreasing* swimming mode assumes that hatchlings don't have much energy to swim vigorously in the direction perpendicular to the coast [30]. That direction being generally opposed to the direction of the waves, it require more energy to sustain such as swim. After a relatively short period of time, hatchlings would thus start to swim in the direction of the currents as it requires less energy. The *Stokes* swimming mode makes more sense "biologically". As turtles have no way of knowing the direction opposite to the coasts and as waves are generally propagating perpendicularly to the coasts, it seems more likely that hatchlings could direct themselves by swimming against the waves. This amounts to swim in the direction opposite to the Stokes drift. As we did not have the time to simulate the wave dynamics with a fine resolution wave model (such as SWAN), we used the coarse-resolution Stokes drift model outputs provided by Mercator. That data has been produced by the large-scale MF-WAM wave model that runs on the same grid as NEMO (hence with a 10km resolution). Unfortunately the output of such a coarse resolution model are not very accurate near the coast and especially in the vicinity of artificial structures that are much smaller than the model resolution. Thus, even though simulations have been ran with the "Stokes" swimming mode, results will not be shown here as they could be misleading because of the lack of precision near the coast.

We performed a qualitative comparison between the *Perpendicular* and *Decreasing* swimming mode (see results in Appendix A). It illustrates the impact of the initial active swimming period on the overall dispersal. From those qualitative results, we decided to keep only the perpendicular swimming mode as allows hatchlings to move away from the coast much more effectively. The interactions with artificial structures is also much lower in that case. Even though the perpendicular swimming might not be based on a strong physical rationale, it certainly makes sense from an evolutionary point of view to assume that marine turtles adopted a swimming mode that tries to follow the direction perpendicular to the coast. We will therefore only consider this swimming mode in the rest of this study.

3.4 Indicators

Here we describe how we process the outputs of the biophysical hatchlings dispersal model to derive indicators that will allow us to answer the research questions put forward in the introduction.

Local-scale analysis

For the analysis of the interactions of hatchlings with the artificial structures near the nesting beaches, we will estimate the fraction of the total simulation time that particles have spent interacting with those structures. We will consider two different measures: (1) the fraction of time interacting with the entire structures, either inside or outside and (2) in the particular case of the LNG terminal of Ras Laffan, the fraction of time spent inside the terminal.

For this analysis, we ran SLIM from June 15 to August 31 for years 2019, 2020 and 2021 to account for the inter-annual variability of the oceanic circulation. For each year ≈ 340000 particles (corresponding to virtual hatchlings) have been released between June 15 and July 31 to increase the possibility of interactions between turtles and structures. This is probably more than the actual number of hatchlings that hatched on Qatar's beaches but since we only compute relative quantities, the absolute number of particles is not important.

We considered interactions with all the structures composing the LNG terminal of Ras Laffan (as shown in the green box in Fig. 3.4), as well the interaction with only the structures inside the LNG terminal (blue box in Fig. 3.4) and the interactions with the intake of Ras Laffan's desalination plant (red bow in Fig. 3.4). We managed to distinguish these different structures by "tagging" them differently in the shapefile that defines the boundaries of our computational domain.

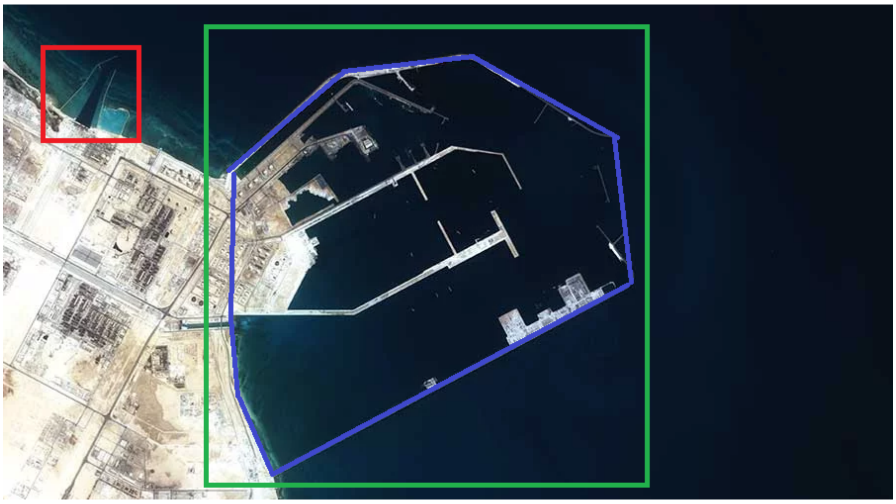


Figure 3.4: Ras Laffan : water desalination plant (red), Ras Laffan LNG terminal (green) and polygon used to distinguish the inside of Ras Laffan LNG terminal (blue)

For each particle, we counted its interactions with the artificial structures only during the first 30 days following its release. This means that particles that where seeded on June 22 at 19:00:00 were removed on July 22 at 19:00:00 and that particles released on July 4 at 19:00 were removed on August 4 at 19:00. Each time a particle is associated with an individual "counter" that is incremented by one each time the particle interacts with a structure. This allows us to keep track of all interactions made by each individual particle. Afterwards, we associated each particle with a nesting beach in order to summarize the number of hatchling-structure interactions for each nesting beach.

Figure 3.5: Halul island with artificial structures (yellow)

Regional-scale analysis

For the regional-scale hatchlings dispersal analysis, the simulations took place between January 1, 2020 and April 1, 2022 but as turtles generally start hatching during mid June, we will only start looking from June 15, 2020 instead of January 1, 2020. We will estimate the following quantities: (1) the probability distribution function of the hatchlings position and its seasonal variability, (2) the fraction of all hatchlings originating from Qatar's nesting beaches that could leave the Gulf and (3) the period of the year during which the ocean circulation patterns allow hatchlings to leave through the Strait of Hormuz.

The probability distribution function representing hatchlings position was calculated as follows. If e_i represents the triangular element with index i of the hydrodynamic model mesh (that has a total of N elements), we let $D_{e_i}(t)$ be the density $[km^{-2}]$ of turtles in element e_i at time t and A_{e_i} the area of e_i. Let $\mathcal{S}$ denote the season : winter (December-January-February or DJF), spring (Mars-April-May or MAM), summer (June-July-August or JJA) and autumn (September-October November or SON). The probability density function, named $\mathcal{P}_G(e_i)$ for the general pdf, and $\mathcal{P}_S(e_i)$ for the seasonal pdf were then defined as:

$$\begin{aligned}
\mathcal{P}_G(e_i) &= \sum_{t=0}^{T} \frac{D_{e_i}(t)}{T \sum_{i=0}^{N} D_{e_i}(t) A_{e_i}}, \\
\mathcal{P}_S(e_i) &= \sum_{t \in \mathcal{S}} \frac{D_{e_i}(t)}{T \sum_{i=0}^{N} D_{e_i}(t) A_{e_i}}.
\end{aligned} \tag{3.10}$$

$\mathcal{P}_G(e_i)$ and $\mathcal{P}_S(e_i)$ being probability density functions, they satisfy the property that their integral over the whole domain (the region defined by the mesh) is equal to 1, which means that:

$$\begin{aligned}
\sum_{i=0}^{N} \mathcal{P}_G(e_i) A_{e_i} = 1 \\
\sum_{i=0}^{N} \mathcal{P}_S(e_i) A_{e_i} = 1
\end{aligned} \tag{3.11}$$

Chapter 4

Results

Here we first validate the outputs of the local-scale hydrodynamic model with currents observations just offshore of Qatar's mainland nesting beaches. The regional model outputs are not validated as we don't have regional-scale data that we could use to do that. However, NEMO being a data-assimilated model, observations of the state of the ocean have already been taken into account to correct the model predictions. We will then present the local and regional circulation patterns obtained with the two models considered here. Finally, we will assess the dispersal patterns both near the nesting beaches and over the entire Gulf for the years 2019, 2020 and 2021.

4.1 Local-scale model validation

Before using the currents simulated with SLIM, it is important to assess if they are sufficiently close to reality. This is achieved by validating the model results with respect to current observations. Here, we used current velocity observations collected by researchers from the Qatar University in November 2019 off Fuwairit $(51.373283°E, 26.123733°N)$, on the northeast coast of Qatar. That site is very close (less than 20 km away) to the nesting beaches on Qatar's mainland. Measurements were gathered by a Recording Current Meter (RCM) which was deployed $2m$ above the seabed between October 29^{th} and November 26^{th}, 2019. The mean accuracy of the RCM is of $\pm 0.15\frac{cm}{s}$ for the current velocity [52] and $\pm 3°$ for the current direction. As can be seen on Figs. 4.1 and 4.2, around 6 Nov and on 19-22 Nov, the currents dynamics is quite different. This is due to strong Shamal winds [53] that blew during those periods. This phenomenon is clearly apparent on figure 4.3.

We further developed the analysis by computing the amplitude and phase of the main tidal components (Fig. 4.2). This was done by using the UTide package [54], which computes the tidal current ellipse parameters and reconstructs the tidal

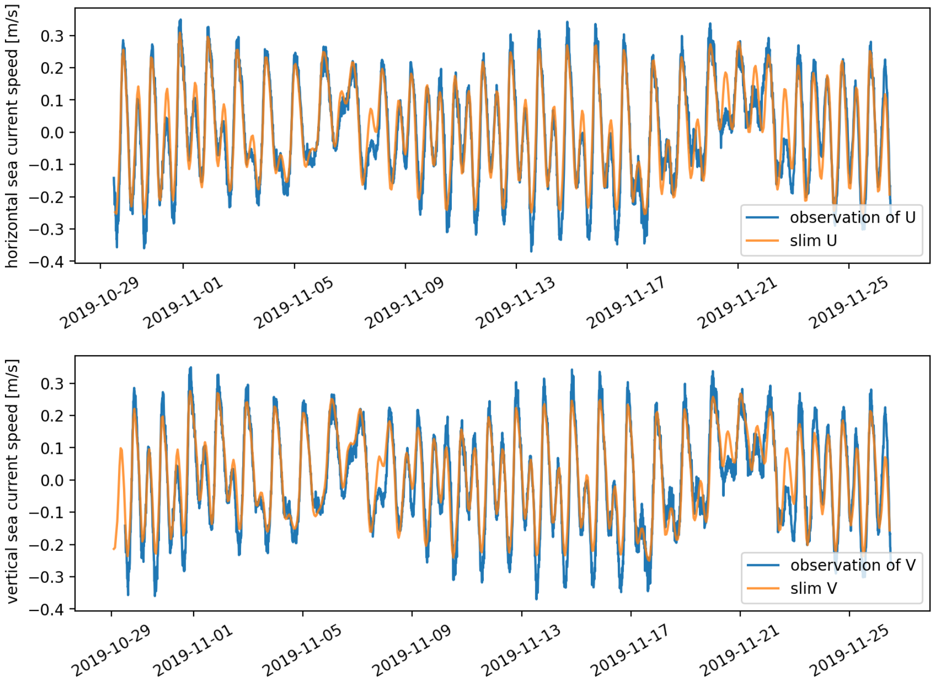


Figure 4.1: Comparison between simulated and observed currents on 29 Oct - 26 Nov 2019 offshore of Fuwairit in northeastern Qatar.

signal based on those parameters and for the different tidal components. In this case, 7 tidal components were retained (K1, M2, S2, O1, MSF, N2 and J2) contain around 99.8% of the energy. All the other components were therefore not included in the analysis. The RMSE [1] and MAE [2] for the velocity are : $RMSE = 0.0074\frac{m}{s}$, $MAE = 0.008\frac{m}{s}$. Overall, the validation of SLIM's velocity is very satisfactory.

[1] Root Mean Square Error
[2] Mean Absolute Error

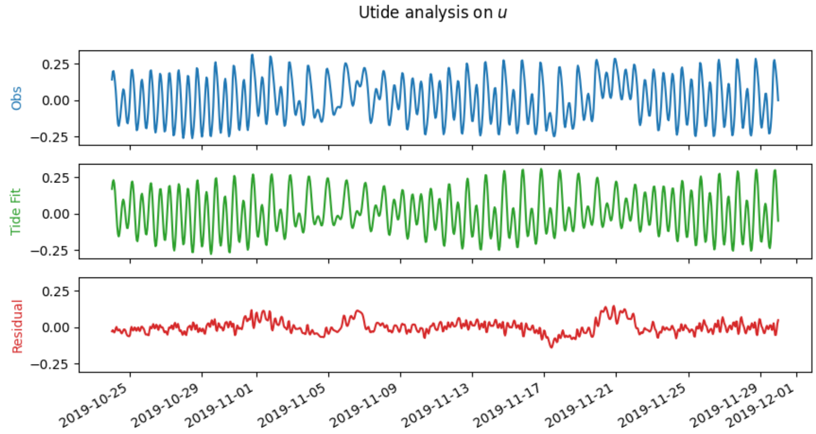


Figure 4.2: Tidal current ellipse parameters for current meter observations and simulated currents.

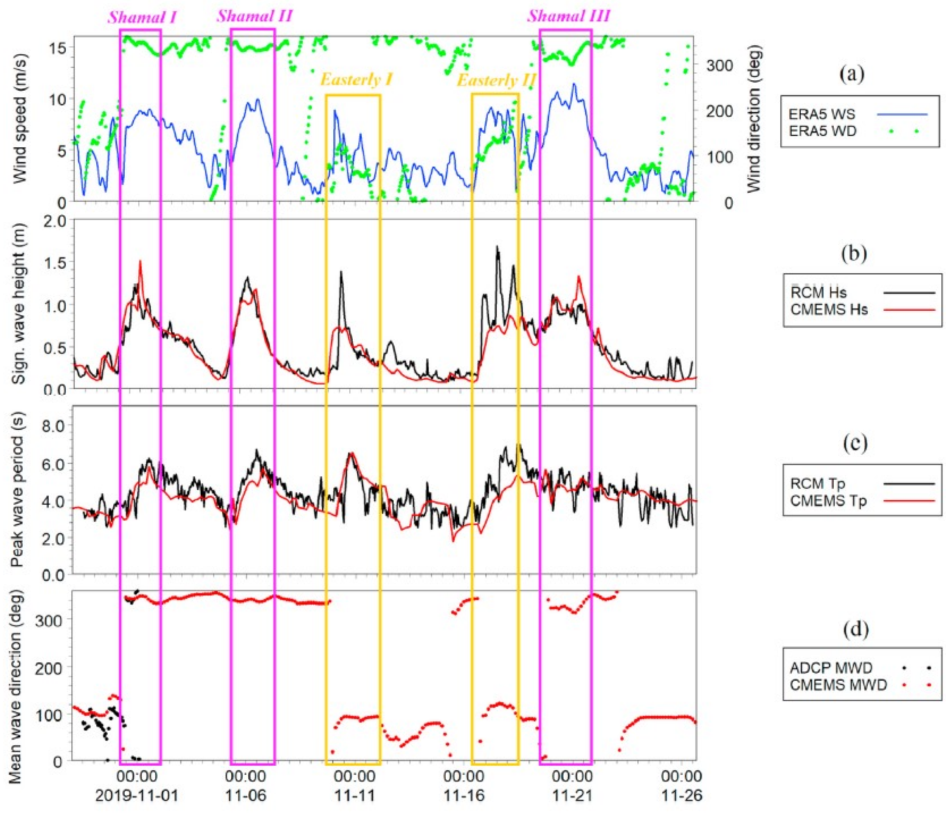


Figure 4.3: (a) ERA5 wind speed and direction, (b) Hs from RCM and CMEMS, (c) T_p from RCM and CMEMS and (d) MWD from ADCP and CMEMS [53]

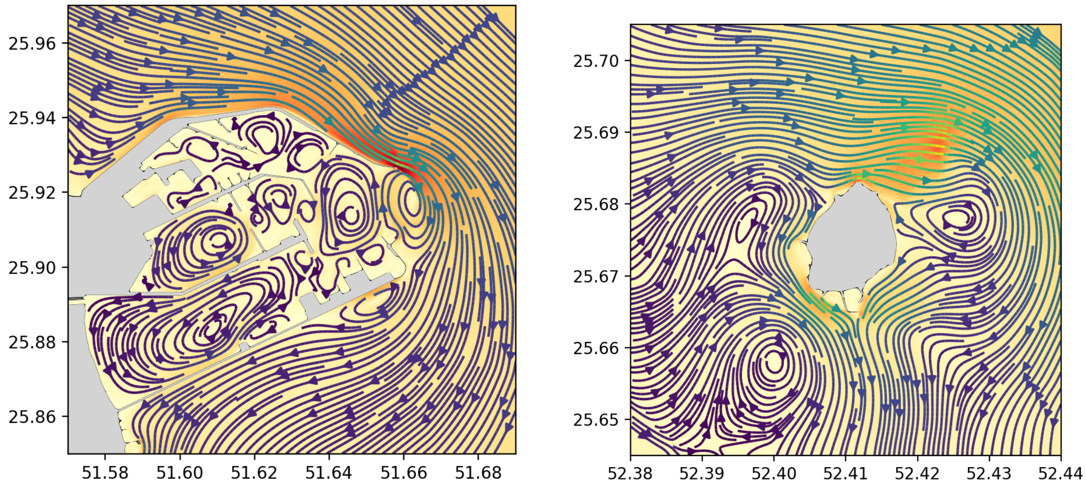


Figure 4.4: Monthly mean circulation patterns (shown with streamlines) in Ras Laffan LNG terminal (left panel) and around Halul Island (right panel) in June 2021

4.2 Local-scale circulation patterns

As we we will investigate the interactions of hatchlings with two main sites : Ras Laffan and Halul, it is interesting to first take a look at how the currents behave in those areas. On figure 4.4 we can see the mean current velocity for June 2021. As the currents are mainly tidally driven, they are quite stable from month to month, which is why only June 2021 is shown. For other months and other years, the results are pretty similar. We can observe that the residual currents in front of the nesting beaches north of Ras Laffan are directed towards Ras Laffan. This means that hatchlings originating from those beaches could very well drift towards the LNG terminal. We can also see eddies at the entrance and inside the terminal. These eddies, generated by the flow-structure interactions, could possibly keep hatchlings inside the terminal. Around Halul Island, the mean circulation patterns again changed very little from month to month. June 2021 is a clear representation of what seems to happen around the island. We see two eddies on the left of the island and one on the right side. Looking specifically at the artificial structures south of the island, the Halul oil terminal, currents seem to drag hatchlings away from it. As the nesting beaches are located on the North of the island, it does not make a significant difference anyway.

The current speed can be quite large near the artificial structures (Fig. 4.5). It can exceed 0.5 m/s and, in some locations reach 1 m/s. This is due to the "sharp edges" of those structures that lead to rapid changes in the current direction and amplitude. In the case of Ras Laffan, this currents could easily pump hatchlings inside the terminal when the tide is rising. Around Halul, the strong currents will probably have the opposite effect of transporting hatchlings quickly away from the island. At the regional scale, we also note the strong currents near the Strait of Hormuz, through which hatchlings could leave the Gulf.

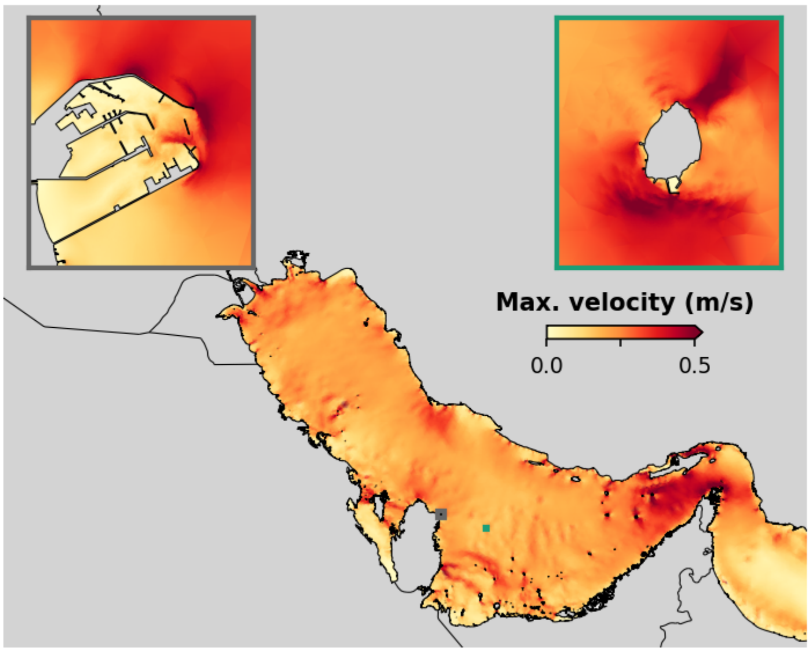


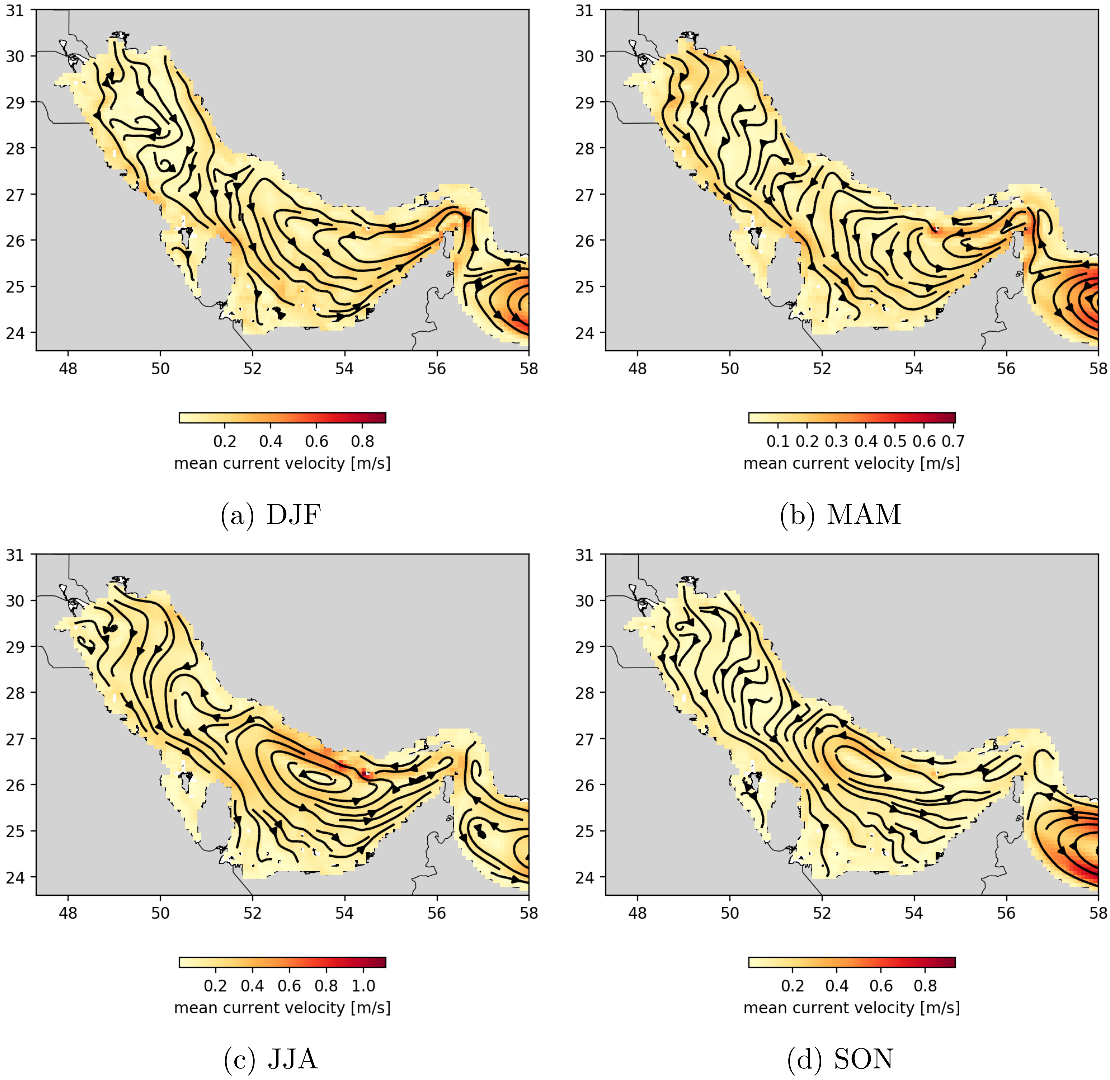
Figure 4.5: Maximum currents speed for the simulation of 2020 with close-up views on Ras Laffan LNG terminal (upper left) and Halul Island (upper right)

4.3 Regional-scale circulation patterns

The regional circulation in the Gulf shows some seasonal variations (fig. 2.6). As discussed by [55], the summer circulation is dominated by a dynamically stable anticlockwise gyre that then becomes unstable and breaks up into many mesoscale eddies during the winter. This is a well-known circulation pattern of the Gulf that is driven by changes in the stratification and wind regime. During the summer, surface waters warm up and lead to very stratified conditions that result in a stable cyclonic circulation that extends to almost the entire Gulf in August and September. In autumn, surface waters cool down and wind intensifies leading to a decreasing stratification and hence a destabilisation of the circulation, which produces meso-scale eddies. The stronger mesoscale activity during the winter leads to a weaker mean circulation.

4.4 Local-scale hatchling dispersal patterns

In order to have a clear and more graphic idea of the turtles' dispersal, we can observe in table 4.4 the state of turtles at certain times during the simulation (every two weeks) for each year. Different colors correspond to the different nesting beaches and on each image there is a zoom on Ras Laffan (upper right when rotating the table by 90°) and on Halul (lower right). We can observe different, even though not drastically different, dispersal pattern depending on the year.



(a) DJF (b) MAM

(c) JJA (d) SON

Figure 4.6: Average seasonal current circulation

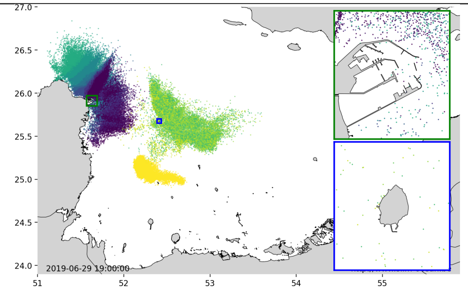
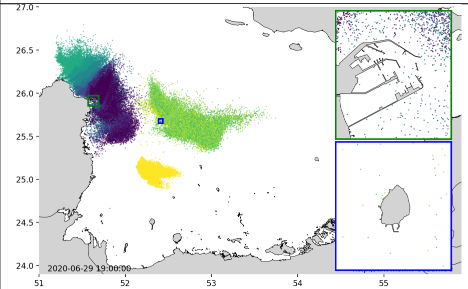
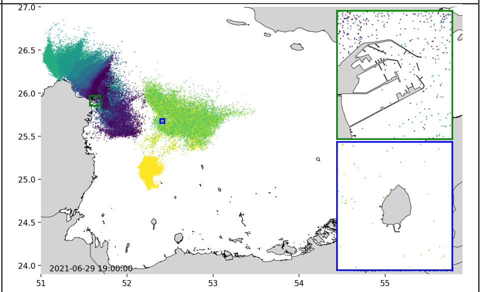
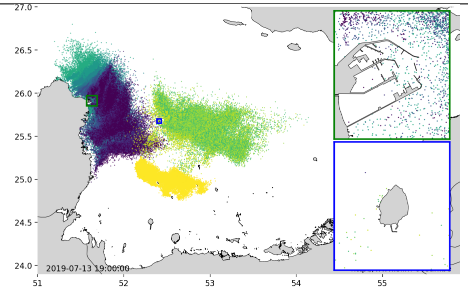
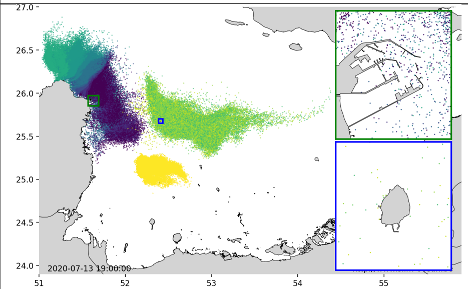
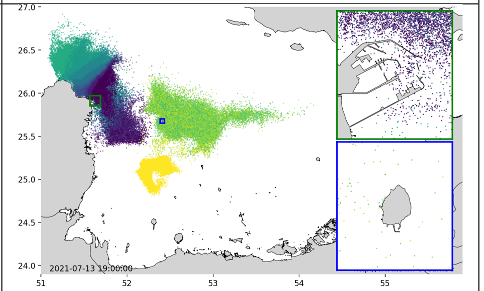
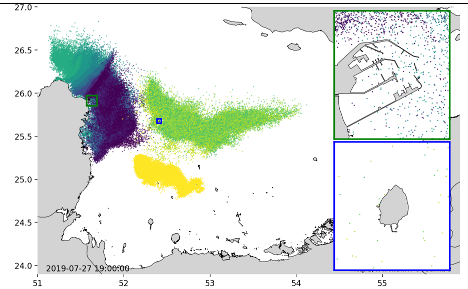
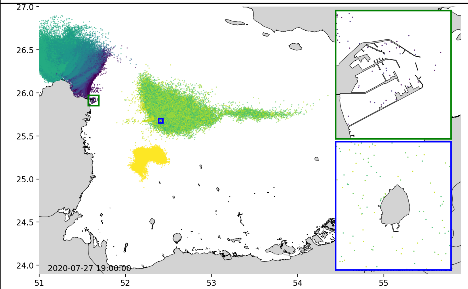
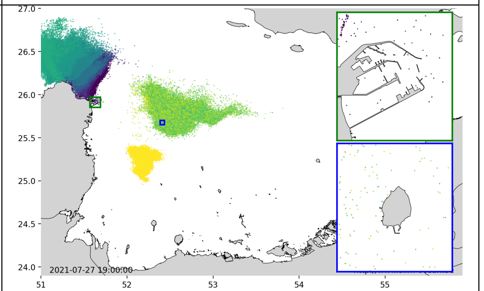
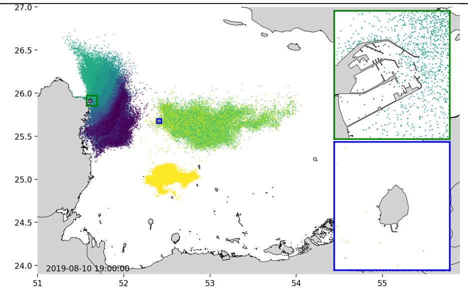
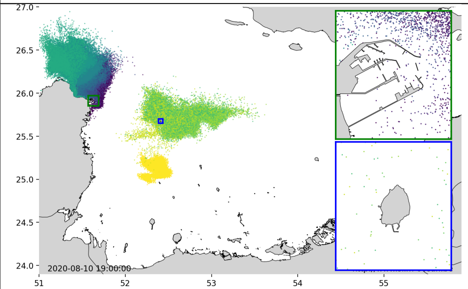
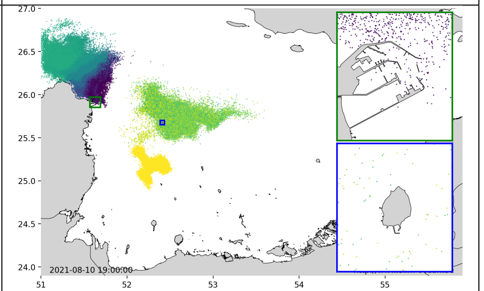
	2019	2020	2021
T = 14 days			
T = 28 days			
T = 42 days			
T = 56 days			

Table 4.1: Comparison of dispersal patterns between each year of simulation

To monitor the interactions between hatchlings and Ras Laffan LNG terminal, we estimated the time spent by each particle bouncing against the structures seawalls. This allowed not only to monitor the fraction of all hatchlings originating from a given nesting beach that interacted with a given structure but also to record how long they have interacted. As there were no significant interannual variability, we decided to show the average over the 3 simulated years. The fraction of all particles interacting with Ras Laffan's LNG terminal is quite small (Fig. 4.7), less than about 0.1% for some nesting beaches. Among the particles that did interact with the structure, an even smaller fraction (about 0.01%) did so most of the time. This probably corresponds to particles that got trapped inside Ras Laffan and never managed to escape. We can also observe significant differences in distribution between nesting beaches. As expected, beaches near Ras Laffan's LNG terminal appear to have a higher amount of interactions than further beaches like Al Mafyar for exemple. Nevertheless we can observe that for Umm Tais and Ras Rakkan reasoning doesn't really apply as they are relatively far away from the LNG terminal and still seem to interact as much as the neighbouring beaches. This is probably because turtles hatching at the North of Qatar seem to get transported along the coasts of Qatar to the South.

Exactly in the same way and for the same reasons as the previous paragraph, on figure 4.8 we can see the average over 3 years of the time hatchlings spend inside Ras Laffan LNG terminal (see figure 3.4). By taking a quick look, we can see that the percentage of turtles getting inside the LNG terminal is higher than the percentage of turtles interacting with the borders. This means a (small) quantity of turtles get inside the LNG terminal without actually interacting with its walls. Furthermore we can see that for those who do get inside the LNG terminal, they seem to spend a relatively short amount of time in it. The fact there are more hatchlings getting inside the terminal than hatchlings interacting with the borders could be explained by the currents depicted on figure 4.7 (left panel) : we can see vortexes at the entrance of the structure. These vortexes might suck the turtles inside the LNG terminal but also reject them outside pretty soon after.

As for the other artificial structures, the exact same process was followed to monitor the interactions. Unfortunately, or rather fortunately for the turtles, what came out of these simulation was that very few to no interactions happened over the 3 years. This is apparent of figures A.3 and A.2. For that reason, I decided not to elaborate on those two artificial structures by simply stating that the number of interactions is so small that it does not make sense to make an extensive analysis of it.

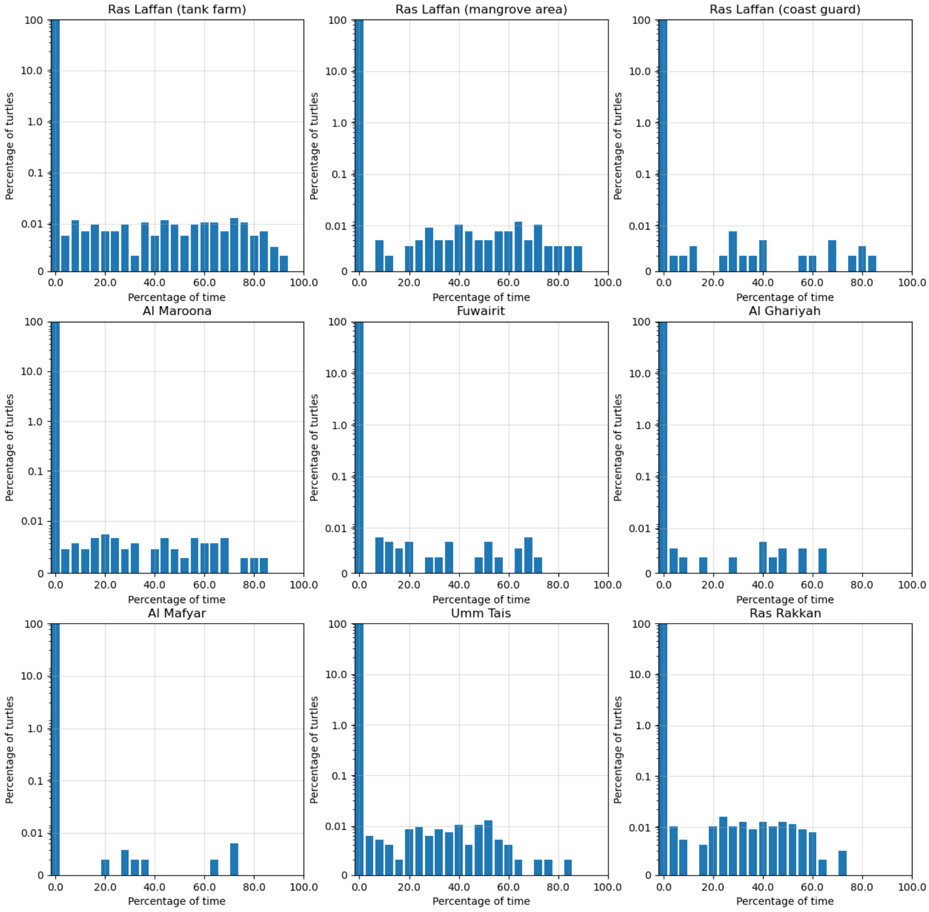


Figure 4.7: Average interactions with Ras Laffan LNG terminal over the 3 years

4.5 Regional-scale hatchling dispersal patterns

Let's now take a broader point of view on how the hatchlings disperse throughout the Gulf. Again, in order to have a clear and graphic representation of what we are talking about, on figure 4.5 we can observe the dispersal for each month of the simulation. The gyre that seemed to take place in the Gulf (see figure 4.6) is very apparent on these figures as we can observe small vortexes of turtles. Clearly on those figures, turtles seem to disperse southwards at the beginning before getting carried out by the gyre and dispersing throughout the Gulf.

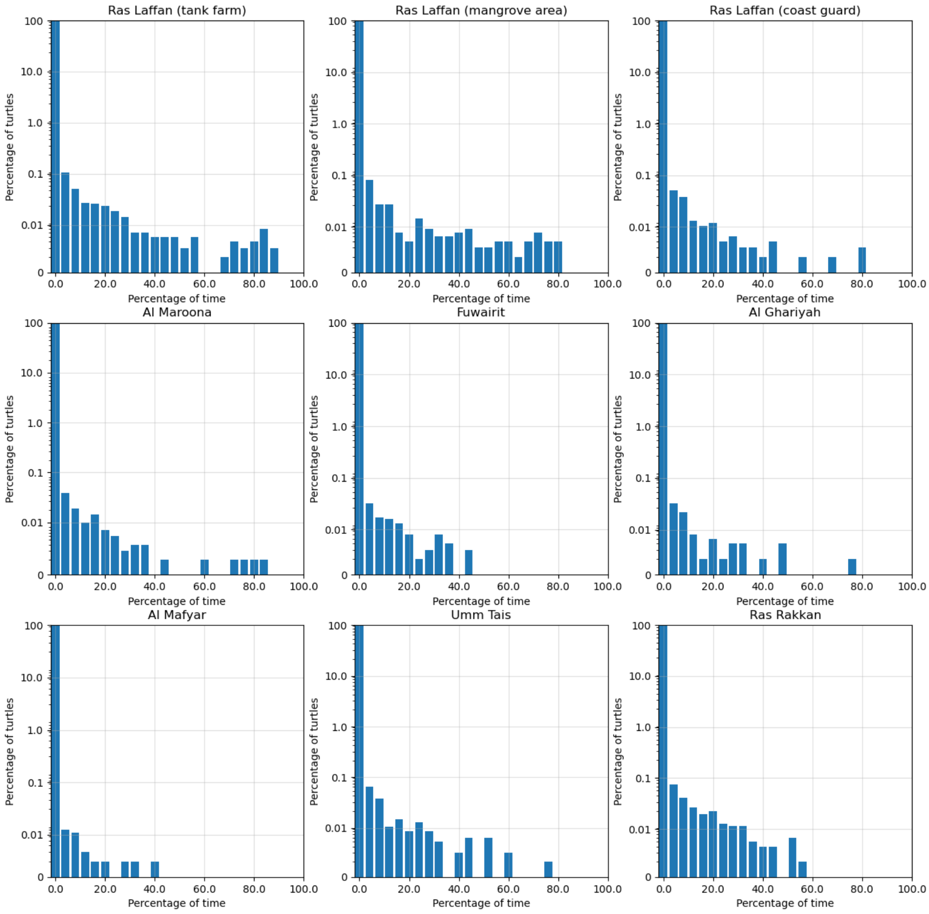
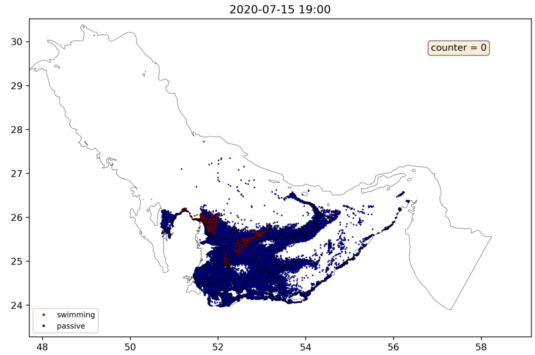
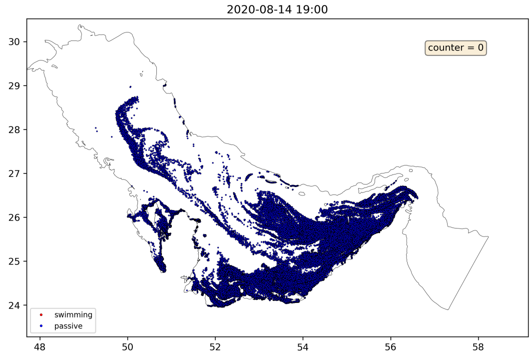


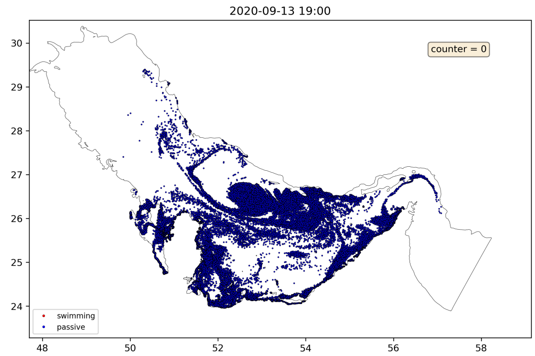
Figure 4.8: Average percentage of turtles spending a certain amount of timesteps inside of Ras Laffan over the 3 years



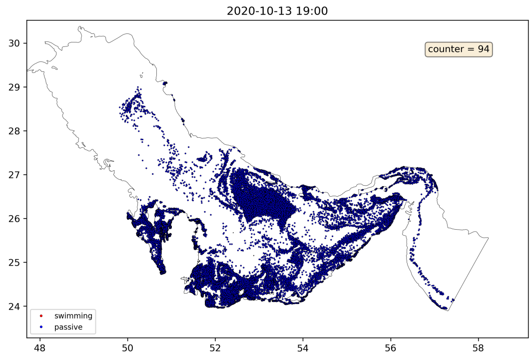
(a) Dispersal after 1 month



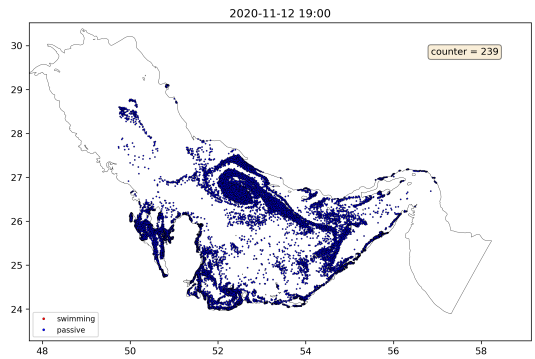
(b) Dispersal after 2 months



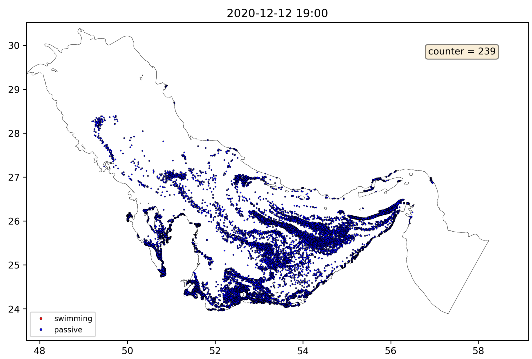
(c) Dispersal after 3 months



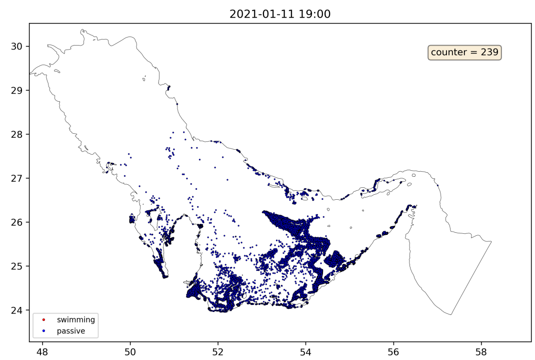
(d) Dispersal after 4 months



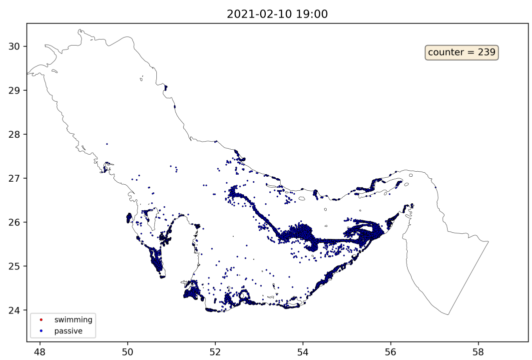
(e) Dispersal after 5 months



(f) Dispersal after 6 months

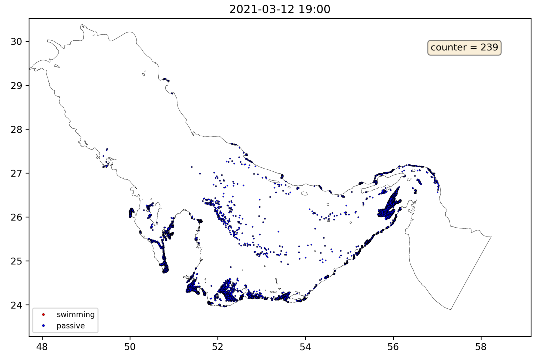


(g) Dispersal after 7 months

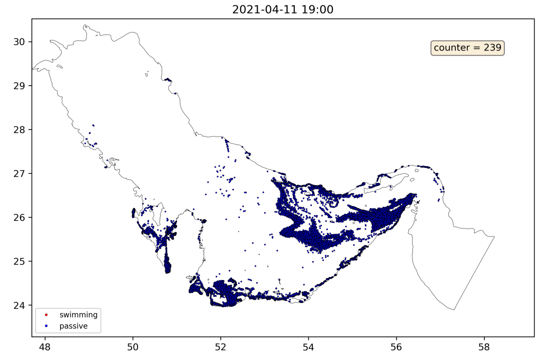


(h) Dispersal after 8 months

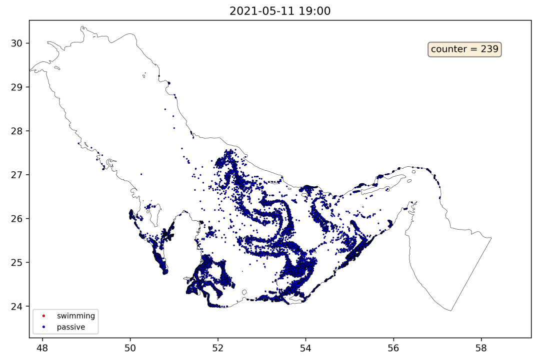
Figure 4.9: Dispersal of turtles with MERCATOR data



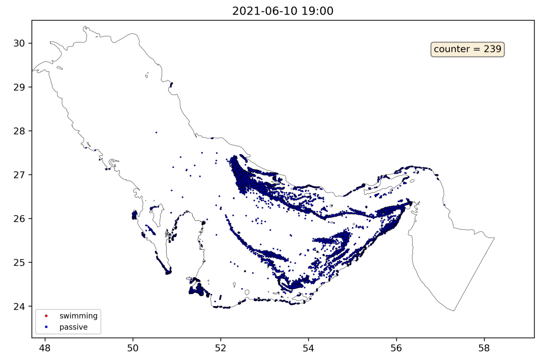
(i) Dispersal after 9 months



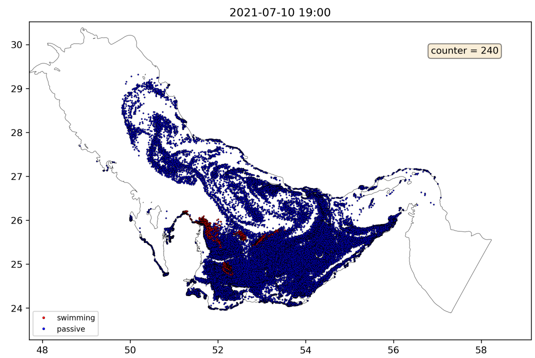
(j) Dispersal after 10 months



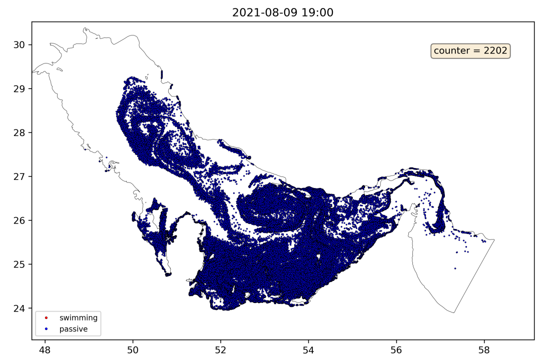
(k) Dispersal after 11 months



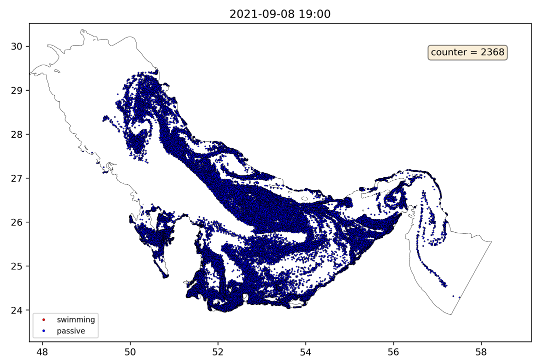
(l) Dispersal after 12 months



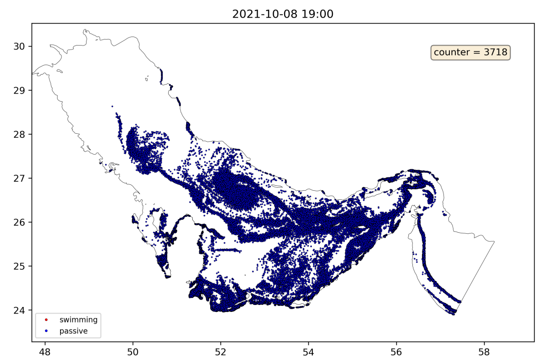
(m) Dispersal after 13 months



(n) Dispersal after 14 months



(o) Dispersal after 15 months



(p) Dispersal after 16 months

Figure 4.9: Dispersal of turtles with MERCATOR data

4.5.1 Hatchlings distribution in the Gulf

On figures 4.10 we can observe the probability of presence in the Gulf as defined in equation 3.4. We can see very distinct patterns depending on the season. Indeed, we can note for example that during September-October-November, and as well during June-July-August but on a smaller scale, there is a higher probability of presence past the Strait of Hormuz. This will appear even clearer in the next pages. What needs to be retained from figure 4.10 is that the hatchlings seems to occupy the southern and eastern parts of the Gulf way more than the rest.

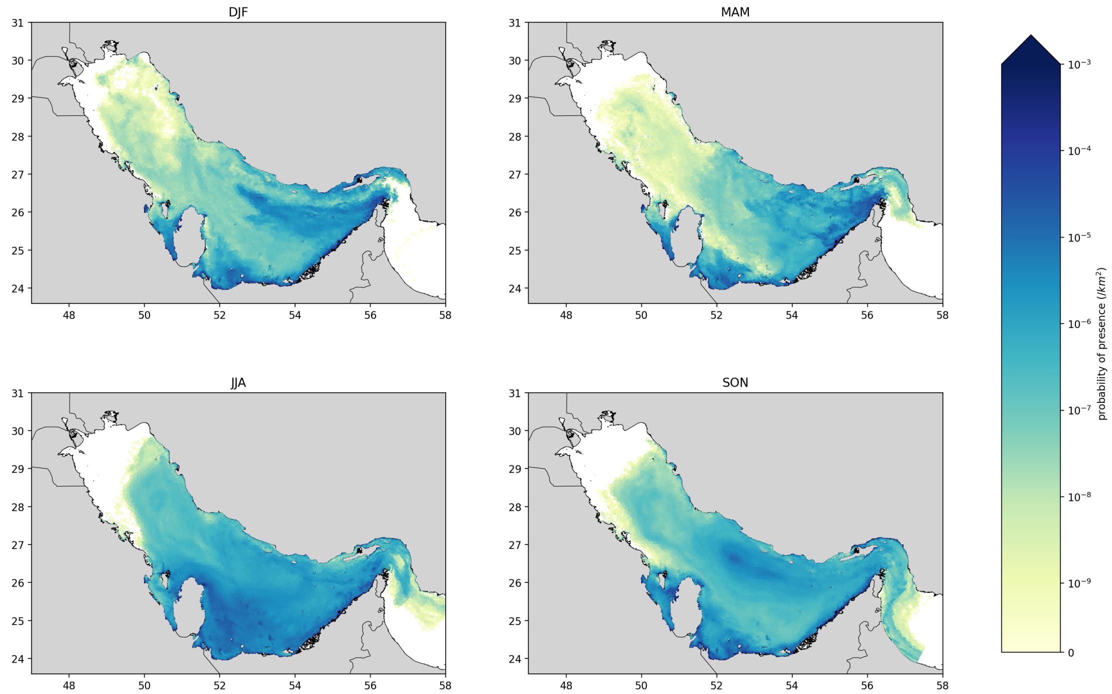


Figure 4.10: Seasonal probability of presence $[km^{-2}]$

4.5.2 Fraction of hatchlings leaving the Gulf

As can be seen in Fig. 4.5, particles can leave the Gulf through Hormuz channels. Here we try to estimate what fraction of particles leaves the Gulf, from which nesting beach they come from and when they leave. Over the duration of the regional scale simulations, i.e. from June 2020 until April 2022, there have been two hatching seasons (in 2020 and 2021). Our results suggest that hatchlings are most likely to escape in autumn, although not necessarily on the same year as the year when they hatched (Fig. 4.11). During our simulation, about 1% of the hatchlings present in the Gulf managed to leave the Arabian Gulf and reach the Gulf of Oman. For more than half of them, they did not leave during the year when they were hatched but the year after. Much more virtual hatchlings left the Gulf in 2021 than in 2020, which suggests that the inter-annual variability in the circulation patterns plays an important role. Hatchlings from the nesting beaches of Halul Island are 2 to 3 times more likely to leave the Gulf than those from the nesting beaches north of Ras Laffan.

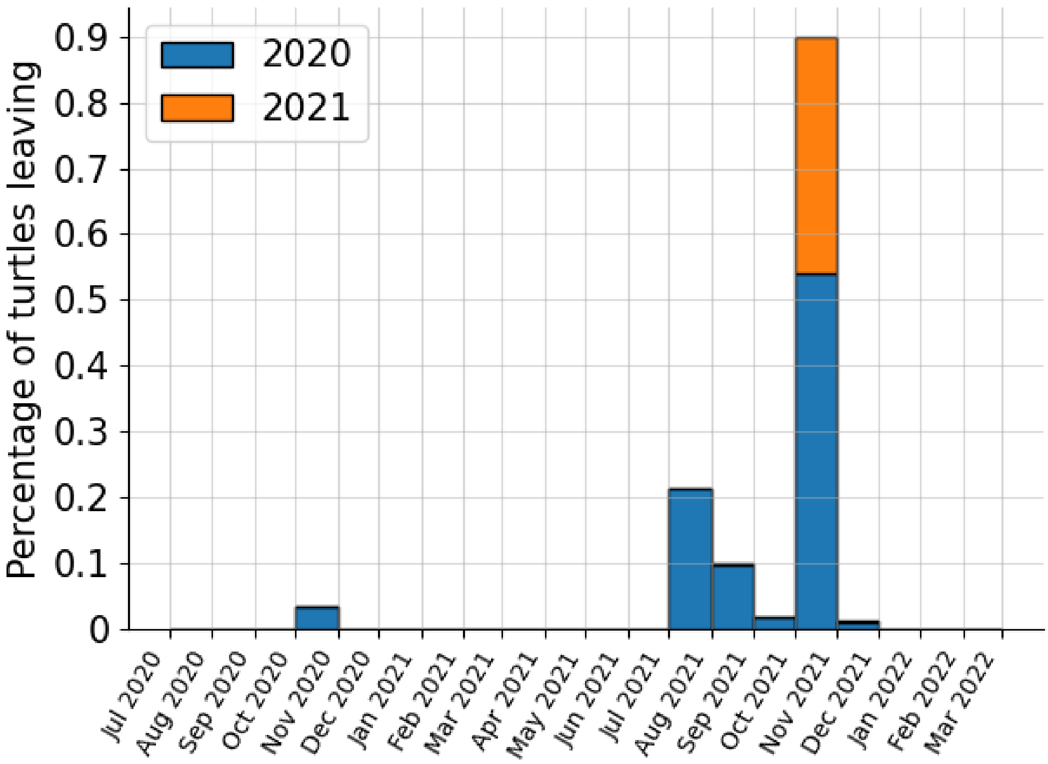


Figure 4.11: Time at which turtles leave the Gulf (released in 2020 : blue, released in 2021 : orange)

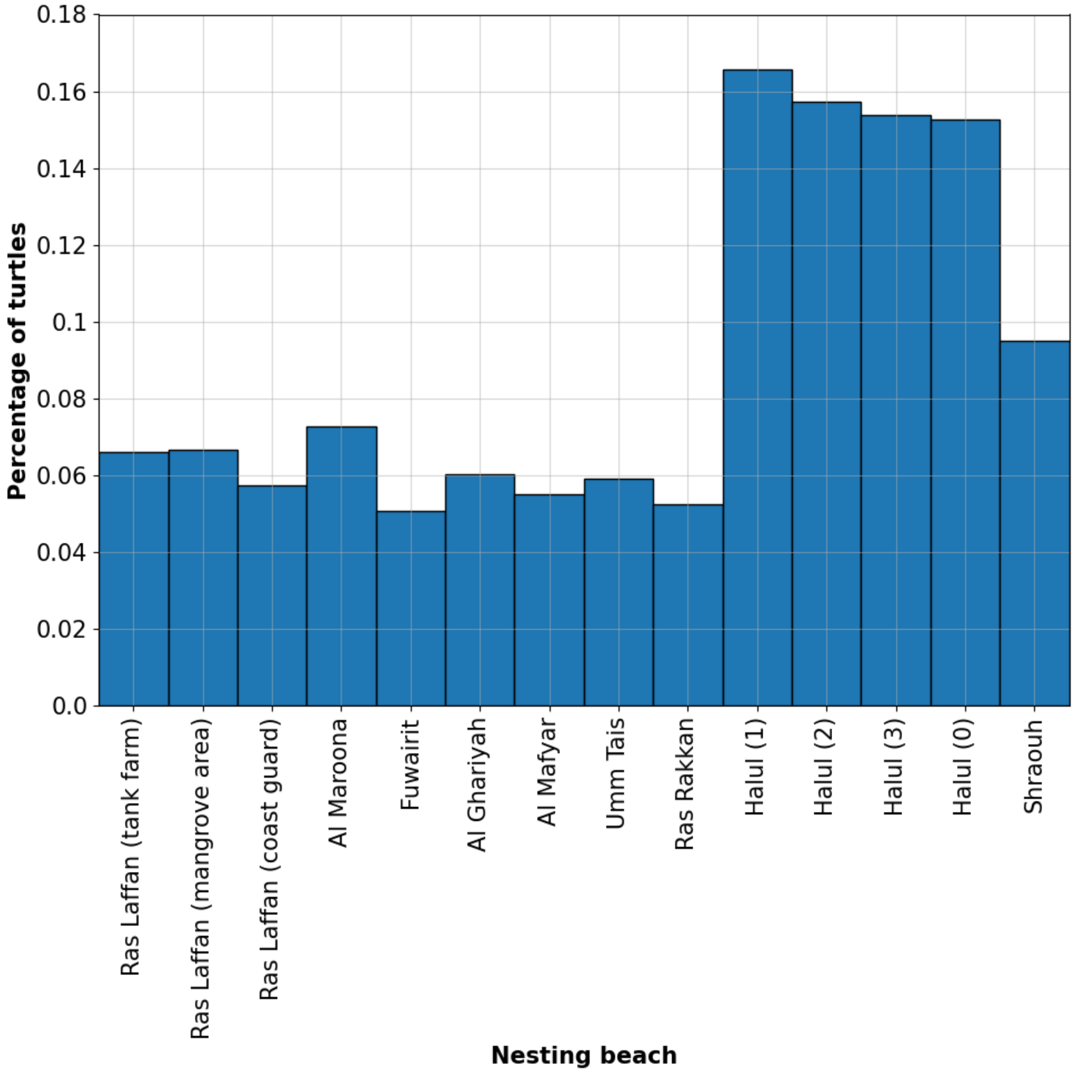


Figure 4.12: Percentage of turtles that leave the Gulf per nesting beach (with regards to the total number of particles released)

Chapter 5

Discussion

The purpose of this section will be to analyze and discuss the results of the previous section. I will try to explain in a concise and comprehensible way the main take-home messages of this study. First, I will discuss the local-scale results and afterwards I will discuss the regional-scale results.

Our results suggest that hatchlings' interactions with the Ras Laffan LNG terminal are quite limited. Some hatchlings are impacted by the structure as they are being transported southeastward by the residual current along the coast but the number of those interactions (and the duration during which they occur) remains quite limited. A slightly higher number of turtles find themselves transported inside the LNG terminal but, again, for relatively short periods of time and sometimes without hitting the inner seawalls. Ras Laffan's water desalination plant intake and Halul oil terminal appear to have almost no impact on the hatchlings. At a regional scale, what comes out is that there it a relatively strong seasonal variability of the oceanic circulation in the Gulf, which influences the hatchlings distribution and the fraction that can leave the Gulf. Over the whole simulation (from June 15, 2020 to April 1, 2022) a total of 1.26% of all hatchlings escaped the Gulf through the Strait of Hormuz. This happens mostly at the end of summer and in autumn : among those 1.26%, more than 1% escaped during September, October and November. We also observed that those remaining in the Gulf seem to stay mostly in southern part of the Gulf. This area includes the North Gas Field, the largest gas field in the World, through which navigation is heavily controlled. This area located North of Qatar is known to host a large population of whale sharks that find there a quiet environment [56]. Hawksbill turtle hatchlings could also benefit from this in that area.

Indeed, when we look at the distribution of interactions in Figs. 4.7 and 4.8, we can see that the percentage of turtles interacting a certain percentage of time reaches at most $\approx 0.03\%$. This is a very small fraction of turtles but some of them get stuck in the LNG terminal for a very long time, up to 90% of the time for some of them. We also see large differences of interactions between nesting beaches. As some nesting beaches are very close to Ras Laffan's LNG terminal while others are located many kilometers away, it is normal that some are more impacted than others. As there is little literature this topic, it is difficult to compare the results to anything previously obtained. But some criticism can be made on the methodology followed for the analysis of interactions with artificial structures. As the choice of swimming mode considered for this study was to make hatchlings swim perpendicularly to the closest border, they were naturally repelled from the coasts and thus from the concerned artificial structures. Even though turtles probably try in some way to get away from coasts, it might not be in such a precise way. As turtles have no way of knowing the location of the closest border nor to find the exact perpendicular direction to it, it is probably not very realistic. This might be one of the reasons that so little interactions were recorded in this study. This will be discussed in further detail at the end of this section.

Our results suggest that a small fraction of Hawksbill hatchlings originating from Qatar's nesting beaches could leave the Gulf. As very little data is available on the topic of Hawksbill hatchlings migratory activity, it is difficult to assess if it is consistent with reality. In the study of Pilcher et al.[40], one of the turtles was recorded **entering** the Gulf, at the surprise of the researchers. The surprise comes from the fact that the sea turtle migrated from the sea of Oman, where foraging quality is higher than in the Gulf, into the Gulf (see figure 5.1) . In that study, the tracked turtles were adult post-nesting females, so not a lot can be infered about hatchlings but it could make a lot of sense for turtles to escape the Gulf in order to find better foraging range quality. Moreover, one clear outcome of the results presented here is that sea turtles seem to leave around the same period during the year. As observed by J. Pilcher et al. again, Hawksbills in the Gulf migrate during summer to escape higher surface water temperatures [57]. As the hatchlings emerge right during summer, this might lead them into currents that could drive them outside of the Gulf. There is also clear internesting variability for turtles leaving the Gulf. Most of the turtles leaving the Gulf hatched from Halul Island's nesting beaches. This could be due to the fact that Halul island is geographically closer to the Strait of Hormuz and thus the probability for them to reach the Strait of Hormuz is higher.

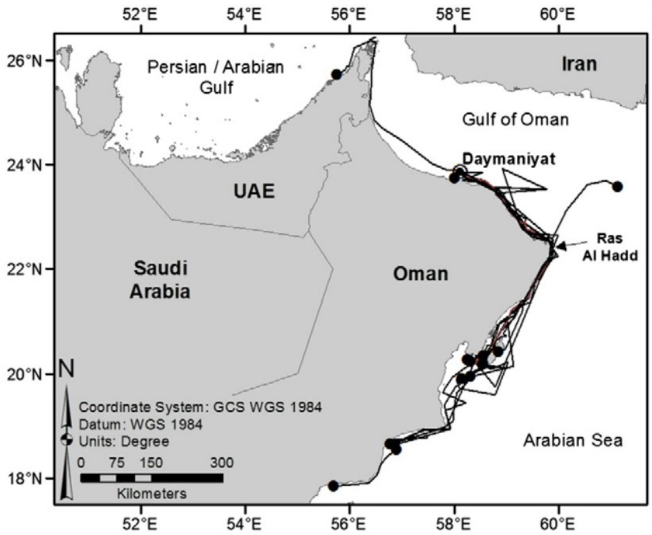


Figure 5.1: Trajectories from post-nesting turtles departing from Daymaniyat islands, Oman [40]

By looking at the hatchlings distribution in the Gulf, it first clearly appears that there is strong seasonal variability. What also appears is that hatchlings seem to shelter in the southern part of the Gulf more than anywhere else. This is in fact consistent with in situ research [40]. Indeed, even though the research is about adult Hawksbill sea turtles, we see that their foraging grounds are mostly located in that southern part of the Gulf, in the waters between Qatar and UAE. We can observe that, in the June-July-August and September-October-November seasons for example, the turtles concentration is high around and the North of Qatar. This coincides with the North Dome/South Pars as we can observe on figure 5.2 or with other structures such as the Al Shaheen oil field [56]. This area is a safe shelter for whale sharks in the Gulf as navigation is heavily controlled due to the presence of sensitive oil and gaz extraction platforms. This could also be a safe heaven for the turtles.

As with all modelling studies, our results rely on a set of assumptions that might not always be valid and could be questioned. One strong assumption concerns Hawksbill hatchlings swimming mode during their initial phase of active swimming as they move away from the beach. As data was only available for the swimming speed but not direction, duration, etc. choices had to be made. Our assumption is that the most realistic swimming mode would be for the turtles to swim against the waves ("Stokes" swimming mode of section 3.3) but due to lack of time we were unable to generate the wave dynamics with a fine resolution model. Even though turtles can dive underwater to avoid the effect of waves, i.e. being pushed back

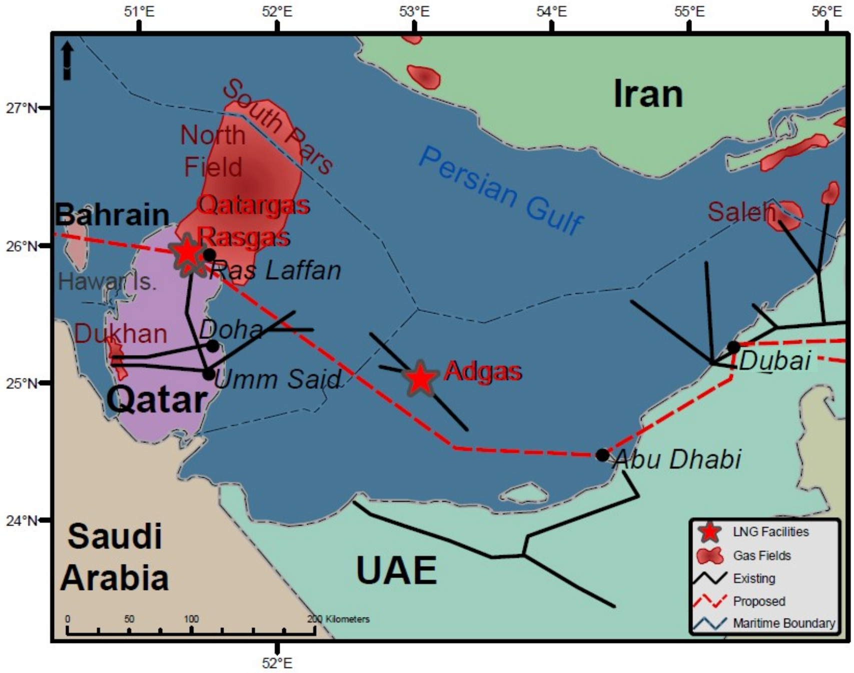


Figure 5.2: Location of a large gas field at the North of Qatar [58]

towards the coast, waves probably do influence their dispersal. This phenomenon is probably even amplified during times were intense Shamal winds occur, as they generate stronger waves. For the regional-scale analysis, a limitation of this research is that currents near the coasts aren't precise enough because of the rather coarse regional model used and again that the early days of dispersal might not be modelled in the most realistic way. The lack of precision on the coastal currents can be clearly observed on figure 4.5 where we can see that turtles accumulate strongly in various coastal zones without being able to escape from this. This is probably due to the fact that they are constantly pushed against the border with no escape possibility.

Despite these assumptions, we believe that this study sheds new light on the dispersal of sea turtle hatchlings and could pave the way for more detailed modelling studies. As it remains almost impossible to fit a GPS tracker on hatchlings to follow their position, biophysical models like the one developed here remain the only approach to understand their dispersal and fate during the first stage of their life. Biophysical models could thus quantitatively inform sea turtles conservation to devise protection measures for all their life stages.

Chapter 6

Conclusion

As many marine turtles species are currently endangered, it is of crucial importance to study them in order to make the best decisions to improve their chances of survival. This fact is definitely true for Hawksbill sea turtles in the Arabian Gulf. Little to nothing is known about those turtles except their nesting sites. The lack of information about juvenile Hawksbills is what motivated this research.

The main goal was to investigate the behaviour of Hawksbill sea turtles hatchlings during their early days. In particular, we wanted to investigate the possible impact of artificial structures such as Ras Laffan's LNG terminal on hatchlings. Secondly, we wanted to monitor what fraction of turtles leave the Gulf during their 'lost years'. This was made possible thanks to the multi-scale ocean model SLIM developped by UCLouvain. The model was validated with in situ measurements of a current meter and achieved very reasonable results. What came out of the analysis was that only a small fraction of turtles do actually interact with artificial structures near the coasts. Ras Laffan's LNG terminal was the only structure that had decent interactions with hatchlings as Ras Laffan's desalination plant and the Halul oil terminal did not yield enough interactions for them to be analyzed in depth. To monitor the regional-scale behaviour of turtles, the NEMO model was used. This allowed to come to the conclusion that approximately 1.26% of turtles left the Gulf over the simulation and during specific months of the year : mostly during September, October and November. Next, we were able to highlight specific areas were the probability of presence of hatchlings was higher depending on the season. This could be used to enforce protection measures in those areas.

Strong assumptions were made to model the turtles' movement which could possibly have led to biased results. The main assumptions were based on the direction and duration of swimming once turtles hatched. For example, a fine resolution wave model could be used in order to be able to model turtles' swimming direction in the most realistic way. There is a clear pathway for improvement on the modelling of turtles movement, assuming further research is made on the real-life behaviour of those hatchlings. For the regional scale analysis, a finer resolution model could be used in order to have more precise currents near the coasts as well as modelling the effect of waves on the turtles' dispersal. Hopefully this study will be a stepping stone for further and more detailed research on Hawksbills in the Gulf.

Appendix A

Appendix

A.1 dispersal patterns for different swimming behaviours

First of all, let's have a graphic representation to observe the differences between the swimming modes. Here below (A.1, A.2, A.3) are shown the dispersal patterns each 2 weeks for the two different swimming modes for 2019, 2020 and 2021. As we can observe, the main difference between both swimming modes is that for the perpendicular swimming mode (left side of the tables), the turtles scatter more and further away from closed borders. This is logical as the swimming mode implies that they swim perpendicularly to the closest border.

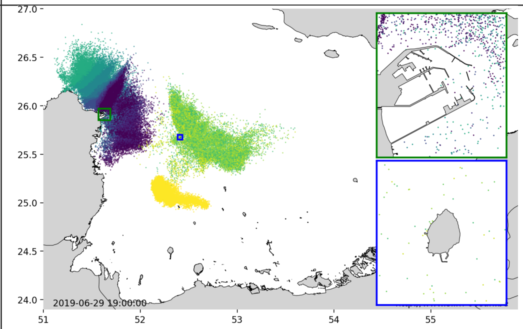
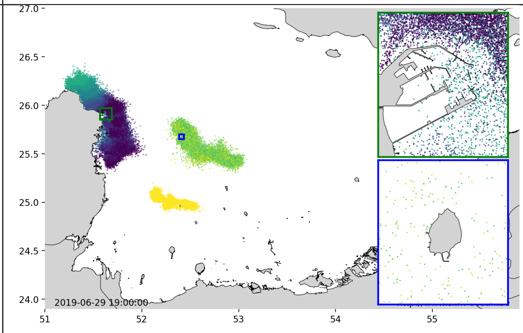
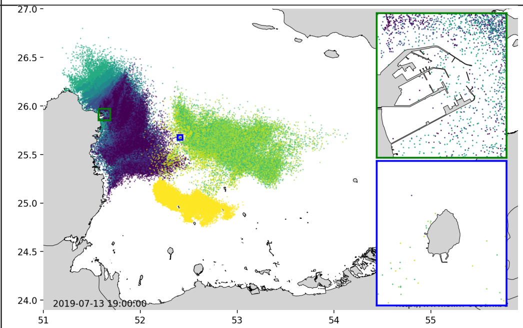
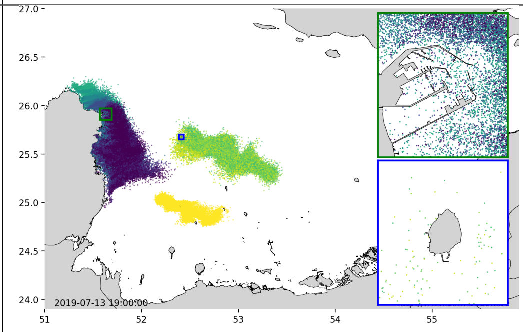
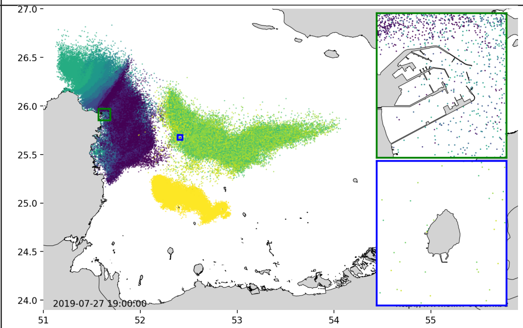
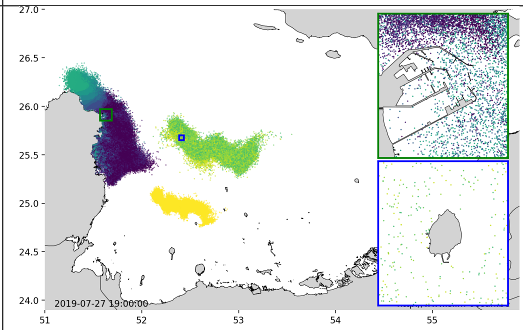
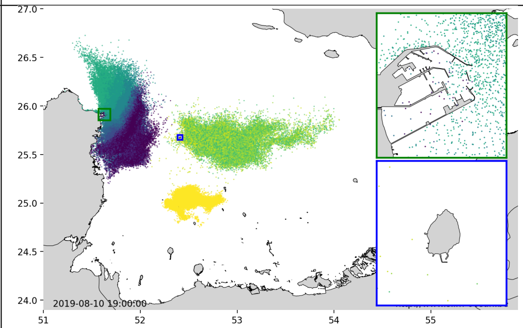
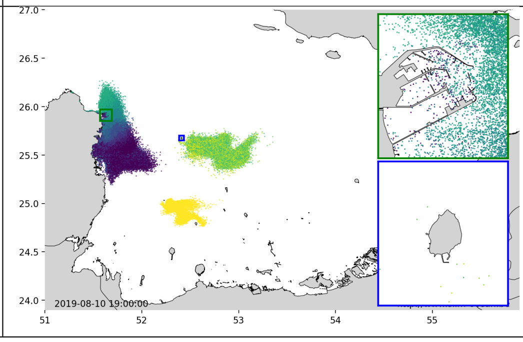
	Swimming mode	
Period	"Perpendicular"	"Decreasing"
T = 14 days		
T = 28 days		
T = 42 days		
T = 56 days		

Table A.1: Dispersal for 2019. Colors of the dots correspond to the nesting beaches. Zoom on Ras Laffan (upper right) and Halul (Lower Right).

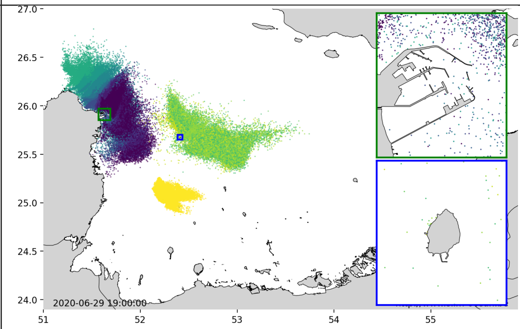
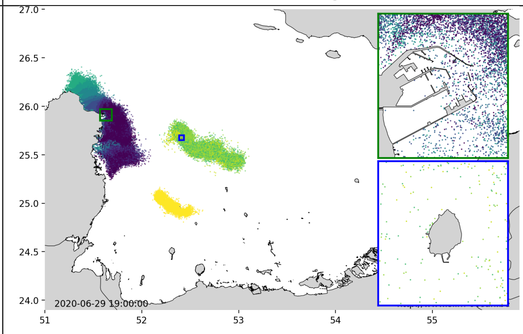
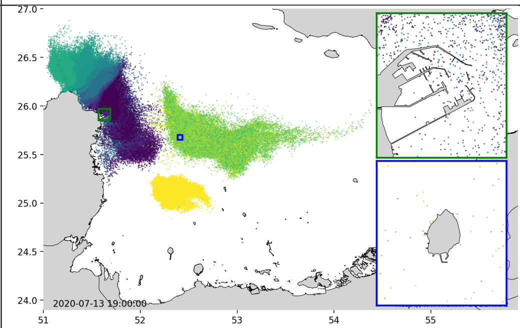
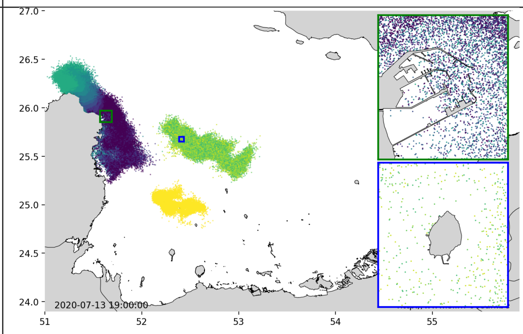
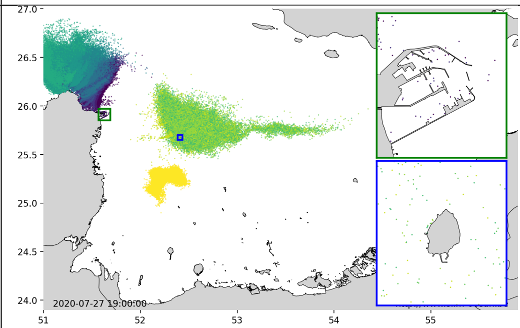
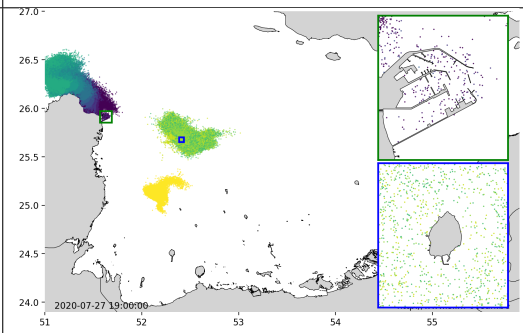
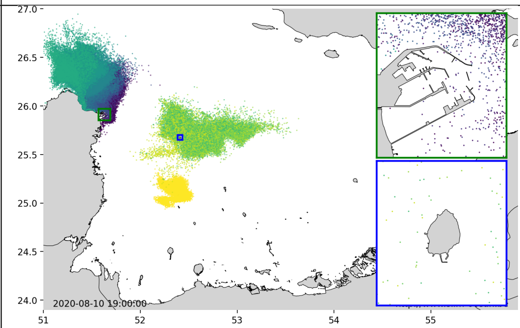
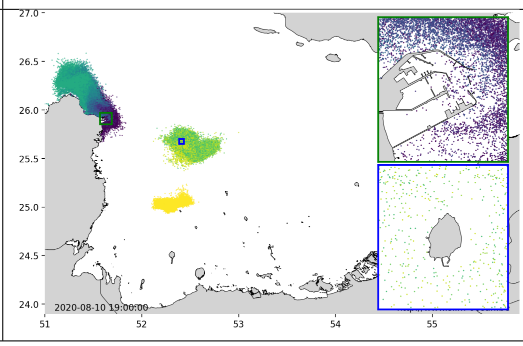
	Swimming mode	
Period	"Perpendicular"	"Decreasing"
T = 14 days		
T = 28 days		
T = 42 days		
T = 56 days		

Table A.2: Dispersal for 2020. Colors of the dots correspond to the nesting beaches. Zoom on Ras Laffan (upper right) and Halul (Lower Right).

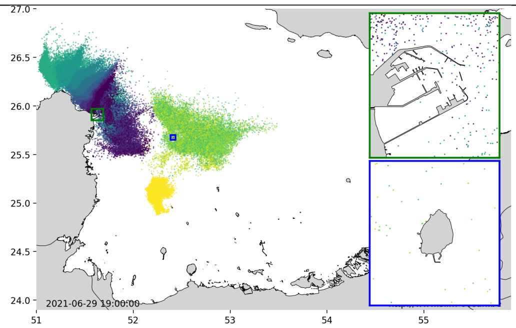
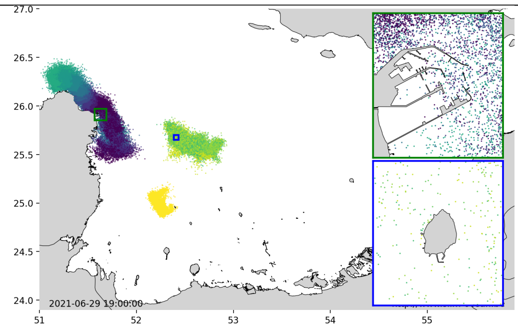
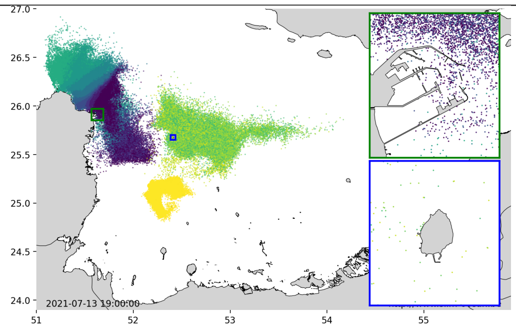
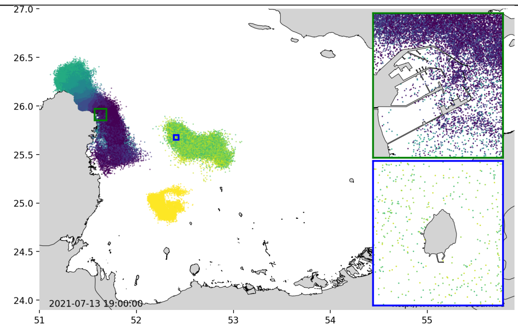
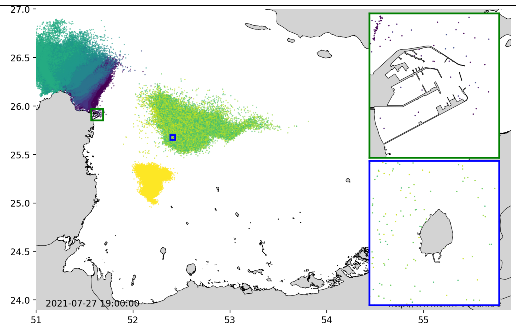
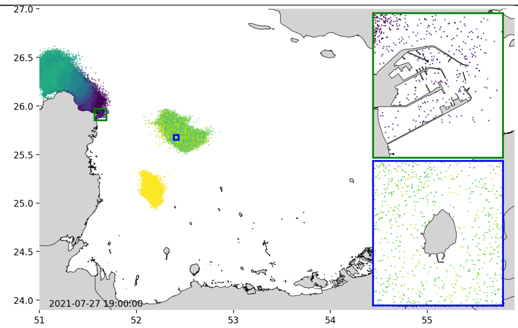
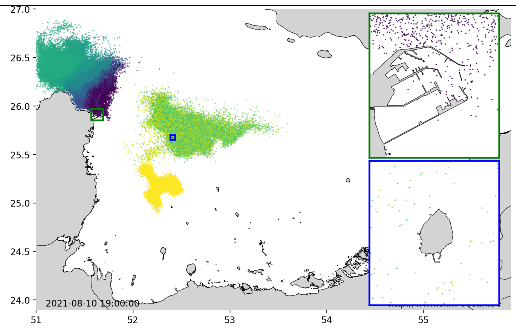
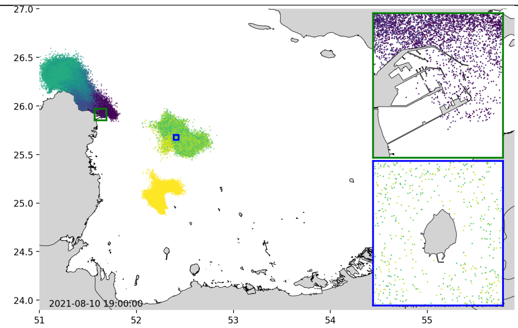
	Swimming mode	
Period	"Perpendicular"	"Decreasing"
T = 14 days		
T = 28 days		
T = 42 days		
T = 56 days		

Table A.3: Dispersal for 2021. Colors of the dots correspond to the nesting beaches. Zoom on Ras Laffan (upper right) and Halul (Lower Right).

Comparison of interactions

Now that we have seen a graphical representation of the dispersal phenomenon, let's take a more statistical approach. on figures A.1, A.2 and A.3 we can see the total percentage of turtles interacting with the concerned artificial structure. On the left side, the perpendicular swimming mode is represented while on the right side it is the decreasing swimming mode (see 3.3) Each row represents one year. As can be observed for the three structures of interest, we clearly observe a larger number of interactions for the decreasing swimming mode. Generally the number of interactions is $5 \sim 10$ times greater with the decreasing swimming mode. This makes sense as the currents might not necessarily bring turtles away from the borders but rather make them crash against it while for the perpendicular swimming mode, turtles *ignore* the currents and swim in a direction perpendicular to the borders which of course takes them away from the artificial structures. For the interactions with Ras Laffan LNG terminal and Ras Laffan desalination plant, only the nesting beaches on the coast of Qatar were taken into account as offshore nesting beaches (Halul and Shraouh) didn't have any interactions with Ras Laffan's artificial structures. The exact opposite principle was applied for the interactions with the Halul oil terminal.

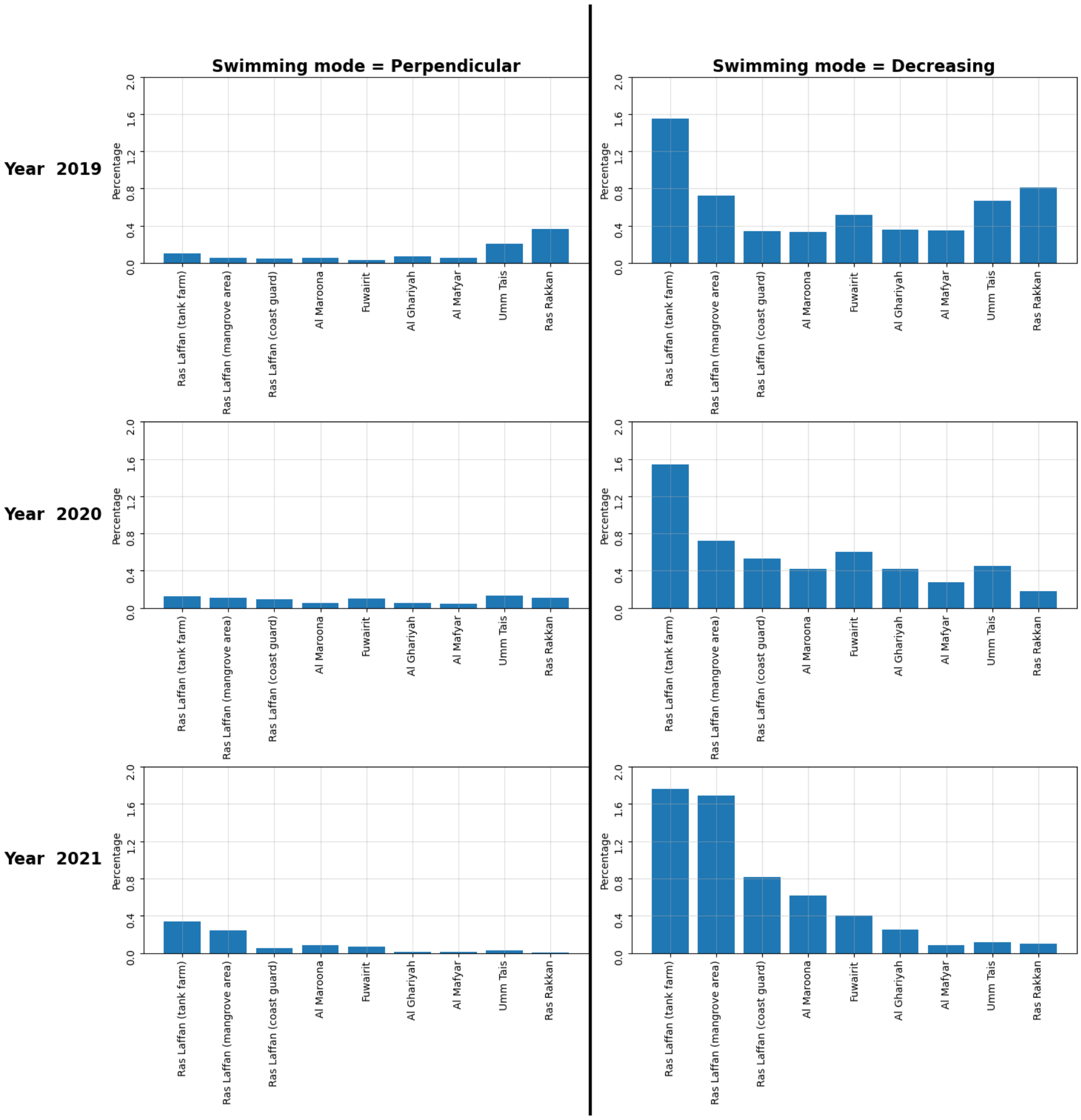


Figure A.1: Total percentage of interactions with Ras Laffan LNG terminal

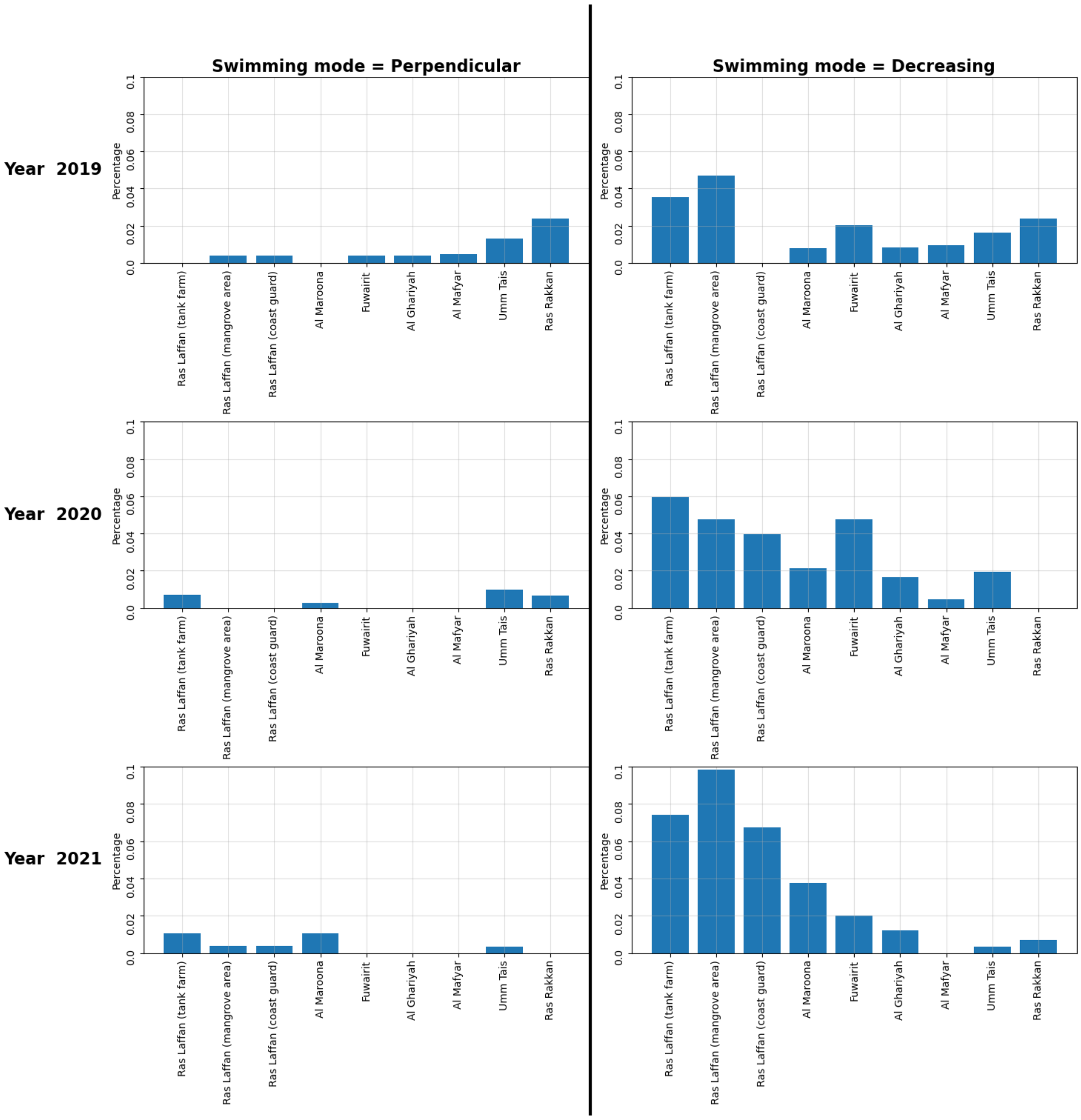


Figure A.2: Total percentage of interactions with Ras Laffan desalination plant

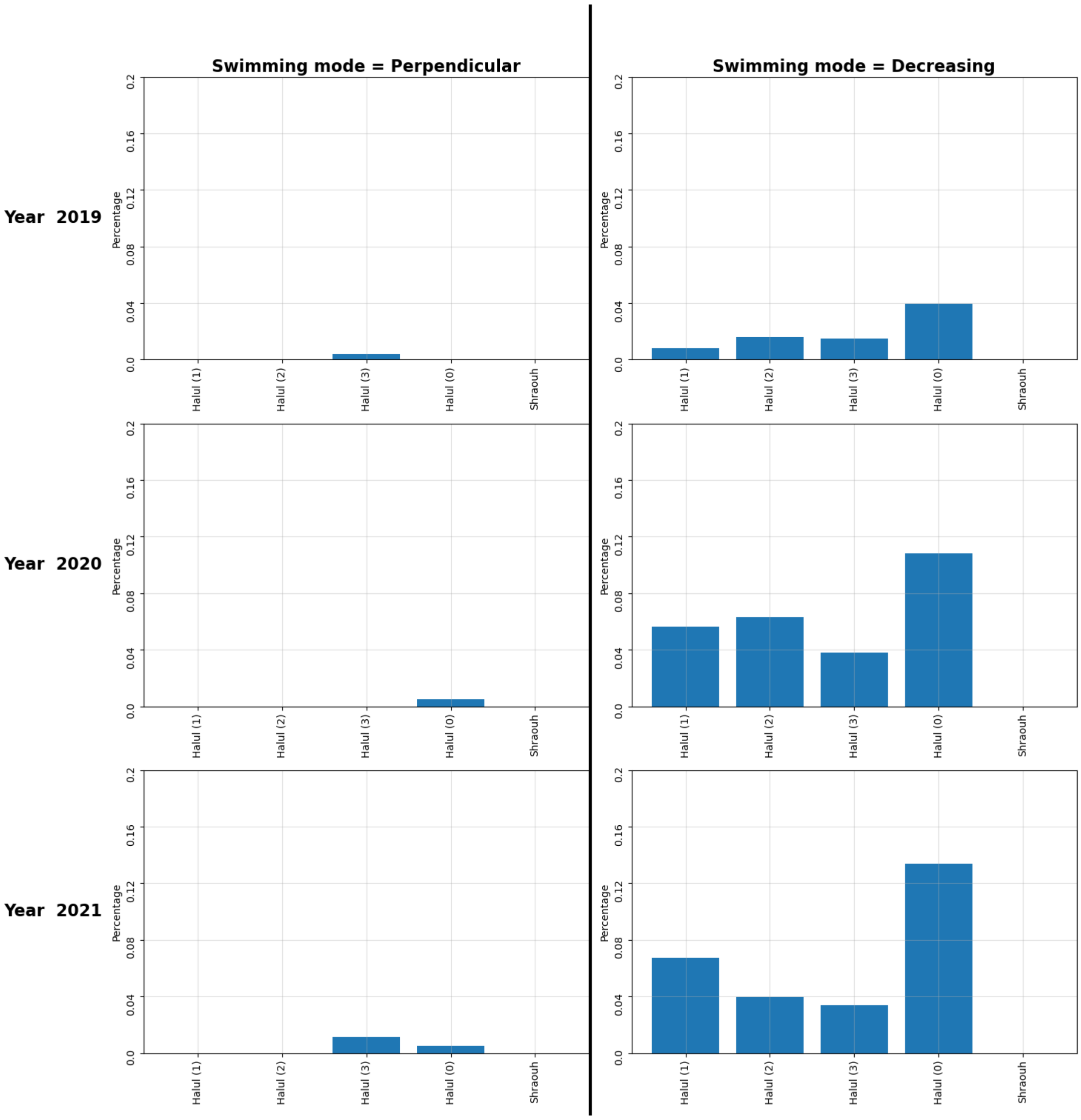


Figure A.3: Total percentage of interactions with Halul oil terminal

Bibliography

[1] C. Josh Donlan et al. "Using Expert Opinion Surveys to Rank Threats to Endangered Species: A Case Study with Sea Turtles". In: *Conservation Biology* 24.6 (2010). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1523-1739.2010.01541.x, pp. 1586–1595. ISSN: 1523-1739. DOI: 10.1111/j.1523-1739.2010.01541.x. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1523-1739.2010.01541.x (visited on 12/11/2021).

[2] NOAA Fisheries. *Hawksbill Turtle | NOAA Fisheries*. NOAA. Archive Location: Pacific Islands, Southeast. July 26, 2021. URL: https://www.fisheries.noaa.gov/species/hawksbill-turtle (visited on 12/02/2021).

[3] *History of Commercial Fishing - Development of the Fishing Industry*. URL: http://www.historyoffishing.com/fishing-history/history-of-commercial-fishing/ (visited on 12/11/2021).

[4] John B. Heppes and Eric J. McFadden. "The Convention on International Trade in Endangered Species of Wild Fauna and Flora: Improving the Prospects for Preserving our Biological Heritage Symposium: The Convention on International Trade in Endangered Species of Wild Fauna and Flora". In: *B.U. Int'l L. J.* 5.2 (1987), pp. 229–246. URL: https://heinonline.org/HOL/P?h=hein.journals/builj5&i=235 (visited on 12/11/2021).

[5] *Sea Turtle | Species | WWF*. URL: https://www.worldwildlife.org/species/sea-turtle (visited on 12/01/2021).

[6] Shadrack Omuka. *Illegal Fishing Is Devastating Kenya's Sea Turtles*. Hakai Magazine. June 17, 2021. URL: https://hakaimagazine.com/news/illegal-fishing-is-devastating-kenyas-sea-turtles/ (visited on 03/01/2022).

[7] Humood A. Naser. *Marine Ecosystem Diversity in the Arabian Gulf: Threats and Conservation*. Publication Title: Biodiversity - The Dynamic Balance of the Planet. IntechOpen, May 14, 2014. ISBN: 978-953-51-1315-7. DOI: 10.5772/57425. URL: https://www.intechopen.com/chapters/46202 (visited on 12/01/2021).

[8] Mohammad Heidarzadeh et al. “Meteorological Tsunami of 19 March 2017 in the Persian Gulf: Observations and Analyses”. In: *Pure Appl. Geophys.* 177.3 (Mar. 2020), pp. 1231–1259. ISSN: 0033-4553, 1420-9136. DOI: 10.1007/s00024-019-02263-8. URL: http://link.springer.com/10.1007/s00024-019-02263-8 (visited on 12/01/2021).

[9] *Hawksbill Sea Turtle (Eretmochelys Imbricata) 5-Year Review : Summary and Evaluation.* URL: https://repository.library.noaa.gov/view/noaa/17041 (visited on 12/11/2021).

[10] National Oceanic and Atmospheric Administration. “Title : Hawksbill Sea Turtle (Eretmochelys Imbricata) 5-Year Review : Summary and Evaluation”. In: (2013), p. 92. URL: https://repository.library.noaa.gov/view/noaa/17041.

[11] R. N Gibson, Margaret Barnes, and R. J. A Atkinson. *Oceanography and marine biology: an annual review. Volume 39 Volume 39.* OCLC: 52875983. London; New York: Taylor & Francis, 2001. ISBN: 9780585464381 9780203247198 9780415238748 9786612372971. URL: http://site.ebrary.com/id/10101013 (visited on 12/12/2021).

[12] Karen A. Bjorndal. “Nutritional Ecology of Sea Turtles”. In: *Copeia* 1985.3 (Aug. 5, 1985), p. 736. ISSN: 00458511. DOI: 10.2307/1444767. URL: https://www.jstor.org/stable/1444767?origin=crossref (visited on 12/12/2021).

[13] John Davenport. “Temperature and the life-history strategies of sea turtles”. In: *Journal of Thermal Biology* 22.6 (Dec. 1997), pp. 479–488. ISSN: 03064565. DOI: 10.1016/S0306-4565(97)00066-1. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306456597000661 (visited on 12/12/2021).

[14] Laura B. Hannan et al. “Dune Vegetation Fertilization by Nesting Sea Turtles”. In: *Ecology* 88.4 (2007). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1890/06-0629, pp. 1053–1058. ISSN: 1939-9170. DOI: 10.1890/06-0629. URL: https://onlinelibrary.wiley.com/doi/abs/10.1890/06-0629 (visited on 12/12/2021).

[15] *Information About Sea Turtles: Why Care? – Sea Turtle Conservancy.* URL: https://conserveturtles.org/information-about-sea-turtles-why-care/ (visited on 12/11/2021).

[16] Nathan F. Putman and Katherine L. Mansfield. “Direct Evidence of Swimming Demonstrates Active Dispersal in the Sea Turtle “Lost Years” | Elsevier Enhanced Reader”. In: (2015), p. 8. DOI: 10.1016/j.cub.2015.03.014.

[17] Robson G. Santos et al. "The anti-predator role of within-nest emergence synchrony in sea turtle hatchlings". In: *Proceedings of the Royal Society B: Biological Sciences* 283.1834 (July 13, 2016). Publisher: Royal Society, p. 20160697. DOI: 10.1098/rspb.2016.0697. URL: https://royalsocietypublishing.org/doi/full/10.1098/rspb.2016.0697 (visited on 12/12/2021).

[18] *Information About Sea Turtles: Threats from Invasive Species Predation – Sea Turtle Conservancy*. URL: https://conserveturtles.org/information-sea-turtles-threats-invasive-species-predation/ (visited on 12/12/2021).

[19] Benjamin Mayne et al. "Lifespan estimation in marine turtles using genomic promoter CpG density". In: *PLoS ONE* 15.7 (July 31, 2020). Ed. by Ulrike Gertrud Munderloh, e0236888. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0236888. URL: https://dx.plos.org/10.1371/journal.pone.0236888 (visited on 12/15/2021).

[20] *Hawksbill_sea_turtle_-_NOAA.jpg (Image JPEG, 1024 × 640 pixels)*. URL: https://upload.wikimedia.org/wikipedia/commons/e/eb/Hawksbill_sea_turtle_-_NOAA.jpg (visited on 12/02/2021).

[21] K. A. Bjorndal. "Conservation of Hawksbill Sea Turtles: Perceptions and Realities". In: *Chelonian Conservation and Biology* 3 (1999), pp. 174–176. URL: http://www.turtles.org/bjorndal.htm (visited on 12/15/2021).

[22] *Hawksbill Turtle | Sea Turtles | Species | WWF*. World Wildlife Fund. URL: https://www.worldwildlife.org/species/hawksbill-turtle (visited on 12/01/2021).

[23] *Hawksbill sea turtle*. In: *Wikipedia*. Page Version ID: 1056349214. Nov. 21, 2021. URL: https://en.wikipedia.org/w/index.php?title=Hawksbill_sea_turtle&oldid=1056349214 (visited on 12/01/2021).

[24] *Pacific Hawksbill Sea Turtle - Eretmochelys imbricata bissa*. URL: http://www.californiaherps.com/turtles/pages/e.i.bissa.html (visited on 12/11/2021).

[25] *La CITES en bref | CITES*. URL: https://cites.org/fra/disc/what.php (visited on 12/02/2021).

[26] Abdolrahim Pazira et al. "Hatching success of Hawksbill sea turtles (Eretmochelys imbricata) in a protected hatchery site in Nakhiloo Island, Persian Gulf". In: *Regional Studies in Marine Science* 3 (Jan. 2016), pp. 216–224. ISSN: 23524855. DOI: 10.1016/j.rsma.2015.11.001. URL: https://linkinghub.elsevier.com/retrieve/pii/S2352485515000687 (visited on 12/12/2021).

[27] Mark Chatting et al. “Nesting ecology of hawksbill turtles, Eretmochelys imbricata, in an extreme environmental setting”. In: *PLOS ONE* 13.9 (Sept. 7, 2018). Publisher: Public Library of Science, e0203257. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0203257. URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0203257 (visited on 12/01/2021).

[28] W. N. Witzell. *Synopsis of Biological Data on the Hawksbill Turtle, Eretmochelys Imbricata (Linnaeus, 1766)*. Google-Books-ID: F_CaCWCUEmgC. Food & Agriculture Org., 1983. 88 pp. ISBN: 978-92-5-101356-4.

[29] Jeanette Wyneken and Michael Salmon. “Frenzy and Postfrenzy Swimming Activity in Loggerhead, Green, and Leatherback Hatchling Sea Turtles”. In: *Copeia* 1992.2 (May 1, 1992), p. 478. ISSN: 00458511. DOI: 10.2307/1446208. URL: https://www.jstor.org/stable/1446208?origin=crossref (visited on 12/01/2021).

[30] F. C. Chung et al. “Offshore Migratory Activity of Hawksbill Turtle (*Eretmochelys imbricata*) Hatchlings, II. Swimming Gaits, Swimming Speed, and Morphological Comparisons”. In: *Chelonian Conservation and Biology* 8.1 (May 2009), pp. 35–42. ISSN: 1071-8443. DOI: 10.2744/CCB-0716.1. URL: http://www.bioone.org/doi/abs/10.2744/CCB-0716.1 (visited on 03/05/2022).

[31] Josh D. Butler et al. “A high-resolution remotely sensed benthic habitat map of the Qatari coastal zone”. In: *Marine Pollution Bulletin* 160 (Nov. 2020), p. 111634. ISSN: 0025326X. DOI: 10.1016/j.marpolbul.2020.111634. URL: https://linkinghub.elsevier.com/retrieve/pii/S0025326X20307529 (visited on 12/01/2021).

[32] Elnaiem Ali Elobaid et al. “Spatial variability of summer hydrography in the central Arabian Gulf”. In: *Oceanologia* 64.1 (Jan. 2022), pp. 75–87. ISSN: 00783234. DOI: 10.1016/j.oceano.2021.09.003. URL: https://linkinghub.elsevier.com/retrieve/pii/S007832342100083X (visited on 03/05/2022).

[33] H. Askari. *Collaborative Colonialism: The Political Economy of Oil in the Persian Gulf*. Google-Books-ID: KfvQAQAAQBAJ. Springer, Sept. 18, 2013. 211 pp. ISBN: 978-1-137-35377-1.

[34] Fahad Al Senafi and Ayal Anis. “Shamals and climate variability in the Northern Arabian/Persian Gulf from 1973 to 2012”. In: *International Journal of Climatology* 35.15 (2015). _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/joc.4302, pp. 4509–4528. ISSN: 1097-0088. DOI: 10.1002/joc.4302. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/joc.4302 (visited on 12/14/2021).

[35] Niloufar Bayani. “Ecology and Environmental Challenges of the Persian Gulf”. In: *Iranian Studies* 49.6 (Nov. 1, 2016). Publisher: Routledge _eprint: https://doi.org/10.1080/00210862.2016.1241569, pp. 1047–1063. ISSN: 0021-0862. DOI: 10.1080/00210862.2016.1241569. URL: https://doi.org/10.1080/00210862.2016.1241569 (visited on 12/14/2021).

[36] Francesco Paparella et al. “Coral Bleaching in the Persian/Arabian Gulf Is Modulated by Summer Winds”. In: *Frontiers in Marine Science* 6 (2019). ISSN: 2296-7745. URL: https://www.frontiersin.org/article/10.3389/fmars.2019.00205 (visited on 03/05/2022).

[37] sh Madani et al. “Estimating Total Economic Value of Coral Reefs of Kish Island (Persian Gulf)”. In: *International Journal of Environmental Research* 6 (Dec. 1, 2012), pp. 51–60.

[38] Nj Pilcher et al. “Population structure of marine turtles in coastal waters of Qatar”. In: *Endang. Species. Res.* 28.2 (Sept. 10, 2015), pp. 163–174. ISSN: 1863-5407, 1613-4796. DOI: 10.3354/esr00688. URL: http://www.int-res.com/abstracts/esr/v28/n2/p163-174/ (visited on 12/01/2021).

[39] Jack Frazier. “Prehistoric and Ancient Historic Interactions between Humans and Marine Turtles”. In: (2003), p. 38.

[40] Nicolas J. Pilcher et al. “Identification of Important Sea Turtle Areas (ITAs) for hawksbill turtles in the Arabian Region”. In: *Journal of Experimental Marine Biology and Ecology* 460 (Nov. 2014), pp. 89–99. ISSN: 00220981. DOI: 10.1016/j.jembe.2014.06.009. URL: https://linkinghub.elsevier.com/retrieve/pii/S0022098114001816 (visited on 12/01/2021).

[41] *Arabian Gulf Marine Turtle Conservation Project (2010-2014)*. Marine Research Foundation. URL: https://www.mrf-asia.org/project/arabian-gulf-marine-turtle-conservation-project-2010-2014/ (visited on 05/13/2022).

[42] *Home*. Mercator Océan - Ocean Forecasters. URL: https://www.mercator-ocean.eu/ (visited on 05/14/2022).

[43] Bernardo Cockburn, George E. Karniadakis, and Chi-Wang Shu. “The Development of Discontinuous Galerkin Methods”. In: *Discontinuous Galerkin Methods*. Ed. by Bernardo Cockburn, George E. Karniadakis, and Chi-Wang Shu. Red. by M. Griebel et al. Vol. 11. Series Title: Lecture Notes in Computational Science and Engineering. Berlin, Heidelberg: Springer Berlin Heidelberg, 2000, pp. 3–50. ISBN: 978-3-642-64098-8 978-3-642-59721-3. DOI: 10.1007/978-3-642-59721-3_1. URL: http://link.springer.com/10.1007/978-3-642-59721-3_1 (visited on 05/10/2022).

[44] Benjamin de Brye et al. “A finite-element, multi-scale model of the Scheldt tributaries, river, estuary and ROFI”. In: *Coastal Engineering* 57.9 (Sept. 2010), pp. 850–863. ISSN: 03783839. DOI: 10.1016/j.coastaleng.2010.04.001. URL: https://linkinghub.elsevier.com/retrieve/pii/S0378383910000487 (visited on 05/21/2022).

[45] S. D. Smith and E. G. Banke. “Variation of the sea surface drag coefficient with wind speed”. In: *Q.J Royal Met. Soc.* 101.429 (July 1975), pp. 665–673. ISSN: 00359009, 1477870X. DOI: 10.1002/qj.49710142920. URL: https://onlinelibrary.wiley.com/doi/10.1002/qj.49710142920 (visited on 05/30/2022).

[46] J. Smagorinsky. “GENERAL CIRCULATION EXPERIMENTS WITH THE PRIMITIVE EQUATIONS: I. THE BASIC EXPERIMENT*”. In: *Mon. Wea. Rev.* 91.3 (Mar. 1963), pp. 99–164. ISSN: 0027-0644, 1520-0493. DOI: 10.1175/1520-0493(1963)091<0099:GCEWTP>2.3.CO;2. URL: http://journals.ametsoc.org/doi/10.1175/1520-0493(1963)091%3C0099:GCEWTP%3E2.3.CO;2 (visited on 05/21/2022).

[47] Jonathan Lambrechts et al. “A multi-scale model of the hydrodynamics of the whole Great Barrier Reef”. In: *Estuarine, Coastal and Shelf Science* 79.1 (Aug. 2008), pp. 143–151. ISSN: 02727714. DOI: 10.1016/j.ecss.2008.03.016. URL: https://linkinghub.elsevier.com/retrieve/pii/S0272771408001364 (visited on 05/21/2022).

[48] *GEBCO Gridded Bathymetry Data*. URL: https://www.gebco.net/data_and_products/gridded_bathymetry_data/ (visited on 05/17/2022).

[49] Hans Hersbach et al. “The ERA5 global reanalysis”. In: *Q.J.R. Meteorol. Soc.* 146.730 (July 2020), pp. 1999–2049. ISSN: 0035-9009, 1477-870X. DOI: 10.1002/qj.3803. URL: https://onlinelibrary.wiley.com/doi/10.1002/qj.3803 (visited on 05/30/2022).

[50] Christophe Geuzaine and Jean-François Remacle. “Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities: THE GMSH PAPER”. In: *Int. J. Numer. Meth. Engng.* 79.11 (Sept. 10, 2009), pp. 1309–1331. ISSN: 00295981. DOI: 10.1002/nme.2579. URL: https://onlinelibrary.wiley.com/doi/10.1002/nme.2579 (visited on 05/10/2022).

[51] Akira Okubo. “Oceanic diffusion diagrams”. In: *Deep Sea Research and Oceanographic Abstracts* 18.8 (Aug. 1971), pp. 789–802. ISSN: 00117471. DOI: 10.1016/0011-7471(71)90046-5. URL: https://linkinghub.elsevier.com/retrieve/pii/0011747171900465 (visited on 05/18/2022).

[52] *seaguard recording current meter - Recherche Google*. URL: https://www.google.com/search?client=firefox-b-d&q=seaguard+recording+current+meter (visited on 05/17/2022).

[53] V.M. Aboobacker et al. "Role of shamal and easterly winds on the wave characteristics off Qatar, central Arabian Gulf". In: *Ocean Engineering* 236 (Sept. 2021), p. 109457. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2021.109457. URL: https://linkinghub.elsevier.com/retrieve/pii/S0029801821008611 (visited on 05/17/2022).

[54] Daniel L. Codiga. "Unified tidal analysis and prediction using the UTide Matlab functions". In: (2011). Publisher: Graduate School of Oceanography, University of Rhode Island. DOI: 10.13140/RG.2.1.3761.2008. URL: http://rgdoi.net/10.13140/RG.2.1.3761.2008 (visited on 05/17/2022).

[55] Stéphane Pous, Xavier Carton, and Pascal Lazure. "A Process Study of the Wind-Induced Circulation in the Persian Gulf". In: *OJMS* 03.1 (2013), pp. 1–11. ISSN: 2161-7384, 2161-7392. DOI: 10.4236/ojms.2013.31001. URL: http://www.scirp.org/journal/doi.aspx?DOI=10.4236/ojms.2013.31001 (visited on 06/03/2022).

[56] David P. Robinson et al. "Whale Sharks, Rhincodon typus, Aggregate around Offshore Platforms in Qatari Waters of the Arabian Gulf to Feed on Fish Spawn". In: *PLoS ONE* 8.3 (Mar. 13, 2013). Ed. by Maura Geraldine Chapman, e58255. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0058255. URL: https://dx.plos.org/10.1371/journal.pone.0058255 (visited on 06/05/2022).

[57] Nicolas J. Pilcher et al. "Short-term behavioural responses to thermal stress by hawksbill turtles in the Arabian region". In: *Journal of Experimental Marine Biology and Ecology* 457 (Aug. 2014), pp. 190–198. ISSN: 00220981. DOI: 10.1016/j.jembe.2014.04.002. URL: https://linkinghub.elsevier.com/retrieve/pii/S0022098114000884 (visited on 05/13/2022).

[58] Kohei Hashimoto, Jareer Elass, and Stacy L. Eller. "Liquefied natural gas from Qatar: the Qatargas project". In: *Natural Gas and Geopolitics*. Ed. by David G. Victor, Amy M. Jaffe, and Mark H. Hayes. Cambridge: Cambridge University Press, 2006, pp. 234–267. ISBN: 978-0-511-49349-2 978-0-521-86503-6 978-0-521-08290-7. DOI: 10.1017/CBO9780511493492.009. URL: https://www.cambridge.org/core/product/identifier/CBO9780511493492A023/type/book_part (visited on 06/04/2022).

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