# Kilian BARREIRO – PhD Application – PEPR BRIDGES

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## 1. Scientific Description of the Thesis Project.

### 1.1) Scientific context, state of the art

Understanding the mechanisms driving marine wildlife movements remains a major challenge in ecology and biogeography. Describing and modelling wildlife distribution and mobility across the dynamical seascape is essential to understand how abiotic factors control wildlife movements, with implications for explaining contemporary biogeography and predicting future changes. While foundational tools date back to the early-mid 20th century [20], research interest surged around the early 2000s [14].

Since then, ecological dynamic modelling has advanced toward greater sophistication and interdisciplinarity [10]. Recent models include statistical approaches based on environmental variables [7], integrated "end-to-end" models [23], and mechanistic models focused on real processes [3]. Among the latter, partial differential equation (PDE)-based models, particularly advection-diffusion-reaction (ADR) formulations, excel at simulating spatio-temporal changes in population density [9].

Physical oceanic gradients—such as edge effects, mixing, and horizontal transport [21]—strongly structure marine populations, with small-scale fronts (10–20 km) playing a key role in heat exchange and productivity [19]. Fronts act as concentration hotspots where climate change impacts are amplified [1]. Climate velocities drive species range shifts more than individual traits, as shown across 360 marine taxa [18], with regional effects on diversity and richness at varying depths [11].

In the South-West Indian Ocean (SWIO), a region highly vulnerable to marine climate change [8], species distributions are shaped by multiple factors. By deciphering the relevant spatial and temporal scales, this project will support the design, linkage, and implementation of spatial management tools, including marine protected areas (MPAs).

### 1.2) Scientific objectives and research question(s), originality of the subject

This research aims to characterize and quantify the sensitivity of selected mid-to-high trophic level marine organisms to key oceanic structures in the South-West Indian Ocean (SWIO), including thermal fronts, bathymetry, Lagrangian coherent structures, currents, and eddies, with a focus on their dispersion patterns. The central research question is: "How do marine organisms respond differently to oceanic structures in the SWIO, and what are the implications of these species-specific sensitivities for regional connectivity patterns and population persistence under current and future climate conditions?". The thesis title is: "From reef to open ocean: multi-vertebrate responses to oceanic structures in the SWIO and their connectivity implications under climate change – a mechanistic approach with ADR modelling"

This topic introduces several key innovations related to existing literature. First, it integrates ocean front gradients as an active advection term in an advection-diffusion-reaction (ADR) model, a novel methodological step beyond general connectivity studies [6]. This is justified by the critical role of fronts in species movements and the availability of high-quality telemetry data. Second, the relatively simple, low-computational-cost mechanistic approach—contrasting with complex end-to-end models like Ecopath/Ecosim [17] or APECOSM [13]—enables extensive simulations, future scenario testing, interpretability, and robustness. Third, the comparative multi-taxa framework addresses a gap in SWIO studies, which are often single species focused [5], by spanning diverse ecological strategies (reef vs. pelagic fish, herbivorous vs. spongivorous turtles, seabirds). Finally, incorporating climate projections to assess future sensitivity to oceanic structures fills a major knowledge gap in the region, where no study has yet projected species-specific responses under climate change.

### 1.3) Contribution to the scientific challenges and issues of BRIDGES

The mechanistic (process-based) ADR modelling approach directly supports Challenge 2 (MODÉLISER) by advancing realistic socio-ecological modelling of marine connectivity at relevant spatio-temporal scales, integrating multi-level interconnections and feedback loops in SWIO ecosystems. It contributes to Challenge 3 (ANTICIPER) through simulations of species redistribution under climate change, identification of vulnerable areas/hotspots, and biodiversity risk assessment, providing a foundation for adaptive MPA networks and sustainable fisheries management plans. Innovation in data processing and analysis aligns with Challenge 1 (INNOVER): the model converts multi-source ocean/climate data (satellite, acoustic telemetry, in situ) into predictive distributions and movements, with planned public release of codes and analyses to fully adhere to FAIR principles.

Overall, these outputs enhance anticipation of climate-driven shifts in connectivity and population persistence, supporting resilient, equitable governance of SWIO marine resources.

### 1.4) Project implementation

#### 1.4.1) Methods

***Spatio-temporal scale and target species*** : The spatial scale of 1:50 km and monthly to seasonal temporal scale reflect a balance between data resolution, computational feasibility, and ecological relevance. Sensitivity analyses will evaluate the impact of scale choices on model outputs. The following species have been selected as representative focal species for this study, and are also target species of closely-related projects (funded through the SIOMPA call, providing further in-situ observations from collaborators to calibrate and validate model outputs), including but not limited to: Giant trevally (*Caranx ignobilis*), blacksaddled coral grouper (*Plectropomus laevis*), green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricata*), and sooty tern (*Onychoprion fuscatus*). Additional species may be considered depending on data availability and ecological relevance.

***Environmental and Biological data :***

- Current oceanic fields: 3D currents (WINDS-M : 1/50° regional simulation of the SWIO (1993-2020) ; [24]), surface temperature (SST) (Copernicus Marine Service GLORYS12V1 or PSY4V3 reanalysis, resolution ~1/12° ; period 2000–2025 for validation).
- Front detection: Thermal fronts (2003–2020) and Lagrangian Coherent Structures (FSLE, 1994–2020) at 1 km (NOMAD Dataset; [22]).

- Climate scenarios : Downscaling or bias correction of CMIP6 and CESM-LENS projections (e.g. SSP2-4.5 and SSP5-8.5) via high-resolution CROCO simulations (or CORDEX Africa or SWIO regional products) including historical hindcast (validation & calibration) and future runs (e.g. 2050 and 2100) ; focus on climate velocity, front displacement, currents (Agulhas leakage intensification ; [12]).
- Bathymetry maps (GEBCO).
- Tracking and occurrences: Satellite telemetry data, acoustic tagging (from MERMOZ/SIOMPA project).
- Vital parameters by species (literature review): Swimming speed/active current (adult turtles ~0.5–1 m/s; seabirds foraging flight), natural mortality rate, larval retention time (fish ~20–40 days), attraction to gradients, etc.

***Mecanistic modelling ADR :***

- General formulation :

$$\frac{\partial N}{\partial t} = \nabla \cdot (D \nabla N) \; - \; \nabla \cdot \left[ \left( V_p(x,t) + V_a(x,t) \right) N \right] \; - \; R(x,t) N$$

Where :

- $N$ : density of individuals
- $D$ : diffusion parameter
- $V_p$ passive advection parameter
- $V_a$ : active advection parameter
- $R$ : reaction parameter (population growth, demography)
- $\nabla$ : nabla operator (vector operator, indicates direction and rates)

1.4.2) Site(s) concerned or applicability to site(s) in the case of a methodological thesis

The whole South-western Indian Ocean (SWIO) region site.

1.4.3) Thesis timetable

Thesis timetable will split into four phases. Phase 1 will be the data collection, preprocessing and sensitivity tests to select species and scales (M1-M6). Phase 2 will be development and implementation of ADR models (M6-M12). Phase 3 will be the simulations of the differents scenarios (M12-M24). Finally, phase 4 will be the time for comparative analyses, robustesness and conservation/spatial planning implications (M24-M36). We expect to produce 2 to 3 peer-reviewed publications : one on ADR methodology and validation (mid-thesis), one on current connectivity patterns and species sensitivities (end of thesis), and one on future climate projections and conservation implications (potentially post-defense).

## 1.5) Expected results

We expect this project and the model to produce spatial connectivity matrices and dynamic distribution maps. Key metrics will include indices of species sensitivity to environmental gradients (such as ocean fronts and climate velocities) as well as oceanographic connectivity metrics, like proportional connectivity describing the relative strength of links between ocean structures [4]. We also aim to project species populations under different climate scenarios (e.g., [2]) using graphs or time series.

Spatial connectivity matrices, derived from these metrics, will be central outputs. They will reveal dispersal corridors, barriers, and the emerging spatial structure of marine populations. Often represented as graphs, these matrices will illustrate movement flows between oceanographic features. A key objective is to demonstrate the variability of connectivity and sensitivity across different ocean structures and currents.

Finally, we will map past and future trajectories to compare interspecies strategies in response to the spatio-temporal evolution of oceanographic structures under various climate change scenarios. These dynamic distribution maps will display individual density or the probability of population presence in given areas. We hypothesize a significant (positive or negative) correlation between zones of individual accumulation and their overlap with ocean fronts.

## 1.6) Academic and societal value

This work advances marine ecology by quantifying differentiated responses of key vertebrates (fish, turtles, seabirds) to fine-scale oceanographic structures in the SWIO using innovative mechanistic ADR modelling. The explicit integration of front gradients as an active advection term in a lightweight ADR framework offers a scalable advance over complex or correlative methods. It elucidates dispersion, connectivity, and sensitivity mechanisms to physical/climatic drivers, highlighting inter-taxa and multi-scale variations in a biodiversity hotspot.

The results support sustainable marine management and conservation by identifying priority corridors and hotspots for resilient MPAs, promoting biodiversity preservation amid climate change. Predictive maps, redistribution scenarios, and vulnerability indices provide practical tools for adapting regional policies (MPA plans, quotas, monitoring), thereby strengthening marine governance and decision-making.

## 1.7) Potential risks and measures taken to avoid these

The main methodological risks include uncertainties in oceanographic data (underestimated fine-scale resolution of fronts) and limited biological data (sparse tracking for certain species). The validity of ADR models may be affected by biases (simplified behaviors, submesoscale ignorance) and poor generalizability of calibrated parameters ([15,16]). Mitigation measures: spatio-temporal cross-validation (AUC, Boyce index), Monte Carlo sensitivity analyses, and a progressive iterative approach (prototype → multi-taxa). Systematic quality controls (mass balances, numerical stability) and collaboration with experts (oceanographers, BRIDGES ecologists) minimize blind spots. Awareness of limitations : explicit discussion of simplifications in the final results.

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## 2. Resources provided by the supervisory team for the successful completion of the thesis

### 2.1) Hosting and material conditions

The PhD candidate Kilian BARREIRO will be hosted at the **Mediterranean Institute of Oceanography (MIO)** (part of OSU-PYTHEAS and jointly run by University of Aix-Marseille, the University of Toulon, the CNRS and the IRD (UMR 110AMU, 7294 CNRS, 235 IRD, UTLN)). This site offers a vibrant and interdisciplinary scientific environment dedicated to marine sciences, with strong expertise in physical oceanography and marine ecology. Although social sciences are not present within MIO, previous work undertaken there thoroughly studied Mediterranean socio-ecosystems, allowing interesting discussions with local colleagues and enabling knowledge transfer toward the SWIO.

If selected, this PhD project will be housed by the ECOMAD team (ECOlogie Théorique, Modélisation & Analyse de Données), which is perfectly aligned with the main thematic of this project. Moreover, the PhD candidate will benefit from discussion and potential collaborations essentially with 2 others research teams : Ecologie Marine et BIOdiversité (EMBIO) and Océanographie Physique, Littorale et Côtière (OPLC).

This project addresses the following "défi du laboratoire" : L'identification des liens entre biodiversité/cycles biogéochimiques/phénomènes physiques.

The candidate will benefit from:

- Supervisory team support and expertise: **Vincent Rossi** (CNRS – MIO) for expertise in oceanography, biophysical interactions, Lagrangian modelling, **Valeriano Parravicini** (EPHE / CRIOBE) for expertise in marine biogeography and quantitative approaches and **Vincent Calcagno** (INRAE - ISA) for expertise in ecological quantitative modelling**.**
- Full access to local (shared drive, cluster, etc..) regional and national high-performance computing platforms, technical facilities and resources for heavy simulations and ensemble runs.
- AMU"s library and full digital access to literatureSite-based office with excellent internet connection, enabling seamless access to heavy datasets from collaborative platforms.
- Integration into multidisciplinary research groups, frequent seminars, and direct interaction with ongoing BRIDGES projects on connectivity and climate vulnerability.

### 2.2) Financial conditions:

- **Missions and travel (including mandatory training)**: €12,500
  – €7,500 reserved for transport costs to attend BRIDGES mandatory training events, workshops and annual trips to meet the co-supervisors

(1-2 weeks every year).
– €5,000 for participation in 2–3 international conferences (e.g., WIOMSA Symposium, OSM, ICES Annual Science Conference, ASLO), summer schools and field/regional visits to key SWIO sites and actors for data collection, stakeholder meetings, and model validation with local managers.

- **Operating costs**: €4,000 – Open-access publication fees (2–3 articles targeted), software licences (if needed beyond open-source), and minor data acquisition (high-resolution datasets or telemetry processing).
- **Small investments**: €3,000 – High performance Laptop, aditionnal external storage, large monitor, and possible hardware upgrades to optimise modelling workflows (Obsidian/Notion or note taking application fully available/ Latex paying version)
- **Other**: €500.

**2.3) Potential collaboration projects in France and/or abroad.**
The supervisory team has already thought about potential collaborations directly relevant to the project:

- **In France :** The Ifremer (Sète and Brest) for access to advanced Lagrangian tools and regional ocean modelling. Collaboration with MARBEC Montpellier on end-to-end vs. mechanistic model comparison. Co-directors of BRIDGES RESILIENCE TP (**Stéphanie D'agata (IRD)** and **Quentin SCHULL (Ifremer)**).
- **In the SWIO region** : IRD Mayotte station and local managers (AMP Mayotte, Seychelles Fishing Authority) for stakeholder workshops and model co-interpretation. We are considering collaborating with established researchers in the field, such as **Sylvain Bonhommeau**, **Pascal Bach,** and **Emmanuel Chassot.**
- **International** : Contacts with **Dr. Michael Bode** (QUT, Australia)**, Pr. Anthony Richardson** (UQ/CSIRO, Australia), **A.Pr. Ana Sequeira** (ANU/ Australia) for expertise on mathematical modelling, coupled approaches, marine ecology, biogeography, climate changes impacts on biodiversity, behavioral ecology. Potential collaborations/contact with **Dr. Alberto Baudena** (CNR-ISMAR, Italie) for Lagrangian coherent structures and front dynamics.

These collaborations will provide complementary expertise in physical oceanography, multi-taxa connectivity, and regional governance, while facilitating data sharing and co-publication.