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The MADRidge project — Biophysical coupling around three shallow seamounts in the South-western Indian Ocean, with regional comparisons based on modelling, remote sensing and observational studies

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Background to the MADRidge project — IIOE2 and WIOURI

In December 2015, an international symposium was held in Goa (India) to celebrate two important events — the Golden Jubilee of the Indian National Institute of Oceanography (NIO) and the launch of the second International Indian Ocean Experiment (IIOE-2; https://iioe-2.incois.gov.in/). The original IIOE between 1959 and 1965 was the first large-scale international endeavour in marine science (Urban, 2015). This huge effort involved 47 ships from 13 countries. Outcomes included in-region capacity building, adoption of the Indian Ocean standard plankton net, establishment of reference stations and inter-calibration tests, ocean parameter atlases, an 8-volume set of IOC published reprints (Wirtky, 1971; Zeitzschel, 1973), and the establishment of the National Institute for Oceanography in India — a substantial legacy of the programme. Fifty years later on, technologies such as satellites, ocean models and marine robotics have greatly improved our abilities to study the ocean. The Second International Indian Ocean Expedition (IIOE-2) aimed to take advantage of these. This new IIOE2 programme is under the auspices of the UNESCO IOC, the Indian Ocean Global Ocean Observing System (IOGOOS) and the Scientific Committee on Oceanic Research (SCOR). It was originally planned as a 5-year programme between 2015 and 2020, but has now been extended till 2025.

The IIOE-2 science plan released in 2015 (Hood et al, 2015) revolves around six themes: (1) ocean variability, (2) climate change and ecosystem response, (3) boundary currents and upwelling variability, (4) extreme events and their consequences, and importantly, a strong human component addressing (6) both the human impacts on the ocean and the reliance of human populations on the ocean. Two endorsed flagship projects in the new IIEO-2 embracing these six themes are the WIOURI (West Indian Ocean Upwelling Research Initiative; Roberts, 2015) and its counterpart EIOURI. WIOURI aims to understand how ecosystems in the WIO function, and importantly, how they are changing under global warming. Not only do these ecosystems support the rich biodiversity found in this region, but also some 60 million inhabitants who are directly dependent on them for food security and livelihoods (Taylor et al., 2019).

WIOURI has identified nine Regional Upwelling Projects (RUPs; **Fig. 1a**), three of which are in the South Western Indian Ocean — namely eddy-driven upwelling in the Mozambique Channel (RUP 2), the atypical and poorly known East Madagascar Bloom (RUP 4), and the Madagascar Ridge area which is populated with numerous seamounts (RUP3). The MADRidge project investigates the latter.

Importance of seamounts

Seamounts are exceedingly important as they are capable of inducing upwelling in the open ocean as a result of their interaction with ocean currents. The kind of interaction depends on the combination of flow characteristics, summit depth, seamount shape, water column stratification and seamount location (Coriolis effect) (White et al., 2007). The vertical movement of deeper, nutrient-rich water against the abrupt topography often induces upwelling which stimulates primary production in the often highly oligotrophic upper layer of the ocean. Closed circulation loops around seamount summits (Taylor column or cap) have been theorized but barely observed. These potentially cause retention of water and particles around the seamount summit creating favourable conditions for energy transfer from low to upper trophic levels (Genin, 2004). Internal waves may also result from the interaction between the barotropic tide and topography, generating vertical undulations which induce bouts of 'upwelling' and phytoplankton growth. These processes are the reason for seamounts being biodiversity hotspots as they underpin local benthic and pelagic ecosystems which in turn attract commercial fishing (Pitcher and Bulman, 2007).

The problem facing us nowadays is that many of these fisheries, if not most, are heavily exploited, and have decimated fish stocks (Clark et al., 2007; Pitcher et al., 2010). This is not only due to the stock being isolation at seamounts, but also the slow growth, late maturity and low fecundity of many of the deep species fished here (Morato and Clark, 2007). Added to this is the new emerging threat of mining. This brings into focus important bodies like the International Seabed Authority (ISA, 2019). These threats have raised a number of questions like the legal status of seamounts both within and beyond national jurisdiction, which laws apply, and who will implement the legislation and control this at these faraway isolated sites (Marsac et al., 2020b; Clark et al., 2007).

Certainly to us as scientists, it is clear that research is the cornerstone for the preservation of seamount ecosystems, the resident seamount species, and seamount resilience (Clark et al., 2019; FFEM, 2019).

RUP 3 — the Madagascar Ridge, seamounts and the MADRidge project

The seamounts in the Southwest Indian Ocean are some of the least known in the world's ocean — certainly from a scientific perspective. But they have not gone unnoticed by fishing fleets. French fishing vessels in the 1970s and 1980s (Collette and Parin, 1991) along with Soviet and Ukrainian Institutes between 1972 and 2000 (Romanov, 2003), targeted the numerous seamounts along the South West Indian Ridge. More recently since 1990, the tuna longline fishery, mostly working from Réunion Island (Evano and Bourjea, 2012), has focused on a region south and east of Madagascar where productivity seems to be enriched, a statement supported by studies on seabirds (Pinet et al., 2012). The region south of Madagascar overlies the Madagascar Ridge, an impressive bathymetric feature that to date has received little scientific attention because of its remoteness.

Based on these considerations, an international team of scientists from France and South Africa using the project name 'MADRidge', planned and executed three research cruises to the three most prolific seamounts in this region (**Fig. 1b**) — two located on the Madagascar Ridge and one on the abyssal plain east of Madagascar. The seamount on the northern ridge with a summit at 240 m below sea surface is unnamed, but for ease of reference was called 'MAD-Ridge'. The other on the southern ridge is the Walters Shoal with summit at 18 m. The third, La Pérouse with a summit at 60 m, is 90 nmi north-west of La Réunion Island and is in the flow of the South Equatorial Current. All three have contrasting shapes and environmental settings, and provide an opportunity for comparative studies, not least the latitudinal effect.

The common aim of the cruises was to see whether we could detect a 'seamount effect' at each of these seamounts. The ship surveys were multidisciplinary and included measurements and samples pertaining to the currents, hydrology, biogeochemistry, phytoplankton and zooplankton. Hydro-acoustic and mesopelagic trawling were used to study the micronekton component which is the foraging fauna for larger pelagic species. Specific focus was placed on: (1) the physical processes arising from flow-topography interactions, (2) the biological responses to these processes from plankton to micronekton and top predators, and (3) the isolation/retention effects of the current dynamics, and conversely, the dispersion or connectivity between seamounts and faraway continental shelves. Modelling and remote sensing studies were brought into MADRidge to support the field campaigns.

Two French research vessels (**Fig. 2**) were used in the MADRidge project. The R/V Antea, owned by the IRD, is a 35 m long catamaran with 10 scientific berths. This was used for the La Pérouse (15-30 September 2016) and MAD-Ridge (Leg 1: 8-25 November 2016; Leg 2: 26 November to 13 December 2016) surveys. The limited scientific berths meant that only the pelagic environment could be sampled, i.e. with no benthos sampling. The R/V Marion Dufresne is 120 m in length and has a maximum scientific compliment of 80. This was used for the Walters Shoal cruise (22 April to 17 May 2017), and being larger, allowed the survey to include a benthic component undertaken with the Museum National d'Histoire Naturelle (MNHN).

The MADRidge project resulted in strong collaboration between the French Institut de Recherche pour le Développement (IRD) at Sète and the South African Nelson Mandela University (NMU) at Port-Elizabeth. Other essential partners in France included the Université de Bretagne Occidentale (UBO), Centre National de la Recherche Scientifique (CNRS), and the Université de la Réunion. In South Africa project partners included the University of Cape Town (UCT), the Department of Environmental Affairs (Oceans &

Coasts), and Bayworld Center for Research and Education (BCRE). From Madagascar we involved the Institut d'Halieutique et Science Marine (IHSM) at Tulear. Capacity building has been an important component of the MADRidge project with students (MSc, PhD and post-doc) from France, South Africa, Madagascar and Mauritius being engaged with the cruises, data work-up, analyses and publications. Indeed four of the 13 papers in this special edition are led by a post-doc (Vianello et al.,2020a; this issue; Vianello et al.,2020b; this issue) and PhD student (Annasawmy et al., 2020a; this issue; Annasawmy et al., 2020b; this issue). A Malagasy student obtained a MSc degree through the project and is a co-author of a paper in this special edition (Noyon et al., 2020; this issue).

Our findings

This Special Edition entitled *Bio-Physical coupling around three shallow seamounts in the South Western Indian Ocean, with regional comparisons based on modelling, remote sensing and observational studies* presents a suite of 13 papers that form the main output of the MADRidge project. The sequence of papers are such that the first paper by Roberts et al. (2020; this issue) introduces the topics of seamounts, physical processes around them, their ecosystems, and the huge scientific knowledge gap in the South Western Indian Ocean. Apart from providing greater details on the MADRidge project and field campaigns, it also gives a useful synopsis of the research findings. The second (Vianello et al., 2020a; this issue) and third (Demarcq et al., 2020; this issue) papers provide the oceanographic backdrop to the detailed studies at the three seamounts. In the former, sea layer properties such as SST, MLD, EKE, Chl-a and circulation over the SWIO domain are investigated using remote sensing and described using climatologies with the longitudinal gradient and seasonality in mind. Demarcq et al. (2020; this issue) similarly undertakes a regional view using satellite sea-surface colour (SSC) data and a new chlorophyll-*a* enrichment index to highlight the role of seamounts on chlorophyll production.

These are then followed by the more focused papers, the first of which describes the currents, hydrology and biogeochemical variables (oxygen, nutrients, chlorophyll-*a*) around the MAD-Ridge (Vianello et al, 2020b; this issue) and La Pérouse (Marsac et al., 2020a; this issue) seamounts. The analyses showed little evidence of eddy-topography interactions, with the main driver being the ambient mesoscale eddy field.

The search for seamount effects on the pelagic ecosystems is first tackled by Rocke at al. (2020;this issue) at MAD-Ridge by examining the pico- and nano-phytoplankton distributions. In a more inclusive paper, Noyon et al (2020; this issue) found no significant seamount effect on the mesozooplankton communities at all three seamount but did show a latitudinal effect, reaffirming the gradient analysis by Vianello et al. (2020a; this issue). Fish larvae analysis at the three seamounts by Harris et al. (2020; this issue) similarly found no clear evidence of a seamount effect. But a noteworthy result was the numerous neritic larvae found at the MAD-Ridge which confirmed the potential connections, via chlorophyll filaments, with the Madagascar shelf. Connectivity between seamounts, islands and continental shelves in the SWIO is then further explored by Crochelet et al. (2020; this issue) using an Individual-Base Model (IBM) approach. Results showed weak connectivity between the seamounts, with only MAD-Ridge having a significant connection with the Madagascar shelf. Retention at seamounts was greatest at the Walters Shoal.

The energy flux towards higher trophic levels was explored through the micronekton using three techniques — hydro-acoustics (Annasawmy et al., 2020a; this issue), mesopelagic trawl sampling (Chérel et al., 2020; this issue) and stable isotopes (Annasawmy et al., 2020b; this issue).

The final paper in the special edition by Marsac et al. (2020b; this issue) aims to move the science into governance. Using the Walters Shoal as a case study, it highlights how this new knowledge might be used within the existing regional framework including the Nairobi Convention (UNEP), WIOMSA (Western Indian Ocean Marine Science Association), IUCN, and regional fishery organizations such as SIOFA (Southern Indian Ocean Fisheries Agreement).

It is important to mention that three papers did not make the timeline for this edition. Our tall moorings deployed at the MAD-Ridge seamount could only be retrieved 24 months after deployment, which left insufficient time to meet the publishing deadline. Two other important contributions were manuscripts focused on upwelling on the southern Madagascar shelf using in situ temperature and wind data collected near Fort Dauphine (Collins et al. in prep), and modelling internal tides on the Madagascar Ridge (Koch-Larrouy et al., in prep). The latter is the first of its kind in this region. Both will be published soonest independently.

Also, a large amount of work was devoted to the benthic component of the Walters Shoal cruise in 2017. This was carried out by the French Museum National d'Histoire Naturelle (MNHN), and is reported outside of this special Edition.

Benefits of special editions

Finally, we would like to end this editorial by reemphasising the benefits of publishing in special editions like this. They really are the best format to present the results of large multidisciplinary projects as MADRidge. In one volume the rationale, approach, results, and potential impact can all be articulated, and as a package, is ideal to hand to 'governance' structures — especially in developing countries where the flow of information is not as efficient as elsewhere in the world. They afford the opportunity to synthesise all the results, which is perhaps the most useful output for governance. In the work-up of the MADRidge data, several workshops were held in France and South Africa, providing a good way for the PIs to manage the project data ensuring as much as possible is utilised in the papers, and thereafter, made available to the wider scientific community. In MADRidge, we have used and published (including the three outstanding contributions; see below) some 85% of the data collected by the three cruises.

But we would also like to emphasize that working together as a team has built and strengthened a network between the institutions in the four countries France, South Africa, Madagascar and the UK — as evident in the collection of logos shown in the front pages of this edition. The multidisciplinary nature of the MADRidge project, combined with the cruises, has made for an excellent setting to develop early career researchers and post graduate students — especially for those from developing countries who do not have access to world-class research infrastructure and technologies. As seen, the team approach with senior scientists, has not only provide mentorship, but strongly assisted them in publishing their first results.

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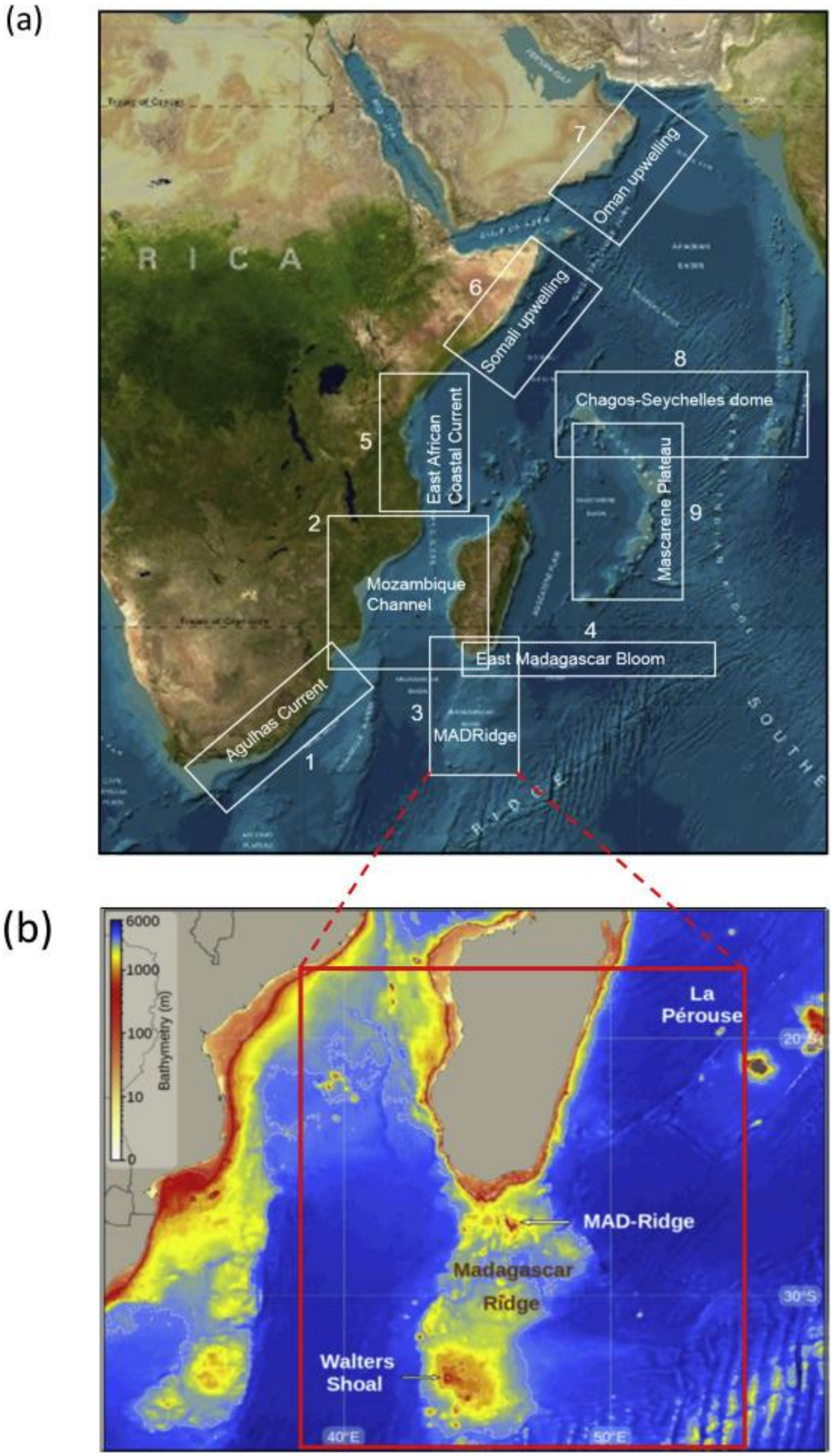
Figure legends

Figure 1: (a) WIOURI consists of 9 Regional Upwelling Projects referred to as RUPs. Each is driven by unique ocean physics. (b) The MADRidge project focused on RUP3 — the Madagascar Ridge and the associated productivity observed here and east of Madagascar. Special attention was given to the three prominent seamounts possibly responsible for the enhanced productivity — Walters Shoal (18 m), MAD-Ridge (240 m) and La Pérouse (60 m).

Figure 2: (a) The two French research vessels used in the MADRidge project. (a) the R/V Antea (35m long, up to 10 scientists) and (b) the R/V Marion Dufresne (120 m long, up to 80 passengers, 25 scientists on-board for the Walters Shoal cruise).

Figure 1



(a)
7
Oman upwelling
6
Somali upwelling
8
Chagos-Seychelles dome
5
East African Coastal Current
Mascarene Plateau
9
2
Mozambique Channel
4
East Madagascar Bloom
3
MADRidge
Agulhas Current
1
(b)
6000
1000
100
10
0
Bathymetry (m)
La Pérouse
MAD-Ridge
Madagascar Ridge
Walters Shoal
40°E
50°E
30°S

Figure 2

(a)

(b)