UK Indian Ocean Initiative

Developing a national contribution to the 2016-2020 International Indian Ocean Expedition

Draft Report of a workshop held 17-19 March 2014 in Dartington Hall, Devon

Peter Burkill*, Greg Cowie**, Trevor Guymer**, Gideon Henderson**, Phil Williamson** and 25 others+

*Workshop convenor. **Workshop Co-convenors, + a full list of participants is given in Annex 1

Executive Summary

We report on the discussions and conclusions of a workshop involving 30 UK marine scientists from 14 universities, research centres and other organisations. We outline current research interests in the Indian Ocean and identify new topics, particularly those requiring long-term planning for ship-time. We identified the following topics that are timely and conducive to innovative oceanographic research in the Indian Ocean: upper ocean processes and the Indian Ocean climate system; Madagascar bloom dynamics; heat transfer to deep-waters of the Arabian Sea; deep-water mixing in the Indian Ocean; biogeochemistry and ecosystem dynamics of oxygen-depleted environments; a longitudinal transect geochemistry study; understanding the microbial biogeochemisty of the oligotrophic southern Indian gyre; and 'exploratory science' in the Chagos Archipelago ecosystem. Almost all topics involve a strategic, multidisciplinary approach and all require ship-time. There was considerable interest both in the Bay of Bengal system and in fostering international collaboration. Several of the topics would build on existing bilateral collaborations with India and other nations in the region, many topics would also build on on-going international programmes such as GEOTRACES and SIBER; such links are expected to provide access to non-UK research vessels, complementing UK deployments and thereby assisting in the cost-effective delivery of research objectives. All topics could collectively be developed as the UK national contribution to the SCOR-IOC International Indian Ocean Expedition that will mostly occur between 2016 and 2020. Although piracy risks are reducing, advice is needed from NERC/FCO on acceptable geographical areas for research vessel operations in the Indian Ocean. A range of workshop follow-up arrangements were planned to widen discussion and engagement in this initiative, recognising that not all areas of expertise and interests were represented at the Dartington workshop. We acknowledge funding support for the workshop from the Royal Society, the Foreign and Commonwealth Office, and the National Oceanography Centre; we also thank Plymouth University for administrative assistance.

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1. INTRODUCTION

Several topics, identified below, converge and interact to ensure that the Indian Ocean will be a particularly important geographical region for strategic marine research in the next decade.

1.1 International Context. During the next decade, the international community will greatly increase research efforts in the Indian Ocean. The Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) are sponsoring a new collaborative, international activity in the Indian Ocean: the "International Indian Ocean Expedition-2" (IIOE-2). This initiative was initially identified by SCOR at its 2011 Annual Meeting, and its development was agreed by the IOC Assembly in June 2013. Ongoing and recent developments to ensure that national and international plans are aligned are summarised in Section 4. In late 2015, SCOR and IOC will co-host an international symposium to celebrate 50 years of research in the Indian Ocean and, at the same time, formally launch IIOE-2 as a new phase of fieldwork in the Indian Ocean.

1.2 National Activities. A substantive, oceanographic UK research contribution to IIOE-2 is considered highly desirable and fully consistent with national interests – addressing important societal, scientific and policy needs, whilst also building on existing capabilities, expertise and international links. In particular, it would: i) add to ongoing/planned research such as Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER), GEOTRACES, and the new NERC programme, Drivers of Variability in the South Asian Monsoon; ii) contribute to national marine stewardship responsibilities in the Marine Protected Area of the British Indian Ocean Territory (BIOT); and iii) complement the increasing research commitments in the region by Australia, China, Germany, India, Japan, South Africa and others. The main temporal focus for the UK fieldwork is likely to be 2016-2020, although it could continue in later years, since IOC is keen to secure longterm involvement in the region.

1.3 Scientific Rationale. The Indian Ocean remains one of the world's least studied major ocean basins. It contains many unique and fascinating features, and is a natural laboratory for studying seasonal dynamics in tropical waters. It is largely landlocked with landmasses bounding the N, W and E sides where land-sea interactions in coastal waters are locally strong. For instance, the Ganges has the second greatest river discharge in the world and freshwater input permeates much of the north-east Indian Ocean. The northern Indian Ocean is strongly influenced by the semi-annual Asian monsoons and these generate unique ocean basin current reversals. The Arabian Sea experiences exceptionally strong air-sea interactions, due to the low-level Findlater Jet that blows during the summer monsoon. This jet generates localised upwelling due to Ekman transport near the coasts of Somalia, Yemen and Oman; yet 500 km offshore the waters remain unmixed. The Arabian Sea, landlocked at its northern end, is highly stratified and supplied with salt from Red Sea outflow; together with locally high monsoonal production, this generates the lowest mid-water oxygen content of any ocean basin. In the south-west Indian Ocean, the Agulhas Current is the largest western boundary current in the world ocean (100 Sverdrups) contributing heat from the tropical Indian Ocean into the Atlantic, as well as feeding the Antarctic Circumpolar Current. On the eastern boundary, the Indonesian Through Flow is an ocean current that provides a low-latitude pathway for warm, fresh water to move from the Pacific to the Indian Ocean, with global climatic consequences. In the south-east Indian Ocean, the Leeuwin Current is unusual in being a warm south-flowing mid-latitude coastal current. Regional climate exhibits decadal changes from the action of the Indian Ocean Dipole, which brings rain or drought alternately to either Kenya or Australia. These changes have major impacts on regional economies.

Indian Ocean microbiology, biology and ecosystems also have very many important scientific features. As pointed out above, the northern Indian Ocean has oxygen deficient mid-depth waters, that provide unique opportunities to study how microbiological processes drive the production of methane and nitrous oxide (two highly potent greenhouse gases). As the Indian Ocean is becoming increasingly O_2 deficient, hydrogen sulphide (H_2S) is now being recorded in open waters for the first time, with consequences for marine life. Under global warming, similar de-oxygenation is projected to increasingly occur elsewhere; the Indian Ocean therefore provides a window to the future.

Effective national and international management of stocks of commercially important species such as yellow-fin tuna and squid not only requires knowledge of their population dynamics and migratory patterns, but also their dependence on, and role in, the ecosystem as a whole, and their sensitivity to environmental stressors. Untapped resources such as myctophid fish which are abundant in the Indian Ocean are now being considered for commercial fishing. Seabed biology can be strongly affected by monsoons and so affords excellent opportunities for understanding vertical linkages from the atmosphere to the seafloor. High-quality coral reefs (with varying degrees of protection) are found throughout much of the central Indian Ocean, providing excellent opportunities to understand the interactions between ocean acidification, sea-level rise and reef resilience.

A key feature of Indian Ocean geology is the Rodrigues Triple Junction – a geological junction in the southern Indian Ocean, where the African Plate, the Indo-Australian Plate, and the Antarctic Plate meet. Little is known of the development of hydrothermal systems on Indian Ocean Ridge crests. The sediments of the Indian Ocean contain important palaeo-climatological records of past climate change both in the tropics, in the upwelling regions, and at the mobile boundary with the Southern Ocean, which has shifted north and south from interglacial to glacial periods. The remoteness of the region means that these changes are poorly sampled and understood, making our appreciation and modelling of climate change processes incomplete. The north-east margin of the Indian Ocean is an active plate boundary subject to massive earthquakes and associated tsunamis. These processes are poorly understood in this region, yet there are signs that a new plate boundary is forming at the southern end of the Bay of Bengal. More knowledge is needed for better predictions of volcanic and seismic activity.

Societally, most countries bordering the Indian Ocean are experiencing rapid development and population growth; they are also highly vulnerable to marine-related environmental risks and hazards (variability in weather and climate, tsunamis and longterm sea level rise), with major consequences. For instance, the Asian Monsoon directly affects the lives of about one-third of the global population. Understanding monsoonal triggering and intensity is crucial. At intra-seasonal time-scales, the Madden–Julian Oscillation (MJO) is the primary source of tropical atmospheric variability, and is most active in the warm pool of the Indian Ocean. It is believed to play a role in triggering the El Niño Southern Oscillation (ENSO), with major effects in the Pacific, North America and South America, as well as modulating rainfall and hurricane activity more widely, particularly in tropical regions. But our ability to simulate and predict the MJO is severely limited due to poor model representation of processes key to the MJO. The role of the Indian Ocean in triggering the MJO (by both air-sea interaction and planetary waves) is a current topic of debate. Better predictions of the weather and climate for the countries around the Indian Ocean are crucially dependent on sea surface conditions, in turn affected by upper ocean dynamics and other oceanographic processes which are currently poorly understood.

1.4 Timeliness. The Indian Ocean has been relatively neglected by the UK oceanographic research community over the last decade for a variety of reasons. These included piracy in the north-west Indian Ocean, and the additional operational costs of working beyond the North and South Atlantic – thus requiring a sequence of research cruises for cost-effectiveness. However:

- the risks of piracy have now decreased, with the development of protective measures by commercial shipping and increased western naval patrols (no vessels have been hijacked since 2012)
- very much more data can now be obtained on physical processes by using modern technologies such as gliders and advanced remote sensing platforms (floats) that are much less ship-dependent; these techniques are relatively unexploited in the Indian Ocean
- despite the hiatus, there is now keen interest in the Indian Ocean by UK researchers (in addition to the 30 workshop participants, many others expressed interest but were unable to attend)
- there is now scope for substantive additional added-value, particularly for interdisciplinary and societally-relevant science, by partnership work through the SCOR/IOC IIOE-2 initiative (see 1.1 above, also www.scor-int.org). IIOE-2 is based on an international field campaign, to start in late 2015/early 2016 and continuing for up to a decade. To date, the UK has been closely involved in the leadership and planning of IIOE-2, and it would be highly desirable for several UK scientists to participate in the NIO-IOC-SCOR Indian Ocean Open Science Symposium to be held in Goa, India in late November 2015.

1.5 Workshop format and goals. The two-day Dartington workshop started with an introductory session that set the broad conceptual and practical background for significant UK participation in IIOE-2. Talks were given on SCOR (Peter Burkill), BIOT (Phil Williamson), GEOTRACES (Gideon Henderson) and SIBER (Greg Cowie). This session was followed by overviews of seven topics of particular relevance to the UK community. Each topic was introduced by a lead speaker who left plenty of time for follow-up discussion. This session was designed as a stepping stone towards identifying important research opportunities that could be addressed by UK researchers through a field campaign (primarily ship-based) in the Indian Ocean. The topic talks were on: Monsoons (Adrian Mathews), Physics (Adrian New), Biogeochemistry (Tom Anderson), Benthos (Alex Rogers), Top Predators (Chris Mees), Geochemistry (Maeve Lohan), and Geology and Geophysics (Karen Sigloch). A talk on NERC funding mechanisms (Mike Webb) provided information on how research support could be obtained. The workshop then switched to a more synthetic focus with discussion of potential future research in physics (Trevor Guymer & Elaine McDonagh), biogeochemistry (Peter Burkill & Tom Bell) and ecosystems (Phil Williamson & Bhavani Narayanaswamy). Each group worked in parallel and were charged with identifying priority research areas that could lead to the development of research proposals. The final session comprised feedback from each of the parallel groups with discussion and agreement on the major research proposals to be undertaken. All talks will be collected in a Dropbox site courtesy of Karen Heywood. The workshop agenda is given in Annex 2.

2. OVERVIEW OF RESEARCH FIELDS

The aim here was to consider present and recent research interests in each field. These were tackled in different ways by each of the groups.

2.1 Monsoons (Trevor Guymer). In his overview, Adrian Matthews described the basics of the monsoon system, with emphasis on the special characteristics of the Indian Ocean, e.g. the closed northern boundary, orographic barriers and seasonal reversals. In January, high precipitation occurs where there are high sea surface temperatures (SSTs); in July, when the SW monsoon is in place, the highest precipitation is found over the Indian subcontinent. Surface waters in the Bay of Bengal then greatly freshen: about half of this change is due to the high rainfall over the Bay, the remainder is due to river input. As a result, interesting barrier layers are formed in the Bay of Bengal.

The monsoon interacts with complex ocean current systems, and also strongly links to ocean biogeochemistry. Most climate models (e.g. the Met Office Unified Model) have a dry bias, some of which is due to lack of seasonally-varying chlorophyll in the Arabian Sea. A 1^oC temperature error gives a 2mm/day change in evaporation.

A specific feature is the Madden-Julian Oscillation (MJO) which occurs in November to April. Rainfall anomalies propagate east with a periodicity of 30-60 days. Individual events can either shut off or double the precipitation and there are coherent wind and temperature anomalies. The MJO triggers Rossby Waves in mid-latitudes and Kelvin Waves at the equator. Two-way coupling also occurs. In June-August, the MJO changes character and develops a more northwards component to its propagation. This is important for the monsoon system in the boreal summer by contributing an intra-seasonal oscillation.

The dynamical component is also important in the MJO: equatorial Kelvin waves give rise to coastally-trapped plus reflected-downwelling Rossby Waves; these travel back to the western Indian Ocean where there is a feedback on the convection. The timescale is such that this process probably affects the next-but-one MJO. However, it is difficult to isolate cause and effect. The primary MJO event appears to be triggered by equatorial Rossby Waves. The response of models to westerly wind bursts is similar to what is observed.

Diurnal time scales are also important in the monsoonal region. A 4-month glider deployment in 2011/12 showed a surface diurnal warm layer (2^oC above ambient) the maximum occurring in mid-afternoon. This layer affects fluxes and hence atmospheric convection, but is not handled well by models. It also rectifies the mean/intra-seasonal SST and influences the phasing of maximum cloudiness as bands propagate seawards from evening convection over land. This means that the timing of the solar radiation varies with location.

The Bay of Bengal Boundary Layer Experiment (BoBBLE), funded by NERC and India, is planned to have its field campaign in June-July, 2016.

There are several open questions in the areas of: multi-scale interactions between components (including the Indian Ocean Dipole, ENSO, monsoon depressions); ocean-atmosphere interactions (observations and coupled modeling strategy); and, physical/biogeochemical interactions.

In the discussion there was the suggestion that the recent UK flooding might be related to anomalous Indian Ocean events, perhaps linked by Rossby Wave propagation in the atmosphere. Other questions raised were: how will the MJO change in warming world? how has it changed on decadal time scales (it undergoes an eastward shift during ENSO events)? how should sub-grid scale processes be represented in models of the Indian Ocean?

A separate set of issues revolved around: what observations are required in addition to BoBBLE? how should satellite data be used, particularly from the Soil Moisture and Ocean Salinity (SMOS) mission? the MJO shows up in sea surface salinity (SSS) data, but is the accuracy adequate? *In situ* profiles and satellite data could be used to extrapolate; there is particular need for river flow data, as models struggle to get the freshwater flow correct.

The session ended with a discussion of topics that needed more research and whether this required a ship programme in the Indian Ocean. The following key issues emerged:

- There are multi-scale aspects to monsoons, e.g. interannual (Indian Ocean dipole, ENSO), planetary waves, intra-seasonal oscillations (MJO), synoptic scale events (monsoon depressions), diurnal variations. How do these interact? How will these change in a warming world?
- The interaction between physics and biochemistry – especially its link to the dry bias in climate models
- Improving understanding of diurnal variability and its implications for surface fluxes and atmospheric convection, and for models. This needs observations.
- Parameterisation of sub-grid scale processes in models. The particular challenges in the Indian Ocean include the different convective regime found there as well as the barrier layers.

A research ship would be required to conduct monsoonal studies in the Indian Ocean in support of BoBBLE and as a platform for ocean glider deployments in the Arabian Sea.

2.2 Physics (Trevor Guymer). Adrian New began his overview by pointing out that the Indian Ocean has recently exhibited the strongest surface warming since the 1900s. During the last 50 years the evaporation minus precipitation pattern has enhanced, providing indirect evidence for the speeding up of the hydrological cycle. Such changes could have major economic consequences, at both the regional and global scale. It is therefore necessary to improve observational studies and modelling, linking those activities on an international basis – not only to advance scientific understanding, but also provide tangible societal benefits.

Several sub-regions of the Indian Ocean were discussed. At the Mascarene Plateau, a westward flow has been observed, constrained to various gaps in the topography. A 1/12^o global model also shows westward flow of relatively fresh water. Radar imagery from satellites reveals internal waves with 100 km wavelength but it is not known where their energy is dissipated.

Data on changes in water masses along the 32^{o}S section since 1987 show that the Sub-Antarctic Mode Waters (SAMW) became fresher, then more saline. Climate models indicated that these waters would continue to freshen, thus raising the question of what is causing the 'anomalous' behaviour later in the period. The US carried out the section in 2009 and are planning another occupation in five years' time.

The South Equatorial Current (SEC) acts as a barrier to water masses lying to both the north and south. Underneath the SEC is SAMW with an oxygen minimum, and high nitrates. It would be interesting to carry out a nitrate budget to see if any of the nitrate feeds the oligotrophic gyre; there is a large interaction between physics and biology.

With regard to deep circulation, there is general deep water overturning in which Antarctic Bottom Water is lifted by mixing and returns at mid-levels. Modelling greatly under-represents the strength of this circulation, likely to be at least partly due to mixing being incorrectly represented. Turbulent dissipation rates derived from CTD and ADCP sections are unable to account for what is needed. However, no observations have been made over the central Indian ridge and this may prove significant. It is important to make the CTD casts in exactly the right place within the deep canyons of the ridge system.

A pronounced feature in the NW Indian Ocean is the Great Whirl. Long records from satellite-derived sea level and sea surface temperature show that it undergoes changes on a variety of time scales. How is this variability related to larger scales in the Indian Ocean – and perhaps beyond?

There are several big questions: what are the processes driving overturning/mixing? what is causing the changes within the SAMW? what is the inter-relationship of the Indian Ocean Dipole/monsoon system with phenomena such as the Great Whirl[1] and the Somali Current? what are the interactions between the physics and biology, and where will effects of climate change be greatest?

Several ideas for a ship-based work programme to address these issues were put forward. These included a repeat of one or more WOCE hydrographic sections (IO-3 at 20^{o}S, also consider doing IO-2 at 12^{o}S); a box survey to allow a budget to be computed over the central ridge; an internal wave process study; direct observations from deep profilers; a tracer release experiment; and analysis of potential vorticity in the deep ocean.

[1] A large, seasonally-occurring eddy off the coast of Somalia

In wider discussion it was stated that Principal Scientists under the GO-SHIP programme have offered to accommodate additional researchers on their cruises, to provide additional platform opportunities. Several suggestions were made about the possible causes of mixing and where measurements should focus, particularly the depth range that needs to be covered. Mention was also made of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) which faces problems with continuity of data and vandalism.

The following key issues emerged for future research:

- Better knowledge of processes driving overturning, including the role of mixing. Where does mixing occur? and how do we explain the mismatch between the mixing that is observed and what is required by the models? (both in terms of intensity of mixing and the depth at which it occurs)
- How is Sub-Antarctic Mode Water changing and what is its relation to surface fluxes? Linked issues include the the nutrient budget and supply to the oligotrophic gyre
- What is the inter-relationship of large-scale Indian Ocean phenomena (such as the Indian Ocean Dipole and monsoons) with well-known regional features (e.g. the Great Whirl and the Somali Current)?
- Interactions between physics and biology, including upwelling in the South Equatorial Current. mixing across shallow banks, links to fisheries, and how physical changes will affect ecosystems under global warming scenarios
- Understanding the flow through gaps on the Mascarene Plateau and the generation of internal waves
- The need for more data in the NW Indian Ocean (where piracy has led to lack of observational programmes) to estimate changes in deep ocean heat uptake in the region, and its wider implications.

A research ship would be required in the Indian Ocean for targeted process studies to investigate mixing, budget studies, tracer release and direct turbulence measurements. The Central Indian ridge might be a focus for such work.

2.3 Biogeochemistry (Greg Cowie). Many Indian Ocean phenomena are of known biogeochemical importance and far-reaching significance. Unlike the Pacific and Atlantic, the Indian Ocean is enclosed to the north by land, contributing to exceptional weather/climate systems (monsoons, Indian Ocean dipole etc) with long-distance interactions and associated features such as major river runoff and monsoon-driven upwelling and productivity. These in turn drive oxygen demand, and the Arabian Sea and Bay of Bengal represent an important fraction of the planet's total volume of oxygen-depleted waters. The processes associated with the productivity, food webs and oxygen-depleted waters, in both the water column and sediments, are globally important with respect to carbon cycling and burial, and also to processes that serve as sources or sinks for N and P, and thus affect ocean nutrient inventories and productivity. The Indian Ocean is also important in terms of production and ocean-atmosphere exchange of climate-critical gases, including DMS, N_2O and CH_4, as well as CO_2. Other features include unique marginal basins such as the Red Sea, as well as important and unusual boundary current systems such as the Agulhas and Leeuwin.

Despite these key roles in Earth system processes, the Indian Ocean remains the least studied of the world's oceans and fundamental gaps remain in our understanding of, and ability to model, biogeochemical processes and ecosystem function, the interactions between physical drivers and system function, and how the Indian Ocean system is likely to evolve with environmental change.

Consequently, a wide range of important research challenges and opportunities exist. These have been the focus of recent international attention, and the Sustained Indian Ocean Biogeochemical and Ecosystem Research (SIBER) initiative has identified six broad research themes, as summarised in Table 1 below. These are already at the heart of existing research programmes (e.g. in India) and many activities planned for IIOE-2.

Table 1. SIBER regional (1-3) and general (4-6) themes

	Theme	***Main research question***
1	Boundary current dynamics, interactions and impacts.	How are marine biogeochemical cycles and ecosystem processes in the Indian Ocean influenced by boundary current dynamics?
2	Dynamic variability of the equatorial zone, southern tropics and Indonesian Throughflow and their impacts on ecological processes and biogeochemical cycling	How do unique physical dynamics of the equatorial zone of the Indian Ocean impact ecological processes and biogeochemical cycling?

3	Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal	How do differences in natural and anthropogenic forcing impact the biogeochemical cycles and ecosystem dynamics of the Arabian Sea and the Bay of Bengal?
4	Controls and fates of phytoplankton and benthic production in the Indian Ocean	What are the relative roles of light, nutrients and grazing limitation in controlling phytoplankton production in the Indian Ocean and how do these vary in space and time? What is the fate of this production after it sinks out of the euphotic zone?
5	Climate and anthropogenic impacts on the Indian Ocean and its marginal seas	How will human-induced changes in climate and nutrient loading impact the marine ecosystem and biogeochemical cycles?
6	The role of higher trophic levels in ecological processes and biogeochemical cycles	To what extent do higher trophic level species influence lower trophic levels and biogeochemical cycles in the Indian Ocean and how might this be influenced by human impacts, e.g., commercial fishing?

These biogeochemical processes have huge societal relevance to the large human populations in Indian Ocean rim countries. For example, pelagic food webs and commercial fish stocks in the Arabian Sea and Bay of Bengal are directly impacted by oxygen depletion. The Indian margin of the Arabian Sea is already the Earth's largest hypoxic "dead zone" during the summer monsoon season, which appears to be intensifying and can already cause massive fish kills. Although the Bay of Bengal and Andaman Sea also exhibit coastal hypoxic events, the Bay of Bengal as a whole is not yet as hypoxic as the Arabian Sea. However, warming, changes in circulation and freshwater runoff, and anthropogenic nutrient inputs all put it at great risk of becoming so, with major potential consequences. The assessment of productivity regimes and oxygen depletion, and how these might evolve in the future, are therefore critical topics for future research. Although the Arabian Sea has received relatively extensive research attention, key questions remain there relating to the control of oxygen depletion and associated processes – and much of the rest of the Indian Ocean remains very poorly studied relative to the Pacific and Atlantic.

Other major biogeochemical questions relating to key physical phenomena include:

- Eastern Indian Ocean upwelling regimes and Indian-Pacific ocean exchange associated with the Indonesian Throughflow
- The southern Indian Ocean gyre
- The Agulhas current and Indian-Atlantic ocean exchange
- Biogeochemical, biodiversity and ecosystem phenomena associated with topographic highs (seamounts, Madagascar plume etc)
- Physical factors currently influencing these phenomena, and their sensitivity to environmental change.

2.4 Benthos (Bhavani Narayanaswamy). In his overview, Alex Rogers highlighted several research ideas and priorities that could be separated into two themes: process-driven research and 'exploratory' science[2].

Process-driven research

Research priorities that could link with biogeochemistry research (complementing topics discussed above) are currently as follows:

- Understanding the mechanisms of carbon cycling and carbon burial in differing redox conditions and investigating the primary controls on organic C preservation / distribution
- Investigating the operation of bentho-pelagic coupling in very different settings (such as under different redox conditions; continental slopes, seamounts, archipelagos etc)
- Understanding how oxygen affects nutrient cycling in a broader sense and more specifically how this relates to current increasing hypoxia in the oceans.
- What is the role of active transport in C sequestration? What does this term mean in terms of the Biological Carbon Pump? This is related to changes in climate.

Exploratory science

[2] At the workshop, the descriptor 'discovery science' was used. This was subsequently changed to avoid confusion with the new name for NERC's responsive mode (see Annex 3)

Here the focus is on investigating the biogeography, biodiversity and conservation of specific regions where next-to-nothing is currently known about benthic communities and their functional importance. The initial requirement is to greatly expand our fundamental knowledge of benthic biodiversity of the Indian Ocean, in particular i) the biogeography of the deep Indian Ocean, including seafloor areas within Marine Protected Areas, and others where deep-sea mining is likely to occur; and ii) population connectivity across topographic highs.

Such knowledge then enables more strategic issues to be addressed, including improved conservation of particularly vulnerable and/or sensitive ecosystems, and determining the direct and indirect human impacts on Indian Ocean ecosystems, both now and in the future.

2.5 Top Predators (Phil Williamson). The main focus of the presentation by Chris Mees was on Indian Ocean fish species that are commercially exploited, with additional consideration given to other species that directly interact with those that are harvested, primarily as bycatch. The latter include sharks (that may also be directly targeted), marine turtles, sea mammals and sea birds; all of these have high conservation value. Two aspects were considered: ongoing management and current understanding, and additional research needed to inform (and improve) the future management of exploited stocks.

The Indian Ocean Tuna Commission (IOTC) has 'open water' fishery management responsibility for highly-migratory stocks of tuna (bigeye, skipjack and yellowfin) and billfish (black, blue and striped marlin; Indo-Pacific sailfish and swordfish), with monitoring of associated bycatch. There are also significant 'domestic' catches within national waters. Vessel-type and fishing technique determines the level of interaction with non-target species: bycatch can be particularly high for gill nets, but lower with pole and line. Management actions to safeguard stocks include catch/effort controls; technical and operational measures to reduce bycatch; closed areas (e.g. the BIOT Marine Protected Area); and nationally-controlled licensing with Exclusive Economic Zones (e.g. Maldives).

Existing knowledge on population dynamics is relatively good for tuna species. Genetic and tagging evidence suggests single stocks of main target species, and main areas for spawning and juveniles have been identified. For billfish, evidence on stock structure and abundance changes is less complete. For elasmobranchs (sharks), there is inadequate reporting and abundances are highly uncertain (although inshore evidence indicates considerable stock depletion). For sea mammals, data are limited or lacking.

The following research gaps were identified:

Tuna species – information on diets; how prey species are affected by oceanographic factors; habitat uses (key areas and 'hotspot' sites of high importance to several species; factors influencing migration). The CLIOTOP initiative (Climate Impacts on Top Predators, now part of IMBER) has framed detailed research questions relating to these issues

Elasmobranchs and marine mammals – basic biology (growth, mortality, reproduction); abundance and stock delimitation/distribution (related to population connectivity and migration; investigated by tagging and genetics); habitat use and interactions with other species. Note that IOTC has a research plan for elasmobranchs, and that marine mammals of particular interest include 8 species of dolphin, blue whales and smaller toothed whales.

Effectiveness of Marine Protected Areas (MPAs) – are the benefits to migratory species only transient, or do some become resident? Should spatio-temporal closures be static, or variable in response to oceanographic variability? How can a short-term, ship-based field campaign best contribute to monitoring? An in-press report by the Bertarelli Foundation and Zoological Society of London has considered critical issues in this regard.

Table 2 below summarises how different approaches applicable to ship-based research could be used to address different research requirements related to Indian Ocean top predators.

Table 2. Research requirements and proposed approaches for top predator research in the Indian Ocean

Requirement	***Approach***
Spatial and temporal distribution/abundance	Photography/video; echo sounders and acoustics; fisheries data (with novel analyses and visualising)
Identifying key areas('hotspots') e.g. spawning aggregations) and their oceanographic drivers	As above, also oceanographic data and site-specific habitat mapping (e.g. seamounts)
Population connectivity: range and rates of movements	Tagging; genetic and chemical markers

Ground-truthing ecological niche models	Photography/video; echo sounders; direct observation; experimental fishing
Habitat mapping	Photography/video and acoustics; autonomous underwater vehicles (AUVs) and remotely operated vehicles (ROVs); other seafloor sampling techniques

2.6 Geochemistry (Alex Piotrowski, Gideon Henderson). The Indian Ocean is a natural laboratory for understanding chemical cycling of elements in seawater. The spatial distribution of oceanic elemental concentrations and isotopic composition are controlled by distinct and large-scale sources and processes, and these have distinctive distributions. Important chemical sources include riverine sedimentary inputs from the Ganges and Indus rivers, aeolian dust input from Arabia, and mid-ocean-ridge hydrothermal inputs – each with a distinct spatial distribution, which is strikingly different to the situation in the Atlantic. Chemical cycling also occurs in large-scale and contrasting environments, for example (as already noted) biologically productive regions of upwelling are linked to monsoon dynamics and control the redox cycling within extensive oxygen minimum zones in the northern Arabian Sea and Bay of Bengal. This contrasts with a highly oligotrophic gyre in the southern Indian Ocean which is isolated from continental inputs.

Advective pathways of transport and physical mixing processes can be investigated with chemical tracers. Surface, intermediate, and deep waters have distinct sources from the Pacific, Southern and Atlantic Oceans, and advective flow-paths within the Indian Ocean are orthogonal to each other at different depths, likely resulting in strong spatial chemical gradients. These currents also often interact with rough bathymetry, as occurs on the Mascarene Plateau, Ninety-East Ridge, ocean margin and three mid-ocean ridge segments of the Indian Ocean. The Indian Ocean thus allows investigation of how chemical patterns in water masses and with depth are controlled by a variety of physical and biological processes.

The Indian Ocean provides a unique opportunity to study a number of processes. Upwelling occurs along both the Arabian and Indian margins, with differences in shelf breadth and lateral extent controlling whether elemental input and cycling is trapped within the upper ocean or exported into the deep ocean. The Bay of Bengal, with its high sediment accumulation and huge freshwater input, is an “estuary in the ocean”. Temporal pulses of elements and changes in density stratification provide a unique environment to study spatial and temporal changes in the continent-ocean link and advection and mixing of chemical tracers from a highly stratified water column into the rest of the ocean. Ganges and Brahmaputra riverine inputs are also important for the interpretation of palaeo-climate records, including Himalayan weathering records such as Sr, Os, and Nd isotopes. Scavenging and reversible cycling of elements affect the distribution of elements which are easily scavenged and have short residence times, such as Fe, Al, Pb, Pa, and Th, being sensitive to spatial and temporal “pulses” in sediment input. Atmospheric deposition includes both mineral dust input and pollutants, thus producing two distinct fingerprints of elements entering the surface ocean and changing cycling within the deep ocean.

Evidence is emerging that hydrothermal plumes provide a significant source of soluble iron to the deep ocean, including the Central Indian Ridge which can be investigated in a similar manner to a passive dye release experiment. Because of the slow horizontal advection in the central Indian Ocean, the mixing of this hydrothermal signal from the lower Indian Meridional Overturning circulation cell to the intermediate circulation regime by rough bathymetry has implications for nutrient input from the ocean depths to productive regions. Changes in deep and surface ocean currents in the recent past, and oceanic gateways on longer geological timescales present linkages to the longer paleo-climate record.

2.7 Geology (Gideon Henderson). Geologically, the Indian Ocean is a young ocean, dominated by seafloor spreading with younger crust than the Pacific and Atlantic. It is bounded to the north by the collision zone of the Himalayan Arc, and to the east by a relatively small amount of destructive plate boundary. The Indian Ocean took a form similar to that at present only after the closure of Tethys Sea, a process that began around 90 million years ago.

The Indian Ocean features abundant basaltic plateau volcanism, offering opportunities to study the relationship between such volcanism and hotspot[3] activity/mantle structure. In general, major hotspots around the world are located under the ocean, so that the water can be seen as getting in the way of study. This feature, however, means that research into hotspot structure must be a marine-based activity. The Indian Ocean has seen significant such research in recent years, including the RHUM-RUM project, a French-German collaboration which studied the

[3] In geological terms, hotspots refer to areas where the mantle is warmer than elsewhere, associated with volcanic activity

Reunion Hotspot. This project deployed 57 broadband ocean-bottom seismometers for a year, coupled to 37 island stations for 2-4 years. This scale of observation is leading to important new insights into mantle structure which would not have been possible with smaller projects, clearly demonstrating the benefits of coordinated international effort in the Indian Ocean.

Future Indian Ocean research might make use of the islands in the basin: Reunion, Crozet, Kerguelan, Amsterdam Saint Paul, and Maurice. The French research vessel, *Marion Dufresne*, makes a regular circuit around these islands, and could be a platform for research or monitoring. Future research might also benefit more generally from technological developments, with present advances in the deployment of geophysical instruments such as ocean-bottom seismometers from ARGO floats. Important topics for future geological and geophysical study include:

- Further investigation of the prominent volcanic hotspots/mantle plumes of Reunion, Kergeulen, Crozet and Marion
- Analysis of seamount population (not only those close to spreading ridges) and their connection with mantle dynamics
- Geochemistry of the Indian Ocean mantle, including the Dupal anomaly (unusual lead isotope ratios, possibly linked to the formation of many micro-continents in the area)
- The South-West Indian Ridge, an ultra-slow spreading ridge, in which there is strong interest by French, Chinese and German scientists
- Oceanic gateway formation and circum-Antarctic current formation, including the possibility of the Kergeulen Plateau as an obstacle to past ocean currents and circumpolar flow.

Geological and geophysical expertise was less well represented than other fields of research at the Dartington workshop and the participants recognised there were a number of other exciting areas in which important scientific questions could be addressed. The destructive plate boundaries to the east of the basin, for instance, are a source of major seismic activity, with associated opportunities to investigate seismic failure, and the challenges of earthquake and tsunami hazard. Regional factors affecting sea-level rise are also of considerable scientific and societal concern. Omission of such topics from this report does not mean they do not warrant UK research attention.

3. EMERGING NEW RESEARCH TOPICS

Three groups met in parallel to consider and develop earlier discussions on the new topics that were emerging. A summary of these synthesis sessions follows.

3.1 Physics (Elaine McDonagh)

The following new topics were identified:

Major processes or observations: Deep overturning and mixing; drivers of variability on a range of timescales from diurnal to decadal of phenomena including mixed layer properties, stratification, Somali Current, Great Whirl and SAMW properties.

Challenges or opportunities that require new research: Estimates of deep ocean heat uptake in the NW Indian Ocean are missing from our global budgets because of a lack of observations since the 1990's; new technologies including wavegliders, bio-Argo and Deep Argo floats and Autosub long range.

Anticipated scientific and societal benefits: Cyclones and storms; natural resources and fisheries; storm surges; potential links to severe weather in the UK; monsoon and agriculture including active break cycles (intermittency in monsoon wet/dry periods); East African highlands rainfall (dependency on Indian Ocean Dipole); monitoring and legacy; climate change.

The above topics could be tackled as new research proposals, grouped as follows:

UPPER OCEAN PROCESSES IN NORTHERN INDIAN OCEAN *(Championed by Adrian Matthews).* Link to biogeochemistry both as a context and also feedback through the diurnal cycle. To include heat and freshwater budget in Bay of Bengal and Arabian Sea (Argo floats, air-sea fluxes, satellite salinity and temperature); meteorological observations from ships; moored and glider observations aimed at understanding upper ocean boundary layer and its interaction with the atmosphere; variability of eastern Indian Ocean upwelling, Somali Current and Great Whirl and interactions with large scale phenomena, through coupled modelling.

PHYSICAL PROCESSES IN BIOT-MPA REGION *(Championed by Miguel Maqueda).* **L**ink to fisheries – use of technology e.g. waveglider to study physical processes including upwelling**.**

WHERE IS THE MISSING MIXING? *(Championed by Adrian New).* **F**ocussed study to the east of Mascarene plateau on central Indian Ridge to observe deep mixing, particularly in troughs associated with ridge rifts. Budget of region ~20^0 square to analyse water mass transformation and implied mixing. Also to include tracer analysis to give integrated estimated of dispersion, with regional modelling of mixing/tracer dispersion.

THE MADAGASCAR BLOOM REGION *(Championed by Meric Srokosz).* Links to biogeochemistry, observations of the oligotrophic subtropical gyre and benthic ecology – including bio-Argo floats and upper-ocean optical measurements, variability of mode water properties and gyre in the region of the bloom, variability of mixed layer properties and stratification from Argo floats. Also link to variability in tuna fisheries.

DEEP OCEAN HEAT UPTAKE IN THE ARABIAN SEA *(Championed by Elaine McDonagh)*. **D**eep temperature and salinity measurements in Arabian Sea from Deep Argo floats or Autosub long range.

3.2 **Biogeochemistry** (Tom Bell)

Three priority biogeochemical research topics were identified that could be tackled as the following proposals:

BIOGEOCHEMISTRY OF O_2-DEPLETED ENVIRONMENTS – A COMPARATIVE ASSESSMENT OF THE BAY OF BENGAL AND THE ARABIAN SEA. *(Championed by Greg Cowie, with interests by Tom Anderson re modelling and Andrew Watson re greenhouse gas measurements).* A multidisciplinary research programme was put forward to focus on the Bay of Bengal (BoB), with comparative assessment of the Arabian Sea (AS). The BoB is comparatively unstudied, but the main premise of the research is that its Oxygen Minimum Zone (OMZ) is critically poised at the edge of becoming fully hypoxic and denitrifying. The BoB and AS are influenced by contrasting physics (monsoon intensity, freshwater input etc) and processes of biogeochemical relevance (atmospheric/riverine nutrient inputs; biological production, export and respiration; river-derived suspended sediment load etc). A study of the biogeochemical drivers in the OMZ of the BoB would require multiple cruises to encompass the changes driven by the seasonal monsoon. Measurements would focus on bioelement cycling and fluxes, both within the water column and the benthos, and on redox variations and cycling of metals and other redox-sensitive elements. Surface ocean trace gas measurements would be essential to quantify the production and sea-to-air flux of, in particular, carbon dioxide, methane and nitrous oxide. Thus, a team would include geochemists, microbiologists, and ecologists, as well as modellers. Research would focus in part on state-of-the-art in situ and shipboard experimental incubation systems for assessment of key process rates and fluxes, organic matter cycling pathways, and response to manipulated environmental conditions. Substantial collaboration with local researchers and foreign partners is envisaged, and the proposed research will fall under the broader IIOE-2 objectives and complement existing Indian research programmes (e.g. SIBER).

A NORTH-SOUTH INDIAN OCEAN GEOTRACES TRANSECT. **(***Championed by Gideon Henderson with interests by Maeve Lohan and Alex Piotrowski).* A N-S transect from low oxygen waters into the oligotrophic gyre would be an important contribution to the international GEOTRACES programme, with focus on the geographic distribution of trace elements and their isotopes. Data on the carbonate system and ocean circulation tracers would also be of great value. Measurements made on this transect would feed synergistically into the OMZ process cruises proposed above. Isotopes sources could be of interest too. A second cruise in the East Indian Ocean is highly desirable to investigate whether the Indonesian Throughflow is a major source of iron to the Indian Ocean.

THE BIOGEOCHEMISTRY OF THE SOUTHERN INDIAN OCEAN GYRE SYSTEM. *Championed by Mike Zubkov with support from Tom Bell.* It is unclear what the limiting nutrient(s) are in the oligotrophic southern Indian Ocean gyre. Low iron and/or phosphate levels are likely to be responsible for the low productivity in the center of the gyre, and the nature of the limitation has consequences for many other important biogeochemical cycles. This region is considered a globally-significant marine source of dimethylsulfide. Furthermore, strong convection transports ocean-derived halogens into the upper troposphere/lower stratosphere, influencing ozone concentrations. Despite the potential importance of the Indian Ocean for trace gas production and sea-to-air flux, data paucity is a major limitation of current flux estimates and atmospheric models. The ocean physics that determine nutrient transport into the most oligotrophic regions are poorly understood. A biogeochemistry cruise was proposed that would travel into the centre of the gyre while using glider technology to observe and improve understanding of the ocean physics. This would facilitate comparison of the Indian gyre with previous studies of the South Atlantic and South Pacific gyres.

3.3 **Ecosystems** (Bhavani Narayanaswamy)

The overarching theme for future research would address ecosystem function, the processes and the connectivity in contrasting waters of the Indian Ocean.

A number of topics were discussed under the heading of ecosystems, and five main themes arose from the discussions:

1) Investigation of the Oxygen Minimum Zone either in the Bay of Bengal or the Arabian Sea.

2) Exploration of the habitats in deeper waters of the Chagos Islands as well as the effectiveness of the current MPA in this region. In addition, the prospect of mining in the deep-sea is increasing rapidly and manganese nodule fields are known to exist in the MPA region.

3) Biogeography of dispersal/tracking of specific fish species and links to hydrographic conditions in the area. If additional MPAs were to be developed to protect the fish stocks, decisions need to be made on both spatial and temporal scales. Would it be feasible, and more effective, to develop mobile MPAs?

4) Topographic highs within the Indian Ocean include a number of seamounts, ridges and plateaus including the Mascarene Plateau. Although the Mascarene Plateau is geographically quite close to the Crozet Islands, they have quite different productivity regimes; a comparison between those sites could therefore be informative. Benthic standing stock can be used to assess the flux to the seafloor. Seamounts on the SW Indian Ridge are already under investigation and current results indicate changes in diversity, linked to hydrography and productivity, across the ridge system. In addition, the pelagic fauna (including micro-nekton) and seabirds should be included in such studies, since they are likely to be closely linked.

5) Investigation of the relationship between the structure of the ecosystem and national fisheries. In particular, to try to forecast pelagic fishery yield around the coast of India, although such a project could be expanded to include larger, further offshore pelagic species.

The first two of these ideas were developed in greater detail as potential proposals, and their main features are outlined below. Other studies – on topographic highs within the Indian Ocean, the biogeography of commercial fish species and their relationship to hydrography, and trying to forecast fishery yield – require further discussion.

BAY OF BENGAL OXYGEN MINIMUM ZONE (*Championed by Ursula Witt).* There have been many studies looking at the oxygen minimum zone (OMZ) of the Arabian Sea, e.g. those published in Deep Sea Research II in 2009. However, by contrast there has been little focus on the OMZ of the Bay of Bengal. It was during the first IIOE that the OMZ in the northeastern section of the Bay of Bengal was reported. The Bay of Bengal has extremely high freshwater input from rivers (7 major rivers flow into the Bay) and precipitation, particularly during the summer monsoon season (June – September), and has a high sediment and nutrient input; all of which are much higher than in the Arabian Sea. Together these impact on the stratification and primary production in the region, and are likely to have contributed to an intensification of the OMZ in the western section of the Bay of Bengal.

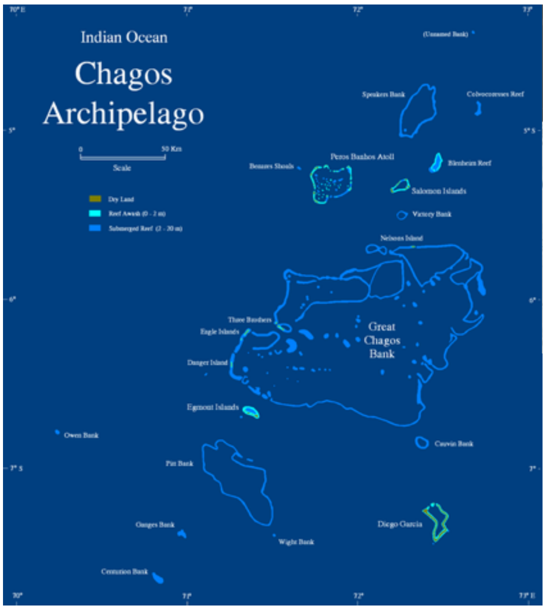
The absence of denitrification in the region is an interesting feature, that does not seem to be due to faster sinking of organic matter or low bacterial respiration rates. Research on this issue would require investigating the links between larger organisms and microbes in the region, as well as exploring other elements of the biogeochemistry in the Bay of Bengal. Other challenges include trying to predict how climate change will impact on the OMZ, assessing the risks of an increase in hypoxic waters around and on the shelf which would severely impact (and potentially wipe out) the benthic communities there. The socio-economic impacts could be immense, with the artisanal fisheries no longer being viable.

Associated research questions include:

- How do both the quantity and the quality of downward organic fluxes impact on the OMZ and the benthic community found within the region?
- How does faunal size change within the OMZ? Are larger, mobile fauna i.e. fish, able to use the OMZ as a refuge?
- How would climate change influence the scale/size of the OMZ and in turn impact on the scale/level of hypoxic waters, especially on the shelf? How would this impact on the biological communities, both benthic and pelagic, and what would be the effect be at societal and economic levels?

WHAT'S THERE? EXPLORATORY RESEARCH IN THE CHAGOS ARCHIPELAGO / BRITISH INDIAN OCEAN TERRITORY (*Championed by Alex Rogers)*. The Chagos archipelago, comprising >50 relatively small islands, is located in the central Indian Ocean, a region thought to have the cleanest seas in the world. In 2010, the waters around the Chagos Islands were declared a Marine Protected Area (see Figure 2); the largest in the world's oceans, with the entire area (shallow to deep-sea) being designated as a fully protected no-take marine reserve. The region contains many atolls, shallow limestone reef systems, seamounts and abyssal habitats. As the Chagos islands are deemed as one of the UK's overseas territories, establishing an MPA in the region requires regular monitoring of the different habitats. However, before a monitoring regime can be established, baseline surveys need to be undertaken in order to understand the biological diversity, composition, structure, the numbers and types of new species etc. of the different habitats in what is considered to be such a pristine region.

There are currently shallow water expeditions to the area focussing on the coral reefs and associated fauna (Figure 3). To date however, there has been no research on the habitats found in the deeper waters surrounding the Chagos islands. The Chagos region would therefore be an ideal region to investigate the connections between shallow water coral reef ecosystems and deeper benthic ecosystems and hence looking at changes in faunal composition and diversity across a bathymetric gradient. In this region there is also some evidence of mesophotic reef systems and thus the deep-reef refugia hypothesis could be tested i.e. to see if these reef systems help replace the loss of coral and other associated fauna in shallower systems.



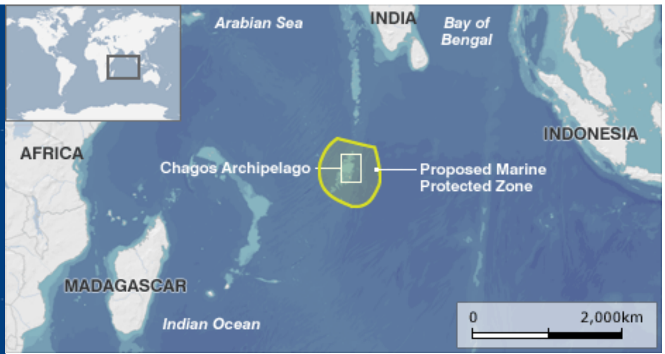


Figure 2.Chagos Islands and map showing the extent of the Marine Protected Area (Wikimedia)

Figure 3. A diver surveying the marine fauna around the Chagos Islands (Wikimedia)

The major questions driving the research focus for this area are:
- What lives in one of the most unexplored oceans of world?
- Is the diversity as high as we expect it to be?
- What is the level of connectivity across the seamounts/trenches in the area?
- What is the effectiveness of the Chagos Islands MPA? Is it working?
- Are we able to determine if there have been any changes in the diversity, composition, ecosystem structure and function?
- Does the MPA help Indian Ocean fish populations regenerate?

The benefits of this research would increase our knowledge of one of the least explored oceans. By doing so we would also be able to assess whether the MPA is actually effective and whether it is being adhered to by fishermen working around the Chagos Islands. In addition we would increase the understanding of the deep-reef refugia hypothesis which may explain why the Chagos Island shallow water coral reef systems seem to be able to recover from extreme events (coral bleaching).

4. NEXT STEPS

The next main step on completion of this report is its circulation to all those with interests, including workshop sponsors and other potential funders; relevant HEI Heads of Departments; and the wider research community. Additional ongoing and specific actions to develop IIOE-2, and its UK contribution, are summarised in Table 3 below.

Table 3. Proposed planning actions and activities relating to coordination of Indian Ocean research, updated since the Dartington workshop

When?	***What?***	***Who?***	***Where or to whom?* [update]**
Ongoing	Prepare and submit research proposals	Researchers	To fit into NERC and other funding timetables
	SCOR sponsorship of IIOE-2, including development of an IIOE-2 Research Plan	Peter Burkill Greg Cowie	*[Draft Research Plan discussed at SCOR Workshop (Bremen, September 2014)]*
	National liaison with IOC re IIOE-2 development	Steve Hall	*[IOC sponsorship confirmed by IOC Executive Council (Paris, May 2014)]*
	Fostering UK interests in IIOE-2	Karen Heywood Steve Hall	Stimulating community networking, via UK-SCOR and UK-IOC *[mailing list established]*
	Obtain advice on geographical areas for UK ships and UK scientist on foreign ships	??	NERC and FCO
31 Aug 2014	Pilot round for submission of ideas to NERC Strategic Programme Advisory Group (SPAG)	Researchers	*[several relevant ideas were submitted]*
10 Sep 2014	Discussions with wider research community	Karen Heywood	Discussion session at Challenger Society Conference, Plymouth *[done]*
12-13 Sep 2014	SCOR Indian Ocean Workshop	Greg Cowie	Bremen, Germany *[done]*
20 Jan 2015	Next deadline for NERC Standard Grants (also late July)	Researchers	
March 2015	Likely next deadline for outlines for NERC large grants	Researchers	
November 2015	Likely next deadline for full proposals for NERC large grants	Researchers	
30 Nov - 4 Dec 2015	Indian Ocean Symposium	All with interests	Goa, India

Acronyms

ADCP	Acoustic Doppler Current Profiler
BIOT	British Indian Ocean Territory (Chagos Archipelago)
BoB	Bay of Bengal
BoBBLE	Bay of Bengal Boundary Layer Experiment
CTD	Conductivity, temperature and depth (water sampling instrument with additional sensors)
EIOURI	East Indian Ocean Upwelling Research Initiative
ENSO	El Niño Southern Oscillation
GEOTRACES	An international research project of marine biogeochemical cycles of trace elements, co-sponsored by SCOR

	(http://www.geotraces.org/).
IIOE	International Indian Ocean Expedition which ended in 1965 (see http://www.scor-int.org/IIOE_History.htm).
IIOE-2	The new IIOE initiative sponsored by SCOR and IOC to mainly run between 2016-2020
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research (co-sponsored by SCOR & IGBP).
IMAREST	Institute of Marine Engineering, Science and Technology.
IOC	Intergovernmental Oceanographic Commission (a body of UNESCO).
IOGOOS	Indian Ocean Global Ocean Observing System (affiliated to IOC).
MJO	Madden–Julian Oscillation
MPA	Marine Protected Area
NERC	Natural Environment Research Council
NIO	National Institute of Oceanography, Goa, India
OMZ	Oxygen Minimum Zone (situated between 200-2500 m deep in the northern Indian Ocean)
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction
SCOR	Scientific Committee on Oceanic Research (an ICSU Body with membership of 42 countries).
SIBER	Sustained Indian Ocean Biogeochemistry and Ecosystem Research (co-sponsored by IMBER and IOGOOS).
UK-IOC	UK section of IOC
UK-SCOR	UK section of SCOR; affiliated to the Royal Society and the Challenger Society
WOCE	World Ocean Circulation Experiment

Annex 1: Workshop Participants

Name	*Affiliation*	*Name*	*Affiliation*
Tom Anderson***	NOC	Bhavani Narayanaswamy****	SAMS
Tom Bell****	PML	Adrian New***	NOC
Brian Bett	NOC	Alex Piotrowski	Cambridge
Peter Burkill*	SCOR & Plymouth	Trevor Platt	PML & POGO
Greg Cowie**	Edinburgh	Dyonisius Raitsos	PML
Trevor Guymer**	NOC	Tom Rippeth	Bangor
Stephen Hall	NOC & UK-IOC	Alex Rogers***	Oxford
Karen Heywood	UEA & UK-SCOR	Shubha Sathyendrenath	PML
Gideon Henderson**	Oxford & UK-SCOR	Karin Sigloch***	Oxford
Simon Josey	NOC	Andy Watson	Exeter
Maeve Lohan***	Plymouth	Mike Webb***	NERC
Miguel Maqueda	NOC Liverpool	Phil Williamson**	NERC & UEA
Adrian Matthews****	UEA	Ursula Witte	Aberdeen
Elaine McDonagh****	NOC	Chris Yesson	ZSL
Chris Mees***	MRAG	Mike Zubkov	NOC

* Workshop Convenor, ** Co-convenor, *** Lead talk, **** Rapporteur

Annex 2: Main Agenda for the Dartington Workshop

Monday 17th March

SESSION 1: BROAD CONTEXT (Upper Gate House)

20:20 – 21.30 Welcome, aims /outputs and international perspectives (Peter Burkill); BIOT (Phil Williamson); GEOTRACES (Gideon Henderson); SIBER (Greg Cowie); open discussion

Tuesday 18th March

SESSION 2: TOPIC TALKS AND DISCUSSION (Upper Gate House)

Time	Topic	Lead talk	Rapporteur	Chairman
08:45	Introductions & interests			P Burkill
09:00 – 09:45	Monsoons	A Matthews	T Guymer	P Burkill
09:45 – 10:30	Physics	A New	T Guymer	P Burkill
10:30 – 11:00	*Coffee/Tea (West Wing Lounge)*			
11:00 – 11:45	Biogeochemistry	T Anderson	G Cowie	G Henderson
11:45 – 12:30	Benthos	A Rogers	P Burkill	G Henderson
12:30 – 14:00	*Lunch (Solar Room)*			
14:00 – 14:45	Top Predators & Biodiversity	C Mees	P Williamson	G Cowie
14:45 -15:30	Geochemistry	M Lohan	G Henderson	G Cowie
15:30 – 16:00	*Tea / Coffee (West Wing Lounge)*			
16:00 – 16:45	Geology & Geophysics	K Sigloch	G Henderson	P Williamson
16:45 – 17:30	Discussion & plans for tomorrow		P Burkill	P Williamson

Wednesday 19th March

SESSION 3: SYNTHESIS & PLANNING SESSION (Upper Gate House except 09:15-10:30)

09:00 – 09:15 The NERC funding mechanisms: Mike Webb (Chair: T Guymer)

09:15 - 10:30 Parallel sessions for small groups to identify key research (locations TBA)

10:30 -11:00 *Coffee/Tea (West Wing Lounge)*

11:00 – 12:15 Plenary group feedback from parallel sessions by Rapporteurs (Chair: P Burkill)

12:15 – 13:00 Next Steps? (Chair: P Burkill)

13:00 *Lunch and Disperse (Solar Room)*

Annex 3: Main (NERC) funding mechanisms

There are many funders – and funding mechanisms – that might be used to support UK research in the Indian Ocean, and the community is encouraged to investigate all realistic possibilities, at a range of levels. Nevertheless, the Natural Environment Research Council (NERC) is likely to be the most important for ship-based oceanographic research, and a short summary (not comprehensive) is therefore given here of the most relevant current NERC schemes. These were re-defined in 2014; for further details see www.nerc.ac.uk/funding and the specific links given below

NERC strategic research

NERC strategic research is directed at "environmental areas of major economic and societal importance". Improved understanding of the physical dynamics and living resources of the Indian Ocean has such importance, as was evident to participants of the Dartington workshop; however, convincing justification of that relevance needs to be made to those with responsibility for strategic funding decisions, in competition with other ideas for other research areas.

The main process for NERC acceptance of a specific initiative as strategic research (with subsequent funding as either a Highlight Topic or a Strategic Programme Area) involves submission of a 2-page outline for consideration by the Strategic Programme Advisory Group (SPAG). That outline ('idea') needs to identify how societal challenges will be addressed, i.e. the wider importance of the research to NERC and the UK, as well as describing the scientific need (including its timeliness and novelty); opportunities for collaborations and partnerships; and the capacity and infrastructure required. For details see: www.nerc.ac.uk/research/portfolio/strategic/ideas/submission-of-ideas-guide.pdf

If approved by SPAG, the distinction is then made between a **Highlight Topic** (up to £4m, ~ 6 month for approval) and a **Strategic Programme Area** (£5 – £20 m, ~ 1 year for approval), with subsequent calls for bids to address the specified strategic research topic/area.

The pilot call for strategic ideas had a closing date of August 2014; those submissions are currently being assessed. Dates for future calls have not been announced; however, two calls per year are envisaged.

Whilst the identification of the UK Indian Ocean Initiative, or components of it, as strategic research would be highly desirable, caution is advised with regard to "putting all eggs in the SPAG basket". Thus other funding mechanisms should also be considered.

NERC discovery research (responsive mode)

For research proposals involving shiptime on NERC research vessels, large grants and standard grants are likely to provide the most straightforward funding routes.

Large grants (between £1.2m and £3.7m FEC) require initial approval of an outline, with March submission date, and subsequent approval of a full proposal in November. *Unless ship-scheduling procedures change, outline bids submitted in March 2015 should aim for shiptime in 2018 at the earliest.*

There are two closing dates each year for **standard grants** (between £65k and £1.2m FEC), in late January and July. *For bids submitted in 2015, it should be possible to obtain shiptime in 2017.*

Joint work with NSF

A mechanism to facilitate joint proposals with US researchers has recently been developed for environmental biology (www.nerc.ac.uk/funding/available/researchgrants/international), with extension to geosciences currently being finalized. An outline is required, with subsequent decision as to whether NERC or NSF should be the lead agency for reviewing the proposal as a whole (avoiding double-jeopardy).

Other schemes

The Newton Fund has potential for supporting joint work with India, but there have not yet been relevant calls either via RCUK (www.rcuk.ac.uk/international/newton/) or other routes (www.gov.uk/government/publications/newton-fund-building-science-and-innovation-capacity-in-developing-countries/newton-fund-building-science-and-innovation-capacity-in-developing-countries).