In support of the IOTC ecosystem report card: a preliminary approach to monitor the status of the ocean climate and environment, variability and trends

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SUMMARY

In support of the development of the IOTC ecosystem report card, this paper addresses the "ocean climate and environmental" ecosystem component and specifically it contributes towards developing the following elements: (1) We describe the importance of this ecosystem component from which we can understand the potential risks of not monitoring it, and make a proposal of a conceptual and an operational objective to measure progress towards monitoring the potential impacts of the ocean climate and environment on the state of IOTC species and associated ecosystems. (2) We present a candidate list of climate and environmental indicators that could be estimated to capture and describe changes in the habitat of large pelagic fishes and open-ocean ecosystems, and (3) we discuss main challenges in indicator development. (4) Finally, we draft a work plan to guide our future work. We invite the IOTC community and others to contribute towards the development of the IOTC ecosystem report card. If interested, contact the corresponding authors to find out how you can contribute to this initiative.

KEYWORDS

Ecosystem report card, indicators, pelagic habitat, climate change and trends

1. Introduction

The WPEB Program of Work (2019-2013) includes the development of an indicator-based ecosystem report card for the IOTC region (IOTC, 2018). The main purpose of the IOTC ecosystem report card is to provide stronger links between ecosystem science and fisheries management to support the implementation of ecosystem-based fisheries management (EBFM) in the IOTC region. Potentially, it could be an effective communication tool to increase the awareness, communication and reporting of the pressures on and the state of the marine ecosystem to the Commission, since it can be used to synthesize large and often complex amount of information into a concise and visual product. Ultimately the ecosystem report card aims to provide an assessment of the relevant *pressures* affecting the state of IOTC species and associated ecosystem (Juan-Jordá et al. 2018).

The development of the indicator-based ecosystem report card requires of a long-term strategy to build ecosystem knowledge, and increase capacity and collaborations in the IOTC community. As a first step, the WPEB14 drafted a workplan to support the development of the indicator-based ecosystem report card for the IOTC region (IOTC, 2018). The workplan included a reporting framework to monitor the full range of interactions between IOTC fisheries and the different components of the pelagic ecosystem with assigned scientists to develop ecosystem indicators and indicator-based assessments to inform the IOTC ecosystem report card.

In support of the development of the IOTC ecosystem report card, this paper addresses the "ocean climate and environmental" ecosystem component and specifically it contributes towards developing the following elements:

1. We describe and highlight the importance of this ecosystem component and explain the potential risks of not monitoring it. We also provide a conceptual and an operational objective to monitor the status of the ocean climate and environmental component and its potential impacts on IOTC species and associated ecosystems, which can be used to measure progress towards management of this component.
2. We present a candidate list of indicators to monitor the oceanic environment
3. We present the state of development of this component and highlight main issues and challenges in monitoring this ecosystem component.
4. Finally, we present a work plan to guide future work.

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2. The "ocean climate and environmental" component and objectives to measure progress

Information on the ocean climate and environment is now recognized as essential in fish stock assessment as it helps to better understand past trends in catch series, to improve the quality of forecasts (Brander 2009, MacKenzie et al 2008, McClatchie 2014, among others), thus contributing to more accurate management advices from RFMOS scientific panels. Life history traits, population growth rates, movements and stock abundance are influenced by factors other than fishing. Environmental cues, gradients and fronts of essential abiotic (temperature, dissolved oxygen, currents) and biotic (ocean color, plankton and micronekton aggregations) factors play a key role in tuna movements (Block and Stevens, 2001).

The Indian Ocean is unique by its geographical shape, i.e. an ocean closed in the tropical north latitudes by a continental landmass. This creates a seasonal reversing monsoon with strong implications in sea surface temperature and current patterns (see Schott and McCreary 2001 for a review), coastal upwellings and subsequent spatial redistribution of biological hot spots (Wiggert et al, 2002). The tuna life cycle (and fisheries) are influenced by such annual cycle, for instance, the main spawning season for yellowfin in the West Indian Ocean takes place during the season of highest temperature and least turbulence (Nov-Feb) (Marsac, 1998). Furthermore, environmental anomalies can occur at inter-annual timescale under the effect of ENSO and more specifically, the Indian Ocean Dipole. During a warm event (positive dipole), The chlorophyll enrichment (and by consequence, trophic conditions for top predators) is dramatically reduced in the West IO during the spawning season and, by contrast, becomes anomalously enhanced in the East IO (Murtugudde et al, 1999). This situation can cause large spatial shifts of the core fishing grounds in the surface fishery (Marsac 2006, 2017). Finally, the Indian Ocean is subject to a significant and steady warming under climate change. The main stressors acting on the pelagic habitat are warming, deoxygenation, acidification and primary production, and each of these must be closely monitored to assess the impact on ecosystems and fisheries and develop mitigation measures.

In order to measure progress towards monitoring the status of ocean climate and the environment and its potential impacts on IOTC species and associated ecosystems, we proposed the following conceptual and operational objective:

Conceptual objective: "Monitor the status of the ocean climate and environments including its trends and variability"

Operational objective: "Monitor the potential impacts of changing climate and environmental conditions on IOTC species and associated ecosystems"

3. Proposal of candidate indicators for the oceanic environment

Many of the proposed variables and indicators are already identified among the Essential Ocean Variables (EOVs) of the Global Ocean Observing System (http://www.goosocean.org). EOVs are a masterpiece of the framework for Ocean Observations (FOO). They were identified and characterized by the GOOS Expert Panels based on relevance, feasibility and cost effectiveness. GOOS has established three readiness level for each EOV, concept, pilot and mature. Such readiness approach allows for timely implementation of components that are already mature, while encouraging innovation and research to improve readiness and capacity building for others.

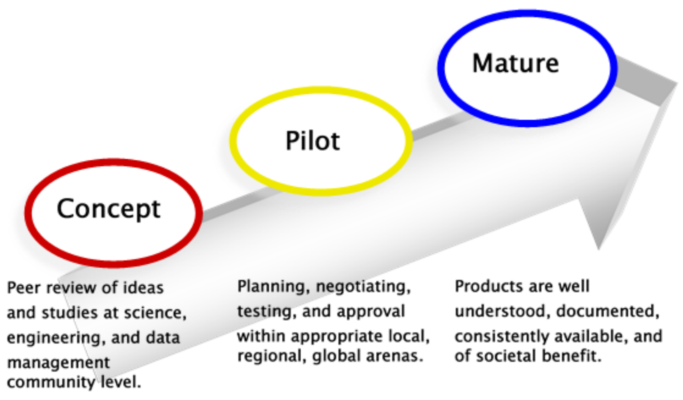

Fig. 1 - Readiness levels of the FOO for Essential Ocean variables, as estimated by the GOOS community

Details on the candidate indicators and their relevance to monitor the state and trends of open ocean ecosystems are given in Table 1. All variables/indicators detailed below are based on a mature observing system.

Table 1 – Potential environmental indicators that can be used to monitor changes affecting the open-ocean ecosystems

Indicator type	Indicator examples	Attributes measured	Potential data sources
Climate indicators.	- Southern Oscillation Index (SOI) - Equatorial SOI - Niño 3.4 - Indian Ocean Dipole / Dipole mode index (DMI)	Times series of monthly values.	Climate Diagnostics Bulletin, Climate Prediction Centre of the NOAA, USA Indian Ocean climate drivers page of the Australian Bureau of Meteorology
Brief description and rationale Climate indicators detailed here are time series established over a long period of time, hence they can document changes at decadal and interannual timescales. - The Southern Oscillation Index (SOI) indicates the development and intensity of El Niño and La Niña events that are mainly observed in the Pacific ocean (ENSO : El Niño Southern Oscillation) , however with worldwide repercussions. The ENSO is the result of interactions between the atmosphere and ocean circulation. The SOI is measured by the difference of sea-level pressure standardized anomalies between Darwin and Tahiti ($P_{tah} – P_{dar}$). El Niño is the negative phase of the SOI and is associated with an extensive warming and above-normal atmospheric moisture in the Central and Eastern Pacific Ocean; and cooler and dryer conditions in the Western Pacific. La Niña events, the positive phase of SOI, corresponds to an increased trade wind regime, increased warming and increased precipitation in the Western Pacific. SOI extends back-to the late 1800s. The atmospheric linkage of the SOI with other ocean basins operates through the Walker cells. - The Equatorial SOI uses the average sea level pressure over two large regions centered on the equator (5˚S to 5˚N) over Indonesia and the eastern equatorial Pacific. This more recent definition is based on the fact that ENSO is mostly focus along the equator, whereas Darwin and Tahiti are only located in the Southern hemisphere. The ESOI is computed in the same way as the SOI between these two remote regions, but extends back to only 1949, a shorter time period than SOI. - The Niño 3.4 depicts sea surface temperature (SST) conditions (anomalies) in the Central and Eastern Pacific (5N-5S, 120W-170W) that are well-sampled regions by in situ measurements from ships passing through this area. The areas 3 and 4 (combined in Niño 3.4) are considered as the most ENSO-representative. - The Indian Ocean dipole (IOD) is recognized as a major atmosphere–ocean phenomenon for the Indian ocean (Saji et al, 1999). The dipole mode index (DMI) is used to characterize the phase of the IOD: it informs on the east–west temperature gradient across the tropical Indian Ocean. DMI is calculated as the difference in SST anomalies between the West (50E-70E/10N-10S) and the East (90E-110E / 0-10S) of the Indian Ocean. During positive IOD, the SST is anomalously low off Sumatra (Indonesia) and anomalously high in the West IO. IOD has been reconstructed back to 1954 (from ERSST dataset of NOAA).			

Indicator type	Indicator examples	Attributes measured	Potential data sources
Physical surface conditions	- Sea surface temperature (SST) - Sea surface height (SSH) - Ocean surface stress - Current	°C M $(M.s^{-1})^2$ for wind stress Velocity and direction for currents	In situ, satellite and model-derived

Brief description and rationale

- SST is a vital component of the ecosystems by influencing metabolic rates and defining habitat boundaries for living organisms. Its influence plays at different timescales, and the most common resolutions explored for pelagic fish are: month/100 km for short term movements and concentration areas; week/10 km for eddies, fronts and upwelling. SST is a basic measurement by ships, is commonly measured by polar orbiting satellites (at 1 km resolution) and is also a key product of ocean circulation models.

- SSH (and its associated anomalies, like the sea level anomaly) is among the primary indicators of global climate change. It is measured along a range of scales from tide gauges to satellite radar altimeters. On the regional scales, substantial variability can occur through combined changes in temperature, salinity and ocean circulation. Mesoscale eddies (anticyclonic and cyclonic) are well described by SSH.

- The ocean surface stress combines both the drag at the bottom of the atmosphere, and the dynamical forcing at the surface of the ocean. It is linked to open ocean surface current convergence and divergence, coastal upwelling and downwelling and associated primary productivity. Surface stress drives coastal currents, storm surge ocean surface turbulence and mixed layer evolution. It is represented as a 2D horizontal vector proportional to the rate at which momentum is transferred from the atmosphere to the ocean. It is measured from ocean platforms and satellites. An example of ocean surface stress product is the pseudo wind stress product of the Florida State University digitized for tropical oceans at a 2-degree/month resolution.

- Surface currents, as produced by models at various space and timescales, is the input for Lagrangian studies to investigate connectivity between remote sites.

Indicator type	Indicator examples	Attributes measured	Potential data sources
Physical sub-surface conditions.	- Mixed layer depth (MLD) - Thermocline depth (TD) and stratification - Vertical current shear (VCS)	M (for MLD and TD) No unit for VCS	World Ocean Atlas Models (i.e. GODAS, CMEMS)

Brief description and rationale

- MLD represents the depth over which surface fluxes have been recently mixed and integrated. We mostly consider temperature and salinity which control the seawater density. There are several definitions of the MLD, such as the depth at which the density increases by 0.03 kg m^{-3} or the depth where temperature varies by at least 0.2°C from a reference depth level set at 10 m (de Boyer Montégut et al, 2014). With the density criterion, the MLD is an isopycnal layer depth. With the temperature criterion, the MLD is an isothermal layer depth (but temperature inversions are not contained in this calculation).

- TD: the thermocline depth is defined as the depth of the maximum vertical temperature gradient. In the equatorial regions, the depth of 20°C isotherm is widely used to represent the thermocline depth (Kessler 1990; Ji et al. 1995; Vialard and Delecluse 1998). The thermocline depth is known to affect catchability of tropical tunas with respect to surface fisheries (Green, 1967; Cayré and Marsac 1993). The thermocline gradient denotes the degree of stratification between upper and deeper layers and can be used as a stratification index. It is hypothesized that stratification will increase with climate change (Capotondi et al 2012) compromising ocean mixing, oxygen ventilation and nutrient inflow from the deep nutrient-rich layers through the sunlit layer.

- The vertical current shear (VCS) is a change of current speed or direction with increasing depth. VCS affects the longline shape and shoaling rather than absolute current velocity (Bigelow et al, 2006). It may be a significant covariate in longline or purse seine CPUE standardization.

Indicator type	**Indicator examples**	**Attributes measured**	**Potential data sources**
Biogeochemical and biological indicators.	- Dissolved oxygen (DO) concentration and oxycline - Ocean acidification - Ocean colour	ml.L^{-1} or mg.L^{-1} or mmol.L^{-1} for DO; pH units for acidification mg.m^{-3} for chlorophyll	Word Ocean Atlas Ocean colour products disseminated on the web Biogeochemi-cal models (e.g. PISCES, CMEMS)

Brief description and rationale

- DO is a critical habitat parameter for living organisms and a factor controlling the depth distribution of tunas and other large pelagic fishes. Oxygen is the third-most often measured water quantity after temperature and salinity. Oxygen solubility is an inverse function of temperature, i.e. less oxygen can be captured in warmer waters. The surface waters are oxygen-saturated however major changes occur at depth, as a result of biological activity and ocean circulation (for ventilation). This variable is measured worldwide and estimated by coupled ocean biogeochemical models concentration to better monitor the expansion of the oxygen minimum zones (OMZ). A specific key feature of the OMZ is the depth of the upper oxycline depth. The oxycline gradient and its location have an impact on both biotic and abiotic processes, and its changes have significant potential impacts on entire ecosystems.

-The ocean acidification is measured by the seawater pH which is decreasing in response to ocean uptake of anthropogenic carbon (Doney, 2010). Lower pH creates more acidic conditions. Despite higher CO2 seawater concentrations being beneficial for autotrophs, they become a threat for calcifying organisms by compromising calcification (Hofmann et al., 2010). Change is expected in the range –0.25 to –0.30 pH unit under highest CO2 (RCP8.5) scenario, which is very significant when compared to the decline by 0.1 pH unit measured since pre-industrial times (IPCC 2013).

- Ocean colour: phytoplankton is the first link in the ocean’s food chain, and is the main source of food for most fish. It is measured globally and synoptically thanks to satellite sensors OCRS). The chlorophyll a (Chl-a) content and the Net Primary Productivity are products derived from the OCRS, and critical variables to measure primary production, as well as of global ocean health. Chl-a levels can vary substantially at interannual scales in relation to ENSO and IOD anomalies (Murtugudde et al., 1999; Sarma, 2006).

4. The state of development of this component and main issues and challenges in monitoring this ecosystem component

Over the years, we have seen a growing interest in the IOTC scientific community to find ways of summarizing information that was only considered by climatologists and oceanographers. The development of open and comprehensive databases (such as the World Ocean Atlas) and dedicated processing tools (e.g. Ocean Data View) has facilitated access to and use of such information. Nevertheless, some oceanographic expertise is necessary to select the most appropriate data sources (especially from model simulations) and to interpret the patterns, while considering parameters being relevant to ecosystem monitoring and fisheries. The IOTC community has become familiar with the climate and oceanographic information which is presented by a few scientists at the WPEB or

WPTT sessions. Environmental covariates are now included in the CPUE standardization analyses using generalized linear or additive models processes, and environmental trends are taken into consideration in outlooks and management advice of executive summaries produced by the IOTC Scientific Committee.

Several of the above listed variables/indicators are readily available for the Indian Ocean. This has been developed and presented at each WPTT since 2012 in working documents entitled “Outline of climate and oceanic conditions in the Indian Ocean” with yearly updates (Marsac 2012, and following years). In 2018, at the WPDCS-14, an ocean-climate web page for the IOTC was proposed (Marsac, 2018). The proposal is being subject to a scoping study, to assess its feasibility, under the supervision of the IOTC Secretariat.

The variables that have been calculated and will be displayed on the ocean-climate web page are:

- The Southern Oscillation Index
- The Dipole mode index
- The sea surface temperature
- The surface current (u and v components)
- The current vertical shear (a temporary version between 0 and 145 m)
- The mixed layer depth
- The thermocline depth
- The surface chlorophyll-a

The challenge for this climate web page proposal is to find the human resources to produce indicators on a quasi-real time basis (i.e. regular updates with a 2-month delay) instead of a yearly frequency as it is presently. It is necessary to develop algorithms for automatically transferring the large amount of information from external portals to be included on the website. This procedure should ensure that there is minimal strain on IOTC resources for the implementation of this initiative. Secondly, additional indicators should be added (see below the future work section).

As noted by the IOTC Scientific Committee at its 2018 session, current models used in stock assessment do not explicitly consider the influence of climate change and variability on ecosystems and fisheries resources. The challenge is then to conduct parallel analyses with ecosystem models (e.g. Atlantis, ECOSIM, APECOSM) to better explore these influences. It was recognized that assessments of the use of these systems could be undertaken by small working groups within the WPEB.

The sources of data on which the indicators are based deserve some discussion. Presently, the ocean circulation model used is the GODAS which is an assimilated system, an approach combining theory (numerical model) with observations on an optimal way. GODAS products start in 1980. Another assimilated ocean model is available through the European Copernicus Marine Environment Monitoring Service (CMEMS), providing simulations on hourly, daily or monthly basis at a spatial resolution of ~9km (1/12 degree), with a temporal coverage starting in 2007. Then, the CMEMS simulations are at a finer scale compared to GODAS (1-degree longitudes by 0.33-degree latitude) but with a significantly shorter time span. Therefore, selecting GODAS or CMEMS depends on the type of analysis to be performed. A comparison between the same indicators generated by these two models should be performed.

Two model simulations are available at CMEMS for biogeochemical parameters (oxygen, nutrients, primary production), at a ¼ degree resolution (daily and monthly means). One simulation does not assimilate observations and covers the period 1993 to present, the other one does assimilate data but covers a much shorter period of time (start: July 2017).

Model simulations have the merit of providing continuous fields whereas in situ observations are limited by spatial and temporal gaps. However, some areas (especially along shipping lines) are regularly sampled, therefore in situ observations coming from these regions can indicate ocean trends. Observations are available on much longer time scales that model outputs.

To minimize the occurrence of blank zones on data fields, we generally perform data averaging in time and space, however this has to be done cautiously because of the smoothing effect caused. For instance, satellite-derived chlorophyll estimates on a daily basis (1, 4 or 9 km spatial resolution) are only distributed along satellite tracks shifting around the globe from one day to another. Weekly or monthly composites are often necessary to cover adequately an oceanic sub-region. We are presently using monthly composites in a rectangular grid (matching

GODAS outputs) which minimize the occurrence of blank regions while providing useful information to score the quality of the tuna habitat in the open-ocean.

5. Work plan

Below we summarize some future steps planned to advance our work towards monitoring the state of "ocean climate and environmental" component in order to understand the potential impacts of ocean climate and environmental trends and variability on the IOTC species and their ecosystems, which we plan to update annually at the WPEB meetings. This is work in progress which requires the collaboration of multiple experts with diverse backgrounds on oceanography, modelling and ecological processes relevant to IOTC species. We invite the IOTC community to contribute towards the development of the "ocean climate and environmental" component to support the IOTC ecosystem report card. If interested, contact the corresponding authors to find out how you can contribute to this initiative.

Future steps:

The list of available variables/indicators will be complemented by

- The equatorial SOI
- The Nino 3.4 index
- The sea surface height (and derived anomalies)
- The pseudo wind stress
- A stratification index
- The oxycline depth
- Ocean acidification indicators

Any other suggestion is welcome to be evaluated by the Ecosystem report card expert panel.

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