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Impacts of climate change and ocean acidification on Indian Ocean tunas

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Context of the report

This report was elaborated in the context of the project "Diagnosis of the tuna industry in the Indian Ocean", co-funded by the Institute for Sustainable Development and International Relations (IDDRI) and the French government in the framework of the programme "Investissements d'avenir", managed by ANR (the French National Research Agency) under the reference ANR-10-LABX-01.

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Table of contents

List of acronyms

CMIP	Coupled model intercomparison project
CPUE	Catch per unit effort
DSL	Deep scattering layer
DWFN	Distant water fishing nations
EEZ	Exclusive economic zone
ENSO	El Niño/Southern Oscillation
ESM	Earth system models
FL	Fork length
GDP	Gross domestic product
IOD	Indian Ocean Dipole
IPCC-AR5	Intergovernmental panel on climate change fifth assessment report
PICTs	Pacific Island Countries and Territories
SST	Sea surface temperature
SSTA	Sea surface temperature anomaly

List of figures

Executive summary

- ✓ The spatial distribution of tunas is influenced by oceanographic conditions (mainly water temperature and dissolved oxygen) that vary with climate. If water temperature exceeds species-specific thermal tolerance, or if oxygen concentration is insufficient for physiological needs, tunas will move to different latitudes, longitudes and depths.
- ✓ Tunas' abundance essentially depends on good spawning and feeding conditions, which are influenced by temperature, currents, and primary production, the basis of marine food webs.
- ✓ Climate change is modifying oceanographic conditions. In the Indian Ocean, projections show increasing sea water temperatures, growing ocean acidification and regional oxygen depletion. Increasing ocean stratification (primarily due to the increase in surface temperature) and decreasing primary production (especially in the upwelling region along the Somalia and Arabia coastline) are also forecasted.
- ✓ Model projections of climate change impacts on Indian Ocean tunas are currently only available for skipjack and yellowfin tuna, under a "business as usual scenario" (RCP8.5[1]). For bigeye, albacore and longtail tuna, model projections are currently missing.
- ✓ Skipjack tuna, presently occurring in equatorial and tropical surface water, is projected to move to higher latitudes. Simulations show an increase of biomass in the first half of this century followed by a strong decrease after the mid-21st century.
- ✓ Yellowfin tuna biomass is also projected to decrease after the mid-21st century.
- ✓ Compared to skipjack and yellowfin, bigeye tuna have a greater tolerance to low level of oxygen and a lower tolerance to high temperature. At low latitudes, water temperature may exceed thermal tolerance, and bigeye may move to deeper water and higher latitudes.
- ✓ Albacore tuna inhabit the subtropical gyre and have a low tolerance to aquatic environments with depleted dissolved oxygen concentrations. Oxygen concentration is projected to decrease in latitudes and depths where they are currently fished. Future distribution of albacore may be limited by oxygen concentration.
- ✓ Given the limited knowledge about longtail tuna biology and their tolerance to environmental conditions, consequences of climate change cannot be assessed.
- ✓ Changes in the current spatial distribution and abundance of tunas will have important consequences on tuna fisheries. Quantity and quality of tuna catch will be redistributed between nations' exclusive economic zones (EEZ) with consequences on national economies of coastal countries.
- ✓ Fishery dependent small islands economies located close to the Equator, such as Seychelles and Maldives, might be the first to suffer from the shift of skipjack tuna biomass from equatorial waters to higher latitudes, projected for the first half of the 21st century. Other countries (e.g. Madagascar and Mauritius) might benefit from the latitudinal shift of skipjack tuna.

[1] Representative Concentration Pathways (RCPs) are four greenhouse gas concentration pathways adopted by the IPCC for its fifth Assessment Report (AR5) in 2014

- ✓ The basin-wide decrease of skipjack biomass in the second half of the 21st century may negatively affect the economy of fishery dependent, vulnerable countries of the Indian Ocean.
- ✓ Projections of yellowfin tuna biomass change (2005-2050) in the western Indian Ocean are even more pessimistic and estimate a decrease between -20% to -40% in the EEZ of tropical coastal countries (from Oman to Mozambique and Madagascar).

1. Introduction

Oceans play a crucial role in climate regulation. Since 1971 they absorbed more than 93% of the heat generated by anthropogenic global warming (Reid, 2016; Rhein *et al.*, 2013) and captured 28% of anthropogenic CO_2 emission (Gattuso *et al.*, 2015). This regulating function comes at the cost of important changes in physical and chemical properties, such as temperature, salinity, sea level, pH, dissolved carbon and dissolved oxygen concentrations (Rhein *et al.*, 2013). Future projections from Earth system models (ESM) forecast increasing sea water temperatures, growing ocean acidification, increasing oxygen depletion and changes in oceanic currents (Ciais *et al.*, 2013, Collins *et al.* 2013). They also project an increase in surface ocean stratification, a reduction of nutrients' supply to surface waters and a decrease of primary production, the basis for marine food webs (Bopp *et al.*, 2013).

Changes in oceans' physical and chemical properties affect the structure and the productivity of marine ecosystems. Marine species respond to climate change by shifting their distribution to higher latitudes and deeper water, modifying phenology and decreasing calcification (Poloczanska *et al.*, 2016). Increasing temperature affects the spatial distribution of mobile species, which move following their species-specific thermal tolerance. Temperature impacts also the physiological rates, with consequences on growth, body size, immune defense and reproductive success (Gattuso *et al.*, 2015). Changes in ocean currents, ocean productivity and temperature are likely to affect the dispersal and survival of larvae, with important consequences on fish recruitment.

Climate change is expected to affect fisheries by modifying the spatial distribution and abundance of exploited fish species. This may impact national economies of coastal countries, since quantity and quality of marine fish catch will be redistributed between nations' exclusive economic zones (EEZ) (Sumaila *et al.*, 2011). Substantial catch declines are projected for tropical fisheries even under the most optimistic RCP2.6 scenario by mid–21st century (Gattuso *et al.*, 2015) and global catches for the next 50 years are projected to shift from tropical waters to higher latitudes (Cheung *et al.*, 2010). This may deeply affect communities in tropical developing countries that depend heavily on coastal fisheries for food and economic security (Barange *et al.*, 2014). Moreover, the price and value of catches may vary, changing fishers' incomes and earnings to fishing companies (Sumaila *et al.*, 2011).

Tuna is a high-value and globally traded resource, which provides important economic revenue, employment and food security to fishing and coastal States (FAO, 2016). In 2014, tropical and temperate tuna fisheries registered a new record catch of almost 4.8 million tons globally. Skipjack tuna (*Katsuwonus pelamis)* represents the largest contribution in terms of weight to the global tuna catches (58% of total catch) with 2.8 million tons fished in 2014. Yellowfin tuna (*Thunnus albacares*) landings were close to 1.3 million tons (28%), while bigeye (*Thunnus obesus)* and albacore *(Thunnus alalunga*) represented 9% (430'000 tons) and 5% (250'000 tons) of total catch, respectively (WCPFC, 2014). In 2014, 58% of global tuna catch was harvested in the Western and Central Pacific Ocean. The Indian Ocean comes second (20%) followed by the Eastern Pacific Ocean (13%) and the Atlantic Ocean (9%).

The objective of this report is to assess the impact of climate change on five commercially important tuna species of the Indian Ocean – skipjack, yellowfin, bigeye, albacore and longtail tuna (*Thunnus tonggol*). We review existing projections of climate change impacts on tuna distribution and abundance in the Indian Ocean and evaluate possible consequences on fisheries and national economies. Model projections are not yet available for all species targeted by this report. In the absence of simulation results, we propose a preliminary qualitative assessment based on the forecasted change in the oceanic/coastal environment and its potential impact on spatial distribution. In addition, we will review 1) the reported effect of climate variability on species biomass and catchability, and 2) the projected trends in other oceans.

2. Indian Ocean response to climate change

2.1 Oceanography and biogeochemistry of the Indian Ocean

The Indian Ocean is the only major ocean with asymmetrical circulation. The basin is characterized by the absence of a temperate and polar region north of the equator and by the seasonal reversal of the monsoon winds, which determine the climate in the northern Indian Ocean. The Northeast or Winter Monsoon occurs during the northern hemisphere winter (December-March) and defines the dry season for most of southern Asia. Conversely, the Southwest or Summer Monsoon determines the climate during the northern hemisphere summer (June-September) and brings the monsoon rains and floods (Tomczac and Godfrey, 1994). The strongest upwelling[2] of the Indian Ocean occurs on the west coast, along the coastline of Somalia and Arabia during the Southwest Monsoon, when the Somali current grows and develops into an intense jet with extreme velocities (Figure 1; Tomczac and Godfrey, 1994). This upwelling is important for the ecosystem, since it supplies nutrients to the surface and supports elevated rates of primary productivity (Levy *et al.*, 2007).

The southern Indian Ocean (south of 10°S) is characterized by a subtropical gyre and water is mostly oligotrophic. Important mesoscale activity occurs in the Mozambique Channel (de Ruijter *et al.*, 2002) where mesoscale eddies[3] have been found to be "hot spots" of productivity, attracting top predators such as tuna or seabirds (Tew Kai and Marsac, 2010).

Water exchange between the Indian Ocean and the Pacific Oceans occurs through the Indonesian throughflow, where water from the Pacific flows into the Indian Ocean, as a narrow band of low salinity water (Tomczac and Godfrey, 1994). At the other end, in the

[2] Wind-driven movement of cool, and usually nutrient-rich deep water towards the surface. By replacing the warmer, nutrient-depleted surface water, it stimulates primary production.
[3] Temporary circular currents of water that can travel long distances before dissipating.

southwestern Indian Ocean, the Agulhas Leakage is responsible for the outflow of the Indian Ocean water to the Atlantic Ocean.

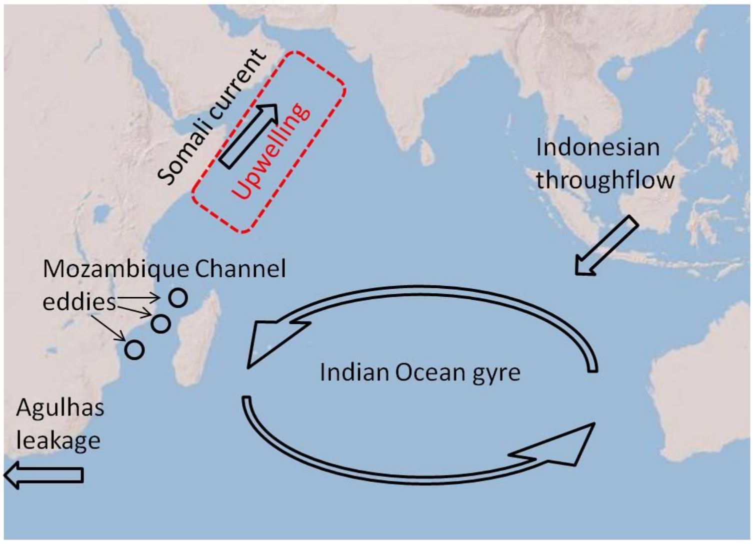


Figure 1: Oceanographic features affecting tuna's spatial distribution in the Indian Ocean

The Indian Ocean is subject to an irregular oscillation of sea-surface temperature, called the Indian Ocean Dipole (IOD). A positive dipole event is characterized by an anomalous cooling in the eastern tropical Indian Ocean (off Sumatra) and warming in the western Indian Ocean (Figure 2b). The opposite pattern is found during a negative event (Saji *et al.*, 1999, Cai *et al.*, 2013). The IOD is the regional equivalent of the El Niño/Southern Oscillation (ENSO), which originates in the tropical Pacific Ocean. Although the two climate modes (IOD and ENSO) are independent, they frequently co-occur. An intense positive IOD/El Niño event occurred in 1997-1998 with important consequences on temperature and productivity. An anomalous negative sea surface temperature anomaly (SSTA) of over 3°C was observed in the eastern equatorial and coastal region, while a warm SSTA that peaked at over 2°C occurred in the west. Moreover, a strong phytoplankton bloom occurred in the eastern equatorial Indian Ocean, an area normally characterized by low productivity (Murtugudde *et al.*, 1999; Murtugudde *et al.*, 2000).

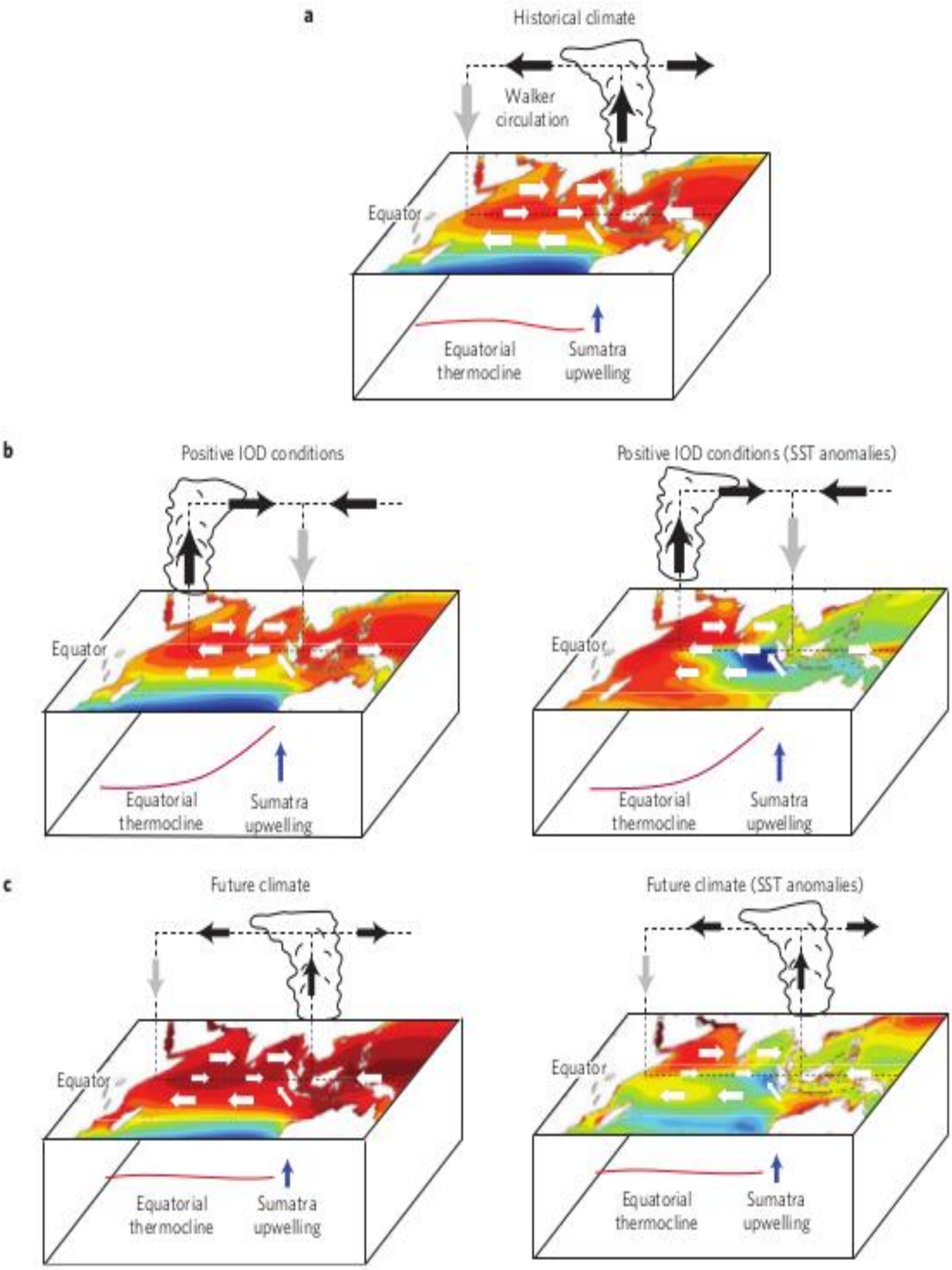


Figure 2: a) Historical mean climate, indicating SSTs, surface winds, the associated Walker circulation, the mean position of convection and the thermocline. b) Typical conditions during a positive IOD event. c) Projected future mean climate based on a CMIP5 multi-model ensemble average (Figure from Cai *et al.*, 2013)

*Diagrams with total SST fields are shown on the left; diagrams with SST anomalies referenced to the 1961–1999 mean for **b)** and referenced to the basin mean for **c)** are shown on the right.*

2.2 Impacts of climate change

Oceans have absorbed a large amount of the heat generated by anthropogenic global warming, but between oceans the increase of heat content is uneven. From 2003 to 2012, the heat content of the Pacific ocean (upper 700 m) has decreased in spite of increased surface heat uptake. Conversely, in the same period, the Indian Ocean has increased its heat content abruptly, explaining more than 70% of the global ocean heat gain (Lee *et al.*, 2015). Simulation experiments suggest that heat is carried from the Pacific Ocean into the Indian Ocean through the Indonesian throughflow. Heat that accumulates in the Indian Ocean may be eventually projected into the Atlantic Ocean through the Agulhas Leakage (Lee *et al.*, 2015).

A recent study shows that the western tropical Indian Ocean has been warming for more than a century, at a rate faster than any other region of the tropical oceans, and turns out to be the largest contributor to the overall trend in the global mean sea surface temperature (SST) (Roxy *et al.*, 2014). During 1901–2012, while the Indian Ocean warm pool (the central eastern Indian Ocean) went through an increase of 0.78°C, the western Indian Ocean experienced anomalous warming of 1.28°C in summer SSTs.

The western Indian Ocean, which hosts one of the largest concentrations of marine phytoplankton blooms in summer, has also shown an alarming decrease of up to 20% in phytoplankton over the past six decades. This trend is driven by enhanced ocean stratification due to rapid warming in the Indian Ocean, which suppresses nutrient mixing from subsurface layers (Roxy *et al.*, 2016).

Future projections of climate change impacts are based on the most recent simulations performed in the framework of the Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5) project. For the tropical Indian Ocean these simulations show an IOD-like warming pattern in the equatorial Indian Ocean, which includes an enhanced warming in the west, a reduced warming in the east, a weakened Walker cell[4], and shoaling thermocline in the east (Zheng *et al.*, 2013, Figure 2c).

The robustness of projected trends under the "business as usual" scenario (RCP 8.5) was estimated by comparing simulations of 10 different ESMs (Bopp *et al.*, 2013, Figure 3). The comparison shows that the previously mentioned IOD-like warming pattern is robust. Trends of surface pH are also consistent between models, showing a smooth, almost uniform decrease in the Indian Ocean. The projected increase of subsurface dissolved oxygen concentration in the Western Indian Ocean (north of 5°S) and the decrease in the southeastern and central Indian Ocean (from the southern boundary of Indonesia to the eastern boundary of Madagascar) are also robust. The decrease of net primary productivity

[4] Conceptual model of the air circulation in the equatorial region, driven by oceanic temperature and pressure gradients. In the Indian Ocean, air flows eastward from the colder, western area to the warmer, eastern ocean. Higher up in the atmosphere, east-to-west winds complete the circulation.

(NPP) in the western upwelling region of the tropical Indian Ocean is consistently simulated between models.

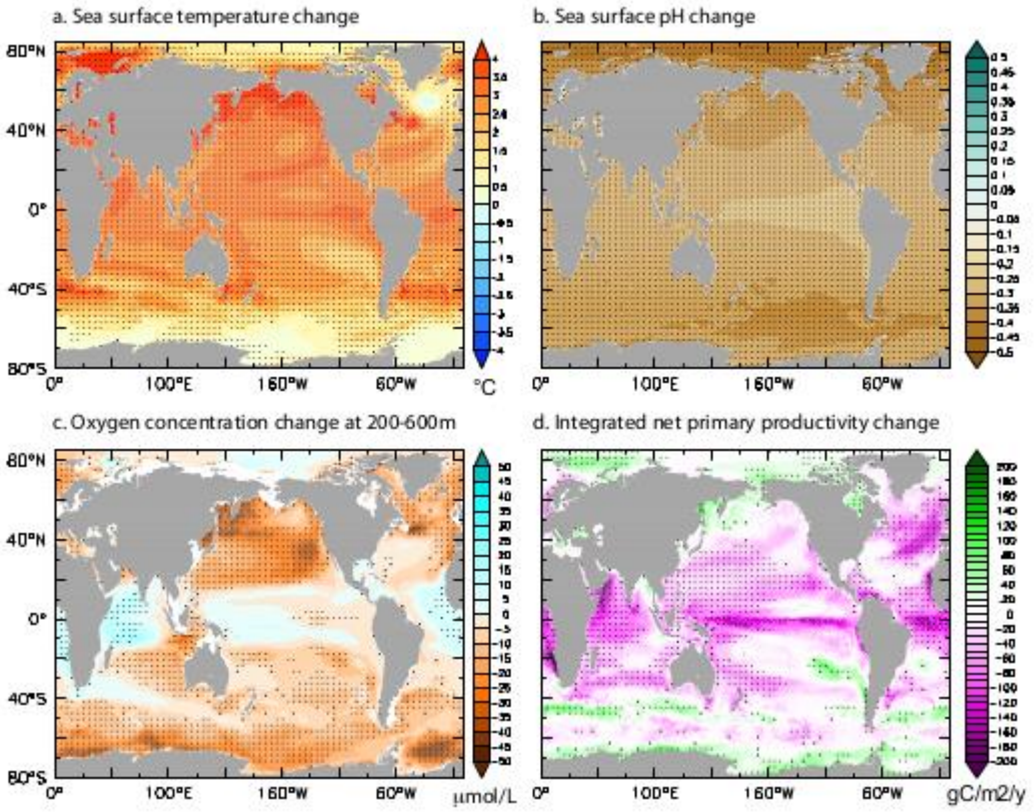


Figure 3: Change in stressor intensity (defined as the change in the magnitude of the considered variable) in 2090–2099 relative to 1990–1999 under RCP8.5

*Multi-model mean of **a)** sea surface warming (°C), **b)** surface pH change (pH unit), **c)** subsurface dissolved O2 concentration change (averaged between 200 and 600 m, mmolm−3), and **d)** vertically integrated NPP (gCm−2 yr−1). Stippling marks high robustness. Robustness is estimated from inter-model standard deviation for SST and pH, from agreement on sign of changes for O2 and NPP. (Figure from Bopp et al., 2013)*

3. Impact of climate change on Indian Ocean tunas

Tunas are strongly influenced by environmental conditions. Each species has a suitable habitat, mainly determined by temperature and oxygen concentration. If water temperature exceeds species-specific thermal tolerance (too warm or cold), or if oxygen concentration is insufficient for physiological needs, tunas will move to different latitudes, longitudes and depths. Coastal upwelling or mesoscale eddies are also important for spatial distribution, because they increase prey availability and influence the feeding habitat of tunas.

These environmental conditions (temperature, dissolved oxygen and prey availability) respond to climate oscillation. During IOD events, changes in primary productivity propagate in the food web through zooplankton, prey of tuna larvae and juveniles, and micronekton, prey of adult tuna, and finally impact the spatial distribution and the abundance of tuna. Tuna catchability is also influenced by climate oscillations. For some tunas, ENSO- or IOD-driven changes in the depth of the thermocline may alter the bathymetric distribution of tuna and impact the vulnerability to surface or subsurface fishing gears.

Climate change will deeply alter the physical and biogeochemical properties of oceans, with important consequences for thermal and feeding habitat of tuna. This will impact the spatial distribution and the abundance of tunas.

Ocean acidification may also affect tunas, although the effects at ecosystem level are difficult to forecast. Negative effects on tuna larvae survival have been observed in laboratory studies (Bromhead *et al.*, 2015; Frommel *et al.*, 2016). Moreover, decreasing pH is expected to reduce sound absorption creating a noisier environment, which might affect the ability to detect prey and predators (Ilyina *et al.*, 2010). In addition, ocean acidification may alter the abundance of some species of calcifying phytoplankton and zooplankton within the lower trophic levels of tuna food webs (Ganachaud *et al.*, 2011). However, these impacts have not yet been included in ecosystem models, and the potential consequences on the recruitment and abundance of tuna are currently unknown.

To determine the response of tunas to climate changes, we first characterize their physiology, phenology and the current spatial distribution (section 3.1). We then review the effect of climate change on habitat and spatial distribution (section 3.2) and on spawning and abundance (section 3.3). Projections will be based on model simulations that represent how tunas respond to changes in temperature, oxygen, currents etc. There are presently only two models that simulate future spatial distribution and abundance of tuna, using the output of ESM as forcing: APECOSM-E (Dueri *et al.*, 2012) and SEAPODYM (Lehodey *et al.*, 2008). However, simulations are not yet available for Indian Ocean stocks of bigeye, albacore and longtail tuna. For these species we propose a preliminary qualitative assessment based on the response of tunas to climate cycles, the forecasted physical and chemical impacts in oceanic/coastal environment, and (if available) the projected trends in other oceans.

3.1 Tuna physiology and current spatial distribution in the Indian Ocean

Tunas are highly specialized fishes with unique physiology and high energy requirements (Olson *et al.*, 2016). Albacore, yellowfin, and skipjack tunas have very high standard metabolic rates, 2–10 times greater than those of other active teleosts (Korsmeyer and Dewar, 2001). Tunas distinguish from other fishes by thunniform swimming, regional endothermy, an elevated metabolic rate, and a particular cardiac physiology. These characteristics support continuous, relatively fast swimming and minimize thermal barriers, allowing them to expand habitat towards high latitudes and ocean depths (Graham and Dickson, 2004).

Tunas are opportunistic predators. In the western Indian Ocean, they feed on fishes, crustaceans, and mollusks (almost exclusively cephalopods). The taxonomic compositions in their diet varies with the species, season, bathymetry, and distance from the coast (Olson *et al.*, 2016). Tuna can dive to great depths to forage on the vertically migrating deep scattering layer (DSL), the diurnally migrating micronekton assemblage of fishes, crustaceans, cephalopods and other organisms. Spawning mostly occurs in warm waters: the temperate tuna migrate and spawn seasonally, whereas the tropical tunas spawn throughout the year.

3.1.1 Skipjack tuna

Skipjack tuna is a relatively small (<80 cm fork length, FL) highly migratory species, which generally inhabits the surface waters of the tropical and subtropical oceans. They range over the tropical Indian Ocean (10°N–10°S), with high biomass around the Maldives Islands and the northern Mozambique Channel (up to 15°S) (Olson *et al.*, 2016; IOTC-WPTT17, 2015). Temperature and oxygen preferences change as a function of size (Figure 4). Skipjack up to 4 kg do not enter waters cooler than 18°C or having less than 3.5 ml O_2 l^{-1}. Larger skipjack (4–9 kg) have higher total O_2 demand and are therefore more spatially confined. They require water cooler than 26°C, while >9 kg skipjack remain below 22°C (Graham and Dickson, 2004; Barkley *et al.*, 1978). Overall temperature tolerances for adults skipjack are reported to be between 14.7°C and 33°C (Boyce *et al.*, 2008).

Skipjack reach maturity at a size of 41-43 cm (< 2 years) and have a high fecundity. They spawn opportunistically throughout the year in the whole inter-equatorial Indian Ocean (north of 20°S, with surface temperature greater than 24°C) (Grande *et al.*, 2014). Skipjack are considered highly resilient to exploitation given their fast growth and their high spawning potential.

Archival tags showed that skipjack tuna (not associated with floating objects) can spend an important amount of time (almost 40%) below the thermocline during the day, displaying repetitive bounce-diving behavior to depths between 50 and 300 m. Conversely, during the night skipjack spend most of time above the thermocline (Schaefer and Fuller, 2007).

3.1.2 Yellowfin tuna

Yellowfin tuna is a larger (usually up to 150 cm FL, but can reach 240 cm FL) highly migratory species, which inhabits the epi- and mesopelagic zones of global tropical and subtropical waters. They are fished in the tropical Indian Ocean (10°N to 10°S), the Arabian Sea, and the Mozambique Channel, expanding southwards along the African coast (Olson *et al.*, 2016; Mohri and Nishida, 2000; IOTC-WPTT17, 2015). Young yellowfin tunas are found between 10°N and 10°S, and large individuals are distributed from the Mozambique Channel to the Cape of Good Hope (Olson *et al.*, 2016). Oxygen concentration < 3.5 ml l^{-1} are limiting to yellowfin tuna (Brill, 1994). Their preferred temperatures lay between 20°C and 26°C while overall temperature tolerances are reported to be between 7°C and 31°C (Boyce *et al.*, 2008).

Yellowfin reach maturity at a size of about 100 cm (3-5 years) and spawning occurs mainly from December to March in the equatorial area (0-10°S), with the main spawning grounds west of 75°E. Secondary spawning grounds exist off Sri Lanka, in the Mozambique Channel and in the eastern Indian Ocean off Australia (Zudaire *et al.*, 2012).

Yellowfin tuna spend most of time above the thermocline (0-50 m) during the night, while during the day they can repeatedly dive below the thermocline (100-300 m) to forage in the DSL (Schaefer *et al.*, 2014). Deep diving behavior (>1,000 m) has also been observed (Dagorn *et al.*, 2006; Schaefer *et al.*, 2014).

3.1.3 Bigeye tuna

Bigeye tuna is a large (maximum size 200 cm FL) highly migratory species, which inhabits the tropical and subtropical waters down to a depth of 300 m. They are fished in the tropical waters of the Indian Ocean (10°N to 15°S) and in the Mozambique Channel (IOTC-WPTT17, 2015; Lee *et al.*, 2005). A southern concentration extends from 23°S to 35°S (Olson *et al.*, 2016). Compared to skipjack and yellowfin, bigeye tuna has a greater tolerance to low levels of oxygen. They tolerate oxygen concentrations as low as 1 ml/l, but they prefer ambient O_2 content > 2 ml/l (Musyl *et al.*, 2003). Their preferred temperature range is between 17°C and 23°C while overall temperature tolerances are reported to be between 3°C and 29°C (Boyce *et al.*, 2008). Based on longline catches in the western Indian Ocean (0°S and 10°N) optimum capture depth, water temperature, and dissolved oxygen range of bigeye tuna were identified as 240 m to 280 m, 12°C to 14°C, and 2 to 3 mg $O_2 \cdot l^{-1}$ (Song *et al.* 2009).

Bigeye tuna reach maturity at a size of about 100 cm FL (3 years) and spawning occurs from December to January and also in June in the eastern Indian Ocean (Nootmorn, 2004).

A study on the vertical behavior of bigeye tuna in the eastern equatorial Pacific Ocean showed that, when unassociated to floating objects, they spend most of their time at depths of less than 50 m (within the mixed layer) throughout the night. During the day, they stay between 200 and 300 m and 13° and 14°C (Schaefer and Fuller, 2002). Occasionally a deep-diving behavior was observed (>1,000 m).

3.1.4 Albacore tuna

Albacore is a medium size (maximum size in the Indian Ocean 128 cm FL), highly migratory, temperate tuna living mainly in the epi and mesopelagic layer of the southern gyre of the Indian Ocean. The biology of the albacore stock in the Indian Ocean is not well known compared to the Atlantic and Pacific oceans (Nikolic *et al.*, 2016). Albacore tuna are found between 5°N and 40°S (Nishida and Tanaka, 2008; Chen *et al.*, 2005; Lan *et al.*, 2012). The main fishing ground is located at intermediate latitudes, between 10°S and 40°S. It is likely that the adult albacore tunas do yearly circular counter-clockwise migrations following the surface currents of the south tropical gyre between their tropical spawning and southern feeding zones (Fonteneau, 2004). Albacore has a low tolerance to hypoxic waters. Their high metabolic rates necessitate oxygen concentrations > 3.7 $mL \cdot l^{-1}$ (Graham *et al.*, 1989). Their preferred temperatures lay between 15°C and 19.5°C while overall temperature tolerances are reported to be between minimum 7°C and maximum 25°C (Boyce *et al.*, 2008).

Little is known of the reproductive biology of albacore in the Indian Ocean, apart from the relatively late maturity (5-6 years). Like other tunas, adult albacore spawn in warm waters (SST > 25°C) (Fonteneau, 2004). Spawning was found to occur east of Madagascar between 10°S and 30°S, from October to January (Dhurmeea *et al.*, 2016).

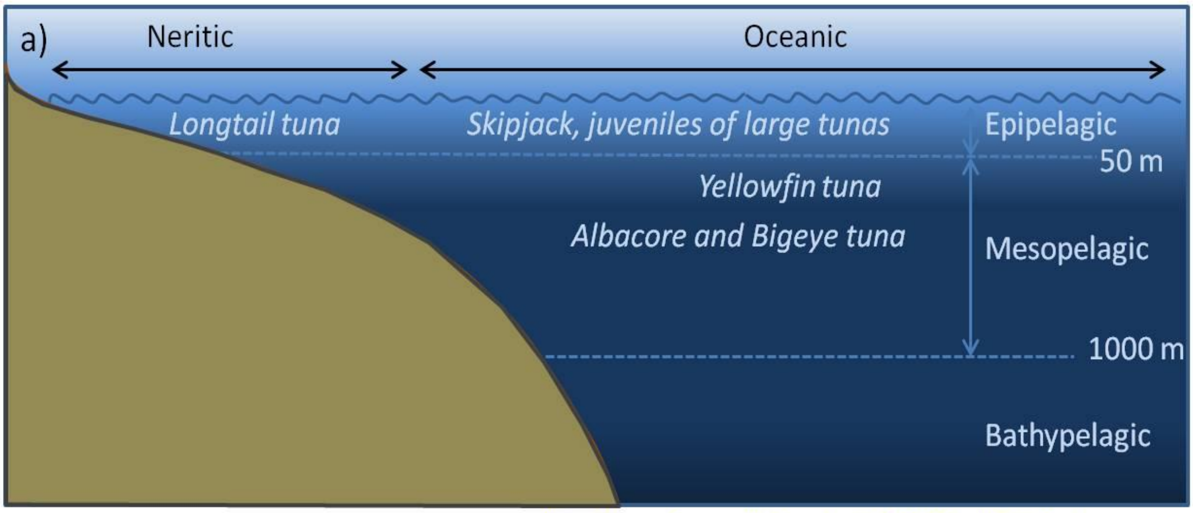
Studies carried out on albacore tuna in the North and South Pacific Ocean show a change in vertical behavior between tropical and temperate latitudes (Williams *et al.*, 2014; Childers *et al.*, 2011). At tropical latitudes, albacore tuna stay in shallower, warmer waters at night, and dive into deeper, cooler waters during the day. In contrast, vertical distribution seems to be limited to shallow waters at temperate latitudes.

3.1.5 Longtail tuna

Longtail tuna is an epipelagic species, mainly inhabiting tropical and temperate coastal areas throughout the Indo-West Pacific region between 47° N and 33° S (Froese and Pauly, 2016). It avoids estuaries, turbid waters and open ocean. Longtail tuna can reach a maximum size of 145 cm FL, but size of longtail tuna caught in the Indian Ocean can vary from 20-45 cm (Adaman Sea) to 50-100 cm (Arabian Sea). Length-frequency data reported in different areas indicate that fish size increases with increasing latitude, suggesting a southward ontogenetic migration from a more northern nursery ground, such as Thailand and Malaysia, towards Australia (Griffiths *et al.* 2010a). Longtail tuna is found in a range of water temperatures between 16°C and 30°C (Itoh *et al.*, 1996), but the optimal water temperature range has been suggested to be 24–25.6°C (Mohri *et al.*, 2005; Mohri *et al.*, 2008).

There is uncertainty about the spawning location of longtail tuna. Based on the capture of mature females and the presence of larvae, possible spawning grounds have been proposed in the Gulf of Thailand (Yesaki, 1982), the western Sea of Japan and the East China Sea (Itoh *et al.*, 1999). The spawning season varies according to location.

Longtail tuna may be vulnerable to overexploitation by fisheries, given the slow growth rates (Griffiths *et al.* 2010b) and the coastal distribution (Collette *et al.* 2011).



(Adapted from: http://www.fao.org/fishery/topic/16082/en#Distribution)

b)

Species	Temperature tolerance	Source	Minimum dissolved oxygen concentration	Source
Skipjack tuna	14.7°C - 33°C	Boyce et al. 2008	$3.5 \cdot ml \cdot O_2 \cdot l^{-1}$	Graham and Dickson 2004
Yellowfin tuna	7°C - 31°C	Boyce et al. 2008	$3.5 \cdot ml \cdot O_2 \cdot l^{-1}$	Brill 1994
Bigeye tuna	3°C - 29°C	Boyce et al. 2008	$2\ ml \cdot O_2 \cdot l^{-1}$	Musyl et al. 2003
Albacore tuna	7°C - 25°C	Boyce et al. 2008	$3.7\ ml \cdot O_2 \cdot l^{-1}$	Graham et al. 1989
Longtail tuna	16°C - 30°C	Itoh et al. 1996	unknown	

Figure 4: a) Distribution of tunas; b) Temperature tolerance and minimum oxygen concentration of different tuna species

3.2 Impact of climate change on habitat and spatial distribution of tuna

In response to climate change, highly migratory species, such as oceanic tunas, are expected to follow preferred species- and size-specific habitat conditions (mainly determined by temperature and oxygen). As a result, tuna may alter the spatial distributions in latitude and longitude, and modify the vertical distribution. In the south eastern Indian Ocean, the thermal habitat of several tuna species (skipjack, yellowfin, bigeye and albacore) is projected to move southwards in the course of this century, with consequences on spatial distribution (Hobday, 2010).

3.2.1 Skipjack tuna

The spatial distribution of skipjack tuna is strongly influenced by ENSO or IOD events. In the Pacific Ocean, ENSO events were correlated to large zonal displacements of the warm pool, affecting the spatial distribution of skipjack tuna (Lehodey *et al.*, 1997). This pattern was confirmed by numerical simulations (Lehodey *et al.*, 2008). In the Indian Ocean the conjunction of an IOD and a strong ENSO event in 1997–1998 lead to important environmental anomalies with significant consequences on fishing activities (Marsac and Le Blanc, 1998; Ménard *et al.*, 2007). The abnormal easterly wind stress along the equator caused the reversal of the E–W thermocline slope and an increase (decrease) of primary productivity in the East (West). The catchability of skipjack tuna for purse seine gears increased in the East, due to the shallower thermocline and the higher surface biological productivity. Conversely, catchability decreased in the West, with the deepening of the thermocline and the reduction in surface schools available to the fishery. This led to massive and very unusual movement of the fishing fleets from the usual fishing grounds in the Western Indian Ocean to the eastern equatorial area. Numerical simulation of this exceptional event confirmed this pattern and highlighted the importance of the thermocline depth for the catchability to surface fishing gears (Dueri *et al.*, 2012).

Climate change projections with the RCP8.5 scenario show important changes in skipjack tuna habitat suitability (Dueri *et al.*, 2014). Simulations project a decline of habitat suitability in the equatorial waters of the Indian Ocean between 2010 and 2050, that progressively intensifies from 2050 to 2095. Along the Somali coast, the model simulates a slight increase of habitat suitability in the first half of the 21st century, followed by a decrease after 2050. At latitudes higher than 10°N or 10°S, simulations project an increase in habitat suitability in the first half of the century, followed by a decrease in the northern part of the Indian Ocean. The degradation of habitat conditions in equatorial surface water of the eastern and central Indian Ocean is mainly driven by warming, while in the Western Indian Ocean it is due to a decrease in food availability (Dueri *et al.*, 2014). The spatial distribution of skipjack tuna biomass follows the trend of habitat suitability. In the first half of the century, biomass is projected to decrease in equatorial surface waters and increase in deeper equatorial waters and in surface waters around 10°N and 10°S. The model projects an increase of biomass along the coasts of the northern Indian Ocean, east of Madagascar and along the South African coast (Dueri *et al.*, 2014).

3.2.2 Yellowfin tuna

Skipjack tuna is not the only species responding to climatic oscillations. The vulnerability of yellowfin tuna to different fishing gears is also strongly influenced by IOD and ENSO events. During the 1997-1998 ENSO/IOD event, the catchability of yellowfin tuna increased for purse seine gears in the eastern Indian Ocean (Ménard *et al.*, 2007; Marsac and Leblanc, 1998). On the other hand, positive IOD events have been correlated to a decrease in catch per unit effort (CPUE) for the longline fisheries and a limitation of the catch area to the northern and western margins of the western Indian Ocean (Lan *et al.*, 2013).

Climate change projections with the RCP8.5 scenario show that yellowfin tuna reaches the upper limit of its current favorable spawning temperature range in many places (except in the Oman Sea) (Senina *et al.*, 2015). Moreover, the decrease in primary production has negative consequences on the feeding habitat.

3.2.3 Bigeye tuna

The impact of climate variability on bigeye tuna distribution in the Indian Ocean is not well documented. Catchability of bigeye tuna to longline fisheries in the Indian Ocean was found to increase during positive IOD events with low Indian Ocean Index value (1972–73, 1977–78, and 1982–83) (Ménard *et al.*, 2007). It was suggested that the decrease in the biological production occurring during positive IOD, decreases prey abundance and patchiness. The resulting scarcity of prey may increase the likelihood that bigeye tuna bites the longline baits (Ménard *et al.*, 2007).

Bigeye tuna has lower temperature preferences, higher tolerance to low oxygen levels and explore deeper vertical layers. Projections of the impact of climate change on the habitat of Indian Ocean bigeye tuna are missing. However, projections for the 21st century were carried out with a "business as usual" scenario in the Pacific Ocean (Lehodey *et al.*, 2010). Simulations showed an enhanced feeding habitat in the eastern tropical Pacific due to the increase of dissolved oxygen concentration in the sub-surface, allowing adults to access deeper forage. Conversely, in the Western Central Pacific, habitat suitability decreases (too warm surface temperatures, decreasing oxygen concentration in the sub-surface and less food) (Lehodey *et al.*, 2010). In the Indian Ocean, warming may force bigeye tuna to move to deeper water and/or higher latitudes. The projected increase in subsurface oxygen in the western Indian Ocean (north of 5°S) may facilitate the expansion of habitat to deeper layer. On the other hand, decreased primary production may negatively affect feeding habitat.

3.2.4 Albacore tuna

The spatial distribution of albacore tuna is strongly influenced by environmental conditions such as ocean temperature, dissolved oxygen, currents and prey concentration. Inter-annual climate variability has an impact on albacore tuna distribution and catch, but the pattern is complex (Nikolic *et al.*, 2016).

Simulations of the impact of climate change on the habitat of Indian Ocean albacore tuna are missing, but projections for the 21st century were carried out with a "business as usual" scenario for the South Pacific albacore tuna (Lehodey *et al.*, 2015). At the end of the 21st century, simulations show a reduced tuna density in the equatorial region, and a southward shift by roughly 5° latitude of the northern boundary of the adult stock. Moreover, dissolved oxygen concentrations play an important role in limiting the spatial distribution of albacore tuna. However, projections of dissolved oxygen concentration in the tropical and sub-tropical Southern Pacific Ocean are not robust (Bopp *et al.*, 2013). This introduces uncertainty in the projected trends.

In the Indian Ocean, projections show an important and robust decrease of dissolved oxygen concentration in areas and depth where catches of albacore are currently reported, i.e. between the East coast of Madagascar and the West coast of Australia. Given the high oxygen requirements of albacore tuna, it seems likely that future distribution of albacore tuna will be limited by oxygen availability, but the consequences are difficult to assess without simulations.

3.2.5 Longtail tuna

Longtail tuna has a coastal distribution and is found in water temperatures between 16°C and 30°C. To our knowledge, there are no studies reporting changes of longtail tuna spatial distribution due to climate variability, nor projections regarding the impact of climate change on this species. Estimated changes in primary production and temperature in the EEZ of the eastern Indian Ocean under a A1B scenario (close to RCP 6, therefore lower greenhouse gas emission than RCP 8.5) show for 2050 an increase of 1-2°C in the mixed layer temperature, from the eastern India coast to the northern Australian coast. The projections also estimate a decrease of primary production in the Indonesian Sea and around Sri Lanka and an increased productivity along the western coast of Indonesia (Barange *et al.* 2014). Projections do not cover the Arabian Sea.

Based on these simulations, it seems likely that, for a "business as usual" scenario, temperature increase in tropical coastal areas of the eastern Indian Ocean could exceed 2°C by the end of the 21st century. Consequences on longtail tuna habitat are difficult to assess and depend on the possible adaptation to the new conditions.

3.3 Impact on spawning and abundance

Tunas abundance mainly depends on spawning efficiency, availability of suitable habitat, prey accessibility and fishing mortality. The size and quality of spawning areas and the survival rate of larvae are strongly influenced by climate (Lehodey *et al.*, 2003). In response to climate change, spawning season may shift or be reduced and new spawning sites may emerge. In addition, survival rates of larvae may be affected by changes in temperature and biological productivity (Gilman *et al.*, 2016). Ocean acidification may also impact larvae survival by modifying otolith formation, important for orientation and hearing during the larval stage (Lehodey *et al.*, 2011; Bignami *et al.*, 2013). Moreover, decreasing pH has been found to decrease the growth and survival rates of yellowfin larvae (Bromhead *et al.*, 2015; Frommel *et al.*, 2016).

3.3.1 Skipjack tuna

Climate change projections with a "business as usual" RCP 8.5 scenario in the Indian Ocean show an increase of global skipjack biomass between 2010 and 2050 followed by a marked decrease between 2050 and 2095 (Dueri *et al.*, 2014). The projected change occurs in two phases. Between 2010 and 2050, there is a temperature driven displacement of biomass toward higher latitudes. The second half of the century is characterized by a strong negative anomaly, with a significant decrease of the skipjack biomass in the whole tropical and subtropical region.

The model also projects changes in spawning rates that are very similar to the trend of biomass abundance of mature tuna. This is consistent with opportunistic spawning.

3.3.2 Yellowfin tuna

Projections of the impact of climate change in the Indian Ocean with a RCP8.5 scenario show a long term decrease in yellowfin tuna biomass after the mid-21st century, with a reduction of 50% on average (Senina *et al.*, 2015). The decline is mainly driven by warming and its negative impact on yellowfin tuna spawning. Also the decrease in primary productivity contributes to the total biomass decline.

3.3.3 Bigeye tuna

There are currently no projections of the impact of climate change on bigeye tuna abundance in the Indian Ocean. Yet, projections exist for the Pacific Ocean with a RCP8.5 scenario and neglecting the effect of fishing effort (Lehodey *et al.*, 2010). These simulations show an improvement of bigeye tuna spawning habitat both in subtropical latitudes and in the eastern tropical Pacific, where the surface temperature becomes optimal for spawning. Conversely, in the Western Central Pacific water becomes too warm for spawning, but there is still a slow increase of the total biomass of larvae due to the increasing contribution of subtropical areas. Adult biomass increases in the eastern tropical Pacific, while in the western tropical Pacific it remains stable then declines at the end of the century. This decline follows the degradation of habitat conditions, due to excessive warming, decreasing oxygen concentration in the sub-surface and reduced prey availability (Lehodey *et al.*, 2010).

The change in abundance of bigeye tuna in the Indian Ocean is difficult to assess. It is unclear how spawning areas may respond to the combined effect of warming and changes in dissolved oxygen concentrations. Lower food availability may possibly cause a decline in abundance.

3.3.4 Albacore tuna

Like bigeye, projections of climate change impacts on albacore tuna in the Indian Ocean are missing, but simulations have been carried out in the Pacific Ocean with a "business as usual" scenario and an average fishing effort based on recent years (Lehodey *et al.*, 2015). Projections show first a decrease of biomass, then a stabilization after 2035. After 2080, the trend is reversed due to the emergence of a new spawning ground in the north Tasman Sea. Interestingly, introducing adaptation, with genetic selection favoring albacore with preferences for higher ambient spawning temperature, has a negative effect on biomass abundance. This scenario maintains a reduced level of spawning in current tropical spawning areas, suppresses the emergence of new spawning area in the north Tasman Sea and keeps stock abundance at low levels.

Unfortunately, given the uncertainties characterizing Indian Ocean albacore tuna biology and ecology (Nikolic *et al.*, 2016), we are unable to make any qualitative assessment regarding future changes in abundance.

3.3.5 Longtail tuna

Projections of climate change impacts on longtail tuna spawning and abundance are missing. The expected changes in temperature and primary productivity (discussed in section 3.2.5), may affect abundance in equatorial areas where longtail tuna is currently present, but consequences are unknown.

Species	Habitat Change	Biomass change	Source
Skipjack tuna	2010-2050 ➢Decrease of habitat suitability in equatorial waters ➢ Increase of habitat suitability along Somali coast and at latitudes >10°S and >10°N 2050-2095 ➢ Strong decrease in equatorial waters ➢ Decrease along Somali coast and in the northern Indian Ocean	2010-2050 ➢ Biomass increase ➢ Displacement towards higher latitudes 2050-2095 ➢ Strong decrease in biomass	Projections using RCP 8.5 scenario (Dueri et al., 2014)
Yellowfin tuna	➢ Upper limit of current favorable spawning temperature range is exceeded ➢ Decrease in food availability ➢ Decrease in habitat suitability	➢Long term biomass decrease after the mid-21st century	Projections using RCP 8.5 scenario (Senina et al., 2015)
Bigeye tuna	➢ Habitat may shift to deeper water and/or higher latitudes (if oxygen is not limiting) ➢ Decrease in food availability	Unknown	Author's evaluation
Albacore tuna	➢Dissolved oxygen concentration decreases in areas and depth where catches of albacore are currently reported ➢Habitat may be limited by oxygen availability	Unknown	Author's evaluation
Longtail tuna	Unknown	Unknown	

Table 1: Summary of projected habitat and biomass changes for skipjack, yellowfin, bigeye, albacore and longtail tuna

3.4 Uncertainties and research gaps

Four main sources of uncertainty affect future projections of the distribution and abundance of tuna. The first is related to the modelling of the global climate system and the coarse resolution of physical models (Dueri *et al.*, 2014). Although the representation of the physical and biogeochemical processes has been considerably improved in the last generation of ESM, the simulation of regional-scale phenomenon is still difficult. Tuna models use the output of ESM as forcing for the environmental conditions, but in some regions these outputs have well-known biases (Dufresne *et al.*, 2013) that affect the biological simulation. Moreover, the horizontal resolution is currently too coarse to represent the effects of mesoscale and sub-mesoscale structures such as fronts and eddies. These features have important effects on the spatial distribution of oceanic tunas (Tew Kai and Marsac 2010; Godo *et al.*, 2012), but their influence is neglected.

Gaps in knowledge on the physiology, biology and ecology of tuna species are the second source of uncertainties (Lehodey *et al.*, 2011). General aspects of tunas lifecycle (growth, migration, spawning) as well as tunas response to climate variability are generally less well documented for the Indian Ocean, than for the Atlantic or Pacific Ocean.

The third source of uncertainties is related to the modelling of the food webs in the tropical ocean (Lehodey *et al.*, 2011). There is uncertainty regarding the response of tunas' prey to climate change impacts on the oceanic environment. Prey species may be less resilient than tuna to changes in dissolved O_2 concentrations, warming or acidification (Le Borgne *et al.*, 2011). Moreover, tuna models currently used for projections are not fully coupled with ESM: ESM supply the environmental forcing for tuna models, but the impact of tuna feeding on the lower trophic levels is neglected (Dueri *et al.*, 2014).

Fourth, the selection of phenotypes tolerant to higher ocean temperatures could occur for some tunas, with important consequences on the outcome of projections (Gilman *et al.*, 2016; Lehodey *et al.*, 2015). However, these aspects are rarely taken into account in ecosystem models.

4. Impact on Indian Ocean tuna fisheries and national economies

4.1 Indian Ocean tuna fisheries and markets: current situation

In the Indian Ocean, tropical and temperate tunas are caught by both coastal countries and distant water fishing nations (DWFN). In recent years (2010-2015), around 54% of total catches of tropical tuna species (skipjack, yellowfin and bigeye tuna) have been reported by the coastal fisheries of five countries (Indonesia, Maldives, Sri Lanka, I.R. Iran, and India), while the industrial purse seiners and longliners flagged as EU-Spain, Seychelles and EU-France reported a further 29% of total catches (IOTC–WPTT17, 2015). Albacore tuna is mainly caught by Taiwan, China and Indonesia, which account for 77% of total catch, followed by Japan (8%). As for longtail tuna, it supports important artisanal and subsistence fisheries in several coastal countries (Abdussamad *et al.*, 2012) and nearly half of catches are accounted for by I.R. Iran (45%), followed by Indonesia (16%), Pakistan (9%) and Malaysia (7%).

The 2010-2015 mean catch of skipjack tuna was estimated close to 400,000 tons, followed by yellowfin with around 375,000 tons (IOTC–WPTT17, 2015). Bigeye tuna catch was reported close to 99,000 tons and albacore recorded slightly more than 36,000 tons (IOTC–WPTT17, 2015; IOTC-WPmT06, 2016). Mean catch of longtail tuna was estimated close to 154,000 tons (IOTC Secretariat, 2016). In 2015, IOTC stocks assessment of skipjack, bigeye and albacore tuna classified these species as not overfished and not subject to overfishing; longtail tuna was assessed as not overfished but subject to overfishing and yellowfin tuna was flagged as overfished and subject to overfishing.

The majority of catches of tropical and temperate tunas are sold to international markets. Large specimens of yellowfin and bigeye tuna are sold to the sashimi market in Japan, while skipjack, albacore and to a lesser extent yellowfin and bigeye tuna are processed in canneries in the Indian Ocean region or abroad. A part of skipjack and albacore tuna catches and the majority of longtail tuna catches, fished by coastal countries in the region, is sold in local markets or retained by the fishermen for direct consumption (IOTC–WPTT17, 2015; IOTC-WPmT06, 2016).

4.2 Impact of climate change of tuna fisheries and national economies

Tuna fisheries are a source of income for several coastal countries and islands in the Indian Ocean. Landings from artisanal and commercial tuna fisheries are sold on local and international markets, generating revenues for fishermen. Coastal countries may also benefit from the sale of tuna fishing rights to DWFN, from expenditures of distant water fleets in ports and from the local employment provided by tuna processing plants.

Climate variability is known to have a significant impact on annual tuna landings in the Indian Ocean (Kumar *et al.*, 2014) by modifying the spatial distribution of fish and the catchability to different fishing gears. During the strong ENSO and IOD event of 1997-1998, tuna purse seiners activity shifted from the western to the eastern basin and vessels operated from Asian ports. This caused a 40% economic loss of tuna industry expenditures for Seychelles (Robinson *et al.*, 2010).

Climate change is expected to relocate fishing grounds, and redistribute benefits of tuna fisheries between coastal countries (Sumaila *et al.*, 2011) with important positive or negative consequences on fisheries-dependent developing nations (Barange *et al.* 2014). Furthermore, climate change is likely to impact price and value of catches, fishing costs, fishers' incomes and earnings to fishing companies (Sumaila *et al.*, 2011). In the southern Indian Ocean, fishing grounds and CPUE are projected to change (Michael *et al.*, submitted). Simulation with a coupled economic-biologic model indicate that the Western Indian Ocean may show the most important climate driven decrease in tuna global catch. The reduced harvest is a consequence of the predicted decrease in primary production and its negative impact on higher tropic levels (Mullon *et al.*, 2016).

Impacts of ocean acidification on tuna fisheries are difficult to quantify, because our knowledge of involved processes and potential synergic interactions (e.g. between pH and temperature changes) is currently very limited. Studies of the effects of ocean acidification on fisheries in general are very scarce, and virtually non-existent for the Indian Ocean (Sumaila *et al.*, 2015; Hilmi *et al.*, 2013).

To assess the vulnerability of Indian Ocean national economies to climate change we have to consider: 1) the exposure to climate change impacts, 2) the sensitivity or the relative importance of tuna fisheries in the national economy and diet, and 3) the capacity to adapt to these changes (Allison *et al.*, 2009). Countries for which tuna fisheries represent an important source of revenue need to anticipate possible future changes in order to adapt (Vivekanandan and Jeyabaskaran 2010). Least developed coastal countries in tropical regions are particularly vulnerable to climate change because of their fewer available resources to invest in climate adaptation (Barange *et al.* 2014).

The projected global declines of biomass and/or catchability at low latitudes may highly impact fisheries-dependent small island economies, located in tropical regions. These islands benefit from the sale of fishing access rights to DWFNs and some of them have tuna processing plants that provide much needed employment in these relatively undiversified economies (Guillotreau *et al.*, 2012).

In the Pacific Ocean, modeling indicates an eastward shift of skipjack and bigeye tuna biomass concentrations (Lehodey *et al.*, 2010; Lehodey *et al.*, 2012; Dueri *et al.*, 2016). This may affect the revenues earned by Pacific Island Countries and Territories (PICTs) from the sale of fishing rights for tuna to DWFNs. These revenues represent an important contribution to gross domestic product (GDP) in some of the smaller PICTs in the central Pacific, with currently few other options for generating national income (Bell *et al.*, 2013).

In the Indian Ocean, simulations with a "business as usual" scenario project in the first half of the 21st century a shift of skipjack tuna biomass from the surface of equatorial waters, which progressively become too warm, to higher latitudes (Figure 5, Dueri *et al.*, 2014). Fishery dependent small islands economies located close to the Equator, such as Seychelles and Maldives, might be the first to suffer from the biomass shift. These islands have already been classified as highly vulnerable to the impact of climate change on their fisheries (Allison *et al.*, 2009). Seychelles has come to rely heavily on the tuna industry. In terms of employment, approximately 10% of the Seychelles' population is dependent on direct, indirect and induced employment (Robinson *et al.*, 2010). Maldives has the second-highest proportion of fishers within the economically active population globally (18%), and the greatest nutritional dependence on fisheries, with 84% of animal protein derived from fish (Allison *et al.*, 2009).

Some countries may benefit from the shift of skipjack tuna, such as Madagascar and Mauritius. Both of them already earn from concessions to EU tuna vessels and have each a tuna processing plant. Madagascar has a tuna industry complex (including cannery) located in Antsiranana which has a capacity of 40,000 t of tuna per year and used to employ 1,700 people. However, in 2010 the cannery processed only half of its capacity, and employment likely decreased to 850 (Goulding, 2016). Mauritius fisheries have limited contribution to GDP and employment (Boistol *et al.*, 2011). However, canning industry, located in Port Louis, is the largest of the Western Indian Ocean: it processes annually over 100,000 t of tuna, the majority of which are transhipped or imported (Goulding, 2016).

Other countries may be impacted by the shift of skipjack tuna biomass projected in the first half of the century, e.g. Indonesia, one of the largest tuna producing countries on the globe for which tuna has recently become an important export good (Sunoko and Huang, 2014). The decrease of skipjack biomass projected after 2050 may have a negative impact on the Indonesian economy, which has been classified as highly dependent on fisheries and with a low adaptive capacity (Allison *et al.*, 2009). Given the ocean-wide nature of the projected skipjack biomass decrease, negative impacts are likely for all countries fishing or processing skipjack tuna in the Indian Ocean.

Projections of yellowfin tuna biomass change (2005-2050) in the western Indian Ocean are even more pessimistic and estimate a decrease between -20% to -40% in the EEZ of tropical coastal countries (from Oman to Mozambique and Madagascar) (Bell *et al.*, 2016).

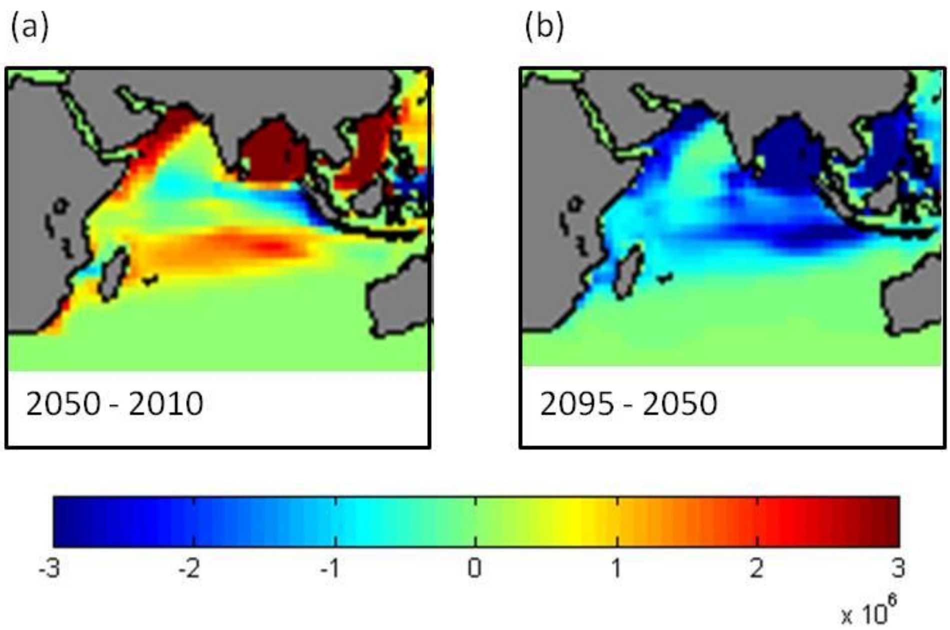


Figure 5: Mean biomass change in kg in surface water for adult skipjack for (a) 2050 relative to 2010 and (b) 2095 relative to 2050 (Projections of APECOSM-E model for RCP8.5 scenario, as reported in Dueri *et al.* 2014)

5. Conclusion

Projections show that climate change may modify the spatial distribution and negatively impact the abundance of commercially important tunas. In the Indian Ocean, under the "business as usual scenario", equatorial surface waters may progressively become too warm for tunas. Feeding and spawning habitat may shift towards higher latitudes and/or deeper water (if not limited by oxygen and light conditions). The consequences on spawning efficiency are difficult to forecast. However, after the mid–21st century, models project a decrease of skipjack and yellowfin tuna abundance.

Fisheries and national economies will have to adapt to climate change impacts. Some coastal countries located at higher latitudes may benefit from the spatial redistribution of tunas. Others, located at lower latitudes, may partly or totally lose the revenues from the sale of fishing rights to DWFNs or from expenditures of tuna vessels in ports. The projected changes in spatial distribution, abundance and catchability of tuna will affect fishing costs. At the same time, the value of landings is likely to change under the influence of the global market, with consequences on fishers' incomes and earnings to fishing companies.

However, the future of tuna fisheries will not only depend on climate change. An increasing demand for tuna, driven by global economic and demographic growth, may raise the price and motivate fishers to increase fishing effort. Effective governance will play a crucial role in the conservation of tunas. Regional Fisheries Management Organizations (RFMOs) should secure the future of tuna fisheries by monitoring the status of stocks and setting catch and fishing effort limits, technical measures, and control obligations.

A coupled economic-ecosystem model was used to evaluate the effect of different management strategies on skipjack tuna biomass and fishery, under a "business as usual" climate change scenario (Dueri *et al.*, 2016). The model shows that, in addition to climate change, technological development (i.e. constantly increasing fishing efficiency) and rising demand for tuna, have an important influence on skipjack biomass, prices and fishery profits trends. Future projections of another coupled economic-biologic model show that an increasing demand of fresh-frozen or canned tuna, driven by increasing world population and consumption, may provoke a global collapse of tuna fisheries in the next few decades, before the climate change driven decrease of tuna stocks (Mullon *et al.*, 2016).

In conclusion, combined effects of climate change, technological developments and socioeconomic changes may lead to a decline of tuna abundance and eventually a global collapse of tuna fisheries. To offset these negative impacts with potentially catastrophic outcome, we need to enforce effective global governance, with strict harvest controls and limitations of technical efficiency.

References

Abdussamad, E.M., Said Koya, K.P., Ghosh, S., Rohit, P., Joshi, K.K., Manojkumar, B., Prakasan, D., Kemparaju, S., Elayath, M.N.K., Dhokia, H.K., Sebastine, M. and Bineesh, K.K. (2012) Fishery, biology and population characteristics of longtail tuna, Thunnus tonggol (Bleeker, 1851) caught along the Indian coast. Indian J. Fish. 59, 7–16.

Allison, E.H., Perry, A.L., Adger, W.N., Badjeck, M.-C., Brown, K., Conway, D., Halls, A., Pilling, G.M., Reynolds, J.D., Dulvy, N.K., (2009). Vulnerability of national economies to the impacts of climate change on fisheries. Fish and Fisheries 10, 173–196.

Barange, M., Merino, G., Blanchard, J.L., Scholtens, J., Harle, J., Allison, E.H., Allen, J.I., Holt, J., Jennings, S. (2014). Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat. Clim. Chang. 4, 211-216.

Barkley, R.A., Neill, W.H., and Gooding, R.M. (1978) Skipjack tuna, Katsuwonus pelamis, 2 habitat based on temperature and oxygen requirements. Fish. Bull. 76, 653-662.

Bell JD, Reid C, Batty MJ *et al.* (2013) Effects of climate change on oceanic fisheries in the tropical Pacific: implications for economic development and food security. Climatic Change, 119, 119–212. doi:10.1007/s10584-012-0606-2.

Bell, J., Cheung, W., De Silva, S., Gasalla, M., Frusher, S. D., Hobday, A. J., Lam, V., Lehodey, P., Pecl, G., Samoilys, M., Senina, I. (2016).Impacts and effects of ocean warming on the contributions of fisheries and aquaculture to food security. Chapter 4.5. In: Laffoley, D. and Baxter, J. M. (editors). 2016. Explaining ocean warming: Causes, scale, effects and consequences. Full report. Gland, Switzerland: IUCN. 456 pp.

Bignami S, Enochs I, Manzello D, Sponaugle S, Cowen R. (2013).Ocean acidification alters the otoliths of a pantropical fish species with implications for sensory function. Proceedings of the National Academy of Sciences of the United States of America 110: 7366-7370.

Boistol, L., Harper, S., Booth, S. and Zeller, D. (2011) Reconstruction of marine fisheries catches for Mauritius and its outer islands, 1950-2008. pp. 39-61. In: Harper, S. and Zeller, D. (eds.) Fisheries catch reconstruction: Islands, Part II. Fisheries Centre Research Reports 19(4). Fisheries Centre, University of British Columbia [ISSN 1198-6727].

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, S.C., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J. Vichi, M. (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosci. Discuss. 10, 3627-3676.

Boyce, D.G., Tittensor D.P., Worm, B. (2008). Effects of temperature on global patterns of tuna and billfish richness. Mar Ecol Prog Ser 355:267–276.

Brill, R. W. (1994). A review of temperature and oxygen tolerance studies of tunas pertinent to fisheries oceanography, movement models and stock assessments. *Fish. Oceanog.* 3, 204-216.

Bromhead, D., Scholey, V., Nicol, S., Margulies, D., Wexler, J., Stein, M., Hoyle, S., Lennert-Cody, C., Williamson, J., Havenhand, J., Ilyina, T., Lehodey, P., (2015). The Potential Impact of Ocean Acidification Upon Eggs and Larvae of Yellowfin Tuna (Thunnus albacares). Deep -Sea Res. II 113, 268–279.

Cai, W., Zheng, X.-T., Weller, E., Collins, M., Cowan, T., Lengaigne, M., Yu, W. and Yamagata, T. (2013). Projected response of the Indian Ocean Dipole to greenhouse warming. Nature Geoscience, 6, 999-1007.

Chen, I.C., Lee, P.F., Tzeng, W.N., (2005). Distribution of albacore (Thunnus alalunga) in the Indian Ocean and its relation to environmental factors. Fisheries Oceanography 14, 71–80.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., Zeller, D., Pauly, D. (2010). Large scale redistribution of maximum fisheries potential in the global ocean under climate change. Glob. Chang. Biol. 16, 24-35.

Childers, J., Snyder, S., Kohin, S. (2011). Migration and behavior of juvenile North Pacific albacore (Thunnus alalunga). Fisheries Oceanography, 20(3), 157-173.

Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao and P. Thornton, (2013). Carbon and Other Biogeochemical Cycles. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Collette, B., Di Natale, A., Fox, W., Juan Jorda, M., Miyabe, N., Nelson, R., Sun, C., Uozumi, Y. (2011). *"Thunnus tonggol"*. IUCN Red List of Threatened Species. Version 2011.1. International Union for Conservation of Nature.

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver and M. Wehner, (2013). Long-term Climate Change: Projections, Commitments and Irreversibility. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Dagorn L, Holland KN, Hallier JP, Taquet M, Moreno G, Sancho G, Itano DG, Aumeeruddy R, Girard C, Million J, Fonteneau A (2006) Deep diving behavior observed in yellowfin tuna (Thunnus albacares). Aquat Living Resour 19:85–88

de Ruijter, W.P.M., Ridderinkhof, H., Lutjeharms, J.R., Schouten, M.W., Veth, C. (2002). Observations of the flow in the Mozambique Channel. Geophysical Research Letters 29(10), 140-1:140-3.

Dhurmeea, Z. , Zudaire, Z., Chassot, E., Cedras, M., Nikolic, N., Bourjea, J., West, W., Chandan Appadoo, C., Bodin, N. (2016). Reproductive biology of albacore tuna (Thunnus alalunga) in the Western Indian Ocean. IOTC Working Party on Temperate Tunas, IOTC-2016-WPTmT06-27.

Dueri, S., Faugeras, B., Maury, O. (2012). Modelling the skipjack tuna dynamics in the Indian Ocean with APECOSM-E: Part 1 Model formulation. Ecological Modelling 245:41-54

Dueri, S., Bopp, L., Maury, O. (2014). Projecting the impacts of climate change on skipjack tuna abundance and spatial distribution. Global Change Biology 20(3): 742-753.

Dueri, S., Guillotreau, P., Jiménez-Toribio , R., Oliveros-Ramos, R., Bopp, L., Maury, O. (2016). Food security or economic profitability? Projecting the effects of climate and socioeconomic changes on global skipjack tuna fisheries under three management strategies. Global Environmental Change 41, 1-12.

Dufresne J-L, Foujols M-A, Denvil S *et al.* (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Climate Dynamics 40(9-10):2123-2165.

FAO (2016). The State of World Fisheries and Aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200 pp.

Fonteneau, A. (2004). An overview of Indian Ocean albacore: fisheries, stocks and research. IOTC Working Party on Temperate Tunas, IOTC-2004-WPTmT-02.

Froese, R., Pauly, D.E., 2016. *FishBase. World Wide Web electronic publication. www.fishbase.org, version (06/2016)*.

Frommel, A. Y., Margulies, D., Wexler, J. B., Stein, M. S., Scholey, V. P., Williamson, J. E., Bromhead, D., Nicol, S., Havenhand, J. (2016). Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, Thunnus albacares. Journal of Experimental Marine Biology and Ecology, 482: 18–24

Ganachaud A, Gupta A, Orr J, Wijffels S, Ridway K, Hemer M, Maes C, Steinberg C, Tribollet A, Qiu B, *et al.* (2011). Chapter 3. Observed and expected changes to the tropical Pacific Ocean. In: Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Bell J, Johnson J, Hobday A. (eds). Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 101-188.

Gattuso, J.-P., Magnan, A., Billé, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Pörtner, H.-O., Rogers, A.D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S., Turley, C. (2015). Contrasting futures for ocean and society from different anthropogenic CO 2 emissions scenarios. Science 349: 6243, DOI: 10.1126/science.aac4722

Gilman, E., Allain, V., Collette, B.B., Hampton, J., Lehodey, P. (2016). Chapter 3.12. Impacts and effects of ocean warming on pelagic tunas. In: Laffoley, D. and Baxter, J. M. (editors). 2016. Explaining ocean warming: Causes, scale, effects and consequences. Full report. Gland, Switzerland: IUCN. 456 pp.

Graham JB, Dickson KA (2004) Tuna comparative physiology. J Exp Biol 207:4015–4024.

Graham, J.B., Lowell, R.W., Lai, N.C., Laurs, R.M., 1989. O2 tension, swimming velocity, and thermal effects on the metabolic rate of the Pacific albacore, Thunnus alalunga. Experimental Biology 48, 89–94.

Grande, M., Murua, H., Zudaire, I., Goni, N., Bodin, N. (2014). Reproductive timing and reproductive capacity of the Skipjack Tuna (Katsuwonus pelamis) in the western Indian Ocean. Fisheries Research, 156, 14-22.

Godo, OR, Samuelsen, A, Macaulay, GJ, Patel, R, Hjollo, SS, Horne, J, Kaartvedt, S, Johannessen, JA (2012). Mesoscale eddies are oases for higher trophic marine life. PLoS ONE 7(1): e30161.

Goulding, I. (2016). Impact of Fisheries Partnership Agreements on Employment in the EU and in Third Countries. Report. European Parliament. DG for internal policies. pp.60. doi:10.2861/009213

Griffiths, S., Pepperell, J., Tonks, M., Sawynok, W., Olyott, L., Tickell, S., Zischke, M., Burgess, J., Jones, E., Joyner, D., Lynne, J., Makepeace, C., Moyle, K. (2008). Biology, fisheries and status of longtail tuna (Thunnus tonggol), with special reference to recreational fisheries in Australian waters. *FRDC Final Report*, *58*(2010), 101.

Griffiths, S.P., Fry, G.F., Manson, F.J., Lou, D.C., (2010b). Age and growth of longtail tuna (*Thunnus tonggol*) in tropical and temperate waters of the central Indo- Pacific. *ICES Journal of Marine Science* 67, 125-134.

Guillotreau, P., Campling, L., Robinson, J. (2012). Vulnerability of small island fishery economies to climate and institutional changes. Current Opinion in Environmental Sustainability, 4(3), 287-291.

Hilmi, N., Allemand, D., Dupont, S., Safa, A., Haraldsson, G., Nunes, P. A., Moore, C., Hattam, C., Reynaud, S., Hall-Spencer, J.M., Fine, M., Turley, C., Jeffree, R., Orr, J., Munday, P.L., Cooley, S.R.. (2013). Towards improved socio-economic assessments of ocean acidification's impacts. Marine biology, 160(8), 1773-1787.

Hobday, A. J. (2010). Ensemble analysis of the future distribution of large pelagic fishes off Australia. *Progress in Oceanography*, *86*(1), 291-301.

Ilyina T, Zeebe R, Brewer P. (2010). Future ocean increasingly transparent to low frequency sound owing to carbon dioxide emissions. Nature Geoscience 3: 18–22.

IOTC Secretariat (2016). Assessment of Indian Ocean longtail tuna (Thunnus tonggol) using data poor catch-based methods. IOTC–2016–WPNT06–17.

IOTC–WPTmT06 (2016). Report of the SixthSession of the IOTC Working Party onTemperate Tunas. Shanghai, China, 18–21July 2016. IOTC–2016–WPTmT06–R[E]:58 pp

IOTC–WPTT17 (2015). Report of the 17th Session of the IOTC Working Party on Tropical Tunas. Montpellier, France, 23–28 October 2015. IOTC–2015–WPTT17– R[E]: 102 pp.

Itoh, T., Tsuji, S., Chow, S., 1996. *Catch information of longtail tuna, Thunnus tonggol, in Japan*. Proceedings of the sixth Expert Consultation on Indian Ocean Tunas, 25-29 September 1995, Colombo, Sri Lanka, pp. 312-315.

Itoh, T., Yuki, Y., Tsuji, S., 1999. Spawning possibility and growth of longtail tuna, *Thunnus tonggol*, in the water around Japan. *Bulletin of the National Research Institute of Far Seas Fisheries* 36, 47-53.

Korsmeyer, K.E., Dewar, H., (2001). Tuna metabolism and energetics. In: Block, B.A., Stevens, E.D. (Eds.), Tuna: Physiology, Ecology, and Evolution. Academic Press, San Diego, CA, pp. 35–78.

Kumar, P. S., Pillai, G. N., Manjusha, U. (2014). El Nino southern oscillation (ENSO) impact on tuna fisheries in Indian Ocean. SpringerPlus, 3(1), 1.

Lan, K. W., Kawamura, H., Lee, M. A., Lu, H. J., Shimada, T., Hosoda, K., Sakaida, F. (2012). Relationship between albacore (Thunnus alalunga) fishing grounds in the Indian Ocean and the thermal environment revealed by cloud-free microwave sea surface temperature. *Fisheries Research*, *113*(1), 1-7.

Lan, K. W., Evans, K., Lee, M. A. (2013). Effects of climate variability on the distribution and fishing conditions of yellowfin tuna (Thunnus albacares) in the western Indian Ocean. *Climatic Change*, *119*(1), 63-77.

Le Borgne, R., Allain, V., Griffiths, S., Matear, R., McKinnon, A., Richardson, A., Young, J. (2011). Chapter 4. Vulnerability of open ocean food webs in the tropical Pacific to climate change. In: Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change. Bell J, Johnson J, Hobday A. (eds). Secretariat of the Pacific Community, Noumea, New Caledonia. pp. 189-249.

Lee, P. F., Chen, I. C., Tzeng, W. N. (2005). Spatial and temporal distribution patterns of bigeye tuna (Thunnus obesus) in the Indian Ocean. Zoological Studies, 44(2), 260-270.

Lee, S.-K., W. Park, M. O. Baringer, A. Gordon, B. Huber and Y. Liu (2015), Pacific origin of the abrupt increase in Indian Ocean heat content during the warming hiatus, Nature Geosci., 8, 445-450.

Lehodey, P., Bertignac, M., Hampton, J., Lewis, A., Picaut, J. (1997). El Niño Southern Oscillation and tuna in the western Pacific. Nature, 389(6652), 715-718.

Lehodey, P., Chai, F., Hampton, J. (2003). Modelling climate-related variability of tuna populations from a coupled ocean–biogeochemical-populations dynamics model. *Fisheries Oceanography*, *12*(4-5), 483-494.

Lehodey, P., Senina, I., Murtugudde, R., (2008). A spatial ecosystem and populations dynamics model (SEAPODYM) – modeling of tuna and tuna-like populations. Progress in Oceanography 78, 304–318.

Lehodey, P., Senina, I., Sibert, J., Bopp, L., Calmettes, B., Hampton, J., Murtugudde, R., (2010). Preliminary forecasts of Pacific bigeye tuna population trends under the A2 IPCC scenario. Progress in Oceanography 86, 302–315.

Lehodey, P., Hampton, J., Brill, R. W., Nicol, S., Senina, I., Calmettes, B., Pörtner, H.O., Bopp, L., Ilyina, T., Bell J.D., Sibert, J. (2011). Vulnerability of oceanic fisheries in the tropical Pacific to climate change. Vulnerability of tropical Pacific fisheries and aquaculture to climate change, 433-492.

Lehodey, P., Senina, I., Calmettes, B., Hampton, J., Nicol, S. (2013). Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Climatic Change, 119(1), 95-109.

Lehodey, P., Senina, I., Nicol, S., Hampton, J. (2015). Modelling the impact of climate change on South Pacific albacore tuna. Deep Sea Research Part II: Topical Studies in Oceanography, 113, 246-259.

Levy M., Shankar D., Andre J. -M., Shenoi S. S. C., Durand F., de Boyer Montegut C. (2007). Basin-wide seasonal evolution of the Indian Ocean's phytoplankton blooms. , *J. Geophys. Res. Oceans*, 112, C12014.

Marsac, F., Le Blanc, J.L., 1998. Dynamics of ENSO events in the Indian OCean: to what extent would recruitment and catchability of tropical tunas be affected? In: Proceedings of the Expert Consultation on Indian Ocean Tunas, 7th session, IOTC, Victoria, Seychelles, 9-14/11/98. IOTC Proceedings 1 : 89-101.

Michael, P.E., Wilcox, C., Tuck, G.N., Hobday, A.J., Strutton, P.G. (submitted). Japanese and Taiwanese pelagic longline fleet dynamics and the impacts of climate change in the southern Indian Ocean.

Mohri, M., Fukada, K., Yamada, H., Inoue, H., (2005). Relationship between longtail tuna catches and water temperature on the Sea of Japan off the coast of Yamaguchi Prefecture. *Memoirs of the Faculty of Agriculture of Kinki University* 38, 68-75.

Mohri, M., Fukada, K., Takikawa, T., Miura, M., (2008). Relationship between Water Temperature and Longtail Tuna Caught by a Set-net Fishery off Futaoi Island (the western Japan Sea). *Mathematical and Physical Fisheries Science* 6, 58-67.

Mohri, M., Nishida, T. (2000). Consideration on distribution of adult yellowfin tuna (Thunnus albacares) in the Indian Ocean based on the Japanese tuna longline fisheries and survey information. Journal of National Fisheries University, 49(1), 1-11.

Mullon, C., Guillotreau, P., Galbraith, E.D., Fortilus, J., Chaboud, C., Bopp, L., Aumont, O., Kaplan, D. 2016). Exploring future scenarios for the global supply chain of tuna. Deep Sea Research II: Topical Studies in Oceanography (in press).

Murtugudde, R., Signorini, S.R., Christian, J.R., Busalacchi, A.J., McClain, C.R., Picaut, J., (1999). Ocean color variability of the tropical Indo-Pacific basin observed by SeaWiFS during 1997–98. Journal of Geophysical Research 104, 18351–18366.

Murtugudde RG, McCreary JP, Busalacchi AJ (2000). Oceanic processes associated with anomalous events in the Indian Ocean with relevance to 1997–1998. Journal of Geophysical Research 105: 3295–3306

Musyl, M. K., Brill, R. W., Boggs, C. H., Curran, D. S., Kazama, T. K., Seki, M. P. (2003). Vertical movements of bigeye tuna (Thunnus obesus) associated with islands, buoys, and seamounts near the main Hawaiian Islands from archival tagging data. Fisheries Oceanography, 12(3), 152-169.

Nikolic, N., Morandeau, G., Hoarau, L., West, W., Arrizabalaga, H., Hoyle, S., Nicol, S.J., Bourjea, J., Puech, A., Farley, J.H., Williams, A. J., Fonteneau, A. (2016) Review of albacore tuna, Thunnus alalunga, biology, fisheries and management. Reviews in Fish Biology and Fisheries, 1-36.

Nishida, T., Tanaka, M. (2004). General reviews of Indian Ocean albacore (Thunnus alalunga). IOTC-2008-WPTe-INF03

Nootmorn, P. (2004). Reproductive biology of bigeye tuna in the eastern Indian Ocean. IOTC–2004–WPTT04–05.

Olson, R.J., Young, J.W., Ménard, F., Potier, M., Allain, V., Goñi, N., Logan, J.M. , GalvánMgaña, F. (2016). Bioenergetics, Trophic Ecology, and Niche Separation of Tunas. In: Advances in Marine Biology, Vol. 74, Oxford: Academic Press, 2016, pp. 199-344.

Poloczanska, E.S., Burrows, M.T., Brown, C.J., Molinos, J.C., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C.V., Moore, P.J., Richardson, A.J., Schoeman, D.S., Sydeman, W.J. (2016). Responses of marine organisms to climate change across oceans. Front. Mar. Sci. 3:62.

Reid, P.C. (2016). Chapter 1. Ocean warming: setting the scene. In: Laffoley, D. and Baxter, J. M. (editors). Explaining ocean warming: Causes, scale, effects and consequences. Full report. Gland, Switzerland: IUCN. 456 pp.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang, (2013). Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of

Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Robinson, J., Guillotreau, P., Jiménez-Toribio, R., Lantz, F., Nadzon, L., Dorizo, J., Gerry, C., Marsac, F. (2010). Impacts of climate variability on the tuna economy of Seychelles. *Climate Research*, *43*(3), 149-162.

Roxy, M. K., A. Modi, R. Murtugudde, V. Valsala, S. Panickal, S. P. Kumar, M. Ravichandran, M. Vichi, and M. Lévy (2016), A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean, Geophys. Res. Lett., 43, 826–833, doi:10.1002/2015GL066979.

Roxy, M. K., K. Ritika, P. Terray, and S. Masson (2014), The curious case of Indian Ocean warming, Journal of Climate, 27(22), 8501-8509.

Saji, N.H., Goswami, B.N., Vinayachandran, P.N., Yamagata T. (1999). A dipole mode in the tropical Indian Ocean. Nature 401 (6751), 360-363.

Schaefer, K. M., Fuller, D. W., Block, B. A. (2007). Movements, behavior, and habitat utilization of yellowfin tuna (Thunnus albacares) in the northeastern Pacific Ocean, ascertained through archival tag data. *Marine Biology*, *152*(3), 503-525.

Schaefer, K. M., Fuller, D. W. (2007). Vertical movement patterns of skipjack tuna (Katsuwonus pelamis) in the eastern equatorial Pacific Ocean, as revealed with archival tags. *Fishery* Bulletin, 105(3), 379-389.

Schaefer, K. M., Fuller, D. W. (2002). Movements, behavior, and habitat selection of bigeye tuna (Thunnus obesus) in the eastern equatorial Pacific, ascertained through archival tags. *Fishery Bulletin*, *100*(4), 765-788.

Senina, I., Lehodey, P., Calmettes, B., Nicol, S., Caillot, S., Hampton, J., Williams, P. (2015). SEAPODYM application for yellow tuna in the Pacific Ocean. WCPFC-SC11-2015/ EB-IP-01

Song, L., Zhou, J., Zhou, Y., Nishida, T., Jiang, W., Wang, J. (2009). Environmental preferences of bigeye tuna, Thunnus obesus, in the Indian Ocean: an application to a longline fishery. Environmental Biology of Fishes, 85(2), 153-171.

Sumaila, U.R., Cheung, W.W.L., Lam, V.W.Y., Pauly, D., Herrick, S. (2011). Climate change impacts on the biophysics and economics of world fisheries. Nat. Clim. Chang. 1, 449-456.

Sumaila, U. R., Samoilys, M., Allison, E., Cinner, J., DeYoung, C., Kavanagh, C. (2015). Indian Ocean and Red Sea. In: Hilmi N., Allemand D., Kavanagh C., Laffoley D., Metian M., Osborn D., Reynaud S. (eds.) (2015). Bridging the Gap Between Ocean Acidification Impacts and Economic Valuation: Regional Impacts of Ocean Acidification on Fisheries and Aquaculture. Gland, Switzerland: IUCN. pp. 136.

Sunoko, R., Huang, H. W. (2014). Indonesia tuna fisheries development and future strategy. Marine Policy, 43, 174-183.

Tew Kai E, Marsac F (2010). Influence of mesoscale eddies on spatial structuring of top predators' communities in the Mozambique Channel. Progress in Oceanography, 86:214-223.

Tomczak, M. and Godfrey, J.S. (1994). Chapter 11: The Indian Ocean. In: Regional Oceanography: An Introduction, pp 422.

Vivekanandan, E., Jeyabaskaran, R. (2013). Impact and adaptation options for Indian marine fisheries to climate change. In: Climate Change Adaptation Strategies in Agriculture and Allied Sectors, Chapter: Impact and adaptation options for Indian marine fisheries to climate change, Publisher: Scientific Publishers, New Delhi, Editors: G.S.L.H.V. Prasada Rao, pp.107-117

Western and Central Pacific Fisheries Commission (2014). Tuna Fishery Yearbook pp 142.

Williams, A. J., Allain, V., Nicol, S. J., Evans, K. J., Hoyle, S. D., Dupoux, C., Vourey, E., Dubosc, J. (2015). Vertical behavior and diet of albacore tuna (Thunnus alalunga) vary with latitude in the South Pacific Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, *113*, 154-169.

Yesaki, M., (1982). Thailand. Biological and Environmental Observations. A report prepared for the Pole-and-Line Tuna Fishing in Southern Thailand Project. *FAO FI: DP/THA/77/008: Field Doc.* 3, 46.

Zheng, X.-T., S.-P. Xie, Y. Du, L. Liu, G. Huang, and Q. Liu, (2013). Indian Ocean Dipole response to global warming in the CMIP5 multimodel ensemble. *J. Climate*, 26, 6067–6080.

Zudaire, I., Murua, H., Grande, M., Bodin, N. (2013). Reproductive potential of yellowfin tuna (Thunnus albacares) in the western Indian Ocean. Fishery Bulletin, 111(3), 252-264.