Collect. Vol. Sci. Pap. ICCAT, 81(3), SCRS/2024/077: 1-15 (2024)

CLIMATE CHANGE EFFECTS ON ALBACORE TUNA, A REVIEW

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SUMMARY

Alterations in ocean properties derived from Climate Change, have a significant impact on the marine ecosystems, and thus on fisheries. The understanding of marine ecosystems responses to global Climate Change plays an important role in predicting future potential impacts on fisheries. The most prominent ecological response for fish populations are changes in the distribution and productivity. In the case of tunas, this is highly important since tunas exert top-down pressure in the ecosystems worldwide and sustain some of the world's most valuable fisheries. Albacore is a highly migratory temperate species distributed in all oceans. Therefore, changes in albacore distribution and abundance would suppose changes in worldwide albacore fisheries, with the subsequent impact on global economy. The present work compiles information on the preferred environmental characteristics of albacore stocks in the Atlantic Ocean, Pacific Ocean, Indian Ocean, and the Mediterranean Sea. Additionally, Climate Change effects on marine ecosystems are summarized, highlighting the potential future impacts on albacore stocks.

RÉSUMÉ

Les modifications des propriétés des océans dues au changement climatique ont un impact significatif sur les écosystèmes marins et donc sur les pêcheries. La compréhension des réactions des écosystèmes marins au changement climatique mondial joue un rôle important dans la prévision des impacts potentiels futurs sur les pêcheries. La réponse écologique la plus importante pour les populations de poissons est la modification de la distribution et de la productivité. Dans le cas des thonidés, cet aspect est très important, car les thonidés exercent une pression descendante sur les écosystèmes du monde entier et soutiennent certaines des pêcheries les plus précieuses de la planète. Le germon est une espèce tempérée hautement migratoire répartie dans tous les océans. Par conséquent, des changements dans la distribution et l'abondance du germon supposeraient des changements dans les pêcheries mondiales de germon, avec l'impact qui s'ensuit sur l'économie mondiale. Le présent travail rassemble des informations sur les caractéristiques environnementales préférées des stocks de germon dans l'océan Atlantique, l'océan Pacifique, l'océan Indien et la mer Méditerranée. En outre, les effets du changement climatique sur les écosystèmes marins sont résumés, soulignant les impacts potentiels futurs sur les stocks de germon.

RESUMEN

Las alteraciones de las propiedades de los océanos derivadas del cambio climático tienen un impacto significativo sobre los ecosistemas marinos y, por lo tanto, sobre las pesquerías. Entender las respuestas de los ecosistemas marinos al cambio climático global desempeña un papel importante a la hora de predecir los posibles efectos futuros sobre las pesquerías. La respuesta ecológica más destacada para las poblaciones de peces son los cambios en la distribución y la productividad. En el caso de los túnidos, es muy importante, dado que los túnidos ejercen una presión descendente en los ecosistemas a nivel mundial y mantiene mantienen algunas de las pesquerías más valoradas del mundo. El atún blanco es una especie templada altamente migratoria distribuida en todos los océanos. Por lo tanto, los cambios en la distribución y abundancia del atún blanco supondrían cambios en las pesquerías mundiales de atún blanco, con el consiguiente impacto en la economía mundial. El presente trabajo recopila información sobre las características medioambientales preferentes de los stocks de atún blanco del océano Atlántico, el océano Pacífico, el océano Índico y el mar Mediterráneo. Además, se resumen los efectos del cambio climático en los ecosistemas marinos, destacando las posibles repercusiones futuras en los stocks de atún blanco.

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KEYWORDS

Albacore, Thunnus alalunga, environmental conditions, environmental effects, long-term changes, pelagic environment, spatial variations, Climate Change, habitat

1. Introduction

1.1 Biology, migration and fishing of albacore

Albacore (*Thunnus alalunga*) (Bonnaterre, 1788) is a highly migratory pelagic predator in the family Scombridae. Despite being a temperate species, it is distributed throughout most tropical waters as well as temperate waters worldwide, mainly between 50ºN and 45ºS, with relatively lower abundance in equatorial areas (Chang et al., 2021). However, there is still high uncertainty about its life cycle, migrations and biology (Nikolic et al., 2017; Fraile et al., 2016).

Albacore is able to maintain internal temperatures higher than ambient. This is because they have a counter-current heat exchange system, characteristics of tunas, which enables them to swim to cooler waters. Given their high metabolic rate and their ability to swim continuously, they can migrate long distances (Goñi and Arrizabalaga, 2010; Nikolic, et al., 2017). Although there is still controversy regarding albacore distribution and worldwide migrations, Nikolic et al. (2017) described spatial dynamics of all stocks, analyzing longline catches as a function of temperature in different oceans. As a temperate tuna species, areas of large catches in warm waters were assigned to potential spawning areas. As such, albacore spawning areas are located in the west basins of the North and South Atlantic Oceans (**Figure 1**), where as in the Indian Ocean spawning areas show a patchy distribution (**Figure 2**), and in the Pacific Ocean spawning areas are located over a wider area in the west (**Figure 3**). By contrast, feeding areas were assigned to locations where albacore catches take place in waters below 24ºC. They concluded that albacore potential migrations take place between described spawning and feeding areas.

Albacore is one of the most important commercially harvested species in the world's oceans. Albacore catches correspond to %4 of total global tuna catches (ISSF, 2024) fished in all oceans and by different fishing gears. **Error! Reference source not found.**SSF (2024) provides an overview of different albacore stock status. S ummarizing, albacore stocks of Atlantic and Pacific Oceans are considered not to be overfished and there are no sustainability concerns on these populations. Similarly, Indian Ocean albacore stock is considered to be on a good state of health, but with considerable uncertainty due to the last stock assessment results. On the contrary, Mediterranean albacore stock catches decreased substantially relative to 2021 and currently the population is considered to be overfished or subject to overfishing. However, there is high uncertainty on this stock status since more data should be collected for an accurate assessment.

1.2 Climate Change

Climate Change, according to IPCC (2007), refers to a change in the state of a climate that can be identified by variations in its properties and that persists for an extended period. Climate change, being currently one of the main threats to ecosystems worldwide, could be due to natural variability or because of human activity. Greenhouse gases (such as CO_2, CH_4 and N_2O), which have been accumulated in the atmosphere since the Industrial Revolution, are partially absorbed by the ocean. Consequently, increasing temperatures and changes in water biogeochemistry have produced water acidification and deoxygenation (Laffoley and Baxter, 2019). There is evidence that most oceans are being affected by regional changes, particularly temperature increases (IPCC, 2007; Hoegh-Guldberg et al., 2018). For instance, the global upper ocean temperature increased by 0.4ºC between 1955 and 2008 (Levitus et al., 2009 in Le Marchand et al., 2020). Climate change impacts such as water warming and sea level rise are expected to continue for centuries (IPCC, 2007) reaching up to 1.64 to 3.51ºC temperature increase by the end of the century (Hoegh-Guldberg et al., 2018). Likewise, future projections reveal that most regions will undergo decreases in oxygen concentrations due to slowdown in ocean ventilation and a decline in surface oxygen solubility due to higher temperatures (Leung et al., 2019). There is evidence that global ocean oxygen content has decreased by -1.2% since the middle of the 20^{th} century (Grégoire et al., 2019) and could continue decreasing by -3.45% in the 21^{st} century (Bopp et aL., 2013).

Under this scenario of global changes in ocean properties, marine ecosystems, and thus fisheries, are significantly impacted. The most prominent biological response from fish stocks are changes in distribution (Cheung et al., 2010; 2013; Le Marchand et al., 2020; Erauskin-Extramiana et al., 2019; Monllor-Hurtado, et al., 2017), phenology (Dufour et al., 2010; Goikoetxea et al., 2017; Chust et al., 2019) and productivity (Cheung et al., 2010; 2012; 2013; Merino et al., 2012; 2019; Erauskin-Extramiana et al., 2023). In addition, climate change may lead to local extinction of some species, as well as the invasion of foreign species coming from other areas. Cheung et al. (2009) mention species turnovers of over 60% of the present biodiversity, which implies not only ecological disturbances but also socio-economic impacts.

The understanding of marine ecosystems responses to global climate change plays an important role in afterwards predicting future potential alterations on fisheries. In the case of tunas, this is highly important since tunas sustain some of the world's most valuable fisheries and dominate ecosystems worldwide (Juan-Jordá et al., 2011). How climate change will impact on marine stocks in general, and tunas in particular, is already being investigated (Chust et al., 2019; Merino et al., 2019; Erauskin-Extramiana et al., 2023). However, the scientific community should place an emphasis on including such information in the design of effective marine management procedures, to ensure sustainability of tunas worldwide.

2. Objectives

The objective of the current review is to provide a summary of latest knowledge about environmental preferences on albacore; particularly, climate change effects on albacore productivity, phenology and geographical distribution is reviewed. This knowledge synthesis aims to provide a basis to discuss robustness scenarios under the new MSE.

3. Material and methods

With the aim of assessing the response of albacore distribution to current climate change, scientific literature on worldwide albacore stocks has been reviewed. This revision includes information on environmental preferences of such stocks, as well as climate change impacts on them and future potential implications for fisheries.

4. Results and discussion

4.1 Relationship between the oceanic climate and the distribution of albacore

The distribution and abundance of species and their prey is established by ocean-climatic conditions. Long time series analysis showed how the dynamics of most of the fishing stocks of commercial interest are affected by climate (Cheung et al., 2013). In the case of albacore there are a vast number of works about the relationship of its distribution and the physical characteristics of its habitat. These studies identified the preferential ranges of different oceanographic factors (e.g. temperature, salinity, oxygen, altimetry, chlorophyll) for albacore in oceans worldwide (Zainuddin et al., 2008; Dufour, 2010; Arrizabalaga et al., 2015; Singh et al, 2015; Erauskin-Extramiana et al, 2019). However, the biology and ecological habitat of Atlantic and Pacific Ocean stocks are relatively better documented, while the Indian Ocean and the Mediterranean Sea stocks are more data deficient.

The influence of global climatic indices on albacore stocks worldwide has been studied. In the North Atlantic, a likely influence of the global index NAO (North Atlantic Oscillation) on the northern albacore recruitment was discussed for the first time in 1997; high NAO years were seen to be associated with decrease in albacore recruitment levels (Santiago, 1998). This opposite association between NAO and albacore recruitment was afterwards confirmed with the analysis of a longer study period (Santiago, 2004). This association is suggested to be more important when spawning stock biomass of albacore is high (Arregui et al., 2006). Years later, Dufour et al. (2010) highlighted the influence of the global indices of NAO and the temperature anomaly of the Northern Hemisphere on the trophic migration of albacore. In the Mediterranean Sea albacore CPUE (catch per unit effort) significantly increases when the NAO is negative (Báez et al., 2011). In the Pacific, albacore recruitment seems to be correlated to the climatic indices of El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO); particularly, albacore shows low recruitment during El Niño and high during La Niña (Lehodey et al., 2003; Zainuddin et al., 2004). In addition, Singh et al. (2015) highlighted those climatic conditions, such as the global mean land and ocean temperature index (LOTI), the Pacific warm pool index (PWI) and PDO should be taken into account when taking albacore stock management decisions given their influence on albacore CPUE.

Global climatic indices' influence on albacore stocks has been documented on a large scale. Similarly, Arrizabalaga et al. (2015), published a global study showing the preference of albacore for surface water temperatures from 14ºC to 22ºC. However, such thermal preference differs among oceans and for different life stages of albacore. This work reviews studies on oceanographic conditions on albacore distribution areas to summarize the optimal ranges of different environmental parameters, as this information could be crucial when assessing the potential impacts of climate variability on fish stocks. The environmental characteristics of albacore habitat is found to be different depending on the stock. **Table 1** summarizes the main optimal ranges for the environmental parameters mostly studied in the literature.

In Northeast Atlantic waters, albacore latitudinal migrations follow isotherms between 16ºC and 21ºC (Havard-Duclos, 1973). Thermal preferences also differ depending on the season of the year, previously demonstrated by Sagarminaga and Arrizabalaga (2010). Goikoetxea et al. (2014) stated that the first catches of each year (May to mid-July) are registered in waters between isotherms 15ºC and 17ºC, whilst catches of the second half of the fishing season (located mainly within the Bay of Biscay and southwest of Ireland) were in warmer waters without a clear preferential range (Goikoetxea et al., 2014). Juvenile catches are not only related to the temporal displacement of the optimal thermal window (Sagarminaga and Arrizabalaga, 2010), but are also linked to chlorophyll fronts in summer months (Sagarminaga and Arrizabalaga, 2014). Goikoetxea et al. (2012) identified the importance of the vertical structure of the water column. In the Bay of Biscay juveniles stay close to the surface (0-50m), preferentially close to the thermocline (Goikoetxea et al., 2017). Also, the presence of mesoscale structures such as eddies influence albacore behavior. The presence of albacore catches between cyclonic and anticyclonic eddies shows that the conditions that can be found in the edges of eddies are optimal for their presence (Goikoetxea et al., 2014). The environmental preferences of albacores suggest that oceanographic changes could influence the spatial and temporal distribution of the stock. Likewise, albacore migration towards productive northeastern Atlantic waters is associated with the seasonal variation of temperature, tracking the seasonal warming.

In the South Atlantic Ocean, albacore feeding habitat is characterized by approximately 16.5º-19.5ºC and 0.11-0.33 mg/m3 optimal ranges of sea surface temperature (SST) and sea surface chlorophyll concentration (SSC), respectively (Vayghan et al, 2020).

In the Pacific Ocean, the highest albacore CPUEs are found in waters characterized by SST of 18.5-21.5ºC, 0.2-0.4 mg/m^3 SSC, and -5 to 32 cm sea surface height (SSH) anomaly values (Zainuddin et al., 2008). Moreover, high albacore CPUE areas are found in regions with high SST gradients, such as the North Pacific Transition Zone; high albacore CPUE are associated not only with the presence of oceanic fronts, by also to frontal strength (Xu et al., 2017). Accordingly, albacore CPUEs were higher near warm, low chlorophyll oceanic waters, and near SST fronts in the Northeast Pacific Ocean (Nieto et al., 2017). Also, albacore presence was related to the transition zone chlorophyll front in the North Pacific (Polovina et a., 2001). In a more recent research with immature albacore tuna in the North Pacific Ocean, the optimal range of environmental variables for the SST, SSH, mixed layer depth (MLD), SSC of the previous month, and eddy kinetic energy (EKE) for the habitat of albacore are suggested to be approximately 17–21°C, 0.24–0.84 m, 15–100 m, 0.07–0.29 mg/m^3, and 0.0001–0.0031 m^2/s^2, respectively (Lee et al., 2019). However, the optimal temperature range is found to be cooler (15-18ºC) in the northeastern North Pacific waters (Christian and Holmes, 2016). A recent study identified the lower thermal tolerance for juvenile albacore tuna in the northwestern and central Pacific Ocean and it was set to be 13ºC, restricting albacore movements vertically (Matsubara et al., 2024). MLD was found to limit albacore vertical distribution in both North Pacific Ocean (Childers et al., 2011) and South Pacific Ocean (Williams et al., 2015). What is more, the vertical distribution of albacore is different whether in tropical waters (shallower, warmer waters above the MLD at night and deeper, cooler waters below the MLD during the day) or temperate waters (limited to shallow waters above the MLD almost all the time) in the South Pacific Ocean (Williams et al., 2015). In the South Pacific Ocean, albacore CPUE were higher at areas closer to thermal fronts and with greater gradient magnitudes (Zhou et al., 2020). In addition, albacore vertical distribution was restricted by water temperature and oxygen availability, and they showed stronger preference for 200 m depth layer. Accordingly, oxygen concentration and SST were also selected variables in the study by Chang et al. (2021) since albacore preferred the areas with dissolved oxygen at 100m of 0.2-0.5 mmol/l and SST of 13-22ºC. Dissolved oxygen was already suggested by Brill (1994) as a good descriptive of albacore habitat suitability.

In the Indian Ocean, the essential habitat for immature albacore feeding is found in waters of 0.07-0.09 mg/m^3 (lagged 2 months in advance) and 16.5-18.5ºC (Mondal et al., 2021). Other studies revealed that higher albacore abundances are found with SST, sea surface salinity (SSS) and SSC ranges of 17-19ºC (mostly centralized near 18ºC), 35.1-35.5 psu and 0.1-0.25 mg/m^3, respectively (Mondal & Lee, 2018; Mondal et a., 2022). However, albacore tuna catches in the whole Indian ocean cover a wide range of temperature values in comparison with other oceans (Chen et al., 2005). For instance, Wang et al. (2019 in Mondal et al., 2022) showed a that albacore catches were recorded at temperatures from 20 to 27ºC. Likewise, albacore SST preference vary according to the life stage of the individuals, from 18.9ºC for immatures, to 19.1ºC for non-spawning matures, and to 24.9ºC for spawning matures (Mondal et al., 2022). Mondal and Lee (2023) described warmer waters (25-29ºC) for mature albacore tunas between 10ºS and 30ºS. SSH and oxygen concentration are observed to be also limiting factors for albacore with preferred values of 0.5-0.7m and 5-5.3 ml/l, respectively (Mondal and Lee, 2023). Lastly, albacore frequently dive to depths below 200 m during the day (Childers et al., 2011) showing a preference for waters from 60-175m (Mondal et al., 2022).

4.2 Projections under climate change scenarios

Climate change is predicted to amplify the uncertainties identified for commercial fisheries (Cheung et al., 2016). Being climate change a matter of fact, its effects on fish stocks should be accounted for in stock assessments. In this sense, this section reviews information on potential climate change effects on different albacore stocks worldwide (**Table 2**). Firstly, the aim is to identify gaps where more focus should be given to analyze climate change effects on albacore. Secondly, it intends to highlight those environmental variables that are confirmed to influence albacore populations to potentially consider them in assessment models and management advice.

In addition to the interannual or multidecadal variability of the oceanographic factors, global warming of the oceans is causing the northward shift of some fish species (increase of warm-water species and decrease of cold-water species), and deepening of other species (Perry et al., 2005; Cheung et al., 2013). As a consequence of global warming fisheries catch is predicted to increase in higher latitudes and to decrease in tropical regions (Cheung et al., 2010). In the case of albacore tuna, the relative abundance is projected to increase in the distribution limits of the Indian and Pacific Oceans but decrease in temperate areas. Generally speaking, albacore tuna expand their northern and southern limits poleward and decrease in temperate waters (Erauskin-Extramiana, et al., 2019). For mature albacore in the Indian Ocean, potential habitats are predicted to shift southward by 2100 (Mondal et al., 2023). In the case of the Bay of Biscay, a northward trend in albacore habitat has been detected (Chust et al., 2019).

In the Pacific Ocean albacore hot spots were concentrated around the 20ºC isotherm and the 0.3mg/m3 chlorophyll-a isopleth, which suggests that the dynamics of high tuna aggregations influenced by the progression of seasonal warming (thermal front) and the movement of chlorophyll front can be predicted using temperature and chlorophyll concentration as indicators (Zainuddin et al., 2006). Changes in any of these proxy variables (e.g given to climate change) would suppose changes in albacore hot spot locations. Other authors (Xu et al., 2017; Lee et al., 2019; Zhou et al., 2020) also highlighted the association of high albacore CPUE with thermal frontal zones. Future projections of albacore distribution concluded that the relative abundance of albacore would increase in the area south of 30ºS from 2020 to 2080, whereas it is projected to decrease in most EEZs in the South Pacific Ocean by 2080 (Chang et a., 2021). They also found that the northern boundary of albacore preferred habitat is expected to shift southward by about 5º latitudes, in accordance with Lehodey et al., (2015). By contrast, albacore distribution may remain stable in the western part of the southern Pacific Ocean (Senina et al., 2018) and may expand in the eastern Pacific Ocean. Considering only thermal conditions, northeastern North Pacific albacore could expand its distribution northward under warming conditions, but other factors influence, such as food availability, remains unknown (Christian and Holmes, 2016). Oceanic warming can alter not only the geographical distribution of albacore stocks, but also their vertical habitat. Albacore vertical distribution is limited by prey availability but also by thermal characteristics of the water column (Williams et al., 2015). Therefore, changes in the thermal structure of oceanic waters associated with climate change might influence the vertical distributions of albacore stocks worldwide.

Changes in the spatial distribution of species may lead local extinction of some species, as well as the invasion of foreign species coming from other areas. That is to say, the northward shift of marine species would suppose the arrival of foreign species to a new community, leading to trophic interactions with native species, like competition and predation. In the Bay of Biscay for instance, the arrival of the tropical bigeye tuna would be a competitor for the native temperate albacore since they would feed on the same prey (Le Marchand et al., 2020).

The changes are not only detected in the spatial distribution. In the Bay of Biscay, climate change could be already influencing the phenology of albacore during its trophic migration towards the Northeast Atlantic (Dufour et al, 2010). These authors demonstrated that albacore arrives, on average, 8 days before than 40 years ago (based on 1967-2005 study period). This change in phenology is expected to be of one month in the future. Goikoetxea et al. (2017) found a possible earliness of the fishing season for the end-of-the-century, when in June the fleet would be fishing in areas where they fish at present in July. Accordingly, based on a longer study period, Chust et al. (2019) also confirmed that albacore migration come 2.3 days earlier per decade, partly associated with the warming of the sea.

Fisheries productivity can be impacted also through changes in individual growth and recruitment. For example, Cheung et al. (2013) concluded that the deoxygenation of the oceans, could suppose the decrease in fish body size. This has been already documented in the case of the Bay of Biscay anchovy (Taboada et al., 2023). Simulations undertaken for North albacore stock analyzed the performance of the current management procedure under changes in productivity and abundance (Merino et al., 2019). Same authors suggested that with an increased recruitment or increase in body growth, the median catch of albacore would increase. However, Erauzkin-Extramiana et al., (2023), using a multispecies model, concluded that albacore are predicted to decrease globally in biomass and size, with the subsequent impact on industrial fishery.

An additional impact of climate change is the deoxygenation of the oceans. The depth at which oxygen concentrations drop below 3.5ml/l is projected to shoal throughout the global oceans and consequently vertical habitat of tunas could be compressed, especially within subtropical and mid-latitude Pacific Ocean regions (Leung et al., 2019). Albacore usually lives in waters with oxygen levels >5mg/l (>3.7 ml/l assuming 15ºC) and experiments showed that albacore are relatively intolerant to hypoxic conditions (Leung et al., 2019). Therefore, changes in oxygen concentration of the water column could have consequences for albacore horizontal or vertical distribution. In addition, the decrease of oxygen concentration in the South Pacific will lead to weaker albacore recruitment in the area, with a decrease on the abundance of young South Pacific albacore (Lehodey et a., 2015). Future projections under fishing and climate change scenarios predicted that the populations would decrease and stabilize after 2035 just below 0.8 Mt, i.e., 55% below the initial biomass of 1960. After 2080 however, the trend was reversed when a new spawning ground emerged in the north Tasman Sea (Lehodey et al., 2015).

Mediterranean sea warming has already been documented (Hidalgo et al., 2018) and it is projected to continue warming in the future. Similarly, salinity anomalies are predicted to increase. Likewise, the sea level rise increase reported so far, is projected to continue in the future and a decrease in ocean pH is likely to occur (Hidalgo et al., 2018). All these changes would affect also marine communities cohabiting Mediterranean waters, from phytoplankton to large pelagic species. In the case of Mediterranean albacore, a meridionalization of its migratory behavior is expected. However, documentation on climate change impacts on Mediterranean albacore is scarce, in comparison with other oceans.

Climate change is a fact, and impacts on marine ecosystems have already been documented through changes in species habitats, productivity of oceans and increased variability of environmental conditions (Poloczanska et al., 2013; Cheung et al., 2016), and indirectly on commercial species fisheries (Monllor-Hurtado et al., 2017). Hence, climate change impact on fisheries is a factor that should be accounted for in the assessments of different species. However, it is unclear how climate change influence should be considered in stock status evaluations.

Likewise, future changes in the distributions of tunas will suppose changes in regional fisheries with important socio-economic effects. As spatial habitats of targeted tuna species shift, CPUE-standardization methods should be adapted to capture stock dynamics accurately, since abundance indices are mostly dependent on fishery data. Consequently, stock assessment of these species will become more complicated, particularly if species move across management boundaries. In effect, there has been an increasing dominance of warmer water species catches at higher latitudes during the past four decades (Cheung et al., 2013), where tuna populations at intermediate latitudes (20-30ºN and 20-30ºS) underwent a large-scale tropicalization from 1965 to 2011 (Monllor-Hurtado et al., 2017). Simultaneously, there is a northward progressive shift of northeast Atlantic albacore fishing areas and it is expected to continue to move in the future since the center of gravity of albacore catches is projected to shift over 500 km for the-end-of-the-century (Goikoetxea et al., 2017). Further, some usual fishing areas of the Bay of Biscay might disappear (Goikoetxea al a. 2017). If targeted tuna abundance decreases or shifts from traditional fishing grounds, fishers will have to navigate longer to locate targeted shoals.

5. Conclusions

Changes in primary production, trophic chain balance, the life history and distribution of fish stocks could impact the productivity of fisheries worldwide. Similarly, climate change (by global warming, deoxygenation, and acidification of the oceans) influences marine ecosystems. Consequently, climate change has a substantial influence on the variability of fish stocks. Some effects have already been documented while others are still to be proved. To the extent possible, environmental variability of marine ecosystems should be accounted for in stock assessments.

There is still high uncertainty in future predictions of marine fisheries under climate change since climate change effect differs among oceans and species. The influence of climate change on tuna stocks is case sensitive and thus each stock should be studied separately, in order to decide whether to consider environmental variability on stock assessments and climate change on management advice, or not; and if so, how. **North Atlantic albacore is, compared to other albacore stocks, relatively well studied. However, there is little knowledge about the impact of climate change on stock productivity.**

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Table 1. Optimal environmental ranges for different albacore stocks compiled from literature (for bibliographic cites refer to the text). NPac. = North Pacific; SPac. = South Pacific; NAtl. = North Atlantic; SAtl. = South Atlantic; Med. = Mediterranean; Ind. = Indian.

Stock	SST (ºC)	SSS (psu)	SSC (mg/m^3)	SSH (m)	MLD (m)	EKE (m^2/s^2)	DO
NPac.	17-21		0.07-0.29*	0.24-0.84	15-100	0.0001-0.0031	
	15-18						
SPac.	13-22				53-173		0.2-0.5***
NAtl.	16-21						
SAtl.	16.5-19.5		0.11-0.33				
Med.							
Ind.	17-19	35.1-35.5	0.1-0.25	0.5	60-175		
	16.5-18.5		0.07-0.09**				
	25-29	34.8-35.5		0.5-0.7			5-5.3 (ml/l)

*1month lag; **2 months lag; ***mmol/l at 100 m depth

Table 2. Potential climate change impacts on different albacore stocks. NAtl. = North Atlantic; BoB = Bay of Biscay; SAtl. = South Atlantic; NPac. = North Pacific; NE NPac. = northeastern North Pacific; SPac. = South Pacific; Ind. = Indian; Med. = Mediterranean.

Stock		**Size**	**Recruitment**	**Horizontal distribution**	**Vertical distribution**	**Phenology**	**Abundance/ Biomass**	**Competition**
NAtl.		Decrease[1]		Poleward shift[3]			Decrease[1,3]	Increase competition with tropical tunas[12]
	BoB			Northward shift of the CoG of fishing areas[5,6] Northward shift of ALB habitat[6]		Earlier arrival[5,6,9]	No change or slight decrease[10]	Increase competition with tropical tunas[12]
SAtl.		Decrease[1]		Poleward shift[3]			Decrease[1,3]	Increase competition with tropical tunas[12]
NPac.			Decrease[2]	Poleward shift[3]			Decrease[1]	
							Decrease in young abundance[2]	
	NE NPac.			Northward expansion[7]				Increase competition with tropical tunas[12]
SPac.		Decrease[1]		Poleward shift[3]	Deepening[8]		Decrease[1,3]	
				Southward shift of the northern boundary[4]			Increase south of 30ºS[4] Decrease in most EEZs[4] Decrease until 2080[11]	
Ind.				Poleward shift[3, 13]			Decrease[1]	Increase competition with tropical tunas[12]
Med.				No clear trend[3]			Decrease[1]	

[1]Erauzkin-Extramiana et al., 2023; [2]Leung et al., 2019; [3]Erauzkin-Extramiana et al., 2019; [4]Chang et al., 2021; [5]Goikoetxea et al., 2017; [6]Chust et al., 2019; [7]Christian and Holmes, 2016; [8]Williams et al., 2015; [9]Dufour et al., 2010; [10]Yeregui, R., 2023; [11]Lehodey et al., 2015; [12]Monllor-Hurtado et al., 2017; [13]Mondal et a., 2023

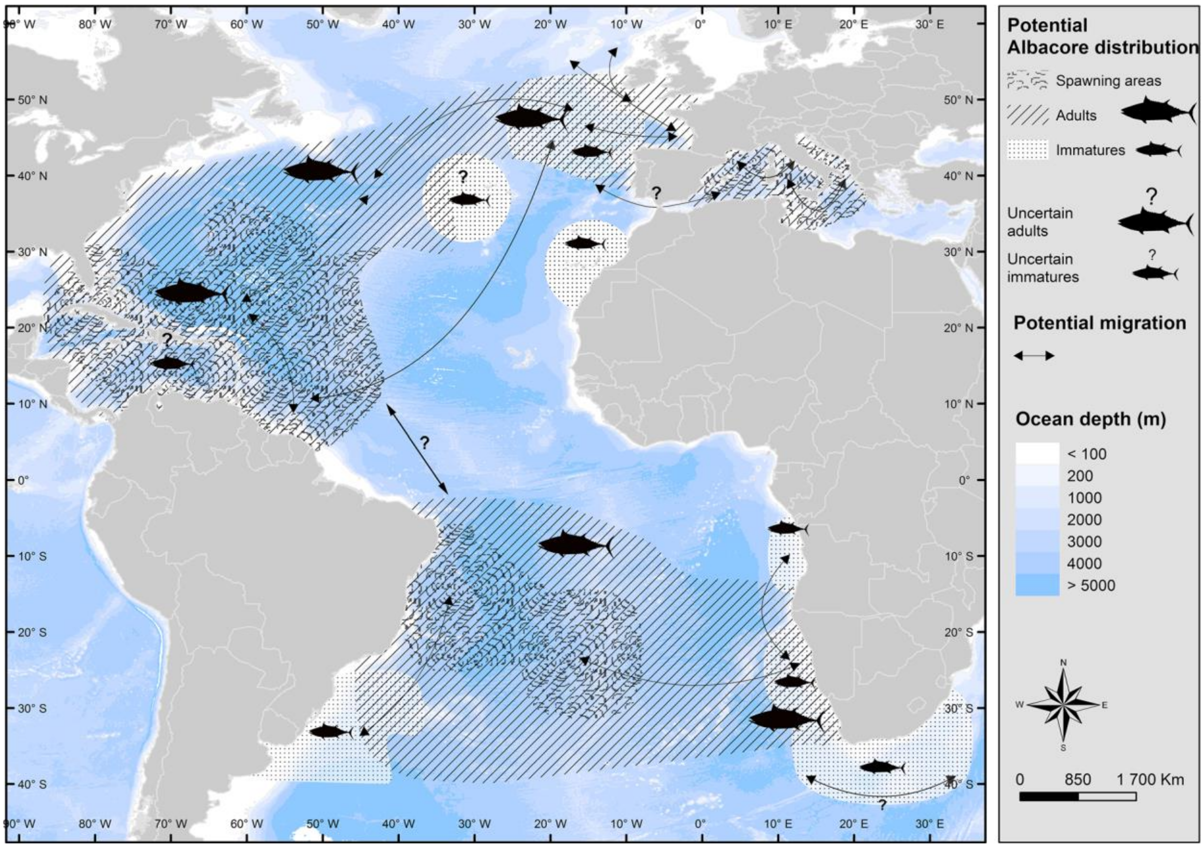

Figure 1. Albacore adult and immature geographical distribution and potential migrations in the Atlantic Ocean and Mediterranean Sea (extracted from Nikolic et al., 2017).

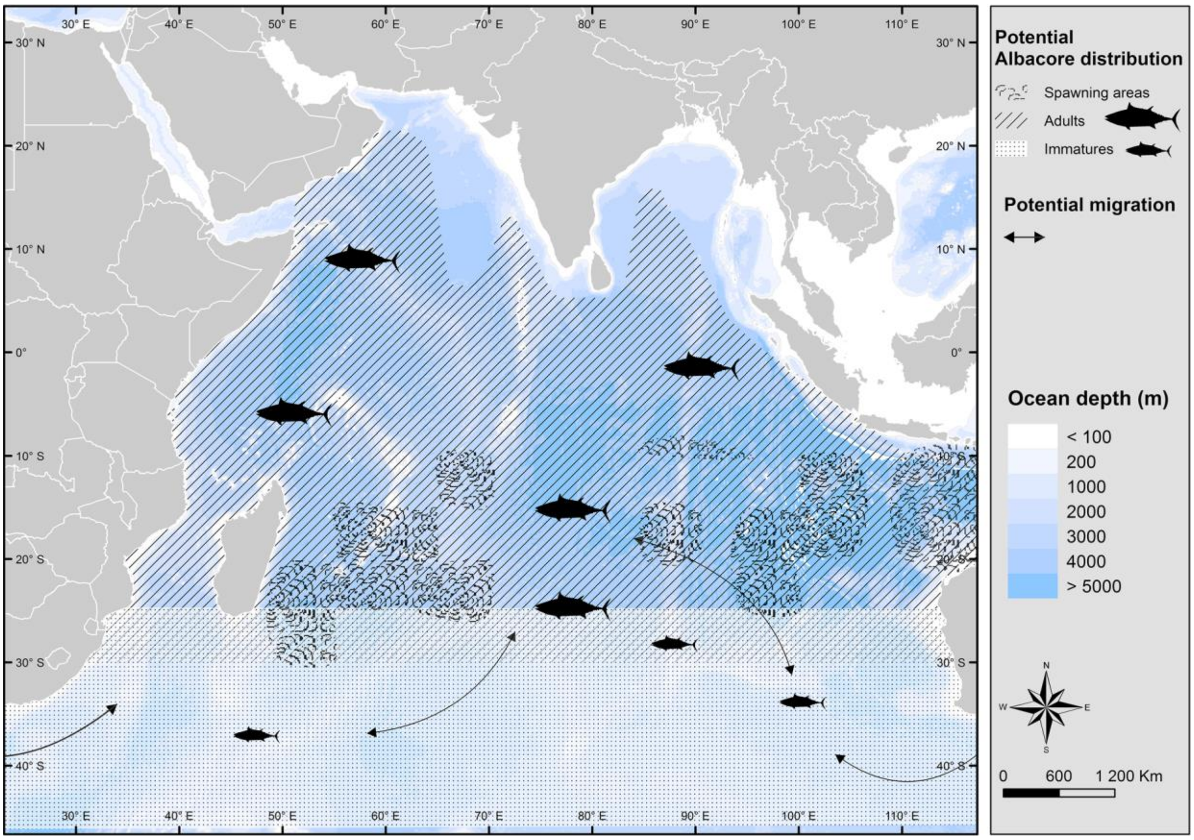

Figure 2. Albacore adult and immature geographical distribution and potential migrations in the Indian Ocean (extracted from Nikolic et al., 2017).

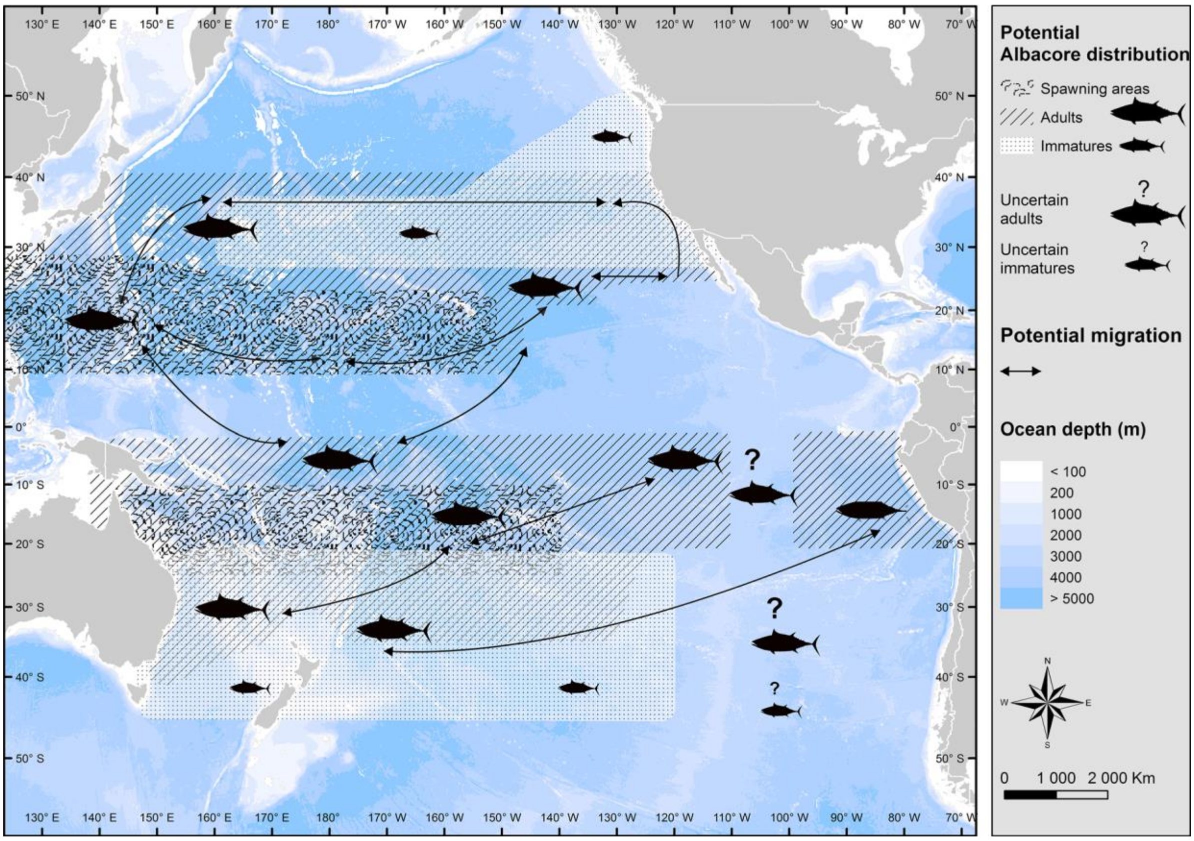

Figure 3. Albacore adult and immature geographical distribution and potential migrations in the Pacific Ocean (extracted from Nikolic et al., 2017).