Potential Impact of Global Warming on Tropical Tuna Habitat

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Abstract: Recent studies suggest a reduction of primary production in the tropical oceans due to changes in oceanic circulation under global warming conditions caused by increasing atmospheric CO_2 concentration. This might affect the productivity of higher trophic levels with potential consequences on marine resources such as tropical tuna. Here we combine the projections of up-to-date climate and ocean biogeochemical models with recent concepts of representation of fish habitat based on prey abundance and ambient temperature to gain some insight on the impact of climate change on skipjack tuna, the specie that dominates present day catches. For a $2xCO_2$ world, our results suggest significant large scale changes of skipjack in the equatorial Pacific. East of the date line, conditions are improved by either an extension or an eastward displacement of the present day favorable habitat zones of the western equatorial Pacific.

Keywords: Climate change; tuna habitat; skipjack tuna; modeling.

1. INTRODUCTION

It is now admitted that the 21st century will show a significant global warming trend induced by the increase of atmospheric greenhouse gases (IPCC-TAR, 2001). Propagation of this perturbation to ocean physics and biogeochemistry was the subject of several studies [Manabe et al., 1991; Manabe and Stouffer, 1993; Sarmiento et al., 1998] during the past decade. They show a more sluggish ocean circulation (reduced upwelling and deep water formation), as well as a stratification of the upper ocean induced by the warming of surface water and higher precipitation at mid and high latitudes. It is also recognized that such changes will reduce the input of essential nutrients [Maier-Reimer et al, 1996; Sarmiento and Le Quéré, 1996; Matear and Hirst, 1999] (such as phosphates, nitrates and silicates) to the surface ocean layer where most of biological production occurs.

It is only recently that the impact of circulation and nutrient changes on primary production (the photosynthetic activity of algae) was estimated [Sarmiento et al., 1998; Bopp et al., 2001]. These studies indicate a changing ocean environment due to global warming. For a world with doubled atmospheric CO_2 concentration, they suggest a change on the order of 20% for oceanic primary production at both regional and global scales. The trend is negative at low latitudes, where lower surface nutrients decrease the productivity, and positive at high latitudes where better light conditions extend the duration of the growing season. At this point an important but difficult question is: how the primary production changes will affect secondary production and possibly propagate through the food web up to higher trophic levels [Heith et al., 2001], thus potentially affecting marine resources in terms of fisheries ?

This study is a first attempt to gain some insight on this open question. Our approach is to combine the global warming projections of up-to-date climate and biogeochemistry models with recent concepts of representation of fish habitat. This bottom-up approach merges novel methodologies developed within the Joint Global Ocean Flux Study (JGOFS) and Global Ocean ecosystem Dynamics (GLOBEC) communities. Here we focus on tuna habitat in the tropical ocean, mostly the equatorial Pacific, for mainly three reasons. First, the tropical ocean is one of the best known and best simulated region by circulation models, second large scale tuna habitat models were recently proposed, and third tropical tuna is one of the major world fisheries and thus of high socio-economic value.

2. TROPICAL TUNA

Tuna are highly specialized fishes in regard to sustained, high levels of locomotive activity. They swim continuously to compensate for their negative buoyancy and travel long distances searching for food to satisfy their high energy requirements. This strategy has resulted in morphological and physiological adaptations particularly for thermoregulation and efficient oxygen extraction. Consequently, in the world ocean, conditions such as ambient temperature and oxygen concentration strongly influence tuna distribution [Brill, 1994; Barkley et al., 1978]. Within waters with favorable physical and chemical conditions, prey abundance (crustaceans, squids, fish) has the major influence on tuna distribution. The combination of those three parameters makes up habitat conditions. Other influences, such as fish behavior (nutrition, reproduction) and fishing pressure, also contribute to the quality of habitat conditions.

In the equatorial oceans abundance of tuna prey, or ``tuna forage'', plays a major role because both physical and chemical conditions are favorable and fishing pressure sustainable [Kleiber et al., 1987]. The secondary and tertiary production that make the base of tuna forage depends on the primary production from algae. The development of tuna forage from primary production takes several weeks (for small crustaceans) to several months (for small pelagic fish), during which both the random movement of organisms and the oceanic circulation generate the distribution of forage chased by tuna. Hence, tuna are preferentially located close to areas with high primary productivity or/and fronts between water masses known to aggregate the small prey organisms [Yamamoto et al, 1986; Power, 1996].

All tuna species are ubiquitous in the tropics, but due to physiological requirements, distribution of species is linked to water temperature. For example, in the western Pacific (i.e. in the warm pool region), most of the tuna catches are of skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*) that live in warm and oxygen rich surface waters, while bigeye (*Thunnus obesus*) that prefers colder subsurface waters is mostly fished in the eastern Pacific. Among all species, skipjack dominates the catch. More than 3 million tons are fished annually, most of which in the surface layer of the warm waters of the western equatorial Pacific, a region of important catches subject to strong zonal displacements in relation with El Nino Southern Oscillation (ENSO) events [Lehodey et al., 1997].

3. TUNA HABITAT INDEX

Among the parameters that define tuna habitat conditions (physical, chemical and prey availability), forage is the most difficult to assess. Because basin scale observations of tuna forage distributions are not available, a model was developed to produce a tuna forage index (TFI) under the hypothesis that forage results from the redistribution of primary production by oceanic currents [Lehodey et al., 1998]. This approach uses primary production and ocean circulation fields issued from ocean biogeochemical models [Stoens et al., 1998; Loukos and Mémery, 1999] (OBM's) and a parameterization of the trophic transfer of primary production to prey level as a characteristic recruitment time and an efficiency term. Despite the simplicity of the parameterization, the imperfections of the OBM's and the limitations of the data used for validation, this approach is consistent with the interannual variability of basin wide tuna catches in both the equatorial Pacific [Lehodey et al., 1998] and equatorial Atlantic [André et al., 1999].

Recently, a habitat index (HI) combining TFI and ambient temperature[19] was proposed to explain the position and the seasonal to interannual displacement of forage specific to a tuna specie:

$$\mathrm{HI} = N_{(\mathrm{Top},\ \sigma)}\ \mathrm{TFI} \qquad (1)$$

where $N_{(\mathrm{Top},\ \sigma)}$ is function of water temperature and represents a normal distribution centered on an optimal value (T_{op}) with a determined variance (σ) based on tuna physiology and behavior. Using T_{op}=30 and σ =2 for adult skipjack, *Lehodey* [in press] shows that the HI index agrees with a compilation of present day catches in the western equatorial Pacific. In this study we made the hypothesis that those habitat parameterizations are still valid in the context of global warming and focus our analysis on the spatial changes of skipjack habitat. We thus define:

$$S^{\mathrm{control}} = \iint_{\mathrm{HI}^{\mathrm{control}} > \mathrm{HI}_S} dS \qquad (2)$$

$$S^{\mathrm{warming}} = \iint_{\mathrm{HI}^{\mathrm{control}} > \mathrm{HI}_S} dS \qquad (3)$$

HI_S is chosen such as the highest value of HI_S delimiting present day fishing zones (HI_S = 12). This somehow empirically chosen value does not significantly affect the robustness of the results.

In order to evaluate the shift from a normal to warmer climate we define a habitat surface ratio (R) as the log of the $S^{warming}$ and $S^{control}$ ratio:

$$R = \log(S^{warming} / S^{control}) \qquad (4)$$

Therefore a positive/negative value indicates a surface increase/decrease of favorable habitat conditions.

4. SIMULATIONS

We use circulation and primary production fields issued from a coupled OBM used to estimate the consequences of global warming on oceanic biological activity [Bopp et al., 2001]. *Bopp et al.* [2001] compared three OBM's to identify the robust patterns of change between a ``control'' (constant atmospheric $CO_2$ concentration) and a ``warming'' simulation (a scenario in which atmospheric CO_2 increases at a rate of 1% y^{-1} until a doubling of the initial concentration, see

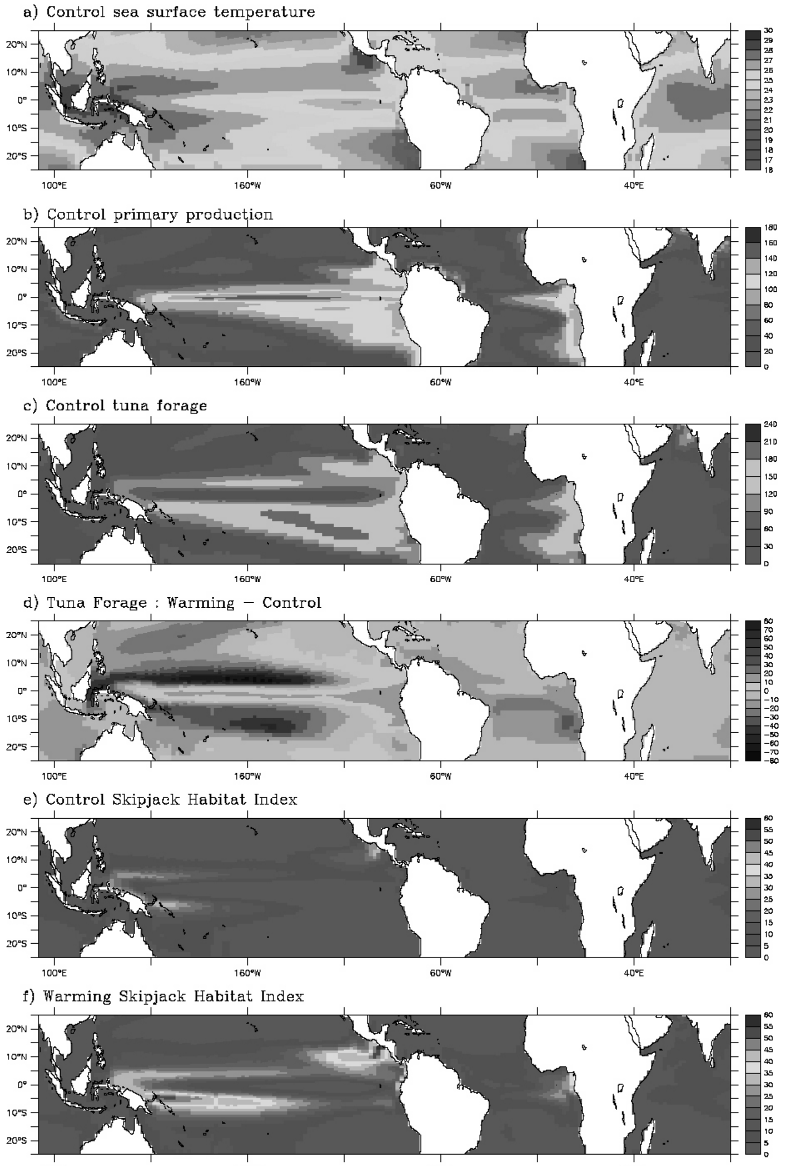

Fig. 2. The first three panels are the averages in the control simulation of a) sea surface temperature, b) primary productivity and c) tuna forage index. The last three panels are averages over the last 15 years of simulation of d) the difference of tuna forage index between the control and warming scenarios, the skipjack habitat index in the e) control and f) warming scenarios.

Fig. 1a). The circulation simulations where made in the context of the Coupled Model Intercomparison Project II (CMIP II) of World Climate Research Programme/Variability and Predictability Programme (WCRP/CLIVAR). Here we use monthly outputs from the OBM composed by the Océan Parallèle Ice (OPAICE) ocean model [Madec et al., 1997], the Laboratoire de Météorologie Dynamique (LMD5) atmospheric model [Sadourny and Laval, 1984], and the P3ZD biological model [Aumont et al., 2001] to drive the TFI model as described in *Lehodey et al.* [1998].

All CMIP models showed the same trend: a global increase in sea surface temperature (SST) and near surface-ocean stratification caused by both warming and increased precipitation in the mid and higher latitudes. At 2xCO_2, the global SST increase in the OBM we use is about +1.5 ^{o}C, which is at the lower range of all the ACMIP models (+1 - 3 ^{o}C). In the tropics, there is also a reduced upwelling (due to weaker Trade Winds) which translate to +1.5 ^{o}C in SST and -15% PP (Fig. 1b and c) for the tropical ocean (Fig. 2a and b).

5. RESULTS AND DISCUSSION

The decrease in primary production in the warming simulation has a direct impact on TFI (Fig.1d). This is not a surprise since there is an explicit link between primary production and forage in the parameterization we use. How realistic is this direct impact can not be assessed here, since several processes that could modify the transfer efficiency of organic matter through the food chain (such as life cycles, time of spawning etc.) are not taken into account. Indeed, there is a whole range of possible effects going from a smoothing by the food web of this relatively small variation, to temperature effects and shifts in phytoplankton species that can affect primary production regimes and the survival of herbivores [Roemmich and McGowan, 1995], and thus the whole tropical ocean ecosystem.

As in previous studies [Lehodey et al., 1998; André et al., 1999], the simulated tuna forage shows a spatial decoupling between the forage-rich areas and the high primary production zone of the equatorial upwelling (Fig. 2). Indeed, tuna forage is “aged"” over 3 months and transported (the time scale over which primary productions evolves towards forage) away from the equator by the surface currents associated with the equatorial upwelling. In the equatorial Pacific greater basin size and stronger surface currents that lead to an asymmetrical annular shape for TFI enhance this feature.

The pattern of primary production in the warming and control remains the same and thus the difference in forage distribution between the two simulations reflects mainly the PP decrease. However, this global reduction hides different regional patterns of change in the three tropical basins. While in the Atlantic and Indian oceans the decrease is almost uniform, the tropical Pacific exhibits asymmetrical TFI changes characterized by an increase on the equator and in the east, and a reduction on each side of the equator (Fig. 2 d). Those patterns are caused by a reduced equatorial divergence that is less efficient in washing forage away from the zones where primary production occurs, i.e. the equatorial and Peruvian upwellings. Therefore, based solely on the tuna forage distribution, changes suggest that tropical tuna fisheries could be affected differently in the equatorial Pacific by reduction in prey abundance in the west and an increase in the east.

However, the habitat of tuna like skipjack is also driven by temperature. Physiological effects that establish water temperature preference are in this study crudely parameterized by the $N_{(Top,\sigma)}$ function and thus the values of both T_{op} and σ are subject to uncertainties. We thus show three experiments differing by the value of those two parameters in order to focus on the most robust trends. First we use the same values as in *Lehodey* [in press] (T_{op} =30 and σ =2). Figure 2 e and f display for those set of values the TFI distribution in the control and warming simulations respectively. In a second experiment we test the influence of a relatively small change in T_{op} (T_{op} = 28 and σ = 2) on the results and in the last experiment we relax the temperature dependency by increasing (T_{op} =29 and σ =4).

In the warming simulation of the first experiment (Fig. 2f), although TFI is globally reduced in the tropics, the associated skipjack Habitat Index (HI see equation 1) in the equatorial Pacific spreads over a larger area reflecting overall better habitat conditions. This is due to a strong positive temperature effect caused by the surface warming of oceanic waters. In this case the decrease of tuna forage (-15% for TFI) can only partly compensate for the HI increase. The other two experiments show similar patterns of HI distribution as presented in figure 2e, but evolve differently under a global warming scenario according to the

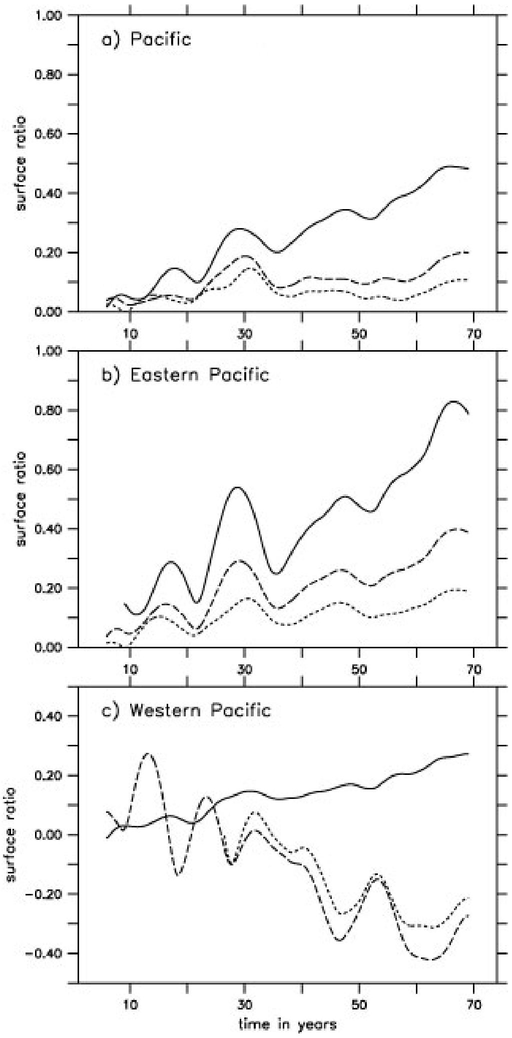

Fig. 3. Tuna Habitat Index surface ratio in the equatorial Pacific between 20^{o}S-20^{o}N. The black line is for T_{op} =30 and σ = 2, the dashed line is for T_{op} = 28 and σ = 2 and the dotted line is for T_{op} = 29 and σ = 4. All data are smoothed with a 10year Hanning filter.

strength of the temperature dependency. Figure 3a shows the time series for the Habitat surface ratio (R) for all three experiments. It shows a potential improvement of habitat surface in the equatorial Pacific up to a factor of three at 2xCO_2. However there is a distinct behavior between the western and eastern basins. East of the date line (Fig. 3b) all three experiments show a clear improvement of habitat surface ratio due to the combination of good forage and temperature conditions. West of the date line, the habitat surface change ranges from positive for the first experiment, when 30 C waters is the optimum temperature, to negative for the other two experiments. The later are sensitive to the tuna forage decrease that occurs in the western basin (Fig. 2d).

Keeping in mind the caveats associated with this approach and considering prey availability and temperature as the main factors controlling the distribution of warm surface water tuna, our results suggest a global improvement of skipjack habitat conditions east of the date line that could result from either an extension or a eastward displacement of present day favorable habitat conditions. More generally, we suggest that changes in oceanic conditions (circulation, temperature, nutrients, primary production) due to global warming could significantly affect tuna prey availability and habitat conditions for top predators of the food chain through “bottom-up mechanisms” as the ones presented here.

Further improvement and coupling of tuna forage and tuna populations models that explicitly take into account the physiological effects of temperature, the ecological interactions among species and fishing pressure is necessary are needed to better quantify the qualitative results presented in this study. On the long term, the assessment of sustainable tuna fisheries will have to take into account not only fishing pressure or short term variability such as ENSO, but also large scale pattern shift in habitat conditions induced by global warming.

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