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Habitat overlap between southern bluefin tuna and yellowfin tuna in the east coast longline fishery – implications for present and future spatial management

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ABSTRACT

Southern bluefin tuna (SBT) are presently a quota-managed species in the multi-species eastern Australian tuna and billfish longline fishery (ETBF). Capture of SBT is regulated by quota, as is access to regions likely to contain SBT. A habitat prediction model combining data from an ocean model and pop-up satellite archival tags is used to define habitat zones based on the probability of SBT occurrence. These habitat zones are used by fishery managers to restrict access by ETBF fishers to SBT habitat during a May-November management season. The zones display a distinct seasonal cycle driven by the seasonal southward expansion and northward contraction of the East Australia Current (EAC) and as a result access by fishers to particular ocean regions changes seasonally. This species also overlaps with the commercially valuable yellowfin tuna (YFT), thus, we modified the SBT model to generate YFT habitat predictions in order to investigate habitat overlap between SBT and YFT. There is seasonal variation in the overlap of the core habitat between these two species, with overlap early (May-Jul) in the management season and habitat separation occurring towards the end (Aug-Nov). The EAC is one of the fastest warming ocean regions in the southern hemisphere. To consider the future change in distribution of these two species compared to the present and to explore the potential impact on fishers and managers of the future, we use future ocean predictions from the CSIRO Bluelink ocean model for the year 2064 to generate habitat predictions. As the ocean warms on the east coast of Australia and the EAC extends southward, our model predicts the suitable habitat for SBT and YFT will move further south. There was an increase in the overlap of SBT and YFT habitat throughout the management season, due to regional variation of each species' habitat. These results illustrate that a management tradeoff exists between restricting fisher access to SBT habitat and allowing access to YFT habitat. We suggest that some options to address this tradeoff are possible by identifying the seasonal variability of the overlap.

1. Introduction

In the majority of marine fisheries, capture of desirable (target) species is accompanied by the incidental capture of other (bycatch) species (Poiner and Harris, 1996; Hall, 1998; Tasker et al., 2000; Kock, 2001). The movement in fisheries management from a single species focus towards ecosystem based fishery management (Link et al., 2002; Hall and Mainprize, 2004) has resulted in an increased research focus on non-target captures of species in fisheries (Raloff, 1999; Stobutski et al., 2001). Major effort has been directed towards minimizing the bycatch of threatened, endangered or protected species, particularly through changing the selectivity of fishing, either through modification of fishing gear or practice (Hall and Mainprize, 2004; Poiner and Harris, 1996; Hall, 1998; Kock, 2001; Lewison et al., 2004; Tallack, 2007) or the time of fishing (Piatt et al., 2006).

In fisheries where gear selectivity for target and bycatch species is similar (e.g. pelagic species such as billfish and tuna; Goodyear, 1999), minimizing bycatch through gear modifications is often not possible. An alternative in such cases is the implementation of spatial management, where the core habitat (e.g. spawning ground, migratory path) is identified and then fisher activity in that habitat modified to protect the species of concern (Howell et al., 2008). Spatial measures have been proposed to reduce unwanted interactions in both horizontal (Goodyear, 1999) and vertical (Luo et al., 2006) dimensions in

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both offshore and coastal marine habitats. These spatial measures can also be changed through time, to provide spatial and temporally flexible management options.

Such a temporally-variable spatial management approach has been successfully employed in the eastern Australian tuna and billfish longline fishery (ETBF; Hobday and Hartmann, 2006; Hobday et al., 2009). This fishery is a pelagic longline fishery targeting tropical and sub-tropical tuna such as yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) and billfish species such as broadbill swordfish (*Xiphius gladius*) and striped marlin (*Kajikia audax*) in the Tasman and Coral Seas. The range of these species seasonally overlap with the more temperate southern bluefin tuna (*T. maccoyii*), a species which is regarded as over-exploited and whose capture is strictly governed by international quotas (Polacheck, 2002; Kolody et al., 2008).

Seasonal spatial management has been implemented by the eastern Australian longline fishery managers since 2003 to allow targeting of southern bluefin tuna (SBT) by fishers that hold quota for SBT, and reduce unwanted interactions with SBT by fishers who do not (Hobday et al., 2009). The region is divided into three management zones based on the expected distribution of SBT habitat (high, medium, low probability), and a report delivered to fisheries managers, who then regulate access by longline fishers to the fishery region based on the three habitat zones. Placing restrictions on where fishers can operate, however, may mean foregone catch of other target species within the eastern Australian longline fishery, such as yellowfin tuna (YFT) at times of year when the distribution of SBT may overlap with the distribution of others.

To estimate potential habitat overlap between SBT and YFT, we extended the currently used habitat model for SBT, to produce a similar habitat model for YFT. Comparisons of overlap between the two species provided by the models were then used to propose potential management options aimed at minimizing penalty to YFT fishers in terms of foregone catch, while still maximizing protection for SBT.

The south-eastern Australian region is also warming rapidly due to climate change, with the East Australia Current (EAC) pushing further south (Ridgway, 2007), which has been predicted to allow southward expansion of northern species (e.g. YFT), and contraction of the northern distribution for southern species (e.g. SBT) (Hobday et al., 2008; Hobday, 2010). The warming is not occurring equally along the coast, raising the possibility that habitats will not change in synchrony. In order to investigate potential changes in the overlap of SBT and YFT in response to predicted warming, we projected habitat models for both species in the year 2064 to provide the first estimates of future overlap in range of these species. In the forecast model, this year represented an average year from this decade. We recognize that this provides managers with a very long-term outlook.

2. Methods

The SBT habitat model uses temperature and depth data from pop-up satellite transmitting archival tags (PSATs) that are released in the study area. The vertically structured temperature preference is combined with remotely sensed sea surface temperature and modeled temperature-at-depth data (CSIRO Bluelink ocean model www.cmar.csiro.au/bluelink/, Ridgway et al., 2006; Oke et al., 2008; Schiller et al., 2008) to create a habitat map with probability of fish being found at each 4 km^2 pixel in the model domain of eastern Australia (see Hobday and Hartmann, 2006). The errors in modeled temperature (from the hindcast) range from 0.5 °C at the surface, 0.75 °C at base of mixed layer and 0.25 °C at 1200 m (Ridgway et al., 2006). The errors for the forecast are larger, but have not been quantified yet. The error in the PSAT temperature measurements is 0.05 °C. This model is currently conditioned on 5,032 days of depth and temperature data obtained from 56 individual SBT tagged with PSATs. The PSATs have been deployed on large SBT with a length to caudal fork of 173.7 ± 9.5 cm (mean ± SD, Patterson et al., 2008). SBT taken in the ETBF between 2002 and 2008 are 160.5 ± 18.0 cm length to caudal fork (mean ± SD, CSIRO unpublished data). As new PSATs are deployed and transmit, these data are incorporated in the near real time habitat predictions (Hartog et al., 2009).

The model used to describe YFT habitat developed here is modified from the model developed for SBT, and is currently conditioned on 18 tags and 1,238 days of data. Tags on SBT collected data over the period 2001–2007 and those on YFT during 2004, 2008 and 2009 in an area bounded by 24-42°S and 148-170°E (Fig. 1). There are potentially large errors in estimating daily position from PSAT light data (Patterson et al., 2008), and because of this, tag data was spatially aggregated within the study area. The assumption here is that the temperature preference of an animal released in the study area is representative of the whole fishery. Analysis of the tagging data suggests that SBT and YFT spend 90% and 96% of time whilst in the area of the study, respectively, in water shallower than 200 m. Given the depth preference of both species, we limited both habitat models to use only sub-surface temperature data from the ocean model to a depth of 200 m. The probability of an SBT being found at a location (pixel) is based on cumulative probability of temperature preferences in the model domain. For example, the 80% value in the probability distribution indicates the temperature below which 80% of SBT are expected to occur. This continuous habitat preference is simplified to create three habitat zones: the core zone is defined as the area in which SBT spend at least 80% of their time based on habitat preferences; the buffer zone, where SBT spend only 15% of their time (i.e. the 80–95% probability region), and the OK zone, where SBT are expected less than 5% of the time (i.e. the 95–100% probability region). Note the name "OK zone" has been used by the fishery since 2003, and refers to the zone being "OK for fishing without restrictions".

Mimicking the current operational use of the model for SBT, we ran the model for each species for each day in the period 1994 – 2008. The habitat model results in a habitat map that shows the spatial extents of the three zones (Fig. 1). Using each day of habitat predictions, we then constructed a time-latitude climatology of the location of the edges of the core and buffer habitats for each species. To do this, the latitude of the edge of the core and buffer zones were defined for each daily habitat prediction map. Edges were defined as the latitude at which 95% of the zone pixels are accounted for (Hobday and Hartmann, 2006). In the case of northern edge of the SBT core zone, it is the latitude at which 95% of the core zone pixels are to the south. Similarly, for the YFT core zone, it is the latitude where 95% of the core zone pixels are to the north of that latitude. The buffer zones for each species on each day were summarized by the location of the 5^{th} and 95^{th} percentiles of the buffer zone pixels. These summary values were then averaged for each day of the year (1 – 365) to generate a mean climatology for each species for the period 1994–2008.

The locations of the zones through the average year for each species were then compared, allowing periods of core YFT habitat and core SBT habitat overlap or divergence to be identified. Hereafter, we restricted the analysis period to May-October, the time when fisheries management uses spatial management for SBT (Hobday et al., 2009).

Given the rapidly changing ocean climate off the east coast of Australia we also considered how the habitat overlap between these two species may change in future. While, Global Climate Models (GCMs) are considered the most effective tool for

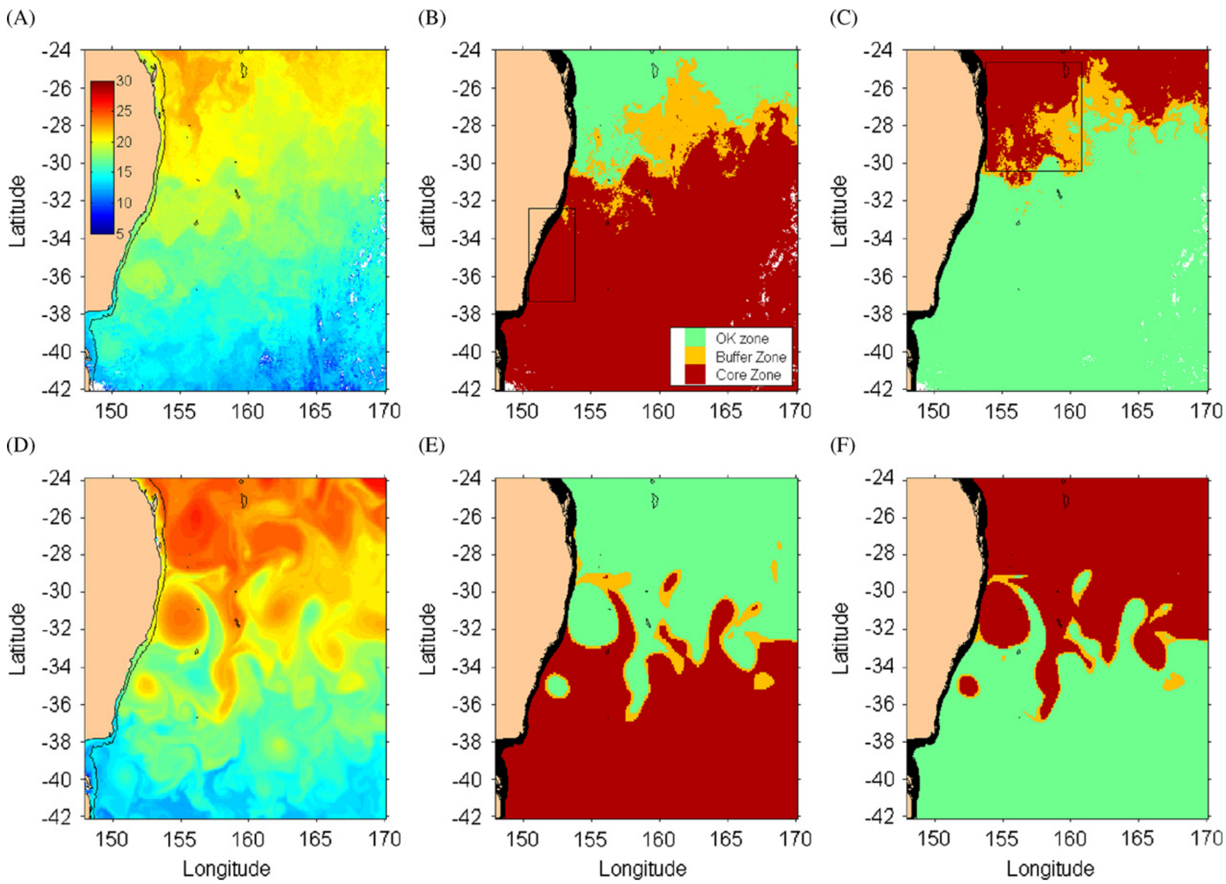

Fig. 1. An example set of sea surface temperature maps and habitat prediction maps for southern bluefin tuna (SBT) and yellowfin tuna (YFT). Upper row is predictions for August 2009; lower row is August 2064. Panels A and D are the sea surface temperature maps for those time periods, panels B and E are SBT habitat predictions, and panels C and F are YFT habitat predictions. The rectangular boxes in panels B and C represent the release location of 56 SBT and 18 YFT tags, respectively, that have been used in the habitat prediction models.

projecting the environmental response to rising greenhouse gases in the atmosphere, due to the complexity of these models they are formulated at relatively low spatial resolution (e.g., typically between 1 and 2 degrees). Therefore, they do not provide sufficient spatial resolution to make useful regional climate change projections. Further, these GCMs fail to capture important features of ocean circulation (e.g. boundary currents and mesoscale eddies) that are relevant to how climate change will impact marine systems. To produce regional climate change projections, it is necessary to apply downscaling techniques to the GCM output. We use dynamical downscaling (Chamberlain et al., 2009), which we briefly summarize below, to provide the impact of climate change on the East Australian region.

The GCM projection is based on the CSIRO Mk3.5 A2 scenario (Gordon et al., 2002) for the years 2061-64 (three spin-up years, 2064 analysis year). The analysis decade (for example rather than a year in the 2020's) was chosen to ensure that the signal we were investigating was a climate change signal and not decadal variability, as shorter term prediction is still a frontier of climate research (Meehl et al., 2009). We dynamically downscaled the climate change projection using the Ocean Forecasting Australia Model (OFAM) that includes a biogeochemical module (Oke et al., 2008; Dietze et al., 2009). OFAM is eddy resolving in the Australian region (0.1° of longitude and latitude around Australia, 20 N to 80 S and 90E to 180E) with much coarser resolution outside this region (Schiller et al., 2008). The initial conditions for the downscaled simulation were generated by combining the present-day ocean state (January 1, 1995 of OFAM SPINUP5, Oke et al., 2008) with the anomaly in the ocean state simulated by the GCM between January 2061 and January 1995. The OFAM forcing fields for the downscaled climate change simulation were a combination of the 6-hourly forcing fields from SPINUP5 starting from January 1, 1995, and the monthly climate anomaly forcing fields derived from the climate change simulation. The monthly climate anomaly forcing fields were calculated as the difference from the reference year 1995 of the GCM. The downscaled simulation was run over the years 2061 to 2064, by adding the monthly anomaly forcing fields to the 6-hourly forcing fields from 1995.

We use the last year of the simulation in our investigation of the impact of climate change of tuna distributions to generate similar habitat probabilities and annual climatologies. The degree of overlap between each species was then compared to the present situation. This overlap was summarized by comparing the mean edge location of a climatology measure from the SBT habitat model with the corresponding climatology measure from the YFT habitat model. The results are summarized by both the management season and the full year.

3. Results

Tagged SBT display temperature preferences of 15.0 – 19.0 °C (25^{th} and 75^{th} percentile) in the upper 200 m in the area of study (Fig. 1), while tagged YFT appear to prefer waters of 20.7 – 23.2 °C (25th and 75th percentile). The differences in preferred water temperatures results in the two species occupying an almost inverse habitat within each model (Fig. 1). Thus, waters classified

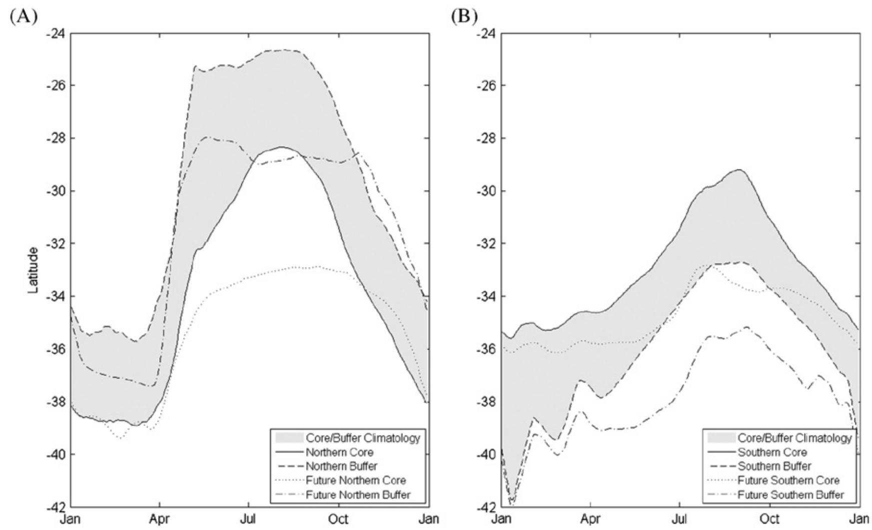

Fig. 2. Habitat zone climatologies for southern bluefin tuna (SBT) (A) and yellowfin tuna (YFT) (B) based on the period 1994-2008 (grey) and the year 2064 (between dotted and dot-dash lines). SBT core habitat is the area below the solid (present) or dotted (future) lines in panel A, and YFT core habitat is the area above the solid (present) or dotted (future) lines in panel B. Buffer habitat for both species is represented by the grey between the solid and dashed lines (present) or dot and dot-dash (future) lines.

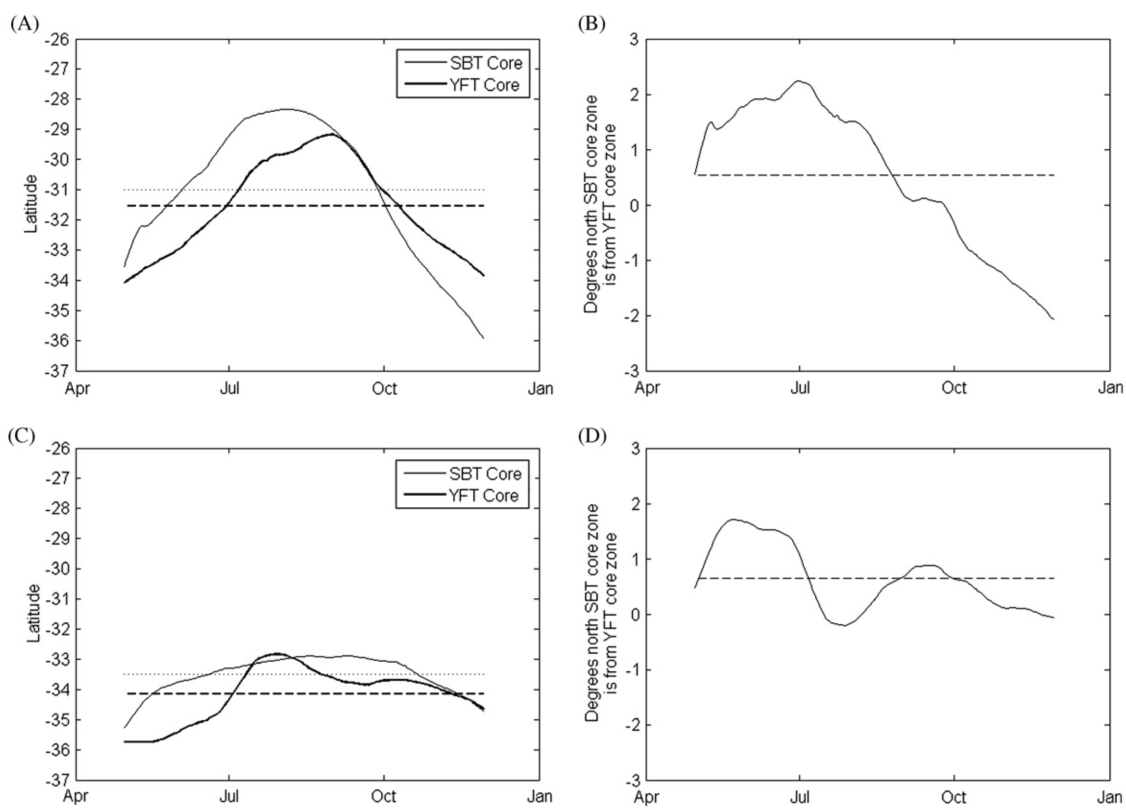

Fig. 3. Climatological comparison between the boundary of the core habitat for both species during the management season (May-Nov) in the present (A) and future (C). The dashed lines in panels A and C (thickness corresponding to SBT or YFT as indicated in the legend) are the mean location of the edge of the core zones for each species. Panels B and D show how far north the southern bluefin tuna core zone is compared to the YFT core zone for the present (B) and future (D). The dashed horizontal line in panels B and D represent the mean zone overlap over the year. A positive (negative) value indicates that zones overlap (are separate).

as core zone for YFT associated with warm water transported south within the EAC, are typically classified as OK zone for SBT. Conversely, SBT core zone habitat is typically classified as OK zone for YFT, and is associated with cool water transported north.

Under present scenarios, the northern SBT core zone edge ranges between a northern latitude of 28.3°S and a southern latitude of 38.9°S throughout the season whereas under future scenarios it ranges between 32.9°S and 39.4°S (Fig. 2). Comparisons between present habitat predictions and those in the future for SBT demonstrate a clear southward shift in the locations of the habitat zones (Fig. 2). There is, however, less seasonal variation (flatter shape) in the future habitat zone climatology, suggesting the present magnitude of the seasonal north-south expansion and contraction of the EAC will be reduced in the future.

Table 1
Summary of mean climatology-based differences in predicted habitat overlap between southern bluefin tuna (SBT) and yellowfin tuna (YFT) for both present (1994-2008) and future (2064). For present and future overlaps, positive numbers (in degrees of latitude) indicate overlap between zones, and negative numbers indicate a separation of the habitat zones for each species. For the separation between present and future habitat, negative (positive) numbers indicate increased (decreased) overlap in future.

	Management Season (May-Nov)			Year (Jan-Dec)		
	Present overlap	Future overlap	Separation between present and future habitat	Present overlap	Future overlap	Separation between present and future habitats
Core zone: Difference between the mean northern edge of the core SBT zone and the mean southern edge of the core YFT zone	0.55	0.65	−0.10	−0.90	−0.50	−0.40
OK zone: Difference between mean southern edge of the OK SBT zone and the mean northern edge of the OK YFT zone	−0.86	0.34	−1.20	−1.08	0.25	−1.33
Buffer zone: Difference between the mean northern edge of the buffer SBT zone and the mean southern edge of the buffer YFT zone	7.85	8.08	−0.24	6.45	6.47	−0.02

Similar shifts in predicted habitat are observed for YFT (Fig. 2) with locations of habitat zones also occurring further south in the year 2064 compared to present. The location of the southern core edge under present scenarios varies between a southern latitude of 29.2°S and a northern latitude of 35.6°S compared to 32.8°S and 36.2°S under future scenarios (Fig. 2).

The comparison of present core zone climatology shows that there is overlap of YFT core with SBT core in the early part of the management season (Fig. 3). In contrast, the comparison of core zone overlap in the future for SBT and YFT show that SBT core habitat is north of the YFT core habitat for most of the management season, with the two zone edges crossing over for a short period of time in late July/early August (Fig. 3).

The summary of mean climatology-based differences in overlap between SBT and YFT habitat for both the present and the future shows a change in the habitat overlap relationship (Table 1). The difference between the present and the future shows that by all zone comparisons, the habitat overlap between SBT and YFT will either increase or remain the same. For example, the present mean separation between SBT and YFT cores zones during the management season is 0.55 degrees of latitude, and increases slightly to 0.65 in the future. For the whole year, while the mean core latitudes do not overlap (0.90 degrees of separation), however, in future, this separation decreases by 0.40 degrees to 0.50, and at some times of the year (management season), there is overlap (Fig. 3).

4. Discussion

4.1. Present and future habitat overlaps in Eastern Australia

A total of 74 PSAT tags for SBT and YFT released on the east coast of Australia have been included in the development of species-specific habitat prediction models, which in turn yielded annual habitat climatologies for comparison. Presently, there is overlap in the model-based distribution of SBT and YFT habitat zones in the early part of the management season, with the maximum overlap occurring around July, and then decreasing later in the season.

In situ warming and strengthening of the EAC over the last 60 years has been observed (Ridgway, 2007) and this pattern is estimated to continue into the future (Hobday et al., 2007). Global climate models are generally too coarse to resolve the dynamics of boundary currents such as the EAC, however, we have been able to take advantage of some of the first downscaled predictions for Australian waters using the Bluelink model. Thus, we present the first model-based predictions of habitat shift for pelagic species in Australian waters. While these results should be viewed cautiously as a first approximation, they are consistent with previous predictions using statistical associations for different species and climate models that showed pelagic species moving further south (Hobday et al., 2008; Hobday, 2010). The results presented in this paper illustrate that the habitat zones for SBT and YFT will occur further south, associated with strengthening of the EAC and warmer waters carried being transported further south.

In estimating these changes in SBT and YFT habitat into the future, we are assuming that both SBT and YFT associate with water masses rather than specific (e.g. topographic) locations. Interannual variation in the catch distribution of east coast species captured in the longline fishery throughout this region (Campbell, 2008) suggest this is a reasonable assumption. Although associated with water masses, tuna distribution is primarily influenced by the distribution of their prey species (Young et al., 2001). Prey species have been shown to be sensitive in distribution to temperature change (e.g. Murawski, 1993; Hawkins et al., 2003), given that they show less thermoregulatory ability than tuna species (e.g. Brill and Lutcavage, 2001). Our assumption is that the larger pelagic fishes such as YFT and SBT will move to where the prey is, and will not be directly limited by physical changes. All seasonal habitat zone measures (OK, core, buffer) suggest that the future overlap between habitat zones of these two species is likely to increase slightly, although future interannual variability cannot be assessed at this stage. This is consistent with future southward extension of the warmer EAC being constrained by cooler Sub-Antarctic Water to the south (Hobday et al., 2008). Thus, the more northern YFT habitat will overlap further with the southern SBT habitat. This is evidenced by the less variable shape of the climatology (the area between the core habitat and the buffer habitat) in the future (Fig. 2), and is seen in Fig. 1, where the future habitat can be partitioned into zones by east-west divisions, rather than a south-west to north-east division. If SBT management plans are successful (e.g. Kolody et al., 2008), we hope that the currently over-exploited SBT stock will be recovered in 50 years, and the current restrictions on capture of SBT can be revised. Until this recovery, a continuing management challenge is to ensure that unwanted capture of SBT does not impair the stock recovery, which has motivated the use of the SBT spatial management approach (Hobday et al., 2009).

4.2. Management implications

Due to this habitat overlap, the present identification of areas for spatial management of SBT on the basis of habitat predictions would therefore suggest foregone catch for YFT. In part, this is because the placement of SBT management lines does not follow the predicted SBT zones exactly (Hobday and Hartmann, 2006; Hobday et al., 2010). As a result, some YFT core habitat is typically grouped with core SBT habitat. For example, fishers seeking YFT may be excluded from YFT habitat when the SBT management lines are placed too far to the north. The analysis presented here suggests that there may be some benefit in imposing fishing restrictions in the early part of the management season, when the overlap of the SBT and YFT core zones is greatest, and then relaxing those quota or fishing location restrictions towards the end of the season, when there is no overlap of core habitat. The relaxation can occur because fishers seeking YFT are likely to find them in different locations than SBT, and the habitat separation may be at a finer scale than a coarse management line can differentiate between. In order to guide this relaxation of restrictions, the amount and distribution of foregone YFT catch (fish within the SBT core zone that were not available to all fishers) during the season could be estimated based on catch distribution records from the fishery.

According to the model predictions we have made, the management problems faced today as a result of two species with different stock status sharing similar habitat are likely to persist in 55 years, and may even increase due to future changes in oceanography. Speculation regarding future management actions, spatial or otherwise, would be just that: here we simply note that model-based predictions of future habitat distribution are now possible using down-scaled ocean models linked to GCM's.

Improved habitat models would require additional information on habitat preference, perhaps related to prey distribution based on chlorophyll-a and temperature fronts (Royer et al., 2004; Druon, 2010) rather than just primary physical variables (e.g. temperature). A limitation of the current habitat model is that the temperature preferences derived from PSATs indicate distributions, but do not show when the animal is feeding. If the environmental preferences when fish are feeding differ from the overall environmental preferences, then a mismatch in predicting catch can result (Maunder et al., 2006; Ward and Myers, 2006). In the current habitat models, habitat preferences are uniform throughout the study area. Defining finer scale location-specific habitat predictions may improve predictive capability – a limit in this regard is the accuracy with which position can be determined from PSAT data (see papers in Nielsen et al., 2009). The amount of data used to condition the habitat model is considered sufficient for SBT, as approximately 100 days of tag data, or 15 PSATs, are required to obtain a stable model such that adding more tags does not substantially alter the model output (Hobday et al., 2010). This minimum data condition cannot be tested for YFT until more tags are deployed. Testing the habitat prediction results with alternative models, such as CPUE-based habitat prediction models (e.g. Maunder et al., 2006), would also improve confidence, and this is expected in future.

We have used a single downscaled forecast model, and acknowledge that more robust results might be inferred from using several models, as now occurs for analysis of GCM results (Hobday, 2010), or by running the future model using a range of years and starting conditions. At the time of analysis this capacity did not exist due to the amount of time required for the downscaled forecast to run.

In a general way, these results may be used for a variety of purposes, including planning of future infrastructure needs to support fishing from new locations, if for example fishers relocated to southern ports, or for development of long-term policy directions regarding allocation of spatially restricted catch rights (Hobday et al., 2008). The future results presented here should be applicable to planning for the near term also, as the climate change in 10 to 20 years will follow the trajectory of the long term climate change. Consideration of these types of present and future alternatives will assist the ongoing management of a sustainable multi-species fishery in this important oceanographic region.

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