Ensemble analysis of the future distribution of large pelagic fishes off Australia

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ABSTRACT

Changes in the climate due to anthropogenic effects are impacting the global oceans and the constituent biology, particularly through changes in water temperature. Impacts of warming water on oceanic species are most likely to be detected as changes in distribution. Pelagic fishes, in particular, respond to changes in ocean temperature, and modify their distribution on seasonal and interannual timescales, and thus are likely to do so in the future. Global climate models provide insight into possible future conditions, but there is also considerable uncertainty regarding future changes because of differences in model structure and future scenarios. To address some of this uncertainty, I considered output from multiple climate models through an ensemble analysis and examined potential changes in the distribution of large pelagic fishes captured by longline fisheries on the east and west coast of Australia by the year 2100. For the east coast, over 95% of model predictions for 14 pelagic species (tunas and billfishes) suggested that core range would move south, and be smaller than what occurs presently. There was less certainty for the west coast, although the core range for all 14 species moved south and was smaller for 63% and larger for 37% of scenario-model combinations. The overall rate of predicted habitat movement for the suite of pelagic species averaged about 40 km/decade. While relatively coarse, these predictions give some confidence to stakeholders about likely changes in future distribution for these regionally important pelagic fishes.

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1. Introduction

Climate change is affecting marine systems globally (e.g. Hays et al., 2005; Rosenzweig et al., 2008) including Australia (Poloczanska et al., 2007). Documented impacts on marine species can be ascribed to four general categories (Walther et al., 2002): changes in distribution (Hobday and Tegner, 2002; Perry et al., 2005; Mieszkowska et al., 2007), abundance (Richardson and Schoeman, 2004), phenology (Sims et al., 2001; Edwards and Richardson, 2004) and physiology (Ishimatsu et al., 2005; Pörtner and Knust, 2007). At an ecosystem level, changes in community structure, diversity and function are also expected, although these are less understood (Harley et al., 2006; Poloczanska et al., 2007). In marine systems, changes in distribution have been documented more often than other category, with the focus largely on coastal or benthic species (Poloczanska et al., 2007).

Pelagic species, such as tunas and billfishes, are likely to show substantial changes in distribution, perhaps before changes occur (or are detected) in other fish species, as they have demonstrated an interannual response to climate variability (Lehodey, 2001; Rouyer et al., 2008). Thus, an initial focus of potential changes in the distribution of pelagic species on the east and west coast of Australia is an appropriate measure to assess the impacts of cli-

mate change. An understanding of future distribution is important in planning adaptation strategies for those involved in harvesting marine species (Roessig et al., 2004; Drinkwater, 2005; Hobday et al., 2007a). For example, Loukos et al. (2003) suggested that changes in skipjack tuna (*Katsuwonus pelamis*) distribution at a basin-level scale are a result of climate change. There are presently no predictions for future distribution changes in key Australian pelagic species, and the approach presented here could be extended to other regions of the world.

In waters of eastern Australia, warming of sea surface temperature, consistent with a climate change fingerprint, has been reported (Ridgway, 2007). There is also evidence for a poleward extension of the East Australia Current (EAC), bringing warmer water from the north (Ridgway, 2007; Hill et al., 2008). Thus, there is the cumulative effect of local warming combined with increased transport of warmer water from the north. Biological changes, particularly range changes linked to these warming patterns, have already been reported for a variety of eastern Australia coastal species (Poloczanska et al., 2007; Ling et al., 2009).

Along the west coast of Australia, warming is consistent with the background pattern of global warming, although recent evidence from the coastal portion of the Leeuwin Current suggests, as on the east coast, that warming is occurring faster than the global average (Pearce and Feng, 2007). Thus, climate-driven changes in these two regions could have a substantial impact on

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the distribution of pelagic species. With both coasts having pole-ward-flowing boundary currents, comparisons between the two coasts will allow estimates of relative impact, and initiate discussion on potential adaptation options.

Knowledge of future physical environments and the resulting biological distributions is limited by several issues related to uncertainty that potentially undermine future predictions (Hughes, 2003; IPCC, 2007). The first source of uncertainty is future greenhouse gas emissions: the future emission trajectory is unknown, and so a range of trajectories are typically used to represent a low to high warming response (IPCC, 2007). Second, global change models (GCM) that incorporate these scenarios to predict the future conditions vary widely in their predictions, particularly at a regional scale (Dessai et al., 2005).

An approach to dealing with this uncertainty is to perform an ensemble analysis including all scenarios and all model combinations (*sensu* Araújo and New, 2006). Predictions of future habitat distribution for a range of pelagic fishes are made for the year 2100. Most GCM outputs are at relatively coarse resolution (>1°), which makes predictions of coastal changes more suspect as physical heterogeneity is greater than offshore. To demonstrate the utility of the ensemble approach for predicting future distribution of marine species, this study uses a suite of pelagic species as in offshore waters model resolution may be less problematic.

This approach is based on the concept of bioclimatic modeling (Pearson and Dawson, 2003), with a very simple description of habitat – sea surface temperature. Strengths and weaknesses of the methods for constructing species distributions are contrasted in Elith et al. (2006). The use of only a single variable in this study is very simple compared to typical analyses in fisheries oceanography that use a range of variables to describe fish-environment associations, including sea surface temperature, sea surface chlorophyll, sea surface height, eddies, fronts, and sub-surface temperatures (e.g. Laurs et al., 1984; Bigelow et al., 2002; Zainuddin et al., 2006). A limitation of current GCM outputs is that few of the above variables that are useful for predicting fish distribution at the mesoscale, are produced. As a result, this analysis will consider only changes in distribution and abundance due to changes in surface ocean temperatures predicted by GCMs.

In this study, the predicted change in the mean latitude of occurrence, and the area occupied within a fixed boundary region on both the east and west coast of Australia was used to derive an impact metric for the year 2100. These metrics can be used at a coarse scale to generalize predictions about future distribution changes for pelagic fishes.

2. Methods

Distribution data for pelagic species were obtained from catch records for two major longline fisheries on the east and west coast of Australia. These fisheries operate year-round: annual effort over this period has averaged over 10 million hooks and 3 million hooks respectively, and both catch a wide variety of species (Dowling et al., 2005; Campbell, 2008). The date and location of capture for the most abundant species was extracted from the ETBF and WTBF commercial logbook database for the years 1997–2005 for the area enclosed by 140–175°E, 10–45°S and 95–130°E, 10–45°S respectively (Fig. 1). The size of fish captured in these fisheries was estimated from a smaller observer dataset, collected from the same fleets for the period 1999–2005.

Because the region of study is fixed, the future distribution within the region of interest may not contain the complete distribution of the fish, and as such, might better represent climate change impacts from a fishery perspective. These most abundant species were those with >1000 records in each of the 12 months for the ETBF ($n = 14$) and more than 200 records for the WTBF ($n = 14$). This dataset contained 332,249 records for 14 species for the ETBF and 31,244 for the WTBF (Table 1). A total of 12 species were common to both coasts. The difference in sample size reflects the fishing effort in each region. Both fisheries operate over a wide region, and hence catch records are likely to reflect distribution of each species within the respective regions. Obviously, distribution can only be reported where fishing occurred. Unfortunately, fishery-independent distributions for many pelagic fishes are difficult to obtain. For commercially valuable species, such as tuna and billfish, electronic tags can provide location information; however, this would limit the number of species that could be examined at this time. As a result, two assumptions in such bioclimatic analyses are relevant here: the first is that the observed distribution indicates an environmental preference, rather than the locations where capture was possible; and the second assumption is that there will be no adaptation that will change habitat preference.

Models used in the ensemble analysis were produced for the IPCC TAR in 2002. While access to climate models is now easier with archiving at the PCMDI (http://www-pcmdi.llnl.gov/), the data volume is significant when considering multiple models and scenarios. A tool called OzClim was used to access the GCM data used in this study (Ricketts and Page, 2007). This tool creates climate change scenarios across Australia for a range of terrestrial climate variables in addition to one marine climate variable, based on
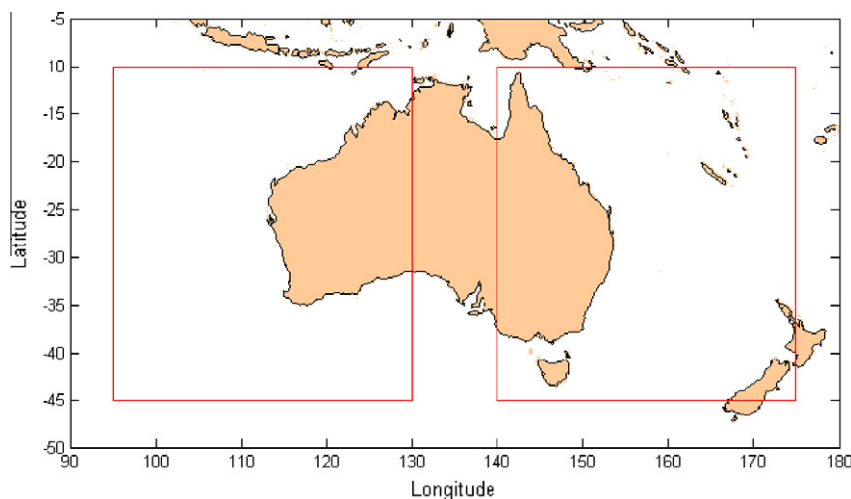

Fig. 1. Map of regions considered for west coast and east coast analysis of future range changes for pelagic species captured in longline fisheries off each coast.

Table 1
Species included in the future habitat prediction for the east coast (ETBF) and west coast (WTBF). The number of records for the period 1997–2005 is shown for each region. The top 14 species for each region, as defined in the text, were included. Size (mean ± SD) was calculated from a smaller observer dataset from the same regions and fisheries for the period 1999–2005, and was determined by A: total length, B: length caudal fork, or C: orbit-fork length. The notation NA indicates that data were not available.

Species		ETBF	Mean size (cm)	WTBF	Mean size (cm)
Shark					
Bronze Whaler (*Carcharhinus brachyurus*)	BWH	4598	266 ± 80[A]	476	NA
Oceanic Whitetip Shark (*C. longimanus*)	OWS			302	196 ± 76[A]
Shortfin Mako Shark (*Isurus oxyrinchus*)	SFM	15,701	163 ± 66[A]	807	165 ± 51[A]
Blue Shark (*Prionace glauca*)	BLS	11,670	208 ± 62[A]	2227	218 ± 47[A]
Scalloped Hammerhead (*Sphyrna lewini*)	SHH			478	NA
Tuna					
Skipjack Tuna (*Katsuwonus pelamis*)	SKT	1189	63 ± 10[B]	214	61 ± 13[B]
Albacore Tuna (*Thunnus alalunga*)	ALT	42,391	81 ± 11[B]	1811	96 ± 6[B]
Yellowfin Tuna (*Thunnus albacares*)	YFT	64,674	116 ± 22[B]	4978	136 ± 15[B]
Southern Bluefin Tuna (*Thunnus maccoyii*)	SBT	3199	157 ± 20[B]		
Bigeye Tuna (*Thunnus obesus*)	BET	46,288	121 ± 23[B]	6286	113 ± 23[B]
Wahoo (*Acanthocybium solandri*)	WAH	4658	129 ± 22[B]	438	135 ± 5[B]
Billfish					
Broad Billed Swordfish (*Xiphias gladius*)	BBL	49,961	134 ± 42[C]	7741	141 ± 36[C]
Striped Marlin (*Tetrapturus audax*)	STM	27,336	190 ± 20[C]	798	150 ± 4[C]
Other Teleost					
Dolphinfish (*Coryphaena hippurus*)	DOL	29,245	114 ± 19[B]	1000	87 ± 8[B]
Ray's Bream (*Brama brama*)	POM	3020	48 ± 7[B]		
Rudderfish (*Centrolophus niger*)	RUD	28,499	80 ± 23[B]	3688	60 ± 41[B]
Total records		332,429		31,244	
Total species		14		14	

patterns of change extracted from global climate model outputs from the IPCC models (for information on the terrestrial version of OzClim see http://www.csiro.au/ozclim). Patterns of change consist of grids of slope parameters. At each grid point, a time series of the value of a climate variable at a particular month and year has been regressed against the estimated mean global temperature computed for that model and year. Changes are expressed relative to a baseline GCM field for the years 1990–2000, such that absolute change is determined by adding the change to the baseline. The OzClim tool produces predictions at a scale of 0.25° by interpolation from the coarser, raw GCM output.

To predict the future distribution of habitat, the location and date for each observation was matched to fine-scale (9 km), 3-day composite SST data processed by CSIRO (http://www.bluelink.com.au). Temperatures in the middle 80% (i.e. the upper and lower 10% of values were excluded) described the core habitat for each species on each coast, as preliminary analysis showed exclusion of more extreme data resulted in better matches between observed and predicted data, but a full sensitivity analysis for this element was not undertaken. Testing the ability of the climate models to predict present species distribution is an important

validation step prior to making future predictions. These suitable temperature ranges were then applied to the GCM baseline data averaged for each month for the year 1990–2000 (baseline) to estimate the ability to "predict" core present distribution. The percentage of all observations for each species that fell within the predicted habitat envelope derived from GCM baseline was then calculated. While interannual variation is present in GCM output, the years do not correspond to particular calendar years. Thus, the baseline GCM averaged for the period 1990–2000 should cover the mean conditions, but not interannual variation. A perfect match between observed catch locations, and the model-based prediction for the same period is not expected, but a high overlap will indicate some prediction skill.

These core temperature ranges were then applied to the future GCM data to produce core habitat maps for each month for the year 2100 for each model and scenario. This time period was selected because the OzClim pattern-scaling algorithm used to access the climate model data is linear (Ricketts and Page, 2007). Changes over shorter time scales will be proportional to the time between the decade 1990–2000 and 2100. Thus, for each species, there were 9 models × 25 scenarios × 12 months (2700) future core habitat

Table 2
Temperatures defining the habitat envelopes for the same species on the east (ETBF) and west (WTBF) coasts of Australia. The envelope includes the middle 80% of all observed temperatures.

| Species	ETBF			WTBF		
	Lower (°C)	Mean (°C)	Upper (°C)	Lower (°C)	Mean (°C)	Upper (°C)
Shortfin Mako	19.00	21.80	25.17	16.89	21.16	25.20
Bronze Whaler	21.20	24.55	27.89	20.02	25.01	29.53
Blue Shark	17.04	21.91	26.16	16.96	21.11	24.66
Dolphinfish	21.45	24.45	27.20	19.92	24.13	29.45
Yellowfin Tuna	19.88	23.19	26.64	19.88	23.08	27.09
Skipjack Tuna	19.99	22.59	25.88	18.93	23.13	29.25
Albacore Tuna	19.32	22.40	25.88	17.62	21.37	24.91
Bigeye Tuna	19.95	23.20	26.45	17.53	21.30	24.53
Wahoo	22.88	25.71	28.70	20.21	24.45	29.56
Broad Billed Swordfish	19.77	22.91	26.20	17.89	21.59	24.91
Striped Marlin	20.10	22.71	25.75	21.06	24.12	28.36
Rudderfish	19.47	22.87	26.34	18.43	21.85	25.02

distribution predictions. These predictions will be treated as independent in the analysis presented here.

2.1. Analysis

For each species, the model-scenario combination each month (225 combinations per month) can be compared to the predicted core distribution based on GCM data for 1990–2000. The probabil-ity of species presence at each location (i.e. each pixel) is based on the percentage of the 225 model-scenario combinations that predict suitable core temperatures at that location. Thus, a visual representation of the probability of occurrence can be obtained for the year 2100 for each month and species.

The distribution of each future habitat in 2100 within the analysis region is summarized using the center of the habitat compared to the center of the habitat in 1990–2000, and by the 2100 area
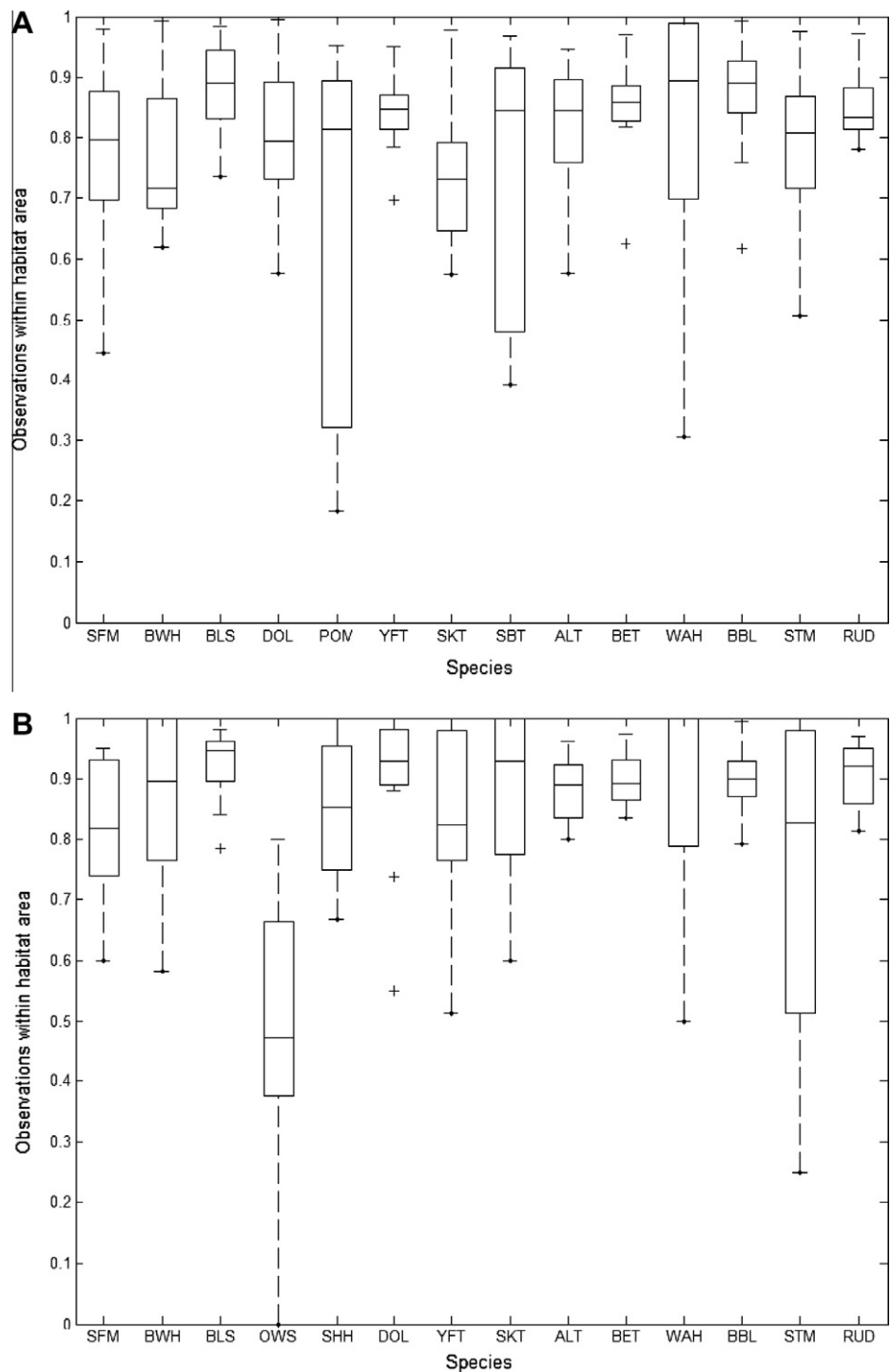
Fig. 2. Box and whisker plots summarizing the base GCM model fit for the observed location (observation) of pelagic fishes as reported from longline catch data 1997–2005 in (A) ETBF and (B) WTBF. For each box and whisker plot there are 12 months per species, and the box has lines at the lower quartile, median, and upper quartile values. Whiskers extending from each end of the box show the extent of the rest of the data. Outliers are data with values beyond the ends of the whiskers. Species codes are listed in Table 1.

compared to the area occupied in 1990–2000. Thus, there are four possible combinations (quadrants) of future habitat distribution: the center of the future habitat can be further north or south, and it can be larger or smaller than in 1990. The distribution of the 2700 predictions can thus be summarized by these four quadrants.

A change index summarized these two elements (area and latitude). Latitude change was in the range 0–10, while area change was a proportion [in the range (−1 to 1)], so it was converted to the range 0–10. The change index was calculated as the Euclidean distance from the origin (mean latitude for species distribution and

area) in 1990 to the predicted mean latitude for species distribution and area in 2100. Mean change indices were compared among species and between coasts to estimate future climate impact. All analyses were undertaken with Matlab 7 (Mathworks), including access of the OzClim-generated future GCM temperature fields for Australia.

3. Results

Habitat descriptions for east coast species were derived from a minimum of 1189 records for skipjack tuna to over 60,000 for
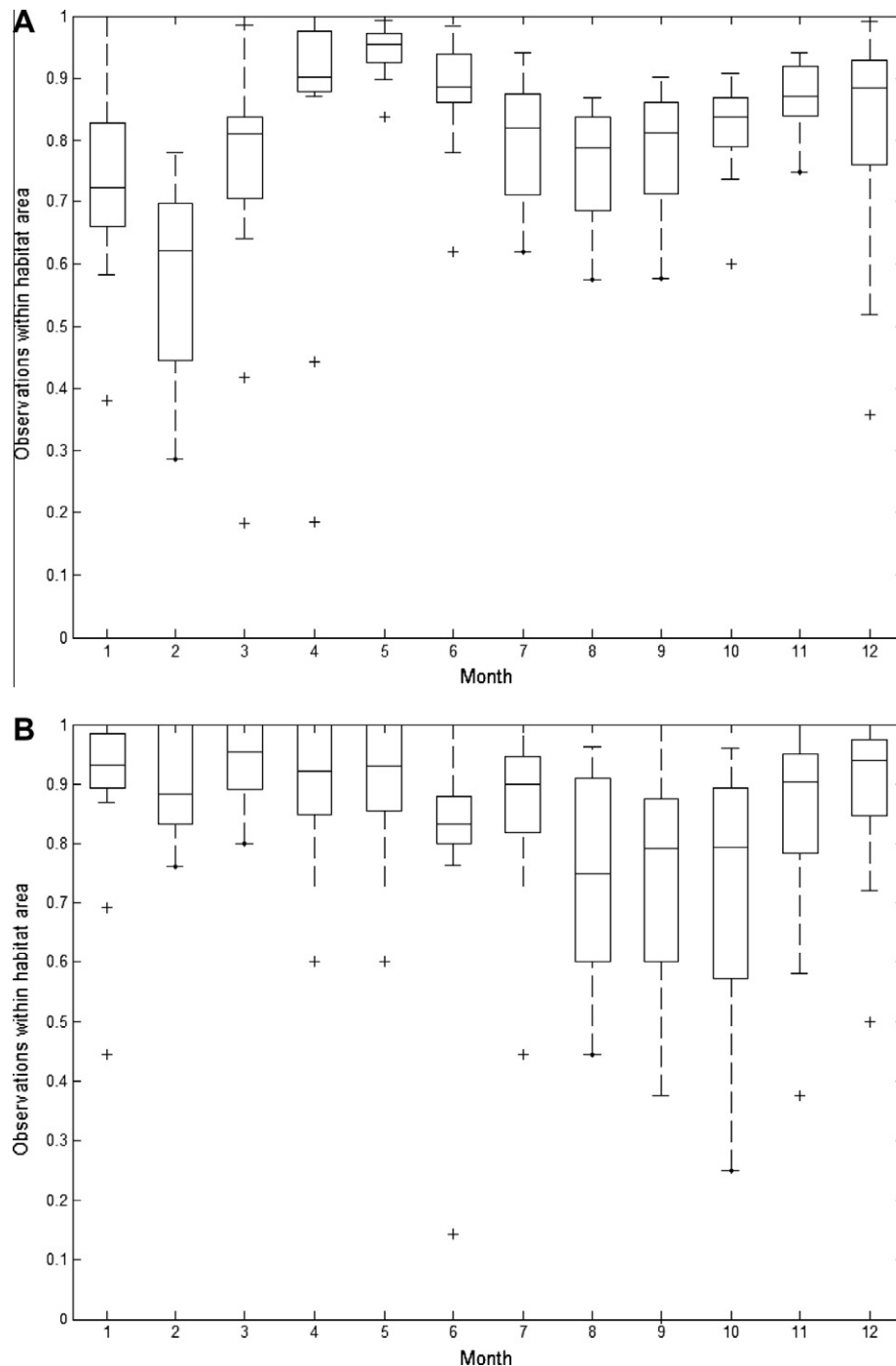
Fig. 3. Box and whisker plots summarizing the base GCM model fit for the observed location (observation) of pelagic fishes as reported from longline catch data for each month of the year 1997–2005 in the (A) ETBF and (B) WTBF. For each box and whisker plot there are 14 species per month and data are presented as described in Fig. 2. Species codes are listed in Table 1.

yellowfin tuna (Table 1). West coast species habitat descriptions were based on between 200 (skipjack tuna) and 7000 (swordfish) records. The upper and lower sea surface temperature limits describing the core 80% of the "habitat envelope" based on longline captures were similar between species on both the west coast and the east coast (Table 2), as were the sizes of the fish on each coast (Table 1), indicating similar thermal preferences.

3.1. Model fit to present distribution

Overall, for the east coast (ETBF), 80% of species observations in the core habitat preference temperature distribution were captured within the area predicted by the CGM baseline for the period 1990–2000, with a range among species (Fig. 2A). On the west coast, 84% of species observations were within the suitable area predicted by the GCM baseline (Fig. 2B). The baseline model enclosed a high proportion (>80%) of the distribution on the east coast for blue shark, wahoo, yellowfin tuna, Ray's Bream, southern bluefin tuna, albacore tuna, bigeye tuna, broadbill swordfish, and rudderfish. The poorest enclosure of present observations was for skipjack tuna, bronze whaler and striped marlin, although the mean for all months was still above 70% (Fig. 2A). For some species in some months, poor fits were derived (e.g. wahoo: lowest fit was 28%), but these were rare (Fig. 2A).

The models ability to fit the present distribution were greater for the species on the west coast (Fig. 2B), with most species having more than 80% of the observed distribution inside the GCM baseline model prediction. The lowest prediction was for dolphin fish; for one month none of the observations were inside the predicted envelope, although sample size was very low in this month.

3.2. Seasonal differences in model fit

The habitat envelope for each species was not described equally well by the baseline GCM for all months. On the east coast, the fit was poorest in February and best in April–June (Fig. 3A). A different pattern was determined for the west coast, with poorest fits for all species in August to October, and best fits in summer (Fig. 3B). These patterns suggest that the seasonal differences in fine-scale oceanography that influence fish distribution are not reproduced in the baseline GCM, and reinforce a known limitation with bioclimatic modelling when the scale of the environmental data is coarse.

An example of habitat predictions is shown for blue sharks (Fig. 4). The observed locations where blue sharks were captured are mostly contained within the predicted habitat envelope based on the sea surface temperature from the ocean model. In some months, the ocean model does not match the observed locations (e.g. January–March in northern Australia), but the majority of observations fall within the area predicted by the baseline climate model (Fig. 2A). Predictions for the year 2100 show a southward movement for this species.
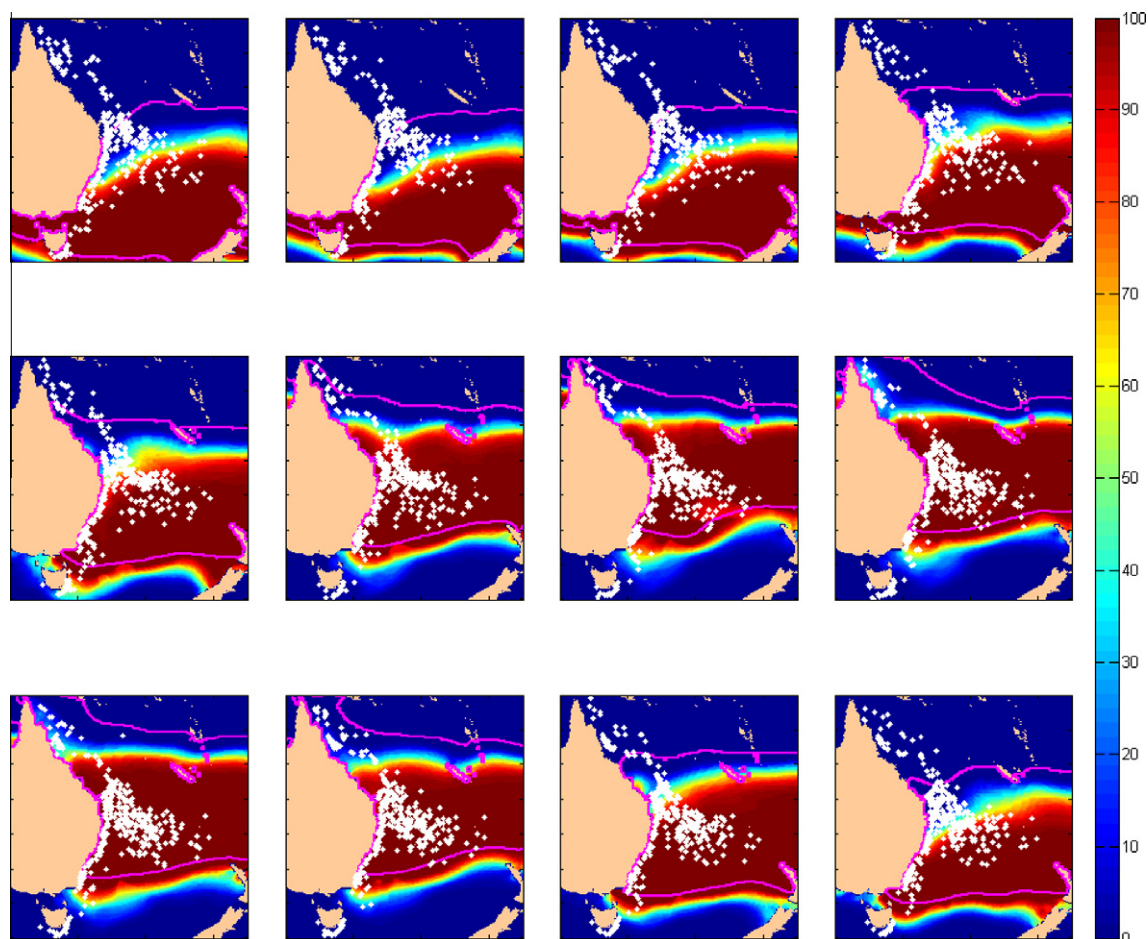

Fig. 4. An example of future habitat prediction for a longline-caught species, blue shark (*Prionace glauca*), on the east coast of Australia, for each month of the year (January–April on upper row, May–August on middle, September–December on bottom row). The observed distribution of blue shark catch for 1997–2005 in each month is shown by white symbols; the magenta lines show the envelope for the present distribution predicted by the base climate model, while the colors indicate the probability of occurrence in the year 2100 as predicted by 225 model combinations for this species each month.

3.3. Future distribution changes

Despite the number of simulations performed and the spread of results, the outcome was overwhelmingly similar for the ETBF species at a coarse scale when predictions were grouped into one of four future habitat categories. A total of 95% ($n = 35,993$) of the

simulations for the 14 species resulted in predicted future habitat that was smaller and further south that presently occurs in the area considered. Only 4.78% ($n = 1807$) of simulations predicted that habitat area within the study region would increase, with a southward movement (Fig. 5A). Between models and simulations, there is wide variation, with some showing almost no change from
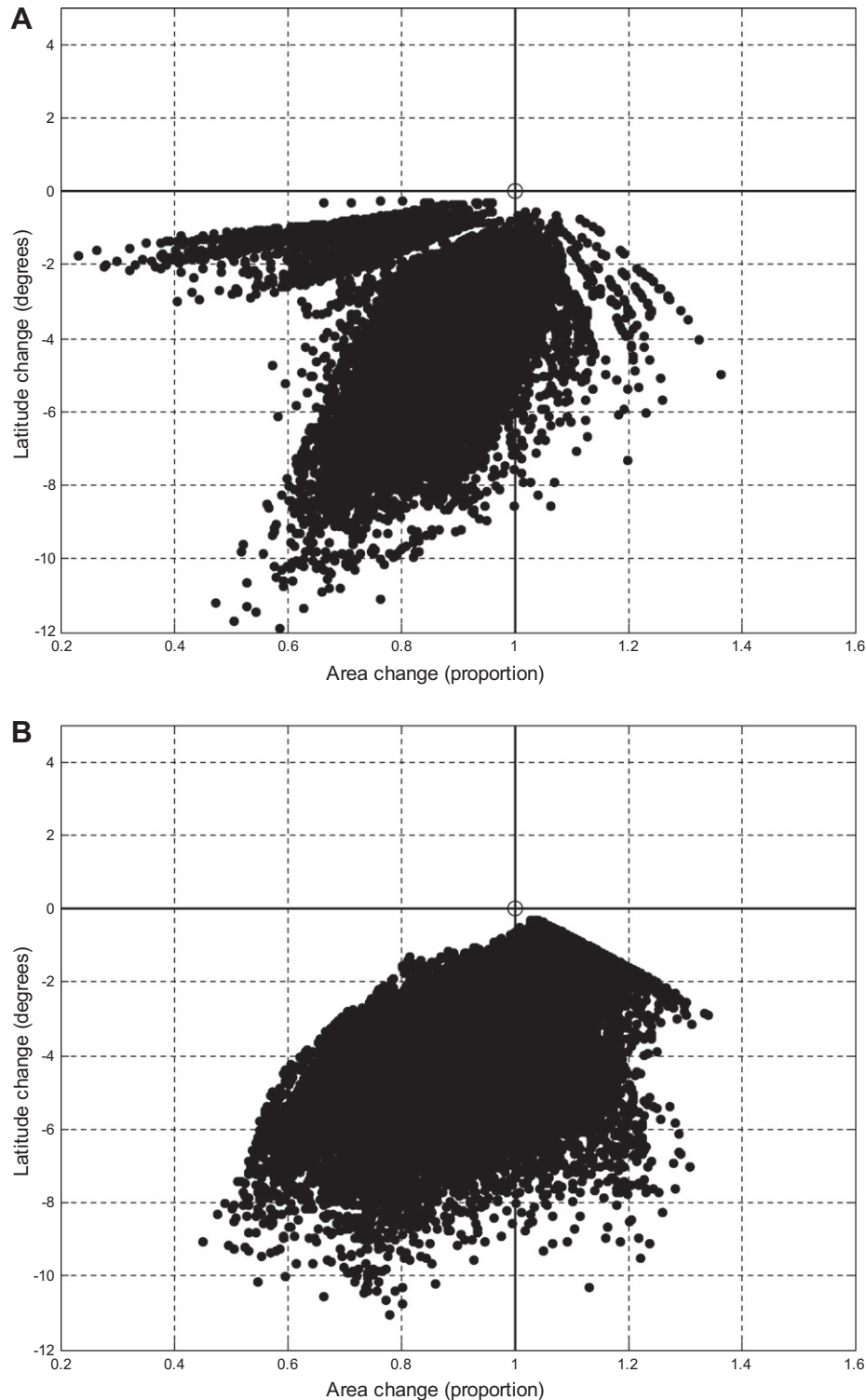
Fig. 5. Overall change in species distribution by the year 2100. The solid lines divide four quadrants for future possibilities. There are a total of 37,000 future predictions (14 species × 12 months × 9 models × 25 scenarios) for the (A) ETBF: lower left, south and small, 95.2% ($n = 35,993$); lower right, south and large, 4.8% ($n = 1807$); upper left, north and small ($n = 0$); and upper right, north and large, ($n = 0$) and (B) WTBF: lower left, south and small, 63.11% ($n = 23,856$); lower right, south and large, 36.89% ($n = 13,943$); upper left, north and small ($n = 0$); and upper right, north and large, ($n = 0$).

the present range and latitude, and others showing large differences.

For species on the west coast captured in the WTBF, there was less agreement with the size of the future habitat: 63% (n = 23,856) of simulations predicting smaller habitat to the south, and 37% (n = 13,943) predicting larger habitat areas within the study area (Fig. 5B). In this case, the increase in habitat within the area considered was due to suitable habitat expanding into southern Australia. Thus, 100% of predictions for both coasts indicated that future habitat would occur further south than at present, although there is wide variation among predictions, with some showing almost no change from the present range and latitude, and others showing large differences (Fig. 5B).

Impact scores for the year 2100 were derived based on the combination of area change and latitude change. On the east coast, the species captured in the ETBF experiencing the highest impact scores in terms of future distribution were wahoo, bronze whaler, and dolphinfish (Table 3). Species with lowest impact were southern bluefin tuna and Ray's bream. For the west coast, the most impacted species were striped marlin, wahoo and yellowfin tuna (Table 3). Species with least predicted impact were skipjack and albacore tunas.

A comparison of species between coasts is also illustrative of the future impacts of climate change on pelagic species. The mean impact for the 14 most common species in the ETBF was 4.26 ± 1.27 compared to 3.74 ± 1.14 for the WTBF (Table 3). The two elements contributing to the overall metric were also higher for the ETBF, with a mean latitude change for all species of 3.98 compared to 3.57 for the WTBF. Area declined less for the WTBF species than for the ETBF species (Table 3).

A comparison of the predicted change in habitat distribution by 2100 between the west and east coast of Australia is possible using the same metrics. The mean change in latitude for the area in which the 12 common species were found was 4.30° farther south for the ETBF and 3.54° farther south for the WTBF, a difference of 0.77° (85.4 km). The size of the core habitat was 0.87 times the 1990 habitat for the ETBF and 0.95 times the size for the WTBF species. The overall mean index score for the 12 common species was 4.51 for the ETBF species, and 3.70 for the WTBF species.

The mean annual range change (i.e. averaged for the 12 months) for each species on each coast is shown in Fig. 6. For all 225 annual predictions (9 models × 25 scenarios), all species on both coasts move south by 2100. For some species, there is a similar change in both area and latitude (wahoo and yellowfin tuna), while for some species, one coast will see a change in both area and latitude, while the other will see a change in latitude only (blue shark; Fig. 6). Overall, for the west coast, habitat models predict species will mostly move south but occupy a similar-sized area. When range changes for the 12 months are averaged (mean latitude and mean area change), all 14 species for the east coast are predicted to occupy smaller areas to the south within the analysis region (Table 3). For the west coast, there are species that show 100% average movement to the south into smaller areas, but some species also show increased area (e.g. albacore and bigeye tunas). Overall, at the annual scale, 82.5% of the west coast species simulations show southward contraction, and 17.5% show southward expansion (Table 3).

4. Discussion

Climate change impacts on pelagic species are likely to be most obvious as changes in distribution (Hobday et al., 2007b). This analysis has shown that on both coasts of Australia, the area and location of suitable habitat for a range of longline-caught pelagic species will change relative to present-day distributions. Because of the uncertainty in future climate projections, results here have been presented in terms of four possible outcomes. Not one of 37,800 future habitat simulations resulted in species moving northward on either coast; the overwhelming majority of simulations for the east coast also predicted a reduction in suitable habitat. This is due in part to a compression of suitable habitat as the East Australian Current (EAC) strengthens and warms before encountering the sub-Antarctic water mass (Poloczanska et al., 2007). It is also because the analysis was based on a fixed region, thus a reduction in habitat can also occur because suitable habitat is now found south of the analysis region. On the west coast, warming is more generally related to the pattern of global warming worldwide, and so an overall movement south without habitat compression explains many of the results. An increase in predicted habitat on the west coast is also due to expansion of suitable habitat into southern Australia.

The ensemble analysis employed here allowed treatment of uncertainty between model and scenario differences (Whetton et al., 2005). Results were not sensitive to the global climate models

Table 3
Mean and standard deviation of impact scores for the eastern (ETBF) and western (WTBF) species for the year 2100. The area change is a proportion of the area occupied in 1990–1999, while the latitude change (degrees) is the difference between the mean latitude occupied in 1990–2000 and 2100. Negative numbers indicate the area has moved south. Each species result is obtained from 2700 model simulations (12 months × 9 models × 25 scenarios). SS (south small) and SL (south large) show the percentage of species simulations (averaged for the 12 months, n = 225) producing range changes to this quadrant. There were no range changes to the north.

Name	East coast (ETBF)								West coast (WTBF)							
	Index mean	SD	Area change	SD	Lat change	SD	SS (%)	SL (%)	Index mean	SD	Area change	SD	Lat change	SD	SS (%)	SL (%)
Shortfin mako	4.00	1.18	0.90	0.04	−3.85	1.15	100	0	3.47	1.08	1.00	0.02	−3.40	1.08	69.33	30.67
Bronze whaler	4.71	1.48	0.87	0.05	−4.50	1.41	100	0	3.75	1.16	0.94	0.04	−3.49	1.14	90.67	9.333
Blue shark	4.20	1.17	0.88	0.04	−4.01	1.12	100	0	3.31	1.05	0.90	0.02	−3.29	1.05	66.22	33.78
Oceanic whitetip shark									3.89	1.22	0.93	0.04	−3.72	1.21	98.67	1.333
Scalloped hammerhead									4.03	1.18	0.90	0.03	−3.84	1.17	100	0
Dolphinfish	4.72	1.53	0.87	0.06	−4.50	1.46	100	0	4.11	1.14	0.90	0.04	−3.78	1.11	100	0
Ray's bream	2.91	0.83	0.87	0.06	−2.57	0.66	100	0								
Yellowfin tuna	4.60	1.41	0.86	0.05	−4.39	1.36	100	0	4.15	1.15	0.89	0.03	−3.92	1.14	100	0
Skipjack tuna	4.45	1.30	0.88	0.04	−4.26	1.27	100	0	3.15	1.18	0.96	0.05	−3.00	1.16	78.67	21.33
Southern bluefin tuna	2.59	0.87	0.80	0.08	−1.58	0.43	100	0								
Albacore Tuna	4.41	1.22	0.87	0.04	−4.21	1.20	100	0	3.38	1.09	1.00	0.02	−3.35	1.08	59.56	40.44
Bigeye Tuna	4.63	1.39	0.86	0.05	−4.41	1.34	100	0	3.29	1.08	1.01	0.03	−3.24	1.07	46.22	53.78
Wahoo	4.83	1.54	0.88	0.05	−4.58	1.48	100	0	4.34	1.20	0.87	0.04	−3.99	1.18	100	0
Broad Billed Swordfish	4.59	1.33	0.86	0.04	−4.37	1.29	100	0	3.34	1.10	0.99	0.03	−3.30	1.10	68	32
Striped Marlin	4.47	1.24	0.87	0.04	−4.26	1.22	100	0	4.73	1.28	0.84	0.05	−4.33	1.25	100	0
Rudderfish	4.53	1.31	0.87	0.04	−4.32	1.28	100	0	3.40	1.10	0.98	0.03	−3.33	1.10	77.78	22.22
Average	4.26	1.27	0.87	0.05	−3.98	1.19	100.0	0.0	3.74	1.14	0.94	0.03	−3.57	1.13	82.5	17.5
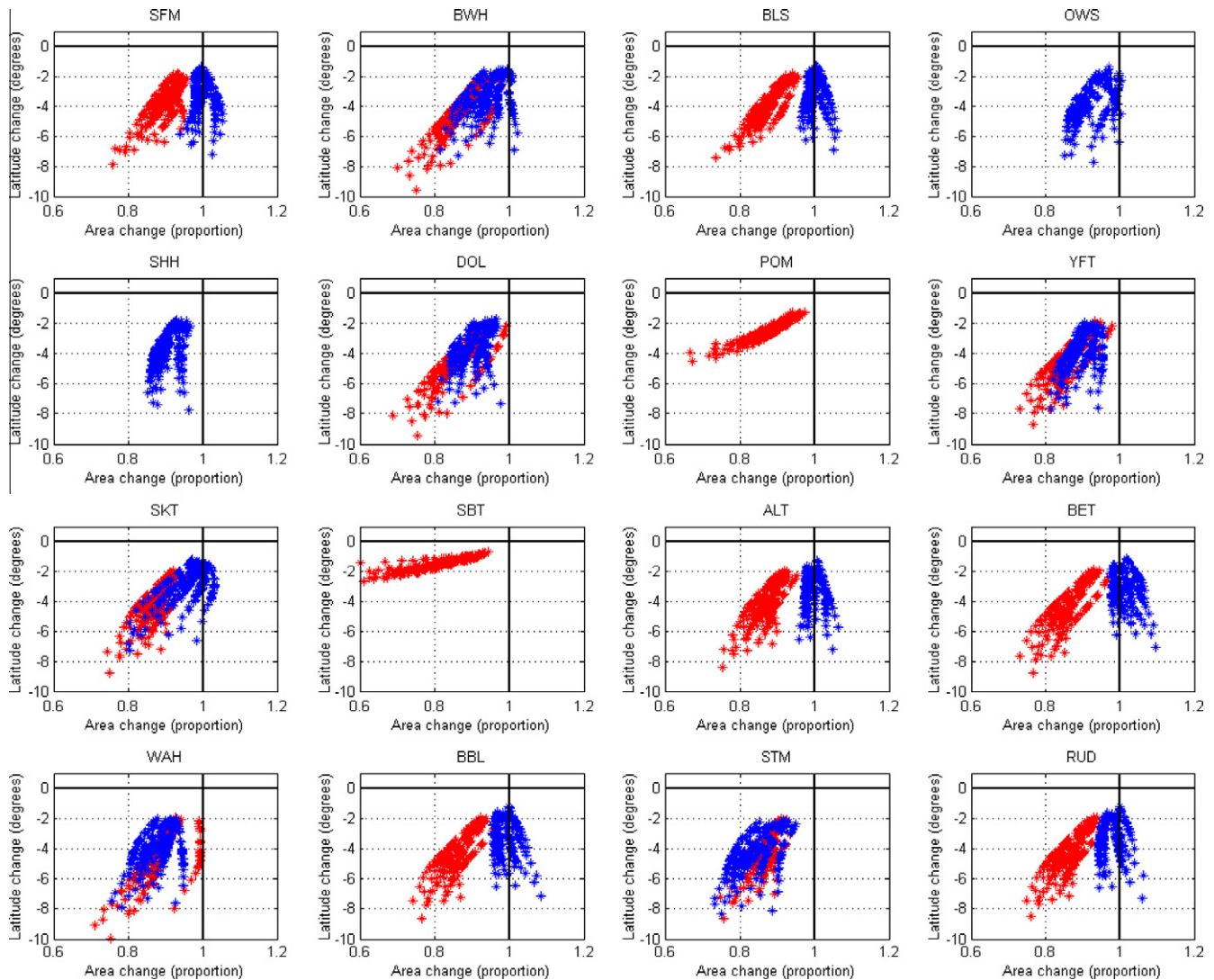
Fig. 6. Predicted change in species range (area and mean latitude) for the 16 total species on the east (red, *n* = 14) and west (blue, *n* = 14) coasts of Australia by 2100. There are a total of 2700 future predictions for each species on each coast. Species codes are listed in Table 1.

used, as overwhelmingly similar results were obtained at a gross level. In time, further reduction in uncertainty will come through validation of models, and inclusion of only the most appropriate set of models for the region.

The ability of models to correctly capture present-day distribution was tested, and the results considered suitable to undertake future predictions, as over 80% of present distribution was captured for most species. This analysis step also showed a seasonal signal in the fit of the model, suggesting that seasonal mesoscale structure in the ocean (e.g. thermal fronts, coastal eddies, upwelling zones) that can influence species distribution is not reproduced by the relatively coarse baseline GCM (0.25° resolution). Interannual environmental variation that would lead to changes in where individual species were captured by longline vessels is also not resolved by the present generation of GCMs. It remains a challenge to translate *in situ* observations from an "observed" month (e.g. January 1999) to an average month (e.g. all Januarys), as represented in climate projections.

Responses to environmental conditions are often size-specific in pelagic species, with juveniles and adults occupying different habitats (e.g. Maury et al., 2001; Graham et al., 2007; Sara and Sara, 2007). Particularly with regard to thermal tolerance, juvenile pelagic fishes are often more limited than adults (Boyce et al., 2008).

While this analysis focused on the adults, future distribution might be modeled as the integration of responses to the future environment from multiple life stages. In particular, vulnerability to climate change might differ dramatically among life stages, and so the results here may be conservative with regard to future impact.

4.1. Implications of distribution changes

By 2100, the simple habitat models predict that all 14 large pelagic species considered here will move southwards and the habitat area within the region considered will mostly decrease. The larger impact for the ETBF compared to the WTBF reflects expected changes in the currents, with the EAC expected to strengthen and continue further south, with the Leeuwin Current remaining relatively unchanged (Poloczanska et al., 2007). Changes prior to 2100 will be less than shown here because the OzClim tool used to analyse future changes in ocean temperature uses linear fits to calculate future climate values at each pixel location, thus the change for shorter periods will be linearly related to the time period considered. For example, changes in 2050 will be 50% of those demonstrated here.

These data on present species occurrence were taken from fisheries, and an assumption is that fish are captured throughout their

range, such that the habitat preference can be described. If a fishery operates from a limited set of ports, this assumption is unlikely to be perfectly satisfied. In particular, for the pelagic species considered here, northern limits are likely to be biased. A number of species are also found at lower latitudes, and while temperatures in the Timor Sea (north-western Australia) and Coral Sea (north-eastern Australia) are warmer than more northern equatorial regions, it is likely that the northern range edge has not been adequately described here. A solution when fishing location can introduce a presence-absence bias is to use CPUE to define habitat suitability. Future habitat modeling, such as that demonstrated here, should also consider alternative ways of defining the core habitat, as bioclimate envelope approaches do have limitations, and more advanced methods may lead to improved habitat descriptions (Elith et al., 2006). With the other issues in uncertainty regarding the scale of the environmental variables, and the future predictions, improvement in this component may not lead to greater confidence for the ensemble approach presented here.

The habitat models were also simple, with only a single variable considered, in contrast to traditional fisheries habitat models (e.g. Zainuddin et al., 2006). Temperature, however, is the single best descriptor of environmental suitability for pelagic fishes (Boyce et al., 2008), and so the analysis may be relatively robust to this limitation. It has also allowed a suite of species to be considered, for which little other data (such as electronic tagging) exists. A challenge for GCM modelers is to generate information on multiple variables (e.g. productivity) that can then be used for future predictions. Downscaling of climate models is one approach that would allow fine-scale habitat models with multiple variables, although results from a range of models are unlikely, such that general findings as presented here will not be possible.

Overall, analyses presented here make robust predictions that can be offered to stakeholders involved in pelagic fisheries. Southward species movements of up to 4° for the center of habitat areas are predicted by the year 2100 for both coasts. This corresponds to approximately 450 km, or 45 km per decade. These rates of range change are an order of magnitude higher than those observed for terrestrial systems (Parmesan and Yohe, 2003), and similar to those seen in northern hemisphere pelagic marine ecosystems over the past 50 years (Beaugrand et al., 2002; Perry et al., 2005).

4.2. Impacts on fisheries

While some authors suggest that the only way to reduce climate impacts is to reduce fishing mortality (Harley et al., 2006; Brander, 2007), they have tended to focus on the situations where abundance is expected to decline in future. Where the climate impacts involve changes in distribution, as modeled here, impacts can be both positive and negative with regard to future exploitation. If there is an increase in suitable habitat area, there is potential for increases in population size. It also means that fish that are not commercially exploited in a region may in the future reach high local abundance and attract harvesting efforts.

Although the total species habitat area was not modeled here (analysis was restricted to a fixed region on each coast), if total species habitat area contracts, then catchability may increase if the same population is contained within the reduced area. Conversely, these models cannot predict if there will be increased species abundance if habitat area expands. A change in horizontal distribution may result in increased availability to fishers. With respect to current fishing practices, these changes may also lead to altered travel times to access fishing grounds. The impact to fishers of these distribution changes is an area for future modeling effort for Australian pelagic fisheries.

Overall, in a changing climate, there will be opportunities and threats for continued harvesting of the ocean, and future predictions for single species must be refined and coupled with population and ecosystem models to better determine the future situation (Araújo and Luoto, 2007). It is with this knowledge that adaptation to both threats and opportunities by the fishers will be enhanced.

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