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Influence of climate-driven sea surface temperature increase on potential habitats of the Pacific saury (*Cololabis saira*)

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Logbook data of the 2006–2008 Taiwanese Pacific saury fishery, coupled with MODIS satellite-derived sea surface temperature (SST) data, were used to determine Pacific saury's SST preferences and predict their potential habitats monthly. Results indicated that the SST preferences ranged from 12 to18.5°C, with significant monthly variability. Possible changes in potential saury habitats were estimated under four scenarios: recent years (2006–2008) and with 1, 2, and 4°C increases in SST because of climate change. Results revealed an obvious poleward shift of potential saury habitats under the influence of increases in SSTs. The southernmost boundary of potential saury habitat in recent years, located at 40.24°N, shifted to 46.15°N under the scenario of a 4°C increase in SSTs. These results improve our understanding of the variability in the spatial distribution of saury habitats and could form the basis for future fishery management and fishing forecasts.

Keywords: climate change, Pacific saury, poleward shift, potential habitat, sea surface temperature.

Introduction

The Pacific saury (*Cololabis saira*) is commercially one of the most important small pelagic fisheries resources in the northwestern Pacific Ocean (NWPO; FAO, 1994; Tian *et al.*, 2004) and the target species of Taiwanese deep-sea saury stick-held dipnet fishing in the NWPO (Huang, 2007, 2010). In fact, the Pacific saury has great economic importance for several Asia–Pacific countries, especially Taiwan, China, Japan, Korea, and Russia. Statistics of recent Taiwanese fisheries yearbooks indicate >60 000 t of annual production, with a value typically exceeding New Taiwan dollar (NT$) 1 billion, from saury fisheries (in 2010, the average exchange rate was US$1 ≈ NT$31.7). Catches of 87 000 t, valued at NT$1.46 billion in 2007, and 139 000 t, valued at NT$2.95 billion in 2008, illustrate the importance of the Pacific saury deep-sea fishing industry in Taiwan. Consequently, an understanding of the spatio-temporal variability of saury foraging habitats and the effects of climate change is important.

The Pacific saury is a highly migratory epipelagic fish. It usually ranges from the surface to ~230 m in the North Pacific Subtropical Gyre, with a preferred water temperature range of 15–18°C (Eschmeyer *et al.*, 1983; FAO, 1994, Ito *et al.*, 2004). Moreover, it typically aggregates in the surface layer where water temperatures exceed 6.5°C (Sablin and Pavlychev, 1982) and probably cannot tolerate lower temperatures encountered below the thermocline (Yamamura, 1997). Scientists typically associate the spatio-temporal migratory patterns with environmental factors (Tian *et al.*, 2004; Iwahashi *et al.*, 2006; Watanabe *et al.*, 2006; Huang, 2007, 2010; Mukai *et al.*, 2007; Yasuda and Watanabe, 2007a, b). Although sea surface temperature (SST) is not the only determinant variable of saury habitat, it plays a key role as the only environmental predictor highly related to diversity across many taxa of pelagic fish (Tittensor *et al.*, 2010). Moreover, the location of the spawning grounds of the Pacific saury corresponds to the location of a sharp SST front in the NWPO (Iwahashi *et al.*, 2006). Furthermore, many distant-water commercial fishing boats (especially Japanese and Taiwanese ones) are known to have used SST-related information to find potential fishing grounds (habitats) of the Pacific saury in recent years. In addition, Oozeki *et al.* (2004) reported that certain environmental factors, especially the SST, are correlated positively with the growth rate of Pacific saury larvae.

Understanding fluctuations in marine fish stocks is important for fisheries management and fishing forecasts. Researchers have attempted to demonstrate links between Pacific saury and climate variability (Attrill and Power, 2002; Tian *et al.*, 2003, 2004). Research results indicated that SST in the NWPO is a dominant signal of climate variability that might have a potential influence in determining the habitat of the Pacific saury (Tian *et al.*, 2003, 2004).

Many studies have used satellite-derived images (e.g. of SST), with relatively high spatial and temporal resolutions, to identify areas of intense fishing activity and identify fish aggregations, especially those of highly migratory species (e.g. tuna and tuna-like species; Laurs *et al.*, 1984; Lehodey *et al.*, 1998; Polovina and Howell, 2005; Kuwahara *et al.*, 2006; Palacios *et al.*, 2006;

Zainuddin *et al.*, 2006). Solanki *et al.* (2005) used multi-satellite oceanographic parameters, including images of SST and chlorophyll *a* (Chl *a*) in the northern Arabian Sea, to determine potential habitats (fishing grounds) for certain pelagic and demersal species. Teo *et al.* (2007) used satellite data and electronic tagging to determine the potential habitat and preference patterns of Atlantic bluefin tuna (*Thunnus thynnus*) in the Gulf of Mexico, and they quantified satellite-derived SST as a key environmental parameter.

Biotic and abiotic processes can influence fish distributions. Water temperature is usually the dominant abiotic environmental factor. In this study, we examined the relationship between Pacific saury catch data and satellite SST data to determine their monthly potential habitats, based on their SST preference as determined by a histogram analysis of saury catch per unit effort (cpue). We also used possible SST increases estimated from global climate simulations under several emission scenarios from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) to evaluate the impacts of climate change on potential habitats of the Pacific saury.

Data and methods

Study area

The main fishing grounds of the Taiwanese deep-sea saury stick-held dipnet fishery are located in coastal waters of the NWPO near the Japanese island of Hokkaido, which is also the Kuroshio–Oyashio transition zone (Figure 1). The northern warm waters of the Kuroshio Current interact with the southern cold waters of the Oyashio Current to form this transition zone extending eastwards into the North Pacific. The convergence of the two strong currents of cold and warm waters forms a number of fronts and eddies, creating a nutrient-rich fishing ground, especially for Pacific saury and other highly migratory species.

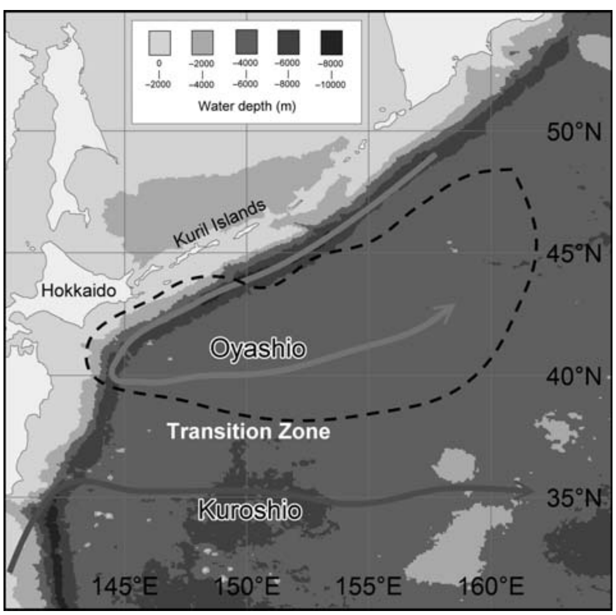

Figure 1. Geographic location and bathymetry of fishing grounds for Pacific saury in the NWPO. The inner area of the black dashed line represents the Taiwanese fishing grounds.

Fishing data

Daily Pacific saury catch data from the Taiwanese deep-sea saury stick-held dipnet fishery in the NWPO were collected for 2006–2008. Logbooks of fishing operations conducted by each vessel indicated the catch (t), effort (the number of hauls), and fishing location (latitude and longitude). The cpue (t haul^{-1}) was calculated and averaged to create a $0.25 \times 0.25^\circ$ latitude/longitude grid using ArcGIS software, which is a professional geographic information system developed by Environmental Systems Research Institute (ESRI, 2010). The monthly cpue layers for 2006–2008 were examined to investigate spatial and temporal variations associated with the corresponding environmental factors, including satellite-derived SST data.

Satellite SST data

For 2006–2008, monthly MODIS SST data were extracted from the ocean colour website http://oceancolor.gsfc.nasa.gov/. The 4-km spatial resolution SST raw data are a scientific dataset in the hierarchical data format. This format is easy to import into the ArcGIS geographic information system (in the form of raster layers) to examine the data in conjunction with the Taiwanese Pacific saury fishing data. Monthly SST data were transferred as point layers and overlaid with the $0.25 \times 0.25^\circ$ latitude/longitude grid. Then, its average SST value was calculated and associated with the corresponding saury cpue for each grid.

Estimate of potential saury habitat

Monthly SST preferences of the Pacific saury were determined using a histogram analysis of the SST data that corresponded to higher cpue values, defined as >3.0 t haul^{-1}. Then, these specific ranges of SST preferences were used as thresholds for selecting and predicting potential habitats (fishing grounds) of the Pacific saury.

Climate-change effects on the increase in SSTs

This study used possible SST increases based on global climate simulations under several emission scenarios (A1FI, A1B, A1T, A2, B1, and B2) from the AR4 of the IPCC to examine the impact on potential habitats of the Pacific saury for the next 100 years. These six climate-change scenarios describe the best estimate of projected global surface warming of 1.8–4.0°C, based on relationships between the forces driving greenhouse gas and aerosol emissions and their global evolution during the 21st century. Each scenario represents different demographic, social, economic, technological, and environmental developments (IPCC, 2007). We simulated SST increases of 1, 2, and 4°C to examine the effects of climate change on possible displacements of potential saury habitats.

Results

Habitat distributions of the Pacific saury

Figure 2 shows average monthly cpue values in 2006–2008. The early fishing season from June to August had a lower average cpue of <2.01 (1.48–1.81) t haul^{-1}. The following 4 months from September to December were the peak fishing season and had a higher cpue of >2.51 (2.50–4.05) t haul^{-1}. The highest average monthly cpue was recorded in October, at 4.05 t haul^{-1}.

Figure 3 shows total average cpue values of the Taiwanese Pacific saury fishery in 2006–2008 in the NWPO in a $0.25 \times 0.25^\circ$ decimal degree latitude/longitude grid to examine the spatial distribution of traditional habitats of the Pacific saury (i.e. the main fishing grounds). The geographic distribution where Taiwanese Pacific saury fishing operations were conducted was divided into two fishing groups: offshore fishing groups in waters of the Kuril Islands outside the Russian exclusive economic zone (EEZ) and inshore fishing groups that have obtained permission to operate in the Russian EEZ close to the eastern waters of Hokkaido. The offshore fishing groups had lower cpue values of <5.0 t haul^{-1} compared with inshore fishing groups with >5.0 t haul^{-1} (Figure 3).

The monthly fishing centres (weighted centre by cpue) of the Pacific saury from June to December indicated a noticeable spatio-temporal variability, as illustrated in Figure 3. The early fishing season from June to August had lower average cpue values of <2.5 t haul^{-1}. Most of the fishing effort was located in the range 40–50°N and 155–160°E. The peak-fishing season from September to December had greater average cpue values, usually of >2.5–5.0 t haul^{-1}. Fishing effort in the peak season was located the area 43–48°N and 145–157°E. Beginning in September, some Taiwanese fishing vessels had a cooperative fishing licence, which allowed them to enter the EEZ of the south Kuril Islands legally, next to the eastern waters of Hokkaido. These fishing grounds are on the southern migration route of the Pacific saury and yielded higher cpue values of >5.0 t haul^{-1}.

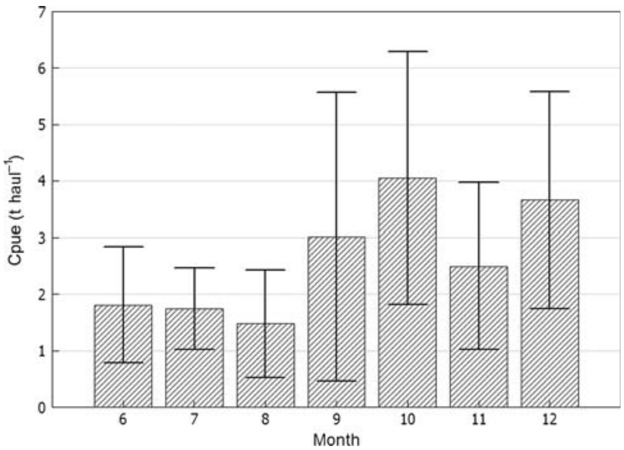

Figure 2. Monthly average cpue values of the Taiwanese Pacific saury fishery during 2006–2008. The bar indicates the s.d. of average cpue values.

SST preferences by the Pacific saury

The 2006–2008 monthly average SST values for the Pacific saury-fishing grounds ranged between 12.8 (in June) and 16.3°C (in

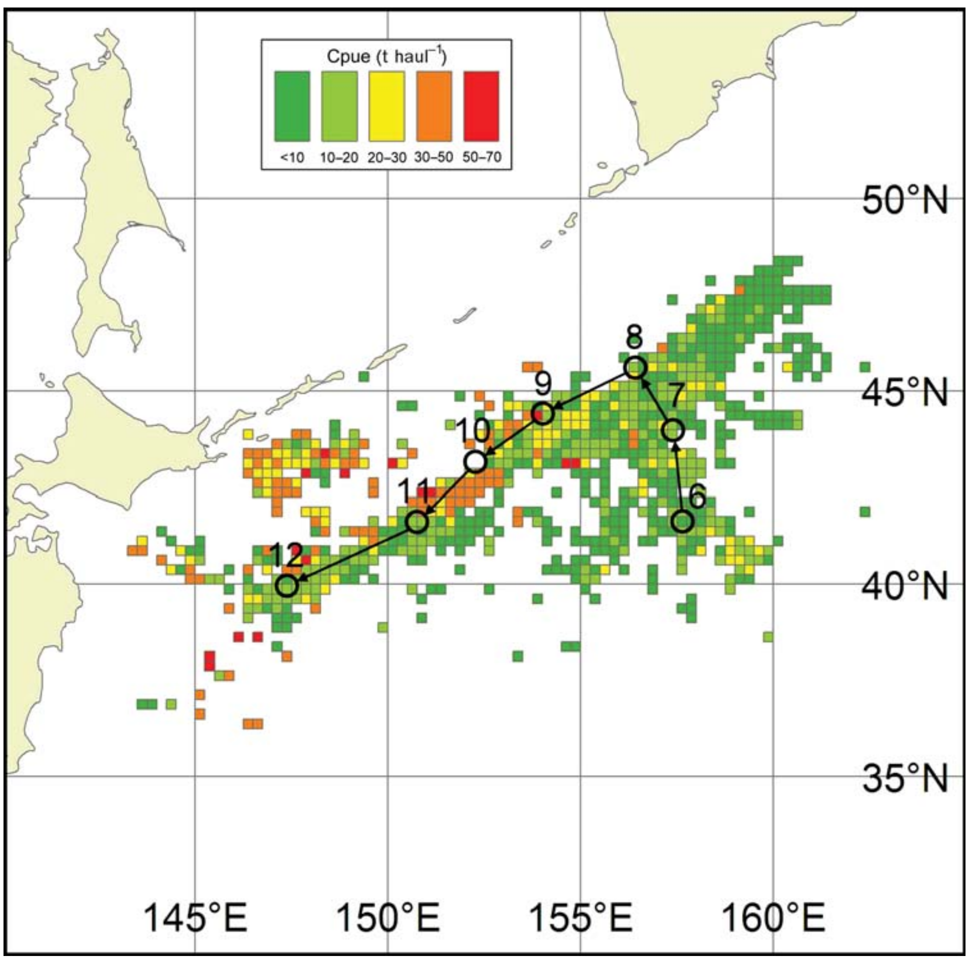

Figure 3. The spatial distribution of total average cpue values of the Taiwanese Pacific saury fishery during 2006–2008 and spatial variations in the monthly centres of fishing activities (black circles).

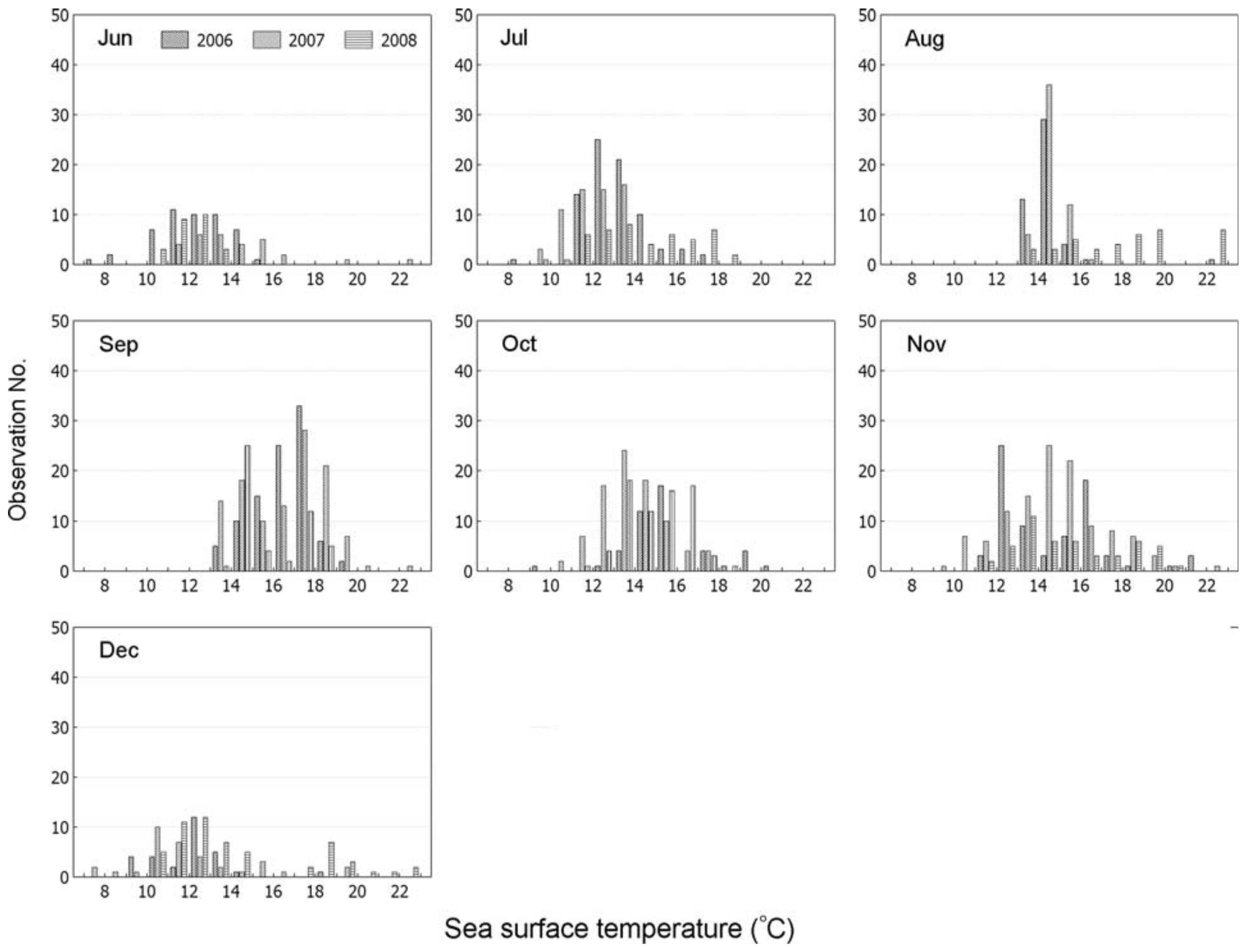

Figure 4. Monthly favourable SSTs of Pacific saury fishing grounds determined using a histogram analysis during 2006–2008.

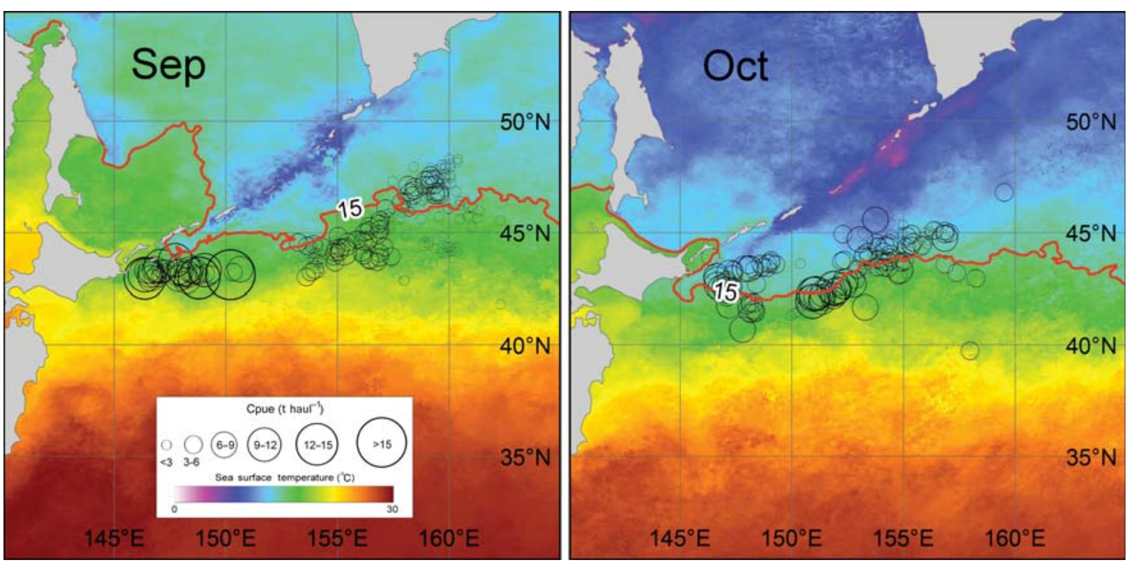

Figure 5. Pacific saury cpue values (black circles) for September (left) and October (right) in association with satellite SST (red lines indicate the 15°C contour) images in the NWPO.

September). This study also examined monthly SST preferences of the Pacific saury using a histogram analysis (Figure 4). The results indicated that the highest cpue values corresponded to areas with SSTs of 12–18°C during the peak fishing seasons. Based on the combined SST data for 2006–2008, twin peaks in the histograms were recorded for September and October. The ranges of SSTs in the preferred months from the two dominant Pacific saury fishing grounds were 14–15 and 17–18°C in September, 13–14 and 15–16°C in October, 13–14°C in November, and 12–13°C in December.

Potential habitat of the Pacific saury

The monthly contour maps of SST satellite images were created using mean values of the preferred oceanographic parameters for relatively high cpue values. Monthly Pacific saury cpue values were overlaid on the corresponding satellite SST images for the main fishing periods for September to October along with the 15°C contours (Figure 5). The strong association between the 15°C contour lines and Pacific saury cpue values indicated that this specific SST value is a good indicator for assessing potential habitats (fishing grounds) of the Pacific saury in the NWPO. The predicted monthly potential habitats of the Pacific saury for September–December (the main fishing season season with higher cpue values) are illustrated in Figure 6.

Effects of climate change on potential habitats of the Pacific saury

Figure 7 shows the monthly potential habitats of the Pacific saury based on the corresponding SST preferences under the conditions of recent years (2006–2008) and the scenarios of 1, 2, and 4°C increases in SSTs. Potential habitats were progressively concentrated into smaller horizontal belts from the early stage (September) to the end of the fishing season (December). However, the maximum saury cpue was measured in October, with potential habitat distributions ranging between 42 and 47°N.

We conducted quantitative analyses of potential saury habitats based on SST preferences to examine temporal and spatial variations in the fishing grounds. Figure 8 shows the southernmost boundary lines of potential habitats of the Pacific saury with increases in SST of 1, 2, and 4°C. During the main fishing season for Pacific saury, potential habitats for all four scenarios displayed a southward latitudinal shift from September to December. For December, the southernmost boundary lines of potential habitat

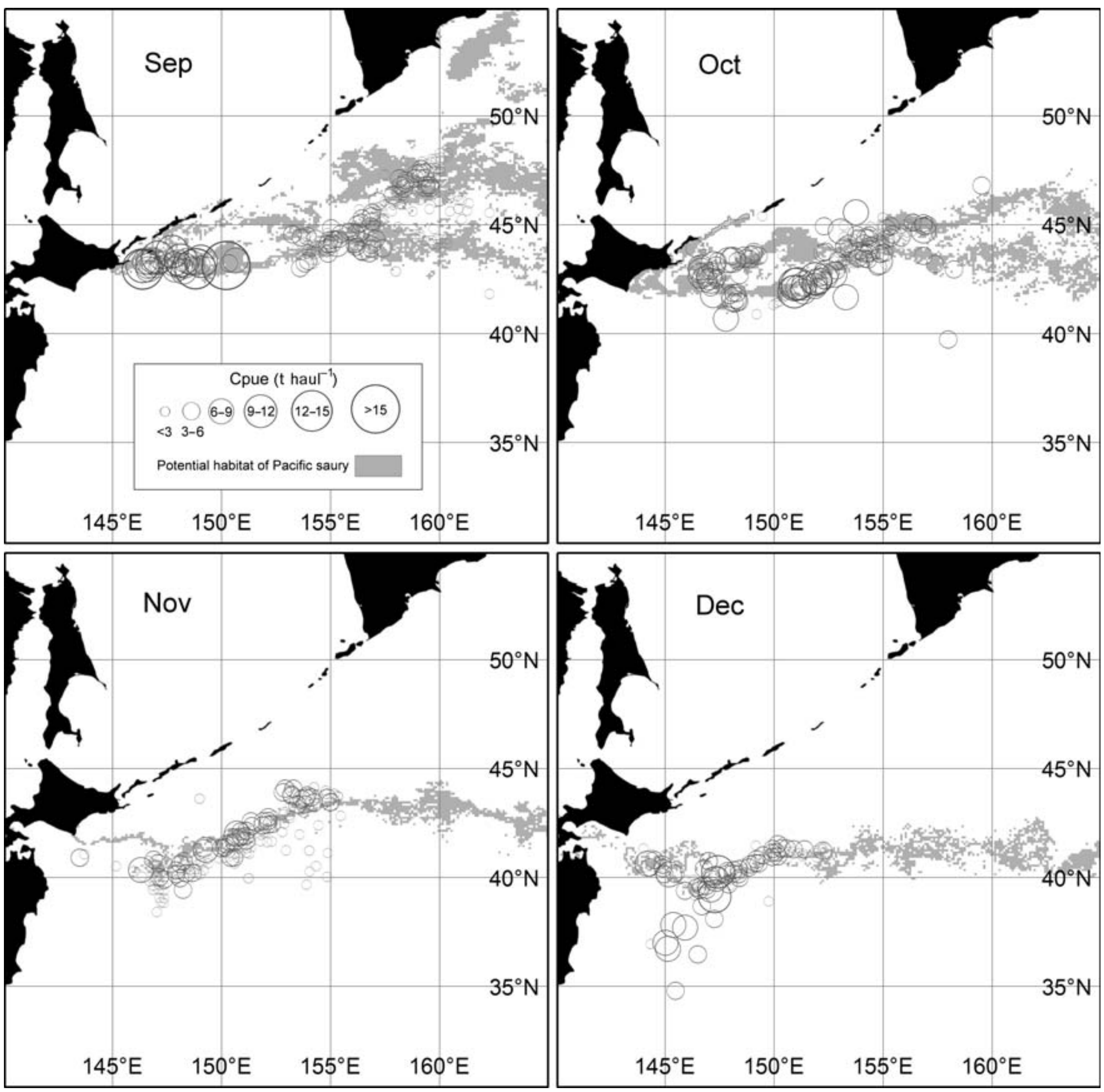

Figure 6. Monthly (September–December) potential habitats of Pacific saury derived from satellite SST data associated with the corresponding cpue values during 2006–2008.

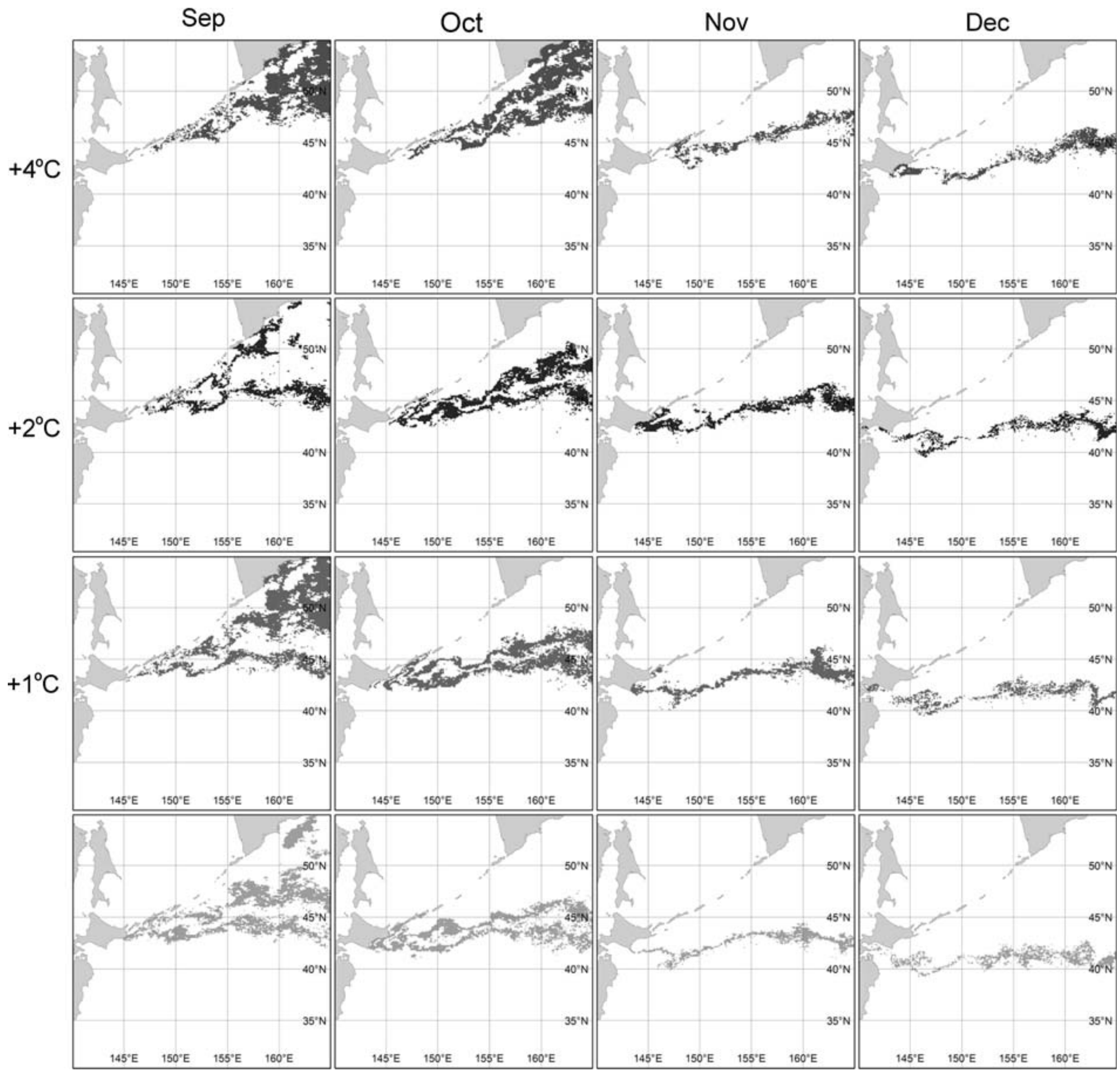

Figure 7. Monthly (September–December) potential habitats of the Pacific saury derived from satellite SST data for recent years (2006–2008) and with SST increases of 1, 2, and 4°C.

extended from 40.24°N in recent years to 42.56°N under the climate change scenario of a 4°C increase in SSTs. An obvious poleward shift in potential saury habitats would happen between recent conditions and the three different climate change scenarios with SST increases of 1, 2, and 4°C. The latitudinal displacements of the poleward shift increased from the 1–4°C scenarios. The largest monthly maximum latitudinal displacements happened between the 4°C scenario and recent years. Changes of 3.11° latitude were noted for September and of 2.32° latitude for December.

Discussion

Spatial changes in Pacific saury habitats

Cold, nutrient-rich Oyashio Current water from the Subpolar Gyre interacts with the warm Kuroshio Current water originating in the Subtropical Gyre in a transition zone (Figure 1). These waters are often referred to as the Kuroshio–Oyashio Extension (Yasuda *et al.*, 1996) and usually exhibit dramatic hydrological variations and features. In particular, frontal areas and eddies appear to influence the recruitment variability of small pelagic fish populations (Watanabe, 2009). The transition zone represents important spawning, feeding, migration, and habitat areas for the Pacific saury (Ito *et al.*, 2004; Iwahashi *et al.*, 2006; Watanabe *et al.*, 2006; Mukai *et al.*, 2007; Yasuda and Watanabe, 2007a; Huang, 2010).

In this study, the monthly Taiwanese Pacific saury fishing centres (Figure 3) indicated a possible linkage between potential saury habitats and spatial variations in the Oyashio Current in the NWPO. The higher saury cpue began in September (Figure 2). Sablin and Pavlychev (1982) mentioned that Pacific saury fishers catch from June to December in waters adjacent to the southern Kuril Islands and Hokkaido.

Huang (2010) demonstrated that the total average cpue was correlated negatively with seawater temperatures, especially in

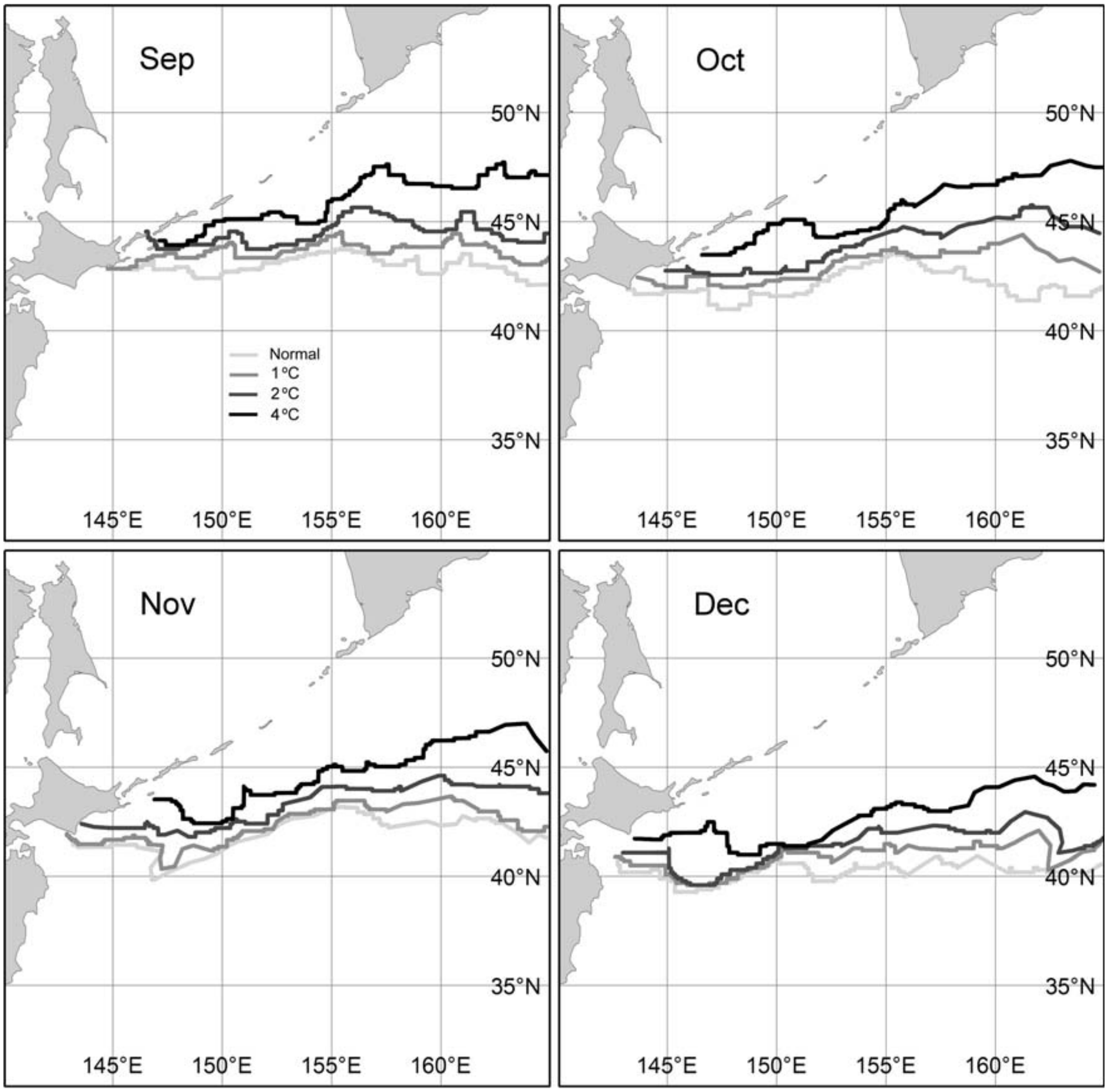

Figure 8. The southernmost boundaries of potential habitats of the Pacific saury, September–December, under SST increases of 1, 2, and 4°C, based on the six scenarios (A1FI, A1B, A1T, A2, B1, and B2) in the IPCC AR4 reports.

the shoreward, southward, and shallower waters of the fishing grounds. Earlier studies reported that Pacific saury fed in the Kuroshio–Oyashio transitional region during spring and summer (Sugisaki and Kurita, 2004; Watanabe, 2009). In this study, the major Taiwanese fishing grounds were located in the range 40–50°N and 155–160°E and had lower average cpue values in the early fishing season, from June to August (Figure 3). After sufficient feeding, the saury migrate back to the warm Kuroshio waters in winter to spawn (Kosaka, 2000; Polovina *et al*., 2001; Watanabe *et al*., 2006; Yasuda and Watanabe, 2007a; Watanabe, 2009). We found higher average cpue values in the peak fishing season from September to December, usually of >2.5–5.0 t haul^{-1}, with the principal fishing grounds located in the area 43–48°N and 145–157°E (Figure 3).

Potential saury habitats based on SST preferences

This study used higher saury cpue values (>3.0 t haul^{-1}) to examine corresponding monthly favourable SST ranges (Figure 4). Peaks on the histogram analysis revealed two SST preferences in September and October. Taiwanese Pacific saury fishing is typically divided into two dominant fishing locations: a small fishing group that operates inside the EEZ (based on fishing cooperative agreements) and a large fishing group that operates outside the EEZ (Figures 3 and 5). The warm Kuroshio water usually controls the higher SST preference (17–18°C in September and 15–16°C in October) in the Japanese EEZ region, close to the coast of Japan. The cold Oyashio Current water usually controls the lower SST preference (14–15°C in September and 13–14°C in October) in the region outside the EEZ, which is located in the transition zone. Tian *et al*. (2003) found that the occurrence of larger and medium-sized Pacific saury was correlated strongly with SSTs; they also reported that the abundance of larger saury was significantly correlated with winter SSTs in the Kuroshio region, whereas medium-sized saury displayed high correlations with SSTs in the Kuroshio–Oyashio transitional and Oyashio regions.

Each fish species lives in a specific range of water temperatures. In the open ocean, the preferred water temperature of a fish species is usually found in a limited range and the species occupies its representative habitat. SSTs serve as a convenient proxy or indicator of potential saury habitats. However, other environmental factors might influence the spatio-temporal distributions of the Pacific saury in the NWPO. Therefore, to predict more precisely the effects of climate change on potential habitats of the Pacific saury, we should clarify the role of other variables, possibly including changes in the peak fishing season, seasonal variations in SST increases, distributions of prey, and prey–predator relationships under the effects of global warming.

A poleward shift and shrinkage of potential saury habitats

Pacific saury feed in the nutrient-rich Oyashio region during summer, then migrate south in autumn and winter (Tian *et al.*, 2004). The major Taiwanese fishing season for the Pacific saury fishery typically begins in July and ends in December (Huang, 2010). One of the more prominent effects of an increase in water temperature is likely to be an increase in the growth rate of saury (Brander, 2009). As a result, Pacific saury are likely to undergo a poleward displacement in response to SST variability attributable to global warming. A variety of studies concluded that many marine populations will expand northward to higher latitudes because of global warming (Kuwahara *et al.*, 2006; Stenevik and Sundby, 2007; Mueter *et al.*, 2009; Hal *et al.*, 2010).

The scenarios of SST increases indicate that by 2050, global warming might have induced the northward displacement of the transition zone between the warm Kuroshio Current water and cold Oyashio Current water. Under these conditions, the higher water temperature in the transition zone would cause the nutrient-rich cold water to retreat to the polar region (Schwing *et al.*, 2010). Kuwahara *et al.* (2006) also reported that this could have a significant impact on the distribution of marine organisms, which would evidently experience northward displacements around Japan under global warming.

Conclusions

Finding an ecosystem indicator for monitoring fish distributions is important. This study demonstrated that SST is a key abiotic factor for effectively predicting potential habitats of the Pacific saury. The histogram analysis of saury cpue revealed a strong association between the areas of high fishing activity and the location of the 15°C SST isotherm, although there was insufficient information about many other interrelated and potentially influential factors. However, investigators could use satellite-derived SST values as an effective proxy or ecosystem indicator for potential saury habitats. The spatial analysis of saury habitat displacements affected by SST variations under different climate change scenarios improves our understanding of the variability of the spatial distribution of saury habitats. These results could form the basis for fishery management and forecasting in future.

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