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Sea surface temperature fronts affect distribution of Pacific saury (*Cololabis saira*) in the Northwestern Pacific Ocean

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ABSTRACT

Pacific saury (*Cololabis saira*) is an important fisheries resource and commercial species of Taiwanese deep-sea saury stick-held dip net fishery in the Northwestern Pacific Ocean. In this study, the logbook data of a 3-year (2006–2008) Taiwanese Pacific saury fishery and corresponding satellite-derived MODIS sea surface temperature (SST) data were analyzed to detect SST fronts and examine their influence on the spatio-temporal distribution of Pacific saury. The fronts were identified by the Cayula–Cornillon single-image edge detection algorithm. The results show that low frequency of SST fronts is associated with lower CPUEs during the early fishing season (June–August), while high frequency of SST fronts is associated with higher CPUEs during the peak fishing season. When fishing locations of Pacific saury are close to the SST fronts, higher CPUEs are observed. Results of this study provide a better understanding of how SST fronts influence distribution of Pacific saury and improve the basis of fishing ground forecasting.

1. Introduction

Pacific saury (*Cololabis saira*) is an important fisheries resource (FAO Fisheries Department, 1994) and the target species of Taiwanese deep-sea saury stick-held dip net fishery in the Northwestern Pacific Ocean (NWP) (Huang, 2007, 2010; Tseng et al., 2011). The Pacific saury is a major commercial species and has a great economic importance among Asia-Pacific countries, especially in Japan, Taiwan, Russia, and Korea. In 2009, Taiwanese capture fisheries production of Pacific saury was about 104 thousands metric tonnes (Mt), with a value of US$92 million. It accounted for almost 25% of global capture fisheries production of Pacific saury, second only to Japan (FAO, 2009) (Fig. 1).

In the Northwestern Pacific Ocean, the Pacific saury fishing grounds are located off the Kuril Islands and Hokkaido (Watanabe et al., 2003; Huang, 2007; Yasuda and Watanabe, 2007). Taiwan and Korea are the two major fishing countries outside the exclusive economic zones (EEZ) of Japan and Russia (Fig. 2A). The fishing season of Taiwanese Pacific saury fishery is from June to December. The Japanese fishing vessels start to capture Pacific saury from August; its major fishing grounds are located inside Japan's EEZ. The main fishing ground of the Taiwanese saury fishery is located east of Hokkaido and Kuril Islands in the Northwestern Pacific. Some of the Taiwanese Pacific saury fishing vessels can operate in Russia's EEZ around the Kuril Island, based on a Taiwan–Russia fishery cooperation agreement. The Transition Zone between the warm Kuroshio Extension Current and the cold Oyashio Current (Fig. 2B) is a major spawning, migratory and habitat area of some important commercial fish species, including Pacific saury.

The Pacific saury is a highly migratory species usually found from the sea surface down to ~230 m with the preferred 15–18 °C water temperature in the North Pacific (Eschmeyer et al., 1983; FAO Fisheries Department, 1994, Ito et al., 2004). The Pacific saury has a wide migratory range from the subtropical Kuroshio Extension Current to the subarctic Oyashio Current. In winter, the Pacific saury migrates southward to the Kuroshio warmer water, its spawning area. Then the Pacific saury swims northward into the Oyashio colder water, its feeding habitat during the summer. The spatio-temporal distributions of the Pacific saury have been linked to environmental factors (Tian et al., 2004; Iwahashi et al., 2006; Watanabe et al., 2006; Mukai et al., 2007; Yasuda and Watanabe, 1994, 2007; Huang, 2007, 2010). Seasonal variations of chlorophyll-*a* (Chl-*a*) concentrations were found in the Pacific saury

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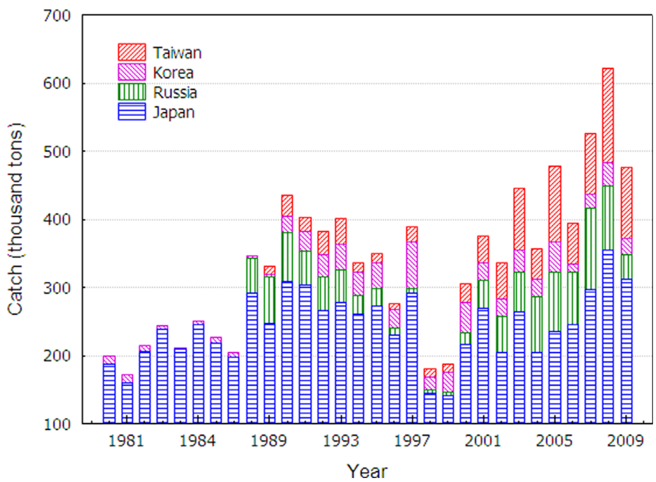

Fig. 1. Annual capture fisheries productions of Pacific saury of the major fishing countries, including Japan, Taiwan, Russia, and Korea, in the Northwestern Pacific Ocean.

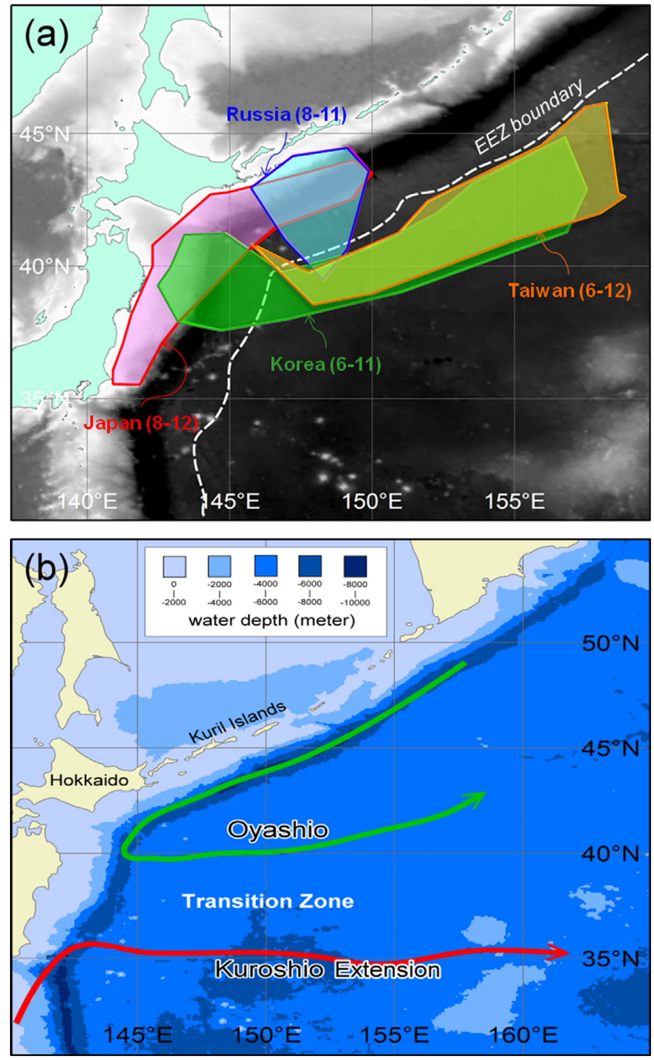

Fig. 2. (a) Schematic map of geographic location and bathymetry of Pacific saury fishing grounds in the Northwestern Pacific Ocean (redrawn from http://abchan.job.affrc.go.jp/). The main fishing countries and their fishing seasons (months in parenthesis) are also shown. (b) Schematic view of Oyashio, Kuroshio Extension, and Transition Zone.

fishing grounds. The maximum Chl-*a* concentration in the mixed layer from winter to early spring (January–April) was related to the Pacific saury recruitment success (Yasuda and Watanabe, 2007). Oozeki et al. (2004) reported that environmental factors, especially SST and Chl-*a*, are positively correlated with the growth rate of Pacific saury larvae.

It is well established that SST is a key environmental factor for fish habitats. Satellite images (especially SST) with relatively high spatial and temporal resolutions can be applied to determine areas of intense fishing activity and correlate oceanic parameters with fish aggregations, especially those of highly migratory species (Laurs et al., 1984; Lehodey et al., 1998; Polovina and Howell, 2005; Palacios et al., 2006; Zainuddin et al., 2006; Tseng et al., 2011). For example, Tittensor et al. (2010) reported that SST is the only environmental predictor strongly correlated with diversity across all 13 groups of fish species (taxa). Evidence mounts that oceanic fronts play a key role in the ecology of fish. Bakun (2006) reported that tuna spawning sites are related to the concentration areas of convergence fronts. Some studies have indicated that the physical processes linked to frontal areas yield productive habitats (Fortier et al., 1992; Munk et al., 2009).

Satellite remote sensing is a powerful tool to monitor and provide reliable global ocean SST coverage, with a relatively high spatial and temporal resolution to identify strong thermal gradients. Previous studies have developed a variety of algorithms to automatically detect oceanic fronts from satellite SST images (Cornillon and Watts, 1987; Holyer and Peckinpaugh, 1989; Cayula and Cornillon, 1992; Vázquez et al., 1999; Ullman and Cornillon, 2000; Diehl et al., 2002; Wall et al., 2008; Belkin and O'Reilly, 2009). However, there is no consensus on a possible link between SST fronts and the temporal and spatial variations of the Pacific saury in the NWP. This study aimed to determine the relationship between the Pacific saury catch data and the oceanic fronts detected from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-derived SST data.

2. Materials and methods

2.1. Pacific saury fishing data

Three years (2006–2008) of daily catch data of Pacific saury from Taiwanese deep-sea saury stick-held dip net fishery were collected in the Northwestern Pacific Ocean. The logbooks of fishing operations conducted by each vessel include records of catch (Mt) and effort (each fishing vessel every day) as well as their fishing locations (latitude, longitude). The catch per unit effort (CPUE, unit: Mt/boat/day) was calculated and averaged on a $0.25^\circ \times 0.25^\circ$ latitude/longitude grid by ESRI ArcGIS software. Monthly averaged CPUE layers between 2006 and 2008 were examined to investigate their spatial and temporal variations and associate the CPUEs with the corresponding environmental key factors, including the satellite-derived SST fronts.

2.2. Satellite SST data

The monthly MODIS SST data between 2006 and 2008 were obtained from the Ocean Color website (http://oceancolor.gsfc.nasa.gov/). The 4-km spatial resolution SST is a scientific data set in the hierarchical data format (HDF), which makes it easy to import the SST data into ArcGIS in the form of raster layers in order to examine the data in conjunction with other environmental factors.

2.3. Oceanic SST fronts detection

The Cayula–Cornillon single-image edge detection algorithm (Cayula and Cornillon, 1992) was applied to detect oceanic fronts

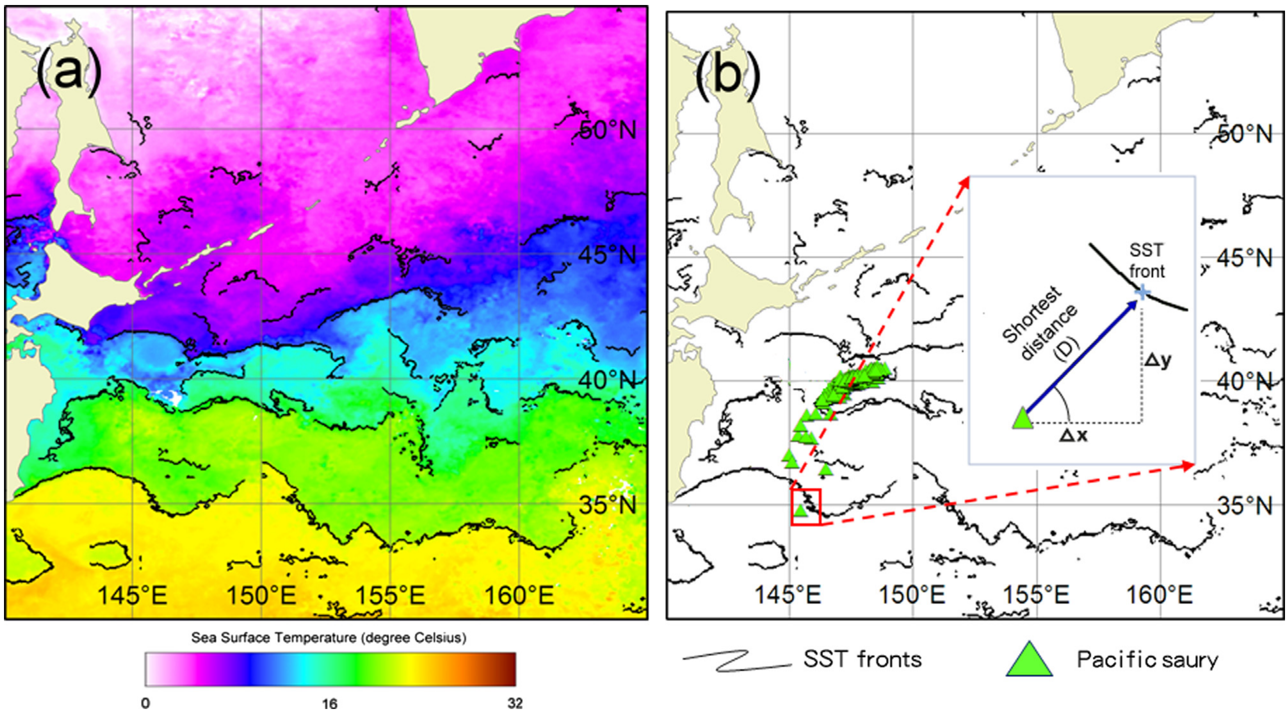

Fig. 3. Satellite-derived sea surface temperature (SST) data (a) was used to extract the frontal areas (black lines in right panel) and calculate the distance between catch and SST fronts (b) based on the Cayula–Cornillon edge detection algorithm.

from MODIS satellite SST data (Fig. 3A). The Cayula–Cornillon single-image algorithm is currently integrated into the Marine Geospatial Ecology Tools (MGET), designed for oceanographic research as an ArcGIS extension toolbox (Roberts et al., 2010). However, the current implementation of this method in the Marine Geospatial Ecology Tools (MGET) (Roberts et al., 2010) still cannot quantify SST gradients across oceanic fronts. Then, the shortest distance ($D=\sqrt{(\Delta x^2+\Delta y^2)}$) ($D$ was calculated between each CPUE grid node and the adjacent SST fronts by the NEAR analysis tool of ArcGIS software (Fig. 3B)). Monthly frontal frequency within the 100-km radius around the each CPUE grid node was calculated to examine the relationship between CPUE and SST frontal frequency.

3. Results

3.1. Spatial and temporal distributions of saury CPUEs

Monthly average CPUEs of Taiwanese Pacific saury fisheries are shown in Fig. 4 during 2006–2008. Its major fishing season is from June to December, with the highest CPUE of 25.4 Mt/boat/day in October. There is a lower CPUE from June to August in the early stage of fishing season. Its average CPUE is 9.7 Mt/boat/day. However, a sharply increasing CPUE is found to start in September, with a CPUE of 19.5 Mt/boat/day. The dominant fishing season is in October, with the highest CPUE of 25.4 Mt/boat/day.

Obvious spatial variation of Taiwanese Pacific saury fishing areas was found in this study. The fishing centers (weighted center by CPUE) derived from the spatial distribution of monthly CPUEs show a distinct seasonal migration pattern (Fig. 5). During the early fishing season in June and July, the fishing centers are located outside Russia's EEZ around the Kuril Islands. Northward migrations of the early fishing season from June to August occur in the Taiwanese Pacific saury fishery. The northernmost fishing center is located at 45° N, off the Kuril Islands. From September to December, fishing centers are gradually shifting southwestward parallel to the Kuril Islands into the southeastern waters of Hokkaido (Fig. 5).

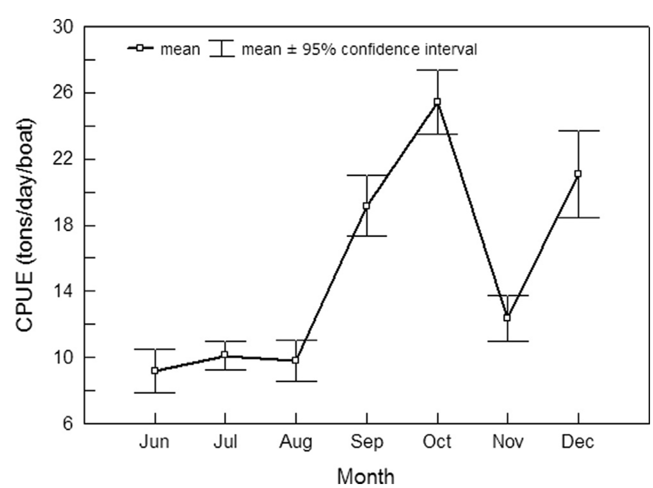

Fig. 4. Monthly averaged CPUEs of Taiwanese Pacific saury fishery during 2006–2008.

The CPUEs of Taiwanese Pacific saury fishery during 2006–2008 were processed onto a 0.25° × 0.25° latitude/longitude grid by ArcGIS software to examine the spatial distribution of the Pacific saury fishing grounds. The geographic distributions of operating fishing grounds of the Taiwanese Pacific saury fishery are divided into two fishing groups: the offshore fishing group operated off the Kuril Islands, outside Russia's EEZ, whereas the inshore fishing group operated within Russia's EEZ, off the Kuril Islands, close to the eastern waters of the Hokkaido. The offshore fishing group had lower CPUE relative to the inshore fishing group with a higher CPUE (Fig. 5). The average daily CPUE was 18.5 Mt/boat (N=12,482, standard deviation=16.4) during 2006–2008. The fishing locations were concentrated in an area bounded by 38–49° N, 143–162° E.

3.2. SST fronts and their effects on Pacific saury

Firstly, the monthly SST frontal frequency maps were categorized into four classes (0%, 33%, 67%, and 100%) according to the cumulative number of monthly frontal occurrences to determine where more or less SST fronts occur (Fig. 6). Every map in Fig. 6 is a composite of three individual monthly maps made for the given month in 2006, 2007, and 2008. The “frontal frequency” is the percentage of occurrences of SST fronts in the given month from 2006 to 2008. For example, if SST fronts were detected at the same location in every June from 2006 to 2008, then the “frontal frequency” at this location in June is 100%.

Less SST fronts were found during the early fishing season from June to August. In contrast, more SST fronts were detected from September to December, which means that the major fishing season coincides with the time of the highest probability of SST fronts. Secondly, the monthly locations of fishing centers (Fig. 5) were compared with the respective monthly frontal frequency maps (Fig. 7). Qualitative comparison of these maps shows that fishing grounds do not correspond with SST fronts during June–August.

Finally, monthly area-averaged frequency of SST fronts in 2006–2008 was calculated (Fig. 8). The average frequency of SST fronts during June–August (the early fishing season) is 9.4%, corresponding to a lower CPUE (9.7 Mt/boat/day). The average frequency of SST fronts increases to 15.6% during September–December (the major fishing season) and is associated with a higher CPUE (19.5 Mt/boat/day). The higher CPUEs were associated with higher frequencies of SST fronts during September–December. Consequently, there is a positive relationship between the quantity of SST fronts and the corresponding Pacific saury CPUEs.

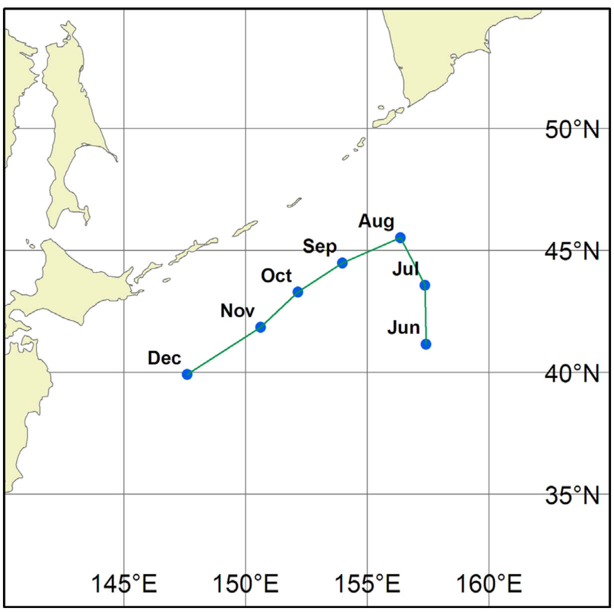

Fig. 5. Fishing centers (weigthed center by CPUE) of Taiwanese Pacific saury fishery during 2006–2008.

3.3. Distance to SST fronts influence Pacific saury CPUE

The histogram analysis of the distance to nearest SST front and variation in CPUE is illustrated in Fig. 9. Results show that the CPUE increases as the distance to SST fronts decreases, especially in the major fishing season from September to November. The fishing positions are far away from the SST fronts during the early fishing season, especially from June to August. In contrast, the fishing positions are much closer to SST fronts during the main fishing season, September–December. During this period, the monthly mean fishing distances to SST fronts are between 20 and 70 km (Fig. 10).

4. Discussion

Distributions of fish species depend on several environmental factors, including but not limited to temperature, salinity, and nutrient availability, which are related to complex, dynamic processes such as currents, upwellings, eddies, and fronts. Convergent oceanographic structures (i.e. SST fronts) can aggregate

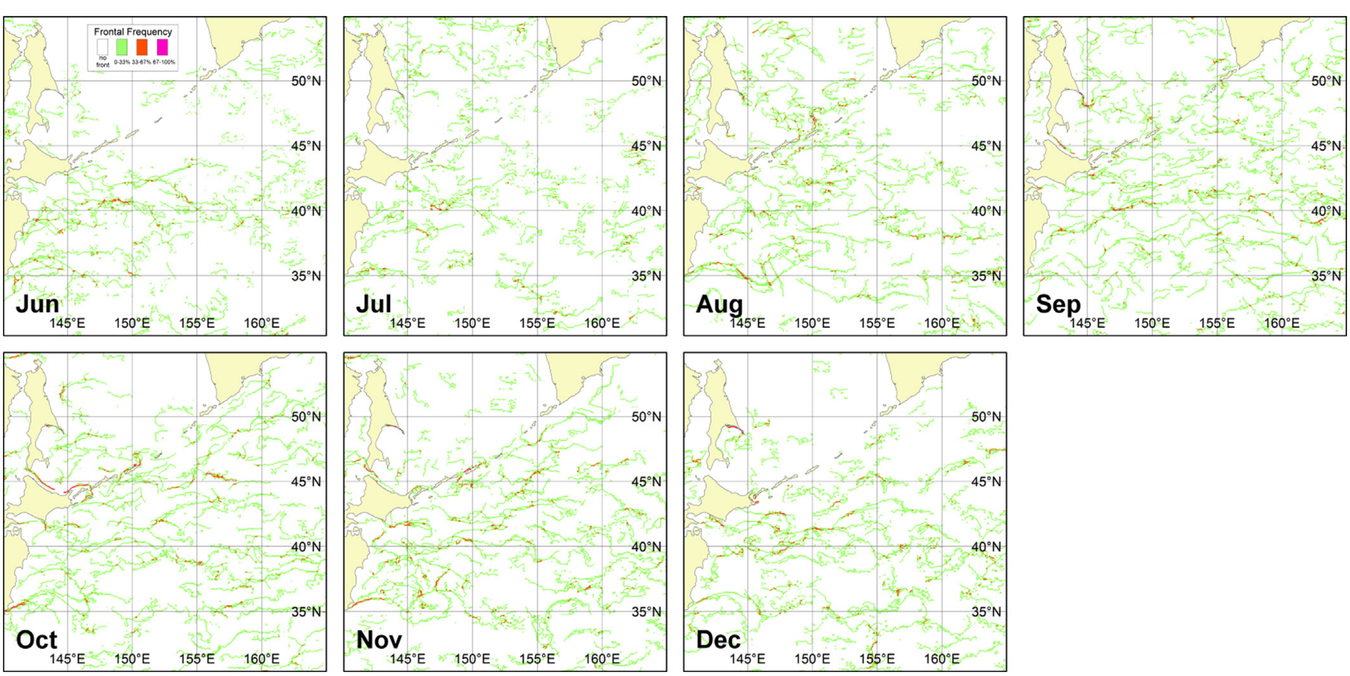

Fig. 6. Monthly distribution maps of SST fronts in the fishing grounds of Pacific saury during 2006–2008.

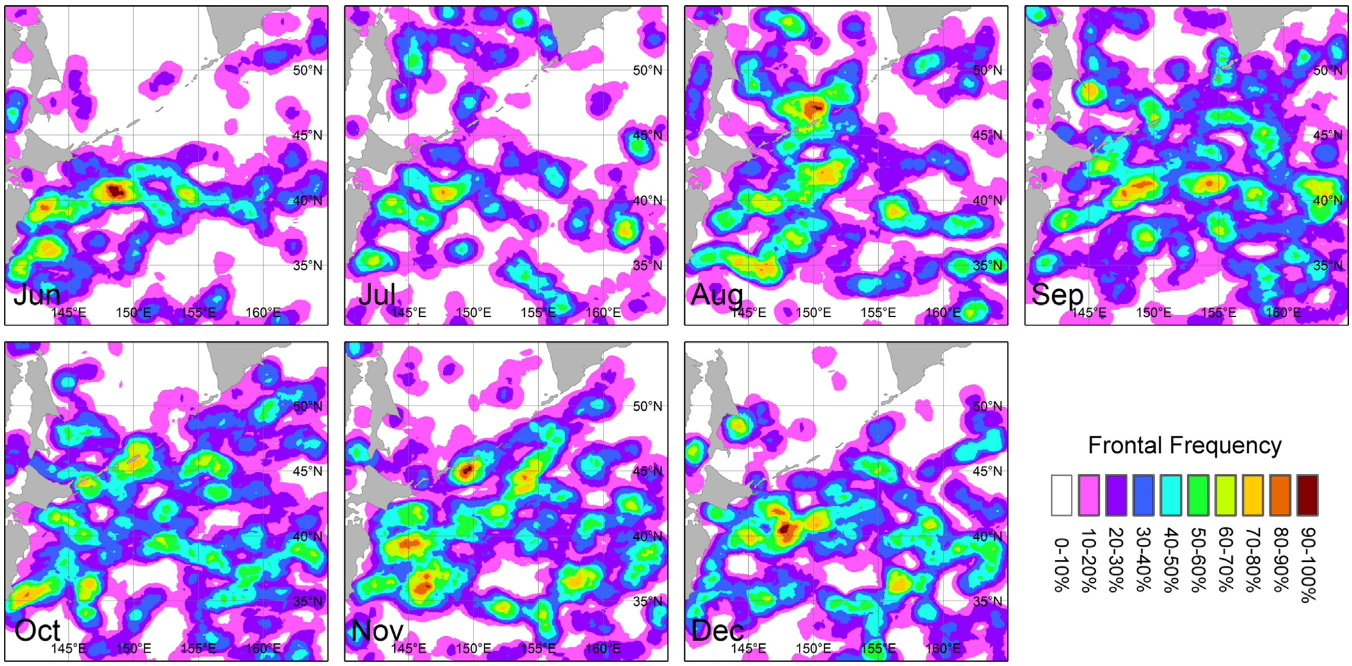

Fig. 7. Monthly frequency maps of SST fronts in the fishing grounds of Pacific saury during 2006–2008.

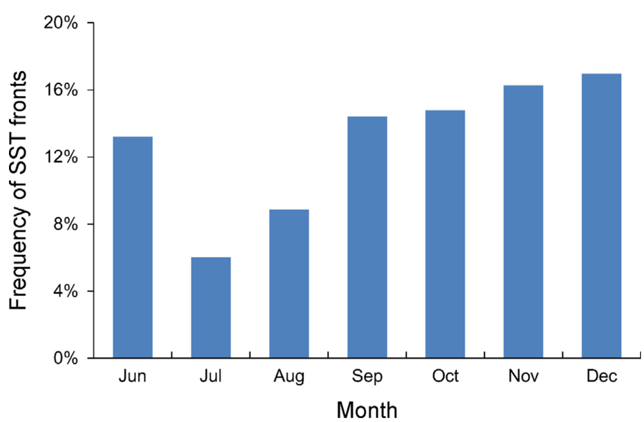

Fig. 8. Seasonal variations of area-averaged frequency of SST fronts during 2006–2008.

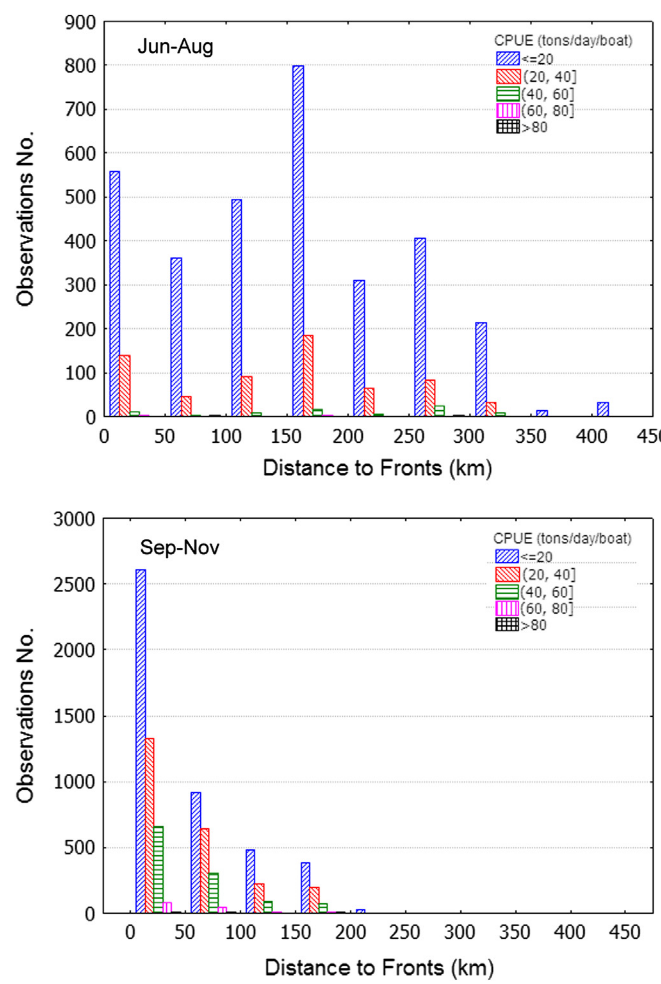

Fig. 9. Seasonal histogram analyses of the distances to SST fronts from the Pacific saury fishing locations in summer (June–August) and fall (September–November).

phytoplankton and attract highly migratory species (Royer et al., 2004; Tittensor et al., 2010).

The Taiwanese deep-sea saury stick-held dip net Pacific saury fishing ground (Huang, 2007, 2010) is located in the coastal waters off Hokkaido and also in the Kuroshio–Oyashio transition zone (Figs. 1 and 4). The convergence of two large oceanic currents usually forms a strong oceanic front with high gradients of SST and other variables such as salinity and nutrients (Polovina et al., 2001). This kind of SST fronts can affect the recruitment of small pelagic fish populations (Watanabe, 2009). The NWP convergence zone is also the spawning, migration and habitat area of the Pacific saury (Iwahashi et al., 2006; Watanabe et al., 2006; Mukai et al., 2007; Yasuda and Watanabe, 1994; Huang, 2010; Tseng et al., 2011). Within this frontal zone, there is a sharp change in surface temperature distribution (high SST gradient) that corresponds to a convergent zone of different water masses resulting in accumulation of planktonic organisms. Such fronts have significant effect on biology (Laevastu and Hayes, 1981). Therefore, it is important to understand where the fronts happen and how they vary in space and time.

The Pacific saury is an epipelagic nekton and highly migratory species inhabiting in the NWP (Brodeur, 1988). Locations of cold rings and streamers of Oyashio water influence the migration routes and aggregation of Pacific saury (Saitoh et al., 1986). Yasuda

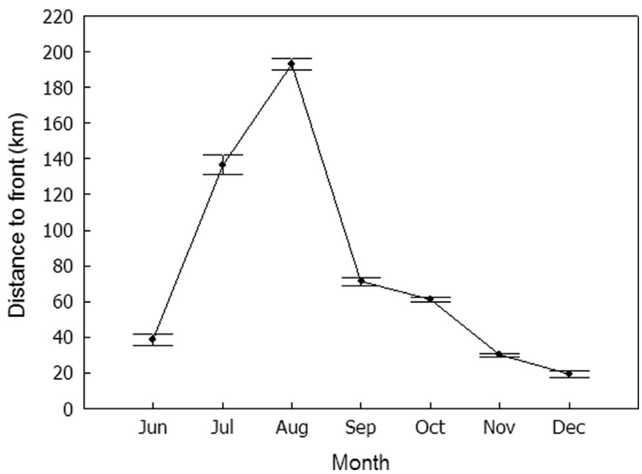

Fig. 10. Monthly averaged distances of Pacific saury fishing locations to SST fronts during 2006–2008. Horizontal lines show standard deviation.

and Watanabe (1994) concluded that Pacific saury use the edges of warm streamers to migrate into the transition zone and then move northward into the Oyashio front.

The Taiwanese Pacific saury fishery moves seasonally depending on the seasonal migration of Pacific saury as well as oceanographic features in the NWP (Kurita, 2006). In winter, the Pacific saury migrates southward to spawn in the Kuroshio Extension. The spatio-temporal variations of the Kuroshio Extension water are usually affected by the subtropical gyre (Chen, 2008). The fishing centers of Taiwanese Pacific saury fishery during June–August were located in the open ocean, alongside offshore waters of the Kuril Islands, outside Russia's EEZ. In May–June (before and during the early fishing season), the larval and juvenile Pacific saury is still located in the Kuroshio–Oyashio transition zone, which is a key region for recruitment of Pacific saury (Watanabe et al., 1997, 2003; Watanabe, 2009). Actually, the Pacific saury undergoes extensive seasonal migrations between the summer feeding grounds at the subarctic fronts (or within the subarctic) and the winter spawning grounds in the subtropical fronts (Batten et al., 2010).

Yasuda and Watanabe (1994) reported that the northward migration of Pacific saury, through the mixed water of the transition zone between the Kuroshio and Oyashio fronts in spring and summer, is closely related to the shift of the offshore Oyashio front. Some previous studies also reported that the Pacific saury grow and migrate to the Oyashio cold water through the Kuroshio–Oyashio transition zone for feeding. After sufficient feeding they migrate back to the Kuroshio warm water in winter for spawning (Kosaka, 2000; Polovina et al., 2001; Watanabe et al., 2006; Yasuda and Watanabe, 1994; Watanabe, 2009). During the southward migration of Pacific saury, more frontal areas had been detected from satellite-derived SST images along the EEZ boundaries of Japan and the Kuril Islands. Higher frontal frequencies corresponded to higher saury CPUEs as found in this study (Figs. 6 and 7). Humphries et al. (2010) reported that some highly migratory species (e.g. shark, billfish, and tuna) prefer to perform the Brownian movement, which is associated with productive shelf or convergence front habitats (abundant prey).

Fundamentally, frontal areas are usually good fishing habitats or feeding grounds. These convergent boundaries and uplifted deep waters usually develop into nutrient-rich frontal areas to aggregate abundant phytoplankton and keep higher net primary productivity. Therefore, the frontal areas are usually regarded as being dominant ecosystems or fish habitats (Lehodey et al., 1998; Harrison and Parsons, 2000; Polovina and Howell, 2005; Palacios et al., 2006; Zainuddin et al., 2006). In the present study, we found that higher saury CPUEs are obtained when the fishing area is close to SST fronts (Fig. 9). Therefore, fronts are important oceanic features associated with high biological production and high fish catch. Solanki et al. (2008) states that the design of fishing strategies for maximum yields usually involves detailed knowledge of locations of oceanic fronts.

5. Conclusions

Satellite remote sensing provides a powerful tool to detect SST fronts. In this study, the satellite-derived MODIS SST data were used to examine the distribution of SST fronts and their effect on the spatio-temporal distributions of Pacific saury in the Northwestern Pacific Ocean. We have shown that fewer SST fronts were associated with lower CPUEs of Pacific saury from June to August. In contrast, more SST fronts are related to higher saury's CPUEs during the major fishing season (September–October). Furthermore, higher saury's CPUE can be obtained within those fishing areas by moving fishing operation closer to SST fronts.

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