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Changes in Patterns of Seasonality Shown by Migratory Fish under Global Warming: Evidence from Catch Data of Taiwan's Coastal Fisheries

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Abstract: In this study, we analyzed the fish species composition data of coastal capture fisheries in Taiwan between 1963 and 2010. The purpose of the analysis was to understand the long-term changes in marine ecosystems. A ratio-to-moving average method was used in conjunction with adjusted seasonal indices to determine the seasonality of individual catch items and to examine the trends shown by the species with the same seasonality. Over the 48-year timespan of the data, 31 species, *i.e.*, 64% of the total number of species, were identified as seasonal migrants. The catch ratio for species showing a single peak in the spring increased steadily over time; however, those species with a single peak in the winter decreased. The catch ratio for those species with dual peaks in both summer and fall varied greatly before 1978. Increasing trends began in the 1980s and accelerated until 1998. As a result of this increase, the previous concentration of the fishing season in the winter months became highly diffuse. Additionally, the winter and/or spring species continued to decrease year after year as the summer and/or autumn species gradually came to dominate the catch. This change in fishing seasonality is likely not an anthropogenic effect. However, the change coincides with trends in sea surface temperature fluctuations. Such variation may not only cause structural change in marine ecosystems but can also significantly impact the economy and the livelihoods of those associated with the fishing trade.

Keywords: China Coastal Current (CCC); Kuroshio Current (KC); seasonality; sea surface temperature (sst); species composition; time series analysis

1. Introduction

The increasing number of publications assessing the impact of climate change on marine ecosystems and fisheries attests to rising scientific and public interest [1]. A selection of recent papers, addressing biological rather than social and economic aspects, is reviewed here, with particular attention given to the climate impact on future fishery yields [1,2]. Climate change has significant effects on marine organisms. It is predicted that by 2050, serious species invasions, local extinctions, and species turnover will have occurred globally; more species will move to higher latitudes [3]. Globally and under the high-range greenhouse gas emission scenario, the 10-year average maximum catch potential will be reduced up to 20% from 2005 to 2055 between 10° N and 10° S. In the Northern Hemisphere, the catch potential will decline moderately in temperate regions (approximately 25–50° N) but increase in higher-latitude regions, particularly in the subarctic region [3,4]. In the Southern Hemisphere, species movement patterns are less clear in the non-tropical regions, except for the large variations in the maximum catch potential (±30% from 2005 level) around the Antarctic region [4]. Therefore, future changes in the position of fish stocks will significantly affect fisheries at both the regional and national levels, especially in low-latitude waters, short-coastline coastal states, and island countries. If these simulations prove true, local fishery resources will change significantly as global warming progresses.

Taiwan is located near the fastest warming marine waters, which can be deemed the "hotspots" of the world [5]; therefore, environmental variation caused by climate change severely affects fishery resources. In the coastal waters of Taiwan, the northward flow of the Kuroshio Current (KC) provides a continuous, year-round addition to the abundant fish resources of Taiwan, influencing the year-round oceanic regime [6]. During the winter north-easterly monsoon period (September to April), the China Coastal Current (CCC) brings cold water from the Yellow Sea and the East China Sea into the Taiwan Strait (TS) [7–9]. Water circulation in the TS varies seasonally due to changes in wind direction [7–9]. Furthermore, the CCC and KC are tied closely to sea surface temperature (SST) variations in the coastal waters of Taiwan (Figure 1) [6]. In recent years, the rate of SST increase in Taiwan's waters has accelerated, and the variability has increased [10]. The increase in SST has been accompanied by a shift in ocean currents. However, the mechanisms behind these changes are the decline of the CCC and the enhancement of the KC [6,11–13]. The ocean environment changes contribute to modifications in the productivity, distribution, and phenology of marine species, affecting ecosystem processes and altering food webs [5,6,14–16].

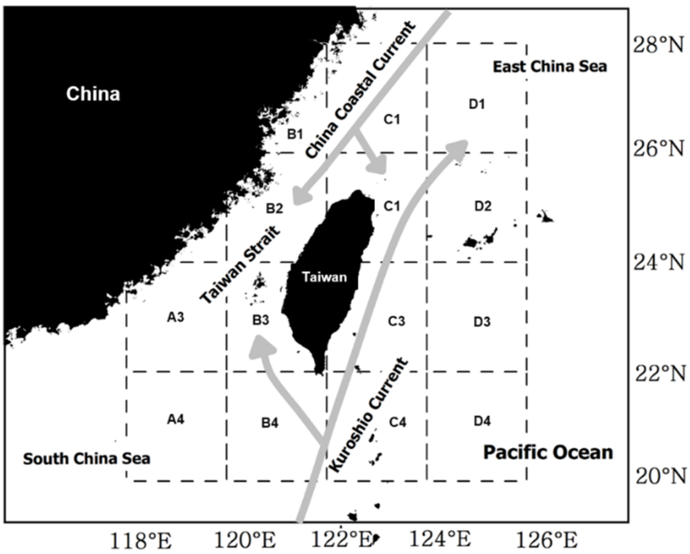


Figure 1. The grids selected for observing the long-term changes of SST from 1963 to 2010: NE, NW, SE and SW. (NE: North East, Grids: C1, C2, D1, D2; NW: North West, Grids: A1, A2, B1, B2; SE: South East, Grids: C3, C4, D3, D4; SW: South West, Grids: A3, A4, B3, B4).

The global ocean temperature has increased at a rate of approximately 0.11 °C every 10 years from 1982 to 2001 [17]. In Taiwan, the water SST increases over this period have been approximately 0.5 °C per decade, a value much higher than the global average. In recent years, the warmer water temperature has caused seasonal variation in the marine species located off the coast of Taiwan [6,18,19]. The SST in Taiwanese waters has been rising since the 1980s, leading to frequent extreme weather and climatic changes. These warmer temperatures are putting the coastal fisheries of Taiwan in a disadvantageous position [6,10,20]. Previous research on this topic has focused on single species in specific local areas. Rare, comprehensive, multi-species, and island-wide surveys were conducted. However, it is difficult to conduct a long-term, fishery-independent survey covering multiple species in the waters surrounding Taiwan. From 1963 to 2010, the fishing capacity of Taiwan rapidly increased. Excessive fishing capacity may result in mixed impacts, and it is difficult to observe the extent of the impact of climate variability. However, the fishing efforts of Taiwanese coastal fisheries are relatively stable compared to other fisheries. The coastal fisheries of Taiwan, defined as those in which fishing activity occurs within 12 nautical miles of the coast, consist of various subsistence fisheries; most are small-scale and multi-gear fisheries that operate year-round. In this study, we sought to compile and analyze the overall coastal fisheries catch data to better understand the change in the seasonality of the fish in response to climate change.

2. Data and Methods

2.1. Catch Data

Fish landing data in weight by species for the coastal capture fisheries were provided by the Fishery Agency for the period 1963–2010, and were filtered. The data were then subjected to seasonal analysis to examine the differences in seasonal fish catch. In the filtering of fisheries data, the set net fishery catch data, representing approximately 20% of coastal catch, were omitted because a fishing moratorium was in place during the typhoon season (July to September). Moreover, catch data representing multiple species of fish were not included (for example, carangidae, shark, herring, and sardines), representing a catch proportion of 22.5%. Newly recorded species (after 1989) were also omitted (for example, cobia, spear shrimp, crimson crab, silver anchovy, blue-barred orange (parrotfish), small yellow croaker, big head shrimp, and file fish), representing 7.5% of the catch. After making these omissions, this study selected 48 fish species for seasonality analysis.

2.2. Seasonality Analysis of the Catch

Monthly catch data from 1963 to 2010 were used to determine the seasonality of the 48 species. The four seasons defined and analyzed were spring (March–May), summer (June–August), fall (September–November), and winter (December–February). The following method was used to determine the smoothed seasonal time series (MA_{i}):

$$MA_i = \frac{Q_{i-2} + 2Q_{i-1} + 2Q_i + 2Q_{i+1} + Q_{i+2}}{8} \quad (1)$$

$$RMA_i = \frac{Q_i}{\mathrm{MA}_i} \times 100\%, \quad (2)$$

where i is the season sequence since 1963 (i = 1, 1963/03–1963/05; i = 2, 1963/06–1963/08; i = 3, 1963/09–1963/11; i = 4, 1963/12–1964/02), Q denotes catch, and RMA is the mean ratio-to-moving-average method.

The Seasonal Index (SI) for a given season k (spring, summer, fall, winter) was calculated as the average RMA of season k from 1963 to 2010 (n = 47). The standard deviation of SI for season k was calculated with the following equations:

$$\overline{SI}_k = \frac{\sum RMA_i}{n} \quad (3)$$

$$SD_k = \sqrt{\frac{\left(SI_k - \overline{SI}_k\right)^2}{n-1}}. \quad (4)$$

Using the mean values and the standard deviation of SI, the seasonality of a fish species was then determined by sequence analysis with an ANOVA and an independent-sample T test. The primary tests were performed for the variances of *SI* across the four seasons ($p1$); the secondary tests were performed for the variances of *SI* for the highest two seasons ($p2$). According to the tests, if the catch yield was concentrated in one season, the seasonality of the species was classified as single-seasonal ($p1 < 0.05$, $p2 < 0.05$). If the catch yield was concentrated in two seasons, the seasonality of species was classified as dual-seasonal ($p1 < 0.05$, $p2 > 0.05$). If the catch yield was not concentrated in a specific season, the seasonality of the species was classified as non-seasonal ($p1 > 0.05$, $p2 > 0.05$). The seasonality of the 48 species was then applied to the catch data for the whole period (1963–2010) to establish the long-term seasonal trend for each species.

2.3. SST Data Process

The SST data with a monthly $1^\circ \times 1^\circ$ grid resolution obtained from the National Oceanic and Atmospheric Administration (NOAA, USA) Extended Reconstructed Sea Surface Temperature (SST) V2 covering all waters adjacent to Taiwan (116–128° E, 18–34° N) were used to observe the trends in SST variability during the period of 1963–2010. For specific months of various years, the number of grids containing data indicating the SST to be more than one standard deviation below and/or above the mean of all grids ($n = 192$) was evaluated. The percentage of areas with positive variability (> +1 sd), negative variability (< −1 sd) and those within the normal range (within ±1 sd) were estimated for individual monthly periods, as well as the aforementioned yearly periods.

To understand the changes in SST in the coastal areas, specified grids were selected to indicate the SST change during the period of 1963–2010. As shown in Figure 1, four areas (NW, NE, SW, SE) were selected to determine the monthly sea surface temperature anomalies (SSTA) time series using the following equations:

$$\overline{SST}_m = \frac{\sum_{y=1963}^{2010} \overline{SST}_{ym}}{n} \tag{5}$$

$$SSTA_{ym} = \overline{SST}_{ym} - \overline{SST}_m. \tag{6}$$

In the above equations, y and m denote the year and month, respectively, and N denotes the year.

The time series of the monthly SSTA of certain areas were used to calculate the annual SST offset relative to the base years (1963–2010). This study also calculated the monthly cumulative SSTA (C-SSTA) to assess the total gain and loss of heat in terms of the SST. The C-SSTA of a certain year and month was defined as the summation of all the SSTA values prior to that year and month.

2.4. Correlation between Seasonal Catch and Regional SSTA

The Pearson correlation coefficients (r) between the seasonal catch proportions (spring, summer, fall, winter) and the corresponding seasonal SST averages in each grid ($n = 192$) were calculated. These coefficients were used to create contours denoting spatial areas with significant coefficients ($p < 0.05$, $r > 0.30$ or $r < -0.30$). Areas with significant correlations ($p < 0.01$, $r > 0.35$ or $r < -0.35$) represented the key waters having a decisive effect on the total catch of each season in Taiwan.

3. Results

3.1. Data Segregation and Seasonality Determination

According to the ANOVA results and the independent-sample T tests of the *SI* for the 48 species, there were 31 species with significant seasonality, representing 65% of the total number of species examined. Among these 31 species, 20 species (42%) were classified as single-season migratory species, and 11 species (23%) were classified as two-season migratory species (Tables 1–3).

Table 1. Single-season migratory species in the coastal capture fisheries of Taiwan.

Common Name	Species Name	Associated Current	*p*1	*p*2	Seasonality
Black pomfret	*Parastromateus niger*	CCC	0.01	0.01	Winter
Black sea bream	*Acanthopagrus schlegelii*	-	0.01	0.02	Winter
East Asian four-finger threadfin	*Eleutheronema rhadinum*	KC	0.01	0.01	Winter
Giant black marlin	*Makaira indica*	KC	0.01	0.01	Winter
Japanese butterfish	*Psenopsis anomala*	CCC	0.01	0.01	Winter
Largehead hairtail	*Trichiurus lepturus*	CCC	0.01	0.01	Winter
Mullet	*Mugil cephalus*	CCC	0.01	0.01	Winter
Red stingray	*Dasyatis akajei*	CCC	0.01	0.01	Winter
Cattlefish	*Sepia pharaonis*	-	0.01	0.02	Spring
Jack mackerel	*Trachurus japonicus*	CCC	0.01	0.01	Spring
Sea barbel	*Arius maculatus*	KC	0.01	0.04	Spring
Slender snoek	*Thyrsitoides marleyi*	KC	0.01	0.04	Spring
Southern mackerel	*Scomber australasicus*	CCC	0.01	0.02	Spring
Black croaker	*Atrobucca nibe*	KC	0.01	0.01	Summer
Octopus	*Octopus vulgare*	-	0.01	0.04	Summer
Oval grouper	*Triso dermopterus*	CCC	0.01	0.01	Summer
Pacific sailfish	*Istiophorus platypterus*	KC	0.01	0.01	Summer
Pike conger	*Muraenesox cinereus*	KC	0.01	0.02	Summer
Red sea bream	*Dentex hypselosomus*	KC	0.01	0.01	Summer
Silver sillago	*Sillago sihama*	-	0.01	0.01	Fall

Sources: Shao and Chen [21]; FishBase [22]; Sea Around Us [23]; Lu and Lee [6].

Table 2. Two-season migratory species in the coastal capture fisheries of Taiwan.

Common Name	Species Name	Associated Current	*p*1	*p*2	Seasonality
Bullet tuna	*Auxis rochei rochei*	KC	0.03	0.14	Spring & Winter
Pacific blue marlin	*Makaira nigricans*	KC	0.01	0.07	Spring & Winter
Silver pomfret	*Pampus argenteus*	KC	0.01	0.06	Spring & Winter
Slender lizard fish	*Saurida elongata*	KC	0.01	0.49	Spring & Winter
Spaniard	*Scomberomorus niphonius*	CCC	0.01	0.37	Spring & Winter
Yellowfin tuna	*Thunnus albacares*	KC	0.01	0.4	Spring & Winter
Dolphinfish	*Coryphaena hippurus*	KC	0.01	0.40	Summer & Winter
Silver sea meagre	*Pennahia argentata*	-	0.01	0.37	Summer & Winter
Mi-iuy croaker	*Miichthys miiuy*	KC	0.02	0.30	Spring & Summer
Sword tip squid	*Loligo edulis*	-	0.01	0.20	Summer & Fall
Tilefish	*Branchiostegus albus*	-	0.04	0.08	Summer & Fall

Sources: Shao and Chen [21]; FishBase (2012) [22]; Sea Around Us [23]; Lu and Lee [6].

Table 3. Species with no seasonal pattern in the coastal capture fisheries of Taiwan.

Common Name	Species Name	Associated Current	*p*1	*p*2	Seasonality
Bullet mackerel	*Auxis thazard thazard*	KC	0.34	0.14	NS
Croceine croaker	*Larimichthys crocea*	-	0.23	0.34	NS
Golden threadfin bream	*Nemipterus virgatus*	-	0.51	0.43	NS
Large yellow croaker	*Larimichthys crocea*	-	0.95	0.4	NS
Moonfish	*Mene maculata*	-	0.07	0.22	NS
Pacific striped marlin	*Kajikia audax*	KC	0.17	0.21	NS
Rainbow sardine	*Dussumieria elapsoides*	-	0.23	0.4	NS
Red bigeye fish	*Priacanthus macracanthus*	-	0.96	0.34	NS

Table 3. *Cont.*

Common Name	Species Name	Associated Current	*p*1	*p*2	Seasonality
Red bokako	*Argyrops spinifer*	-	0.43	0.34	NS
Red seabream	*Pagrus major*	-	0.25	0.06	NS
Redgill emperor	*Lethrinus rubrioperculatus*	-	0.1	0.4	NS
Skipjack tuna	*Katsuwonus pelamis*	CCC	0.55	0.44	NS
Small-mouthed nannygai	*Lutjanus erythropterus*	-	0.69	0.31	NS
Spotted sardine	*Konosirus punctatus*	-	0.43	0.24	NS
Swordfish	*Xiphias gladius*	KC	0.16	0.38	NS
White lady carp	*Cirrhinus Molitorella*	-	0.11	0.13	NS
Yellow band goatfish	*Parupeneus chrysopleuron*	-	0.24	0.31	NS

Sources: Shao and Chen [21]; FishBase (2012) [22]; Sea Around Us [23]; Lu and Lee [6].

3.2. Trend of Catch Proportion for Single-Season Fish

The single-season catch proportion of winter fish species was approximately 60% before 1995. The proportion of spring species and summer species catches represented more than 50% of the total fish catch beginning in 1997. In 2009, the catch of spring species and summer species represented approximately 50% and 15% of all single-season catches, respectively. Conversely, the winter species proportions began to decline from 70% to 30–45% (Figure 2). For the single-season species, the results of this research suggest that winter and/or spring species were diminishing year after year and that summer and/or autumn species gradually began to dominate the catch.

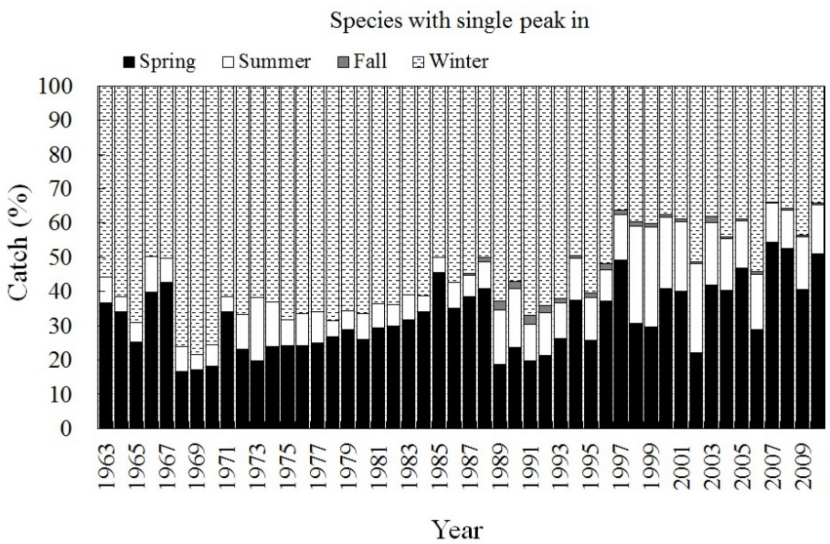


Figure 2. Trend of the catch proportion for single-season species from 1963 to 2010.

3.3. Trend of Catch Proportion for All Seasonally Migratory Species

Figure 3 illustrates the fish catch data, including all seasonally migratory species (including single-season and two-season migratory species) during the period from 1963 to 2010. The proportion of winter and spring species in total catch during the period 1979–1986 was approximately 90%, and has declined since 1998. Before 1998, approximately 10% to 20% of the catch proportion represented the summer and fall species; however, after 1998, these species proportions began to increase (Figure 3).

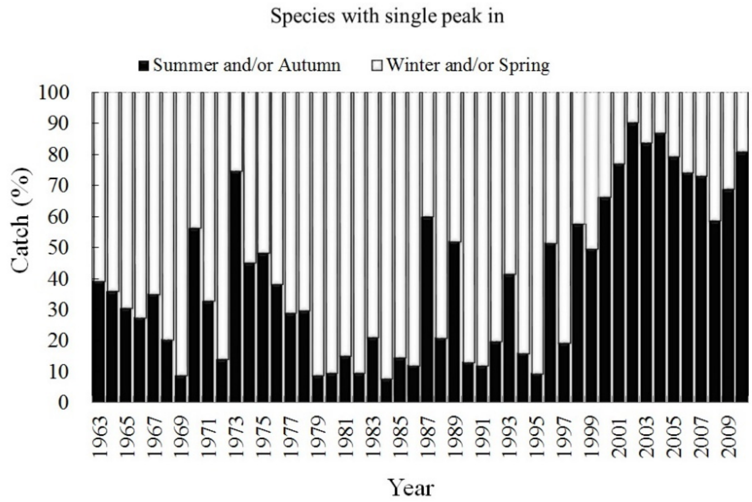
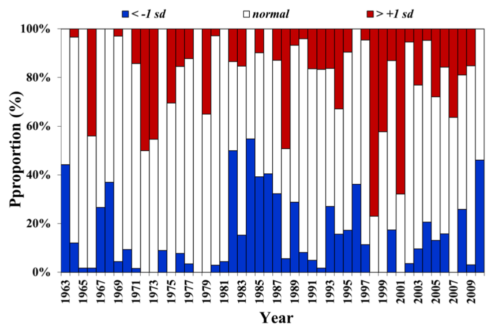


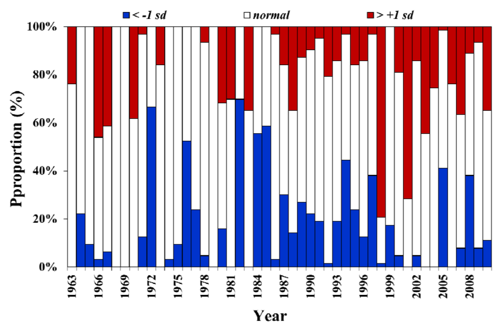
Figure 3. Trend of the catch proportion for all seasonal catches from 1963 to 2010.

3.4. SST Change Trends in the Surrounding Waters of Taiwan

As shown in Figure 4, areas with negative SST variability (< −1 sd) decreased over time, whereas areas with positive SST variability significantly increased (February: $r = 0.305$, $p = 0.034$; August: $r = 0.326$, $p = 0.023$). The highest increased amplitude of the SST in the past decade was in the continental shelf areas of the eastern and southern strait (Figure 5). Since 1997, the rate of increase of SST in Taiwanese waters has accelerated, and the variability has also increased. The increase in SST was characterized by a shift in ocean currents. These changes were directly related to the diminishing CCC and the enhancement of the KC (Figure 5).



(**a**)



(**b**)

Figure 4. Trend of the proportion of the SST variability during the period from 1963 to 2010 in (**a**) February and (**b**) August. Each bar shows the proportion of grids with normal, positive (> 1 sd), and negative (< −1 sd) variability. The positive SST variability increased significantly (February: $r = 0.305$, $p = 0.034$; August: $r = 0.326$, $p = 0.023$).

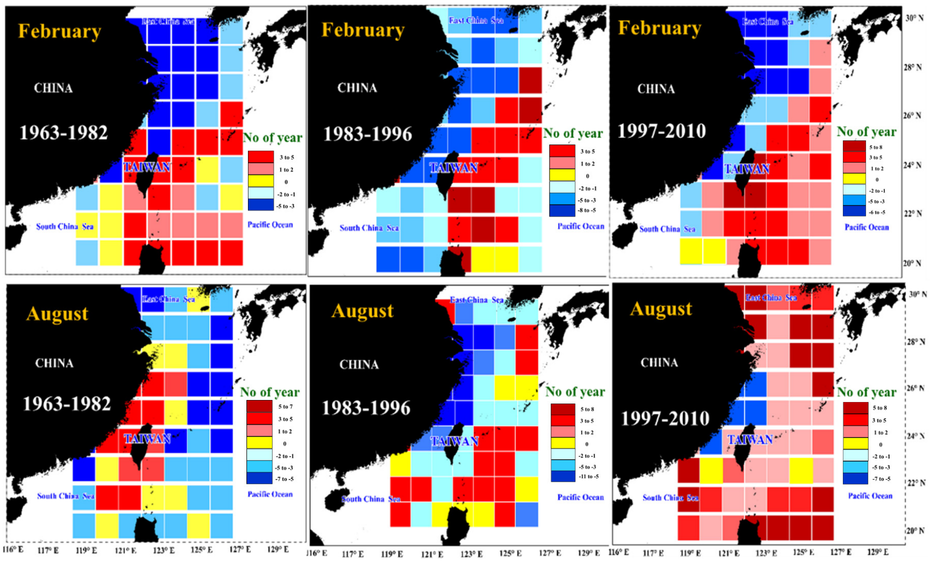


Figure 5. Trend of the accumulated values of the SST variability during the three periods: positive (> 1 sd) and negative (< −1 sd) variability in February and August.

Figure 6 shows the SST variability in the four areas from 1963 to 2010. As observed in the figure, the variation trends of accumulative anomalies of the SST (C-SSTA) differed between the northern and southern areas before 1997. In the northern areas (NW, NE), C-SSTA had increasing trends before 1982; however, the southern areas (SW, SE) indicated the opposite trend. From 1983 to 1997, the C-SSTA of the areas decreased, particularly rapidly in the northeast regions. After 1998, all areas experienced warming trends. There was a change in the NW region with the SST declining rapidly between 1980 and 1996. The declining C-SSTA trend was greater in the NW region compared with other regions, despite the slight SST increase after 1998. According to the long-term trend in the C-SSTA, the warming of the SST in the NW was slower and lower than it had been previously.

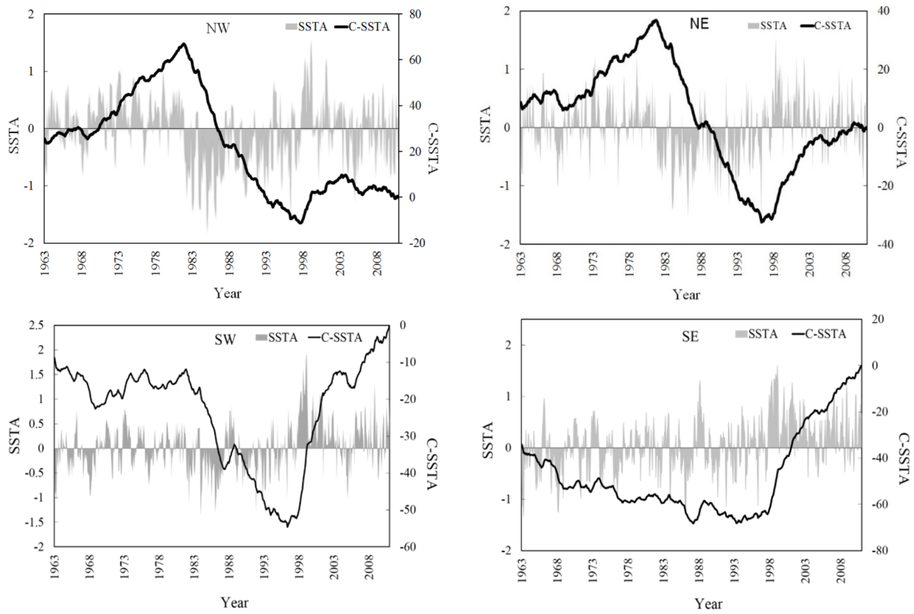


Figure 6. The SSTA and C-SSTA variation trend in Taiwanese waters from 1963 to 2010 (baseline = 1963–2010).

3.5. Spatial Distribution of the Correlation Coefficients between Catch and SST

The spatial distribution of the correlation coefficients between the catch proportion and SST shows that areas with statistically significant r values were primarily located in the continental shelf region in the west and the deep ocean in the east. Areas covered by KC had the highest negative and positive correlation values in the spring, summer, and winter (Figure 7).

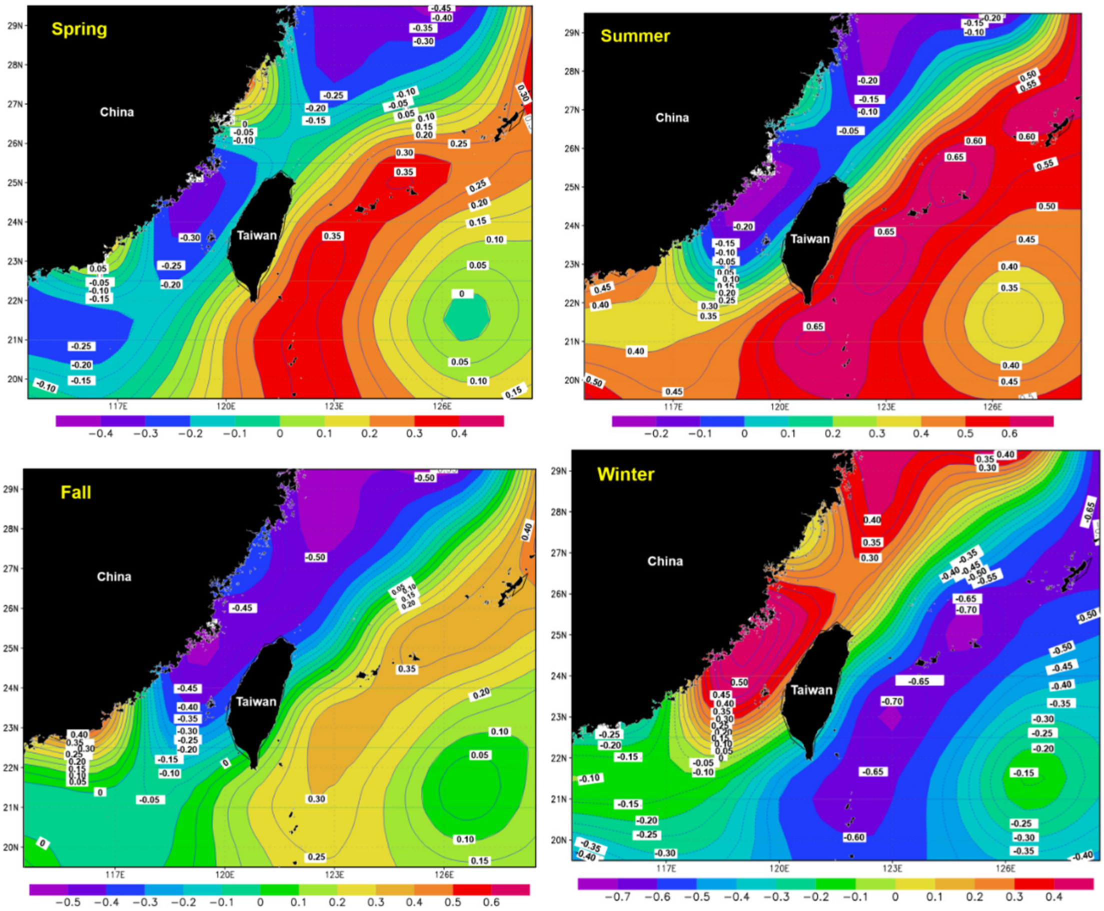


Figure 7. Contours of the correlation coefficient relations between fish catch and the SSTA for the period from 1963 to 2010. Areas with r-values greater than 0.30 or less than −0.30 are significantly correlated ($p < 0.05$).

The spring and summer catch proportions were significantly positively correlated with the SST in the east (spring: $r = 0.35$, * $p < 0.05$; summer: $r = 0.60$–0.65, ** $p < 0.01$). This finding indicated that SST increases produced an increase in the catch proportion in the spring and summer months, such as southern mackerel, slender snoek, and bullet tuna. In the fall, the catch proportion and the SST in the west were negatively correlated ($r = -0.45$, ** $p < 0.01$). In the winter, the eastern SST and catch proportion had a significant negative correlation ($r = -0.60$–-0.70, ** $p < 0.01$). This indicated that a SST increase caused a decrease in the catch proportion, including black pomfret and red stingray. However, according to the C-SSTA of the NW area in Figure 6, the SST warming was not significant in the west and was even lower than the warming that occurred in the 1990s. The catch proportion in the winter and the SST reduction in the west were positively correlated ($r = 0.30$, * $p < 0.05$).

4. Discussion

The 1963–2010 SST in the waters surrounding Taiwan showed increasingly positive variability after 1988 (February: $r = 0.305$, $p = 0.034$; August: $r = 0.326$ $p = 0.023$). In contrast, the negative variability proportion gradually declined (Figure 4). The reasons for this trend are related to the weakening of the CCC and the strengthening of the KC (Figure 5). The weakening of the winter high pressure caused the CCC to extend to the coastal waters of western Taiwan. The KC strengthened gradually (Figure 5). As observed in Figure 6, although the variation trends were different between the north and south regions before 1997, all four regions experienced increases in SST after 1997. The upward trend is significant. A significant intrusion of the KC onto the East China Sea shelf occurred from fall through winter, and the intrusion was associated with monsoon events [7–9]. The frequencies of the KC intrusions have steadily increased in recent decades, consistent with the theory of a more efficient spreading of heat from the KC, as evidenced by the observed coastal warming [24].

The results of the Pearson correlation analysis revealed that the SST in the KC influence areas has a more decisive effect on the tendency for the catch proportions to fluctuate in spring, summer, and winter than the areas dominated by the CCC (Figure 7). The SST increase in the KC enhanced the catch proportion of fish showing spring and summer seasonality (Table 1). In contrast, the catch proportions with winter seasonality were inhibited. Such increases in the catch proportion with spring and summer seasonality were particularly rapid after 1997, when warming accelerated (Figure 2). A similar phenomenon was also discovered in the catch composition from sea-net fisheries in northeastern Taiwan during the period 1993 to 2011 [6]. The proportion of fish associated with the KC gradually dominated the catch after 1997.

In this study, we changed the original fisheries catch data to reflect the long-time trend of Taiwan's coastal fisheries and to enhance the reliability and accuracy of our analysis.

The seasonality analysis of 48 time-series data sets of fishery catches suggested that summer and/or autumn species, such as southern mackerel, slender snoek, red sea bream, and bullet tuna, have gradually replaced winter and/or spring species, such as chub mackerel and jack mackerel (Figures 2 and 3; Tables 1 and 2). Even in the summer, south-to-north migratory species, e.g., the bullet tuna, were more dominant than the north-to-south migratory species, e.g., the sword tip squid (Table 2). In addition to the population changes in the winter and/or spring and summer and/or autumn species (Figures 2 and 3), with the northerly retreat of the CCC (Figures 5 and 7), certain fishing grounds have gradually moved northwards. For example, mullet in the coastal waters of Mainland China have migrated with the CCC to the coastal waters of southwestern Taiwan to spawn during December and January [18,20]. Before 1997, the production of mullet was as much as 300 tons in the coastal waters of Taiwan. Because of the weakening of winter high pressures, however, the CCC does not reach the southern waters of western Taiwan and the mullet catch has decreased [20].

The catch level and the structure of the fish community have been affected by climate change and oceanic regime shifts. The catch proportion of the summer and/or autumn species, mainly consisting of fish with spring and summer seasonality, increased greatly (Figures 2 and 3). Under the warming trend, however, in association with SST variability, species gradually decreased after 2005 (Figures 4–6). The catch proportion of the winter and/or spring species also gradually increased as the SST gradually decreased (Figures 2 and 3). For example, the red sea bream (a summer species) catch proportion was approximately 9% to 47% before 1990, but the population gradually increased after 2005. Similar phenomena can be found for mullet [6,19,20]. Similar regime shifts of fishing communities have been observed in neighboring countries.

Japan is also located near the fastest warming marine waters; the 1976/1977 and 1987/1988 regime shifts significantly influenced the ecosystem of the Tsushima Warm Current (TWC) in the Japan/East Sea [11–13]. Warm-water large predatory fish and cold-water demersal species showed opposite responses to the changes in water temperature in the TWC region, indicating the significant impact of oceanic conditions on fishery production [13]. Regime shifts also occurred in Korean waters in 1976 and 1988 [25,26], as well as in the Kuroshio waters in 1987/1988 [11]. Moreover, Jung *et al.* (2014) [27] used a circulation model to project that the temperature stratification in the Korea Strait will disappear by 2030. They also used empirical relationships to predict that the ranges of five fish species will shift poleward by 19–71 km from the 2000s to the 2030s. Therefore, environmental variation caused by climate change was conspicuous and already severely affects global fishery resources and future fishery yields.

The catch ratio for species with a single peak in the spring increased steadily over time; however, those species with a single peak in the winter decreased (Figures 2 and 3). The catch ratio for those species with dual peaks in both summer and fall varied greatly before 1978 (Figures 2 and 3). Increasing trends began in the 1980s and accelerated until 1998 (Figures 2 and 3). As a result of this increase, the previous concentration of the fishing season in the winter months became highly diffuse (Figures 2 and 3). Such a brief recovery of the winter and/or spring species in reaction to the brief SST decrease cannot sustain the fish catch during the long-term warming trend.

5. Conclusions

In summary, the accelerated SST warming trends in Taiwanese waters occurring since the 1980s have caused changes in the catch proportions of seasonal migratory fish. The winter and/or spring species decreased over time, whereas the summer and/or autumn species gradually dominated the catch. The local marine ecosystems and fisheries face reduction in catches caused by the expansion of fish stocks from the south and withdrawal of fish stocks from the north. Frequent extreme weather and climatic variability during the warming process also influence stock supply. The findings of this study further indicate the distinct vulnerability of fisheries in countries with short coastlines.

The factors that affect changes in fish assemblages are complex [6,17]. Marine capture is a major factor in fishery resources alterations. Climate change may make fishery resources more vulnerable, which is a critical issue for sustaining fisheries across the globe in the future [3,4,6,12,17,19,20]. Because climate change is difficult to predict with high certainty, traditional fisheries management cannot mitigate its impacts on fisheries resources. Therefore, we must arrange mitigation measures to reduce the risks to fisheries and adapt to climate impacts. Such measures include policy making, conserving aquatic resources, implementing precautionary ecosystem-based and integration adaptation management measures, adjusting the scale of fisheries, and adjusting the fishing operations as well as avoidance, transfer, and reduction to establish a resilient fisheries sector [6,17,19,20]. Moreover, to better understand the impacts of climate change on fishery resources, we suggest that future research should adopt statistical methods (e.g., multiple regression) to determine the critical climatic factors and evaluate the composite impact of climate change [17].

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