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Effects of Kuroshio Current Variability and Pacific Decadal Oscillation on Recent Decline in Chub Mackerel (*Scomber japonicus*) Catch in the Northwestern Pacific in the 2020s

DRAFT

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Abstract

Chub mackerel (*Scomber japonicus*), a key commercial species in the Northwestern Pacific, has experienced notable declines in catch since 2019, prompting an investigation into the environmental factors affecting its catch and abundance. This study explores the connections between Chub mackerel catch variability and ocean environmental changes, including upper-ocean temperature, sea level anomaly, net primary production, and influences from large-scale climate phenomena such as the Pacific Decadal Oscillation (PDO) and variations in the Kuroshio Current. Results indicate that variations in the path of the Kuroshio Current around southern Japan and its extension significantly correlate with Chub mackerel catch fluctuations, rather than upper-ocean temperature variability in the feeding and nursery grounds along the east coast of Japan. Additionally, the results underscore the influence of PDO-driven ocean processes on Kuroshio Meandering and its extension, which may establish biologically adverse conditions affecting spawning success and consequently, catch and abundance. These results provide insight into the recent declining trend of chub mackerel catches associated with the PDO-related Kuroshio Meander and its extension variability, provide a basis for estimating catch variability using the relationship between catch and climate variability, and contribute to the development of adaptive management and conservation strategies.

Introduction

The Chub mackerel (*Scomber japonicus*) is a commercially important species in the Northwestern Pacific (Figure 1a), with a wide distribution ranging from the East China Sea to the waters off Japan and around the Kuril Islands. The Chub mackerel spawns in the East China Sea and the waters off southern Japan (Honshu, the largest island of Japan) during spring and early summer, after which the larvae and juveniles migrate northward to their feeding grounds off the northeastern coast of Honshu and the southern waters of Hokkaido (Watanabe et al., 1996; Oozeki et al., 2007). The adult fish then return to the spawning grounds in late autumn and winter (Kume et al., 2021). The fishing seasons for Chub mackerel in the North Pacific typically occur during the feeding periods, with the main fishing grounds located off the northeastern coast of Honshu and the southern waters of Hokkaido (i.e., Kuroshio-Oyashio transition area), and the East China Sea (Kishida and Matsuda, 1993; Yasuda, 2003; Yatsu, 2019). In recent years, there has been an increasing catch in international Waters east of Hokkaido, which is under the jurisdiction of the North Pacific Fisheries Commission (NPFC).

Currently, NPFC members report Chub mackerel catch amounts, which include bycatches of Blue mackerel (*Scomber australasicus*), a species with a broader distribution in the North Pacific. Blue mackerel bycatch accounts for approximately 10% of the total combined catches of Chub and Blue mackerel in recent years (Japan Fisheries Research and Education Agency, 2022a; Japan Fisheries Research and Education Agency, 2022b). The calendar year mackerel (including both Chub and Blue mackerel) catch reported to the NPFC in 2023 was less than half of the 2022 catch (Figure 1c), while the number of fishing vessels and fishing days remained relatively constant between 2022 and 2023 (NPFC, 2024a). Assuming that other conditions, such as vessel size, number of crew on board, and fishing gear used by the vessels, remained unchanged, catch per unit effort (CPUE, in this study catch per fishing days) also decreased significantly (Figure 1c) (NPFC, 2024a). Also, the Chub mackerel catch amounts in the National Waters of Japan have dramatically decreased in recent fishing years (July to next year June) (Japan Fisheries Research and Education Agency, 2022a).

According to the Japan Fisheries Research and Education Agency, one possible explanation for the decline in Chub mackerel catch during the 2020s is an increase in upper-ocean water temperature off the northeastern coast of Honshu and the southern waters of Hokkaido (Japan Fisheries Research and Education Agency, 2023). These warming conditions may create a biologically unfavorable ocean environment for Chub mackerel feeding and nursery grounds, causing schools of fish to move further east where they are less available to the Japanese fishing fleet (Guo et al., 2021; Guo et al., 2022; Wang et al., 2022). The Japan Fisheries Research and Education Agency also suggests that this distribution shift is also influenced by significant changes in regional currents. During the southward migration of Chub mackerel from fall to winter, the Oyashio Current weakened and its extent along the northeast coast of Honshu was reduced, likely pushing the Chub mackerel migration route further offshore. At the same time, the Kuroshio Current shifted northward and moved closer to the coast, preventing the water temperature near Japan's fishing grounds from dropping, resulting in delayed migration to these grounds and a shortened fishing season. These oceanic changes, including the weakened southward extension of the cold, nutrient-rich Oyashio Current and the northward shift of the warm Kuroshio Current, coincide with the reported decline in Chub mackerel catches and may have significant implications for the local marine ecosystem (Japan Meteorological Agency, 2023a).

However, in calendar year 2023, the upper-ocean temperature change in the near south coast of Hokkaido and the NPFC Convention Area was not significant compared to calendar year 2022 (Figure 1b), while the east coast of Honshu shows significant upper-ocean warming (~ 8 °C), and there were even some areas showing subsurface cooling within the

Convention Area (~ -2 °C). Both Japan and China, operating in the National Waters of Japan and the NPFC Convention Area, respectively, reported a significant decrease in CPUE for Mackerel in calendar year 2023 (NPFC, 2024a). If the decrease in catch in the National Waters of Japan in recent years was mainly due to increasing water temperatures in this region causing a shift in distribution to the east (the Convention Area), this should have resulted in increased catch outside of the National Waters of Japan, i.e., the NPFC Convention Area. However, China's CPUE within the Convention Area also declined in calendar year 2023 (NPFC, 2024a), suggesting that distributional shifts due to changes in upper-ocean water temperatures off the northeast coast of Honshu and southern waters of Hokkaido alone cannot fully explain the decline in Chub mackerel catches throughout the Northwestern Pacific. This raises the question of what factors contributed to the overall decline in catches in recent years.

Previous studies have found a relationship between the Pacific Decadal Oscillation (PDO) and the abundance of Japanese sardine (*Sardinops melanostictus*), one of the competitors of Chub mackerel (Yasuda et al., 1999; King et al., 2015; Kuwae et al., 2017; Wang et al., 2021). The PDO is a long-term climate variability pattern that influences the sea surface temperature (SST) and other physical ocean conditions in the North Pacific, with warm (positive) and cool (negative) phases alternating on multi-decadal timescales (Mantua et al., 1997; Hare and Mantua, 2000). Previous studies suggest that PDO-related upper-ocean temperature variability can induce favorable ocean conditions for Japanese sardine to the detriment of its competitor Chub mackerel (Yasuda et al., 1999; Yatsu et al., 2005). However, the exact dynamics of how the PDO regulates sardine abundance through physical ocean dynamics or specific ocean conditions related to the Chub mackerel abundance and catch have not been fully investigated (Kuwae et al., 2017).

One potential mechanism through which the PDO may influence the Chub mackerel abundance is via its effects on the Kuroshio Current (Noto and Yasuda, 1999). Since 2017, the Kuroshio Current has exhibited large meandering (Qiu et al., 2023; JMA, 2023b), coinciding with a decreasing trend in Chub mackerel catch amounts (NPFC, 2024a). The Kuroshio Large Meandering is a phenomenon characterized by the Kuroshio Current taking a large offshore excursion south of Japan, which can significantly impact the regional oceanography, including SST, nutrient distribution, and local circulation patterns (Kawabe, 1995). These changes in the physical ocean environment may have implications for the distribution, abundance, and catch of marine species in the region, including Chub mackerel (Yasuda, 2003). Previous studies have shown that the occurrence of Kuroshio Large Meandering events is linked to basin-scale wind stress curl patterns in the North Pacific (Qiu and Chen, 2005; Qiu et al., 2023). These wind stress curl patterns are influenced by the PDO dynamics, as the PDO-related wind forcing generates westward-propagating sea surface height anomalies that can impact the Kuroshio Current's path, the Kuroshio Extension stability, and meandering behavior (Taguchi et al., 2007; Qiu and Chen, 2021; Qiu et al., 2023). The Kuroshio Large Meandering may act as a conduit between large-scale climate variability and regional oceanographic conditions, influencing Chub mackerel abundance and catch in the upper ocean in a manner similar to that observed in the East China Sea (Sassa and Tsukamoto, 2010).

This study investigates the key oceanographic and environmental factors that may have contributed to the recent decline in Chub mackerel catches in the Northwestern Pacific region. The study assumes that the abundance dynamics of Chub mackerel can be represented by the catch and CPUE patterns of the Chub mackerel fishery. The available data indicates that catch and CPUE are very consistent in the data, at least since calendar year 2012 (Figure 1c). Consequently, the variability in Chub mackerel catch can be considered a proxy for both abundance and CPUE. By examining the relationships between environmental variables and

Chub mackerel catch data, this study aims to identify the critical factors influencing the abundance and catch dynamics of this commercially important species in the region, providing valuable insights for fisheries management and conservation efforts.

Data

Fisheries Data

This study primarily investigated the organized Chub mackerel (*Scomber japonicus*) catch amounts in the National Waters of Japan during the fishing years of 1995–2022 (Japan Fisheries Research and Education Agency, 2022a). Additionally, it utilized annual catch and fishing effort data for the mackerel fishery from the calendar years 1995 to 2023, provided by NPFC members China and Japan (NPFC, 2024a). The Japanese data were confined to catches within Japan's Exclusive Economic Zone (EEZ), while the Chinese data encompassed catches from the entire NPFC Convention Area.

Although the NPFC dataset includes both Chub mackerel (*Scomber japonicus*) and Blue mackerel (*Scomber australasicus*), the proportion of Blue mackerel catches in the National Waters of Japan has been approximately 10% during the most recent five fishing years (Japan Fisheries Research and Education Agency, 2022a; Japan Fisheries Research and Education Agency, 2022b). Consequently, the minor percentage of Blue mackerel catch in recent years does not significantly affect the analysis of Chub mackerel catch and its relationship to ocean environmental variables. Therefore, it is acceptable to use NPFC data as a supplementary dataset for this study, despite the inclusion of both Chub and Blue mackerel catches.

To account for temporal changes in fishing efficiency and abundance, catch per unit effort (CPUE) was calculated as the total annual catch divided by the total number of fishing days. This CPUE serves as a proxy for relative abundance. CPUE in the National Waters of Japan exhibits similar variability to catch amounts in the National Waters of Japan during the calendar years 2011–2023 ($r = 0.95, p < 0.01$) (Figure 1c). This strong correlation suggests that variability in catch amounts can be considered a suitable proxy for variability in Chub mackerel abundance, allowing the relationships between environmental factors and Chub mackerel abundance to be investigated using catch data.

Environmental Data

To investigate the environmental factors influencing Chub mackerel catch in the Northwestern Pacific, a combination of satellite-derived and model-based datasets was utilized. Sea surface temperature (SST) data from calendar years 1995 to 2023 were sourced from the Global Ocean Operational Sea Surface Temperature and Ice Analysis (OSTIA) system, which provides a high-resolution (1/20°, approximately 6 km) daily global SST analysis by integrating satellite observations from the GHRSST project with in-situ measurements (Donlon et al., 2012).

Sea level anomaly (SLA) data were obtained from two complementary datasets: the Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed 1993 Ongoing dataset for the period calendar years 1995–2021, and the Near Real-Time version of the same product for calendar years 2022–2023 (SEALEVEL_GLO_PHY_L4_MY_008_047 product, 2024; SEALEVEL_GLO_PHY_L4_NRT_008_046 product, 2024). These datasets, which have a spatial resolution of 0.25°, are derived from merged altimetry data from multiple satellite missions.

Upper-ocean temperature data for the upper 200 m depth (with a spatial resolution of 1/12°) and net primary production of biomass expressed as carbon per unit volume in seawater (NPPV, with a spatial resolution of 0.25°) were employed to examine the subsurface ocean conditions. These variables were obtained from the Global Ocean Physics Reanalysis and Global Ocean Biogeochemistry Hindcast for the period calendar years 1995–2020

(GLOBAL_MULTIYEAR_PHY_001_030 product, 2024; GLOBAL_MULTIYEAR_BGC_001_029 product, 2024), and from the Global Ocean Physics Analysis and Forecast (updated daily) and Global Ocean Biogeochemistry Analysis and Forecast for the period calendar years 2021–2023 (GLOBAL_ANALYSISFORECAST_PHY_001_024 product, 2024; GLOBAL_ANALYSISFORECAST_BGC_001_028 product, 2024). All environmental anomalies were calculated by subtracting the monthly climatological mean for the period calendar years 1995–2023, except for the SLA. The SLA dataset was adjusted based on computations relative to the reference period from calendar years 1993 to 2012.

Environmental Indices

To investigate the potential influence of large-scale climate variability and regional oceanographic features on Chub mackerel catch, this study incorporated three key indices in our analysis. The Pacific Decadal Oscillation (PDO) index, which represents the leading principal component of North Pacific monthly sea surface temperature variability poleward of 20° N, was obtained from the National Oceanic and Atmospheric Administration (NOAA) (https://www.psl.noaa.gov/gcos_wgsp/Timeseries/).

To assess the variability of the Kuroshio Current, this study utilized the sea level difference (SLD) between Kushimoto and Uragami, a proxy for the Kuroshio Meandering. The SLD data were retrieved from the Japan Meteorological Agency (JMA) (https://www.data.jma.go.jp/gmd/kaiyou/shindan/index_curr.html). Furthermore, to examine the potential influence of the Oyashio Current on Chub mackerel catch, this study incorporated the yearly Oyashio mean southern limit position index, which was also obtained from the JMA. This index indicates the southward extent of the Oyashio Current, which may affect the oceanographic conditions around the Hokkaido. By integrating these indices with the environmental datasets, this study aimed to gain a comprehensive understanding of the interplay between large-scale climate variability, regional oceanographic features, and Chub mackerel catch in the Northwestern Pacific.

Correlation Analysis

The relationship between the annual catch time series of Chub mackerel in the National Waters of Japan and various ocean environmental variables was analyzed using correlation map analysis. This approach, despite the absence of spatial distribution data in the catch time series, enabled the identification of regional-scale ocean dynamics associated with catch variability. Correlation coefficients were computed for each grid cell of yearly averaged sea SST, upper 75 m temperature, SLA, and NPPV anomalies at 5 m depth against the annual catch data from the fishing years 1995 to 2022. The temperature at 75 m depth was selected to align with the typical habitat depth of Chub mackerel, while the NPPV at 5 m depth was chosen to capture the intricate interactions between upper-ocean thermal structure and phytoplankton productivity.

To robustly validate the statistical significance of these correlations, a null model simulation was conducted using an autoregressive model of order 1 (AR(1)). This simulation accounted for temporal autocorrelation in both the ocean environmental variables and the catch time series. By performing 1,000 iterations of the AR(1) null model, the impact of autocorrelation was assessed, thereby strengthening the validity of the findings.

The results from these simulations highlighted statistically significant correlations between the environmental variables and Chub mackerel catches (> 95% of the confidence interval), emphasizing the influence of oceanographic conditions on fishery productivity. The correlation maps revealed distinct spatial patterns where environmental variables were significantly linked to Chub mackerel catch variability, as shown by the contoured areas (Figure 2).

Results

Correlation Analysis of Environmental Variables and Chub Mackerel Catch

Figure 2 presents the correlation maps of environmental variable anomalies with Chub mackerel catch. Notably, the correlation map for SST from the fishing years 1995 to 2022 reveals no statistically significant areas correlated with Chub mackerel catch, except for some regions near the Aleutian Islands (Figure 2a). Similarly, the subsurface temperature at 75 m depth shows no statistically significant correlations, except for a limited area on the northeast coast of Honshu and around the Kuril Islands with a positive relationship (Figure 2b). However, both correlation maps exhibit weak negative correlation coefficients off the coast of southern Honshu, although these failed to pass the AR(1) null simulations (Figures 2a–b).

In contrast, the SLA shows a statistically significant positive relationship far southeast of Honshu and in the northwestern part of the NPFC Convention Area (Figure 2c). While statistically insignificant (failed to pass the AR(1) null simulations), the area south of Honshu exhibits a weak negative correlation, and the Sea of Okhotsk shows a positive correlation (Figure 2c). The NPPV at approximately 5 meters depth from fishing years 1995 to 2022 shows positive relationships with Chub mackerel catch amounts southeast of Honshu, in the southern part of the Sea of Okhotsk near the coast of Hokkaido, and the northwestern part of the Convention Area (Figure 2d).

The correlation maps of environmental variables indicate that the area between the northeast of Honshu and the south of Hokkaido, known as feeding and breeding grounds, does not show a statistically significant correlation with Chub mackerel catch. Interestingly, the limited area of the northeast coast of Honshu even shows a positive relationship with the upper ocean temperature. This finding contrasts with the explanation from the Japan Fisheries Research and Education Agency, which highlights a negative relationship between catch and upper-ocean temperature, suggesting that upper-ocean cooling is related to an increase in catch (Japan Fisheries Research and Education Agency, 2023). In contrast, the area southeast of Honshu, which is part of the recirculation gyre and potentially connected to the Chub mackerel spawning grounds, displays statistically significant correlations. Although the correlation map for environmental variables south of Honshu shows statistically insignificant values except for the region off the southeast coast of Honshu, the spatial patterns around this area exhibit features resembling Kuroshio Path variability, specifically the Kuroshio Current meandering patterns (Qiu and Chen, 2010; Qiu et al., 2023). These results may suggest the potential influence of the Kuroshio Current and its meandering and the recirculation gyre on the distribution and abundance of Chub mackerel in the region.

Relationship between Chub Mackerel Catch and Environmental Indices

Figure 3 illustrates the normalized catch amounts of Chub mackerel in the National Waters of Japan, along with the 2-year low-pass filtered SLD between Kushimoto and Uragami, and the PDO index. The SLD between Kushimoto and Uragami, one of the proxies for the Kuroshio Current meandering, exhibits similar variability to the Chub mackerel catch from the mid-2000s (blue-shaded area) to mid-2010s. During this period, particularly in 2004–2005, the SLD shows a significant shift from negative to positive values, coinciding with a marked increase in the Chub mackerel catch, indicating the occurrence and subsequent dissipation of a Kuroshio Large Meander event.

The PDO shows an overall comparable trend, except for the mid-2000s (blue-shaded area). Notably, the correlation coefficients between the yearly averaged 2-year low-pass filtered PDO and the Chub mackerel catch during fishing years 1995–2022 are 0.60 ($p =$

0.0005) and 0.56 ($p = 0.0005$) when the PDO leads Chub mackerel by 1 year. This suggests that the PDO-related ocean environmental variability may have a lagged influence on the Chub mackerel abundance dynamics. In contrast, while the monthly variability of the SLD between Kushimoto and Uragami shows similar patterns to the Chub mackerel catch during the mid-2000s to mid-2010s, the correlation coefficient is statistically insignificant during this period. Furthermore, the yearly Oyashio mean southern limit position index during the fishing years 1995–2022 does not exhibit a statistically significant relationship with the catch amounts of Chub mackerel ($r = -0.01, p = 0.74$). This finding is consistent with the correlation map of subsurface temperature at 75 m, which shows an insignificant relationship between ocean temperature and catch, and even a positive relationship in a limited area off the northeast coast of Honshu. These results suggest that the southward extension of the Oyashio Current may not be a primary driver of Chub mackerel catch variability over this period.

Chub Mackerel Catch Variability with SST and SLA during Distinct Periods

Although there is no significant correlation between SST and Chub mackerel catch except for some regions (Figure 2a), the correlation coefficients between the PDO and the catch show a statistically significant relationship. To understand the PDO-related ocean environmental variability and its potential connection to catch variability, a composite analysis was conducted using SST and SLA data during periods of increasing and decreasing catch.

Figure 4 illustrates the yearly averaged SST and SLA anomalies for three specific periods (fishing years 1997–1999, 2004–2006, and 2020–2022). These were periods of contrasting trends in Chub mackerel catch, the 2-year low-pass filtered SLD between Kushimoto and Uragami, and the PDO index (shaded areas in Figure 3).

During fishing years 1997–1999, Chub mackerel catch amounts and PDO indices decreased significantly, while the SLD showed no significant change. The yearly averaged SST anomaly exhibited overall warming approximately south of 40° N, with significant warming along the east coast of Honshu (35–40° N) and the south coast of Japan (Figure 4). The SST also showed cooling around the far east coast of Japan, potentially indicating the influence of the Oyashio Current. The SLA displayed significant variability in the Kuroshio Extension, with generally negative anomalies south of 35° N and positive anomalies north of 40° N.

During fishing years 2004–2006, when Chub mackerel catch and SLD showed similar trends, and the PDO exhibited a different pattern with positive amplitude, the yearly averaged SST showed a significant negative anomaly along the east coast of Honshu and south of Hokkaido (Figure 4), a region known as a feeding ground for Chub mackerel and part of the Kuroshio-Oyashio Transition Area. The SLA showed negative anomalies south and east of Honshu, with positive anomalies southeast of Honshu.

In fishing years 2020–2022, similar to 1997–1999, Chub mackerel catch amounts, SLD, and PDO indices decreased. However, in contrast to 1997–1999, the SST anomaly showed a warming north of 40° N (Figure 4), indicating a significantly weakened southward extension of the Oyashio Current, consistent with the Oyashio Southern Limit Latitude Index (not shown). The yearly averaged SST exhibited significant surface warming from the southeast to the east coast of Honshu and the Chub mackerel feeding ground, along with surface cooling around the southwest of Honshu. This surface warming and cooling pattern along the coast of Honshu is physically consistent with the SLA, which showed significant positive anomalies southwest and southeast of Honshu, respectively, indicating the presence of the Kuroshio Large Meandering. Partially similar to 1997–1999, the SLA anomaly in the Kuroshio Extension showed a significant positive anomaly with a northward shift in the Kuroshio

Extension latitude.

Discussion

Ocean Conditions and Chub Mackerel Catch

The analysis of the relationship between environmental variables and Chub mackerel catch in the Northwestern Pacific reveals the complex interplay of oceanographic features and their influence on the abundance dynamics of this commercially important species. The correlation map (Figure 2) highlights the significance of the far southeast coast of Honshu, where the SLA and NPPV exhibit a positive relationship with catch (Figures 2c–d).

Even though they failed to pass AR(1) null simulations, the SST, subsurface temperature at 75 m depth, and the SLA exhibit a negative relationship with catch in the south to southeast of Honshu, suggesting that increasing upper-ocean temperature in those regions, the spawning ground of Chub mackerel, maybe associated with decreased catches. The positive relationship between SLA and catch on from the southwest to south coast of Honshu may indicate a potential link between the variability of the Kuroshio Current's main path, specifically the Kuroshio Meandering, and fluctuations in upper-ocean temperature and catch in this region (Yasuda, 2003).

Interestingly, the previously reported relationship between upper-ocean temperature and Chub mackerel catch was not evident in the correlation map (Figures 2a–b). The results show no significant relationship between upper-ocean temperature and catch variability, not only south of Honshu but also off the southern coast of Honshu and east of the Kuril Islands, which could be considered the Oyashio Current domain. Additionally, the data indicate an insignificant relationship between the Chub mackerel catch and the Oyashio mean southern limit. This finding suggests that the influence of upper-ocean temperature on Chub mackerel catch may be more complex than previously thought, and other factors, such as prey availability and oceanographic processes, may play a more significant role in determining the species' abundance and distribution (Yatsu et al., 2005). These results suggest that upper-ocean cooling associated with the southern extension of the Oyashio may not be the primary factor influencing the variability of chub mackerel catches.

Instead, the positive correlation between NPPV and catch in the southern Sea of Okhotsk suggests that plankton blooms in this area may favorably influence the Chub mackerel feeding ground, thereby contributing to increased catches (Figure 2d) (Radchenko et al., 2003; Sakurai, 2007). The positive relationship between surface NPPV and Chub mackerel catches in the southeast of Honshu, located south of the Kuroshio Extension's main path and characterized by a clockwise southern recirculation gyre, further emphasizes the connection between the Kuroshio Extension and catch variability (Figure 2d) (Sugisaki, 2010; Nishikawa et al., 2013). This finding highlights the importance of considering the spatial and temporal variability of primary productivity when investigating the factors influencing the population dynamics of Chub mackerel in the Northwestern Pacific (Yatsu et al., 2005).

Potential Influence of the PDO on Chub Mackerel Catch through Kuroshio Meandering

While the PDO is related to upper-ocean temperature variability south of Japan and in the Kuroshio Extension region, the results of this study also highlight the potential relationship between PDO-related Kuroshio Meandering and Chub mackerel catch. Previous studies have linked Kuroshio Meandering to basin-scale wind stress curl in the North Pacific, which is closely related to the PDO (Qiu and Chen, 2005; Qiu and Chen, 2010; Qiu and Chen, 2021; Qiu et al., 2023). During the positive phase of the PDO, the surface wind stress curl in the North Pacific influences not only the regional SST but also the anticyclonic wind forcing over the Subtropical Counter Current and the Kuroshio Current's path southeast of Kyushu. This induces cyclonic-anticyclonic eddy interactions around the Subtropical Counter Current region and positive relative vorticity along the coast, preceded by 1–2 years by the Kuroshio Large Meandering (Taguchi et al., 2007; Sasaki et al., 2008; Qiu and Chen, 2021). The Kuroshio Meandering-like spatial patterns can be observed in the correlation maps of SST and subsurface temperature at 75 m depth south of Honshu, even though their correlation coefficients did not pass the AR(1) null simulations. Additionally, significant correlations were found with SLA from southeast of Honshu, exhibiting a pattern resembling Kuroshio Meandering. These findings suggest that the Kuroshio Current's meandering, influenced by PDO-related ocean process, may play a crucial role in affecting Chub mackerel catch variability.

Furthermore, approximately three years after the positive PDO phase, the Kuroshio Extension transitions to an unstable state due to the arrival of negative SSH anomalies originating from the interior of the North Pacific, which reaches the coast of Japan 2–3 years later (Qiu and Chen, 2005; Qiu and Chen, 2010; Sasaki et al., 2013; Sasaki et al., 2014; Qiu and Chen, 2021). These processes trigger the development of large-scale meandering patterns and promote a more stable Kuroshio Extension (Qiu and Chen, 2010; Qiu and Chen, 2021). Simultaneously, the intensified southern recirculation gyre associated with the stable Kuroshio Extension further contributes to the anchoring of the Kuroshio Current across the Izu Ridge (Sugimoto and Hanawa, 2012; Sasaki et al., 2014; Qiu and Chen, 2021). The stability of the Kuroshio Extension and the intensified recirculation gyre may induce biologically favorable ocean conditions, such as positive NPPV anomalies, which can support spawning, feeding, and nursery grounds for Chub mackerel, ultimately leading to increased catches in the Northwestern Pacific (Sassa and Tsukamoto, 2010; Kamimura et al., 2015). This positive relationship between PDO-related NPPV anomalies and catch amounts is evident south of the Kuroshio Extension, particularly southeast of Honshu (Figure 2d). These findings suggest that NPPV in this region significantly influences Chub mackerel catch not only within the EEZ of Japan but also across the entire Northwestern Pacific. By regulating the biological environmental variability, PDO-related NPPV may affect the spawning, feeding, and nursery grounds for Chub mackerel, thereby impacting their overall abundance and distribution.

Kuroshio Meandering and Chub Mackerel Catch

During the mid-2000s, particularly in 2004–2005, the PDO exhibited a different variability pattern compared to the catch amounts and the SLD between Kushimoto and Uragami, which serves as an indicator of the Kuroshio Meandering (blue shaded area in Figure 3). In this period, a short but large Kuroshio Meandering event occurred (Qiu et al., 2023), as evidenced by the negative values of the SLD. A previous study has suggested that the occurrence and extinction mechanisms for the Kuroshio Large Meandering during this period (2004–2005) may have been slightly different from other Kuroshio Large Meandering events and that the meandering may have occurred due to reasons other than PDO-related wind forcing (Qiu et al., 2023). This observation is consistent with the findings of the previous study, highlighting the different variability patterns exhibited by the SLD between Kushimoto and Uragami and the PDO index during the mid-2000s. Furthermore, the SLA variability between fishing years 2004–2006 and 2020–2022 (Figure 4) further supports the notion that the Kuroshio Meandering behavior during these periods may have been influenced by factors beyond the PDO, emphasizing the complex nature of the Kuroshio Current system and its impact on the ocean environment and fisheries in the Northwestern Pacific (Qiu and Chen, 2005; Qiu and Chen, 2010; Qiu and Chen, 2021; Qiu et al., 2023).

While the PDO exhibits a statistically significant relationship with Chub mackerel catch during fishing years 1995–2022, it is crucial to recognize that the PDO and its associated influence on the meandering of the Kuroshio Current are not the only factors influencing the variability of the Chub mackerel catch. Instead, the results of this study suggest that various factors related to the Kuroshio Current system and the broader Northwestern Pacific environment may contribute to the variability in Chub mackerel catch in the region (Yatsu et al., 2013). The intricate interplay between large-scale climate patterns, such as the PDO, and regional oceanographic features, like the Kuroshio Meandering, underscores the necessity for a holistic approach to understanding the multiple drivers that influence the abundance dynamics and catch variability of commercially significant species like Chub mackerel (Overland et al., 2010; Yatsu, 2019).

Ocean Conditions, Age Structure, and Catch of Chub Mackerel

The observed relationship between PDO and chub mackerel catch, with significant correlations in both contemporaneous and 1-year lagged relationships, is consistent with the known dynamics of the age structure of this species in Japanese National Waters. The domestic chub mackerel fishery in Japan typically catches individuals up to age 7 or 8, but the majority of the catch in most years since fishing year 1995 has consisted of age 0 and age 1 fish (Japan Fisheries Research and Education Agency, 2024). This age composition of the catch may confound the ability to make direct inferences about recruitment dynamics, as the annual signals from climate indices such as PDO may be distributed across multiple age classes represented in fishery landings. The observed relationship suggests that large-scale oceanic climate drivers influence on spawning and early life stage dynamics. Shifts in the path of the Kuroshio Current and eddy activity may alter the location and suitability of spawning habitat, as well as the transport and survival of early life stages, ultimately affecting recruitment and catch amounts (Taguchi et al., 2007; Qiu and Chen, 2021; Qiu et al., 2023).

The age-structure effect may partially explain some of the recent trends observed in chub mackerel catch. The most recent stock assessment by the Japanese authorities indicates that a strong 2013 year class progressed through the fishery until around 2020, during which time catches measured in numbers of individuals remained relatively stable since approximately 2014. However, the fishery catches over the past 3 years have been increasingly dominated by age-0 and age-1 fish. As these younger age classes are generally smaller in individual size, the observed declines in total catch weight during this period likely reflect a shift towards a greater prevalence of smaller-bodied individuals in the landed catch, rather than necessarily indicating a decline in overall population abundance.

Concluding remarks

This study investigates the relationship between ocean environmental variability and Chub mackerel (*Scomber japonicus*) catch variability in the National Waters of Japan, providing a possible explanation for the recent decrease in catch by integrating data from Japan and China. The findings suggest that the variability of the Kuroshio Current path around the south of Japan and the Kuroshio Extension variability may be the main factors influencing Chub mackerel catch variability, not only in the National Waters of Japan but also in the High seas (the Convention Area of the NPFC) of the Northwestern Pacific.

The results indicate that the upper-ocean temperature variability in the regions known as feeding and nursery grounds for Chub mackerel (Yasuda, 2003; Yatsu et al., 2013), such as the south of Hokkaido and the east of Honshu, may not be the most critical factors influencing the species' catch. Instead, the variability of the Kuroshio Current south of Japan, which encompasses the spawning grounds for Chub mackerel, and the Kuroshio Extension, including the recirculation gyre south of the Kuroshio Extension (Figure 2), appear to be significantly related to Chub mackerel catch affecting the upper-ocean temperature variability. Furthermore, this study suggests that the PDO-related wind forcing and oceanic processes influence both the Kuroshio Extension and the Kuroshio Current south of Japan, potentially inducing the Kuroshio Meander and creating biologically unfavorable conditions near the south coast of Honshu. These conditions may ultimately affect the spawning success and abundance of Chub mackerel, as well as the total catch of this species not only within the National Waters of Japan but also throughout the entire Northwestern Pacific (Figure 1c) (Noto and Yasuda, 1999; Sugimoto and Hanawa, 2012; Qiu et al., 2023).

The limited availability of spatially resolved catch data for Chub mackerel within Japan's National Waters and the NPFC Convention Area, in this study, poses challenges in analyzing the spatio-temporal variability of the species' distribution. Despite this limitation, the annual catch data from both regions exhibit similar variability patterns (Figure 1c), supporting the findings of this study that large-scale ocean environmental variability around the spawning grounds (south of Honshu) and the Kuroshio Extension region significantly influences the overall catch amounts of Chub mackerel in the Northwestern Pacific. To further elucidate the spatio-temporal dynamics of Chub mackerel in response to ocean environmental variability, it is crucial to obtain comprehensive spatial distribution data for the species. Such data would enable a more in-depth analysis of the relationship between environmental factors and the spatial distribution of Chub mackerel.

Although Kuroshio Meandering can occur independently of the PDO (Usui et al., 2008; Qiu et al., 2023), the results suggest that the recent significant decrease in Chub mackerel catch is primarily attributed to PDO-induced Kuroshio Large Meandering. This finding highlights the importance of considering the interplay between large-scale climate variability and regional oceanographic features when assessing the dynamics of commercially important fish abundances in the Northwestern Pacific (Yatsu et al., 2013).

Looking to the future, it is essential to recognize the potential impact of climate change and extreme events on the relationships between environmental factors and Chub mackerel abundance. The increasing frequency and intensity of phenomena such as super El Niño events, marine heat waves, and sea level rise could significantly alter marine ecosystems, with far-reaching consequences for commercially important fish species (Overland et al., 2010; Yu et al., 2018; Holbrook et al., 2019; Miyama et al., 2021). To better understand and anticipate these impacts, it is crucial to incorporate environmental variables, such as the PDO, into future stock assessments for Chub mackerel and to develop adaptive management and conservation strategies (King et al., 2015; Yatsu, 2019).

While this study primarily investigates the influence of environmental factors on Chub mackerel catch variability, it is crucial to recognize that human activities, such as overfishing and illegal, unreported, and unregulated (IUU) fishing, can also have significant impacts on fish abundances (Pauly et al., 2002; Sumaila et al., 2006). Addressing and preventing overfishing and IUU-related activities are essential, as the factors affecting catch and abundance dynamics are not limited to environmental variables but also include anthropogenic factors.

To promote sustainable fisheries in International Waters, the NPFC has implemented a total allowable catch for the Chub mackerel fishery in the NPFC Convention Area starting in 2024 (NPFC, 2024b). Furthermore, the NPFC is actively evaluating changes in catch associated with anthropogenic human activities (i.e., fishery) to ensure the long-term sustainability of the Chub mackerel fishery. Ongoing monitoring of fishing practices and continuous efforts in conservation and research are imperative to ensure the sustainability of marine resources and to support the development of effective management strategies (Worm et al., 2009; Yatsu, 2019; Hong et al., 2022).

In conclusion, this study provides valuable insights into the recent declining trend in Chub mackerel catches and offers a basis for forecasting catch variability through its statistical relationship with basin-scale ocean environmental variability. These findings underscore the need for a holistic approach to fisheries management that considers the complex interactions between climate, oceanography, and human activities in the Northwestern Pacific.

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Conflict of interest

The authors declare no competing interests.

Data Availability Statement

The data that support the findings of this study are available within the article. The environmental datasets and indices used in this study are publicly available. Additional data related to this study are available from the corresponding author, the North Pacific Fisheries Commission, or the Japan Fisheries Research and Education Agency upon reasonable request.

Author contributions

JK conducted the analysis, prepared the figures, and wrote the manuscript. JK designed the research and CR, SN, KO, RD, and AZ discussed the results. All authors contributed to the article and approved the submitted version.

Figure set

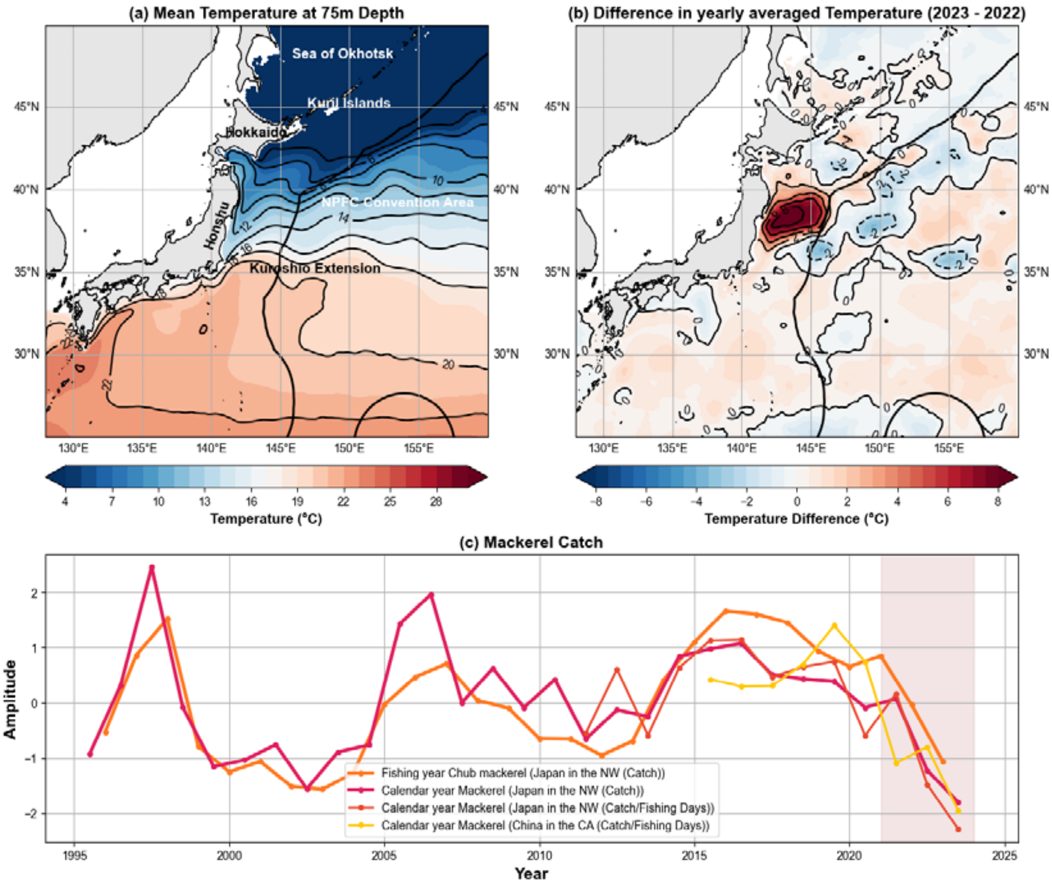

Figure 1. (a) Spatial and temporal variability of ocean temperature and normalized Chub mackerel catch in the Northwestern Pacific. (a) Mean temperature at 75 m depth during the calendar years 1995–2023. (b) The difference in mean temperature at 75 m depth between the calendar years 2023 and 2022, with positive values indicating warmer temperatures in 2023 compared to 2022. Thick black lines delineate the North Pacific Fisheries Commission (NPFC) Convention Area. (c) Normalized time series of Chub mackerel catch amounts during the fishing year 1995–2022 (orange), calendar year Mackerel catch amounts during 1995–2023 (pink), calendar year catch per unit effort (CPUE, catch per fishing day) during 2011–2023 (red) in the national waters of Japan, and calendar year CPUE in the NPFC Convention Area for China during 2015–2023 (yellow). The red-shaded area highlights the period from 2021 to 2023.

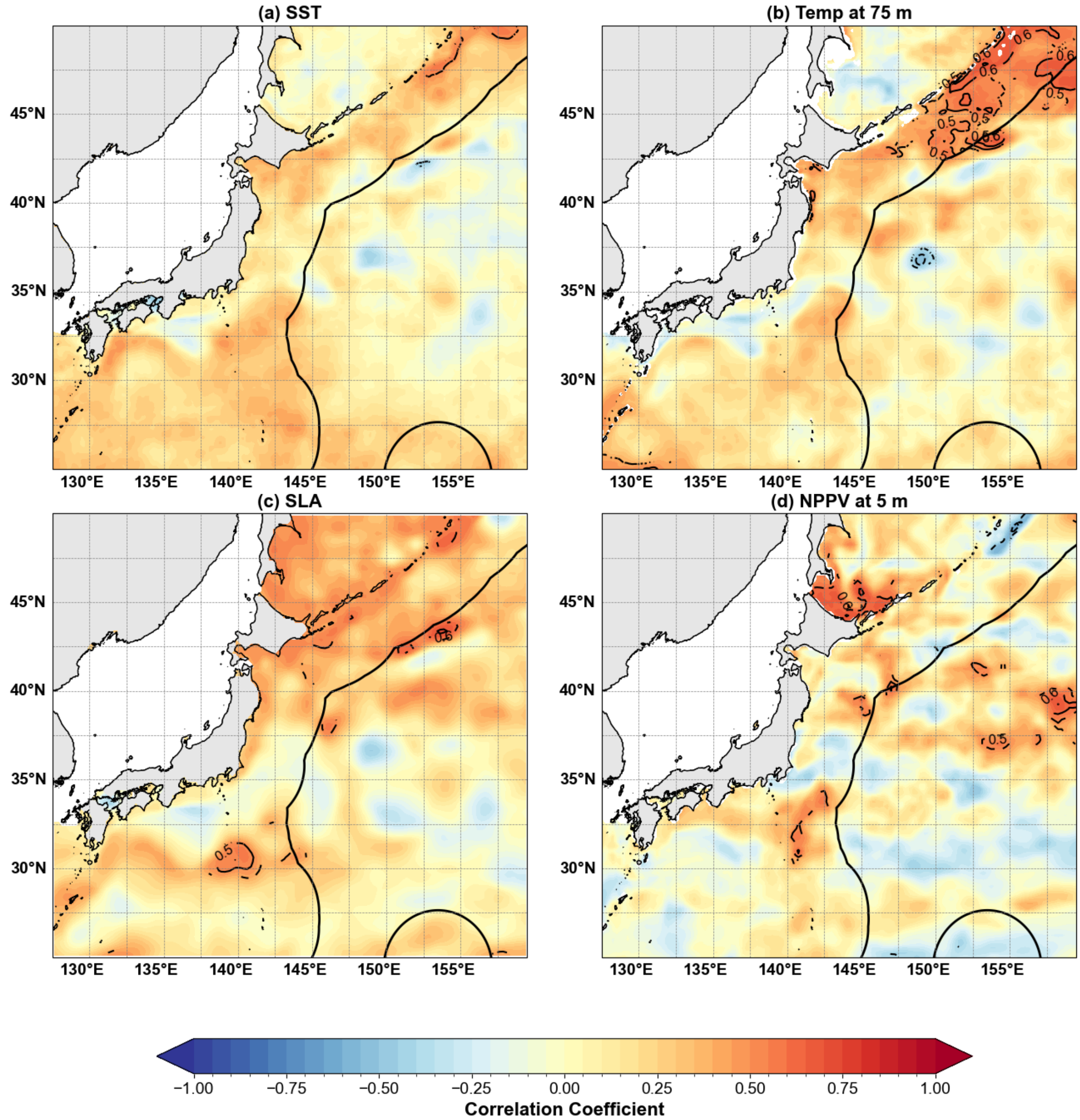

Figure 2. Correlation maps between anomalies of ocean environmental variables and annual Chub mackerel catch in the National Waters of Japan from the fishing years 1995 to 2022. (a) Sea surface temperature (SST), (b) temperature at 75 m depth, (c) sea level anomaly (SLA), and (d) net primary production volume (NPPV) anomalies at 5 m depth. Contour lines indicate areas with statistically significant correlations (> 95% of the confidence interval), validated through 1,000 iterations of an autoregressive model of order 1 to account for temporal autocorrelation. Thick black lines delineate the North Pacific Fisheries Commission (NPFC) Convention Area.

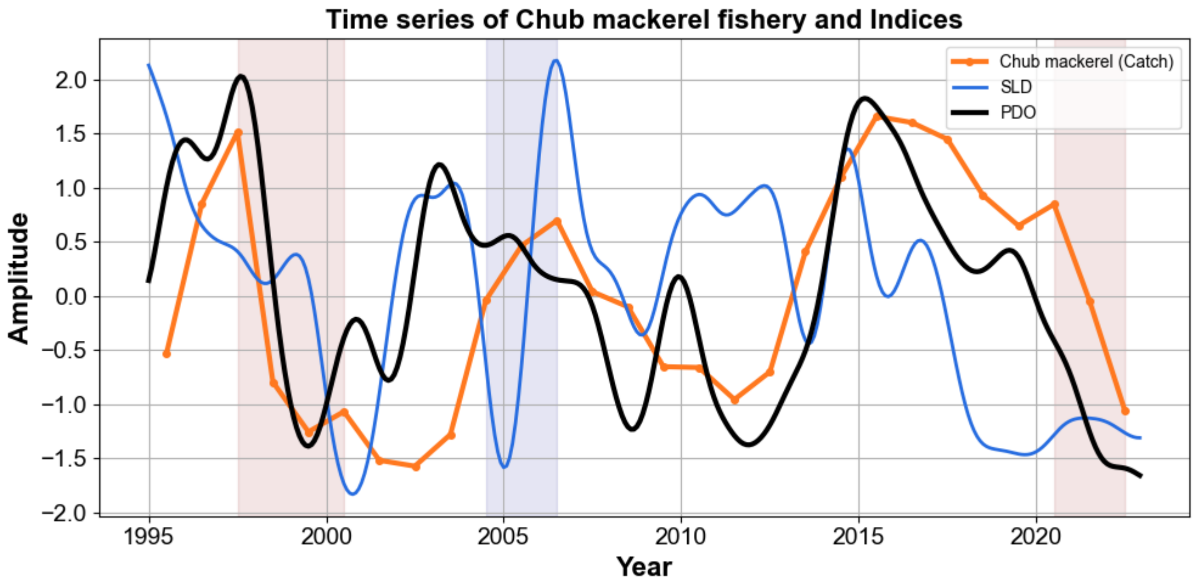

Figure 3. Normalized time series of Chub mackerel fishery in the National Waters of Japan and environmental indices from fishing-year (July to next year June) 1995 to 2022. The blue line shows the 2-year low-pass filtered monthly sea level difference (SLD) between Kushimoto and Uragami, and the black line represents the Pacific Decadal Oscillation (PDO) index. Red-shaded areas highlight the fishing years 1997–1999 and 2020–2022, while the blue-shaded area indicates the period fishing years 2004–2006.

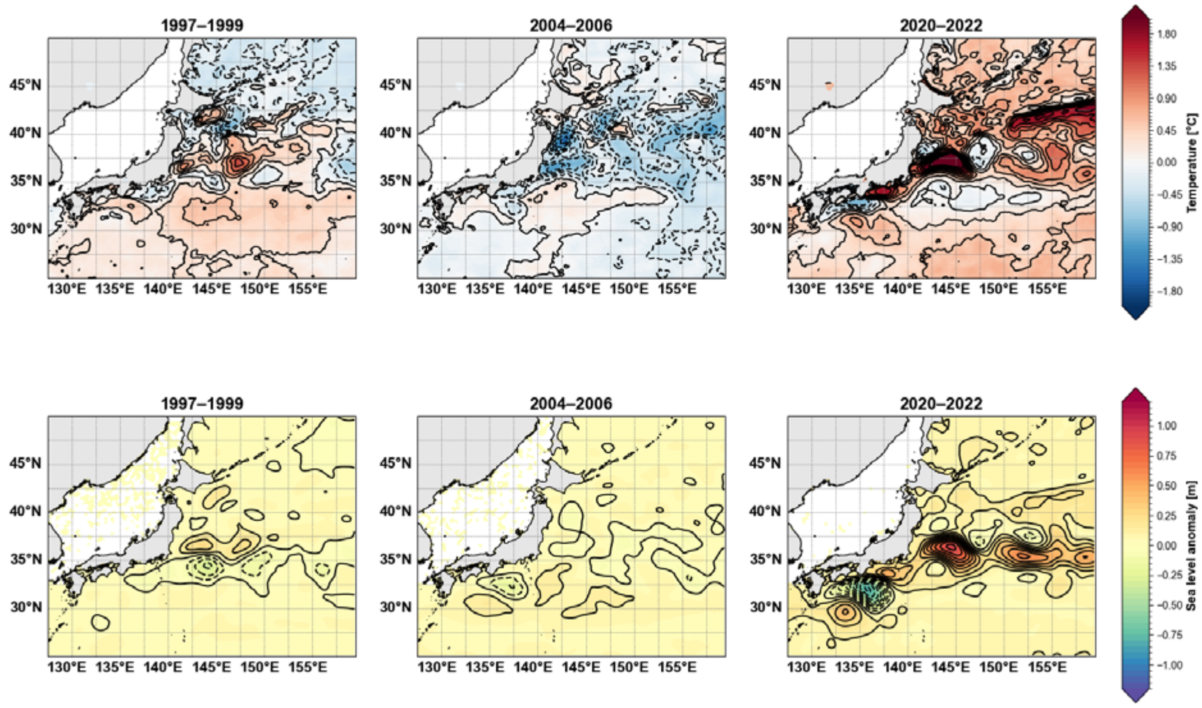

Figure 4. Spatial patterns of sea surface temperature anomalies (top row) and sea level anomalies (bottom row) averaged over three distinct periods in the Northwestern Pacific: fishing years (July to next year June) 1997–1999 (left column), 2004–2006 (middle column), and 2021–2023 (right column). Contour intervals are 0.25°C for sea surface temperature anomalies and 0.1 m for sea level anomalies.