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Chasing Catch:Climate-driven distribution and abundance of Pacific bluefin tuna and Japanese anchovy

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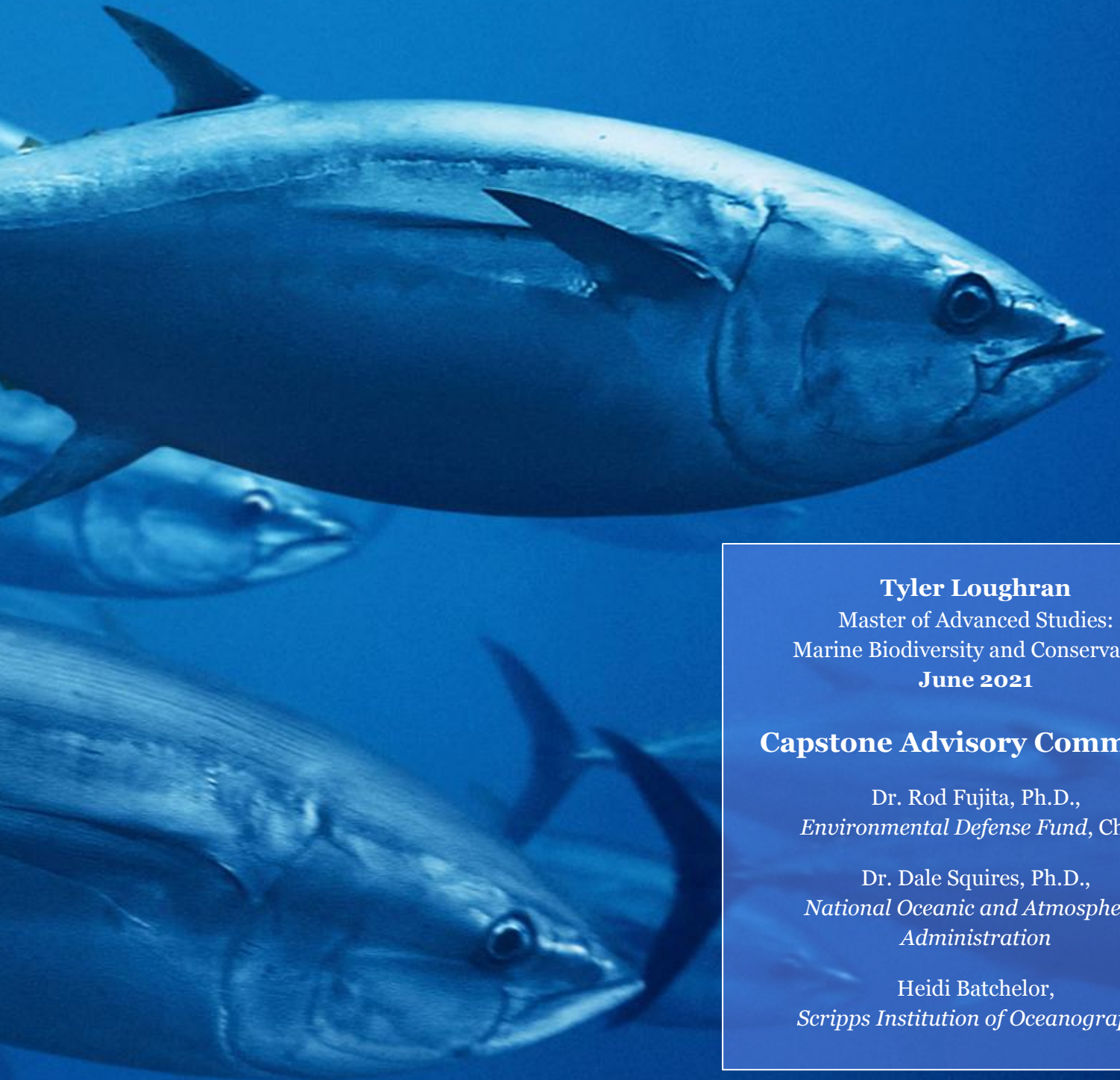
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**Chasing Catch:**  
Climate-driven distribution and abundance of  
Pacific bluefin tuna and Japanese anchovy



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Master of Advanced Studies:  
Marine Biodiversity and Conservation  
**June 2021**

**Capstone Advisory Committee**

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**UC San Diego**



**SCRIPPS** INSTITUTION OF  
**OCEANOGRAPHY**

***Chasing Catch: Climate-driven distribution and abundance of Pacific bluefin  
tuna and Japanese anchovy***

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## Executive Summary

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Climate change impacts are projected to shift the distribution and abundance of global fisheries, affecting revenues and livelihoods worldwide (Barange et al., 2018; Lam et al., 2016). The creation of climate-resilient fisheries requires knowledge of how culturally and economically valuable species will be impacted by rising sea surface temperatures, ocean deoxygenation, and climatic variability. Two Western Pacific fisheries, the Pacific bluefin tuna (PBF; *Thunnus orientalis*) and Japanese anchovy (JA; *Engraulis japonicus*), may be particularly vulnerable to the impacts of climate change due to overfishing, sub-tropical spawning grounds, and declining prey availability (FAO, 2020; ISC, 2020). Chasing catch may become the new reality for commercial fleets around the world as PBF and JA inhabit new waters away from historic fishing grounds. In order to promote sustainable management of major global fisheries, policymakers must have the best tools and information available for how climate change will affect fisheries distribution and abundance through the 21st century.

This study is aimed at improving the scientific basis for creating fisheries that are resilient to climate change by using climate change projections, species-specific life history traits, and ecological information to project potential fish stock distribution in response to changing coastal and oceanic conditions. Current projections focus on the use of suitable thermal habitat as a proxy for future species distribution and abundance (Morley et al., 2018). The aim of this study is to improve on these projections by evaluating the potential effects of changes in ocean mixing, nutrients, and other factors in addition to temperature as well as by incorporating information on how the target species (PBF and JA) are likely to respond to these changes using life history characteristics.

Based on a decision tree provided by the Environmental Defense Fund, climate change is expected to impact every life stage of PBF and JA and centered around changes in sea surface temperature, ocean deoxygenation, and climatic variability. Future abundance of both species' hinges on the survival of larval stages, recruitment success, and conservation measures to prevent the depletion of young age classes. Northward shifts in distribution are anticipated for both species into the next century, raising concerns about future international management. The entrance of new players into the PBF and JA fisheries may require international agreements based on the shift in distribution of each stock. International cooperation and adaptive management measures must be adopted by fisheries management entities to maintain productive fisheries that continue to generate social and economic benefits associated with PBF and JA.

**Keywords:** Fisheries, climate change, global warming, Pacific bluefin tuna, *Thunnus orientalis*, Japanese anchovy, *Engraulis japonicus*, fisheries management, RFMO, Japan, Western Pacific, Eastern Pacific

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## Introduction

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Climate change stands to alter not only the furthest reaches of the world, but also the deepest waters (FAO, 2018; Fasullo et al., 2018; Laffoley and Baxter, 2019). The fundamental chemical composition and structure of the ocean are changing as excess atmospheric greenhouse gases lead to warmer sea surface temperatures and weaker oceanic circulation patterns (FAO, 2018; Fasullo et al., 2018; Li et al., 2020). Rising temperatures and expansion of low-oxygen habitats are projected to significantly shift the distribution and abundance of marine fisheries (Barange et al., 2018; FAO, 2018). Deviations from historic distributions paired with changes in abundance of major fisheries species will have global ramifications in food and financial security (Lam et al., 2016). According to Lam et al. (2016) the global marine fisheries industry accounts for USD \$100 billion of revenue annually, economically supports 10% to 12% of the world's population, and acts as a major source of protein for nearly 3 billion people worldwide.

One fishery stands out within the global market in terms of cultural and commercial value. The global tuna fishery, which includes tuna species across all oceans of the world, accounts for an end value of approximately \$40 billion USD annually (McKinney et al., 2020). The Pacific tuna fishery, which includes PBF, bigeye (*Thunnus obesus*), yellowfin (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*), and albacore tuna (*Thunnus alalunga*) species, accounts for an end value of \$26 billion USD, over half of the global end value of tuna (McKinney et al., 2020). Bluefin tuna species across all ocean basins accounted for 1% of total landings, but 6% of the end value of the global tuna fishery (McKinney et al., 2020). In 2018, PBF accounted for an end value of \$800 million USD, the second largest proportion of all bluefin species (McKinney et al., 2020).

The Western and Central Pacific Fisheries Management Organization (WCPFC) and Inter-American Tropical Tuna Commission (IATTC) currently oversee PBF stock management. According to the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC), the PBF stock reached an all-time low of 1.7% of its virgin biomass in 2010 (ISC, 2020). This percentage has since increased to 4.5% in 2018, however, PBF remains overfished and continues to be subject to overfishing (ISC, 2020). Similarly, JA have experienced low stock levels since 1990 and are considered to be overfished due to high fishing pressure (Wang et al., 2020) These fisheries remain in precarious positions that may be further exacerbated by climate variability and environmental stressors into the next century.

The Japanese archipelago, home of the PBF and JA, contains some of the world's most productive fishing and spawning grounds due to the convergence of subtropical and subarctic ocean currents. The sub-tropical Kuroshio and sub-arctic Oyashio currents carry an abundance of nutrient and oxygen-rich waters to coastal habitats, resulting in strong upwelling processes that support high levels of productivity (Yatsu et al., 2013). Projected impacts of climate change include the deterioration of the Oyashio current and associated upwellings, ultimately leading to the disappearance of primary and secondary productivity (Ohshima et al., 2009). Decreases in productivity, as well as rising deoxygenation and sea surface temperatures, may hinder the growth and development of both the PBF and JA.

There is a general consensus that Pacific tuna populations will begin to shift eastward and poleward as climate change impacts intensify, however, there is much uncertainty about how

strong this shift will be in the latter half of the century (FAO, 2018). Shifts in the distribution of PBF due to climate change would likely have far-reaching consequences for international relations and economics. Further, impacts to prey species such as the JA may influence shifts in PBF diets, abundance, and migration if the distributions of both species no longer coincide. This project seeks to determine how PBF and JA distribution will change in response to climate change, which environmental factors are most strongly associated with distribution shifts, and ultimately how abundance will be affected.

## **Methodology**

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### **Japan Climate Impact Profile**

Determining the impacts of climate change on each target species required knowledge of not only the species itself, but its surrounding environment. The Western Pacific contains a complex set of oceanic currents that fuel productive habitats, and therefore long trophic chains that span from secondary productivity to forage species and apex predators. Possible impacts of climate change to the physical and biological oceanography of the Western Pacific were determined via a literature review. Primary literature discussing future projections of precipitation, sea ice, sea surface temperatures, and primary productivity in the areas between the Sea of Okhotsk and East China Sea were evaluated to form a comprehensive overview of climate change impacts to the Japanese archipelago. Results of the literature review can be found in the Japan Climate Impact Profile.

### **Suitable Thermal Habitat**

Current and 2050 suitable thermal habitat projections for each species were downloaded via AquaMaps (aquamaps.org). Each dataset was imported into ArcGIS Pro using the XYTable to Point function. Using the attribute table view, any points that contained values less than 0 or greater than 1 in the 'Overall Probability' column were removed prior to analysis. Each point layer was symbolized using Manual Intervals to reflect the value categories used in AquaMaps (0.01-0.19; 0.20-0.39; 0.40-0.59; 0.60-0.79; 0.80-1). A continuous gradient color scheme was used to describe each value category, with the darkest color representing the greatest overall probability of a species inhabiting the area. The mapping of current and projected suitable thermal habitat was used as a basis for understanding how the distribution of each target species may change by 2050 (**Appendix A**).

### **Decision Tree**

A literature review of the life history, adaptations, stock status, and resilience of each target species was completed to fully answer each question presented in the decision tree for evaluating the likelihood of climate impacts provided by the Environmental Defense Fund (**Appendix B**). Each life stage of the target species was evaluated for possible climate change-induced stressors that could affect movement or mortality. Findings of the Japan Climate Impact Profile and suitable thermal habitat mapping aided in determining areas that are both integral to the survival of each species and are expected to warm over the next century, such as spawning grounds. Results of the decision tree were then used to evaluate possible impacts to the predator-prey relationship between the target species, which was also supported by further literature review.



# Japan Climate Impact Profile

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## Introduction

Japan is a large archipelago made up of nearly 7,000 islands spanning 3,000 km in the Northwestern Pacific Ocean. The exclusive economic zone of Japan is the fifth-largest in the world, covering 4.48 million km<sup>2</sup> (FAO, 2019). The flow and convergence of subtropical and subarctic ocean currents throughout the Japanese archipelago form some of the world's most productive fishing grounds and fosters a wide array of marine ecosystems. Sea ice forms in the northernmost reach while coral reefs line the coasts of the southern islands. Kelp forests, seagrass beds, and rocky shores are found along the coastlines of the central islands. The Sea of Japan, which lies between Russia, North and South Korea, and the western coast of Japan, features two underwater mountain ranges: the Yamato and Musashi Banks. Commercially important species, including eels, tuna, squid, pollock, and mackerel utilize the productive waters and diverse bathymetry of the Sea of Japan and northeastern shores of Japan as spawning grounds. Intensive coastal development, especially on the east coast of Honshu has led to nearshore habitat degradation and water pollution in the Seto Inland sea, Tokyo Bay, and the Sea of Japan (Kabir et al., 2020; Sasaki et al., 1976; Tamaki et al., 2002). Fisheries cooperatives have engaged in habitat restoration efforts in these regions and large-scale ocean ranching efforts have been mounted in an attempt to compensate for loss of habitat with mixed success (Arnason, 2001; Higa et al., 2017; Mizuta and Vlachopoulou, 2017). With these exceptions, deep-sea habitat and offshore waters appear to remain relatively untouched, though advances in aquaculture and deep sea mining practices may threaten the health of these ecosystems in the future (Takaya et al., 2018; Towers, 2016).

## Relevant bio-physical features that may be impacted by, or affect the systemic impacts of, climate change:

- Biogenic Habitats (coral reefs, seagrasses, kelp forests, seamounts)
  - Ice-dominated in northern latitudes
- Current and upwelling dominated (Kuroshio and Oyashio currents)
- Semi-enclosed Sea of Japan (ocean acidification)
- Seto Inland Sea (will pollution and habitat loss exacerbate impacts of climate change?)
- Fukushima (will large-scale coastal reinforcement after the tsunami and nuclear disaster result in nearshore habitat loss and altered circulation, affecting climate change impacts such as sea level rise?)

## Climate/ latitude zone:

- Subarctic in northern latitudes
- Temperate in central latitudes
- Subtropical in southern latitudes

## Climate-Driven Marine Ecosystem Changes

### *Summary*

Major climate impacts to Japan and its surrounding waters include rising sea surface temperatures, declining ocean mixing, increased frequency and intensity of precipitation events, sea level rise, changes in ocean circulation patterns, and ocean acidification. In northern latitudes, increasing sea surface temperatures are anticipated to further exacerbate declines in sea

ice coverage along the coast of Hokkaido by weakening stratification within the Sea of Okhotsk. The sub-arctic Oyashio current responsible for delivering sea ice from the Sea of Okhotsk is anticipated to decline over time, hindering upwelling processes and primary production. Increasing sea surface temperatures in southern latitudes put coral reefs at higher risk of bleaching due to sustained warm water events. While suitable thermal habitat for corals may expand to the north, perhaps as far as Tokyo, the rate of mortality due to bleaching and other factors affecting coral recruitment and survivorship may preclude expansion of corals into these waters. Warmer water may result in the introduction of tropical species or expansions in their ranges in Japanese waters. In addition to changes in sea surface temperature, ocean acidification is expected to reduce the growth of several types of species, including calcareous algae, corals, molluscs, crustaceans, and larval-stage fish. Finally, sea level rise and increases in extreme precipitation events may lead to high levels of stormwater run-off and less light availability, reducing the productivity of sensitive habitats such as seagrass beds and coral reefs. Coastal development may hinder the upland migration of habitats such as mangroves and tidal wetlands in response to sea level rise.

### ***Temperature & Physical Forcing***

Anticipated warming of 3°C by 2050 and 5°C by 2080 throughout East Asia is predicted to have far-reaching impacts on primary, secondary, and fisheries productivity into the 21st century (Alam et al., 2007; Case and Tidwell, 2019). Japan has already begun experiencing rapid warming. Mean annual temperature across Japan has increased by approximately 1°C over the past 100 years and is projected to increase by a further 2°C to 3°C throughout the next century (Ministry of the Environment, 2006). Warming effects of climate change are anticipated to alter the diverse marine habitats throughout Japan, most notably by decreasing nutrient and dissolved oxygen flux via major oceanic currents surrounding the archipelago.

The many islands of Japan function as a western boundary of the North Pacific Gyre, a series of oceanic currents carrying nutrient-rich waters throughout the coasts of the Northern Pacific. The subarctic Oyashio current and subtropical Kuroshio are major contributors to the productivity of the Pacific (**Figure 1**) (Qiu, 2019; Tatebe and Yasuda, 2004). The Oyashio current originates in Arctic waters and transports cold, dense waters to the northern islands of Japan (Tatebe and Yasuda, 2004). The Kuroshio current flows northward from the tropics, carrying warmer, nutrient-rich waters from reef systems (Tatebe and Yasuda, 2004). The two currents converge on the eastern shore of Japan near Hokkaido, forming nutrient-rich feeding and spawning grounds for commercially important species such as salmon, pollock, sardine, and squid (Yatsu et al., 2013).

Hokkaido is historically the southernmost extent of sea ice in the northern hemisphere (Ohshima et al., 2009). Cold, northwestward Siberian winds and freshwater flow from the Amur River aid in the formation of sea ice in the Sea of Okhotsk (Ohshima et al., 2009). Drift sea ice and dense, oxygen and nutrient-rich waters are then carried southward via the subarctic Oyashio current to the coast of Hokkaido. The warming of surface air within East Asia, notably Siberia, is highly correlated with the decline of sea ice within the Sea of Okhotsk (**Figure 2**) (Ohshima et al., 2009). The formation of sea ice is vital to the transportation of dissolved oxygen-rich waters via thermohaline circulation. In the past 30 years, sea ice coverage in the Sea of Okhotsk has declined by an estimated 10%, or 150,000 km<sup>2</sup> (Ohshima et al., 2009). Additionally, sea surface temperatures along the coast of Hokkaido are projected to rise between 1 to 6°C into the latter

half of the present century. As rising surface temperatures continue to impact sea ice formation, dissolved oxygen and nutrient concentrations of subarctic waters are projected to decrease and weaken the role of the Sea of Okhotsk as a biological pump of the Northern Pacific (Ohshima et al., 2009).

The northern Sea of Japan faces a similar future as the subarctic waters near Hokkaido. Decreases in annual maximum snow depth on the western and eastern shores of the Sea of Japan over the past 50 years are indicative of warming surface temperatures (Ministry of the Environment, 2018). During winter months, the northern Sea of Japan cools at the surface allowing for the formation of a dissolved oxygen and nutrient-rich deep-water layer (Yoon, 2000). Heightened temperatures prevent the cooling of surface waters and limit the vertical mixing responsible for distributing dissolved oxygen and nutrients throughout the water column (Yoon, 2000).

The greatest threat of rising sea surface temperatures to the southern islands of Japan is coral bleaching. Major coral bleaching events occurred in 1998, 2001, 2007, and 2016 (Hongo and Yamano, 2013; Yamano, 2014). Sekisei Lagoon, the largest coral reef in Japan, lost an estimated 70% of corals during the 2016 bleaching event due to prolonged elevated sea surface temperatures exceeding 30°C (Harvey, 2017; Sato et al., 2020). Coral bleaching and mortality events are anticipated to increase in frequency, though poleward expansion for warm water and temperate coral species has been observed (Nakabayashi et al., 2019; Takao et al., 2015; Yara et al., 2012). Favorable sea surface temperature conditions for tropical and subtropical species of coral may occur as far north as Tokyo on the eastern coast of Japan (Yara et al., 2012). However, a disparity exists between the time scales of coral bleaching and poleward expansion. The loss of southern occupied coral habitat is projected to occur faster than the poleward expansion of favorable coral conditions (Yara et al., 2012).

### ***Precipitation & Storms Events***

The frequency of high-intensity precipitation events and dry periods is expected to increase throughout the latter half of this century (Fujibe et al., 2006; Kimoto et al., 2005). Less intense precipitation days (defined at 1 to 20 mm per day) may decrease by up to 16 days per year, whereas heavy precipitation days (over 30 mm per day) may increase by 5 days per year (Kimoto et al., 2005). Mean precipitation is predicted to increase by 17% to 19% throughout Japan during summer and autumn seasons when the Baiu front is strongest (Kimoto et al., 2005; Nishimori and Kitoh, 2006). Winter precipitation may remain the same or slightly decrease due to weakened monsoon winds (Kimoto et al., 2005). Hokkaido, famed for sea ice and snow during winter months, is projected to experience a 115% increase in precipitation during the month of July according to the statistical downscaling method employed by Nishimori and Kitoh, 2006. A 2°C increase in temperature was found to result in a 30 day decrease in snow covered days and a 30% to 40% decrease in snow cover in Hokkaido (Katsuyama et al., 2020). Flooding, landslide, and cyclone events may become more common and severe as precipitation increases (Lee et al., 2020; Takemi et al., 2016).

### ***Sea Level Rise***

Japan's 34,000 km of coastline is particularly vulnerable to accelerated sea level rise (Case and Tidwell, 2019). The annual rate of sea level rise within Japan has increased from 3.3 mm per year in the 1980s to 5.0 mm per year since 1993, far exceeding the global rate of 1.4 mm throughout the 20th century (Lindsey, 2020). A further 0.18 to 0.59 m of sea level rise is

expected to occur by 2100 (Solomon et al., 2018). These rates of sea level rise have the potential to negatively impact the resilience and area of seagrass bed and coral reef habitat. Increases in sea level can be expected to limit light availability to coral and seagrass beds, outpacing the shift of these communities to shallower waters (Davis et al., 2016; Perry et al., 2018). Sedimentation, run-off, and coastal erosion also pose challenges to the survival and productivity of coastal marine habitats. Approximately 46% of Japan's population lives within 10 km of the coast (Case and Tidwell, 2019). Major urban centers paired with increases in precipitation may lead to influxes of pollutants and sediment entering coastal systems, further reducing light availability and overall water quality of coastal areas. The effects of sea level rise may also be aggravated by high-intensity storm events (Case and Tidwell, 2019).

### ***Ocean Acidification***

The North Pacific has one of the world's highest acidification rates at -0.004 per year, concentrated at depths between 200 m to 500 m (Chen et al., 2017). Ocean acidification has been detected within Japan's coastal waters, both in the Sea of Japan and Pacific Ocean (Chen et al., 2017; Ishii et al., 2011). Aragonite saturation state and pH are currently declining at a rate of approximately -0.02 and -0.12 per decade, with a possible increase to -0.8 per decade within the next 50 years (Ishii et al., 2011). Acidification effects can be felt throughout the water column, though are largely concentrated in deeper waters around 200 to 500 m (Chen et al., 2017). Acidification within coastal regions may be occurring at a faster rate than that within open ocean habitats, putting calcareous and skeleton forming species at risk (Chen et al., 2017). The skeleton and shell building processes of larval fish, molluscs, crustaceans, calcareous algae, and coral are significantly impacted by the reduced amount of carbonate available due to ocean acidification (Chen et al., 2017; Gazeau et al., 2013; Hofmann and Bischof, 2014; Whiteley, 2011). The Sea of Japan and convergence of the Kuroshio and Oyashio currents on the eastern coast of Japan are both vital spawning grounds for harvested species such as tuna and shellfish, which may be impacted by ocean acidification into the 21st century.

### ***Primary and Secondary Production***

The largest threat to primary and secondary productivity within Japanese waters is the decrease of the influx of dissolved oxygen and nutrients via the oceanic currents surrounding the archipelago. Winter mixing induced by the Oyashio current produces a spring bloom off the eastern coast of Japan in late April to May (Yatsu et al., 2013). Fish prey upon the diatoms and copepods that dominate the bloom, resulting in the transfer of a relatively high percentage of primary and secondary productivity to top trophic levels. Light availability is the limiting factor in the Oyashio bloom, whereas productivity in the Kuroshio current is limited by nutrient availability. The Kuroshio current also undergoes winter mixing but is weakly stratified and ultimately results in a smaller bloom of diatoms in February to March. The convergence of the Oyashio and Kuroshio currents results in high phytoplankton production and forms a nutrient-rich environment favored by pelagic species, known as the Kuroshio-Oyashio Transition Zone (Yatsu et al., 2013).

Rising sea surface temperatures will act as the main driver of change in the Oyashio and Kuroshio currents, though further modeling is required to elucidate the full extent of biological and physical impacts. Intensification of the Kuroshio current is anticipated under higher sea surface temperatures but will be further impacted by reduced vertical mixing (Yatsu et al., 2013). Eggs and fish larvae may be carried further north by an extended Kuroshio current, however,

lower trophic level productivity will probably continue to decrease. Primary productivity driven by the Oyashio current is projected to increase under moderate rises in temperature due to retention of phytoplankton within the euphotic zone (**Figure 3**) (Yatsu et al., 2013). This increased primary productivity is not anticipated to continue once sea surface temperatures increase to the point at which sea ice fails to form in the Sea of Okhotsk. Without the formation of sea ice, thermohaline circulation will not occur and less nutrients will be transported to surface waters. Phytoplankton blooms of the Oyashio and Kuroshio currents are projected to occur earlier in the calendar year, which may cause increased larval mortality as hatching periods become misaligned with the spring bloom (Yatsu et al., 2013). The combined impacts of acidification, rising sea surface temperatures, and intensification of physical forcing processes pose challenges to the development and survival of commercial species found throughout Japan's exclusive economic zone and Northern Pacific Ocean.

## **Life Histories & Adaptations**

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### **Pacific Bluefin Tuna**

There are three bluefin tuna species found throughout the world - the Atlantic bluefin (*Thunnus thynnus*), the Southern bluefin (*Thunnus maccoyii*), and the Pacific bluefin (Kitagawa and Kimura, 2016). All bluefin tuna species are considered highly migratory, occupying different ocean basins but exhibiting similar morphology (Kitagawa and Kimura, 2016). The PBF has the largest native range of all bluefin species, found throughout the entire Pacific Ocean and occasionally in sub-polar waters (Shiels et al., 2015). Famous for their blood-red meat, bluefin tuna species across all oceans account for approximately 1% of global tuna landings but 6% of the end value of the global tuna fishery (McKinney et al., 2020). In 2018, PBF accounted for an end value of \$800 million USD, the second largest proportion of all bluefin species (McKinney et al., 2020). Largely used for sashimi, PBF support a valuable commercial fishery that will likely be impacted by climate change conditions (FAO, 2018).

### ***Adaptations and Ecosystem Role***

As a large predator and highly migratory species, PBF grow to a maximum length of three meters and can weigh nearly 450 kilograms (ISC, 2020). PBF reach sexual maturity at approximately 5 years of age, and live for an average of 15 years and a maximum of 26 years (ISC, 2020). While many tuna and billfish species are endothermic, meaning they can maintain their body temperature, bluefin tuna species have the strongest endothermy capabilities which allows them to occupy a highly varied range of habitats spanning sub-polar to tropical sea temperatures (Graham and Dickson, 2001; Shiels et al., 2015). A countercurrent heat exchange system allows for PBF to maintain a higher body temperature than their surroundings (Shiels et al., 2015). Adaptations of their calcium cycling and adrenaline levels allow for their heart to continue beating during dives of up to 500 meters, where sea temperatures drastically drop when approaching a thermocline (Shiels et al., 2015). The physiological adaptations of PBF that enable them to inhabit an entire ocean basin may give them an advantage as seas warm and fisheries distribution shift poleward in response to climate change (FAO, 2018).

### ***Spawning & Larval Stages***

Originating from Western Pacific spawning grounds, PBF undergoes ontogenetic migrations across the Pacific and reside in the California Current Large Marine Ecosystem (CCLME) during

juvenile stages before returning to the Western Pacific upon reaching sexual maturity (**Figure 4**) (Shiao et al., 2020). PBF utilizes two confirmed and one unconfirmed spawning region located in the Western Pacific (Shiao et al., 2020). The spatial distribution of spawning PBF is associated with the network of warm, oligotrophic currents surrounding the Japanese archipelago (Landry et al., 2019). PBF rely on these currents to transport larval stages and support the thermal tolerances and dietary needs of early life stages (Landry et al., 2019; Shiao et al., 2020).

The PBF spawning ground accounting for the largest proportion of recruitment lies directly within the warm-water Kuroshio current in the Western North Pacific (WNP) (Shiao et al., 2020). The Sea of Japan contains the second confirmed spawning ground (Shiao et al., 2020). PBF have been found to travel to different spawning grounds with no natal site fidelity (Shiao et al., 2020). The last, unconfirmed, spawning ground appears to lie in the Kuroshio-Oyashio Transition Zone off the eastern coast of Honshu (Ohshimo et al., 2018b; Tanaka et al., 2020).

The PBF spawning season begins in late April within the Kuroshio region and late June within the Sea of Japan, following a northward trend as sea temperatures warm throughout the summer (Chen et al., 2006). Sex-ratios of spawning PBF tend to follow a one-to-one trend (Ashida et al., 2015; Chen et al., 2006). Adult female PBF can spawn every day over the course of a few days and were found to have a mean batch fecundity of 6.4 million oocytes (Okochi et al., 2016). Batch fecundity, egg diameter, and egg quality was found to increase with maternal length and body size (Chen et al., 2006; Ohshimo et al., 2018a). Larval PBF hatch after 24 hours in approximately 26°C waters and are carried north to coastal waters by the Kuroshio current (Satoh, 2010). Hatchlings were found to have an average length of 3 mm, growing into early juvenile fish at 10 mm over the following 20 days (Satoh, 2010; Watai et al., 2017).

### ***Juvenile, Adult Stages & Ontogenetic Migration***

Juvenile PBF remain along the coastal waters of Japan for the first 1 to 3 years of their life (Itoh et al., 2002; Satoh, 2010). The Kuroshio and Tsushima currents carry juvenile PBF to the southern coasts of Japan, where they begin a northward migration towards nutrient-rich current convergence zones throughout summer and early autumn (Itoh et al., 2002). Juveniles begin traveling south when sea temperatures begin to fall around late-autumn, residing along the southern coast of Japan during winter months (Itoh et al., 2002). Some juvenile PBF undergo a trans-Pacific migration to the Eastern Pacific, a defining interval of their overall ontogenetic migration (Fujioka et al., 2018b).

Between year 1 and year 3, a fraction of juvenile PBF begin their journey across the Pacific towards the CCLME (Itoh et al., 2002). These trans-Pacific migrations are thought to be triggered by colder sea temperatures nearing or below 14°C, and may begin in early summer, late autumn, and late winter (Fujioka et al., 2018b). The average length of the trans-Pacific migration is 2.5 months and may depend on factors such as prey availability in offshore convergence zones or starting points closer to the Eastern Pacific (Fujioka et al., 2018b). Upon arrival to the CCLME, juvenile PBF exhibit seasonal north-south movements similar to those observed in Japan along the United States and Mexico coasts (Boustany et al., 2010). These north-south movements are likely driven by prey availability in areas of high primary productivity due to upwelling and oceanic conditions such as optimal temperatures (Runcie et al., 2019). Juvenile PBF remain in the CCLME until they reach sexual maturity around the age of 5, at which point

they return as adults to Western Pacific spawning grounds (Runcie et al., 2019). PBF presence within the CCLME has grown in recent years, with the 2018 sampling season yielding higher numbers of age 5 individuals (Heberer and Lee, 2019).

### **Japanese Anchovy**

The JA is a coastal pelagic species concentrated in the waters surrounding Japan, but can be found as far south as Indonesia (Hayasi, 1967). JA are one of the coastal pelagic species of Japan, called *iwasi*, which includes other fish such as sardine (*Sardinops melanosticta*) and round herring (*Etrumeus micropus*) that share similar elongated and compressed body morphology (Hayasi, 1967). The JA stock within the Western Pacific has been subdivided into four regional populations, including the Honshu Pacific, Kyushu Pacific, West Kyushu Coast, and Japan Sea populations (Hayasi, 1967). These regional populations are largely based on spawning behaviors and are connected by current-driven egg and larval transport, and therefore do not display any genetic variations between the populations (Funamoto et al., 2004).

### ***Ecosystem Role***

JA serves as an integral part of oceanic food chains, providing an abundant source of nutrients to piscivorous fishes and human populations alike (Funamoto et al., 2004). Anchovy are commonly found in areas of high primary productivity, where nitrogen is introduced to a habitat via upwelling or current mixing such as in the Kuroshio-Oyashio Transition Zone. Areas of high primary productivity result in an abundance of phytoplankton, zooplankton, and particulates which anchovy predate on via filtration and biting mechanisms (Checkley et al., 2017). Coarse gill rakers enable anchovy to capture larger prey species, such as copepods (Checkley et al., 2017). Coastal pelagic species such as anchovy fill the gap between plankton and larger, piscivorous fishes and marine mammals in the trophic chain. For example, as the most abundant fish species in the Yellow Sea, anchovy is a major prey species for over 30 high-trophic level species (Zhao et al., 2003).

### ***Spawning & Larval Stages***

The JA spawns throughout Western Pacific waters, including inland seas such as the Yellow Sea and Seto Inland Sea, estuaries, and up to 1,000 nautical miles offshore (Hayasi, 1967; Zhang et al., 2020). JA begin migrating north in late March and shift south in November once complete. Over wintering grounds can be found in the Yellow Sea and East China Sea (Liu et al., 2020). JA undergoes an annual migration beginning in early spring, moving northward into basins such as the Yellow Sea and coastal areas of China, Japan, and Korea to spawn (**Figure 5**) (Liu et al., 2020). Spawning activities commence from the late spring to early autumn. Post-spawning, shoals of adult anchovy migrate south into offshore waters in the Kuroshio region to overwinter and feed in warmer waters (Liu et al., 2020).

Spawning activities occur between April and November but are most concentrated in May to August (Funamoto et al., 2004). The JA has been found spawning in sea surface temperatures between 12 to 30°C and salinities between 24 to 34.5 parts per thousand, encompassing a wide ranging area that includes the Tsushima and Kuroshio currents (Oozeki et al., 2007). Similar to other broadcast spawning species, JA eggs and larvae are transported by the Kuroshio and Tsushima currents depending on location (Hayasi, 1967). Egg and larval distribution is most concentrated within 10 miles of shore, and shallower than 30m (Hayasi, 1967). Eggs hatch

between 30 and 48 hours post fertilization depending on sea surface temperature (Hayasi, 1967). Post hatching, larvae measure between 3.2 mm and 3.6 mm (Hayasi, 1967).

Larvae absorb their remaining yolk prior to entering the post larval and juvenile stages (Hayasi, 1967). Postlarval and juvenile anchovy begin to display shoaling behaviors and remain closer to shore, inhabiting bays, inlets, and nearshore waters. Fishers can target shoaling post larval anchovy, called *shirasu*, within the Seto Inland Sea and along the central and northern coastlines of Japan (Hayasi, 1967).

### ***Juvenile, Adults Stages & Migration***

Juvenile and adult JA migrate away from coastal areas to pelagic waters, where they complete diurnal vertical migration and shoal in surface waters (Hayasi, 1967; Zhao et al., 2008). Copepods make up the majority of their diet which also includes diatoms, mollusc larvae, small crustaceans, and other fish egg and larvae (Hayasi, 1967). JA are able to swim at speeds up to 10-12 cm/sec and grow to lengths of 16 cm (Hayasi, 1967). JA have a short life span of 2 to 3 years (Hayasi, 1967).

### ***Population Fluctuations***

Coastal pelagic species populations are driven primarily by fluctuations in climate and mortality (Checkley et al., 2017). The El Niño Southern Oscillation (ENSO) leads to increases in temperature and precipitation, followed by increases in river output and decreases in salinity (Liu et al., 2020). JA can inhabit a wide range of temperatures and salinities and ultimately benefit from influxes of nitrogen from estuarine systems. Additionally, high water temperatures accelerate growth of larval anchovy and improves recruitment of adult fish (Liu et al., 2018). Favorable changes in conditions that impact growth rates and prey availability can lead to population booms as seen in the 1980's, when the ENSO led to high outputs of freshwater into the Kuroshio region (Kim et al., 2005).

## **Stock Status & Catch**

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### **Pacific Bluefin Tuna**

The WCPFC and IATTC oversee PBF stock management throughout the Western and Eastern Pacific. PBF is managed as a single stock within the Pacific Ocean. The ISC completes stock assessments for PBF and has tracked the decline of spawning stock biomass (SSB) of the PBF since 1996 (ISC, 2020). Continued overfishing of juvenile PBF has led to a historic low of 1.7% of its SSB in 2010 (**Figure 6**) (ISC, 2020). This percentage increased to 4.5% in 2018, however, PBF continues to be subject to overfishing despite recent conservation measures implemented by IATTC and WCPFC (IATTC, 2020; WCPFC, 2009). The International Seafood Sustainability Foundation (ISSF) has listed the PBF as “Needs Improvement” since 2013 (**Figure 7**) (ISSF, 2021).

### ***Traditional Fishing***

Traditional PBF fishing has been documented since the 17th century and expanded from small-scale fishing practices to modern day major commercial and recreational fleets (ISC, 2020; Suzuki and Kai, 2012). Trapping, also referred to as set nets, is a form of traditional fishing in Japan that targets a variety of marine species based on the size of the trap (Suzuki and Kai,



2012). Trapping is often managed by local fisheries cooperative unions or other forms of local, prefectural government (Suzuki and Kai, 2012). Traps account for approximately 12% (2,000 tons) of PBF caught by Japan, though PBF ultimately makes up less than one percent of total catch for all trapping efforts (Suzuki and Kai, 2012). Due to the size constraints of the traps, juvenile PBF are disproportionately targeted by this small-scale fishing method. Trapping is also recognized to be an important traditional fishing practice that preserves historical techniques and promotes community-based management (Suzuki and Kai, 2012).

### ***Recreational***

The United States contains the largest recreational PBF fishery of any country, though this may be due to insufficient records of recreational fleets in other countries of the Pacific (Heberer and Lee, 2019; WCPFC, 2005). The majority of recreationally caught PBF within the United States recreational fishing sector are either on private boats or Commercial Passenger Fishing Vessels (Heberer and Lee, 2019). PBF catch is counted as individual fish, rather than tons, within the recreational fishing sector. Nearly 96,000 PBF individuals were caught between 2014 and 2018 (Heberer and Lee, 2019). San Diego is considered the epicenter of recreational PBF fishing within the Eastern Pacific (Heberer and Lee, 2019).

### ***Commercial***

The commercial PBF fishery extends throughout the entire Pacific Ocean, falling under both WCPFC and IATTC jurisdiction (ISC, 2020). According to the ISSF, roughly 70% of commercial PBF is caught using purse-seine gear, followed by 10% caught via longline gear, and the remainder caught by a variety of gears, possibly including traditional traps, troll, or hook and line (ISSF, 2021). PBF are caught throughout the Eastern and Western Pacific along the coastlines and offshore of Japan, Taiwan, Korea, the United States, and Mexico (ISC, 2020). Catch of PBF has declined drastically since 1950 as the stock began to decrease and conservation measures were put in place (ISC, 2020). In 1956, Japan landed an all-time maximum of 34,000 tons of PBF (ISC, 2020). Forty years later in 1990, Japan landed only 6,000 tons of PBF (ISC, 2020). Purse-seine and longline operations of the Western Pacific target the spawning grounds of PBF in the East China Sea and Sea of Japan (Shimose et al., 2016; Shin et al., 2018).

### ***Aquaculture***

Commercial fishing of PBF feeds directly into tuna ranching, a form of aquaculture that began in Japan in the late 1960s (Kurokura et al., 2012). PBF ranching is defined as capture-based aquaculture, or the taking of wild populations to rear in captivity (Normile, 2009; Vergara-Solana et al., 2019). Juvenile PBF are caught by purse-seine vessels and transported to sea pens where they are fed until harvest and sold to wholesalers (Vergara-Solana et al., 2019). Researchers at Kinki University, Japan, were able to capture the full life cycle of PBF in captivity, yielding a fully farmed tuna product that can compete with wild-caught PBF (Normile, 2009). Other countries are pursuing PBF aquaculture for monetary benefit. In Mexico, nearly all of the PBF quota is put towards tuna ranching (Vergara-Solana et al., 2019). PBF production only accounts for 1.8% of total tuna production within Mexico but makes up 14% of the total value (Vergara-Solana et al., 2019).

### ***Processing & Distribution***

Tuna processing and distribution occurs on a global scale. Until the 1960s, tuna caught at sea were offloaded to local markets for distribution (Miyake, 2010). This changed with the invention of transshipment routes that no longer required fishing vessels to return to port to offload catch. Instead, individual tunas caught at sea are now semi-processed on the boat (Miyake, 2010). The fish are bled and iced to keep the meat fresh until offloading. From that point, PBF may be frozen until reaching its destination, where it is thawed and can be marketed as sashimi (**Figure 8**) (Miyake, 2010). Other tuna species, such as albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*), and yellowfin (*Thunnus albacares*) can be used for canning purposes where volume, rather than quality, is key (McKinney et al., 2020). According to McKinney et al., 2020, the value of a single bluefin tuna exceeds that of a ton of canned yellowfin.

Once arrived on shore, PBF can be distributed to central markets such as the Tsukiji Fish Market of Tokyo, or sold to large-scale retailers (Miyake, 2010). If frozen and destined for further travel, the PBF must be kept in cold storage. If it is meant for local consumption, the PBF is laid out to begin thawing at a central market. Central markets tend to supply local markets, which are then able to supply local retailers and restaurants with fresh, but possibly previously frozen, sashimi-grade fish (Miyake, 2010).

### ***Japanese Anchovy***

At 3.8 million tons, the JA fishery is the seventh largest anchovy fishery in the world (Checkley et al., 2017). JA management is composed of total allowable catch (TAC), vessel controls determining the size and number of fishing fleets as well as time-area closures managed by the Fishery Agency of Japan (Jiang et al., 2009; Wang et al., 2020; Yatsu, 2019). JA catch has risen since the 1940s, peaking in the late 1950s at over three million tons and again in the early 2000's at over four million tons (**Figure 9**) (Oozeki et al., 2007). JA catch follows an inverse trend compared to Japanese sardine catch, attributed to population fluctuations of coastal pelagic species and species alteration of fishing fleets (Garcia et al., 2018; Yatsu, 2019). When the Japanese sardine population boomed in the early 1980s, JA catch fell by two million tons (Oozeki et al., 2007). Conversely, during the Japanese sardine collapse of 1988 JA catch rose by approximately three million tons (Oozeki et al., 2007). Japanese sardine catch rose once again during the 2010's, causing a decline in JA catch (Yatsu, 2019). Global catch of JA has decreased in recent years, falling below one million tons for the first time since the 1950's (FAO, 2020). Acoustic surveys revealed a two million ton decrease in stock biomass of JA between 1993 and 2000 (Liu et al., 2020).

### ***Traditional & Recreational Fishing***

Traditional Japanese cuisine incorporates several coastal pelagic species, prominently featuring the juvenile stages of Japanese sardine and JA. The juveniles of these species are referred to as whitebait, or *shirasu* and can be boiled, dried, or fried (Yatsu, 2019). Dip nets were introduced into the coastal pelagic fisheries in the 1950's to 60's (Yatsu, 2019). Schooling fish are caught using handheld nets in nearshore waters.

### ***Commercial***

JA are caught via trawl and purse seining vessels throughout the Western Pacific, notably in the Yellow Sea during winter months (Liu et al., 2020). Purse-seine fleets are generally made up of

one main fishing vessel, followed by two catch transportation vessels and one searching vessel (Garcia et al., 2018). Each fleet is managed via 5-year licenses and can hold roughly 560 tons of catch (Garcia et al., 2018). Based on volume, coastal pelagic species make up most of the catch volume within Japan with JA ranking as the second most common species (Popescu and Ogushi, 2013). JA accounts for approximately 10% of total catch in China and 6% of total catch in Japan (Liu et al., 2020; Popescu and Ogushi, 2013).

### ***Aquaculture***

JA are not farmed within Asia but do play an important role in aquaculture. Around the world, coastal pelagic species are processed into fishmeal for aquaculture operations (Checkley et al., 2017). Processing fishmeal became popular in the 1950s with the invention of fishmeal production factories (Merino et al., 2014). Species such as anchovy are targeted for their oil-rich meat, which is wet-pressed into dry pellets. Currently, fishmeal makes up a 5.1 billion yen industry in Japan and is 7% of the total volume of Japanese fisheries exports (Popescu and Ogushi, 2013). Japan is currently the world's fourth largest producer and second largest consumer of fishmeal (Merino et al., 2014).

### ***Processing & Distribution***

Processing and distribution of anchovy varies considerably between culinary and aquaculture purposes. JA juveniles harvested as *shirasu* are distributed fresh, boiled, dried, or fried. Fresh *shirasu* is distributed within the locality where it was caught, as its fragile nature prevents long distance transportation (Hale, 2014). Other preparation methods are traditionally completed onshore by the fishermen. Adult JA are caught by purse seine fleets may fulfill several purposes. In addition to culinary use, adult stages are caught as bait for other commercial fisheries and are processed into fishmeal and oil for aquaculture (Merino et al., 2014). Processing of fishmeal and oil includes cooking the anchovy, separating the coagulated oil from the solids, and further processing the oil and pressing the remaining dehydrated solids into fishmeal (Merino et al., 2014). Distribution of fishmeal and other packaged goods, such as dried *shirasu*, is global.

## **Climate Change & Habitat Suitability**

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### **Introduction**

This portion of the report discusses the physiological, behavioral, ecological attributes of two major fisheries species that may be impacted by climate change into the next century. Each life stage of the PBF and JA, as well as any adaptations that may advantage these species, will be investigated using the decision tree found in **Appendix B**. This qualitative analysis is meant to build upon suitable thermal habitat projections and further detail how distribution and abundance of both species may change over time. Addressing the interactions between climate and life history characteristics, including migration, spawning, feeding patterns, and predator-prey relationships of both species play an integral part in the formation of appropriate fisheries management strategies.

### **Pacific Bluefin Tuna**

Twenty of twenty-two global tuna species shifted northward in distribution between 1958 and 2004, a trend that is projected to intensify over the next century (Erauskin-Extramiana et al., 2019). These shifts are generally tied to estimates of suitable thermal habitat which provides a

generalized estimate of future distribution. Historic suitable thermal habitat of PBF was compared to projected 2050 suitable thermal habitat extent using computer-generated maps collected via AquaMaps (**Figures 10, 11**) (Kaschner et al., 2019a). A general poleward shift into historically subarctic waters was observed. However, many factors in addition to water temperature and adult temperature tolerance affect tuna distribution and abundance - including the varying thermal tolerances and prey requirements of different life stages (Kaschner et al., 2019a; Kimura et al., 2010). This report seeks to generate improved projections of PBF distribution relative to generalized suitable thermal habitat projections by investigating how climate change may impact each life stage of the PBF.

PBF thrive in habitats that push them to the edges of their physiological limits. Their efficient feeding abilities, fast growth rate, and long life span allow them to traverse the largest ocean basin in the world and survive in a multitude of habitats. Likewise, their ability to complete transoceanic migrations and rapidly respond to changing ocean conditions enables them to balance their need to maximize energy intake while remaining in their thermal tolerance range (Whitlock et al., 2015). PBF are able to control their body temperature via endothermy, allowing them to enter cooler and warmer waters to feed. Moreover, adult and juvenile life stages show the ability to adapt to extreme environments such as deep, cold waters, and historically warm near-surface temperatures caused by recent marine heatwaves (Runcie et al., 2019; Whitlock et al., 2015).

These attributes of PBF contribute to their resilience to climate-induced changes in ocean conditions in general. However, climate change may pose a risk to earlier life stages and influence movement in juvenile and adult migrations. Overall, PBF may prove to be quite resilient to climate change by virtue of their ability to find and move into suitable habitat unless recruitment is constrained by warming and other impacts. Resilience may also be compromised by the current state of the fishing stock and increased exploitation.

## **Egg & Larval Stages**

### ***Spawning Grounds & Larval Transport***

The first obstacle PBF face under climate change conditions is surviving the warming waters of spawning grounds. The PBF spawns in distinct locations throughout the Western Pacific, in oligotrophic areas of warm water movement as a result of oceanic currents and convergence zones (**Figure 12**) (Muhling et al., 2017). The largest spawning ground that contributes the greatest percentage of recruitment lies in the East China Sea, directly in line with the subtropical Kuroshio current (Shiao et al., 2020). PBF are broadcast spawners, releasing millions of eggs into the water column where they hatch within 24 hours (Satoh, 2010). Optimal temperature for hatching and early-stage larval stages is 26°C (Satoh, 2010). Hatchlings drift within the warm eddies of the Kuroshio for several weeks before the current transports larvae to colder, highly productive coastal environments (Kimura et al., 2010). Extended residence time in eddies allows larval PBF to metamorphose prior to entering colder waters, where they feed on a variety of prey including zooplankton and coastal pelagic species.

Climate change is expected to impact larval PBF in at least two major ways: By 2100, sea surface temperature is projected to increase to 29°C on southern spawning grounds and the Kuroshio current is anticipated to strengthen, potentially transporting larval fish to coastal

grounds before they are developed enough to withstand colder sea surface temperatures (**Figure 13**) (Kimura et al., 2010; Nishikawa et al., 2020). Warmer sea surface temperatures have been shown to improve recruitment, however, sudden increases in water temperature are lethal to larval PBF (Kimura et al., 2010; Muhling et al., 2018). Water temperatures exceeding 29.5°C have been shown to result in increased mortality of PBF larvae, which is further exacerbated by the shortened transport time to colder waters in which younger larvae will be unable to survive (Kimura et al., 2010). Combined, these stressors could increase larval mortality by 36% and severely impair recruitment (Kimura et al., 2010). However, these findings were the result of laboratory experiments meaning that temperatures of 29.5°C may not result in larval mortality depending on other ocean conditions and the possible development of adaptations over a 100 year time frame (Muhling et al., 2018).

Increased larval mortality tied to climate change may be mitigated by the increased use of northern spawning grounds, located in the Sea of Japan and possibly the Kuroshio-Oyashio Transition Zone (KOTZ) (Ohshimo et al., 2018b; Shiao et al., 2020; Tanaka et al., 2020). The successful use of these alternate spawning grounds by PBF depends on the severity of sea surface warming in northern latitudes as well as the behavior of spawning PBF (Kimura et al., 2010; Ohshima et al., 2009). Warming of surface air throughout East Asia has led to the decline of sea ice formation within the Sea of Okhotsk, weakening the transport of cold, oxygen and nutrient-rich waters to coastal habitats via the Oyashio current (Ohshima et al., 2009). The weakening of the cold water Oyashio current, paired with the strengthening of the warm water Kuroshio current, is anticipated to warm sea surface temperatures throughout the Sea of Japan and KOTZ (Ministry of the Environment, 2018; Ohshima et al., 2009). Growth patterns and survival of larval stages may change as sea surface temperatures rise and primary productivity changes throughout the Sea of Japan and KOTZ (Ohshima et al., 2009; Yoon, 2000). Given the effects of climate change on the East China Sea and Sea of Japan, spawning grounds may constrict or shift north, and larval recruitment may be prone to spikes in mortality due to rising temperatures and premature larval transport to cooler waters.

### **Juvenile Stage** *Western Pacific*

Juvenile PBF are likely more resilient to the effects of climate change than larval PBF because they have undergone rapid growth during their earliest life stage (Hunter, 1981; Satoh, 2010). Once deposited in coastal nearshore waters by the Kuroshio current, juvenile PBF undergo a northward migration towards the Sea of Japan and the eastern coast of Kyushu and Honshu (**Figure 14**) (Kitagawa et al., 2006b). Juvenile PBF take advantage of colder waters during the summer months, feeding in the convergence zones of nutrient-rich waters and sub-tropical currents that harbor coastal pelagic species (Fujioka et al., 2018a; Kitagawa et al., 2006b). A southward migration towards the East China Sea commences in late autumn (Itoh et al., 2002).

The poleward extent and timing of this cyclical migration is largely driven by thermal and metabolic tolerances of juvenile PBF (Kitagawa et al., 2006b; Whitlock et al., 2015). Juvenile PBF are still developing endothermic capabilities as they grow, and begin to maintain higher body temperatures that allow them to occupy colder, deeper waters (Blank et al., 2007; Kubo et al., 2008; Shiels et al., 2015). Juvenile PBF movement is tied in part to their thermal metabolic minimum zone, or the temperature range in which they are able to optimize the tradeoff between

metabolic costs and maintaining optimal internal body temperature (Blank et al., 2007; Fujioka et al., 2018b). The thermal minimum zone of juvenile PBF is estimated to be 15°C to 20°C (Blank et al., 2007).

PBF are capable of quickly responding to changing climatic conditions in order to remain within their thermal minimum zone which is colder than that of other tropical tuna species (Kitagawa et al., 2006b). By undergoing poleward migrations, juvenile PBF are able to remain within their thermal minimal zone while venturing into colder, productive waters for feeding opportunities (Whitlock et al., 2015). Past studies have revealed that juvenile PBF movement can shift further poleward in part to follow sea surface temperatures within their thermal minimum zone during ENSO events (Kitagawa et al., 2006b).

During an El Niño event in 1998, sea surface temperatures throughout the Kuroshio current reached 26°C, a warmer than preferred temperature that requires increased energy expenditures for juvenile and adult PBF entering current systems (Kitagawa et al., 2006b). In response, juvenile PBF shifted their migration northward to remain in cooler waters. A similar shift was seen during La Niña events. Juvenile PBF shifted further south than in previous years to pursue optimal temperatures and feeding grounds (Kitagawa et al., 2006b). Based on the plasticity previously seen in juvenile PBF migration routes, projected northward shifts in both the Kuroshio and Oyashio currents by 2100 would likely result in a northern shift of PBF distribution (Kitagawa et al., 2006b; Nishikawa et al., 2020). As sea surface temperatures rise throughout the East China Sea, Sea of Japan, and the KOTZ, PBF juveniles may have to expand their poleward migration to remain within their thermal minimum range (Blank et al., 2007; Kimura et al., 2010; Ministry of the Environment, 2018; Ohshima et al., 2009; Whitlock et al., 2015). Meeting energy intake requirements while remaining in suitable thermal ranges may prove to be difficult if the timing and extent of prey species movement no longer coincides with poleward juvenile PBF migration.

### ***Trans-Pacific Migration***

After completing the Western Pacific migration along the shores of Japan, a subset of PBF juveniles aged year 1 to year 3 complete a migration across the Pacific Ocean to the California Current Large Marine Ecosystem (CCLME) (Itoh et al., 2002). Fujioka et al., 2018b, provided evidence that juvenile PBF initiate this transoceanic migration when exposed to cooler sea surface temperatures nearing or below 14°C rather than being tied to a particular season. Three waves of latitudinal migrations take place in May to July, October to December, and February between the 30°N and 50°N latitudes (**Figure 15**) (Fujioka et al., 2018b). Earlier migrations beginning in May tended to culminate at higher latitudes, approaching 50°N when reaching the western coastline of North America in the summer. In comparison, later migrations trended south and reached the western coastline of North American near 40°N in the late autumn and 30°N in winter (Fujioka et al., 2018b). The latitudinal differences exhibited between each migration wave is indicative of juvenile PBF following suitable sea surface temperatures when crossing the Pacific Ocean, generally occupying areas ranging from 10°C to 20°C (Fujioka et al., 2018b; Kitagawa et al., 2009). This latitudinal band of water is also known as the Subarctic Frontal Zone (SFZ), a thermohaline structure spanning across the Pacific Ocean (**Figure 16**) (Fujioka et al., 2018b; Kitagawa et al., 2009; Yuan and Talley, 1996).

The SFZ separates colder waters of the North Pacific from warmer waters found in southern latitudes (Yuan and Talley, 1996). Location and extent of the SFZ is influenced by a number of factors, including weather events, underwater topography, and oceanic currents, among others (Roden, 1991). Variability of the SFZ in the Western Pacific has been found to be three to six times greater than that of the Eastern Pacific due in part to topographic diversity of the Emperor Seamounts and an eastward extension of the Kuroshio current into the Pacific Ocean basin (Roden, 1991). The strengthening the sub-tropical Kuroshio current, concurrent with the weakening of the Oyashio current, has the potential to constrain the SFZ to higher latitudes by heightening warm water inputs into offshore habitats (Ministry of the Environment, 2018; Ohshima et al., 2009; Roden, 1991). Given the ability of juvenile PBF to alter migratory routes based on changing oceanic conditions, intensification of variation in the SFZ may lead to a northern shift in the migration routes and arrival of juvenile PBF to the Eastern Pacific (Fujioka et al., 2018b; Kitagawa et al., 2009).

### ***California Current Large Marine Ecosystem Migration***

After a two to three month journey across the Pacific Ocean, juvenile PBF arrive at the CCLME, the eastern boundary current of the North Pacific Gyre (Itoh et al., 2002). Similar to the subarctic currents found within the Western Pacific, the CCLME is a highly productive environment characterized by cool, nutrient-rich waters along the western coasts of the United States and Mexico (Runcie et al., 2019). Juvenile PBF migration routes follow a seasonal pattern associated with spring upwelling off the coast of Southern and Baja California (**Figure 17**) (Boustany et al., 2010). Juvenile PBF began a northward migration in early autumn, reaching the northern extent of the CCLME where upwelling is strongest along the Northern California coast (Boustany et al., 2010; Kitagawa et al., 2007). Offshore movement of juvenile PBF is most common during autumn and winter seasons, indicating that foraging for prey is a major motivator of movement between areas of high and low productivity (Boustany et al., 2010). Juvenile PBF migrate south to the Southern California Bight and Baja California in spring where they feed in the highly productive coastal environment (Boustany et al., 2010).

Impacts of climate change to the CCLME and associated upwelling systems may alter the distribution of juvenile PBF throughout the Eastern Pacific. Pozo Buil et al., 2021, found that climate change induced impacts to the CCLME will likely become evident in the latter half of the 21st century. Upwelling is projected to intensify in the northern extent of the CCLME during winter and weaken in the southern extent during summer (Brady et al., 2017; Pozo Buil et al., 2021; Xiu et al., 2018). The Southern California Bight is considered a hotspot for foraging juvenile PBF targeting coastal pelagic species such as anchovy (Boustany et al., 2010; Kitagawa et al., 2007; Pinkas, 1971). Weakening of upwelling systems may decrease the abundance of lower trophic level fish species within the Southern California Bight, in turn affecting the distribution of foraging juvenile PBF within the CCLME (Boustany et al., 2010).

Timing and extent of juvenile PBF poleward migrations within the CCLME are also driven by the appearance of marine heatwaves (Runcie et al., 2019). A marine heatwave exacerbated by El Niño conditions appeared within the CCLME from 2014 to 2016 (Peterson et al., 2017). A 3°C increase in sea surface temperature led to earlier and higher catch of juvenile PBF within the CCLME, suggesting that the marine heatwave may have improved thermal habitat for PBF while also shifting PBF distribution north based on prey availability (Runcie et al., 2019). Similar,

though lesser, responses in distribution and abundance of juvenile PBF within the CCLME are seen during El Niño years (Runcie et al., 2019). Marine heatwave events are anticipated to increase in frequency and intensity within the next century, leading to reductions in prey species abundance and introducing possible mismatches in timing of prey availability and PBF movement (Cheung and Frölicher, 2020). Overall, PBF within the CCLME may shift northward to follow forage species into more productive habitats.

### **Adult Stage**

Throughout the juvenile life stage, PBF forage, grow, and ultimately become more resilient to extreme environmental conditions. Juvenile PBF remain in the CCLME for up to five years before returning to the Western Pacific (Madigan et al., 2018; Runcie et al., 2019). PBF reaching 120 cm to 160 cm are small adults, generally 4 to 5 years of age (Itoh, 2006). Adult PBF over 4 years of age within the CCLME were found to have a greater northern extent when compared to smaller size classes of PBF (Boustany et al., 2010). Growth and distribution of adult PBF are linked to increased endothermic capacity, allowing for larger PBF to inhabit colder and deeper waters than earlier life stages (Kitagawa et al., 2001; Malik et al., 2020).

Though adult PBF are able to expand their range latitudinally, the vertical distribution of PBF in the water column may be impacted at older life stages due to global decreases in dissolved oxygen (Leung et al., 2019). PBF dive to depths of 500 m in order to feed or thermoregulate, foraging in the cold waters beneath thermoclines and expending energy to maintain optimal internal temperature (Kitagawa et al., 2007). Warming sea surface temperatures may cause PBF and other tunas to dive deep in order to find refugia in cold waters, however, this may be constrained by declining dissolved oxygen concentrations in these waters (Leung et al., 2019). The most significant decreases in dissolved oxygen are projected to occur within the North Pacific between depths of 200 m to 700 m, overlapping the transoceanic migration route of PBF (Leung et al., 2019). Constraints in vertical habitat may push PBF distribution further north in order to find adequate food sources and areas that reflect their thermal minimum zone (Blank et al., 2007; Boustany et al., 2010; Leung et al., 2019).

### **Conclusion**

PBF, when compared to other less mobile fish stocks, appear to be relatively resilient to climate change. Fast growth rates, generalist diets, and endothermy make them one of the fastest and wide-ranging predators of the Pacific Ocean. These attributes have resulted in a very widespread distribution of PBF in all dimensions - latitudinally, longitudinally, and throughout the water column. Yet this species will likely still feel the effects of climate change because spawning success, larval survivorship, and juvenile growth appear to be somewhat vulnerable to climate change impacts. The reliance of PBF on specialized spawning grounds and highly productive systems, exacerbated by fishing pressure on juvenile and adult stages, could lead to further declines in biomass and the disappearance of PBF from areas within and surrounding the East China Sea (Blank et al., 2007; Hunter, 1981; Pinkas, 1971). The abundance and distribution of prey species, namely coastal pelagic fisheries like sardines, anchovy, and squids will also likely be an important determinant of PBF response to climate change (Boustany et al., 2010). In the following section, the resilience of a coastal pelagic species, Japanese anchovy, is reviewed and related to PBF distribution and abundance.



## Japanese Anchovy

Coastal pelagic species such as anchovy serve as a key connection between primary productivity of coastal areas, zooplankton, and large marine predators like tuna (Checkley et al., 2017). Anchovy and other coastal pelagic species influence their surrounding environment through top-down control of phyto- and zooplankton and bottom-up control of predators (Ma et al., 2019). Their population dynamics follow a boom and bust cycle driven by climatic variability and mortality events (Checkley et al., 2017). Favorable conditions, including optimal temperatures, an abundance of zooplankton, and adequate dissolved oxygen lead to periods of high fecundity resulting in successful spawning and recruitment (Checkley et al., 2017; Ma et al., 2019). Anchovy in particular are highly sensitive to environmental changes and rely on coastal upwelling and vertical mixing to introduce nutrients into coastal waters, which are then taken up by phytoplankton (Checkley et al., 2017). JA favor the western boundary currents of the North Pacific Gyre, taking advantage of coastal upwelling processes as well as the convergence of subarctic and subtropical currents along the coast on Honshu in order to feed on zooplankton (Checkley et al., 2017; Niu and Wang, 2017).

Climate change is expected to impact the distribution and abundance of all anchovy stocks throughout the world (Checkley et al., 2017). Increased climatic variability is anticipated to result in poleward shifts and changes in phenology of anchovy populations (Checkley et al., 2017). Poleward shifts in distribution over the next century are apparent in suitable thermal habitat projections provided by AquaMaps, but fine-scale effects of climate change on different life stages of species with volatile population dynamics such as JA could affect future JA distribution, thus potentially affecting the distribution and abundance of PBF (**Figure 18, 19**) (Kaschner et al., 2019b). This report describes possible climate change impacts to each life stage of the JA, as well as impacts to overall population dynamics.

## Egg & Larval Stages

### *Spawning Grounds*

Adult JA spawn from late spring to early autumn throughout Western Pacific waters, favoring the Seto Inland Sea, Yellow Sea, Goto-Nada Sea, and coastal waters of Japan (**Figures 20**) (Hayasi, 1967; Liu et al., 2020; Takeshige et al., 2015; Zhang et al., 2020). JA eggs hatch after 30 to 48 hours and larvae are transported by the subtropical Tsushima and Kuroshio currents (Hayasi, 1967). JA are a warm water species within the Western Pacific, differing from other coastal pelagic species such as sardine that thrive in cooler temperatures (Nakayama et al., 2018; Takasuka et al., 2007). Optimal growth temperature for JA is 22°C, in contrast to 16.2°C for Japanese sardine (*Sardinops melanostictus*) (Takasuka et al., 2007). JA are advantaged during select periods of climatic variability, generally during warming cycles of the Pacific Decadal Oscillation (PDO) or El Niño years which lead to higher sea surface temperatures throughout the Western Pacific (Nakayama et al., 2018). Shifts in the PDO and ENSO tend to be associated with regime shifts and oscillations in species composition between coastal pelagic communities dominated by JA and communities dominated by Japanese sardine (Kim et al., 2005).

Greater abundance and increased recruitment of JA have been detected throughout the Western Pacific during periods of above average sea surface temperatures (Hayashi et al., 2016; Kim et al., 2005). In 1990, JA larvae were detected in the subarctic waters of the Oyashio current, far north of their historic spawning grounds within the subtropical Kuroshio current and Yellow Sea

(**Figure 21**) (Hayashi et al., 2016). An El Niño event had begun and caused sea surface temperatures within the Oyashio region to reach 15°C in summer months, coinciding with the lowest spawning temperature for adult JA (Hayashi et al., 2016). Increased abundance of JA led to spawning adults moving northward into suitable, though seldom used, spawning habitat. Larval stages of JA were then transported south to the warmer waters of the Kuroshio, where they encountered suitable sea surface temperatures for growth. Similar movements into optimal spawning grounds have been observed in the East China Sea during El Niño events. Adult JA accumulated in the Chinese coast along the outfall of the Yangtze River, attracted to the high productivity of estuarine waters (Kim et al., 2005). Increased precipitation brought on by El Niño conditions led to higher primary productivity, an abundance of zooplankton prey, and suitable sea surface temperatures for spawning and foraging JA (Kim et al., 2005). JA spawning grounds may shift north in response to warming temperatures, and recruitment may become more unpredictable as climatic variability increases into the next century.

### ***Larval Transport***

Climate change induced impacts to early stages of JA are invariably connected to the anticipated intensification of the PDO and ENSO (Fasullo et al., 2018; Li et al., 2020; Nakayama et al., 2018; Sugihara et al., 2012). Heavy precipitation events and rising sea surface temperatures within Asia are projected to become more frequent as climate change progresses, potentially leading to movement of adult JA out of historic spawning grounds as they search for more suitable temperatures and abundant prey (Hayashi et al., 2016; Kim et al., 2005; Kimoto et al., 2005). Previous observations in shifts in JA have led to both decreases and increases in recruitment, largely based on the state of surrounding boundary currents (**Figure 21**) (Hayashi et al., 2016; Takeshige et al., 2015). A northward shift in JA spawning grounds within the Goto-Nada Sea, exacerbated by a weakened Tsushima current, led to retention of JA larvae in oligotrophic offshore waters instead of transport to highly productive coastal waters (Takeshige et al., 2015). Inversely, models anticipating a strengthening of the Tsushima and Kuroshio currents revealed that JA abundance would decrease within the Yellow Sea due to low sea surface temperatures and increase in the Korean Strait and Sea of Japan (Jung et al., 2016). The slightest of changes brought by regime shifts in the PDO or El Niño have the potential to alter mortality of early life stages, leading to rapid population growth or decline (Fasullo et al., 2018; Li et al., 2020; Takasuka et al., 2007). The transport of larval stages relies on the boundary currents of the North Pacific Gyre, meaning survival may shift depending on the strengthening of the Kuroshio or weakening of the Tsushima current.

### **Juvenile & Adult Stages**

#### ***Spawning Migration***

Upon reaching juvenile stages, JA begin to exhibit shoaling behaviors along the coasts of Japan, China, South Korea, and other coastal countries (Hayasi, 1967). Adult JA foray into offshore waters where they feed on copepods, diatoms, and the egg and larvae of other marine species (Checkley et al., 2017; Hayasi, 1967). Increases in precipitation, sea surface temperatures, and reduced mixing via oceanic currents in the East China Sea could severely impact and limit JA distribution along coastlines (Checkley et al., 2017; Howard et al., 2020; Nishikawa et al., 2020). Influxes of freshwater via river systems can lead to eutrophication, ultimately creating hypoxic areas with little to no primary and secondary productivity (Laffoley and Baxter, 2019). This is of particular concern in the Yellow and East China Sea, which hosts the outfall of several rivers

including the Yangtze River (Kim et al., 2005). Additionally, weakening of the Oyashio current and loss of sea ice extent in the Sea of Okhotsk is projected to reduce the transport of dissolved oxygen and nutrients from subarctic waters, further limiting distribution of JA in northern reaches (Yatsu, 2019).

Adult JA undergo a northward spawning migration in spring months to coastal areas of the Yellow Sea, East China Sea, and Japan (**Figure 5**) (Zhang et al., 2020). After spawning throughout the summer, adult JA make a return migration to southern overwintering grounds located in the Yellow and East China Sea (Zhang et al., 2020). Adult JA feed in deeper waters during this migration and dive to depths of up to 50m where water temperature may be as low as 5°C (Jung et al., 2016). JA and other anchovy species are poikilotherms, meaning their body temperature often reflects that of the surrounding environment (Jung et al., 2016). Optimal temperatures for juvenile and adult JA are between 11°C and 13°C (Jung et al., 2016). While JA are able to survive in cooler and warmer waters, exposure to unsuitable temperatures can exceed metabolic tolerances (Lluch-Belda et al., 1991). Migration and spawning movements of JA may shift to follow suitable thermal temperatures based on their inability to regulate body temperature.

### ***Winter Migration & Overwintering Grounds***

Unlike other fish species, a long-term poleward shift in distribution has not been detected in JA populations (Niu and Wang, 2017). Migrations of JA are driven by variations in sea surface temperatures and can vary year to year (Liu et al., 2018; Zhou et al., 2015). Adult JA follow 11°C and 13°C isotherms during their winter migration, and are expected to shift poleward if sea surface temperatures become too warm or cool (Zhou et al., 2015). A similar relationship is seen between JA moving their overwintering grounds in the Yellow and East China Sea based on where the Yellow Sea Warm Current reaches suitable temperatures (Niu and Wang, 2017). Variations in movement of JA coincide with changes in the PDO and El Niño events. In the mid-1990s, JA abundance increased due to the effect El Niño had on summer sea surface temperatures and decreased once the El Niño event ended and a La Niña event began in 2005 (Ma et al., 2019). The lack of a general poleward shift in JA distribution may be related to ontogenetic changes in thermal tolerance. Depending on recruitment, the JA population can be made up of primarily older adults or younger juveniles. As JA grow in age and size, resilience to both colder and warmer temperatures increases. Poleward shifts may not be necessary in some years depending on if 2 year old adults comprise the majority of the population rather than new recruits (Niu and Wang, 2017). JA response to climate change shift may vary based on population structure, with older adults possibly requiring less movement to remain in their thermal tolerance zones.

### **Conclusion**

The largest impact of climate change to JA in the Western Pacific will likely be the projected increase in intensity of climatic variations via the PDO and ENSO (Checkley et al., 2017; Zhou et al., 2015). Warming sea surface temperatures throughout the Western Pacific may provide an initial advantage to JA and provide an expansion of suitable thermal habitat (Hayashi et al., 2016). However, impacts to primary productivity and larval transport via oceanic currents may restrict feeding and spawning grounds of JA, forcing the populations further north in order to find quality habitat. The timing of migrations and spawning activities may also be impacted

depending on severity of climatic variability under climate change conditions, possibly reducing the abundance of this important forage species from the trophic chain of the West Pacific. A general poleward shift in the JA distribution may not occur due to the tendency for JA to increase in resilience to both colder and warmer temperatures as they age.

## Climate Change & Predator-Prey Relationships

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### Introduction

Beyond pursuing suitable thermal habitats, movement of fish and other marine animals is driven by the need to forage for prey. As climatic variability and oceanic conditions change throughout the world in response to a warming climate so too will species distribution and abundance (Barange et al., 2018). Many marine species are shifting poleward in response to warming sea surface temperatures or prey movements (Osland et al., 2021). Highly migratory species such as the PBF have developed migration patterns that allow for them to remain in their thermal minimum zone while also moving in and out of areas of high productivity, characterized by the presence of upwelling and often coastal pelagic fish species (Blank et al., 2007; Boustany et al., 2010; Leung et al., 2019). JA has become an important food source for migrating juvenile PBF throughout the Western Pacific (Shimose et al., 2013; Tanaka et al., 2007).

As climate change progresses, the phenology of major fisheries species may change as temperatures increase earlier in the year and regime shifts in the PDO and ENSO become more pronounced (Fasullo et al., 2018; Li et al., 2020). Certain species, such as JA, benefit from El Niño cycles and undergo explosive population growth as warmer sea surface temperatures emerge (Hayashi et al., 2016; Kim et al., 2005). Large marine predators like PBF may be able to take advantage of prey species population booms if they can withstand the high temperatures and if their movement throughout the region coincides with the movement of the forage species. Mismatches in phenology could lead to predators facing a tradeoff between optimal metabolic performance and pursuing energy sources into unsafe territory.

### Western Pacific Migrations

#### *Spawning Grounds*

Though the JA is considered a warm water species and PBF a temperate species, considerable spatiotemporal overlap exists between the two species' migration patterns (**Figure 22**) (Kitagawa et al., 2006a; Nakayama et al., 2018). The Western Pacific migrations of PBF and JA share a poleward trend into northern waters during spring and summer and a return to southern waters in autumn and winter (Fujioka et al., 2018a; Zhang et al., 2020). PBF migration throughout the Western Pacific has a greater extent than that of the JA due to adaptations for increased thermal tolerances (Blank et al., 2007; Zhou et al., 2015). Both PBF and JA foray into oligotrophic offshore areas and eutrophic waters along coastlines in search of suitable temperatures and food.

PBF and JA migrations share the greatest overlap in the Kuroshio/East China Sea region during spring and summer months, when both species utilize the area for spawning (Malik et al., 2020; Zhang et al., 2020). Another area of possible concentrated overlap is the KOTZ, off the northwestern coast of Honshu. Larval JA were found in the subarctic reaches of the Oyashio current and KOTZ during an El Niño event that raised temperatures to 15°C in summer months (Hayashi et al., 2016; Tanaka et al., 2020). The KOTZ has also been described as an

unconfirmed third spawning ground of PBF in summer months (Tanaka et al., 2020). Overlap of spawning grounds of both species provide foraging opportunities for large juvenile and adult PBF, though these overlaps may decrease towards the end of the century. A 2°C to 3°C increase in temperature is expected to occur throughout Japan by 2100 (Alam et al., 2007; Case and Tidwell, 2019; Tanaka et al., 2020). A 3°C increase in sea surface temperature found in East China Sea spawning grounds has shown to result in greater rates of PBF larval mortality in laboratory experiments (Kimura et al., 2010). Based on previous PBF response to sea surface temperature increases in the East China Sea, adult PBF may prefer the northern Sea of Japan and KOTZ spawning grounds as climate change impacts intensify. JA would benefit from this increase in sea surface temperature and likely increase in abundance as a result of successful recruitment.

### ***Boundary Currents***

Northern shifts in distribution are anticipated for both species, though the deterioration of boundary currents of the North Pacific Gyre may complicate upwelling processes and in turn alter the trophic chain of the KOTZ. The degradation of the Oyashio current as a result of sea ice decline in the Sea of Okhotsk will result in less transport of dissolved oxygen and nutrients from subarctic waters (Ohshima et al., 2009). These cold waters converge with the strengthening Kuroshio current within the KOTZ, introducing a source of warm water favorable for both PBF and JA. Declines in primary productivity may impact the trophodynamics of the region. Blooms of phytoplankton have historically provided food for zooplankton, which in turn feeds coastal pelagic species which are then foraged by apex predators like PBF. The disruption of dissolved oxygen and nutrient transport may decrease the amount of suitable habitat available to both species in terms of available oxygen and food (Yatsu et al., 2013).

### ***Phenology***

Timing of seasonal migrations is difficult to anticipate in a changing climate due to external factors such as changes in boundary currents, regime shifts in the PDO and ENSO, and warm water anomalies (Fasullo et al., 2018; Li et al., 2020; Muhling et al., 2017). Anchovies have complex population dynamics that rely on favorable conditions to flourish (Checkley et al., 2017). One effect of climate change is the increased difficulty of predicting regime shifts in the PDO. Uncertainty surrounds the timing of JA seasonal migrations and spawning, as the movement of this species are closely related to ongoing environmental conditions.

PBF have been shown to temporally respond to warm water events during their migration in the Eastern Pacific Ocean. PBF arriving in the CCLME during the marine heatwave of 2014 were shown to arrive earlier and in greater abundance (Runcie et al., 2019). The same response can be expected if warm water anomalies appear in the Western Pacific, though PBF will need access to cooler waters in order to maintain optimal internal body temperature. JA may favor warm water anomalies depending on intensity, as JA pursue temperatures between 11°C and 13°C (Jung et al., 2016).

### **Conclusion**

Anticipating changes in the distribution, abundance, and predator-prey relationships of major commercial fisheries within the Western Pacific will aid in the formation of conservation management strategies going forward. PBF, a climate-resilient species, may have to contend

with decreases in available food when shifting north despite its generalist diet. JA population booms and busts may become more pronounced as climate regime shifts intensify and alter previously productive environments. Anticipated northern shifts in distribution of both species will probably allow for the continuation of their predator-prey relationships. Predator-prey relationships of both species will influence how far they are able to expand from their native range and determine if they will be successful in evading mortality under climate change conditions.

## **Policy & Economic Implications**

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### **Introduction**

Under high emissions scenarios, climate change is forecasted to decrease global fisheries revenue by 35%, or \$10 billion USD per year, by 2050 (Lam et al., 2016). PBF alone supports a \$800 million USD international fishery (McKinney et al., 2020). Addressing shifts in fisheries productivity and range via policy and adaptive management measures has the potential to mitigate the effects of climate change on key fisheries (Barange et al., 2018; Gaines et al., 2018). Currently, climate change plays little to no part in international fisheries management of PBF and JA. The recent development of conservation measures by the IATTC, WCPFC, and FAJ are intended to address the high fishing pressure placed on juveniles of both species but fail to account for the effect shifting distributions will have on international relations and fishing pressure. Addressing potential sources of conflict and additional fishing mortality by establishing jurisdiction of overlapping treaties and maintaining open communication channels to aid in the creation of bi- and multilateral agreements could help abate strains on international relations and maintain the sustainability and profitability of the fisheries.

### **Current Conservation Measures**

#### ***IATTC & WCPFC***

IATTC and WCPFC, the two regional fisheries management organizations (RFMOs) responsible for managing PBF, use stock assessments provided by ISC and recommendations made by their respective Scientific Advisory Committees (SAC) to determine appropriate management measures. As an immensely valuable species both economically and culturally, PBF are pursued throughout the entirety of its range. Fishing in the Western Pacific accounts for 84% of fishing pressure of PBF, whereas fishing in the Eastern Pacific accounts for the remaining 16% of fishing pressure (IATTC, 2016). Overfishing of young age classes led to declines in SSB from 1996 to 2010 and prompted discussions of conservation measures throughout both RFMOs (IATTC, 2016). The WCPFC established the first commercial catch limit in 2009, followed by IATTC in 2012 (IATTC, 2012; WCPFC, 2009). Rebuilding targets were implemented by both RFMOs, requiring monitoring, reporting, and adjusting TAC if the probability of meeting a target falls below 60% (IATTC, 2018).

#### ***FAJ***

The Fishery Agency of Japan oversees stock management of JA within Japan's EEZ. As the most abundant fish in the Yellow Sea, JA experiences high fishing pressure during periods of rapid population growth (Wang et al., 2006). The population boom of the early 1990s led to increased fishing pressure and subsequent declines in biomass (Liu et al., 2020; Wang et al., 2020). Acoustic surveys and stock assessments suggest that the JA stock is overfished, though

this may be complicated by the rapid population fluctuations of anchovy (Wang et al., 2020). In 2001, a TAC of 10,000 tons was recommended and a quota system was implemented (Xian-Shi et al., 2001). Additional management measures for JA include gear controls, limited 5-year licenses, and seasonal closures for larval and juvenile anchovy (Garcia et al., 2018; Wang et al., 2006).

## **Climate Change & Fisheries Governance**

### ***Fisheries Management***

PBF and JA both have complex life histories and pose unique challenges in fisheries management. PBF are highly migratory, occupying an entire ocean and supporting fisheries in several nations. JA favor coastal areas but are highly variable in their population dynamics and occur throughout the waters of several Western Pacific countries. Both stocks have been subject to high fishing pressure for decades, leaving them vulnerable to slight changes in climate, catch, and recruitment (ISC, 2020; Wang et al., 2020). Despite their differences in size, behavior, age, and ecological niches, management of both species share similar controls and require international coordination.

Even with mitigation efforts, the effects of climate change will not be felt evenly amongst the countries of the world. In the case of PBF and JA, a northward shift in distribution could lead to higher fisher effort per unit catch for countries who have historically accounted for the greatest amount of catch (ISC, 2020). Northern shifts in distribution have been detected in both the Southern and Atlantic bluefin tunas (*Thunnus maccoyii* and *Thunnus thynnus*, respectively) as well as other tropical tuna species (Erauskin-Extramiana et al., 2019). Each bluefin species is anticipated to move out of historic distribution ranges, including waters that lie within the exclusive economic zones (EEZs) of countries with major bluefin fisheries (Erauskin-Extramiana et al., 2019). Previous solutions to mismatching distributions and management of marine fisheries point to bi- and multilateral negotiations between affected nations.

### ***Bi- and Multilateral Negotiations***

Successful management of highly migratory stocks depends on the cooperation and communication of many countries representing differing incentives. Tuna RFMOs and member countries may communicate with each other to establish side agreements and payments, or to bring accusations of misconduct to light. Bi- and multilateral negotiations between countries seeking to maximize their economic gains may become increasingly complex as historic fishing grounds no longer yield adequate catch. Further, the entry of free riders and uncertainty of stock rebuilding have led to landmark legal cases in the past, which may become more common as access to the stocks of PBF and JA increase in the North Pacific.

Fisheries stocks that cross international borders are found throughout the world, one of the most prolific being salmon of the Pacific Northwest. Shifts in stocks of salmon have been documented as the PDO and ENSO influence sea surface temperatures and productivity throughout coastal regions (Miller, 2002). In the case of Canada and the United States, northward shifts of salmon led to increased fishing pressure and stock declines in the 1990's (Miller, 2002). Eventually, the incentives of both countries aligned as Pacific Northwest salmon stocks dwindled and conservation actions were deemed necessary (Miller, 2002). The bilateral agreement between the

United States and Canada could serve as a roadmap to navigating the shift of international stocks, such as PBF and JA, into historically sparse fishing grounds.

Canada and the United States first formed a bilateral treaty in the 1930's to address the catch of Fraser River salmon that straddled the waters of British Columbia and Washington State (Miller, 2002). Historically, Fraser River salmon are caught within the Strait of Juan de Fuca where it is accessible to both Canadian and American fleets. Renegotiation of the original treaty to allow for a greater proportion of Canadian catch was underway in the 1980's, when changing ocean conditions due to ENSO led to salmon stocks shifting northward into Canadian and Alaskan waters (Miller, 2002). Alaskan and Canadian salmon catch sharply increased throughout the 1990's whereas catch in Washington, Oregon, and California dropped to historic lows. By 1999, the National Marine Fisheries Service (NMFS) listed multiple salmon stocks as "threatened" under the Endangered Species Act (NOAA, 2000).

Unfavorable oceanic conditions and anthropogenic impacts to Pacific Northwest salmon continued to suppress population growth to the point where neither Canada nor the United States could support historic harvest rates. A shift from an emphasis on fishing incentives to conservation incentives allowed for a decades-long battle to conclude with the establishment of the 1999 Pacific Salmon Agreement (Miller, 2001). The revised agreement focuses less on the division of catch and more on flexible, abundance-based harvesting limits that aim to rebuild salmon stocks throughout international and state waters (Miller, 2002).

Bi- and multilateral agreements between similarly incentivized member countries of the IATTC and WCFPC could support current conservation efforts for PBF as distribution shifts north and abundance changes in response to recruitment. Side payments, an additional form of bi- and multilateral agreements, can incentivize conservation of a species while improving economic welfare (Squires et al., 2014). Side payments are provided by a country to incentivize another country, often one sharing a marine boundary, to limit fishing activities (Reppas, 2018). Depending on regulations put in place by international management bodies, these payments can ensure that more TAC is available to the country offering the side payment. In the case of Atlantic bluefin, an economic study revealed that Canadian side payments made to the United States could increase Canadian welfare by \$5 to \$10 or \$9.7 to \$16.3 million USD, depending on the economic model (Reppas, 2018). International agreements in the form of side payments could alleviate the economic effects of shifting fisheries distribution. Countries with the most historical catch could accept side payments from countries with novel fishing grounds, in exchange for a greater share of available TAC. However, side payments may also incentivize overfishing if an effective TAC is not established (Squires et al., 2014).

### ***Jurisdiction of Treaties***

In order to address overfishing as a result of mismanagement or countries exceeding quota, the implementation of temporary protective measures and subsequent penalties is key. Timeliness of protective measures can help aid stock rebuilding efforts in heavily overfished species. Determining which treaties apply to certain cases of international conflict can help speed the process of resolution and minimize ecological damage. The 1999 case of the southern bluefin tuna has major implications for establishing jurisdiction of international tuna fishing disputes, as well as determining the timing and efficiency of conservation measures (Sturtz, 2001).



Similar to PBF, southern bluefin tuna stocks have been subject to overfishing throughout the past century. Previous bi- and multilateral negotiations between Australia, New Zealand, and Japan fell apart in 1999 due to Japan unilaterally pursuing higher TAC in response to recent rebuilding measures (Sturtz, 2001). The establishment of Japan's experimental fishing program for southern bluefin tuna prompted Australia and New Zealand to sue Japan for violating the Convention of the Conservation of Southern Bluefin Tuna (CCSBT) and the United Nations Convention for the Law of the Sea (UNCLOS). At first, the International Tribunal for the Law of the Sea (ITLOS) ruled in favor of Australia and New Zealand and issued protective measures. This preliminary decision was later struck down by an arbitral tribunal, which found that the jurisdiction of the case fell under the CCSBT rather than UNCLOS. The deference of UNCLOS to the CCSBT treaty severely limits the power of the ITLOS to quickly and efficiently address cases of harm to marine environments and resources (Sturtz, 2001).

As PBF and JA stocks shift in abundance and distribution, determining jurisdiction of overlapping treaties, incentivizing swift responses to overfishing, and maintaining communication channels between countries can help lead to favorable bi- and multilateral negotiations that put conservation efforts at the forefront. Free riding may still present a complication in conservation of highly migratory stocks, particularly as stocks shift into non-member countries' waters. For example, Japan has the largest PBF fishery in the world and is an active member of the IATTC and WCPFC (NOAA, 2017). As PBF distributes north, there is potential for the fishery to expand into previously subarctic waters in Russia's EEZ (Kaschner et al., 2019a). Though Article 64 of the UNCLOS rules that non-members of tuna RFMOs, such as Russia, have an obligation to cooperate with existing management regulations, introducing an extremely valuable fishery in competition with Japan may lead to international tension if a bi- or multilateral agreement is not reached (United Nations, 1982). Given the international nature of both species, transboundary agreements and well-monitored catch limits will become vital to effective management regimes under climate change.

### ***Seafood Supply Chains***

As climate change impacts alter oceanic conditions and influence the redistribution of fisheries species, seafood supply chains may adapt or falter depending on the redistribution of fishing fleets (Barange et al., 2018). Poleward movement of commercially valuable species such as PBF may cause the cost per fishing trip to increase beyond the monetary benefit of catch. Fuel, personnel, and maintenance costs would increase and become less accessible to transshipment routes as PBF travel further from the coastal areas of Japan, the United States, and other countries (FAO, 2018). The movement of fishing grounds could leave historic fishing fleets operating with overcapacity and becoming a source of stranded capital (Barange et al., 2018). This could lead to further overfishing as fleets pursue declining stock to minimize the effects of overcapacity. Another option available to fleets is operating under a flag of convenience by changing the country under which a vessel is registered. This allows a vessel to avoid countries with stricter domestic and international regulations in favor of those that have little to no obligations (DeSombre, 2006). Despite recent increases in spawning stock biomass, the PBF remains overfished and subject to overfishing, leaving the stock particularly vulnerable to shifts in fishing pressure as a result of changing distribution of fleets (ISC, 2020).

Further ramifications of climate change may include the closure of capture-based aquaculture operations (Normile, 2009). Sea level rise, increased runoff, and rising sea temperatures have the potential to negatively impact water quality and increase outside of PBF thermal tolerances (Fujioka et al., 2018b). Demand for sashimi products, including PBF, continues to grow and inspire innovation in aquaculture operations (McKinney et al., 2020; Normile, 2009). Climate change may necessitate the movement of aquaculture operations and transshipment routes north, in order to account for rising sea temperatures and longer travel time to viable fishing grounds. Competition for PBF landings may increase as countries such as Russia are able to access PBF, depending on movement into the Sea of Okhotsk. Overall, projected distributions of PBF indicate a poleward shift that may hinder accessibility to PBF stocks in new, northern latitudes, limiting global availability of a valuable natural resource.

## **Concluding Remarks**

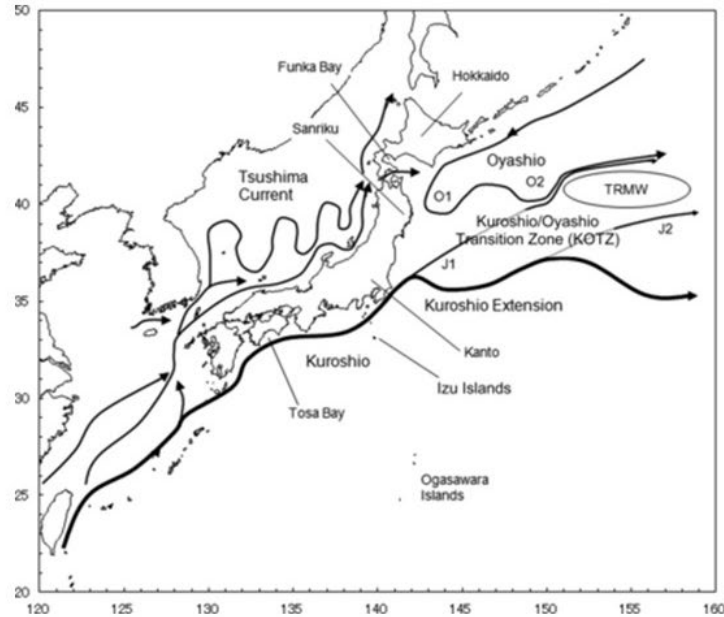
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Diving deep into the projected impacts of climate change on the distribution and abundance of PBF and JA reveals a network of complex relationships between species and their environment. Suitable thermal habitat projections capture the basic trend; species, marine and terrestrial, are anticipated to shift north (Erauskin-Extramiana et al., 2019; Osland et al., 2021). Beneath the surface, environmental factors such as deoxygenation, current velocity, thermohaline circulation, and freshwater inputs highlight the nuances of how species with different biology and adaptations will respond to climate change. The resilience of each species to climate change was determined using a decision tree to further investigate the trends shown by suitable thermal habitats. The endothermy, longevity, and highly migratory nature of PBF makes this species more climate resilient than the JA, a short-lived, coastal poikilotherm. Further research on the movement of adult stages of PBF and forage species in response to climatic variability is needed to improve our understanding of what environmental factors are most responsible for driving species poleward.

The effects of climate change extend beyond the biology and into the international relations, seafood trade, and livelihoods of those who rely on fisheries. Shifting distributions and abundances of marine fisheries, particularly those of high value like the PBF, could ignite conflicts between countries and result in unregulated, unreported fishing, increasing the risk of overfishing. Maintaining clear paths for conflict resolution and bi- and multilateral negotiations will aid in the conservation and survival of each fishery. Ensuring speedy responses to changes in stock status via TAC controls, fishing seasons, and moratoriums can help minimize damage to struggling populations and protect strong year classes. Chasing catch into novel fishing grounds may become a reality as climate change alters the world around us. With proper foresight and actions, international policies, treaties, and conservation measures can rebuild overfished stocks while improving the resilience of global fisheries to climate change.

## Appendix A: Figures

**Figure 1:** Kuroshio-Oyashio Boundary Currents of the North Pacific Gyre



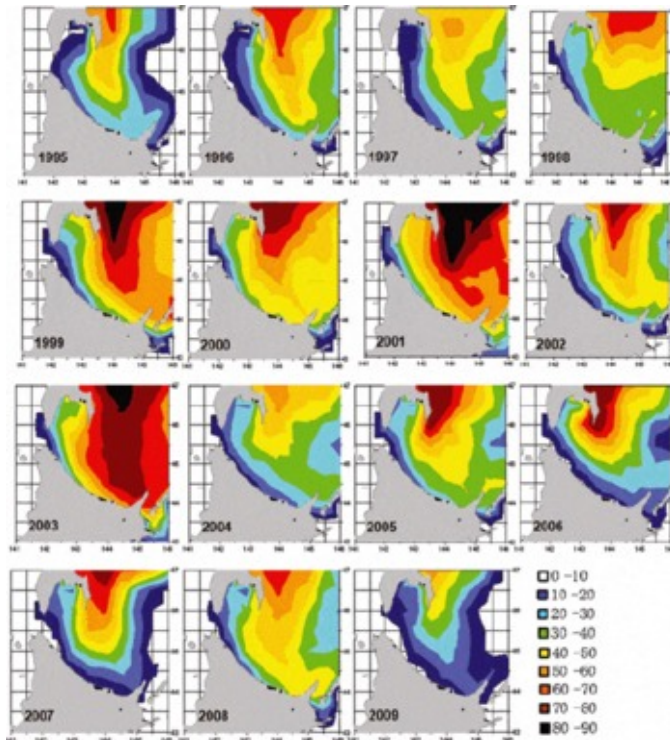
*ICES J Mar Sci*, Volume 70, Issue 5, September 2013, Pages 922–933, <https://doi.org/10.1093/icesims/fst084>

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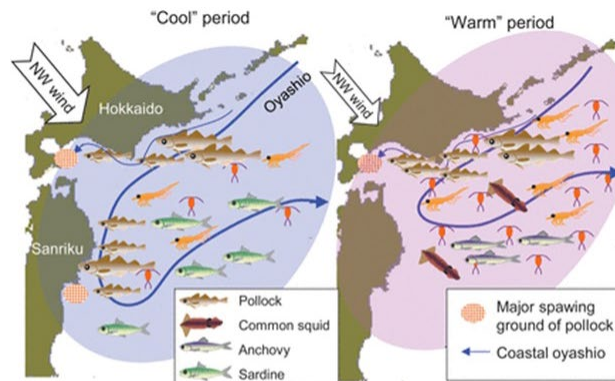
The Kuroshio and Oyashio currents make up the western boundary of the North Pacific Gyre and converge at the Kuroshio-Oyashio Transition Zone (KOTZ) (figure from Yatsu et al., 2013).

**Figure 2:** Decline of sea-ice extent off the coast of Hokkaido



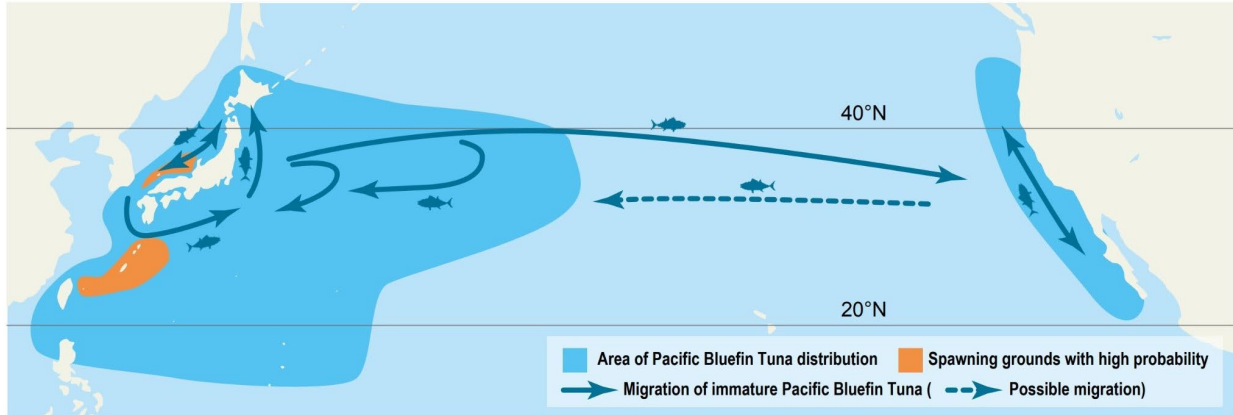
Distribution of sea-ice duration at the coast of Hokkaido (43–47° N, 141–146° E) from 1995 to 2009. Legend shows duration periods in number of days (figure from Takahashi et al., 2011).

**Figure 3:** Ecosystem effects of climatic regime shifts in the KOTZ



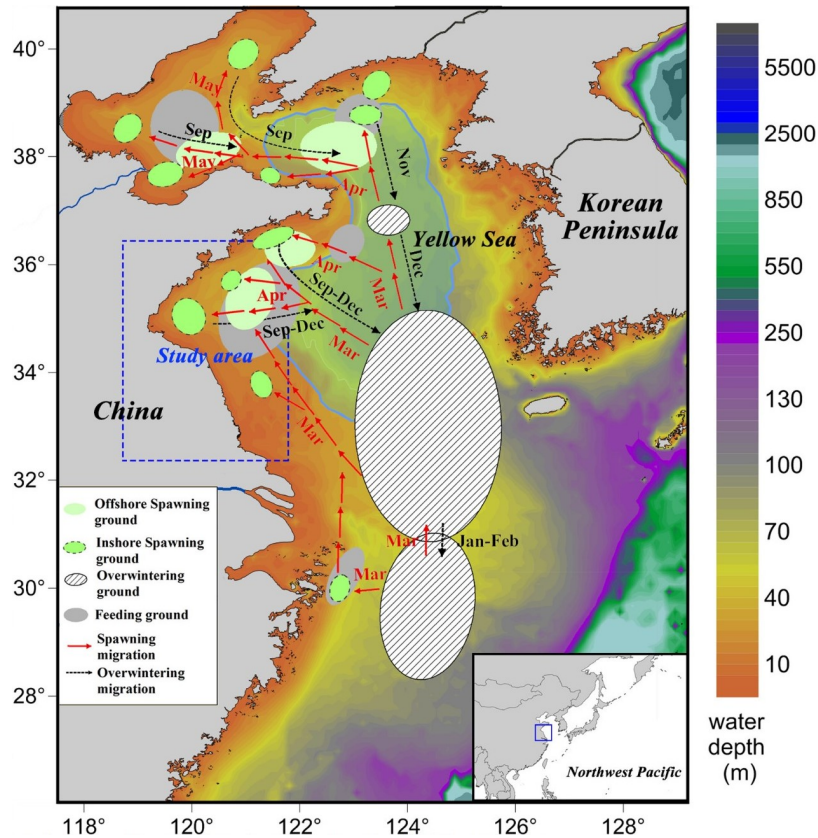
Conceptual model of the Oyashio current during cool and warm periods, showing population variations in coastal pelagic species and primary/secondary producers (figure from Yatsu et al., 2013).

**Figure 4:** Migration of Pacific bluefin tuna (*Thunnus orientalis*)



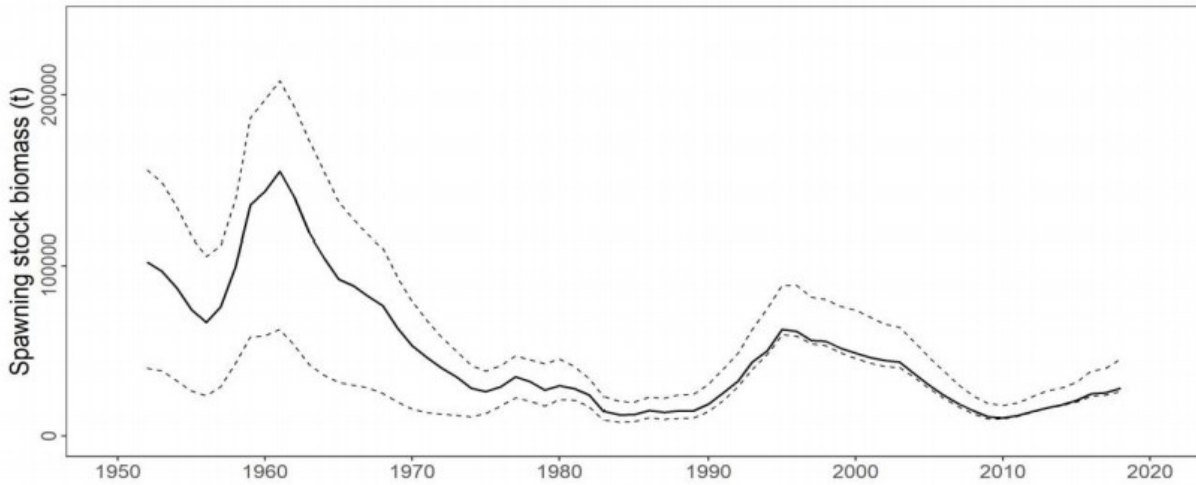
Pacific bluefin migration patterns across the Western, Central, and Eastern Pacific Ocean (figure from Uematsu, 2014).

**Figure 5:** Migration, Spawning, and Overwintering behaviors of Japanese anchovy (*Engraulis japonicus*) in Yellow and East China Sea



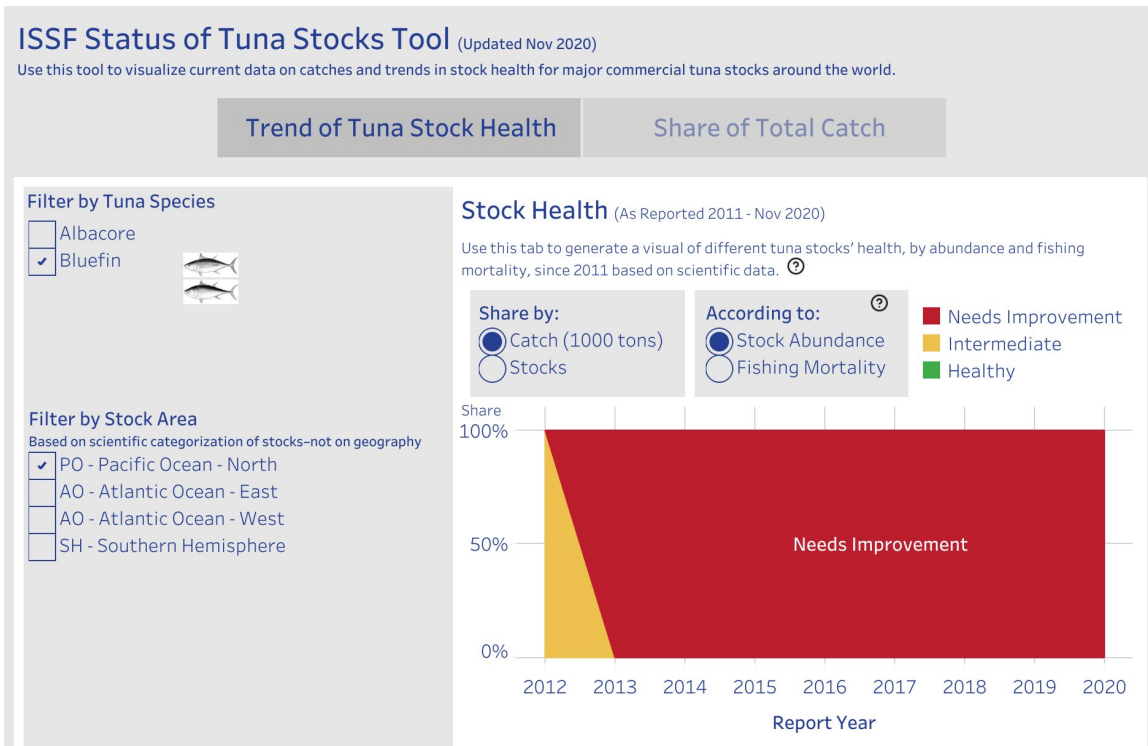
JA undergo a poleward migration within the Yellow and East China Sea (figure from Zhang et al., 2020).

**Figure 6. Pacific bluefin tuna Spawning Stock Biomass**



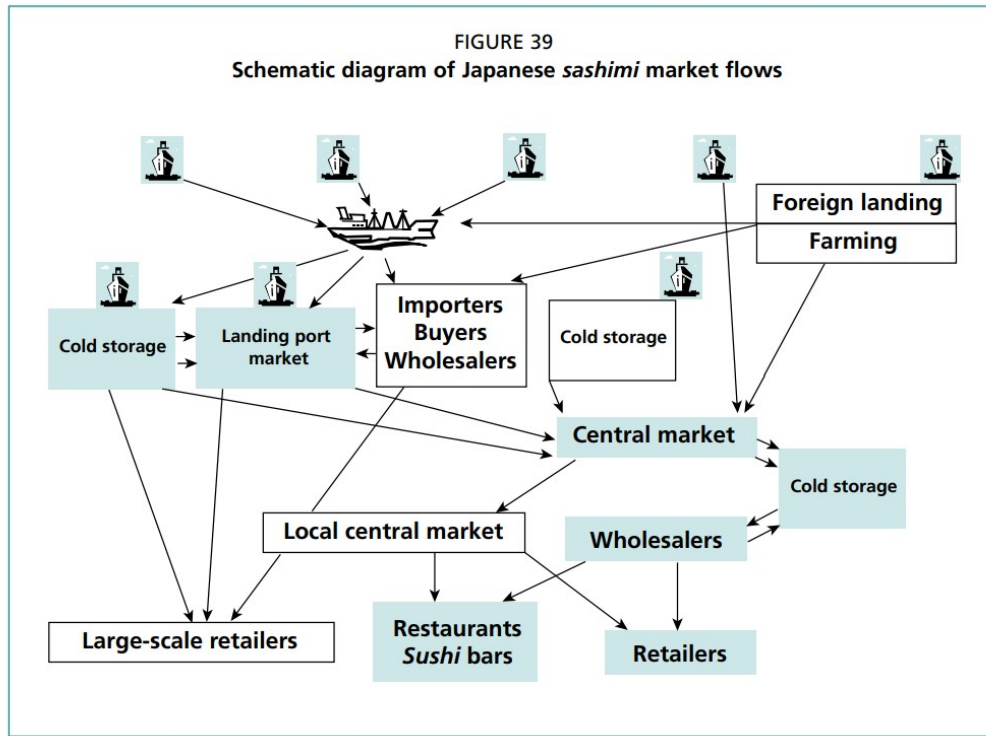
The PBF spawning stock biomass reached an all-time low of 1.7% in 2010. This percentage has since increased to 4.5% in 2018 (figure from ISC, 2020).

**Figure 7. ISSF Stock Status: Pacific bluefin tuna**



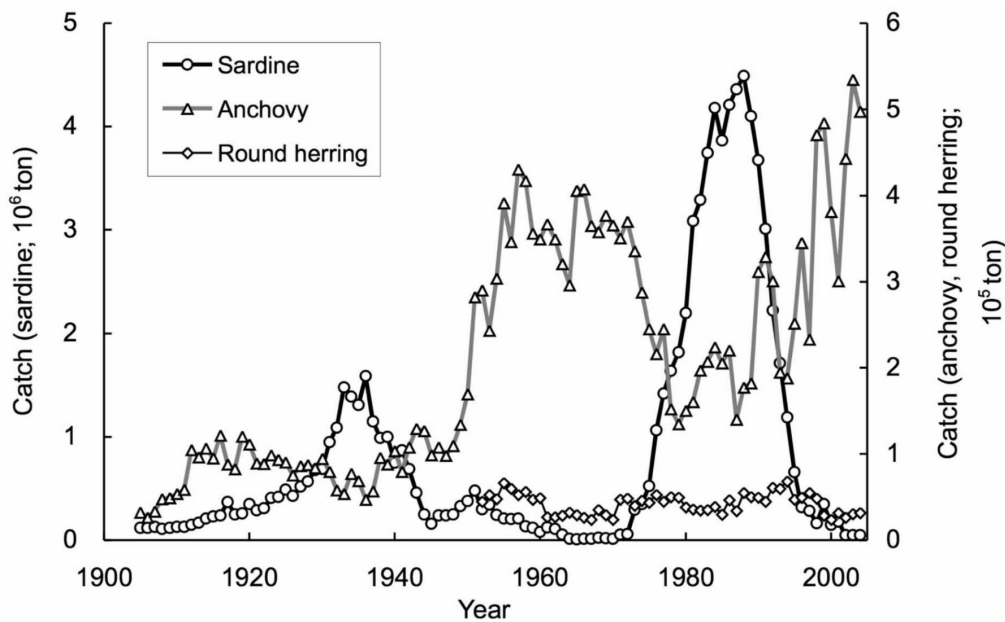
The International Seafood Sustainability Foundation has listed the PBF as “Needs Improvement” since 2013 (figure from ISSF, 2021).

**Figure 8:** Japanese Tuna - Sashimi Supply Chain



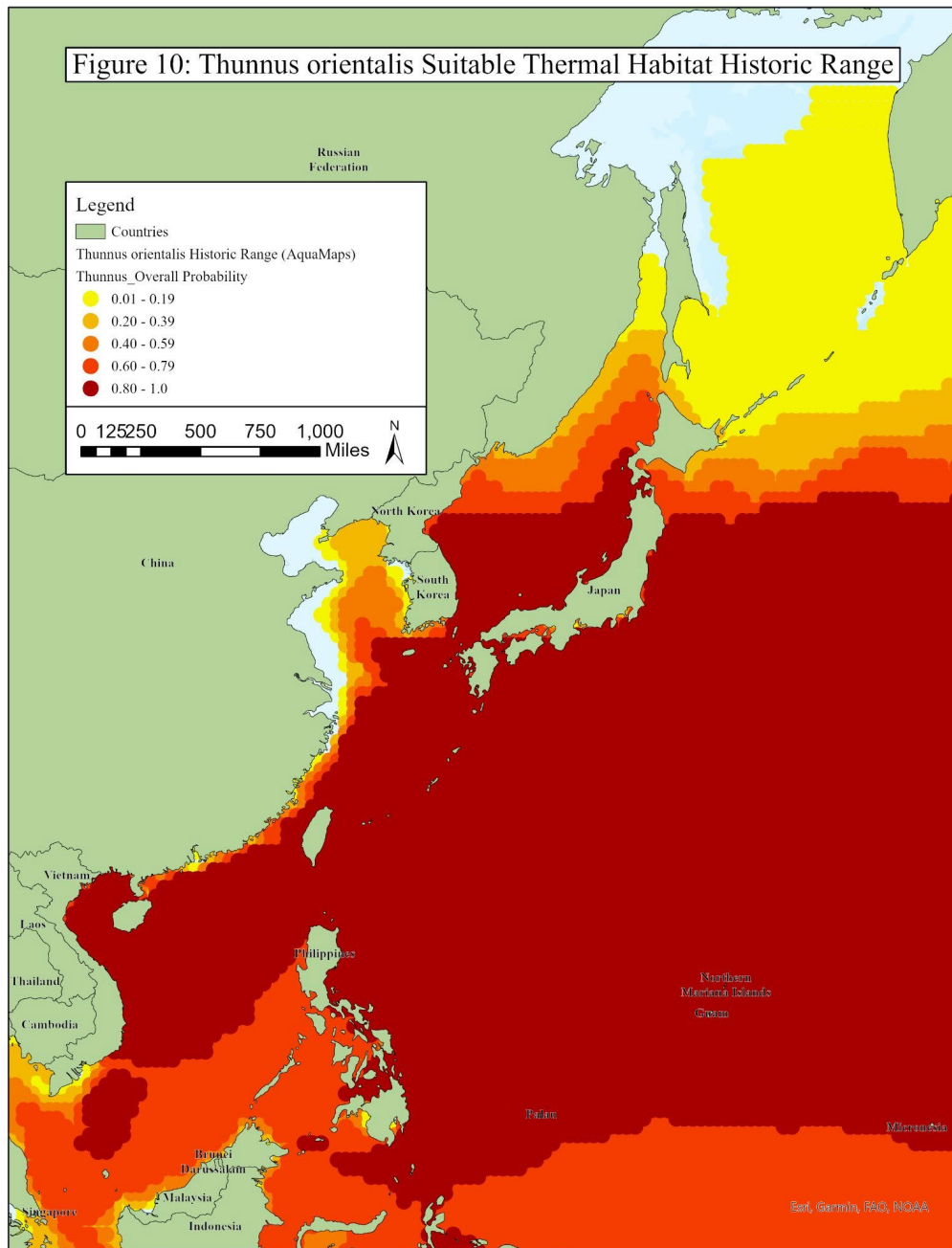
The journey a PBF catch may take until consumed as sashimi (figure from Miyake, 2010).

**Figure 9:** Japanese anchovy catch in comparison to round herring and Japanese sardine



JA catch follows an inverse trend to sardine catch based on climatic variability (figure from Oozeki et al., 2007).

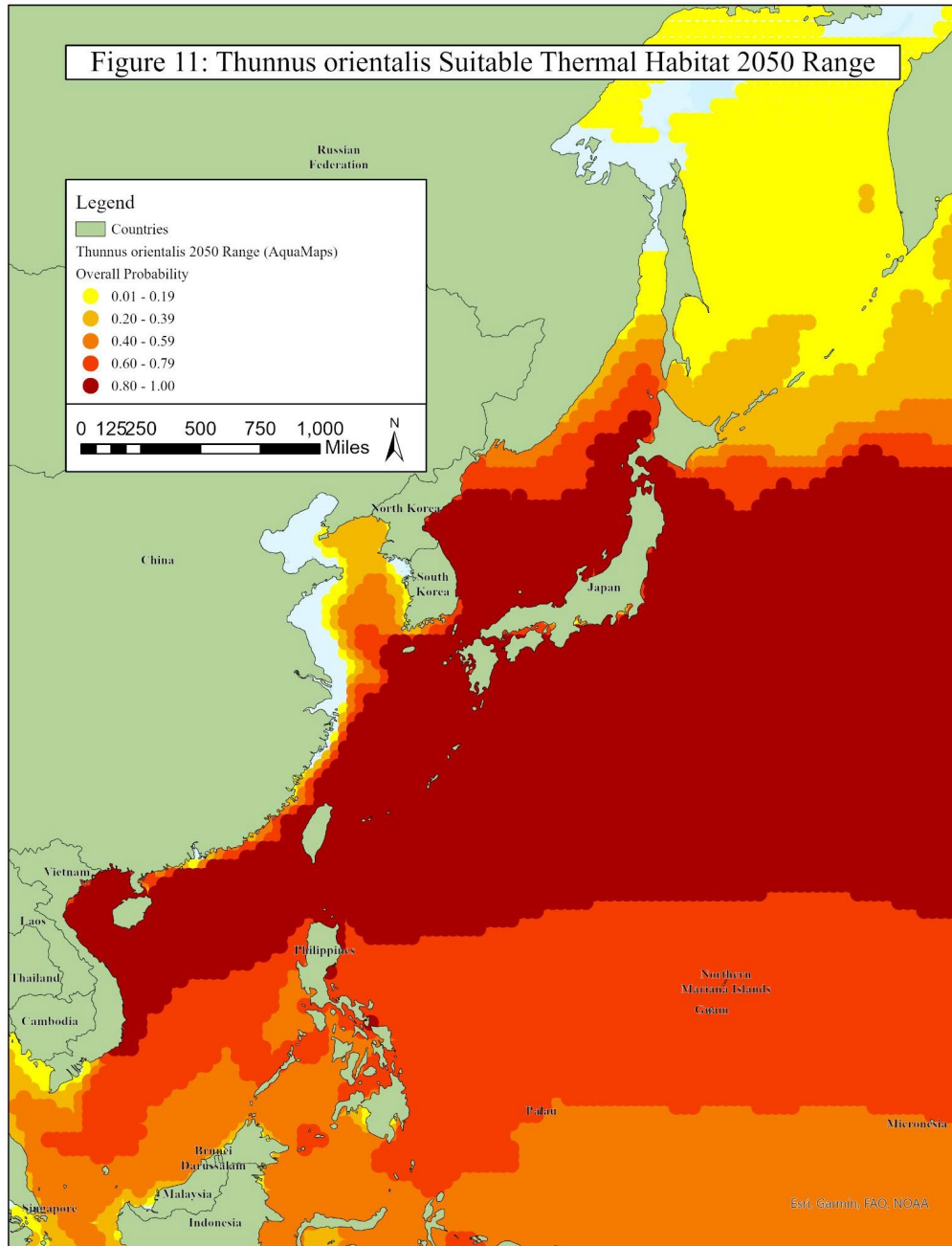
**Figure 10:** Historic Suitable Thermal Habitat of Pacific bluefin tuna



A Western Pacific view of historic suitable thermal habitat distribution of *Thunnus orientalis* (PBF) downloaded from AquaMaps (Kaschner et al., 2019a). Made by Tyler Loughran.

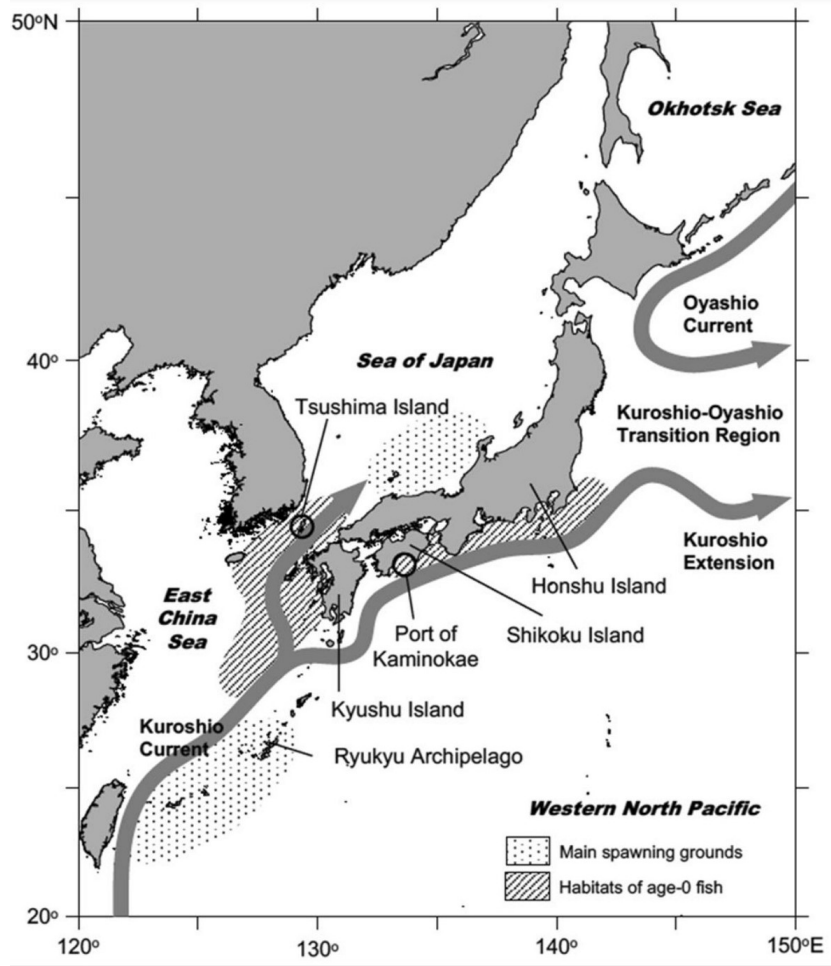


**Figure 11:** 2050 Projected Suitable Thermal Habitat of Pacific bluefin tuna



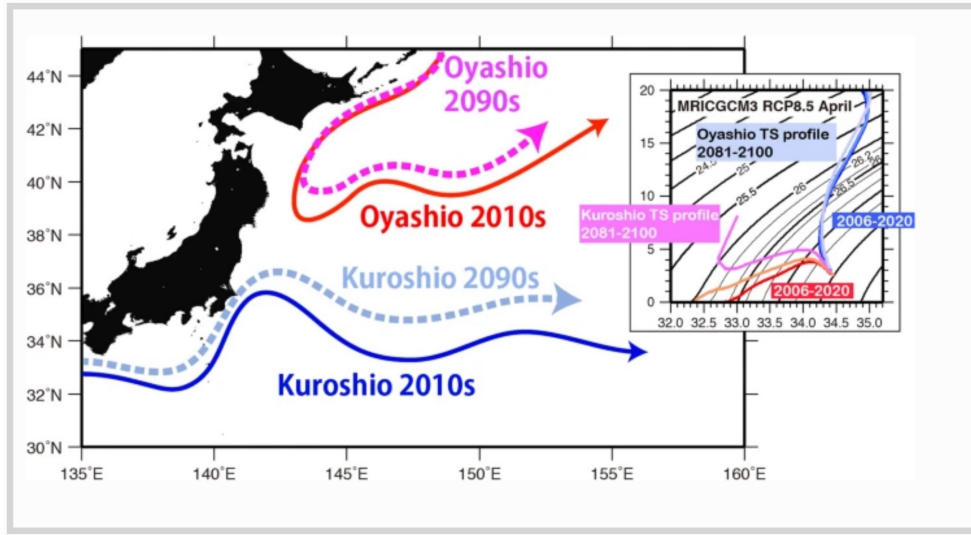
A Western Pacific view of 2050 suitable thermal habitat distribution of *Thunnus orientalis* (PBF) downloaded from Aquamaps. A northern shift in distribution is apparent in subarctic waters (Kaschner et al., 2019a). Made by Tyler Loughran.

**Figure 12:** Pacific bluefin tuna Spawning Grounds



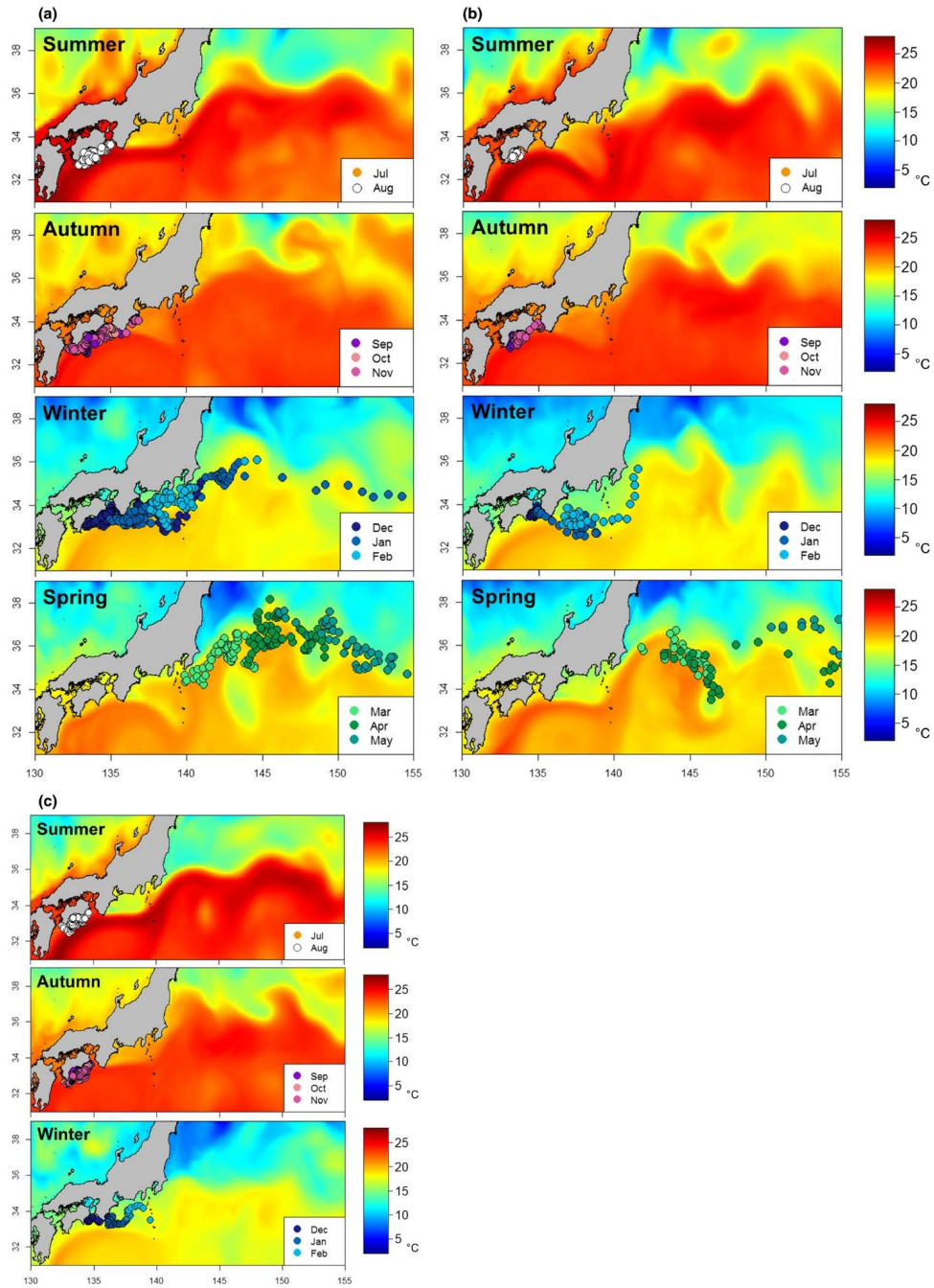
The major spawning grounds of PBF located in the East China Sea and Sea of Japan. A third unconfirmed spawning ground is located within the Kuroshio-Oyashio Transition Region (figure from Malik et al., 2020).

**Figure 13:** Kuroshio and Oyashio Currents 2090 Projection



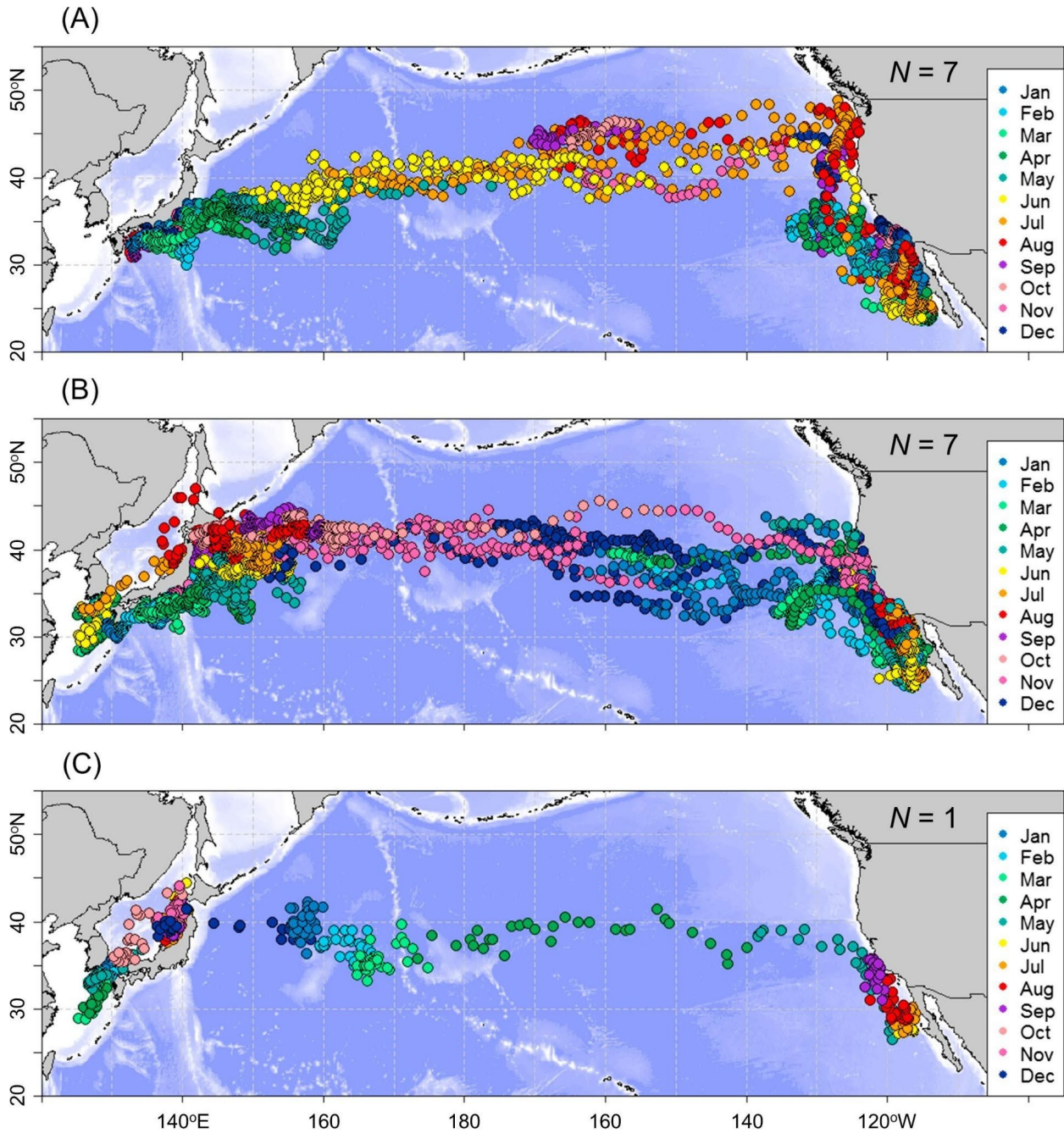
A northern shift in the subtropical Kuroshio and subarctic Oyashio currents is anticipated by 2090 (figure from Nishikawa et al., 2020).

**Figure 14:** Western Pacific Pacific bluefin tuna Migration



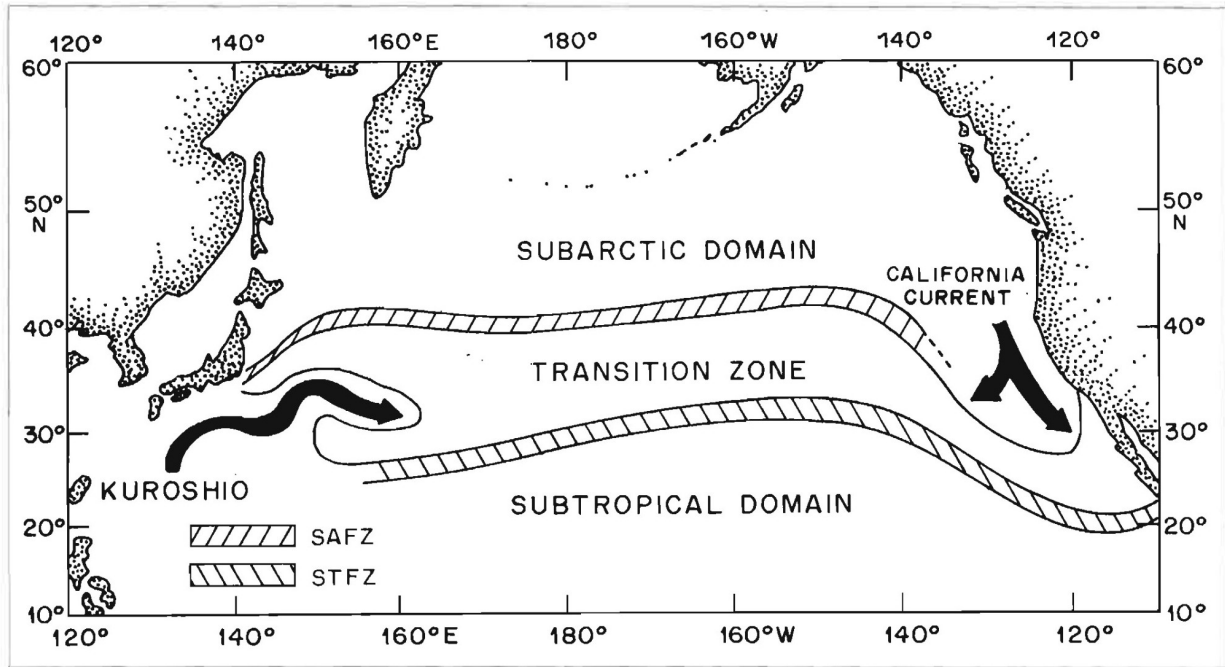
Juvenile PBF migration poleward on the western and eastern shores of Japan (figure from Fujioka et al., 2018a).

**Figure 15: Transoceanic PBF Migration**



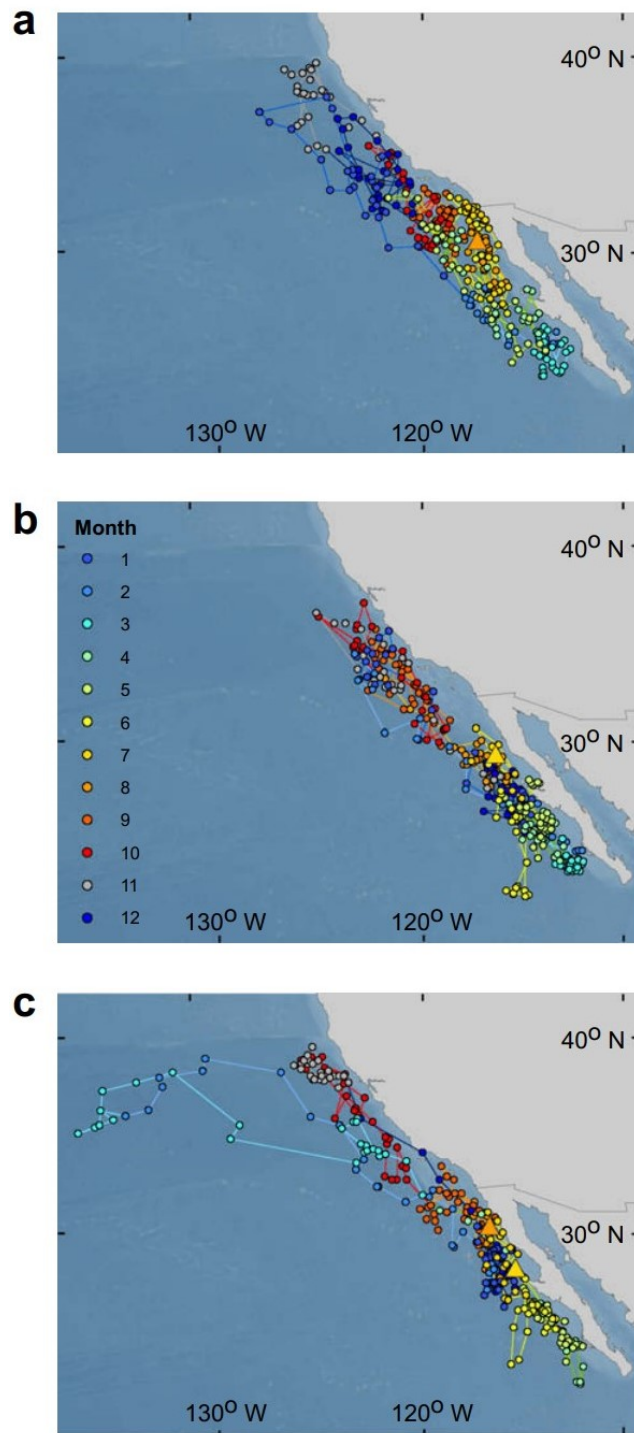
After remaining in the Western Pacific for a year, a subset of juvenile PBF undergo a transoceanic migration across the Pacific Ocean (figure from Fujioka et al., 2018b).

**Figure 16:** Subarctic Frontal Zone



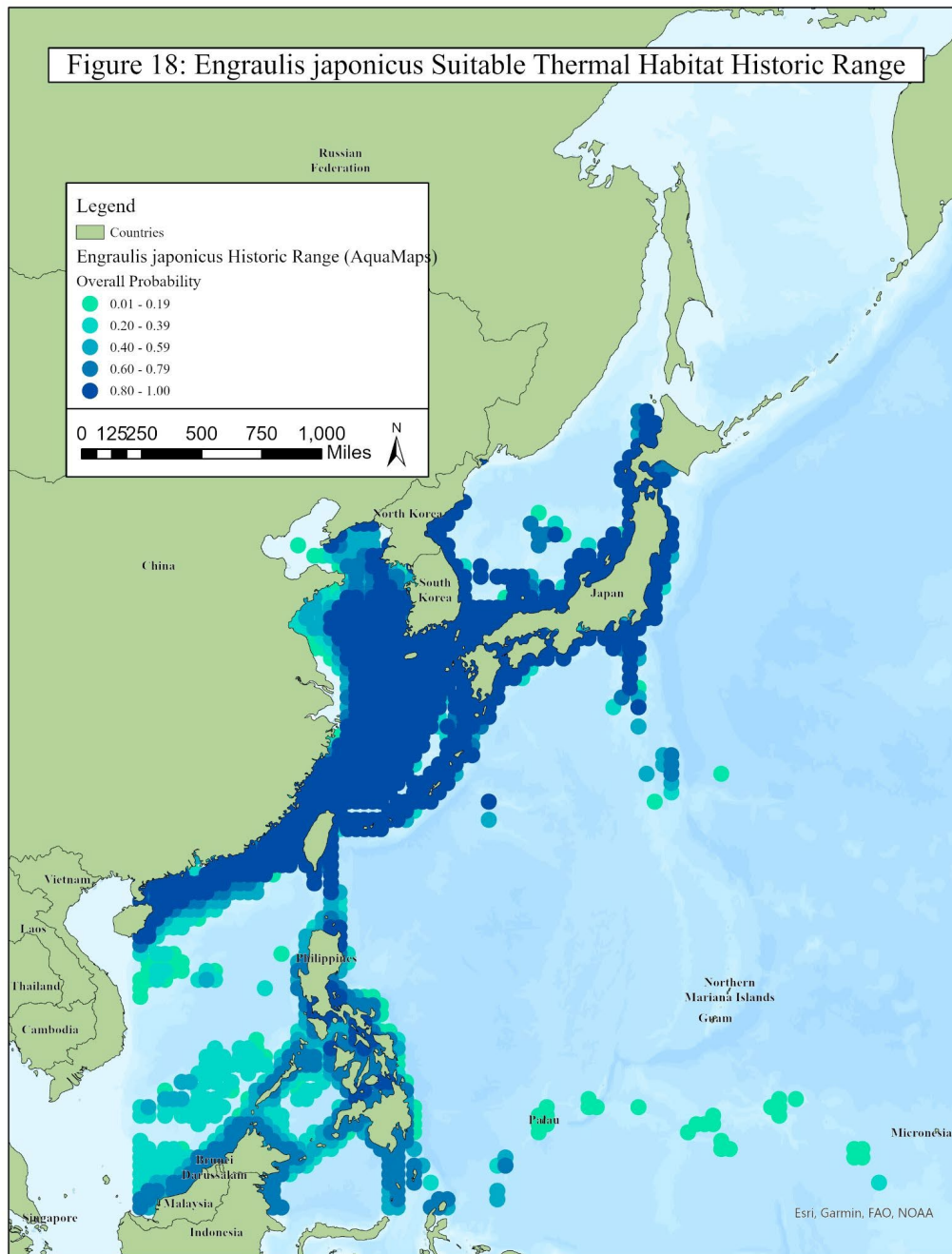
Juvenile PBF migrate eastward following the Subarctic Frontal Zone (SAFZ) (figures from Roden, 1991).

**Figure 17:** California Current Large Marine Ecosystem Pacific bluefin tuna Migration



Juvenile and adult PBF undergo a poleward migration once reaching the CCLME (figure from Boustany et al., 2010).

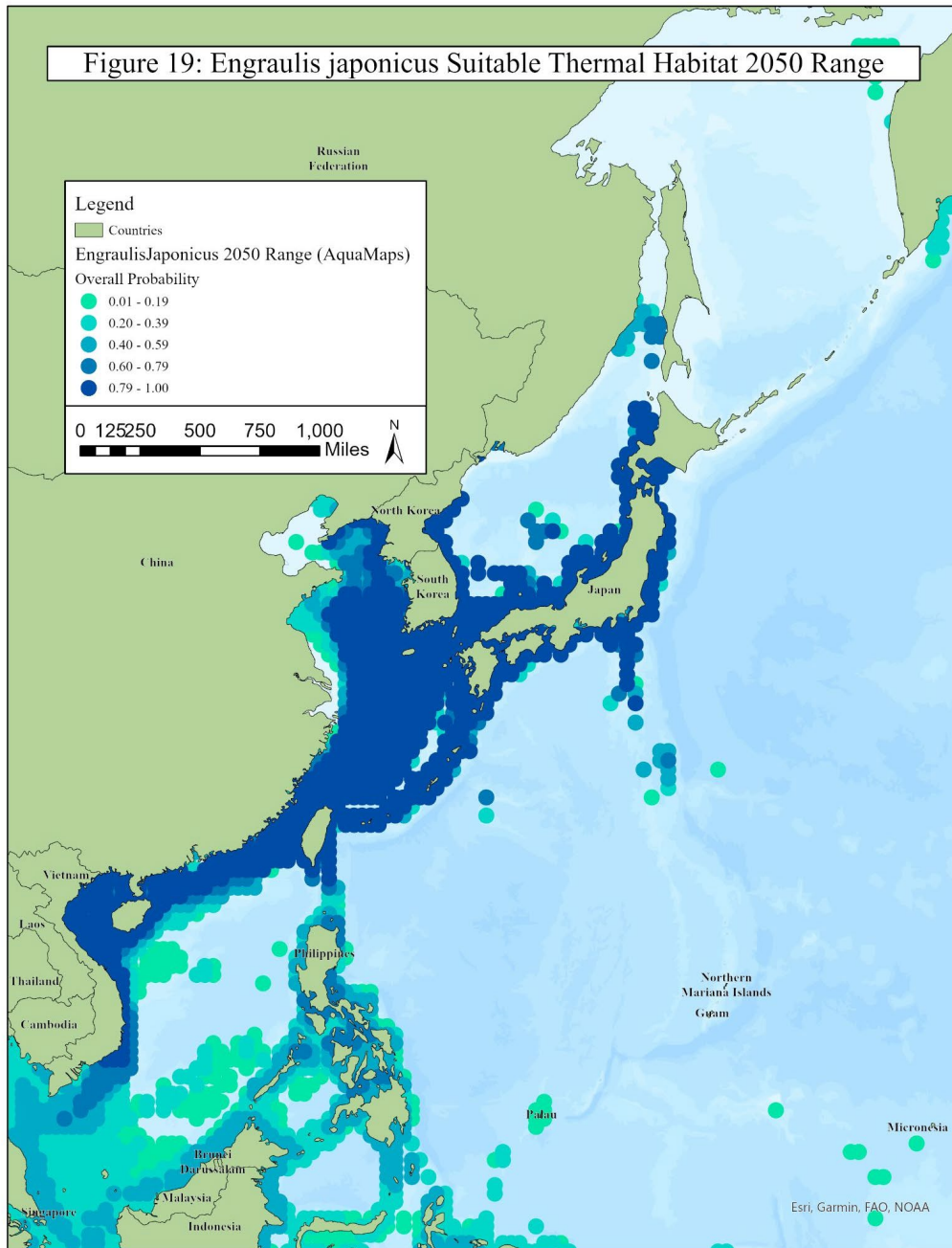
**Figure 18:** Historic Suitable Thermal Habitat of Japanese anchovy



A Western Pacific view of historic suitable thermal habitat distribution of *Engraulis japonicus* (JA) downloaded from AquaMaps (Kaschner et al., 2019b). Made by Tyler Loughran.

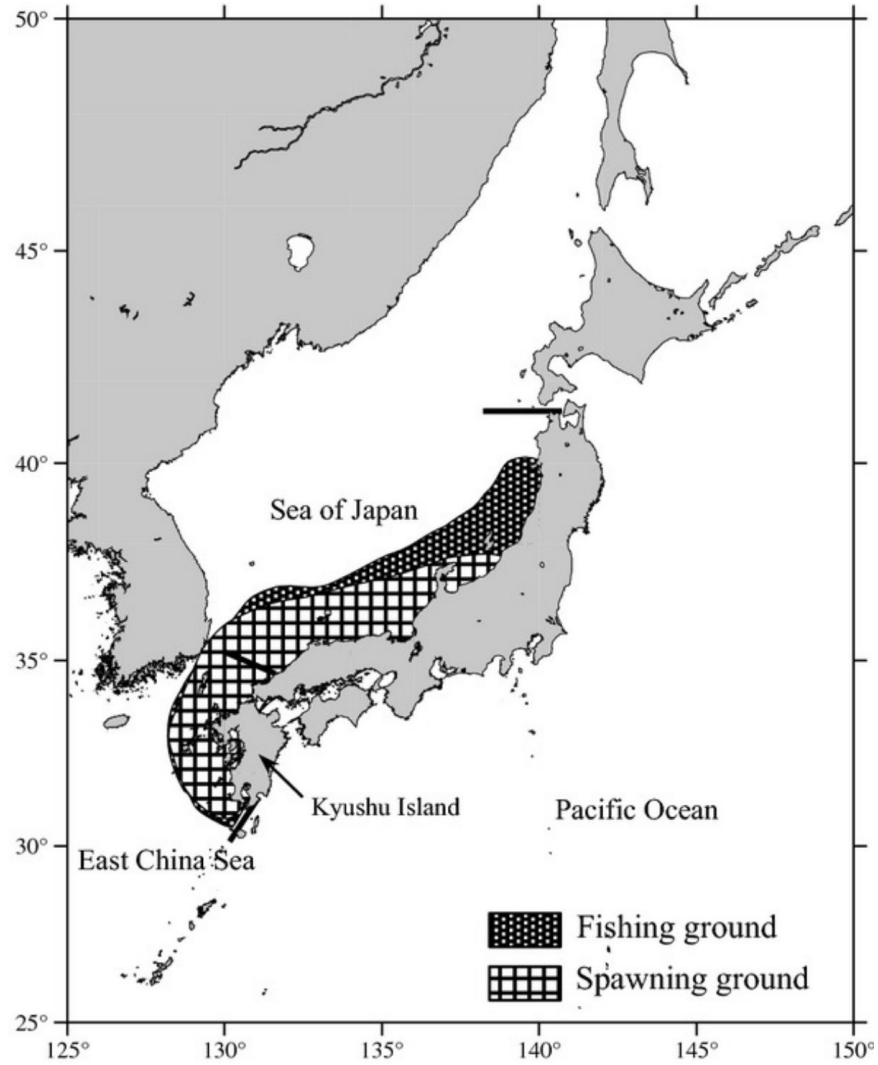


**Figure 19:** 2050 Projected Suitable Thermal Habitat of JA



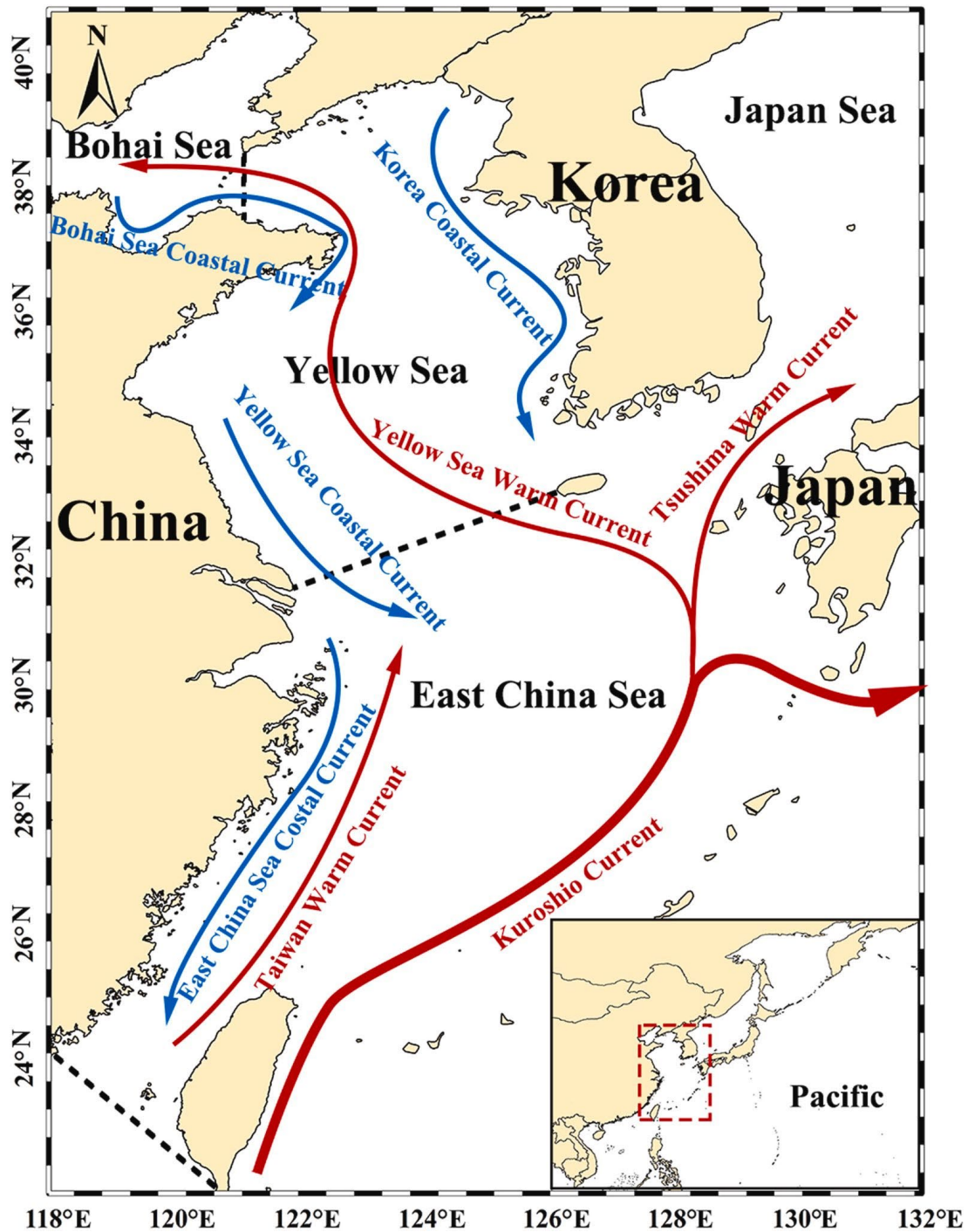
A Western Pacific view of 2050 suitable thermal habitat distribution of *Engraulis japonicus* (JA) downloaded from Aquamaps. A northern shift in distribution is apparent in subarctic waters (Kaschner et al., 2019b). Made by Tyler Loughran.

**Figure 20:** Spawning Grounds of Japanese anchovy throughout Japan



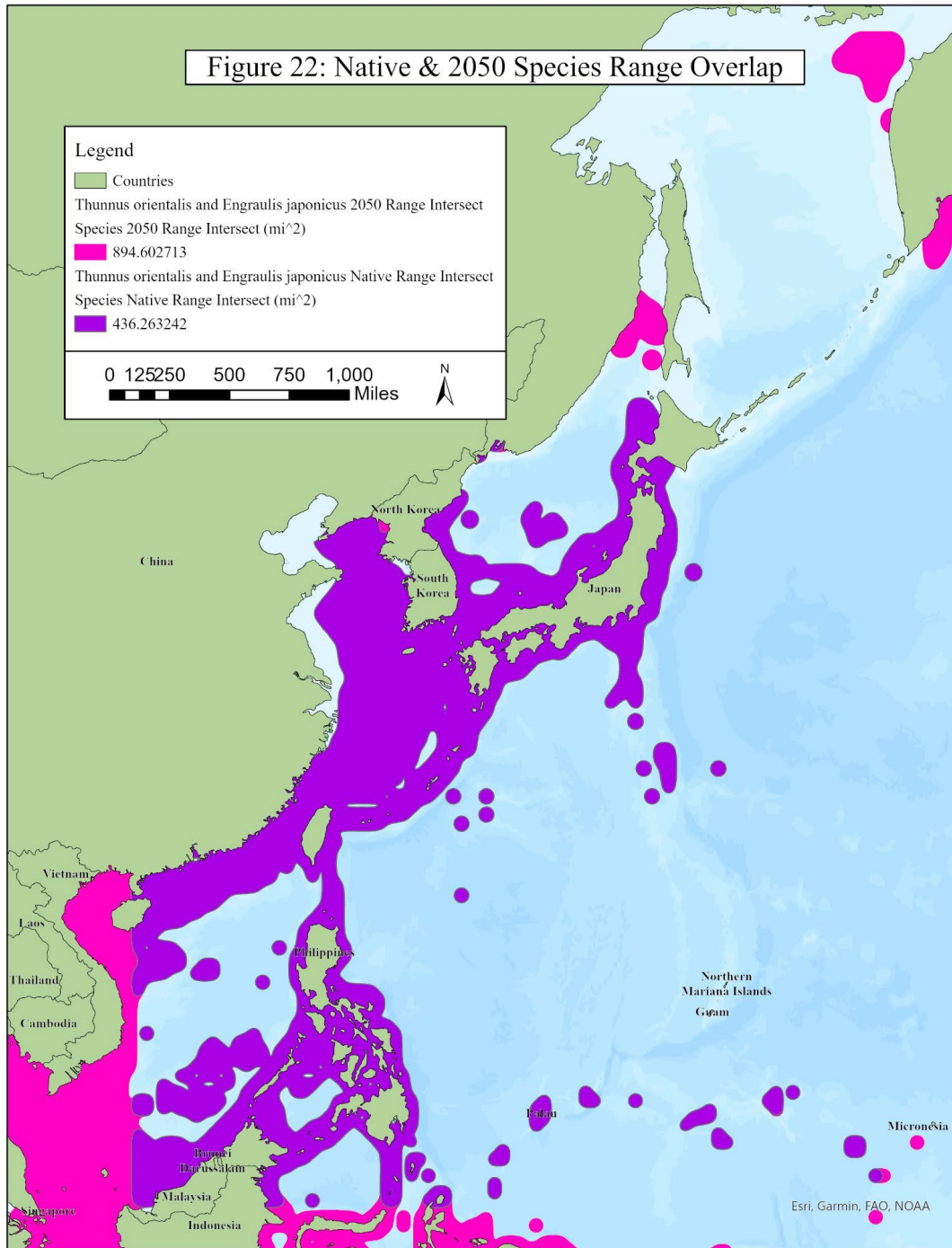
Japanese anchovy spawn along the coast of the Kyushu and Honshu Islands of Japan (figure from Takeshige et al., 2015).

Figure 21: Boundary currents influencing Japanese anchovy distribution



Boundary currents of the North Pacific Gyre influence the movement and distribution of JA (figure from Ma et al., 2019).

**Figure 22:** Native and Projected Species Range Overlap of Pacific bluefin tuna and Japanese anchovy



Species ranges were downloaded from AquaMaps and intersected in ArcGIS Pro. Purple polygons represent existing overlapping habitat, and pink polygons represent new areas of possible overlap in 2050 (Kaschner et al., 2019b, 2019a). Made by Tyler Loughran.

## Appendix B: Decision Tree

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1. Is the species “tolerant” of expected climate-driven changes (e.g., temperature changes, pH changes)?
  - a. *If yes, species may be less likely to be impacted by climate change (but see below).*
  - b. *If no, species may be likely to try to move away or productivity may decline (see below).*
2. Is the species mobile during any life stage (including as larvae)?
  - a. *If yes, species that are intolerant of may shift their ranges poleward (either through juvenile/ adult movement, or through larval drift) to track their preferred temperature and pH gradients (but see below).*
    - i. Does the species have a limited depth range, or are they able to survive in deeper waters?
      1. *If yes, species may shift ranges deeper rather than, or in addition to, poleward, potentially moving outside the range of existing fishing gear.*
  - b. *If no, species that are intolerant of expected changes may see declines in productivity.*
3. Is the species dependent on an immobile and non-ubiquitous habitat type during any life stage?
  - a. *If yes, even mobile species may not be able to find suitable habitat in new areas that conform to their preferred temperature and/or pH tolerances, and thus may see declines in productivity.*
  - b. *If no, species that are intolerant of expected changes, and that are mobile, may be likely to move away (but see below).*
4. Is the species a “prey specialist,” feeding only on one or a limited range of foods/ species?
  - a. *If yes, even tolerant and/ or mobile species that are not habitat dependent may not be able to find suitable prey in areas that conform to their preferred temperature and/or pH tolerances, and thus may see declines in productivity.*
  - b. *If no, species that are intolerant of changes, mobile, and not habitat dependent may be likely to move away.*

## Appendix C: Abbreviations

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ENSO.....	El Niño Southern Oscillation
FAO.....	Food and Agriculture Organization of the United Nation
FAJ.....	Fishery Agency of Japan
IATTC.....	Inter-American Tropical Tuna Commission
ISC.....	International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean
JA.....	Japanese anchovy ( <i>Engraulis japonicus</i> )
KOTZ.....	Kuroshio-Oyashio Transition Zone
NOAA.....	National Oceanic and Atmospheric Administration
PBF.....	Pacific bluefin tuna ( <i>Thunnus orientalis</i> )
PDO.....	Pacific Decadal Oscillation
RFMO.....	Regional Fisheries Management Organization
SFZ.....	Subarctic Frontal Zone
WCPFC.....	Western and Central Pacific Fisheries Commission

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