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SALOSIS
(SALMON OCEAN SURVEILLANCE INFORMATION SYSTEM)

by

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Abstract

The overarching objective is to understand the distribution of Pacific salmon in relation to oceanographic features that can be measured remotely from satellites or other global ocean observing assets. This first pilot project examined the relation between salmon and sea surface temperature. An historical data analysis and literature review was conducted to develop and understanding of monthly sea surface temperature frequency distributions where pink salmon and sockeye salmon were caught beyond territorial limits in the North Pacific Ocean, particularly in the Gulf of Alaska where British Columbia salmon are known to be abundant. For comparison, a preliminary exploration of the northwestern North Pacific was conducted using Hokkaido University's HUFODAT database to understand the relationship between salmon distribution there and sea surface temperature. Maps of suitable thermal habitat for pink and sockeye salmon in the Gulf of Alaska were computed for the months April through July 2013 using the NOAA/OIv2SST 1° x 1° lat/long. database. Extrapolation of suitable thermal habitat, based on measurements in the Gulf of Alaska, to the northwestern North Pacific did not accurately represent known distributions. Salmon are known to be subarctic animals, so the monthly position of the Subarctic Boundary was computed monthly for 2013 using salinity data that are transmitted from profiling lagrangian floats (deployed by Project Argo) to the US-GODAE Argo server. While the Subarctic Boundary may potentially be a relevant feature in the northwestern North Pacific, in the eastern North Pacific, it veers sharply southward and does not correspond with the known offshore limits to salmon distribution. SST frequency data where salmon have been known to be caught, combined with the monthly SST data described above for 2013 produced monthly coloured maps of salmon relative vulnerability to IUU fishing at 1° x 1° lat/long. Vulnerability is a function of the overlap of the salmon-SST probability distribution function (pdf) with the SST pdf. No overlap indicates no vulnerability to IUU fishing, and complete overlap indicates high exposure. Mismatches in some regions between suitable thermal habitat and known salmon distributions suggests that surveillance planning will require a more comprehensive view of salmon oceanic habitat than can be ascertained from SST alone. Ocean colour, hydrography, and altimetry are sources of additional information that could be fruitfully explored, perhaps within the context of an ocean circulation model.

0. SALOSIS - SALmon Ocean Surveillance Information System

The over-arching objective is to develop SALOSIS as an information and planning support system for operational aerial surveillance missions by enforcement agencies of North Pacific rim salmon producing nations. Remotely-sensed oceanographic data obtained from satellites can be combined with related ocean observing assets and ocean models to generate nowcast and 10-day forecast maps of salmon habitat based on historical salmon and oceanographic data, and relative vulnerability to Illegal, Unreported, or Unregulated (IUU) fishing for salmon on the high seas. The initial step is to explore the association between salmon abundance, distribution, and sea surface temperatures as these data are obtained reliably by satellites.

1. Ancient History of High Seas Surveillance

In the mid-1980s, governments became interested in the activities of large-scale pelagic high seas fisheries that operated broadly across the Pacific Ocean (Burke et al. 1994). Initially, the major political issue in North America was the potential for interception of salmon of North American origin by fleets operating near the Subarctic North Pacific. Under increasing political pressure, Canada, Japan, and the U.S. negotiated two pilot programs in the spring of 1989 to place scientific observers on the Japanese squid driftnet fleet (Fitzgerald et al. 1993). These programs augmented high seas scientific research programs that were already in place to investigate the issue (Bernard 1986; LeBrasseur et al. 1987).

In June 1989, a letter from staff of the Pacific Biological Station was written to the Commander of Maritime Forces – Pacific to inform the Commander about the seasonally varying boundaries of the high seas squid driftnet fleet, and the need for information about vessel abundance and location, whether fishing within or beyond the boundaries. In response, regular aerial surveillance of North Pacific region of interest was initiated that summer by the Canadian Department of National Defence (DND). Flights included a Canadian fisheries biologist from the Pacific Biological Station to help the crew to identify appropriate fishing vessels and any species found on-deck or in nets (McKinnell 1989). Focusing on the Gulf of Alaska, the circuit followed a general path from Comox, BC to Allendorf Air Force base in Anchorage, Alaska to Hickam Air Force base in Hawaii and back to Comox. Belly mounted cameras in the Lockheed Orion surveillance aircraft were capable of providing high resolution photographs of any fishing vessels that were detected (Figure 1).

The first science-enforcement coordinating meeting between the U.S. and Canada was convened in Esquimalt, BC in the spring of 1990. Mr. William Lutton, Office of Enforcement/NOAA represented the United States. Messrs. McKinnell and T. Gjernes represented DFO/Science, and Col. Thomas led the DND participants. The most noteworthy outcome of that meeting was a realignment of areas of surveillance responsibility after discovering that there was significant geographic overlap between agencies (DND and US Coast Guard) in the regional coverage. Science provided a knowledge of fleet locations and behaviour and information on the known distributions of flying squid and salmon and their temperature preferences. The practice of enforcement coordination was formalized in the ENFO Committee when NPAFC was established in 1993 (Figure 2).

Optimizing the flight paths for aerial surveillance to focus on regions where Pacific salmon are expected to be depends on the abundance of salmon and their distribution, and these differ somewhat among species and among years. An optimal path also depends on whether the goal is to survey any location where a salmon may be found, or the areas where the greatest abundance of salmon is likely to be found. The optimal flight path may also be affected by a species of greatest interest, or perhaps greatest value. In general, catches of Pacific salmon on the high seas have a contagious distribution, i.e. there are many locations with lower catches and fewer locations of high catches. In some parts of the North Pacific, especially the warmer subtropical waters, Pacific salmon have never been caught. Various hypotheses have been developed to suggest what causes this distribution. Maturing salmon will behave differently from immature feed salmon and that in turn will give rise to different geographical patterns. The abundance of the prey of salmon tends to have the same property of contagious distribution as the salmon. What occurs at the margins of distributions has been a popular topic. The thermal limit hypothesis (Welch et al. 1995, 1998) posed that a critical SST is the sole determinant of the southern distribution of salmon. Below the critical temperature, SST has no influence on their distribution. The hypothesis has been updated to include distribution in relation to salinity (Azumaya et al. 2007) but the focus of this pilot study is surface temperature. The thermal limit hypothesis will generate different expected distributions from a model where salmon are imagined to have a thermal preference, but are found both above and below their thermal preference. Although there are many similarities, the northwestern and northeastern North Pacific also have many differences (Beamish et al. 1999).

2. Northwestern Pacific

The HUFO-DAT database was created recently by Hokkaido University. This university has been deploying Training Vessels (TV) to the high seas since the mid-1950s. A major part of their training activities was the collection of salmon abundance data based on fishing with research gillnets (multiple mesh sizes), and the collection of associated oceanographic data. The database provides a unique opportunity to examine the relationship between salmon abundance and oceanography, including SST. Beginning in 1982, the cruises of the Training Vessel *Hokusei maru* changed location to focus its spring surveys on the North Pacific Transition Region, with repeated sampling for many years along the 155 ± 1°E meridian (Figure 3). By repeatedly occupying the same stations along a narrow band of longitude, it is possible to examine in some detail how the distributions changed, or did not, from year to year.

From 1982 to 2007, the total numbers caught were: 9 sockeye, 7,357 chum, 25,902 pink, 511 coho, 70 chinook, and 74 steelhead trout. These results indicate that the species with greatest exposure to IUU fishing along the southern part of the 155 ± 1°E meridian are chum salmon and pink salmon.

2.1 Pink and chum salmon

The abundance of Asian pink salmon is known to differ significantly between odd and even years, with odd years more abundant (Radchenko et al. 2007). Based on national catches reported to the NPAFC between 1981-2007, average coastal catches of Asian pink salmon during these years were significantly different (ANOVA, $P<0.03$). However, no significant differences were found between the average abundances of pink salmon in odd and even years during the *Hokusei maru* surveys on 155°E (ANOVA, $P>0.2$). Fifty percent of the samples were taken between June 9-26, but the total range of dates during these years varied from May to July. These results suggest either that the gillnet research sampling was not adequate to provide a general index of abundance, or that the stations occupied by the *Hokusei maru* on the 155°E meridian were distant from the general centre of abundance of pink salmon. The latter appears to be the case, because prior to 1980 when the *Hokusei maru* occupied more northerly stations on the 155°E meridian, there was a strong difference between the average pink salmon catches on the *Hokusei maru* in odd years and even years (ANOVA, P<0.01). Fifty percent of the samples in the years before the 1980s occurred between July 9 – August 4, or about 1 month later than the period after 1980.

Based on extensive high seas surveys that occurred before 1980, the preferred range of SST for maturing pink salmon is 4-11°C while the tolerable range is 3-15°C (Takagi et al. 1981). Pooled across all years, the distributions of SST where pink salmon were caught on the 155°E meridian and where they were not caught are significantly different, but there is no evidence in these data of an abrupt upper limit (Figure 4 and 5). The shape of the distribution is nearer to Gaussian than a knife edge.

At northern stations before 1980 the average SST where pink salmon was caught (9.0°C) was significantly higher than the average SST in sets where pink salmon was not caught (8.0°C). At the southern stations after 1980, the average SST in sets were pink salmon was caught (9.9°C) was significantly cooler than stations where pink salmon was not caught (17.6°C).

<u>2.2 Southern limits to distribution</u>

The annual regularity of fishing locations along 155°E spanning the subarctic-subtropical transition zone provides an opportunity for close examination of the oceanic properties at the southernmost locations where salmon catches have occurred each year. From 1982 to 2007, the average latitude where the southernmost catches of pink salmon occurred was at 41° 20' N (95% c.i. = 40° 51'N - 41°53'N). The average SST at the southernmost station where pink salmon were caught was 14.2°C (c.i. 12.4°-15.9°C). The 3.5°C wide confidence interval indicates that the mean SST is quite variable at the southernmost location of pink salmon catch. The coefficients of variation for latitude of southernmost catch and SST at southernmost catch are 3.2% and 32%, respectively. The “order of magnitude” lower coefficient of variation for latitude indicates that latitude was a better guide to determining the southern distribution of pink salmon than SST along 155°E from 1982 to 2007. This suggests that in the western North Pacific, surveillance activities in search of vessels actively fishing for pink salmon need fly no further south than approximately 40°N in offshore regions near 155°E.

Very similar results were obtained for chum salmon where the average southernmost latitude was 40°34' N (c.i. 39°54' N - 41°13' N) and SST – 12.8°C (c.i. 13.1°C – 16.6°C). Coefficients of variation were also very similar to pink salmon (4.1% for latitude and 30% for SST). The confidence intervals for the average locations of southernmost catches of pink salmon and chum salmon have a broad overlap, as do the average SSTs. From this, one might imagine that a similar factor or factors are regulating their southernmost distributions. As the major geostrophic currents in the region have a relatively constant latitude, one can imagine that this major transition is a potential limit to their southern distribution in spring. Gradients in other properties at the transition are also evident (Figure 6).

In a similar analysis of 410 fishing operations in the Gulf of Alaska (east of 179°E), the pattern that emerges is not so different from what is described above. The distribution of SSTs where pink salmon were caught tended toward a Gaussian, with a mean temperature of 9.9°C (95% c.i.: 9.6° - 10.1°C) which is not significantly different from that observed in the western North Pacific. The mean SST in sets where pink salmon were not caught was 13.9°C. However, as longitude accounted for 56% of the variation in SST in June longline stations in the Gulf of Alaska, the effect of longitude on the relationship between catch and SST needs to be considered. Sampling in June of 1962 and June of 1966 was so widespread in the Gulf of Alaska that it was possible to determine that the (linear component of the) relationship between SST and longitude did not differ among these two years. There was no significant relationship between SST and latitude, probably because the isotherms curve northwards in the eastern Gulf of Alaska.

2.3 Sockeye salmon

Sockeye salmon were not caught on the 155°E meridian in sufficient abundance after 1982 to understand their distribution in relation to SST.

3. Northeastern Pacific

Most of what is currently known of their distributions in the Gulf of Alaska was learned by Canadian scientists fishing on the high seas during the period from the 1950s to 1970s (Takagi et al. 1981). During the late 1980s and early 1990s, smaller research programs focused on understanding the southern limits to distribution (McKinnell et al. 1989, Welch et al. 1995), and to learn about their distributions in winter (Welch et al. 2002A, 2002b, 2002c). Since the late 1990s, Canadian and American research directed at the biology of salmon at sea has focused on juveniles migrating along the continental shelf so there are no contemporary data on their oceanic distribution (Fisher et al. 2007, Tucker et al. 2009).

During the 1960s, Canada and the U.S.A. developed an ambitious high seas sampling program in the Gulf of Alaska that relied on catching, tagging, and releasing salmon caught with surface longlines to examine the possibility of providing forecasts of return abundance (Shepard et al. 1967). Unlike gillnets, the longlines were deployed and retrieved quickly so they could provide an abundance of live salmon to tag and release.

The longline gear and methods were developed in Japan but were adopted for use in the Gulf of Alaska by Canada and the USA. Hooks baited with small dried fishes (e.g. *kata kuchi iwashii* - salted anchovy) were deployed at nautical twilight and retrieve shortly thereafter. The gear appeared to be equally effective at catching all species that were present. Chinook salmon were rarely caught on the high seas. Effectiveness of the gear, however, relies on a willingness of fish to take the bait. In most years, sampling during the 1960s was sufficiently widespread in the Gulf of Alaska to understand the seasonal distribution of salmon from April until August. Contemporary understanding of salmon distributions relies heavily on these data as equivalent surveys have not occurred since then. Inferring distribution from longline catches assumes that salmon are equally likely to encounter the gear and equally likely take a baited hook throughout the Gulf of Alaska. While this assumption may not hold in coastal waters where a spawning anorexia develops near their rivermouths, at the present, there is no reason at the moment to assume otherwise for the high seas.

3.1 Pink salmon

Pink salmon migrate to sea as underyearlings so they do not spend significant amounts of time rearing in freshwater after emerging from the spawning gravels. Mortality is likely high during the initial weeks in the sea, but growth is rapid for the survivors. In summer, juvenile pink salmon have been be found migrating along the continental shelf, generally in a counterclockwise direction around the Gulf of Alaska (Perry et al. 1996). No fisheries, legal or otherwise, are directed at this life-history stage. Winter distributions of pink salmon in the Gulf of Alaska are not well known because of the difficulty of fishing with nets or longlines in inclement weather. As pink salmon mature and spawn at two years old, only a single cohort can be found in the ocean at any one time, except for the brief period in spring/summer the outgoing juveniles and the maturing adults are at sea but in different parts of the ocean.

While many pink salmon may begin their oceanic life in the northern Gulf of Alaska on the continental shelf, by April they have abandoned the shelf region and the northern Gulf of Alaska and are found only in the southern Gulf of Alaska, predominantly in the southeastern part near the British Columbia Bifurcation of the North Pacific Current (Figure 8). Their distribution spreads northward with the season, presumably because feeding and spawning migrations are affecting where they are found.

3.2 Sockeye salmon

What is evident in the data for all years combined is that sockeye salmon in the Gulf of Alaska were rarely missing from longline sets that occurred in spring within a range of SSTs from 4-6°C, whereas pink salmon were not often caught at these colder SSTs in spring. For the most part, this is because the two species are inclined to occupy different parts of the Gulf of Alaska at the end of winter, with pink salmon in the south and sockeye salmon in the north. This may help to explain how two species with rather similar oceanic diets are partitioning the oceanic habitat. With adequate food, the warmer temperatures in the southeastern Gulf of Alaska may facilitate the rapid growth that is required by pink salmon to reach maturity at two years of age. There is evidence that the distribution of SSTs where sockeye salmon were caught is bimodal, with a second mode in the 10-12°C range. This is readily apparent in 1962, 1967 and all years combined (Figure 9). These sets at the higher mode generally occurred along the eastern border of the Gulf of Alaska in the region of the Alaska Current.

4. Subarctic Boundary

Pacific salmon are a subarctic fauna so a comparison of their distribution with that of the subarctic North Pacific may provide some useful insights. The Subarctic Boundary is the southernmost extent of the subarctic North Pacific. Historically it has been defined as the location where the 34 psu isohaline reaches the ocean surface (Dodimead et al. 1963). Its location was determined by oceanographic vessels on meridional transects across the subtropic-subarctic transition. These cruises occurred relatively rarely compared to the large-scale coverage now available through Project Argo since 2003. Azumaya et al. (2007) found that some species of salmon were found in surface waters beyond the Subarctic Boundary but these incidences were likely rare.

Monthly contours of the 34 psu isohaline at ~5 m depth (uppermost measurement provided by each profiling float) were computed using the kriging algorithm in Surfer 12 for latitudes north of 35°N for the months April through August of 2013 (Figure 11). From its location in 2013, centred on 40°N, it appears that the Subarctic Boundary may play a role in determining the southern limits to salmon distributions in the western North Pacific. It is a region of strong gradients in several oceanic properties so understanding which is affecting distribution is a challenge (Figure 6). However, the Subarctic Boundary was clearly not of much relevance to salmon distribution in the eastern North Pacific. In 2013, and likely in other years as well, it had a strongly zonal orientation (east-west) from the coast of Japan to about 205°E (155°W). Thereafter, it swung southward to latitudes where salmon have never been caught, at least beyond national jurisdictions (Figure 8 and 10). Other hydrographic properties in the eastern North Pacific, such as the location of the North Pacific Current may provide a more meaningful representation of salmon habitat in the eastern North Pacific than the Subarctic Boundary.

5. Suitable Thermal habitat

The range of temperatures where fishes are caught is bounded by observed extremes that vary by species, population, season, or developmental stage. As a subarctic fauna, the Pacific salmon tend toward the lower part of the oceanic thermal range. Temperatures experienced in freshwater can be considerably higher than those encountered at sea, but the focus of this discussion is the oceanic domain. For the moment, consider that *suitable thermal habitat* is a range of SSTs, calculated monthly by species, where salmon were caught on longlines during the high seas surveys of the 1960s (1436 longline sets). One can imagine that if these observed temperatures are physiological preferences, that the relationship between the incidence of salmon and the SSTs where they are found would not change substantially in the 60 year period since those observations were made. Using this rather major assumption, it is possible to examine contemporary SSTs provided by global remote sensing programs to develop contemporary distributions of suitable thermal habitat. The colours of Figure 12, for example, show the suitable thermal habitat for four months in the spring and summer of 2013. Historical fishing effort was greatest from April to June and tended to diminish in July and August, with very few sets in the fall and winter months.

The lower 25% of SSTs where salmon were known to be caught and the upper 25% of SSTs are coloured in yellow, while the middle 50% of SSTs are coloured red. SSTs where salmon were not caught in the Gulf of Alaska in the 1960s are coloured in white in Figure 12. The region of suitable thermal habitat available to salmon in the Gulf of Alaska was qualitatively similar to what was found there during the 1960s. In some months, the thermal habitat of pink salmon that was available in 2013 was much larger than what was actually occupied by pink salmon during the 1960s. This suggests that other factors are important for determining their distribution.

Thermal limits reported by Azumaya et al. (2007) were narrower for sockeye (3.3-13.3°C) for sockeye and broader (2.8-16.6°C) for pink salmon. The differences may have arisen from various causes but care should be taken when interpreting all results of this kind to distinguish true physiological limits from simple observed ranges. The latter may be known, but the former may be more difficult to understand.

6. Thermal limit hypothesis

While there is widespread agreement that Pacific salmon are not found in subtropical waters of the North Pacific, there are differing opinions of what regulates their distribution within the Subarctic North Pacific. Welch et al. (1995, 1998) suggested that the southern limit of the distribution of Pacific salmon in the North Pacific Ocean was determined solely by a critical surface temperature beyond which salmon would not pass. Estimates of the critical values were determined by fitting an edge model that described the relationship between average salmon abundance and temperature as a cumulative normal curve with the critical SST as the point of its inflection. These thermal limits in spring differed for each species: 10.4°C for pink and chum salmon, 9.4°C for coho salmon, and 8.9°C for sockeye salmon. Estimates of uncertainty in the critical limit were nil for pink and chum, 0.3°C for coho salmon and 0.2°C for sockeye salmon. Data for the study were obtained from two cruises of the *R/V TINRO* in the Gulf of Alaska in April/May 1990, and from three Canadian research cruises in June/July of 1987, 1988, and 1990. There were significant differences among the critical thermal limits measured by the three gear types (longline, trawl, gillnet) but no explanation was offered. If the limit to salmon distribution is a critical field for planning surveillance activities, the data provided by Hokkaido University suggests that it may be instructive to delve more deeply into the hypothesis.

In April and May for both sockeye salmon and pink salmon, suitable thermal habitat defined by observations in the Gulf of Alaska provides for only a narrow region of suitable habitat in the western North Pacific. One explanation is that the associations between temperature and distribution in the Gulf of Alaska are purely coincidental and not an inherent property of the species. Another possibility is that Asian and North American salmon populations have adapted or evolved to have different thermal preferences and/or limits.

7. Acknowledgements

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Table 1. Minimum, maximum and quartiles of sea surface temperatures where sockeye salmon (pink salmon in parentheses) were caught during longline surveys in the Gulf of Alaska from 1961-1967. The distributions of these temperatures in equivalent months in 2013 can be seen in Figure 12.

Month	Minimum	25%	75%	Maximum
April	3.0 (4.0)	4.3 (5.7)	6.1 (8.1)	9.5 (10.2)
May	3.9 (4.2)	5.5 (6.5)	7.5 (8.8)	10.0 (11.6)
June	5.7 (5.9)	8.0 (8.25)	10.6 (10.75)	12.6 (12.8)
July	7.3 (9.4)	10.5 (10.5)	12.05 (11.9)	14.5 (13.9)

Figure 1: Aerial surveillance photograph of an high seas squid driftnet fishing vessel (Photo credit: DND).

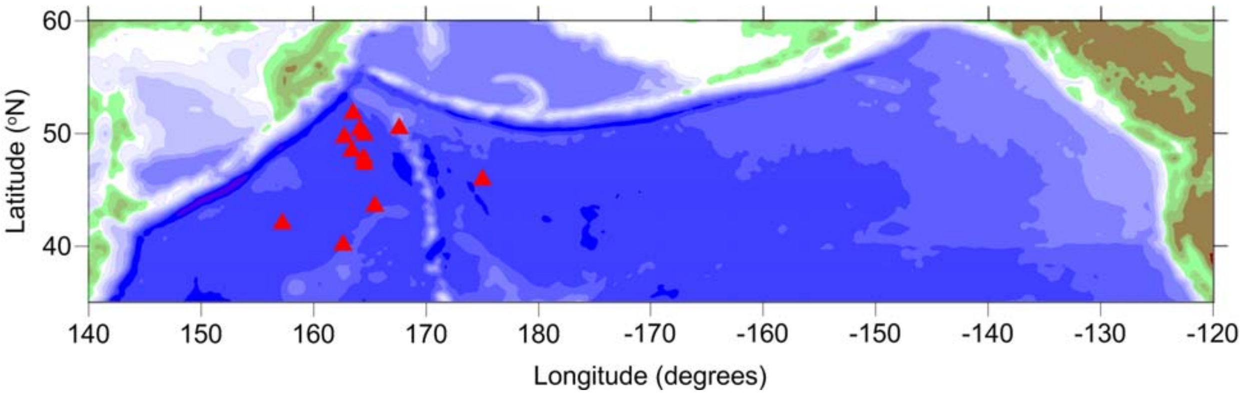

Figure 2: Locations of IUU fishing vessels from 1993 to 2011 with precise locations. Vessels with imprecise location information are not shown.

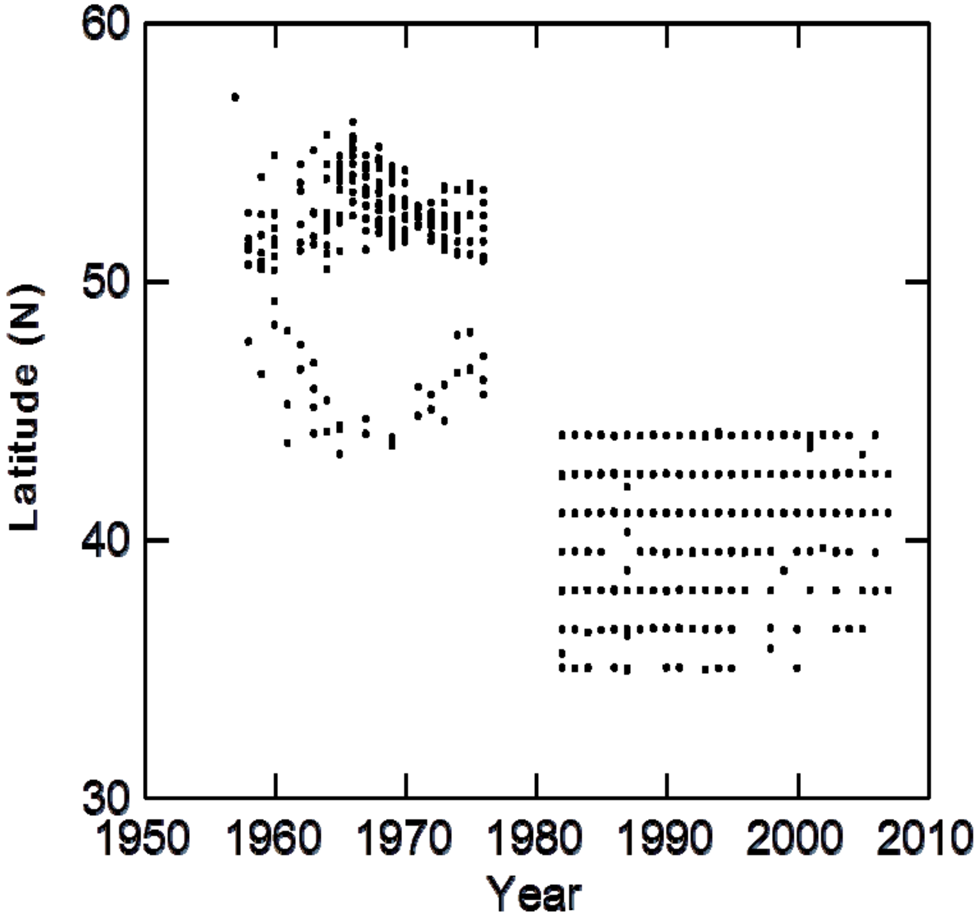

Figure 3: Latitudes sampled by research gillnets deployed by the T/V Hokusei maru (Hokkaido University) along the 155°E meridian.

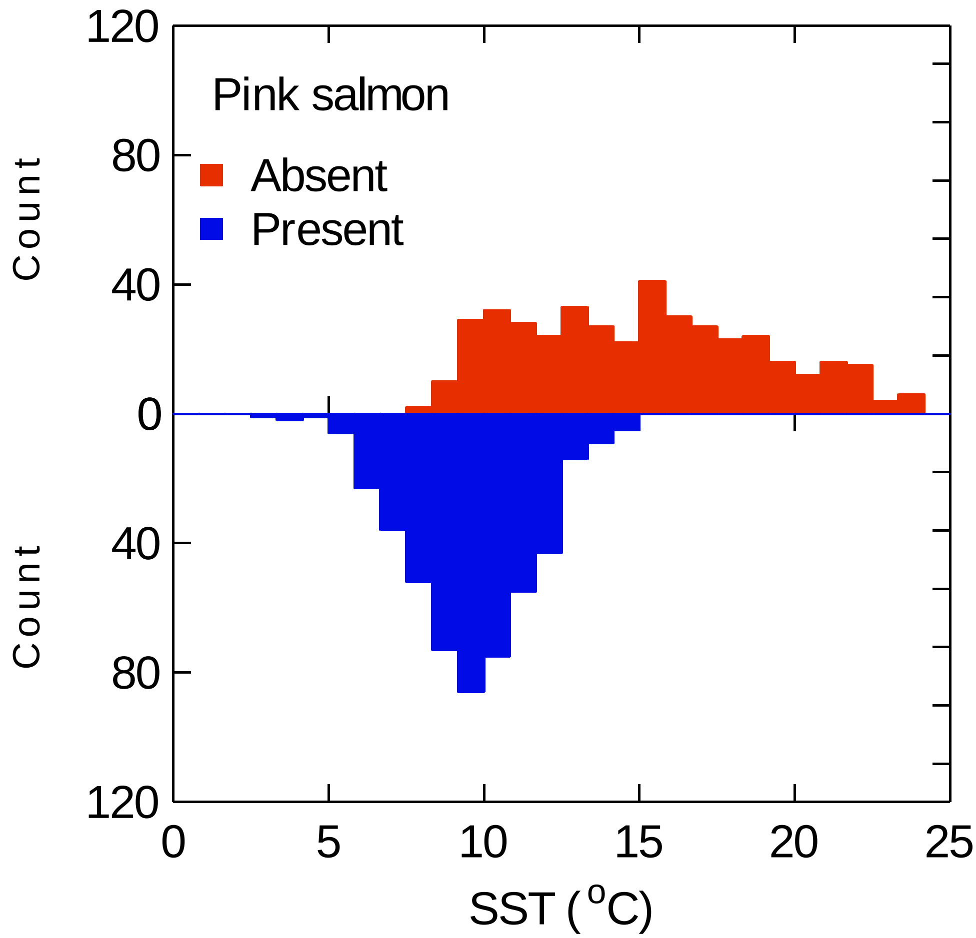

Figure 4 Distribution of SST where pink salmon were caught in research gillnets along the 155°E meridian from 1982-2007 (Data Source: HUFO-DAT Vol. 2)

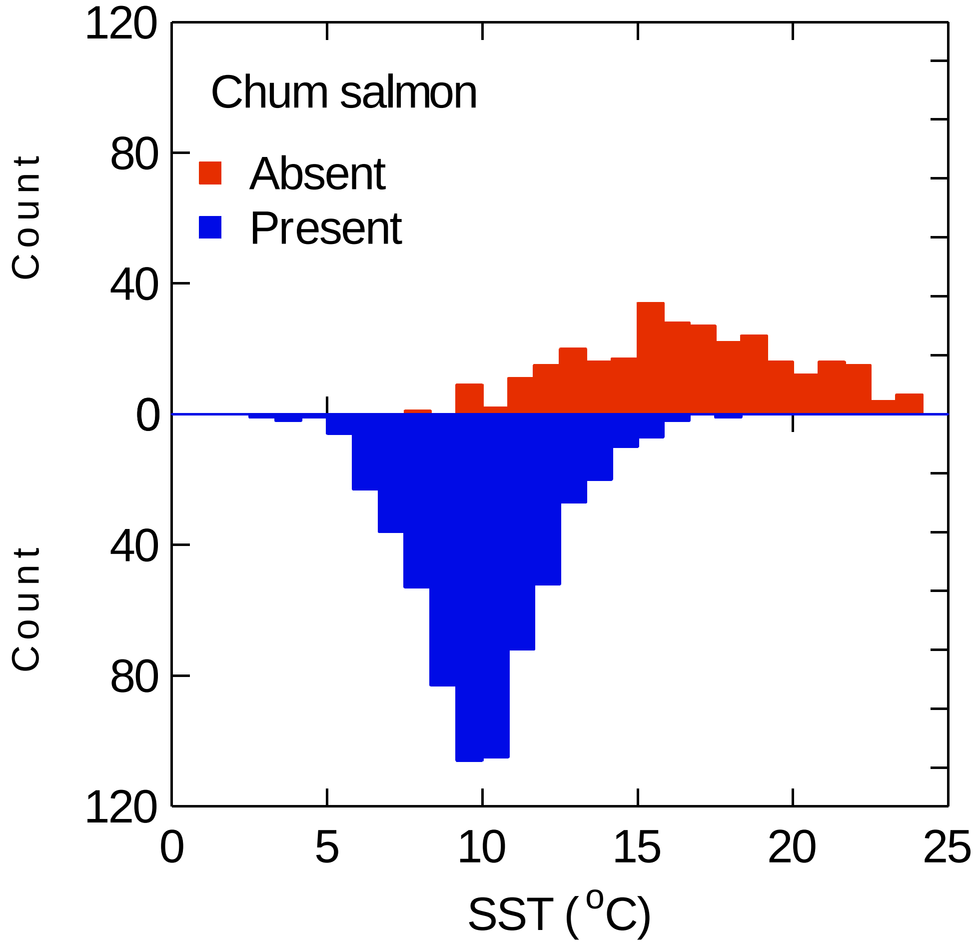

Figure 5: Distribution of SST where chum salmon were caught in research gillnets along the 155°E meridian from 1982-2007 (Data Source: HUFO-DAT Vol. 2)

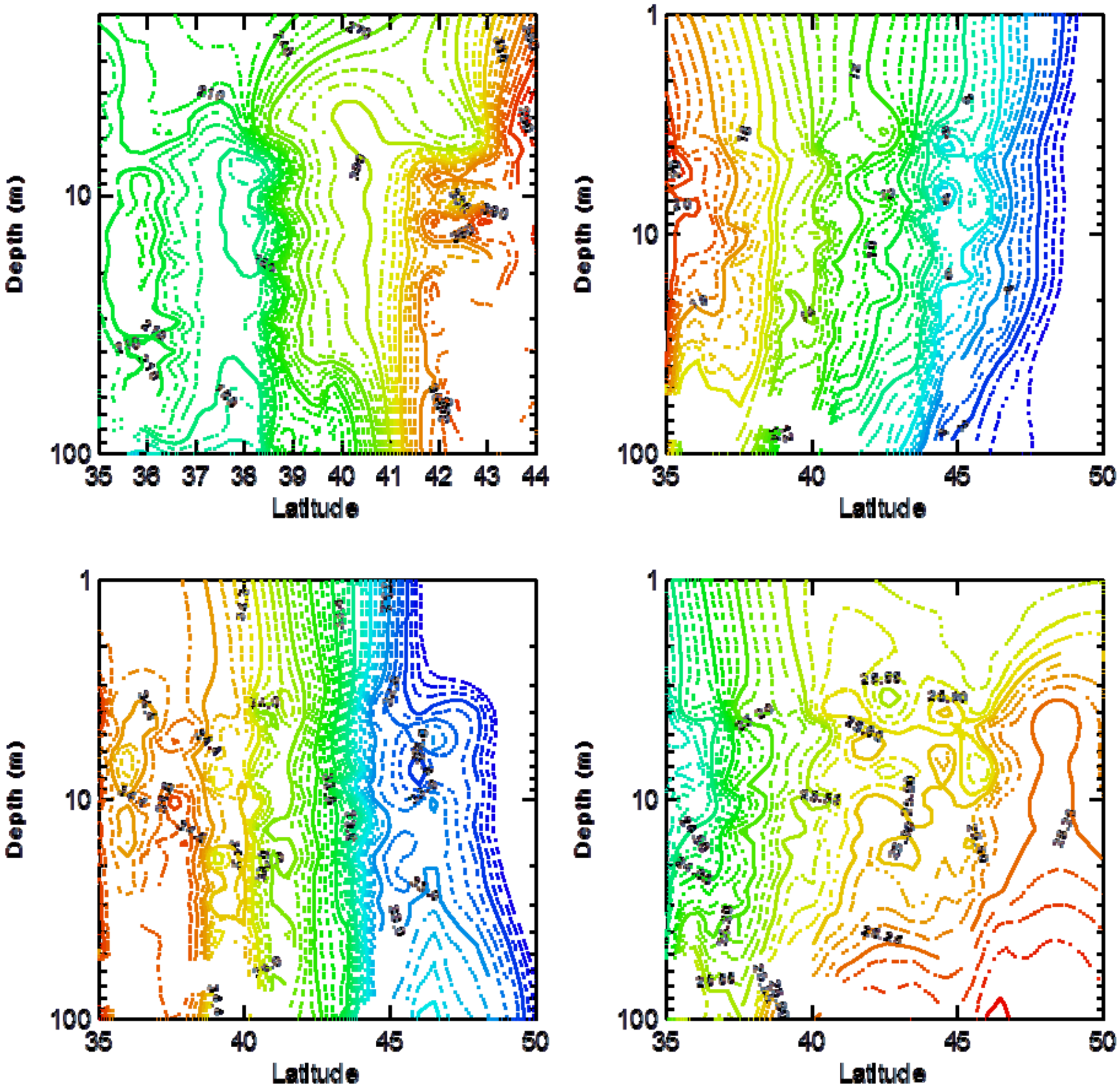

Figure 6: Dissolved oxygen (micromole per kg), Temperature, Salinity, and Density in the region of the 155°E meridian based on Project Argo profiling floats.

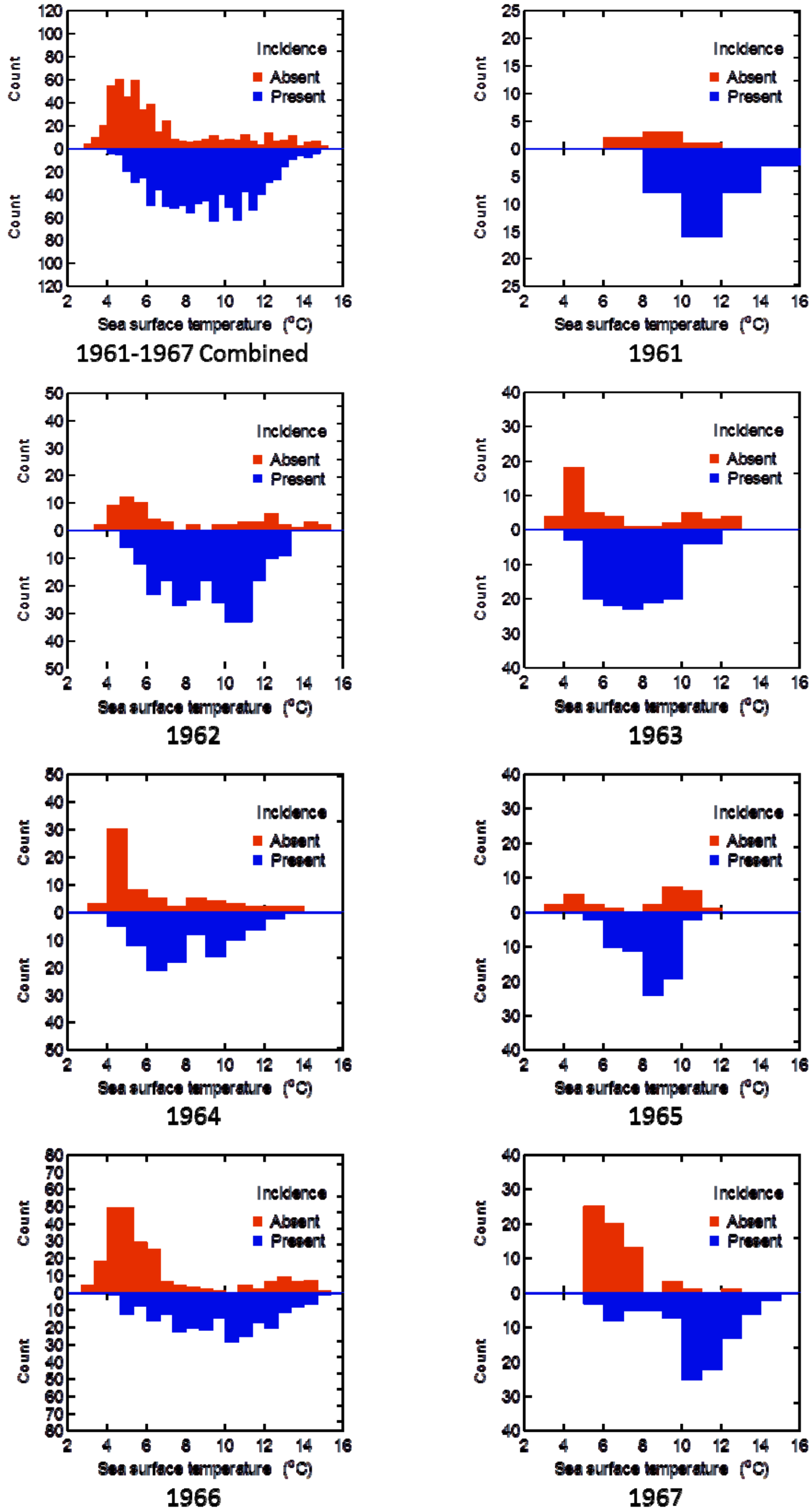

Figure 7: Sea surface temperatures where pink salmon were/were not caught in the Gulf of Alaska from 1961-1967 and all years combined (top left panel).

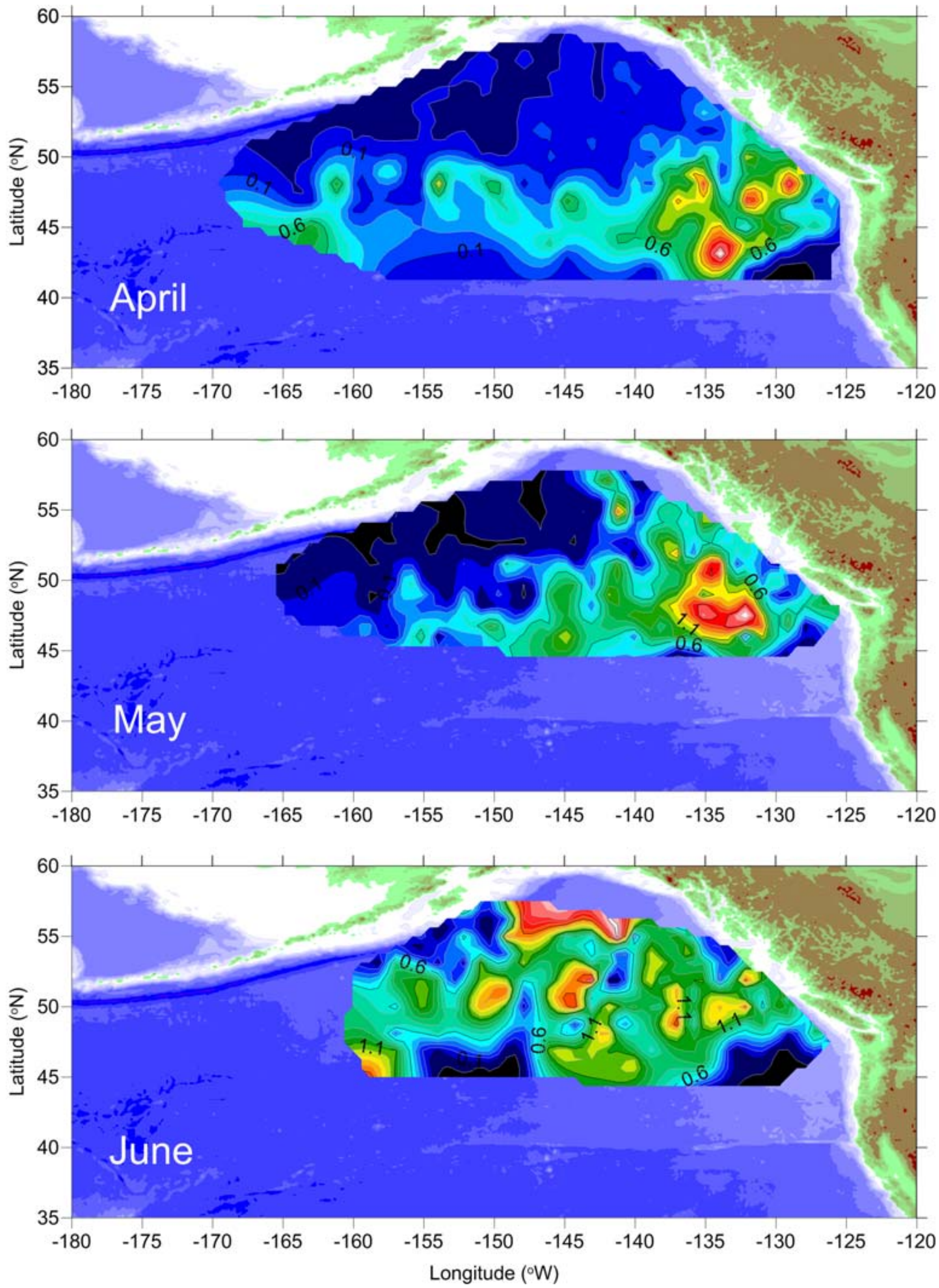

Figure 8. Contours indicate the average cpue ($\log_e$ transformed) of pink salmon in April, May, and June based on Fisheries Research Board of Canada longline surveys from 1961-1967. Reddish colours indicate high average abundance and bluish colours indicate low cpue. The colour scale is identical in each panel. The jagged perimeter of the contour region indicates the envelope where sampling occurred.

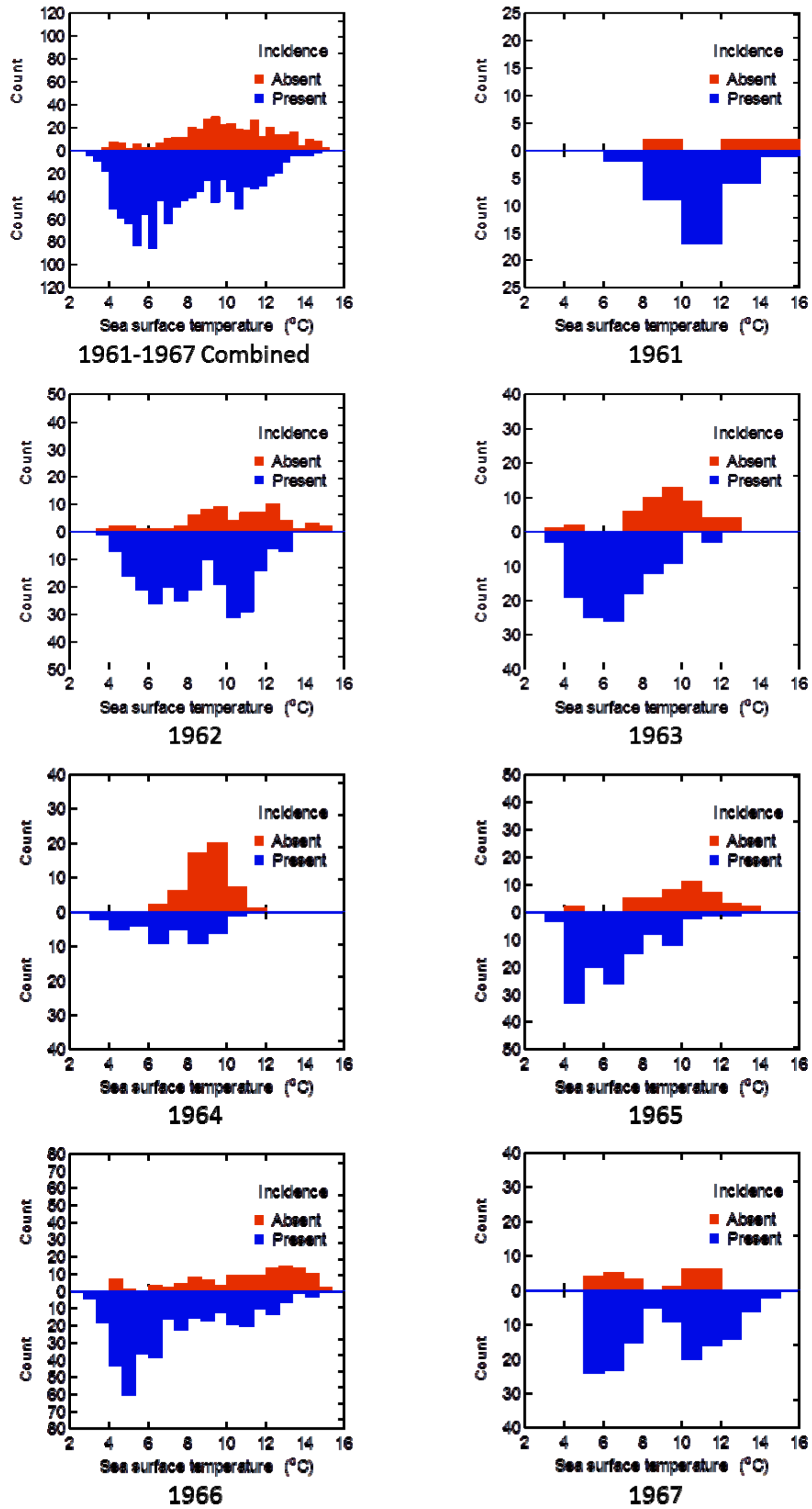

Figure 9: Sea surface temperatures where sockeye salmon were/were not caught in the Gulf of Alaska from 1961-1967 and all years combined (top left panel).

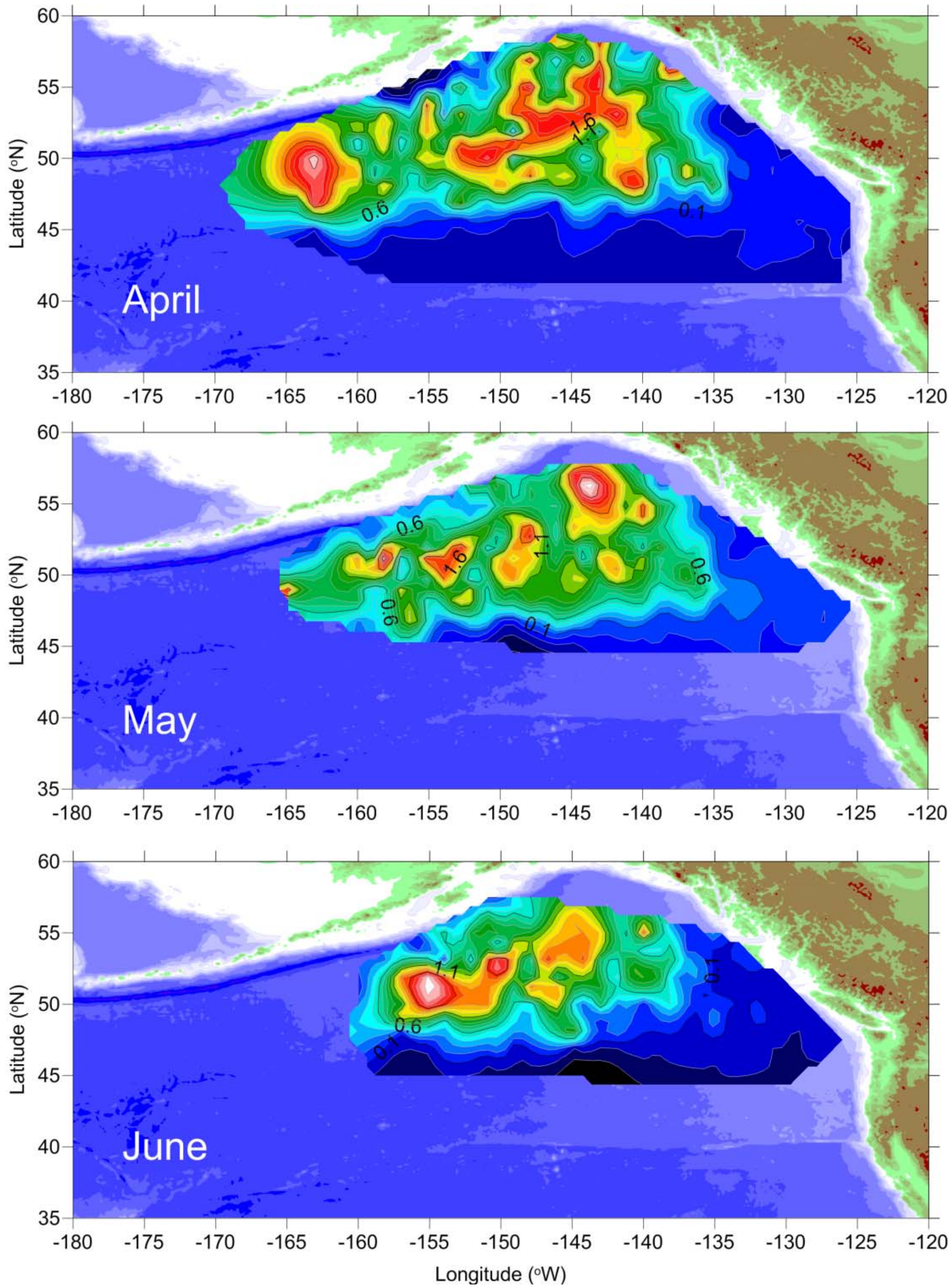

Figure 10: Contours indicate the average cpue (log$_e$ transformed) of sockeye salmon in April, May, and June based on Fisheries Research Board of Canada longline surveys from 1961-1967. Reddish colours indicate higher average abundance and bluish colours indicate low cpue. The colour scale is identical in each panel. The jagged perimeter of the contour region indicates the envelope where sampling occurred.

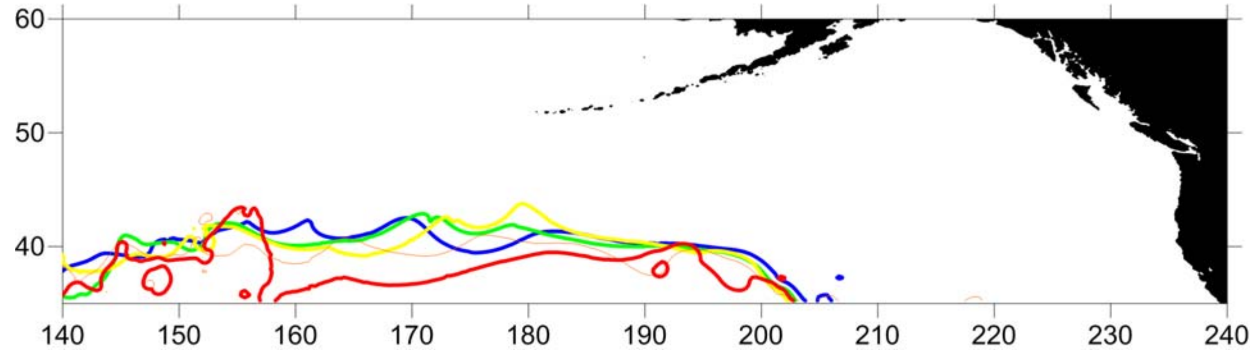

Figure 11: Location of the Subarctic Boundary (34 psu) by month estimated by a kriging algorithm applied to profiles from Project Argo database. Colours represent months: April (blue), May (green), June (yellow), July (orange), August (red).

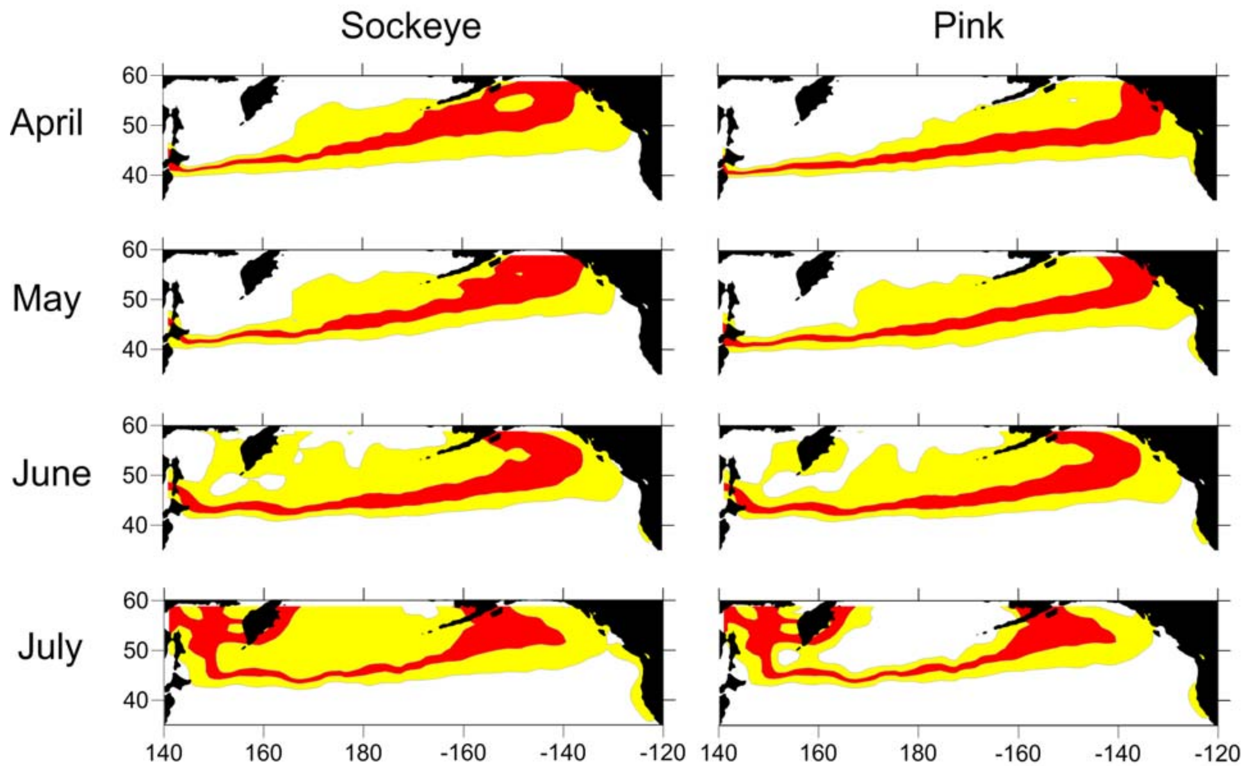

Figure 12. Colours indicate the distribution of salmon thermal habitat in 2013 by month and species, based on sea surface temperatures (SST) where longline catches of salmon occurred in the Gulf of Alaska from 1961-1967. White indicates SSTs where salmon were not caught during that era. The red zone indicates the thermal habitat where 25-75% of all catches occurred. Yellow zones indicate SSTs where the coldest and warmest 25% were caught.