

Sea surface temperature variation on the continental shelf of the Gulf of Alaska in relation to sockeye salmon survival at selected British Columbia watersheds

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ABSTRACT

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An objective of this study was to define spatio-temporal subdomains based on sea surface temperature (SST) variability that might be associated with marine survival of sockeye salmon and to develop annual indices of variability for each subdomain. The study focused on the continental shelf (< 500 m depth) from the Columbia River to Kodiak Island. Empirical orthogonal analysis of weekly SST anomalies on a $\frac{1}{4}^\circ$ by $\frac{1}{4}^\circ$ latitude-longitude grid found that anomalies were positively correlated across the entire region of interest so there was little incentive to subdivide it into subdomains based on SST anomalies alone. Variation in the dominant EOF was compared with variation in large-scale indices to determine how well the continental shelf was reflected in those indices. Historical marine survival time series of British Columbia sockeye salmon were compared to determine if survival variation in each river was independent of the others. Fraser River sockeye salmon marine survival varied independently from Barkley Sound and Columbia River, which were more correlated. The difference was attributed to different postsmolt migration routes and tends to reinforce the idea that the greatest mortality occurs shortly after postsmolts arrive at the ocean. Simulations of the thermal experience of migrating postsmolts from their natal river found that Fraser River sockeye salmon have a significantly warmer experience ($\sim 2^\circ\text{C}$) than other rivers. The report concludes by describing some outstanding issues related to SST variation on the British Columbia coast.

RÉSUMÉ

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L'objectif de cette étude était de définir des sous-domaines spatio-temporels, basés sur la variabilité de la température de surface de la mer (TSM), susceptibles d'être associés à la survie en mer du saumon rouge, et de développer des indices annuels de variabilité pour chaque sous-domaine. L'étude s'est concentrée sur le plateau continental (profondeur < 500 m) du fleuve Columbia à l'île Kodiak. Une analyse orthogonale empirique des anomalies hebdomadaires de TSM sur une grille de $\frac{1}{4}^{\circ} \times \frac{1}{4}^{\circ}$ de latitude-longitude a révélé une corrélation positive entre ces anomalies sur l'ensemble de la zone d'intérêt, rendant peu pertinente sa subdivision en sous-domaines sur la seule base des anomalies de TSM. La variation du mode EOF dominant a été comparée à celle des indices à grande échelle afin d'évaluer la représentativité du plateau continental par ces indices. Des séries chronologiques historiques de survie en mer du saumon rouge de la Colombie-Britannique ont été comparées pour déterminer si la variation de survie dans chaque fleuve était indépendante des autres. La survie en mer du saumon rouge du fleuve Fraser variait indépendamment de celle du détroit de Barkley et du fleuve Columbia, ces deux derniers étant positivement corrélés. Cette différence a été attribuée aux différentes routes migratoires des post-smolts et tend à confirmer l'idée que la mortalité la plus élevée survient peu après leur arrivée en mer. Des simulations de l'expérience thermique des post-smolts migrant depuis leur rivière natale ont révélé que le saumon rouge du fleuve Fraser subit une température nettement plus élevée (environ 2 °C) que ceux des autres rivières. Le rapport conclut en décrivant certaines questions en suspens liées à la variation de la température de surface de la mer sur la côte de la Colombie-Britannique.

INTRODUCTION

*“We know little about ocean migration pathways,
so cannot confidently suggest the potential changes in this life stage.”*
...from Potential responses to climate change... (Crozier et al. 2008)

Despite longstanding gaps in understanding, the clouds have begun to part and some clarity is emerging from historical data about where and when sockeye salmon can be found in the ocean (Langan et al. 2023). Not total clarity, to be certain, but enough to speculate on where and when variable oceanographic conditions, primarily those made apparent by sea surface temperature (SST), might reveal something about the survival of BC sockeye salmon stocks¹ after entering the ocean.

Scale is important, so determining the extent of spatial and temporal covariance of the environment can help to determine how many oceanic subdomains are encountered by a migrating stock after entering the ocean. Once each is identified, it should be possible to develop indices of environmental variability to assess the statistical support for potential effects of its variation on marine survival. Temperature indices can be developed from average SST values within each subdomain, or average anomalies (SSTA), or temporal scores of empirical orthogonal functions (EOF). Average SST can be useful for comparing the temperature experienced by different stocks, or for modelling those aspects of sockeye salmon biology (and survival) that are directly affected by temperature. Anomalies are useful for identifying and quantifying the nature of departures from normal. EOF scores capture the dominant temporal patterns within each subdomain, which hopefully will be low if the subdomains are selected on the basis of their similarity within. Ultimately, the main goal is to distill the environmental information into a single time series that can represent the conditions of a given subdomain in a given year that can be compared with marine survival.

The present study was focused on identifying oceanic subdomains relevant to juvenile sockeye salmon migrations shortly after ocean entry, with particular attention to their survival. This life-history phase was chosen as a focus because it includes the period of greatest marine mortality (Parker 1962, Ricker 1962, Clark et al. 2016). The report is organized as follows: (1) define the study area (domain), (2) understand how its temperature varies and covaries, (3) examine the relationships between the domain and large-scale climate indices, (4) examine patterns of non-seasonal (SSTA) variation in the domain, (5) examine the relationship of environmental variation to sockeye salmon migration and survival, (6) define subdomains and indices, (7) simulate migrations of postsmolts along the shelf to understand their thermal experiences, and finally (8) to

¹ Stock, in this study, is defined as the lake-type individuals from a watershed large enough to have a marine estuary.

discuss some potentially relevant things to consider, or perhaps ignore, when making forecasts.

1.1. STUDY DOMAIN

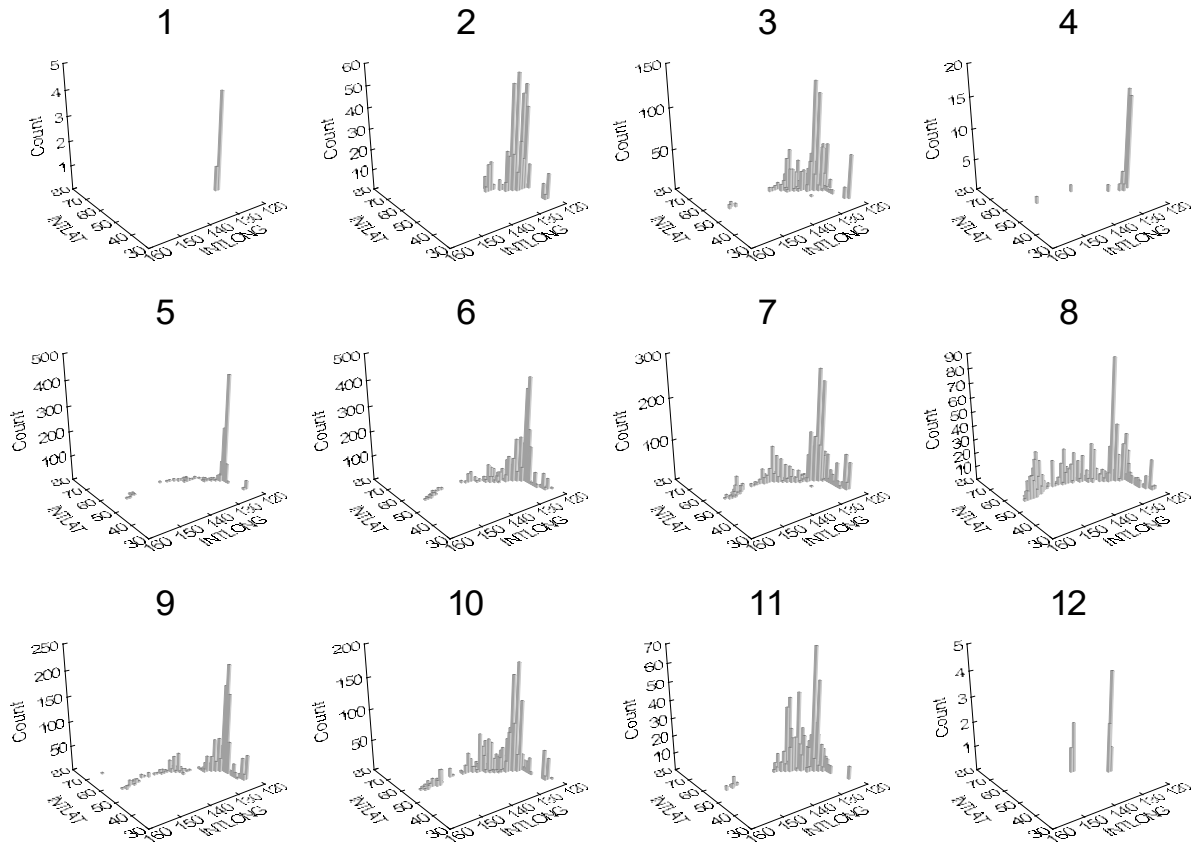


Figure 1: By month, latitude and longitude, numbers of hauls in the IPSDL in the shelf domain IPSDL.

Understanding where and when young of year (YOY) lake-type anadromous sockeye salmon from BC can be found is an important issue for this study. The fork length data of the International Pacific Salmon Data Legacy (IPSDL, McKinnell & Langan 2024) was useful in this regard because YOY sockeye salmon are readily distinguished from older ocean ages by their small body length. Version 1.3 of the IPSDL has 12,817 fishing operations (hauls of all gear types) located in the shelf domain (Figure 1), of which 2,996 hauls had caught at least one sockeye salmon (all ages). Total sockeye salmon catch on the shelf in all years was 65,415 (Figure 2), of which 33,583 individuals were <250mm fork length (presumed to be age x.0, where x= freshwater annuli and 0= saltwater annuli). During their first winter in the ocean, postsmolts rarely exceed 250mm fork length, regardless of their freshwater age (Figure 3) so all individuals in this mode were extracted. Of these, only 184 (0.6%) turned out to be age x.1 individuals. Their ocean age was clearly indicated because they were large and caught prior to week 15

before the smaller YOY fish had left fresh water (Figure 4). The x.1 fish may have remained on/near the shelf through their first winter (Freshwater et al. 2016). Some

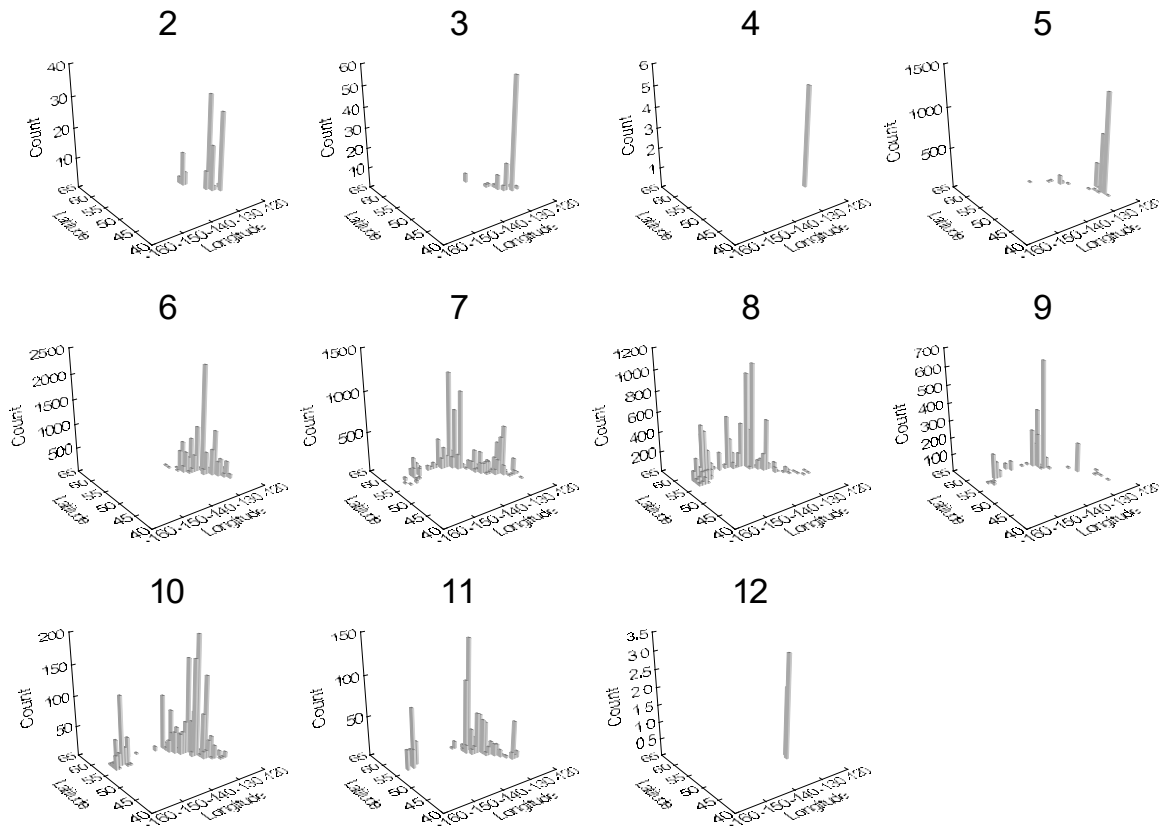


Figure 2: By month, latitude and longitude, bar heights are weighted by YOY sockeye salmon CPUE ($\sqrt{\text{transformed}}$) on the shelf in the IPSDL. Note that scales vary on the z-axis.

may have been age 0.1 sea-run sockeye salmon from the Fraser River (Birtwell et al. 1987). This was the only life-history type found on the west coast of Vancouver Island during an autumn survey (Tucker et al. 2009). Again, none of these samples were aged so it is not possible to know.

Sockeye salmon postsmolts² are caught on the continental shelf, primarily within 20 nm of the coastline during their first summer (Hartt & Dell 1986). Purse seining in 1965, for example, followed the postsmolt migration northward, around the northern Gulf of Alaska, to Shelikof Strait (Hartt et al. 1965). Postsmolts have only rarely caught beyond the continental slope in the Gulf of Alaska from ocean entry in summer (Trudel et al. 2010). Generally, however, they are never caught in deep water in any season (Manzer & Dodimead 1964), confirmed by recent winter sampling (Weitkamp et al. 2024). The

2 Juvenile sockeye salmon in the ocean up to the end of their first winter at sea.

implication is that the mass migration of postsmolts northward around the Gulf of Alaska in summer must overwinter somewhere to the west of Kodiak Island and likely nearer to land than away from it as they are not caught offshore. Sea-run sockeye salmon postsmolts are known to overwinter on the shelf (Tucker et al. 2009). Six individuals (fork length: 170-200 mm) of unknown freshwater age were caught in a midwater trawl survey near Hecate Strait (LeBrasseur & Barner 1964). The lack of YOY individuals offshore in historical and contemporary sampling is the strongest evidence that they are associated with the coast during their first winter.

The bottom depths where YOY sockeye salmon were caught have been examined to assess how much of the shelf to include in the shelf domain (Figure 5). A bottom depth of 500m includes 96% of YOY sockeye

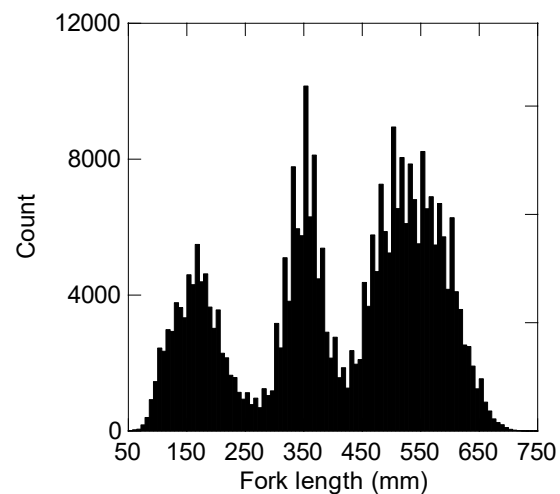


Figure 3: Length frequency of sockeye salmon caught in the North Pacific Ocean and recorded in the IPSDL ($n=318,825$).

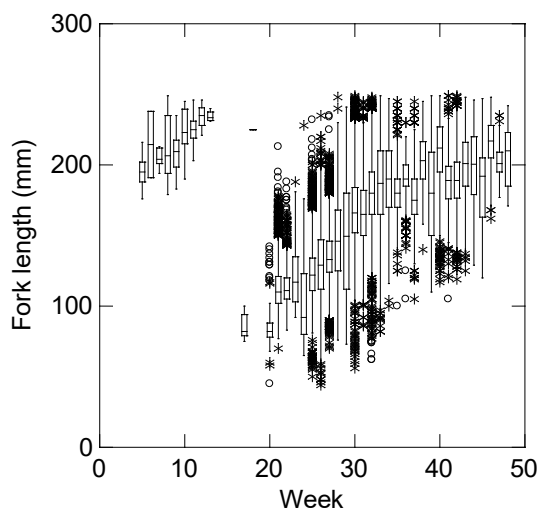


Figure 4: Box and whisker plot of weekly fork lengths of all sockeye salmon caught on the shelf domain that were <250 mm fork length. Boxes in weeks 1-15 are age x.1 and, except for 1 individual, weeks thereafter are age x.0 individuals based on size at capture.

salmon in the IPSDL so that defined the shelf region of interest. Most were caught at even shallower depths than 500m. The only significant departure from this pattern was observed off SE Alaska in 2010 (Trudel et al. 2010) when only ~50% were caught at bottom depths <500m. An eddy was proposed as the cause. Between the Taku and Stikine rivers off Southeast Alaska is a region of anticyclonic eddy formation (Thomson & Gower 1998, Ladd et al. 2007, Henson & Thomas 2008). Sites of formation appear as black triangles in Figure 6.³ The clockwise flow around the eddy is poleward on its seaward edge and equatorward on the inner edge so any postsmolt seeking a poleward boost would follow the outer edge. Conversely, southbound adults could choose the inner edge (Hamilton & Mysak 1986).

Migrations of BC sockeye salmon postsmolts along the shelf are generally northwestward

3 <https://www.aviso.altimetry.fr/en/news/image-of-the-month/2010/mar-2010-eddies-in-the-gulf-of-alaska.html>

after ocean entry (Hartt & Dell 1986) but Tucker et al. (2009) also found that postsmolts, likely lake-type and identified by DNA to Owikeno Lake (Rivers Inlet),

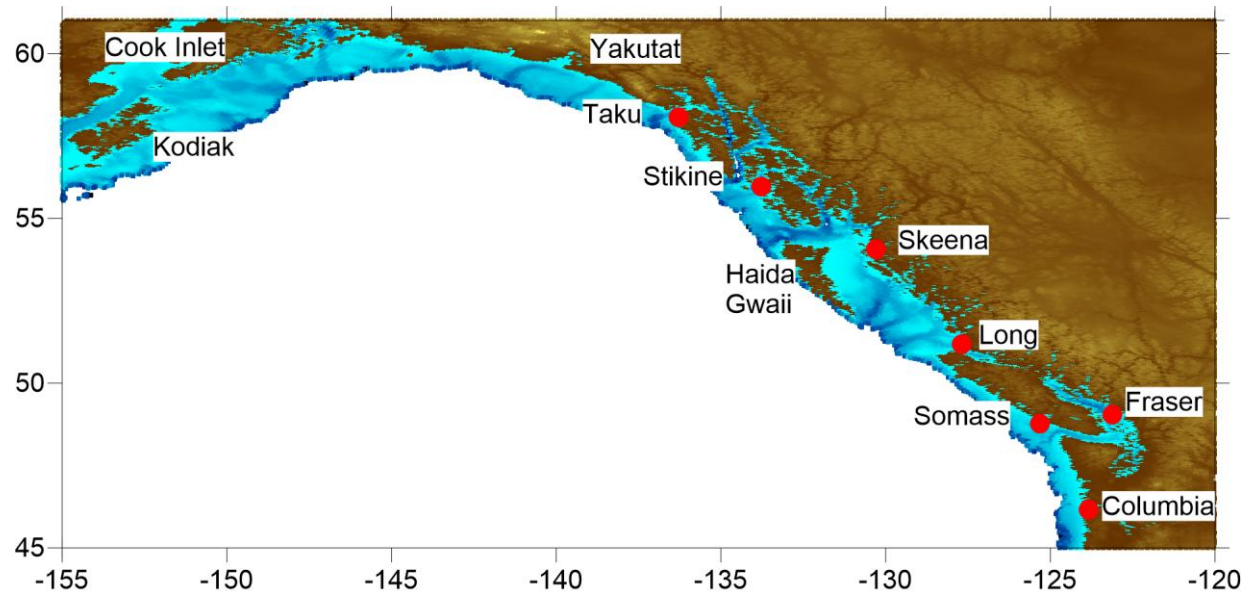


Figure 5: Continental shelf in the Gulf of Alaska with bottom depths less than 500 m. Red dots indicate approximate locations of the estuaries of the sockeye salmon of interest to the study.

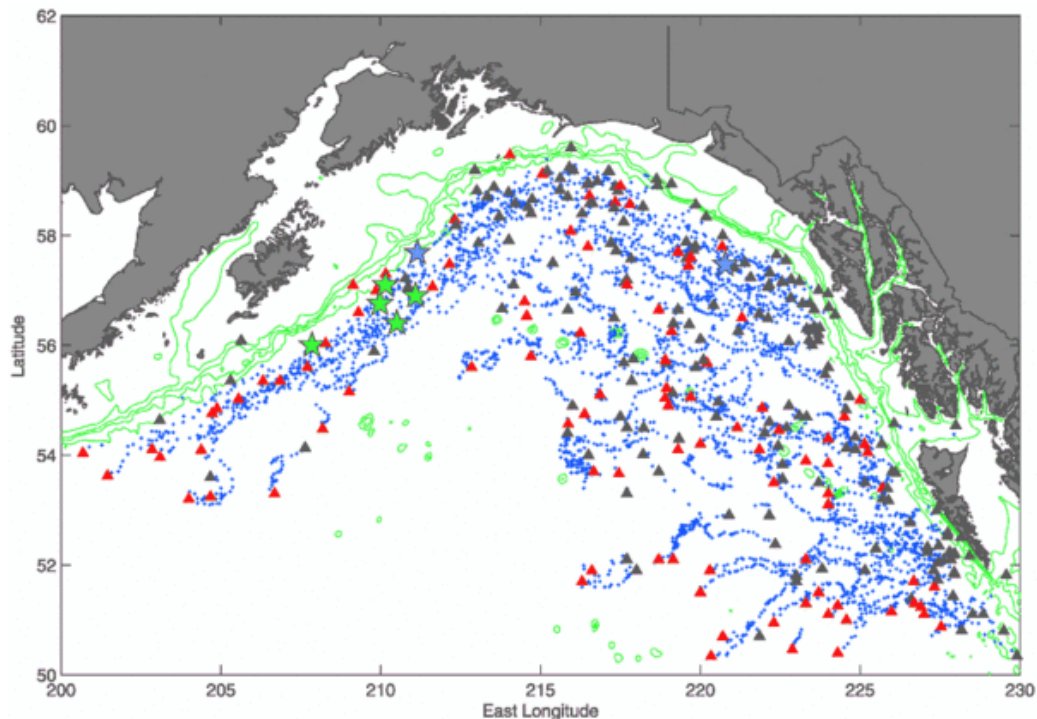


Figure 6: Start (black triangles), end (red triangles), and intermediate (blue dots) locations of eddies.

continued to be found near the point of ocean entry (Queen Charlotte Sound) into autumn. Owikeno Lake has the smallest sockeye salmon smolts (McKinnell et al. 2001) so their small size may have played a role in their slower migration. Small pink salmon (*O. gorbuscha*) fry, for example, are found closer to shore than larger fry after ocean entry (LeBrasseur & Parker 1964).

Having selected the 500m bottom contour as the seaward extent of the shelf domain, based on postsmolt catches, the NOAA database ETOPO1⁴ (NOAA 2009) was used to determine where such depths exist. ETOPO is a global database of bathymetry-altimetry on a 1 arc-minute grid. To align the finer resolution of the ETOPO grid with the $\frac{1}{4}^{\circ}$ latitude/longitude grid of the SST data, average bottom depths were calculated within each SST grid cell from 45°N (just south of the Columbia River estuary) around the Gulf of Alaska to include Kodiak Island (Figure 5). A total of 1401 $\frac{1}{4}^{\circ}$ grid points was created but not all have valid SST data. At $\frac{1}{4}^{\circ}$ spatial resolution, the global NOAA land-sea mask⁵ is a grid of 1440 pixels longitude by 720 pixels latitude, indicating 0 for land and 1 for ocean. After comparing the land-sea mask with the ETOPO1 grid, the number of shelf SST pixels was reduced to 919. Most of the exclusions occurred in pixels where there is more land than ocean, e.g. narrow channels and inlets. The 500m depth portion

4 <https://www.ngdc.noaa.gov/mgg/global/relief/ETOPO1/data/>

5 <https://downloads.psl.noaa.gov/Datasets/noaa.oisst.v2.highres/lsmask.oisst.nc>

of the shelf is narrowest along the coast of Haida Gwaii and to a certain extent off the coast of Washington State. Northward, the shelf broadens somewhat just south of Icy Strait (near Taku in Figure 5) and westward to Kodiak Island.

1.2. BASIC SST STATISTICS

At each of 919 grid points, average SST, standard deviation (SD) and coefficient of variation (CV) were computed by year and week. The primary interest was to determine when and where interannual variability in SST was high as these are potentially times/place where migrating sockeye salmon may encounter greater differences from year to year. Average weekly SST varied from a low of -0.92°C (week 5, 61.125°N 150.125°W , head of Cook Inlet) to a high of 17.5°C (week 30, 49.375° 123.875°W , Strait of Georgia). Cook Inlet also had the highest standard deviation (week 21) and the lowest standard deviation (week 4), both likely due to sea ice dynamics as sea ice temperature is nearly invariant. In the following study, the “warm” season was defined as the period between the equinoxes when the northern hemisphere is warm; the cold season the reverse.

Standard deviations are lowest in the cold season and highest in the warm season reaching an annual maximum in early July (week 27). No doubt, the spring freshet plays a role in this timing. The interannual variability of SSTs tends to diminish northward except in Cook Inlet and Shelikof Strait region (Figure 7; middle). The most extreme interannual variability was found in/near Cook Inlet and it did not diminish until after the summer solstice. Some grid points have $\text{CV}=400\%$ while most of the shelf ($\sim 99\%$) has much lower interannual variability, $\text{CV}<40\%$.

The annual seasonal signal is the dominant feature of SST variation (not shown). For most of the shelf it is warmer in summer and cooler in winter, but this pattern can be reversed close to the Washington/Oregon coast where seasonal upwelling winds bring nutrient rich cold water to the surface in summer as the surface waters are advected seaward. Generally, strong SST outliers tend to be negative in the cold season and positive in the warm season. When smolts are entering the ocean beginning about week 20, the warmest average temperatures in the domain are in the northern part of the

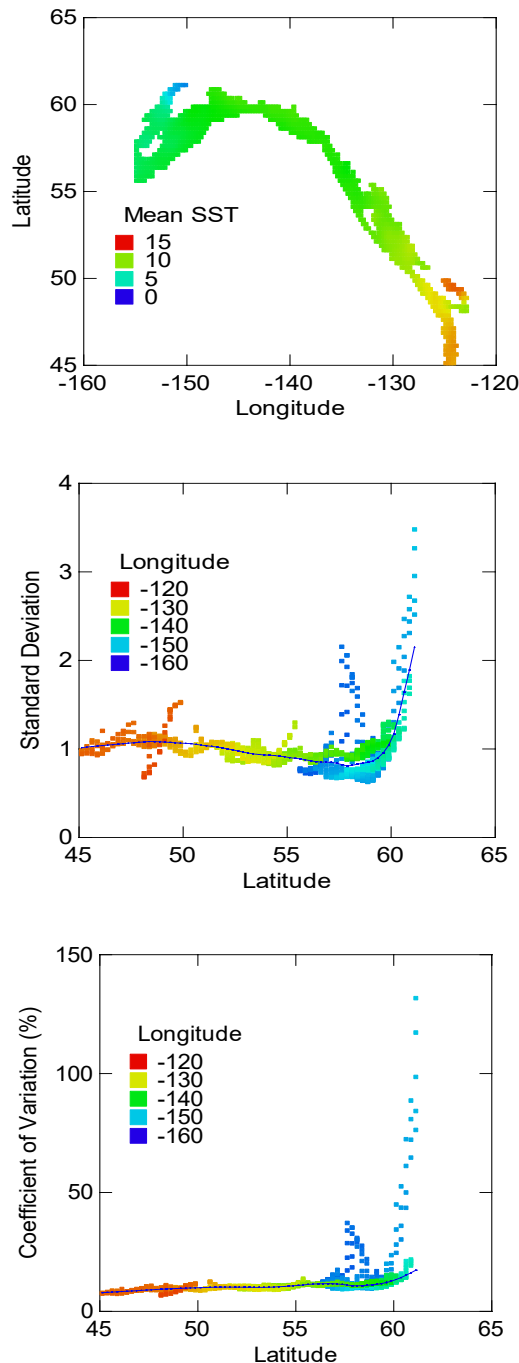


Figure 7: In week 20, [upper] Mean SST, [middle] SD versus latitude, and [lower] CV versus latitude. Loess smoothers were applied to the middle and lower panels.

Strait of Georgia and to a lesser extent off the coast of Washington (Figure 7; upper). The coldest average temperatures are in Cook Inlet.

1.3. EXTREMA

In any particular week, it can be of interest to know if any of the 919 grid points had an extreme SST (high or low) in that week over the entire time series. If an extremum is found at some place and time, how many grid points shared the extreme SST that week? Simply counting all such extrema each year provides an indication of the nature of extremes in that year.

The year with the most observed maxima was 2016 (23.3% of all week/grid combinations), most of which were observed in the late winter/early spring which is not so unusual during a winter with a strong el Niño (Figure 8; upper). The year with the most SST minima was 1985 (13.5%) and most of these were observed in the autumn (Figure 8; lower). Since 1981, the frequency of cold extremes on the shelf has diminished, especially since the marine heat wave began in late 2013. The frequency of warm extremes has increased over that period.

2.0. SST ANOMALIES

The intent of this section is to examine the nature of non-seasonal variation and covariation in sea surface temperature anomalies (SSTA) in the shelf domain from several different perspectives. Understanding what covaries and how strongly may provide indications of where boundaries for subdomains might be placed, or indeed whether any are indicated at all. As the focus of the study is juvenile sockeye salmon migrating along the shelf in

spring/summer, the correlations among SSTA timeseries were computed using only the weeks from the warm season.

2.1. E-FOLDING SCALE

The first perspective on SSTA covariation was to calculate correlations among time series at all grid points. By definition, the correlation of a time series with itself is 1.0, but a nearby grid point might be nearly as high. How correlations diminish with increasing geographical distance separating them can reflect the scale of the force(s) responsible for the correlations. This has been called an e-folding scale (Myers et al. 1997, McKinnell and Karlström 1999). The second perspective was to use the covariance matrix of SSTA time series in a standard empirical orthogonal function (EOF) analysis. This reveals the geographic patterns of SSTA covariation at zero lag, indicating if and where regions of high and low coherence can be found. The EOF analysis also generates the temporal patterns (scores) for each EOF which can be used as indices of each pattern. As this is a study of a small number of widely separated watersheds, the third perspective on SSTA covariation was to select a single grid point located near the mouth of each river, where the sockeye salmon first encounter the ocean, to see how SSTA near these estuaries compare among them.

The e-folding scale is measured as the distance required for the correlation to drop from 1.0 to $1.0/e$, where $e \approx 2.7183$. Of the 844,561 correlations (919^2) among SSTA at grid points on the shelf, 844,521 (99.95%) were positive. The median correlation at maximum distance between grid points (~ 2500 km) was 0.28 (Figure 9). The e-folding scale was a relatively large 902 km, the equivalent of $\sim 8^\circ$ of latitude. Mueter et al. (2002) had previously described the temporal correlation scale among Gulf of Alaska salmon rivers as

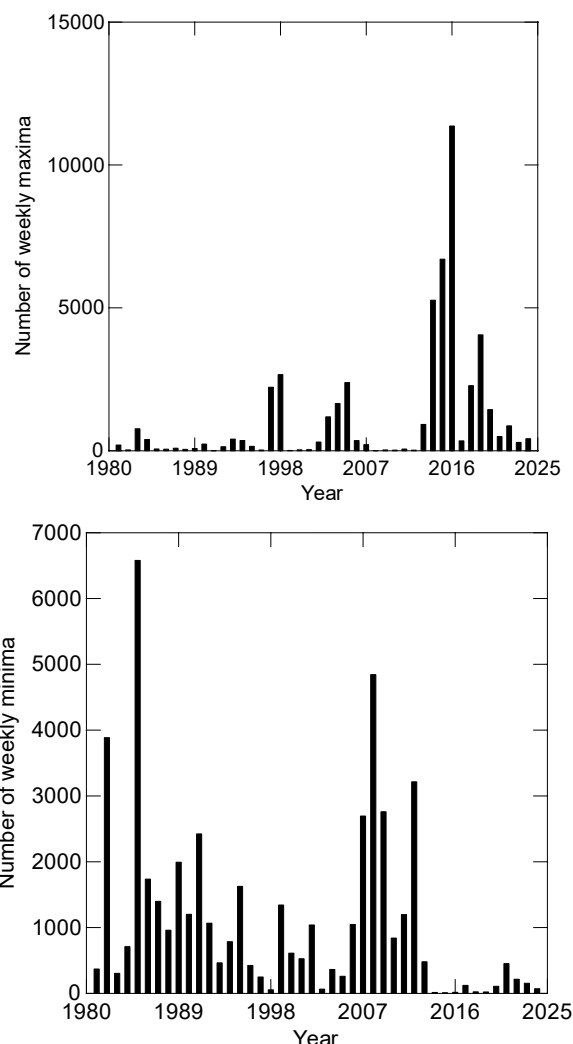


Figure 8: Numbers of weekly SSTA extrema [above= maxima, below=minima] observed in each calendar year (all weeks).

being on the order of hundreds of kilometres.

2.2. EOF SPATIAL PATTERNS

The SSTA covariance matrix was calculated from area-weighted anomalies. Area-weighting of the anomalies by the cosine of latitude ($\sqrt{}$ transformed) was done because grid points represent a decreasing area of the ocean as latitude increases. At 90°N, the ocean area represented by that grid point is infinitely small so polar grid cells should not be given the same influence as a grid point on the equator.

The dominant and subdominant eigenvectors were extracted from the covariance matrix using the IMSL subroutine EVESF. This FORTRAN subroutine is useful because the number of eigenvectors to extract is determined arbitrarily by the researcher. As the dominant eigenvector accounted for so much of the covariance in this SSTA

analysis, there was no need in this study to extract more than two. EOF factor score coefficients were calculated with FCOEF, then factor scores with FSCOR.

The covariance matrix was based on 2248 weeks of data from September 1981 to August 2024. The dominant EOF of SSTA (EOF1) accounted for 57% of the covariance while the subdominant EOF (EOF2) accounted for only 11%. All EOF1 loadings (correlations between the temporal variation in EOF1 and that of SSTA) were positive (range: 0.41 – 0.87) indicating that the dominant pattern of non-seasonal covariation from week to week on the shelf is widespread (Figure 10) as was reflected in the e-folding scale above. Put more simply, it means that SSTA at all grid points are varying up and down in synchrony. A pattern of coherent widespread variation is akin to a “breathing mode”, a term coined by Freeland (2006) to describe North Pacific Current circulation in the Gulf of Alaska but it seems to apply to the EOF analysis as well.

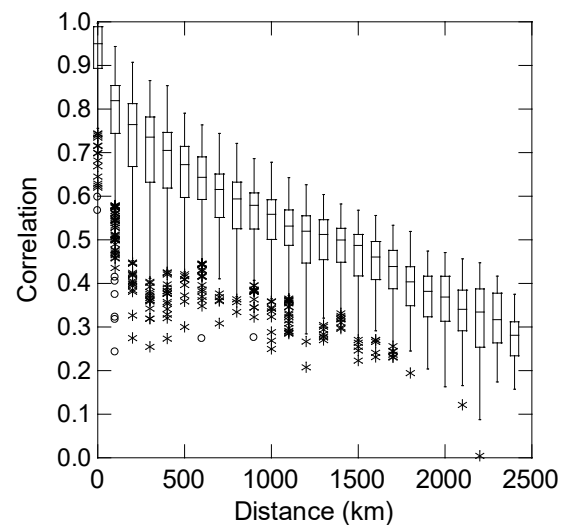


Figure 9: Box and whisker plots showing the decrease in median correlation among SSTA time series with increasing distance between grid points. Correlations were computed from 2248 weeks of data at each grid point.

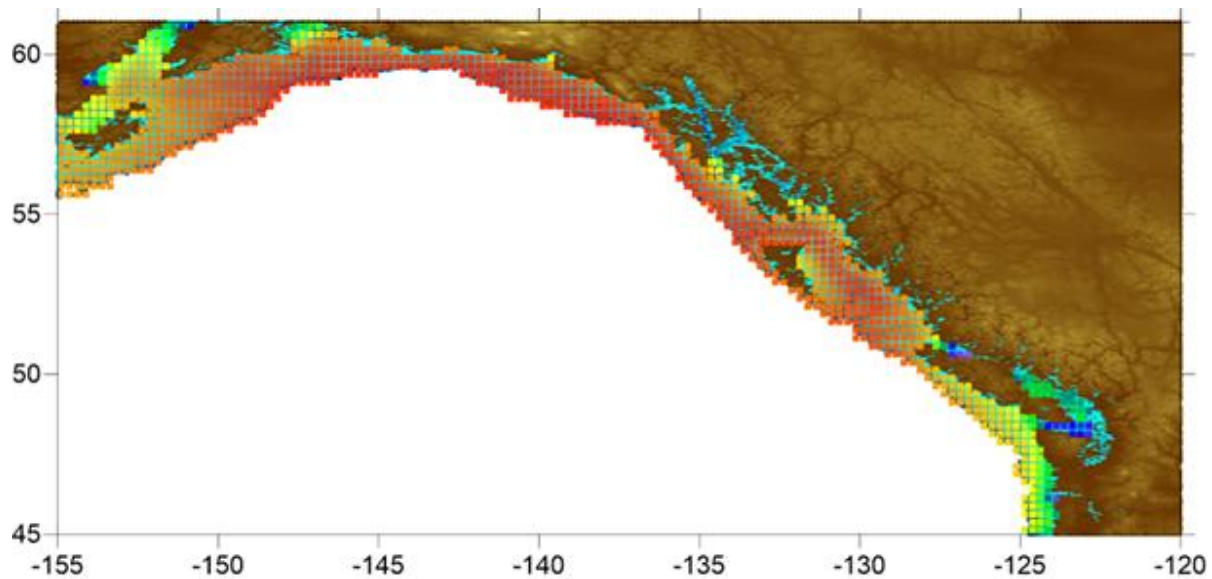


Figure 10: Spatial pattern of EOF1 (weekly SSTA from 1981 to 2024). Loadings are all positive ranging from 0.4 (blue) to 0.9 (red).

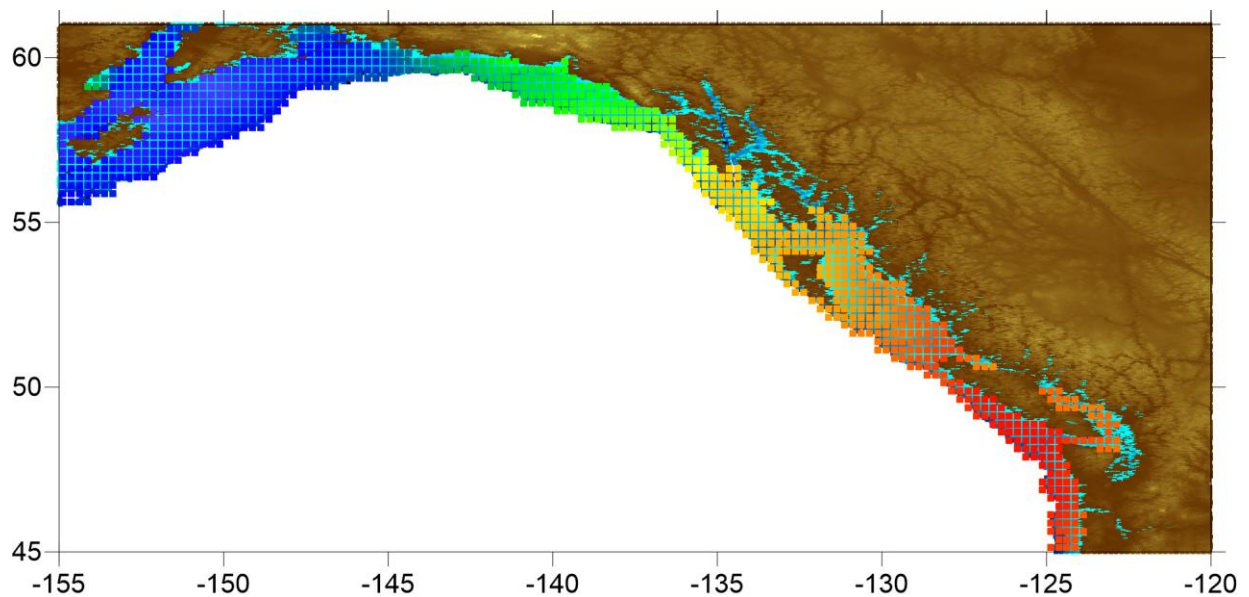


Figure 11: Spatial pattern of EOF2 (weekly SSTA from 1981 to 2024). Loadings range from -0.5 (blue) to 0.5 (red). The transition from negative to positive occurs at about 57°N (near Sitka, Alaska).

Grid points with the highest loadings are the most representative of this variation. The greatest single positive loading on EOF1 was located near 58°N 138°W, just north of

Icy Strait, Alaska. It was part of a region of high correlation with EOF1 that included most of the shelf from Queen Charlotte Sound to Kodiak Island. The least positive loading was located near 50.5°N 126.5°W in Queen Charlotte Strait. Other parts of the shelf with lesser correlation with EOF1 included Cook Inlet and shelf region west of it, the Strait of Juan de Fuca, Strait of Georgia, and near the mouth of the Columbia River.

EOF2 loadings had a geographical arrangement that is often termed a dipole (Figure 11), with negative loadings in the north and west and positive in the south with little/no interleaving of areas with both positive and negative loadings. Unlike EOF1, no loadings were particularly strong (range: -0.43 to 0.54), indicating that no place on the shelf was particularly representative of this dipole pattern. The division between positive and negative loadings on EOF2 occurs near 57° (Sitka, Alaska). The frequency distribution of EOF2 was bimodal, i.e. few loadings had values near zero. Stronger negative loadings on EOF2 were found from Prince William Sound westward, while stronger positive loadings were found from Queen Charlotte Sound southward, but only west of Vancouver Island in the latter case. While having the same sign as other southern locations, the loadings in the Strait of Georgia were weaker than on the outer coast. This EOF analysis was repeated using monthly SSTA data to facilitate a comparison with the PDO that is described in the next chapter. The traditional PDO index has a monthly time interval.

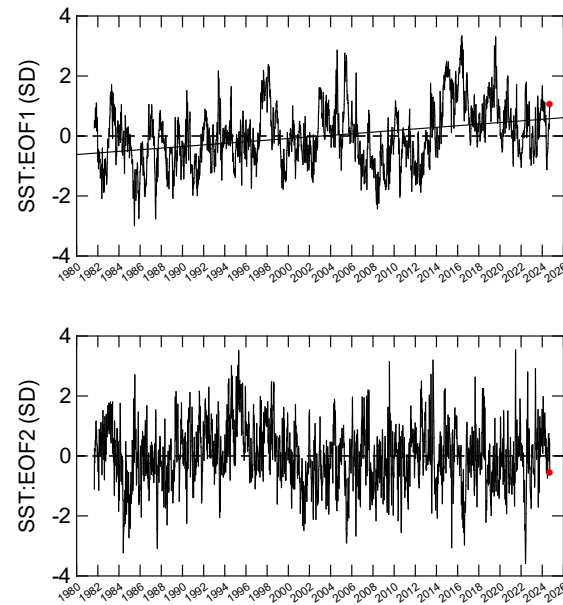


Figure 12: Weekly temporal variation in EOF1 (57%) and EOF2 (11%) of shelf SSTA from 1981 to 2024. Week 39, 2024 is indicated by a red dot.

2.3. EOF TEMPORAL PATTERNS

The time series of both EOFs exhibit high and low frequency variation, although the high frequency variation is more evident in EOF2 (Figure 12). Fourier analysis of detrended scores indicated that the dominant period of variation in both EOF1 and EOF2 is 19.3 years which does not coincide with any long-period solar or lunar variation. The nearest period with known expression in the NE Pacific is the lunar nodal cycle at 18.61 years (McKinnell and Crawford 2007). Fitting a trigonometric wave model to EOF1 gave a similar result as the Fourier analysis ($R^2=16.8\%$) but not for EOF2 where the estimated period was 16 years ($R^2=8\%$). Little of the low frequency variation was described by these trigonometric models. Time series exhibiting low frequency variation are often too short to distinguish red noise from forced signals.

2.4. OCEAN ENTRY SST

Assuming that a grid point located near each rivermouth is a proxy for SST where smolts enter the ocean (Table 1), a principal component analysis (SYSTAT V9.01) of the correlation matrix of the SSTA, warm season only, found that all rivermouths loaded positively on the dominant PC (53%) (Figure 13) indicating that all estuaries share a substantial fraction of their non-seasonal variation despite the distance between them. The grid point near the Taku River was the least correlated with PC1. The subdominant PC (14%) was clearly linked to geography with the Taku having the most negative value and the Columbia/Fraser having the most positive values. Skeena, Long, and Barkley/Somass were uncorrelated with the subdominant PC. The main conclusion to draw from this analysis is that SSTA variation near where sockeye salmon enter the ocean is dominated by regional rather than local processes on these monthly temporal/ $\frac{1}{4}^\circ$ spatial scales. Lag correlations within each SSTA time series found that the temporal decay of SSTA was slightly more rapid in the north than in the south, although the watershed with the steepest correlation decay (Long) is located midway along the coast. Perhaps this more rapid decay is due to enhanced diapycnal mixing in Queen Charlotte Strait due to tidal activity over rough topography.

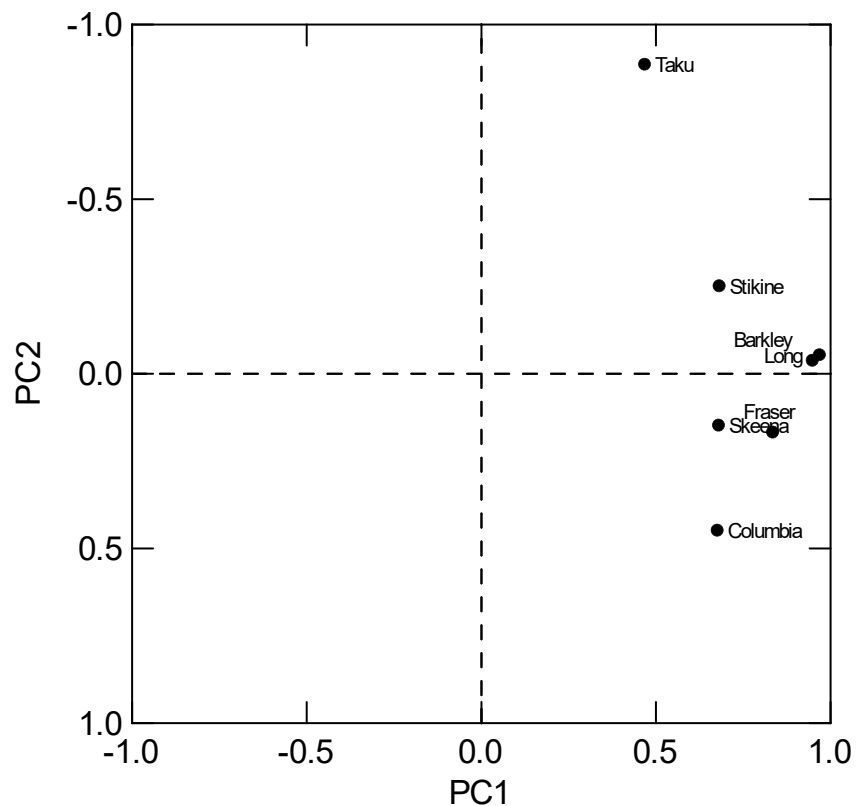


Figure 13: Loadings from a Principal Component (PC) analysis of weekly SSTA, warm season only for rivermouth grid points. Note that the ordinate has been reversed to highlight the geographical association.

Table 1. Approximate locations of marine estuaries of sockeye salmon watersheds in Figure 5.

Longitude	Latitude	Watershed
-136.41	58.2	Taku
-133.90	56.1	Stikine
-130.42	54.2	Skeena
-127.81	51.3	Long
-125.43	48.9	Somass
-123.23	49.2	Fraser
-123.955	46.3	Columbia

3.0. OCEAN CLIMATE

For several decades, climate indices (PDO, SOI, ONI, NPI, ALPI, etc.) have been used to study climate effects on salmon survival. Nearly all are based on correlations that, if statistically significant, have led to speculation about their causal interconnections (eg. Beamish & Bouillon 1993, Francis & Hare 1994, Hare & Francis 1995, Mantua et al. 1997). The best known of these indices in the Pacific is the PDO (Pacific Decadal Oscillation, Mantua et al. 1997). As of October 24, 2024 it had been cited 9,102 times (Google Scholar).

When comparing salmon survival and some aspect of climate, the null hypothesis tested, more often than not, is $H_0: r = 0$. Unfortunately, if any time series of a natural phenomena is sufficiently lengthy, chances seem rather good that there will be some low frequency variation in one or both that will lead to H_0 being rejected. The more stringent test “is the temporal correlation spurious?” is rarely considered as doing so requires both a testable mechanism and external data that are not often not available. It seems that connecting the dots between environmental pressure and biological response is rarely done satisfactorily. Doing so requires some knowledge of when/where salmon will be found, understanding what they are experiencing, or have likely experienced, and importantly, whether that pressure would be sufficient to affect survival. Doing that requires a focused view on the pressures and responses at appropriate scales when and where salmon are known to exist. Grappling with issues of scale is one of the major challenges of marine science (Francis & Hare 1994).

The present study is not the first to consider this issue. While examining a somewhat larger domain that included the eastern Bering Sea sockeye salmon populations, Mueter et al. (2002) made some important observations. Notably, they found that sea surface temperatures (SST) located within several hundred kilometres of a salmon’s natal estuary were better predictors of survival rates than large-scale climate anomalies

associated with the Pacific Decadal Oscillation (PDO), suggesting either that survivals are primarily linked to environmental conditions at subregional spatial scales, or perhaps that the PDO does not reflect what salmon are experiencing at the time and place where they either live or die; primarily the continental shelf.

3.1. THE PDO AND THE SHELF

As the PDO index of Mantua et al. (1997) has a monthly time step, it seemed desirable to re-compute the shelf EOFs using monthly average SST data (also a $\frac{1}{4}^\circ$ grid). The monthly time series begins in September 1981 and ends, in the present analysis, on September 2024 when downloaded on 13 November 2024.⁶ Various versions of the PDO index were available at the NOAA site, each derived from a different average SST product. Their spatial patterns differed so little that the Hadley Center version was selected arbitrarily. The Hadley Center data were used in constructing the original EOFs (Zhang et al. 1997) as was the PDO, which was developed from monthly average SST data from 1900-1993 on a 5° latitude/longitude grid (Mantua et al. 1997)⁷.

Although it did not have the PDO moniker at the time, the analysis of Zhang et al. (1997) had the primary goal of examining the ENSO-like spatial pattern in the North Pacific that appeared in its dominant EOF. To focus on this particular pattern, seasonality was removed to create SSTA by subtracting long-term monthly means from the monthly SSTs. They also removed the effect of any secular warming trend that may have occurred during the 20th century by removing the monthly grand mean (of SSTA) from each monthly

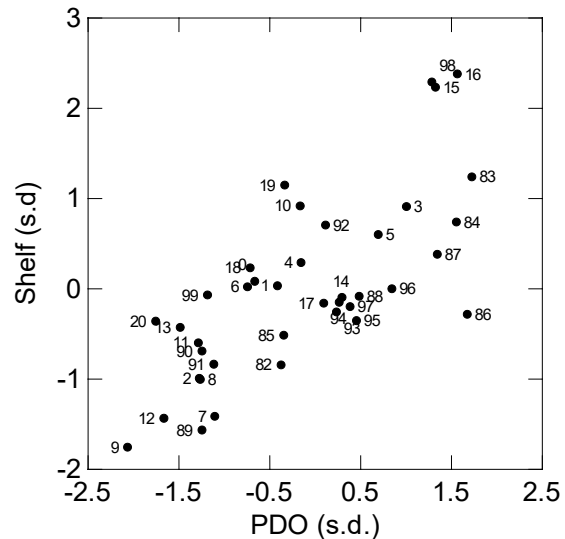


Figure 14: Shelf SSTA-EOF1 vs PDO in the month of March from 1982. Plot point labels indicate year.

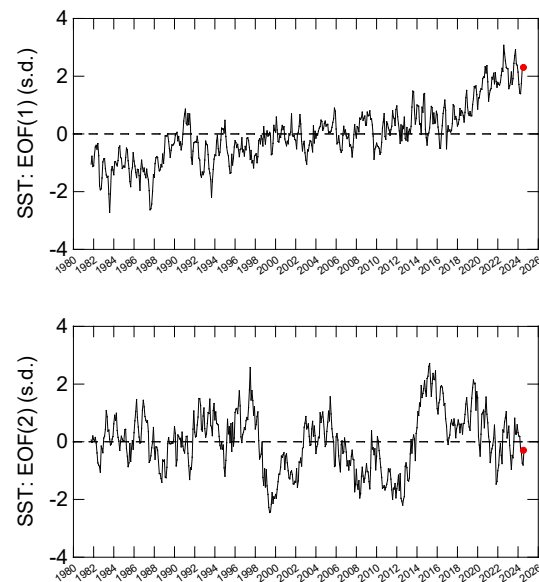


Figure 15: EOF analysis of monthly SSTA in the PDO domain of the North Pacific (20° - 66° N). EOF1 is the Victoria pattern and EOF2 is the PDO pattern.

⁶ <https://downloads.psl.noaa.gov/Datasets/noaa.oisst.v2.highres/sst.mon.mean.nc>

⁷ Monthly 1° resolution OISST data from 1994-96 were rolled up to 5° resolution to extend the time series to 1996.

SSTA. Their EOF analysis was calculated after making these adjustments. There was no mention of area-weighting the SSTA in Zhang et al. (1997).

From 1981 to 2024, the PDO is positively correlated (weakly) with shelf EOF1 (0.40) and also with EOF2 (0.10). Therefore, the PDO accounts for about 16% of the overall variation in shelf EOF1, which in turn accounts for 58% of shelf SSTA covariance. The magnitude of the correlation between shelf EOF1 and the PDO varies with season, with the PDO more strongly correlated during the cold season than in the warm season, and the two are virtually uncorrelated during the warm season. The highest correlation between the PDO and shelf EOF1 is in the month of March (0.65) at zero lag (Figure 14). Much of the strength of this correlation, and that in any other month, is due to the strong influence of the most negative and positive values of the indices. Where most of the data lie in the interior of the distributions their correspondence is relatively weak. For example, PDO values >1.5 correspond to a range of EOF1 values on the shelf varies from weakly negative to very positive. Therefore it seems that using the PDO as an indicator of the dominant variation of the coastal ocean may be misleading.

3.2. VARIATIONS ON THE PDO THEME

Given that warming of the World Ocean is of greater interest now than 30 years ago when the PDO was being compared to el Niño, it is of interest to recompute the SSTA EOFs on the same PDO domain but without removing secular trends in the data. Until about 10 years ago the results of EOF analyses with and without removing a trend differed little. The correlation between the two was 0.95 (Bond et al. 2003) but that appears to have changed. The PDO differed little from an EOF analysis of SSTA that retained any trend in the anomalies.

Today however, the PDO is the dominant EOF pattern in the North Pacific only if the secular trend is removed from the SSTA. If an EOF analysis is conducted on the SSTA without adjustment, the Victoria pattern becomes dominant (21%) while the PDO pattern becomes subdominant (14%). The Victoria pattern was named after the location where it was first noticed at a PICES workshop. It appears that the spatial scale of warming in the North Pacific is now sufficiently widespread that it has become the dominant EOF (Figure 15). The PDO pattern, seen in this figure as EOF2, retains its low frequency variation which appears to remain unchanged.

The low frequency pattern of the PDO is evident in local indices. Using time series of air temperature (Olga, San Juan Island),

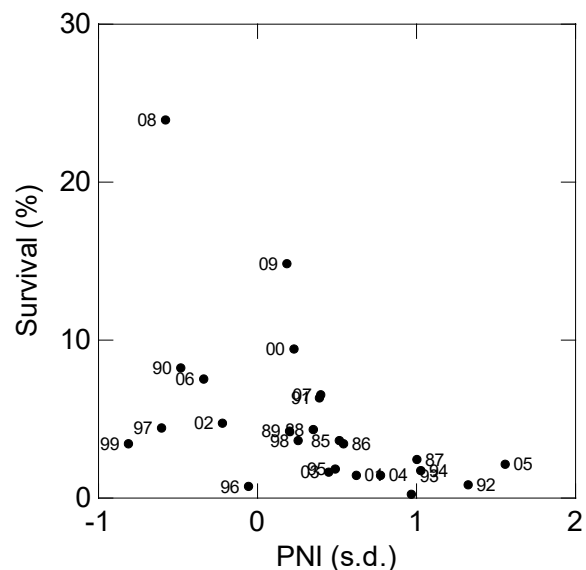


Figure 16: Association between Columbia River sockeye salmon smolt to adult returns versus the PNI index. Plot point labels are ocean entry years.

snow pack (Mt. Rainier) and total precipitation (Cedar Lake), the low frequency component of variation in the Pacific Northwest Index (Ebbesmeyer and Strickland 1995) reflects the climate regimes that are also evident in the PDO (Figure 17). The air temperature time series at Olga ended in April 2016 but an attempt was made to estimate recent observations to keep the time series going.⁸ Years of positive Pacific Northwest Index (PNI) tend to be warmer and drier and years with negative PNI are cooler and wetter than average.

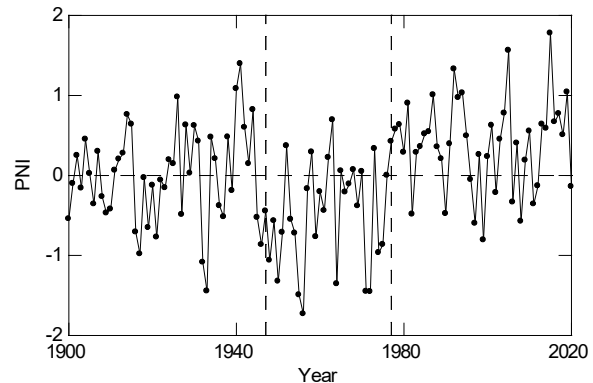


Figure 17: Pacific-Northwest Index (San Juan Is. Air Temperature, Mt. Rainier snowpack and Cedar rainfall, annual). Vertical lines (1947, 1977) indicated abrupt changes in mean values of the index.

Andersen and Hinrichsen⁹ concluded that the PNI was not correlated with survival of Columbia River spring chinook salmon, at least on an annual basis. They felt that the timing of the spring transition (shift from generally southeasterly winds to generally northwesterly winds) played a greater role. On the other hand, the relationship between the PNI and Columbia River sockeye salmon marine survival (Williams et al. 2014) has a negative correlation, perhaps heavily influenced by 2008 and 2009, but the negative correlation remains statistically significant if these extreme years are excluded from the calculation (Figure 16). No adjustments for auto-correlation were made as the first-order autoregressive (AR1) correlations for both time series are <0.2 . Regardless, from the 1980s to 2009 there are no instances of high survival associated with high PNI.

3.3. EQUATORIAL TELECONNECTION

The atmosphere/ocean interaction in the equatorial Pacific Ocean has a major influence on global climate via teleconnections (Bjerknes 1969). Various indices including the Southern Oscillation Index (SOI) have attempted to simplify the nature of the variation. The SOI reflects monthly sea level pressure differences between Tahiti and Darwin. NOAA's Ocean Niño Index (ONI) reflects monthly average SSTa from 5°S to 5°N, 170°W to 120°W.

Considering that it might be of interest to create an index that captures variation across the entire equatorial Pacific Ocean, monthly SSTAs were computed at grid points from the Coral Sea (146°E) to the coast of Ecuador (78°W), and from -5°S to 5°N. As the number of $\frac{1}{4}^\circ$ grid points in this domain (order= 22,224) exceeded the maximum array size allowed by the compiler, grid points within this domain were randomly selected to reduce the number of time series to a manageable number (matrix order=10,500). The spatial and temporal correlations in SSTa at the equator are relatively high compared to

8 https://www.cbr.washington.edu/sites/default/files/papers/Olga_Surrogate_DFA_FINAL.pdf

9 <https://www.researchgate.net/publication/253739085>

other regions of the globe so the selected grid points are likely very representative. The dominant EOF accounts for 68% of the non-seasonal variation in SSTA near the equator. The AR1 correlation of the dominant EOF is 0.95 which is a much larger temporal autocorrelation (persistence) than most other regions. The el Niño – la Niña cycle is the dominant feature of EOF1, hereafter the EQ-Niño Index (ENI).

A comparison of the variation in the Gulf of Alaska shelf EOF1 with the ENI through all months of the time series finds a maximum correlation ($r=0.7$) when the February ENI is lagged to the April EOF1 on the shelf (Figure 19). In other words, about half of the variation in the dominant EOF on the shelf in spring is due to the dynamics of equatorial climate in the boreal winter. McKinnell and Crawford (2007) found a similar lag period. The follow-on question is how long does an SSTA anomaly persist on the shelf? It depends where you look, but the auto-correlation of SSTA decays to non-significance (as defined by the e-folding scale) over 3-8 weeks (Figure 18). What might this imply for postsmolt migration?

Assuming a migration speed of 15 nm (19.5 km) per day, the equivalent in terms of distance is about 400 to 1100 km. The total migration distance from the Columbia River to Kodiak Island along the shelf is approximately 2850 km. Even at half the migration speed, a juvenile sockeye salmon will experience an SSTA that becomes established in spring through a substantial fraction of its shelf migration.

3.4. SHELF EOF1 VERSUS HYDROGRAPHY

So far, much of the discussion of SST variability has been viewed through the lens of an EOF analysis of satellite-derived data. The region of positive loadings on the shelf is extensive, from the Columbia River to Kodiak Island. To verify that the results of the EOF analyses correspond with reality, especially in a region where cloud

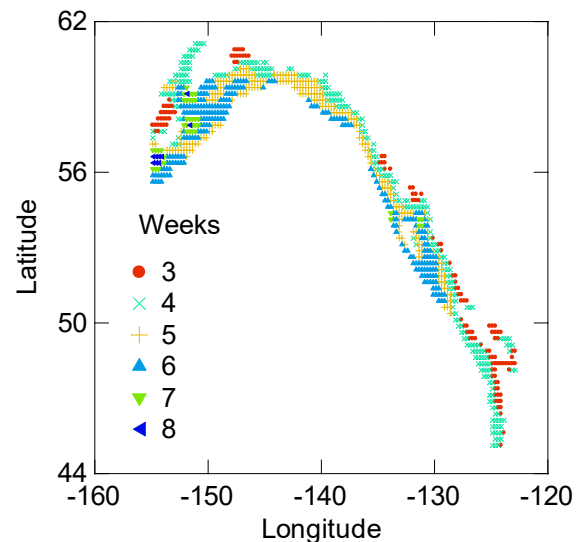


Figure 18: Persistence (temporal e-folding scale in weeks) of SSTA from the equinox to the solstice.

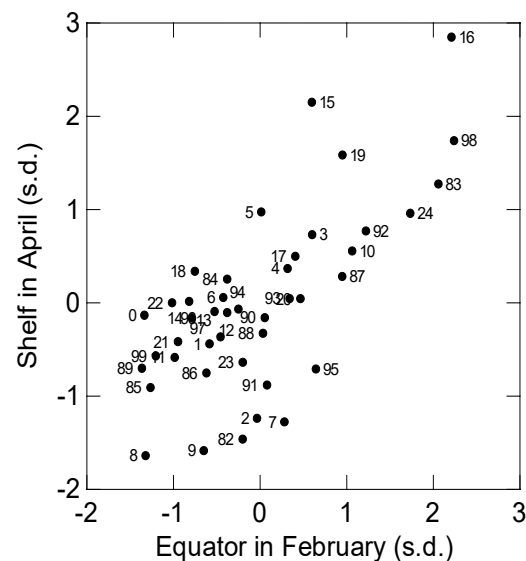


Figure 19: Comparison of Shelf EOF1 (ordinate) with Equator EOF1 since 1981; a 2 month lag.

cover is high, a comparison was made between SSTA:EOF1 and *in-situ* hydrographic measurements in the northern Gulf of Alaska.

The Seward Line (hydrographic) runs cross-shelf from Resurrection Bay and its stations have been occupied since the 1970s. GAK-1 is the innermost station (59° 50.7' N, 149°28.0' W) at bottom depth ~250m. If an argument is to be made that the most substantial anomalies in the Gulf of Alaska have an equatorial origin, and that they are widely felt in the GoA, then it might be of interest to compare how well the shelf EOF1 variation is reflected in the *in situ* observations made at GAK-1. Shelf EOF1 is highly correlated ($r = 0.87$) with GAK-1 SST in March when the equatorial influence is greatest. GAK-1's correlation with the PDO in March is weaker (0.63) (Figure 20).

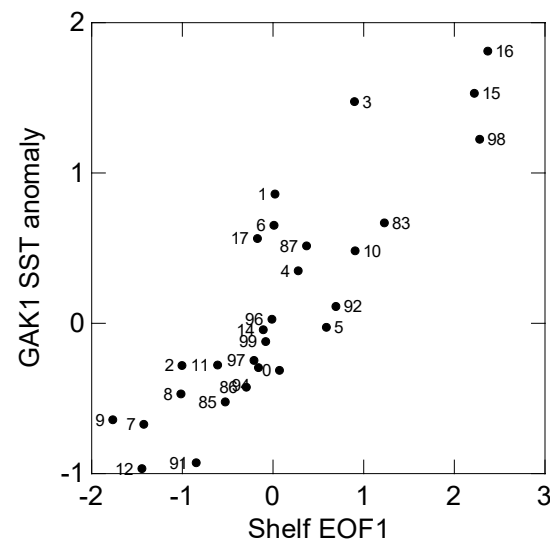


Figure 20: March SST anomalies at GAK-1 compared to shelf EOF1 scores, 1982-2017.

4.0. SURVIVAL

Table 2. Number of years of juvenile to adult (marine) survival of BC sockeye salmon populations since 1981.

Watershed	Years of survival data
Chilko	38
Chilliwack	6
Cultus	20
Francois	2
Fraser	8
GCL	38
Osoyoos	34
Shuswap	18
Sproat	38
Tahltan(wild)	34
Tahltan(hatchery)	27
Tatsamenie	11
Wenatchee	8

Most assessments of the spatial patterns of sockeye salmon survival come from recruits per spawner data (Mueter et al. 2002, Peterman and Dorner 2012). Estimates of marine survival (recruits per juvenile) are few. Where they exist, sampling was often intermittent resulting in a marine survival data set with few years of comparable estimates (Table 2). Nevertheless, the few longer time series that do exist are potentially valuable in determining where to establish survival subdomains.

Consider this. If the marine survivals of all sockeye salmon populations in BC were strongly positively correlated, it would not be unreasonable to conclude that some region-wide environmental pressure was affecting them all in a similar manner. At the other extreme, if none of their marine survival histories were correlated, it would not be unreasonable to conclude that local pressures, perhaps near estuaries, were responsible for determining the survival of a cohort in the ocean. If the result of such comparisons lies somewhere between these extremes, the patterns of correlations among watersheds might provide some insight as to the nature and scale of forces affecting marine survival, especially if the patterns have a geographical pattern.

Most marine survival time series are not exclusively marine as the initial observations of cohort abundance have been measured in fresh water. Smolts are counted at fences as the emigrate from nursery lakes or if there is no outlet observation point, late-fry stages are assessed by echo-counting and trawling nets in lakes in the fall. There are instances where predators such as bull trout (*Salvelinus confluentus*) have taken advantage of the annual emigration of sockeye salmon smolts (Furey et al. 2016). High survival during downstream migrations has been reported, particularly where the migration to the ocean is short (Wood et al. 1993) and/or where the rivers are large and/or turbid (Welch et al. 2011).

Four of the longer juvenile to adult survival time series¹⁰ (Table 2) were selected as sufficiently long for a principal component analysis of the correlation matrix: Great Central Lake, Sproat Lake, Osoyoos Lake, and Chilko Lake. Two additional time series with smolt to adult survival estimates were also included: Columbia River (Williams et al. 2014) and the Skeena River (Babine Lake) (Cox-Rogers and Spilsted 2012). The correlation in survival between any two locations was calculated from all years where survival data were available for pairs of rivers (pairwise correlation). As each time series has a different duration, some with short gaps, the number of years of joint data from which to calculate a correlation will vary among pairs of locations.

Large fractions of acoustically-tagged sockeye salmon postsmolts have died (or are assumed to have died) during the first part of their coastal migration (Welch et al. 2011). These studies have added weight to the longstanding view that most of the mortality of salmon in the ocean occurs shortly after arriving at the estuary (Parker 1962). It is generally assumed that the untagged fraction has a similar mortality schedule although few data can be brought to bear on that issue. Surgically implanted tags are known to have reduced swimming speeds of sockeye salmon compared with PIT tagged individuals (Furey et al. 2016) but comparable mortality to untagged fish is not known. Nevertheless, it will be assumed that something like the tagged mortality schedule applies to the untagged fish, but perhaps with a different (larger) intercept.

4.1. COVARIATION OF MARINE SURVIVAL

A bootstrap loop of 1000 iterations was wrapped around a principal component (PC) analysis, randomly resampling the original survival data (with replacement) at each iteration to get some understanding of the statistical uncertainty of the PC loadings. Note that the Columbia River and Osoyoos Lake time series are from the same river but by different authors. Both were included to provide some perspective on within and between river results.

PC1 accounted for an average of 51% of the covariation among the six watersheds and PC2 accounted for an average of 22%, for a total variance explained of 73% in the two leading PCs. If they were uncorrelated time series the expected value for two PCs would be 34% so there is clearly some shared history of survival among these watershed. Some of the shared variance in survival is due to including both the

¹⁰ Provided by DFO on November 7, 2024

Williams' Columbia River SAR time series and the DFO/Osoyoos series in the same analysis.

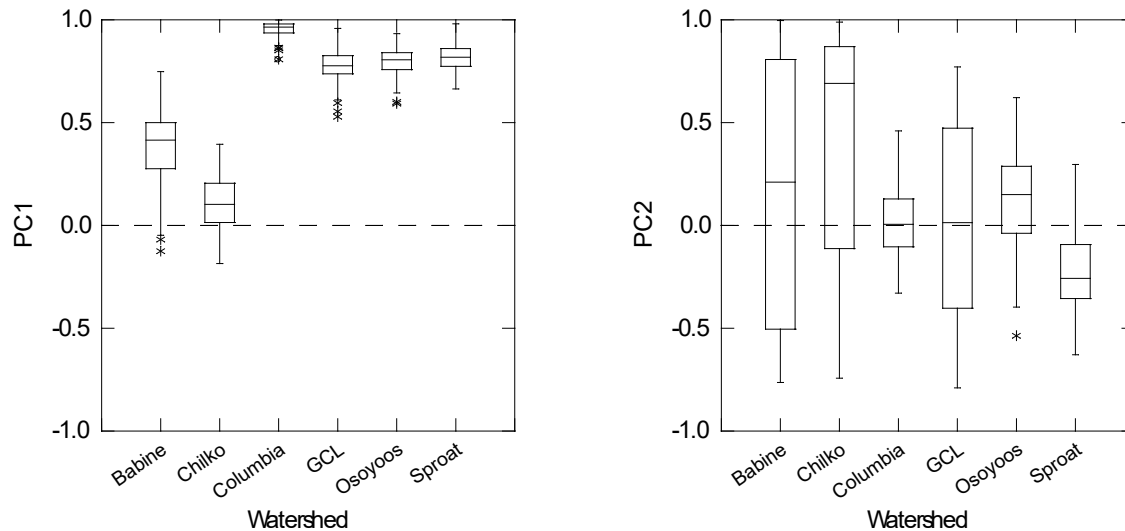


Figure 21: PC1 (left) and PC2 (right) loadings from 1000 bootstrap iterations of a principal component analysis of pairwise correlations among six time series.

The main result of the bootstrap PC analysis is that the four marine survival time series with the highest loadings and least uncertainty on PC1 are those that migrate past the coast of Washington and/or the west side of Vancouver Island (Figure 21). As they share a significant fraction of their interannual variation in survival, whatever is allowing them to live or die is affecting this part of the coast. Chilko Lake postsmolts emigrate northward from a southern location but via the Strait of Georgia and the through the trophic gauntlet (Welch et al. 2011) but its marine survival is uncorrelated with PC1, suggesting that some independent pressure on survival is at play. The bootstrap quartiles of the Babine Lake sockeye salmon do not include zero suggesting that at least some of the shared survival signal has an influence on there, but not to the degree of the southern populations.

4.2. ECOSYSTEM VARIATION AND SURVIVAL

In the fall of 1997, one of the warmest years in the Gulf of Alaska, and harbinger of the 1997/98 el Niño, US GLOBEC and NOAA established a coastal survey from the Columbia River to the BC border to study chinook (*O. tshawytscha*) and coho (*O. kisutch*) survival in relation to variability in the coastal ocean (Peterson & Schwing 2003, Peterson et al. 2014). Similar activities were occurring in BC and Alaska making it possible for regional comparisons (Grimes et al. 2007). Attention by NOAA scientists was directed at large-scale and regional climate indices as well as the physical and biological properties measured on annual cruises in the coastal ocean. Variables

currently included in the index are: PDO, ONI, SST (WMO Meteorological Buoy 46050), Upper 25m T, deep T, deep S (Newport Hydrographic Line – Station NH5), copepod species richness, copepod biomass, spring transition (biological), ichthyoplankton biomass, ichthyoplankton composition, juvenile chinook salmon CPUE, and juvenile coho salmon CPUE. The results were distilled using principal component analysis into an index, the Peterson Index, that has continued since 1998. The Peterson Index popularized the use of stoplight charts to indicate environmental variability relevant to Pacific salmon survival and forecasting.¹¹

Notably, the abundance and survival of sockeye salmon of these surveys was rarely mentioned, perhaps because each cruise began after the sockeye salmon postsmolt migration had begun. Below are figures showing the relation between the Peterson Index and marine survival of BC sockeye salmon (longer time series only) that migrate along the west coast of Vancouver Island (Figure 22), those within the Fraser River watershed (Figure 23), and northern stocks (Figure 24). The relation between the Peterson Index and survival is stronger for stocks migrating along the west coast of Washington and BC (Figure 22) than for those migrating through the Strait of Georgia (Figure 23), the latter being, at best, only weakly correlated with the Peterson Index, as is also the case for the Taku River. Of interest, the Stikine River appears to be associated with the Peterson Index despite considerable distance between estuaries (Figure 24).

The Peterson Index is a composite index so it might be instructive to make the comparisons of marine survival with the component parts of the index, many of which are from station NH5 which is located 5 miles west of Newport, Oregon (44.63°N) in just over 50m of water. A forward stepping linear regression of the DFO Osoyoos Lake sockeye salmon survival on the NOAA indicators (Table 3) began by adding the biological transition date (BTRANS)¹². The coefficient is negative indicating that an earlier biological transition is better for sockeye salmon survival than a later transition. The second indicator added is the winter (Dec-Mar) average of the PDO index.

The coefficient is negative indicating better marine survival for Osoyoos Lake sockeye salmon when the PDO is more negative. The third indicator added was copepod richness (number of species) from May to September; the sign of the coefficient is

¹¹ <https://www.fisheries.noaa.gov/west-coast/science-data/ocean-conditions-indicators-trends>

¹² Date when Bill Peterson noticed a shift from predominantly winter/warm water species to summer/cold water species.

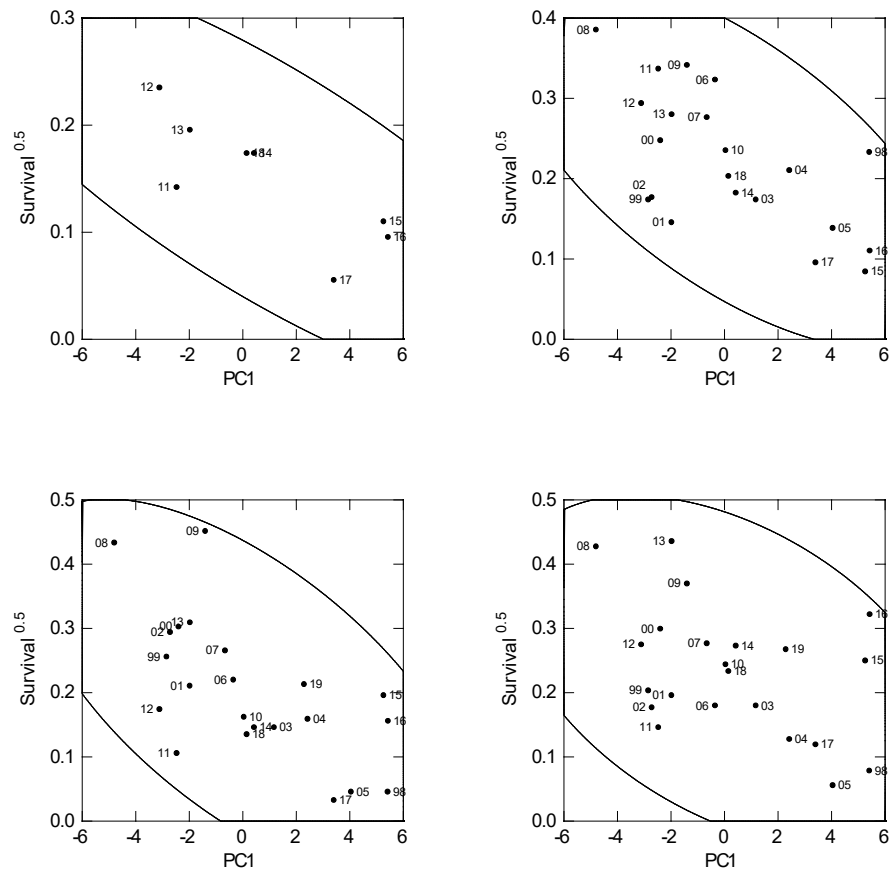


Figure 22: Bivariate plots of juvenile to adult survival ($\sqrt{\cdot}$ transformed) versus the Peterson Index for Wenatchee (top left), Osoyoos (top right), Great Central Lake (lower left), Sproat Lake (lower right) since 1998. Ellipses indicate where 95% of the points should lie.

positive. The fourth indicator added was an ichthyoplankton index of community composition. Its negative coefficient indicated that greater numbers of smelts, sandlance, and sculpins was better for survival than greater numbers of sardines, anchovies, rockfish (when coefficient was positive). Together, these four indicators accounted for ~75% of the variation in Osoyoos Lake sockeye salmon survival.

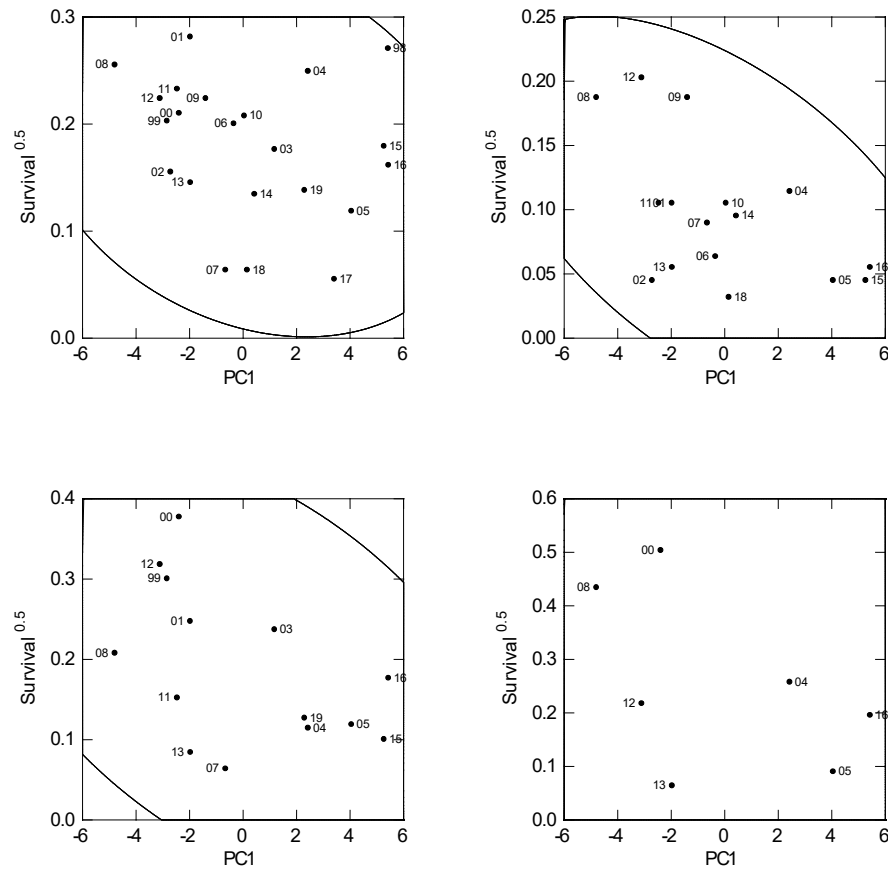


Figure 23: Bivariate plots of juvenile to adult survival ($\sqrt{\cdot}$ transformed) versus the Peterson Index for the longer time series within the Fraser River: Chilko (top left), Cultus, Quesnel (bottom left), Shuswap Lake since 1998. Ellipses indicate where 95% of the points should lie. In the lower right panel the ellipse lies beyond the ranges of the axes.

The Wenatchee time series is too short for a similar comparison, but the longer ones from Barkley Sound are of interest because of the high correlation between Barkley Sound and Columbia River smolt survivals. For Great Central Lake, the first variable added was BTRANS as in the Osoyoos Lake analysis; earlier transition has been better for survival. The second added was bottom (50 m) temperature at station NH5; the sign was negative so colder was better for survival. As there were a couple of years identified as outliers or having high leverage, the regression was redone with these removed. Only BTRANS was included in the regression ($R^2 = 80\%$, $n = 17$), again sign was negative. The same result was found for the Sproat Lake data, $R^2 = 51\%$ ($n = 17$), or when one outlier was excluded, $R^2 = 65\%$ ($n = 16$). Twenty years of marine survival data from the Stikine River had better survival in years when northern copepod biomass was high at NH5. There was no equivalent relation further north at the Taku River which seems to be disconnected from the NOAA indicators.

Where the relationships appear to be real, i.e. persisting for over two decades, there are generally higher(lower) survivals at low(high) values of the Peterson Index in what appears to be a relatively linear pattern. Though recall that the $\sqrt{}$ transformation of the survival data reined in the influence of the relatively rare years of very good survival and to expand the range of variability of the many years of lower survival. So what appears to be somewhat linear would be, after backtransformation, curvilinear with survivals increasing more rapidly as the Peterson Index shifts to lower values.

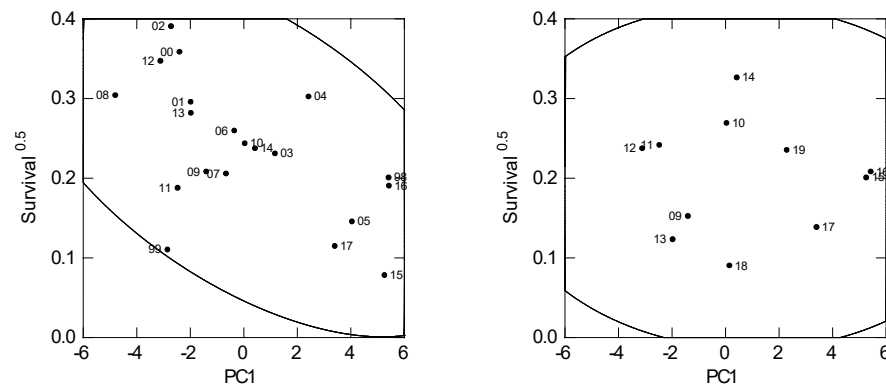


Figure 24: Bivariate plots of juvenile to adult survival ($\sqrt{}$ transformed) versus the Peterson Index for Stikine (left) and Taku (right) since 1998. Ellipses indicate where 95% of the points should lie.

Table 3. Forward stepping linear regression of Osoyoos Lake survival ($\sqrt{}$ transformed) versus NOAA Ecosystem Indicators: PDO1203 (December to March average), COPERICH0509 (average numbers of copepod species May to September), BTRANS (biological spring transition date), ICHTHYINDEX (scores from a Principal Coordinate Analysis of ichthyoplankton species).

Effect	Coefficient	Std Error	P(2 Tail)
CONSTANT	0.392	0.056	0.000
PDO1203	-0.015	0.005	0.009
COPERICH0509	0.032	0.009	0.004
BTRANS	-0.001	0.000	0.010
ICHTHYINDEX	-0.001	0.001	0.086

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Regression	0.084	4	0.021	9.870	0.001
Residual	0.028	13	0.002		

4.2.1. Caveat

A recently published estimate (Bailey et al. 2025) of sockeye salmon survival (late-fry trawl abundance to adult returns) in Osoyoos Lake from 1998 to present is highly correlated ($r = 0.96$) with the data in the DFO marine survival time series and highly correlated with the SAR time series published by William et al. (2014) for the years of

overlap ($r = 0.91$). Despite these similarities, if the Bailey data are fed to the forward-stepping regression with the NOAA indicators, the winter (Nov-Mar) average SST at NH-5 (UPPER1103) was the first variable to enter the regression, and the winter (Dec-Mar) average PDO (PDO1203) was second but in combination they accounted for only 47% of the variability in survival ($\sqrt{}$ transformed). The indicators themselves are so correlated among themselves that slight variations in the data will allow one variable to appear more correlated with survival rather than another. BTRANS, that had entered the regression first in previous analyses, is correlated with UPPER1103 ($r = 0.74$) and with PDO1203 ($r = 0.65$). The changing of relative importance of interrelated ecological indicators from one analysis to another or with the addition or deletion of some years of data should not be too surprising to an ecologist. Hence the need for the Peterson Index that attempts to distill the shared signals from the data. From a salmon's perspective, however, it seems that BTRANS could be the single indicator of choice even though its variation may be a consequence of physical events.

5.0. MIGRATION TIMING AND SPEED

What a smolt will experience during its postsmolt migration may depend on when and where it enters the ocean and its subsequent behaviour and migration path. One of the impediments to identifying oceanic subregions through which juvenile BC sockeye salmon must migrate in the coastal ocean is a general lack of stock-specific data on their migration route, speed, and phenology. Knowledge gaps are being filled slowly with improvements in methods.

Freshwater et al. (2016) used otolith microstructure to identify days at sea, and DNA to identify origin and found that that migration speeds of sockeye salmon are bimodal, differing according to smolt age for WCVI individuals (older/larger faster), and differing significantly depending upon recovery location (northern BC recoveries migrated faster). They concluded that variation in ocean entry characteristics within populations could influence the migratory behaviour of juvenile sockeye salmon and, as a result, how they interacted with their marine environment.

Historically, the best known of migration characteristics was phenology and migration route. The former can be observed and measured when smolts leave nursery lakes and the latter can be inferred, generally, from where and when they have, and have not been found in the ocean. Speed of migration of untagged postsmolts can be determined, approximately, by the timing and abundance of coastal catches where individuals have been subjected to DNA analysis.

5.1. OCEAN ENTRY PHENOLOGY

Operational programs that count or estimate the daily abundance of sockeye salmon smolts passing through estuaries or beyond are few so dates are typically calculated from the last point of observation in fresh water. In some watersheds (e.g. Columbia River and Chilko River) this can be a considerable distance upstream (Williams et al.

2014, McKinnell 2019, McKinnell & Irvine 2021). Some observation points are close enough to the estuary that a good index of passing abundance in fresh water should also be a good index of estuarine abundance, e.g. the Somass River (Wood et al. 1993) or the downstream trap on the Fraser River at Mission (Preikshot et al. 2012). All too often, however, smolt weirs operated only intermittently. The weir on the Babine River (Skeena watershed) ran for a couple of decades but was abandoned at the turn of the millennium (Cox-Rogers et al. 2012). Determining average ocean entry dates (OED) can be challenging; more so if some specific year is of interest. The following describes how OEDs were determined for each river in the present study.

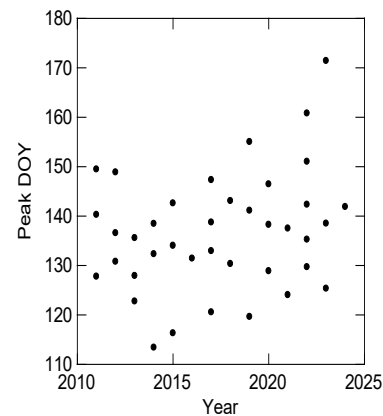


Figure 25: Smolt migration peak dates at McNary Dam (river km 470) by year from 2011 to 2024. For reference, DOY 120 (week 18) is the last day of April and DOY 151 (week 22) is the last day of May, in non-leap years.

5.1.1. Columbia River

Smolts are sampled primarily at McNary Dam (river km 470) and used with flow data to produce a smolt passage index, which among other things, is used to indicate smolt timing.¹³ Samples are collected over a 48 hour period and processed every other day. The passage index data from 2011 to 2024 were downloaded on November 11, 2024. A pulse migration model (McKinnell 2019) was used to identify the number of pulses of abundance and dates of peak abundance in each pulse. Pulses had to be at least 5 days apart and account for >5% of the run. From 2011 to 2024, only 2016 and 2024 had a single large pulse of downstream smolt abundance. There were two pulses in 2018, four in 2017, five in 2022, while the remaining 8 years had 3 pulses. Some of the diversity could be due to the differential timing of Wenatchee and Okanagan smolts (Peven 1987), and now Skaha Lake, but could also be multiple peaks from the same source. The earliest peak at McNary Dam was in week 17 and the latest was in 2023 at week 25. Without weighting for differences in abundance of pulses, the average peak passage at McNary Dam since 2011 was DOY 137 (week 20). The median migration speed between McNary and Bonneville dams was slightly more than 50 km d⁻¹ for Osoyoos Lake and Skaha Lake sockeye smolts (Murauskas et al. 2021). Continuing at this rate to the ocean would set the average OED in week 21. There is variability among years (Figure 25). In 2024, when only one pulse was observed at both McNary and downstream at Bonneville Dam (river km 236), the peak at McNary was DOY 136 while the peak was one week later at Bonneville was DOY 143 (week 20); only 34 km d⁻¹. This would place the smolts in the coastal ocean during the time when NOAA/Fisheries has its trawl surveys.

¹³ https://www.fpc.org/111_sharedfiles/SMPMetadata.pdf

The most consistent periods of coastal trawl sampling occurred in the last two weeks of May (weeks 21/22) and the last two weeks of June (25/26). Median sockeye salmon CPUE ($\sqrt{}$ transformed) among tows is zero within both sampling periods across all years. In weeks 21/22, however, the upper quartile of CPUE is non-zero and there is an abundance of positive outliers, neither of which are observed in weeks 25/26. In principle, an estimate of YOY sockeye salmon abundance should be possible from this sampling because they leave the river from mid-May to mid-June (Williams et al. 2014), but their contagious distributions may not be accommodated by the sampling regime.

The total number of sockeye salmon postsmolts measured in NOAA/Fisheries sampling weeks 21/22 and 25/26 to the year 2023 was 3,623. ANOVA of fork length by week and bottom depth indicates significant differences in abundance among weeks and a weak (0.04 mm m^{-1}) but statistically significant association between mean fork length and bottom depth. Larger individuals moving to deeper water has also been observed in pink salmon (Parker 1966). The least number sampled was 2005 (1 individual), a year of widespread ecological anomalies that attracted sufficient attention for a special issue in *Geophysical Research Letters*. The greatest number was observed in 2018 ($n=732$). The greatest adult sockeye salmon return in recorded history occurred in 2024 but the number of postsmolts caught two years earlier was only 72. Indeed, there have been 4 years with markedly greater trawl catches (2007, 2008, 2016, 2018) than was observed for the ocean entry year of the peak adult return.

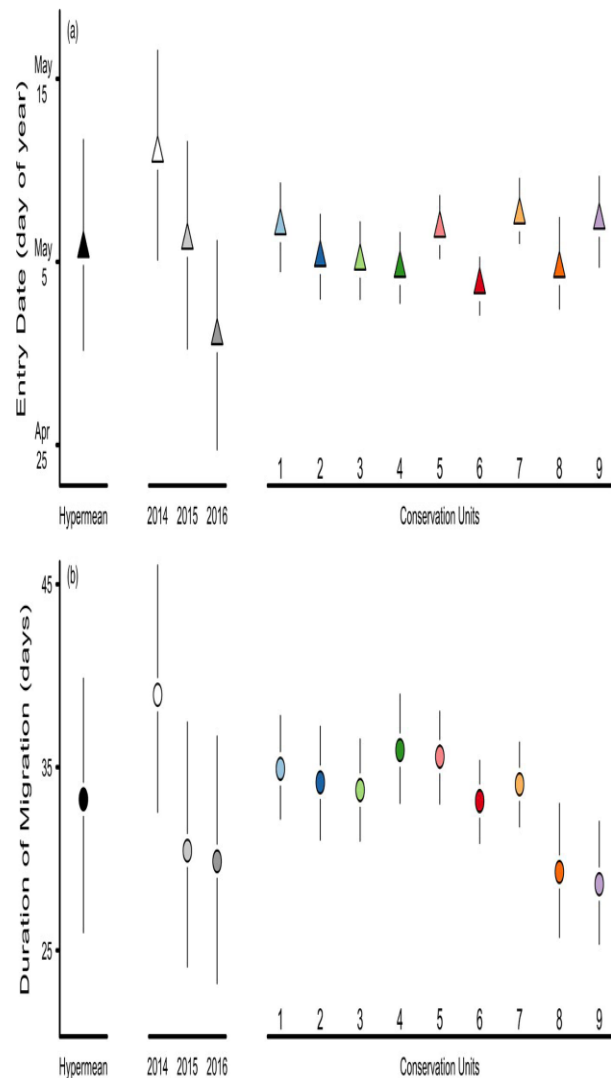


Figure 26: Cropped from a figure in Freshwater et al. 2019.

5.1.2. Fraser River

Estimates of the timing of sockeye salmon smolts through the Fraser River estuary have been derived, with variable success, from observations elsewhere, but there appears to be reasonable agreement on the timing of freshwater emigration by Chilko Lake smolts. The statistics of lake emigration timing differ mostly in whether or not they account for multiple emigration peaks that are commonly observed (McKinnell 2019). Regardless,

estimated travel times of the peak from the weir to the estuary are consistent with none exceeding one week. One diffusion-type model had the longest time to the estuary at 7 days (Crittenden 1994). The average time of acoustically-tagged smolts to the estuary was 5 days (Stevenson et al. 2019). Rapid downstream migrations suggest that the emigration pattern at the smolt weir is an indication of what might be observed, at least for the Chilko component, at the estuary.

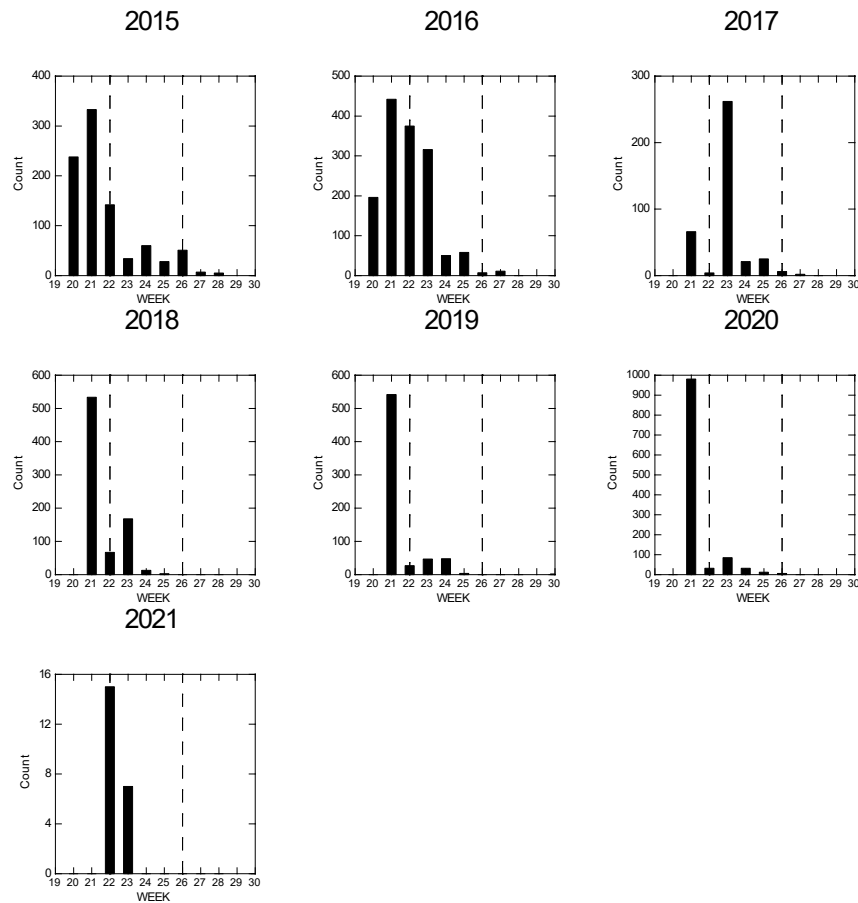


Figure 27: Weekly CPUE of juvenile sockeye salmon sampling by the Hakai Institute in Discovery Islands. Vertical dashed lines indicate approximately the end of May and the end of June. Note that ordinate scales differ among panels.

To simplify the analysis in the present study, the pulse model was constrained to a single annual peak at the weir. The average of this statistic, from the 1950s to the present, is May 3 which implies an average peak abundance in the estuary around May 8 (week 19). This is similar to an estimate (May 5) that was derived from sockeye salmon bycatch (mixed populations) in a pink and chum fry sampling program at Mission (Preikshot et al. 2012), and is close to an estimate (May 5, Figure 26) determined independently by Freshwater et al. (2019) who back-calculated dates from otolith daily growth rings of postsmolts captured primarily in Johnstone Strait and the

Discovery Islands. As these are peak dates, smolts are entering the Strait of Georgia before the peak in mid to late April. Historical trawl sampling from the 1960s, when the Fisheries Research Board was conducting the Fraser Plume Study (Parsons et al. 1969) found that in 1968, for example, sockeye salmon were observed at Tsawwassen on April 24 when sampling began that year (McKinnell & Perry 2016). The highest single haul of sockeye salmon in five years of sampling the southern Strait of Georgia occurred in April 1966. Note also that the multi-year average peak date of smolt emigration from Cultus Lake was earlier, April 25 (see Fig. 2 in Foerster 1937).

Sampling in 2014 at Mission (rotary trap) and in the Discovery Islands (seine) (Neville et al. 2016), yielded estimates of peak dates of April 28 at Mission and June 13 in Discovery Islands in 2014.¹⁴ Oddly, the DNA analysis of the Mission samples in 2014 found that Chilliwack smolts accounted for 49% of the total numbers, yet Chilko Lake smolts were ~7x more abundant than the Chilliwack Lake smolts (DFO, unpublished data).

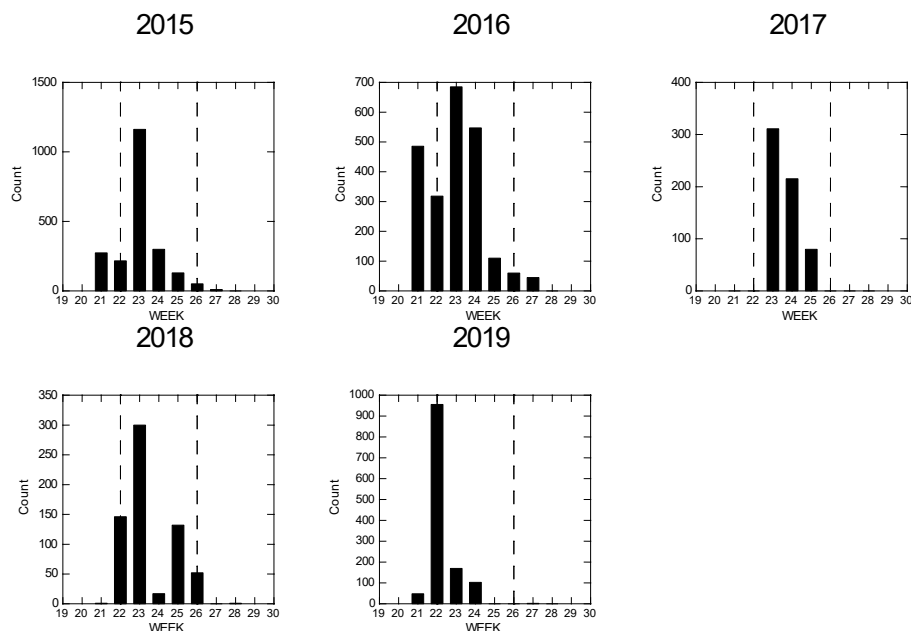


Figure 28: As above but in Johnstone Strait.

Sampling juvenile sockeye salmon migrants by the Hakai Institute from 2015 to 2021 found peaks of abundance in the Discovery Islands in late May in most years with most of the postsmolt abundance passing into Discovery Passage by the end of June (Figure). Hakai Institute sampling within Johnstone Strait from 2015 to 2019 has a similar pattern but the peak is about week later (Figure). Among years there is consistency, with the peak appearing in week 21 in the Discovery Islands and week 22 in Johnstone Strait. The peak is relatively compressed in both locations with lesser numbers of migrants in June and early July. Postsmolt ages were not determined by examination,

¹⁴ Calculated from abundance data (their Figure 4) and fit to a migration pulse model (McKinnell 2019).

but by size-frequency analysis. Length frequency distributions indicated that sampling later in the run resulted in increasing proportions of smaller fish in the samples. This can arise from size-structured migration timing of age x.0 postsmolts (Freshwater et al. 2016) or from increasing proportions of sea-type individuals leaving the Strait of Georgia, primarily from Harrison Lake (McKinnell et al. 2010). Both could explain a decreasing mean size of the samples by the Hakai sampling at a time of year when individuals are growing rapidly. A similar pattern was observed in the 1960s (McKinnell et al. 2010).

There are inconsistencies in rates of passage through the Strait of Georgia. DFO sampling in 2014 places the Fraser River peak in the Discovery Islands at June 13 (week 24) whereas multiple years of Hakai sampling after 2014 indicated a peak about 3 weeks earlier. Preikshot et al. (2012) also reported much later peak dates in the Strait of Georgia in 1997 (June 15) and 2010 (June 19). Including the (abundant) sea-run sockeye salmon in the timing analysis may have been the cause as might be the tendency for smaller age 1.x to migrate more slowly (Freshwater et al. 2016).

5.1.3. Somass River

Peak catches within the Somass River occurred around May 1 (week 18) in 1989 with 85% of the emigration occurring between April 23 and May 25 of that year (Wood et al. 1993). Migration speed through Alberni Inlet was reported to be 1.9 and 1.6 km d⁻¹, remarkably slow compared to other stocks, but discussion of that point by the authors suggested that migration speed could have been underestimated because of low sampling frequency.

Sampling was more frequent two years earlier in 1987 using purse seines but determining a migration speed had issues (Cooke and Groot 1990). There was one peak of abundance in Alberni Inlet prior to

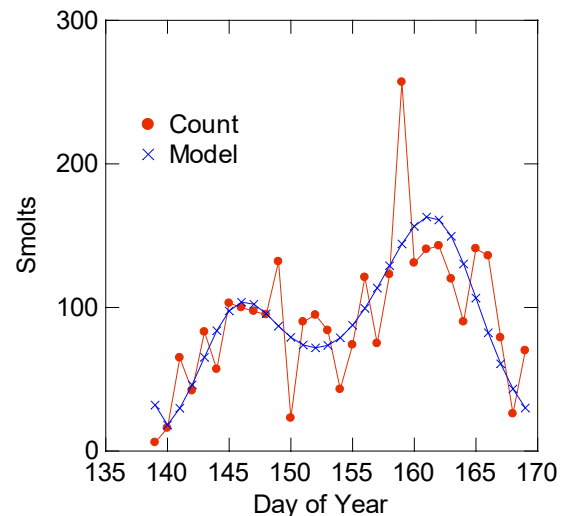


Figure 29: Daily sample sizes of sockeye salmon smolts taken by fyke net for length measurements during emigration from Owikeno Lake in 1916.

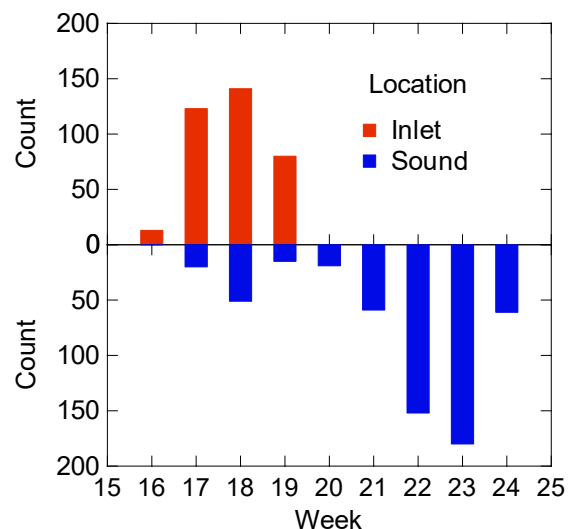


Figure 30: Bar heights are sockeye salmon smolt abundances (weighted CPUE^{0.5}) by week in Alberni Inlet and Barkley Sound in 1987.

week 20 but then sampling stopped (Figure 28). The Alberni Inlet peak aligns within a few days of the early peak in Barkley Sound, Barkley Sound lagging. As it is not known whether the early peak in Barkley Sound is made up of Somass River smolts or Huchuktis Lake (formerly Henderson Lake) smolts that enter the ocean near Barkley Sound (Hyatt et al. 2020). If the Alberni Inlet peak and the second Barkley Sound peak reflect the abundance of Somass River postsmolts, a slow migration is indicated in these data as well, consistent with Freshwater et al. (2016). On the other hand, if the two peaks at week 18 are Somass River postsmolts, a more typical rapid migration is indicated. Somass River postsmolts have been found in SEAK and northern B.C. by June (Tucker et al. 2009, Freshwater et al. 2016).

5.1.4. Long Lake

There do not appear to be any historical records of sockeye salmon smolts emigrating from Long Lake but sampling was conducted in nearby Owikeno Lake from 1914-1916 (Gilbert 1918). Except for 1916, a fixed number was measured daily as the main interest was smolt size not abundance. In 1916, sample sizes from DOY 139 (week 21) to 169 (week 25) varied with few collected on the first and last days of deployment, suggesting that sample sizes reflect the timing of emigration that year (Gilbert 1918). Three missing days were estimated by interpolation and the counts were fit to a pulse timing model (McKinnell 2019) which found two pulses of abundance (Figure 27) in samples with peaks on DOY 145 (week 22) and DOY 161 (week 24). Given the similarity between Rivers and Long Lake life-histories, an OED for Long Lake was chosen as the midpoint DOY 152.

5.1.5. Skeena River

From 2014-2018, the average peak abundance of postsmolts sampled in the Skeena River estuary was May 15 (week 20) (Sharpe et al. 2021). Field notes¹⁵ of sampling near the outlet of Lakelse Lake in the late 1940s and early 1950s included smolt counts. The average day of peak passage (observed) in four years (1946, 1947, 1952, 1953) was May 23 (week 21); also reported in the smolt timing review by Hartman et al. (1967). Because of the relatively short distance to the estuary, this would have placed the peak at the Skeena River estuary about 3 days later which does not conflict with the average OED reported above.

Early and late timed smolt runs are reported from Babine Lake, the largest producer, with the early emigration peak made up of smolts rearing near the lake outlet (McDonald 1964). Historical peak smolt emigration dates are approximately what has been reported more recently as the peak estuarine abundance (May 13, week 20). The Babine Lake late peak is June 4 (week 23); both Babine dates are from Hartman et al. (1967).

5.1.6. Stikine River

¹⁵ Copies obtained by DFO/North Coast from the PBS Archive before the archive was disbanded.

The average date of 50% emigration from Tahltan Lake from 2005-2014 is May 24 (DOY 144, week 21) (Foos et al. 2019).

5.1.7. Taku River

A scoop trap was installed at Canyon Island (Alaska) near the estuary and sampling continued from April 23 to June 15, 1961 (Meehan and Siniff 1962). Two peaks of abundance occurred, a minor one from April 23-29 (week 18) and a larger one centred on week 23 in early June. The length frequency distribution of sockeye salmon smolts was bimodal. The authors were not confident of the age determinations from scales but speculated that two ages were caught with age 1.x being the more abundant. They made no mention of the sea-run life-history type which suggests that they did not know of its existence.

Smolt sampling was conducted in 1987 using a fyke net located 17 km upstream from the estuary, and using beach seines along the shores of Taku Inlet (Murphy et al. 1988). Peak catches of age 1.x smolts occurred on May 7 (DOY 127, Week 19) but they were not very specific about timing estuarine timing, saying only that age 1.x smolts moved through the estuary in May and June. As 17 km is approximately a 1-2 day migration, the peak at the OED was deemed to be May 9 (week 19).

5.2. MIGRATION SPEED

Published migration speeds of sockeye salmon postsmolts in the ocean are rare and vary widely among populations with the two lowest at 0.8 km d⁻¹ (Freshwater et al. 2016) and 1.9 km d⁻¹ (Wood et al. 1993) and both were associated with reported from Alberni Inlet (Barkley Sound). where weekly purse seine samples along the 37 km long inlet were used to track the shifting location of peak abundance (Wood et al. 1993). At the other extreme, migration speed of 40-48 km d⁻¹ was observed from Redfish Lake, Idaho postsmolts, but that estimated included a lengthy period of in-river downstream migration (Tucker et al. 2009). Acoustic tags and detection arrays have made considerable progress on the issue of migration speed (Welch et al. 2011) but all of these measurements were derived from fish recovering from an invasive surgical procedure which can affect survival (Clark et al. 2016), and presumably swimming speed. After reaching the mainstem of the Fraser River, speed over ground of acoustically tagged sockeye salmon smolts from Chilko Lake to the estuary was up to a remarkable 220 km d⁻¹ (Clark et al. 2016), slowing to ~14 km d⁻¹ through the Strait of Georgia (Welch et al. 2011), and ranging from 10-25 km d⁻¹ through the coastal marine habitat (Clark et al. 2016). Smolts were reported to emigrate toward the Babine River from the lake at 20-30 cm s⁻¹ or 2.75 – 3.75 body length s⁻¹ after the migratory urge was triggered (Johnson and Groot 1963). There is good evidence of at least two migratory behaviours, slower and faster (Freshwater et al. 2016), but it may be even more complicated.

Using data from multiple years of coastal trawl sampling, Tucker et al. (2009) described seasonal abundances of sockeye salmon postsmolts at various locations around the Gulf of Alaska shelf but did not estimate the migration speeds that could have created

the observed abundance patterns apart from a few that had been tagged in nursery lakes. A range of (minimum) migration speeds varied from 0.8 to 21.3 km d⁻¹ in the Freshwater study with the upper mode having an average speed of 12.1 ± 3.0 km·d⁻¹.

5.2.1. Speed from coastal tagging

The NPAFC tagging database¹⁶ has 8 sockeye that were tagged in the 1960s as postsmolts and recovered as adult salmon in Skeena River fisheries 2 and 3 years later (Table 4). Tagging locations of these (assumed to be Skeena River fish) were located on the continental shelf, and ranged from 373 to 1091 km from the estuary by Great Circle Distance. Tagging dates ranged from DOY 206 (week 30) to DOY 239 (week 35) and size at tagging varied from 166 to 190 mm. If the average OED for Skeena River smolts is applied, the migration speeds from estuary to the tagging sites varied from a low of 4.5 to 12.8 km d⁻¹. Applying the same procedure to 7 tagged postsmolts that were recovered in the Fraser River fishery as adults (NPAFC General Areas 77 and 81), the migration speeds as postsmolts from the estuary to tagging location range from 10 to 24 km d⁻¹, almost double the Skeena speeds. With the fastest speeds in the southernmost rivers, perhaps the proximity of estuaries to postsmolt oceanic winter habitat plays a role in migration speed.

Table 4. Sockeye salmon tagged as postsmolts and later recovered in coastal fisheries as adults. OED=average ocean entry DOY, Days= number of days from OED until tag date, KM= Great Circle Distance between estuary and tagging.

River	Year	Month	Day	DOY	Length	Lat	LongE	LongW	OE	Days	KM	KM/D
Skeena	1965	8	8	220	175	59.7	218.6	-141.4	135	85	903	10.6
Skeena	1965	8	8	220	180	59.7	218.6	-141.4	135	85	903	10.6
Skeena	1965	8	8	220	190	59.62	218.6	-141.5	135	85	1091	12.8
Skeena	1965	8	8	220	180	59.62	218.6	-141.5	135	85	1091	12.8
Skeena	1967	8	27	239	166	58.32	222.7	-137.3	135	104	625	6.0
Skeena	1968	7	24	206	173	56.82	224.3	-135.7	135	71	443	6.2
Skeena	1968	7	24	206	178	56.82	224.3	-135.7	135	71	443	6.2
Skeena	1968	8	6	219	167	56.28	225.0	-135.0	135	84	373	4.4
Fraser	1965	8	9	221	205	59.37	214.3	-145.7	125	96	1833	19.1
Fraser	1965	8	26	238	195	57.82	223.4	-136.6	125	113	1305	11.5
Fraser	1967	7	20	201	195	58.22	222.9	-137.1	125	76	1355	17.8
Fraser	1968	7	24	206	185	56.82	224.3	-135.7	125	81	1190	14.7
Fraser	1968	7	24	206	188	56.82	224.3	-135.7	125	81	1190	14.7
Fraser	1968	8	7	220	188	55.28	226.2	-133.8	125	95	991	10.4
Fraser	1968	9	15	259	215	58.17	222.9	-137.1	125	134	1350	10.1
Fraser	1967	7	20	201	195	58.22	222.9	-147.1	125	76	1853	24.4
Fraser	1967	7	20	201	185	58.22	222.9	-147.1	125	76	1853	24.4

5.2.2. Speed from IPSDL Catch

Although not stock-specific nor weighted by catch or fishing effort, after the summer solstice (week 25), 50% of the YOY samples taken that week were caught north of Triangle Island (50.7°N) off the northern end of Vancouver Island and that fraction is

¹⁶ NPAFC (North Pacific Anadromous Fish Commission). 2024. INPFC/NPAFC High-seas salmonid tag-recovery database. North Pacific Anadromous Fish Commission, Vancouver. Available: npafc.org (October, 2023).

rapidly increasing as the sampling shifted to early July (Figure 29). Indeed, if the medians in this figure are traced through latitude, the curve formed by that line resembles the latitudes that would be encountered by following the shelf latitude from the Columbia River to Kodiak Island, where latitude begins to decline toward the Alaska Peninsula; a proxy for the postsmolt migration route. Some additional comments about migration speed in the section below entitled Thermal Experience. A postsmolt's migration speed will affect what it experiences after ocean entry, although perhaps not substantially because of the SSTA decorrelation scale described above.

6.0. REGIONAL SIMILARITY

The quest for meaningful bioregions in the Northeast Pacific has a long history that began with the relatively intensive surveys of the 1950s when frigates and navy personnel were deployed to study the oceanography of the North Pacific; often as part of international activities such as the 20 vessel NORPAC survey of 1955. Because of their basin-scale perspective, defining meaningful boundaries around regions with relatively unique water properties was a tractable problem (Dodimead et al. 1963, Favorite et al. 1976). Regions defined initially by water properties later served as a basis for fisheries production domains (Ware and McFarlane 1989) but it was not until the early 20th century that the relationship between oceanography and coastal fisheries production came into focus (Ware and Thomson 2005). Defining coastal zones had been explored since the 19th century in other disciplines (Bernard et al. 1991).

Subdividing the North American shelf according to fisheries production zones had its own challenges because what is possible is constrained by the level of aggregation of fish catches. Ware and Thomson (2005) identified five subdomains between the Columbia River and Kodiak based on non-migratory fish yields and primary productivity. Longhurst (1995) said that the most important processes affecting plankton dynamics on the shelf were associated with either tidal fronts, coastal divergences (upwelling) or shelf-break fronts. These features can be associated with elevated levels of algal biomass that arise from plankton growth *in situ* or frontal convergences that concentrate planktonic prey. Subdividing on the basis of primary production and/or its surrogates has challenges too. The recently published Konik et al. (2024) regions of the North Pacific Ocean, based on phytoplankton composition and

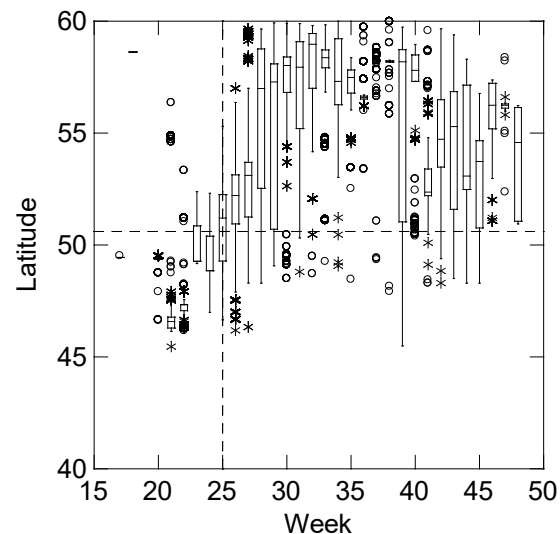


Figure 31: Box and whisker plot of latitude of capture of YOY sockeye salmon samples (<250mm) in the IPSDL (n=32,979).

phenology, excluded data shallower than 500 m because terrestrial runoff is a dominant feature of the satellite-derived water properties.

Bernard et al. (1991) cited attempts by 15 authors working between 1856 and the 1980s to define coastal subdomain boundaries based on the incidence of marine bivalve species along the North American coast. The numbers of regions appears to depend on whether the author was a splitter or a lumper but for major divisions, such as Point Conception at the northern end of the Southern California Bight, there tended to be widespread agreement.

6.1. CLUSTERING SSTA

One method of defining subregions based on SSTA is to identify grid point with time series that are more similar to each other than to others. As there is greater interest in the sockeye salmon migratory period on the shelf, the SSTA data used in this analysis were restricted to the warm season. Time series were compared by measuring their dissimilarity (Euclidean distance). Euclidean distance was computed using the IMSL¹⁷ subroutine CDIST. The dissimilarity matrix was processed by the IMSL subroutine CLINK which does the cluster analysis, using complete linkage method, which was then fed to subroutine CNUMB which assigns group membership to each grid point. Complete linkage avoids the chaining of clusters when the subject data form a gradient.

The number of clusters to create from the dissimilarity matrix is arbitrarily and was varied from 2 to 10 clusters. After cluster membership was assigned to all grid points, the average SSTA within each cluster was computed in each individual week of the time series, generating time series of weekly average SSTA for all clusters. The resulting time series can then be compared among clusters. If, for example, there is little difference between two clusters, there is little value added by retaining them as separate clusters, except perhaps when they happen to be geographically distant. Given the large e-folding scale in SSTA reported above, large differences between SSTA time series, particularly adjacent ones, are not expected.

There is also the issue of whether a single analysis of the entire warm season would resemble what may result from a temporal subdivision of the data into “salmon seasons”. Differences in smolt emigration dates seem to be rather slight so the analyses were grouped into three seasons: from the equinox up to ocean entry (weeks 12-17), ocean entry (weeks 18-24), and shelf migration (25-33).

6.1.1. OED 1 week early

In weeks before ocean entry, a two cluster analysis clusters separates Cook Inlet, Shelikof Strait and Prince William Sound from the rest of the coast (Figure 30). Increasing from three to six clusters further subdivides only this northern region. This continues until 7 clusters when a small region in southern SE Alaska appears to separate from the above, but only the nearshore grid points in SEAK. Throughout the entire exercise of demanding greater numbers of clusters, the entire region from Prince

¹⁷ International Mathematical & Statistical Library

William Sound to the Columbia River is retained as a single cluster, except for that small region in SE Alaska. Most of the SSTA diversity was in the north. The seasonal dynamics of sea ice may play a role, but this is speculation at the moment.

6.1.2. OED average

The cluster pattern becomes more diverse at the time when smolts are entering the ocean. Most of the shelf is but a single cluster (Figure 31). As in the pre-season analysis, much of the initial differentiation with few clusters is a result of differences in the northwestern part of the shelf near Kodiak Island. Even at 10 clusters, the entire shelf area south of Icy Strait is but 3 clusters, and one of these is but a single grid point located at the mouth of the Columbia River due to increasing discharge of fresh water.

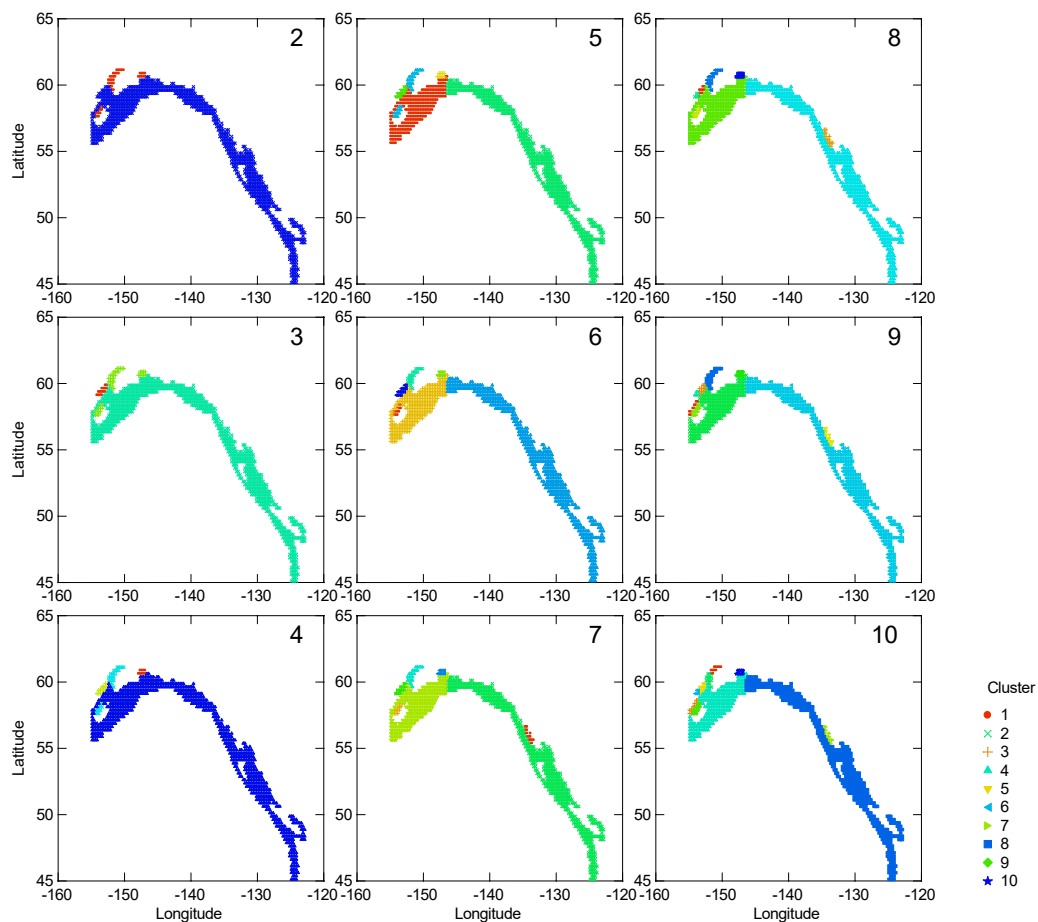


Figure 32: Cluster analysis of SSTA data for weeks 12-17, prior to ocean entry by sockeye salmon smolts. The number in each panel indicates the number of clusters requested in that analysis. The colours/symbols in the legend apply only to the adjacent panel with 10 clusters.

6.1.3. OED 1 week late

After the summer solstice, the pattern of cluster development from 2 to 10 clusters is very different from previous weeks (Figure 32). The primary subdivision at two clusters divides the Strait of Georgia from everywhere else on the shelf. Much of this difference will be due to the influence of the Fraser River freshet. In the 10 cluster analysis, most are aligned with oceanographic features that are characteristic of each area: Columbia River mouth, upwelling coast, Strait of Juan de Fuca, Haro Strait, Strait of Georgia, Queen Charlotte Strait, Hecate Strait-Dixon Entrance-SE Alaska, northern Gulf of Alaska, northern Cook Inlet.

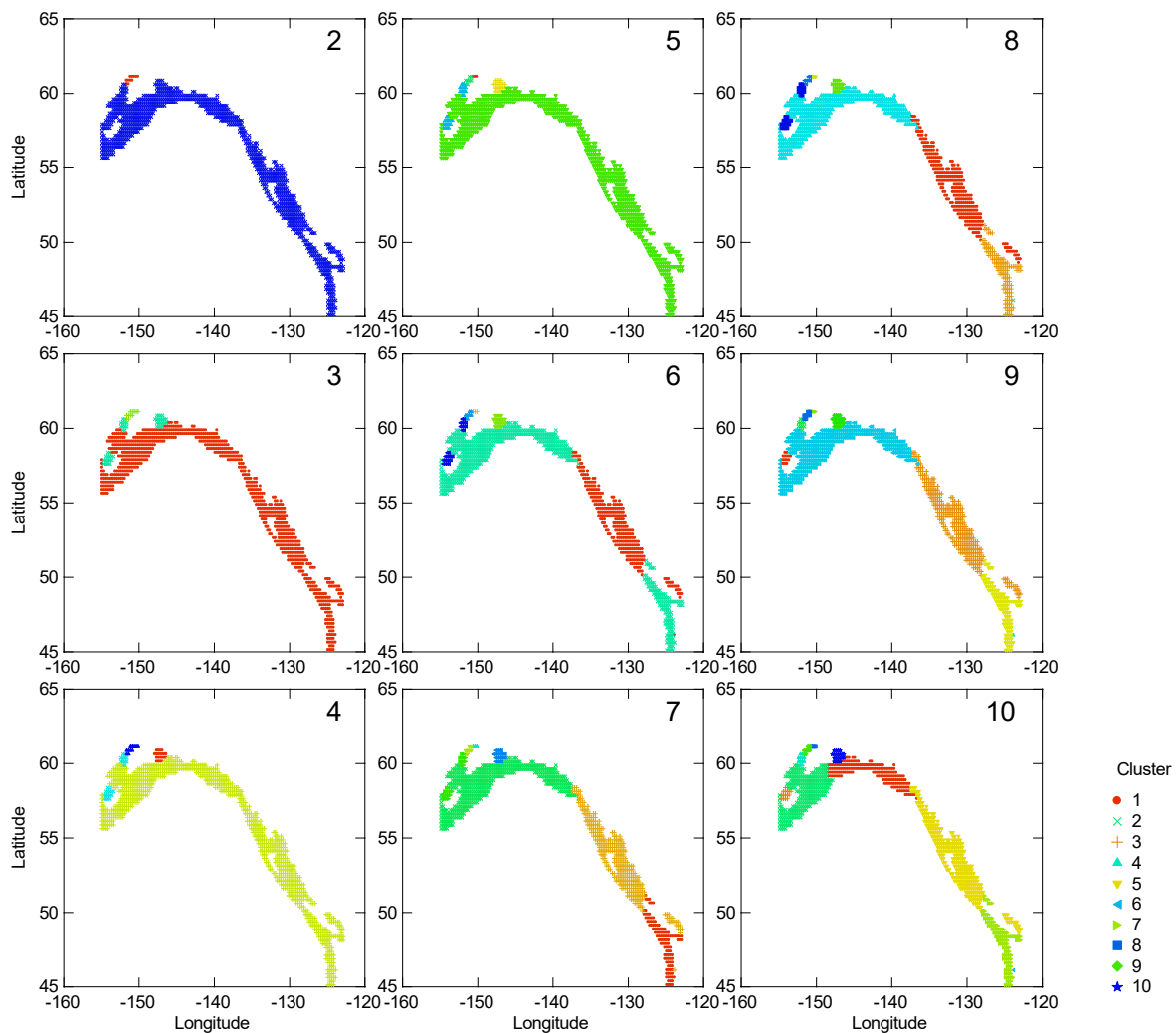


Figure 33: Cluster analysis of SSTA data for weeks 18-24, at ocean entry by sockeye salmon smolts. The number in each panel indicates the number of clusters requested in that analysis. The colours/symbols in the legend apply only to the adjacent panel with 10 clusters.

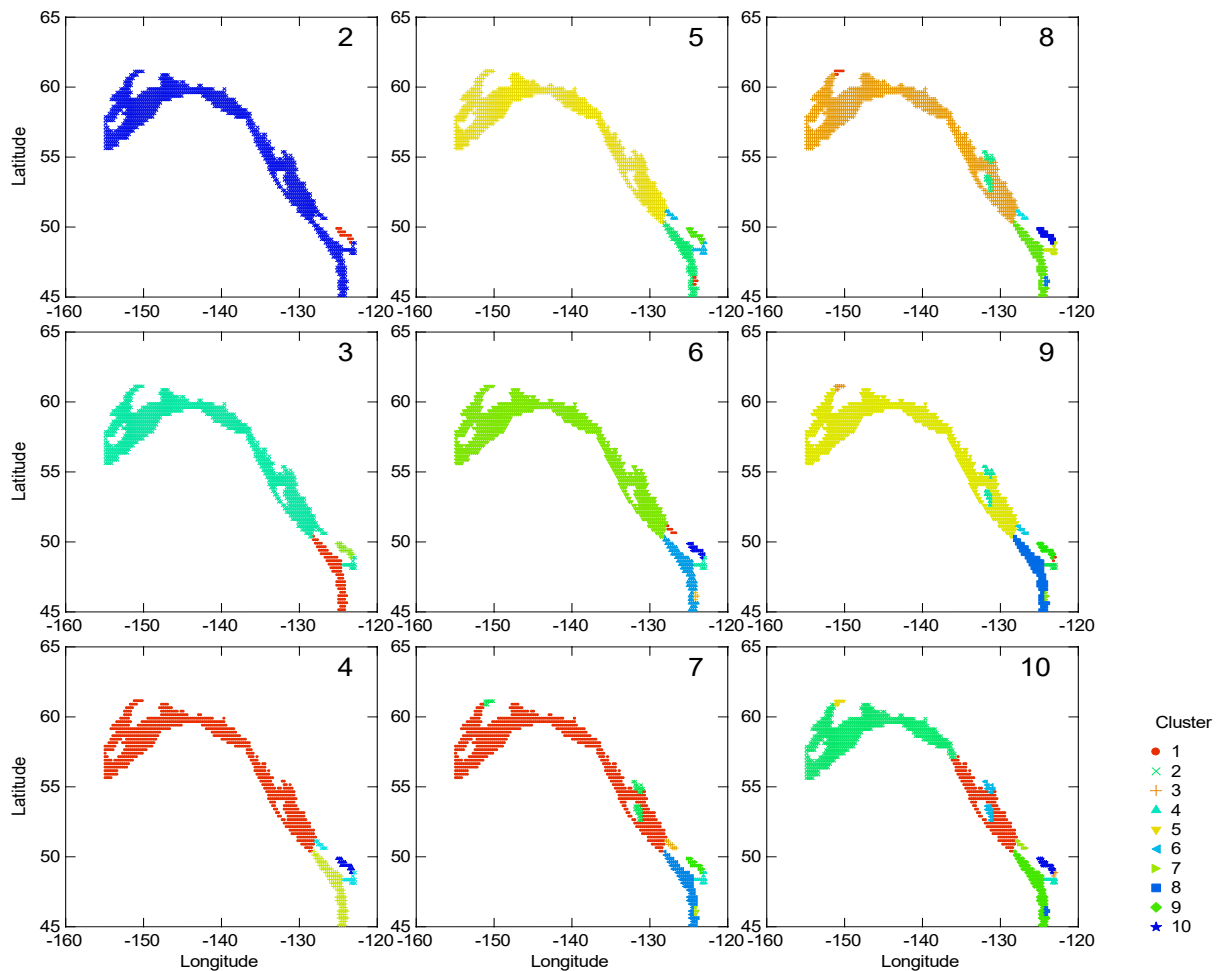


Figure 34: Cluster analysis of SSTA data for weeks 25-33, at ocean entry by sockeye salmon smolts. The number in each panel indicates the number of clusters requested in that analysis. The colours/symbols in the legend apply only to the adjacent panel with 10 clusters.

The only cluster that is divided into two parts was the shallower east coast of Haida Gwaii and Clarence Strait, each separated by Dixon Entrance. Notice in the 9 cluster analysis that most of the shelf has yet to be subdivided, so there is a contiguous cluster from Queen Charlotte Sound to Kodiak Island. Only at 10 clusters does the shelf subdivide into major northern and southern parts, which suggests that the basis for that subdivision is weak (correlation is 0.97). At 10 clusters, the two least similar within-cluster average SSTA time series still have correlations of 0.71. In other words, the most dissimilar clusters share about 50% of their SSTA variation in common. These pairs were Columbia River mouth versus Queen Charlotte Strait, the upwelling coast versus all grid points north and west of Icy Strait (Alaska).

7.0. THERMAL EXPERIENCE

Determining the paths of sockeye salmon postsmolt migrations relies mostly upon where they have and have not been found in the ocean. The multi-year study using purse seines that began in 1964 led, rather quickly, to the conclusion that postsmolts migrated nearshore along the continental shelf as they were rarely if ever caught beyond the continental shelf (Hartt et al. 1965). These early studies tended to focus on species distributions as there was little help from technology to identify individual populations with any precision. Thanks to the identification of genetic differences among populations, some refinement of the migration story has been made in the 21st century (Tucker et al. 2009). Notably, when sockeye salmon postsmolts were caught off the west coast of Vancouver Island in winter, DNA confirmed them as the sea-run life-history type from the Harrison River (Fraser). No lake-type sockeye salmon were caught in those samples. Postsmolts had been caught in a midwater trawl further up the BC coast in winter (LeBrasseur & Barner 1964), but no one published the age of the fish to reveal whether they were lake-type or sea-run.

Unfortunately, Tucker's stock-specific information about sockeye salmon postsmolts was published only with seasonal temporal resolution so migration speeds are difficult to determine precisely (Tucker et al. 2009). However, occasional comments in that paper had a finer temporal resolution as follows:

For Southeast Alaska, 40% of the juvenile sockeye salmon caught in the spring [before June 21] were allocated to southern stocks (WCVI, Fraser River and Washington/Puget Sound). A closer inspection of the data revealed that postsmolts caught in Southeast Alaska early in the spring (May 23–26 [week 21]) were identified as from the Nass and Skeena Rivers. All postsmolts caught during spring in Southeast Alaska that were allocated to southern stocks were caught late in the spring (June 17–19 [week 25]).

7.1. SIMULATED MIGRATION

A simple simulation was developed to determine the daily SSTs that a postsmolt might experience after leaving its estuary on its OED, migrating around the Gulf of Alaska shelf to the west end of Kodiak Island (155°W). Using the ¼° latitude/longitude grid, for simplicity, each iteration of the simulation caused a shift in a fish's location by 1 grid point in 1 day. If migrating due north, a step of ¼° latitude is 28 km, less if due west as lines of longitude are closer together. The simulation ended on the day when the fish reached 155°W at the edge of the study domain on the west side of Kodiak Is.

The choice of migration direction at each step along the shelf was constrained, initially, to be northward, northwestward or westward. Walter et al. (1997) had applied a similar approach to constrain postsmolt migration to the shelf. After reaching 145°W at the head of the Gulf, a southwestward direction was added to the range of possible directions to accommodate the YOY migration corridor at that part of the Gulf (Hartt et al. 1965). The choice of which direction to move was determined by selecting which direction offered the greatest number of subsequent grid points of ocean water in that direction, within the domain; essentially a "follow the fetch" algorithm. The 500m depth

contour constrained the migration to the shelf as there were generally many more oceanic grid points in the along-shelf direction.

The results for 2023 appear in Figure 33. Estuaries in the north are closer to Kodiak which explains why some lines are shorter if all are migrating at the same speed. Another approach, not yet programmed, is to assume that northern stocks need not migrate as quickly as southern stocks if the migration is destination-oriented (e.g. arrive at the Shumagin Islands for winter) and this may be a model worth considering. The faster migrants based on tagging data (Table 4) appear to be the ones that had gone the farthest distance, i.e. southernmost ocean entry. Recall that sockeye salmon postsmolts from Bristol Bay linger on the eastern Bering Sea shelf in the autumn, not far from their natal estuaries (Smith et al. 2011), so they don't appear to be in any hurry to reach to Gulf of Alaska.

A notable feature of the 2023 migration, and perhaps in other years, is the relatively unique (initially warmer) experience of Fraser River postsmolts from all others at ocean entry (Figure 33, Figure 34). The drop in SST between the Strait of Georgia to the lower temperatures of Queen Charlotte Strait was the greatest change during any migration in this simulation.

7.2. SIMULATION VERSUS OBSERVATION

Tucker et al. (2009) reported that trawl hauls from Southeast Alaska between May 23-26 (year not specified but perhaps multi-year) caught mostly Nass/Skeena fish; the identification based on microsatellite DNA. As this is the same as the OED these must have been in the vanguard of the Skeena migration. The 2023 simulation of the Skeena River migration, with OED set to its multi-year average for the initial run, was then repeated with OED 1 week earlier and again at 1 week later. Results compared favourably with the observations for the average OED and early OED runs, i.e. at simulated migration speeds, the peak of the Skeena River postsmolt migration was found in Southeast Alaska (Figure 35). For late OED, however, the migration peak had yet to leave Dixon Entrance.

7.2.1. Caveats

In their summary of DNA sampling of juvenile sockeye salmon from 1996 to 2011 (Beacham et al. 2012) reported:

- no Columbia River or Lake Washington sockeye salmon were found north of SEAK.
- Early Stuart (Fraser) juveniles were detected as far away as the Bering Sea.
- Stellako River (Fraser) juveniles were not found west of Prince William Sound.
- Other Fraser River populations (Cultus, Birkenhead, North Thompson) and also Rivers Inlet fish were detected in the Bering Sea but not at intermediate locations.

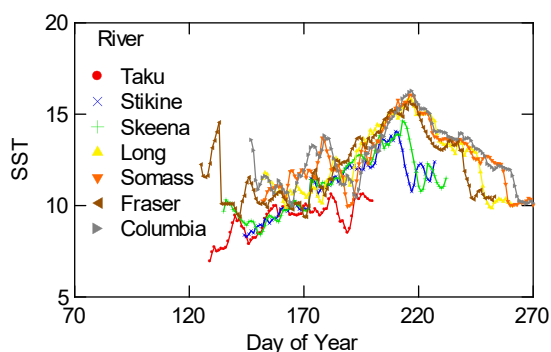


Figure 35: Daily SSTs encountered by each stock from its estuary to 155°W longitude, assuming a daily swim speed of 15nm per day, for the 2024 ocean entry year. As 2024 is a leap year, DOY-120 is April 29, DOY-170 is near the summer solstice, DOY-220 is August 7, and DOY-270 is September 26.

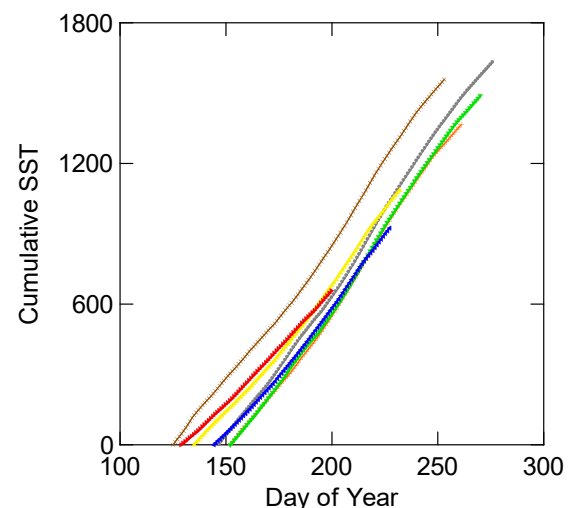


Figure 36: Cumulative SST of data in Figure 35 using the same colour legend.

- Individuals from transboundary river stocks (Stikine River, Taku River, Alsek River) were not detected in British Columbia waters.

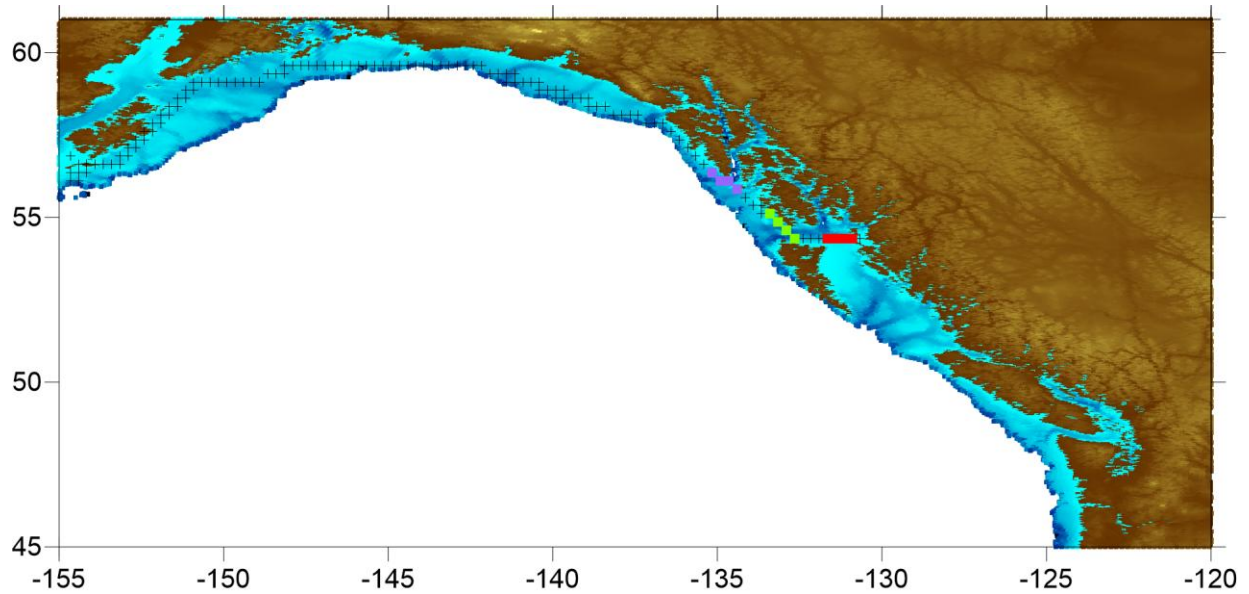


Figure 37: Simulated migration of Skeena River sockeye salmon postsmolts from the estuary to Kodiak (1 plot point=1 day migration). Coloured symbols indicate where the postsmolts would be between 23-26 May (when Tucker et al. 2009 observed them in SEAK) if leaving the estuary on the average OED (green), one week earlier (mauve), and one week later (red).

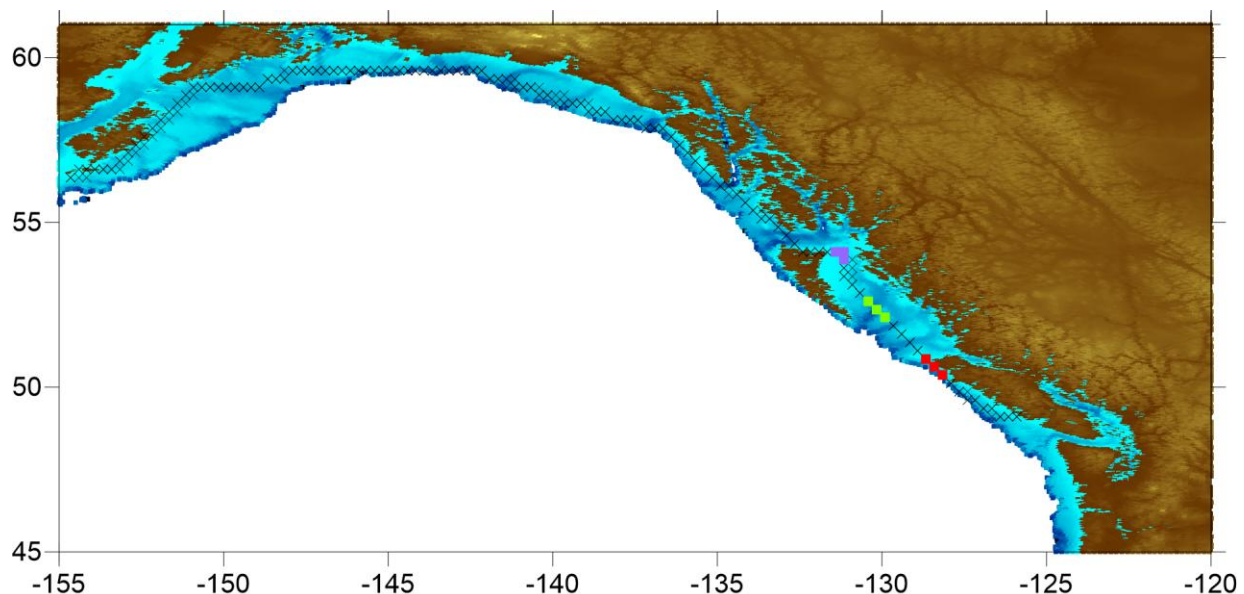


Figure 38: Simulated migration of Somass River sockeye salmon postsmolts from Alberni Inlet to Kodiak (1 plot point=1 day migration). Coloured symbols indicate where the postsmolts would be between 17-19 June (when Tucker et al. 2009 observed them in SEAK) after leaving the Inlet on the average OED (green), one week earlier (mauve), and one week later (red).

Inconsistencies in relative abundance of different populations and spatio-temporal detections were attributed to inadequate sampling in some regions. The Alaska Peninsula (south side) was represented by 1% of total samples and only for 1997. Kodiak Is. and Prince William Sound had about 6%, each, of all samples.

Some BC salmon, identified by stock composition analysis of microsatellite DNA, have been reported from the Bering Sea (Beacham et al. 2012, 2016), but alternative interpretations are possible. Canadian proportions were based on the sum of maximum likelihood estimates of proportions of 9 Canadian regional groupings, estimated from an extensive baseline (Beacham et al. 2016). They reported that the average Canadian fraction taken in the central Bering Sea was 5% in 5 years of Japanese sampling (Beacham et al. 2016). Assuming that migratory behaviour in sockeye salmon improves fitness, does it make sense that immature Canadian sockeye salmon have evolved to improve their survival by going into the Bering Sea, when Bristol Bay sockeye salmon are emigrating from that sea to improve their own survival? Perhaps there is another explanation for Canadian sockeye salmon in the Bering Sea.

Fortunately, the 95% confidence intervals of proportions of individual contributors were reported in Beacham et al. (2016), where it can be understood that 5% is probably an overestimate. In only three instances (of 9 stock groups $\times$ 5 years) did the interval estimates of exclude zero, and then only slightly. These include the Alsek River in 2009, the Skeena River in 2013, and the Alsek River in 2014 with non-zero lower bounds on the estimated proportions. The other 42 instances have 95% interval estimates that

include zero. Sample sizes, of both mixtures and baselines, the genetic differences among groups, and other technical factors affect the estimates (Fournier et al. 1984, Wood et al. 1987). It appears that the true Canadian proportions in the Bering Sea do not emerge from the noise. Under these circumstances a conservative approach is to assume that any contributor, whose 95% c.i. includes zero, was not part of the sample. In the author's experience, this becomes an increasing problem when baselines grow large.

The IPSDL can offer some clues as to when sockeye postsmolt abundance appears near Kodiak as NOAA was sampling this region routinely in the 21st century using trawls and the FRI in the 1960s using purse seine (Figure 39). Purse

seine sampling in the 1960s spanned the warm season while trawl sampling several decades later did not begin until summer, with the greatest number of hauls occurring from weeks 30-35 and a lesser number in the autumn which do not occur in the 1960s data. Peak catches occurred in week 33 (mid August) in both eras. Although sockeye salmon from Bristol Bay rear in the western Gulf of Alaska, sampling did not detect any in coastal trawl sampling from 1996-2011 (Beacham et al. 2012) so these are likely fish from the major southern stocks.

There was speculation that certain BC stock groups, because they were not found in northern samples, may have left the continental shelf before the postsmolts that were found in more northern locations (Beacham et al. 2016). It seems that their absence from shelf samples is only half of what is needed to embrace this idea. The other half is to find YOY sockeye salmon offshore, which as of 2025, has yet to be done.

8.0. DISCUSSION

Considering that they've been around since the Miocene, endured the Pleistocene and now the Holocene, they must be resilient by nature, but that resilience may rest with a sea-type life-history type that is not considered in this study (Wood et al. 2008). Lake-type sockeye salmon require lakes, which are ephemeral features on geological time scales. At one time, Chris Wood has described them as evolutionary dead ends.

Some general observations on the survival of BC sockeye salmon during the last half century can be made. Although there are certainly departures from any generalization, wherever it has been estimated, marine survival of BC sockeye salmon is often lower

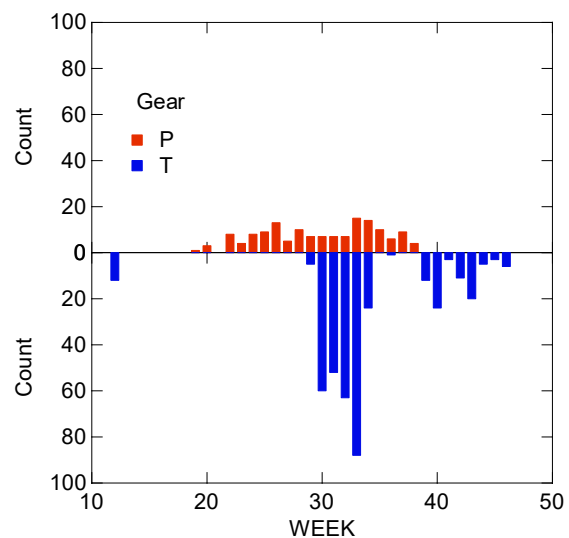


Figure 39: Numbers of research fishing operations by week and gear between 155°W and 147°W.

than average in years when the surface ocean temperatures on the shelf are warmer than average in spring. The spatial footprint of this phenomenon appears to be regional rather than local and, with the exception of the Taku River, it also appears to have the same effect regardless of the migration route encountered by postsmolts.

Evidence for there actually being regional-scale variability of the shelf ecosystem is found in both SST (present study) and, at least in the southern portions of the shelf domain, in zooplankton community composition as well (Mackas et al. 2001, Mackas et al. 2004, Mackas et al. 2006, Mackas et al. 2007, Peterson et al. 2014). In the 21st century, the timing of the biological spring transition in the zooplankton community was a better descriptor of postsmolt survival than the physical spring transition although clearly the two are interconnected. Which leads to the question of what makes the shelf warm? To date, it appears that the equatorial influence has the greatest role, but the role of fresh water should not be overlooked. Indeed, if the glaciers are diminishing, less volume in the freshet should translate into cooler SSTs in places where the role of surface fresh water is important.

8.1. ESTUARIES

Analysis of SSTA at individual grid points near rivermouths produced a result that was similar to the EOF analysis of SSTA of the entire shelf. Loadings on PC1 were relatively high and all were positive, while loadings on PC2 indicated a north/south dipole. Lag 1 autocorrelations of estuarine time series indicated that, once established, SST anomalies persisted beyond 2 months.

How juvenile sockeye salmon live or die in an anomalous environment may be of greater interest to future projections than how they live in a near-average world. Presumably, extant sockeye salmon have adapted or evolved to cope with average, whatever the average might be where each lives. So it is perhaps of greater interest to understand how environmental anomalies are organized in space/time on the shelf rather than how the average is organized. The EOF analysis revealed that weekly SSTA on the shelf was coherent, to varying degree, from the Columbia River to Kodiak Island, especially from Queen Charlotte Sound northward (Shelf EOF1 loadings >0.8). The degree of covariation diminishes somewhat along the BC/Washington coast and in the inlets and straits north of Kodiak. Which raises the question, are the differences sufficient to warrant any subdivision of the shelf? Projections may want to consider using the entire domain as well as subdomains to gauge the extent to which subdivision matters.

8.2. 1992

A satisfactory explanation for the widespread increase in average mortality of BC sockeye salmon beginning with the 1992 ocean entry year has yet to be offered, nor for the persistence of greater mortality thereafter. Its greatest effect was on the southern Queen Charlotte Sound populations (McKinnell et al. 2001, Rutherford & Wood 2000), but the decline in Fraser River sockeye salmon productivity occurred in this OEY as well (McKinnell et al. 2011). It seems as though a force of unknown origin, but likely oceanic,

killed many BC sockeye salmon, then hung around for years after to keep doing it. Perhaps some effort to discover what it is might provide some insight about the future of these stocks.

8.3. SST IN THE HOLOCENE

The Strait of Georgia was deglaciated shortly after 13,000 years Before Present (yBP). The Cordilleran ice sheet that covered most of BC persisted until about 11,000–10,500 yBP (Clague & James 2002). The lower Fraser River valley was deglaciated by 10,900 yBP (Saunders et al. 1987). Glaciation puts large volumes of fresh water on land and deglaciation sends it back to the ocean in various ways ranging from sudden outbursts of huge volumes as water accumulated behind an ice dam is released when the dam melts and collapses (e.g. Lake Missoula) to the regular fluctuations from the annual seasonal signal. Regardless of how it gets there, the coastal ocean had to have been fresher at the surface 10,000 yBP than today. Surface fresh water increases water column stability. All else being equal, the surface ocean will be warmer as a result and perhaps a lot warmer. Evidence that sockeye salmon may have been affected by an abundance of glacial meltwater can be seen in spawning migration timing.

It has been argued, using the adult migration and spawn timing data from many sockeye salmon populations (Figure 38), that their spawning migration timing has evolved to ensure that the river migration will occur when temperatures are suitable (Hodgson & Quinn 2002). The underlying linearity of Figure 38 provides good support for this hypothesis. It is clear from several outliers that river temperature cannot be the entire story. The cause of the outliers has yet to be determined (Quinn et al. 2015). That may be a result of seeking answers in the wrong life-history stage. These anomalous spawning migration behaviours, i.e. entering fresh water much earlier than is typically required for maturation and spawning, are found elsewhere but they are predominant in the southern part of the range (Figure 39). Perhaps the behaviours evolved during an era when “normal” migration timing through southern BC and Washington State would have resulted in high mortality due to more extreme SSTs in the region.

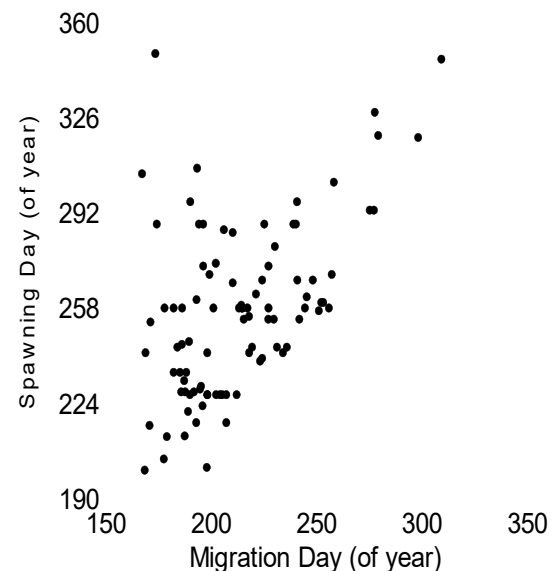


Figure 40: Average spawning dates of sockeye salmon vs dates of average migration to freshwater (Hodgson & Quinn 2002).

Contemporary studies have reported that during years of higher SST, the route taken by Fraser River sockeye salmon to pass Vancouver Island was via Johnstone Strait (Groot & Quinn 1987). On the other hand, prior to 1978 only the most extreme years (1936 and

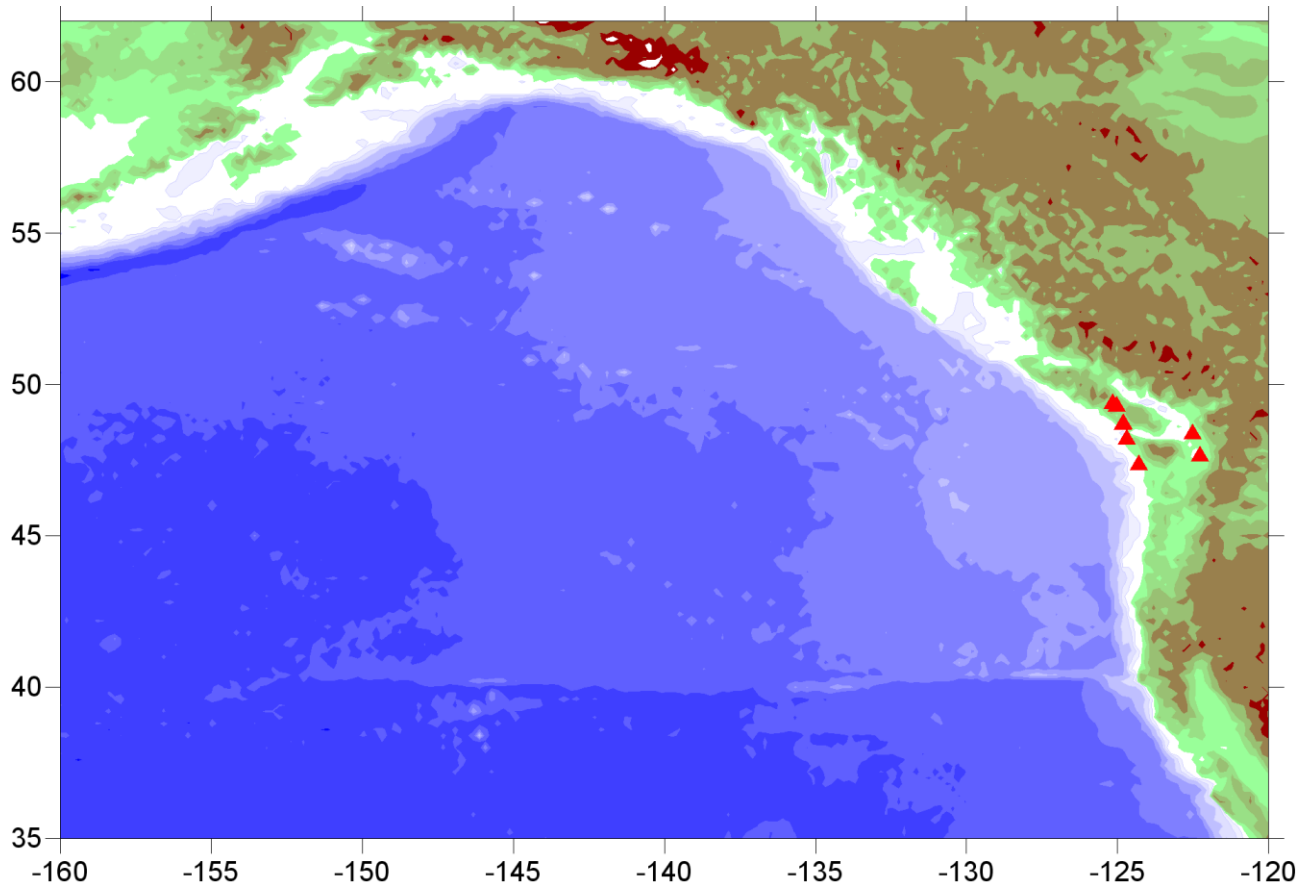


Figure 41: Red triangles indicate locations of sockeye salmon estuaries where adult migration timing is much earlier than required.

1958) were associated with a departure from the “normal” migration route through the Strait of Juan de Fuca (Tully et al. 1960, Royal & Tully 1961, McKinnell et al. 1999).

8.4. SHELF TEMPERATURE REGIMES

It is not uncommon in ocean/climate science to have a time series of data displayed, with a linear regression applied to show the trend, and then to make an inference from the model trajectory. The difficulty with this naive approach is that the slope implies a constant rate of change. Rarely are model diagnostics provided to indicate whether a constant rate of change is indicated by the data. If for example, the true state of nature is a linear trend in temperature, then dividing the time series into two halves should exhibit the same trend in both halves because the rate of change is a constant. The

time series of residuals, whether taken from the whole time series or its parts will be homoscedastic.

An equally naive but perhaps more thoughtful approach is to ask how has temperature changed in BC's coastal ocean? The concept of abrupt changes (Ebbesmeyer et al. 1991) and their origins were discussed vigorously in the 1990s. So at a minimum, asking whether a time series is described by an abrupt shift, or by a series of them, or by a constant is a better approach. The answer will likely affect the hunt for where the cause might lie.

Not much is required to answer the simple question, "Is the change in any time series of SSTA better represented by a linear trend or by a shift (at some time determined by the data). First, subtract the overall average SSTA from the SSTA time series to zero centre it, then apply a linear regression, correcting for autocorrelation, to determine whether the trend was significant, and record the residual sum of squares (RSS) as a measure of the degree of correspondence of the model and data. The number of parameters estimated is two, the intercept and slope. Secondly, for the shift detector, three parameters are involved; s_1 is the SSTA average before the shift, s_2 is the average SSTA after the shift, and t is the point in the time series where the absolute difference between s_2 and s_1 is greatest. An ANOVA can be used to determine whether the s_1 is significantly different from s_2 . A function minimizer can be used to determine where the breakpoint is located. The RSS from the model (a single shift) is calculated and compared with the RSS of the trend. The lower of the two is chosen as the better fit to the data. This approach was applied to Shelf SSTA EOF1 with the following result.

From 1981 to 2024, the linear trend is statistically significant (Figure 12). Based on a comparison of RSS between models, the time series is better described by a shift in the mean of EOF1 after April 2014 (RSS= 1789.5) rather than a trend (RSS=1999.2). In each model, the residuals are trended suggesting that there is more to consider. The trend in EOF1 after April 2014 is negative, presumably because the ocean temperature is coming down from the effects of the marine heat wave in the Gulf of Alaska. The next step in the analysis was to remove the effect of the April 2014 shift, leaving a time series of residuals where the trend/shift models can be fit again. In this example, there was no linear trend in the residuals after removing the April 2014 shift (Figure 42), however, a significant downward shift was identified in November 2020.

If the same approach is applied to the much longer Kains Island SSTA time series from 1936-2018, there is a significant positive linear trend but an abrupt shift (+0.5°C) in the mean state after November 1976 was a better fit to the data; i.e. the classical regime shift of 1976/77 explains most of the secular trend. After removing this shift, there was no linear trend remaining in 83 years of monthly anomalies. Prior to 1976, the linear trend was declining from 1936. The main point of raising these historical examples is that the trajectory of future BC coastal temperatures may be more complex than a constant rate of change.

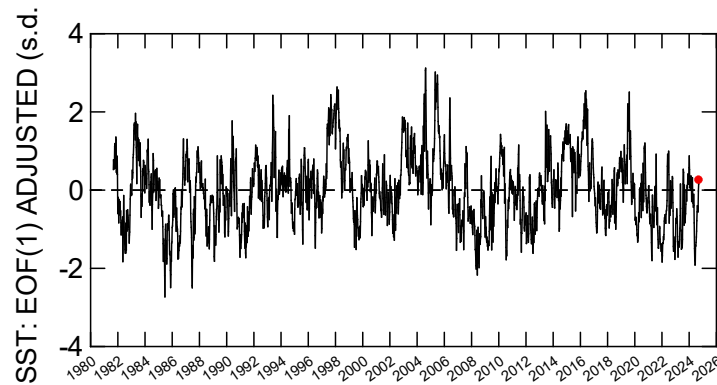


Figure 42: Effect on EOF(1) after removing the April 2014 step change from the time series in Figure 12.

9.0. ACKNOWLEDGEMENTS

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