2022

Marine Climate Indicators for Pacific Salmon in British Columbia

A report prepared by Alicia Andersen, UBC BRITE Intern
for the Salmon Watersheds Program

Citation

Andersen, Alicia (2022). *Marine Climate Indicators for Pacific Salmon in British Columbia*. The Pacific Salmon Foundation, Vancouver, BC, Canada.

PACIFIC SALMON FOUNDATION

Pacific Salmon Foundation, 300 – 1682 West 7th Avenue, Vancouver, BC V6J 4S6

Cover image by Tavish Campbell

This report was produced as part of the UBC BRITE Internship Program, a partnership between the University of British Columbia and various local governments and organisations in support of providing graduate students with opportunities to do applied research on projects that advance sustainability across the region.

This project was conducted under the mentorship of the staff of the Salmon Watersheds Program at the Pacific Salmon Foundation. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of the Pacific Salmon Foundation or the University of British Columbia.

Contents

Background

Climate change is one of the primary factors influencing salmon habitat conditions in the marine environment. Climate change is increasing sea surface temperature, reducing salinity in coastal waters, and changing ocean chemistry with effects on ocean currents, species distributions, and community composition (Okey et al., 2014). Pacific salmon inhabit the ocean for a large duration of their life cycle (1 – 5 years) where they are impacted by these climate change effects. Some of these climate change effects are negatively associated with growth and survival of salmon during the marine phase; for example, warmer temperatures are associated with slower growth (Claiborne et al., 2021; Wells et al., 2007). Growth during the early marine phase is particularly important due to mortality bottlenecks during the first marine year (Beamish & Mahnken, 2001; Duffy & Beauchamp, 2011) and has been linked to survival of returning Chinook (Claiborne et al., 2021; Duffy & Beauchamp, 2011), coho (Beamish et al., 2004), sockeye (Farley et al., 2007), and pink (Moss et al., 2005) salmon adults. Climate change effects impacting salmon growth may further threaten already declining salmon populations (Peterman & Dorner, 2012). Climate also influences salmon's marine phase in the open ocean (Wells et al., 2007), although this phase is understudied and generally less understood than the early marine phase. Overall, there is strong evidence linking climate to salmon survival, so it is important to understand, monitor, and communicate climate changes in the ocean when determining at-risk populations and developing effective management strategies.

Shifts in physical and biological conditions in the marine environment can be summarized by tracking indicators, which are measurable attributes that can be quantified with available data and are sensitive to change. Indicators may also be attributes known to affect the survival or recruitment of a species of interest – in our case, salmon. Many studies examining the impact of climate on salmon growth and survival rely on climate indicators to quantify the inter-annual, seasonal, and sometimes spatial variability in climate. Studies that have included climate indicators, such as sea surface temperature (SST), in spawner-recruit analyses have determined lower salmon recruitment was associated with higher SST years (Chittenden et al., 2010; Hertz et al., 2016). Identifying and displaying relevant marine climate indicators can provide information on potential impacts to salmon populations and how they are changing with climate change (e.g., NOAA's Ocean Ecosystem Indicators of Pacific Salmon Marine Survival).

Motivation

The Pacific Salmon Foundation's Salmon Watersheds Program has developed an online data visualization tool, the Pacific Salmon Explorer (www.salmonexplorer.ca), that provides access to the best publicly available data for salmon populations and their habitats in British Columbia. The Pacific Salmon Explorer displays information on a suite of both habitat and population indicators that represent broad-scale pressures on freshwater salmon habitats and provide an overview of the state of salmon populations, respectively. To date, habitat assessments in the Pacific Salmon Explorer have been focused on freshwater indicators. Given the importance of marine conditions to salmon survival (Chittenden et al., 2010; Claiborne et al., 2021; Hertz et al., 2016), the Pacific Salmon Foundation is looking to incorporate marine climate indicators into the Pacific Salmon Explorer to better reflect the full suite of pressures salmon face across their life cycle. Climate change is currently one of the biggest threats to salmon, and indicators related to climate will be a focus in the Pacific Salmon Explorer moving forward.

This report describes and provides evidence for several potential marine climate indicators and their associations with salmon survival. These indicators are categorized as large-scale climate indices, local physical indicators, and local biological indicators (Figure 1). Next, we describe specific quantifiable metrics and associated datasets for each marine climate indicator. Lastly, we conclude with our recommendations for metrics that have the potential to be incorporated into the Pacific Salmon Explorer.

1.0 Marine Climate Indicators

1.1 Large-scale climate indices

Large-scale climate indices capture interannual or interdecadal atmospheric-oceanic climate fluctuations that drive local physical and biological marine conditions. In the North Pacific, the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) are two common climate indices driving temperature and productivity in local environments. The PDO undergoes interdecadal fluctuations between a positive and negative phase, associated with warm and cool ocean temperatures, respectively. Similarly, ENSO fluctuates every 2-7 years between a positive (warm) and negative (cool) phase. The coincidence of positive deviations in both ENSO and PDO has been known to reflect even warmer conditions. Specifically, El Niño events (i.e., positive ENSO phases) are classified as periods of warmer conditions when temperatures are anomalously higher for at least five consecutive months (Peterson et al., 2014). In addition to PDO and ENSO, the North Pacific Gyre Oscillation (NPGO) is an index of interdecadal climate oscillation driven by atmospheric pressure changes in the North Pacific, linked to changes in sea surface height, temperature, salinity, and chlorophyll-a (Di Lorenzo et al., 2008). Due to these relationships between these large-scale climate indices and local physical and biological conditions, these climate indices can act as an overall summary of ocean temperature and productivity.

Some evidence links these large-scale climate indices to salmon recruitment, productivity, and survival. In the 1900s, shifts in PDO explained shifts in sockeye and pink salmon production regimes in Alaska, but no link was evident for Chinook and coho salmon in southern Washington and Oregon populations (Mantua et al., 1997). Alternatively, since the early 1980s, NPGO as opposed to PDO, explained Chinook and coho salmon survival rates for populations ranging from California to southern Alaska (Kilduff et al., 2015). Poor coho salmon survival has also coincided with strong and extended El Niño events (Rupp et al., 2012). Recent years from 2014-2019 demonstrate a negative correlation between PDO and salmon production, as opposed to the previous 25 years which demonstrate a positive or neutral relationship (Litzow et al., 2020), suggesting a shift between salmon and these large-scale indices given climate changes. Overall, studies suggest contrasting links between large-scale climate indices and salmon survival. Stronger relationships have been established between salmon production and survival to local conditions, suggesting these local physical and biological indicators may be preferred indicators to consider relevant to salmon.

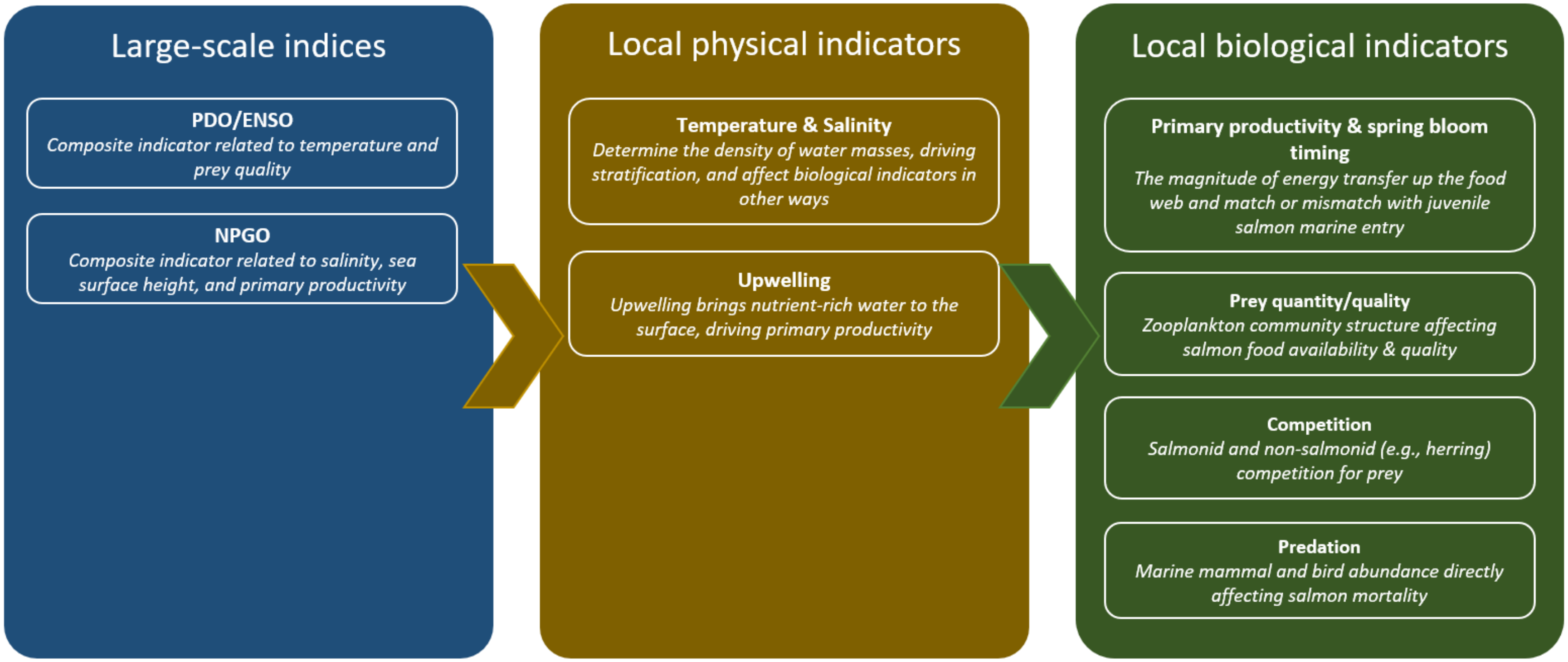

Figure 1. Conceptual diagram identifying marine climate indicators in three broad categories: large-scale indices, local physical indicators, and local biological indicators. Large-scale indices include PDO, ENSO, and NPGO. Local physical indicators include temperature, salinity, and upwelling. Local biological indicators include primary productivity, spring bloom timing, prey quantity / quality, competition, and predation. Directional causal relationships are identified by arrows linking the different indicators.

Due to the complexity of these large-scale climate indices, there is not consensus among model projections in how they might shift with climate change (Achuthavarier et a., 2017; Newman et al., 2016). Projections suggest the North Pacific Ocean will shift towards more negative PDO conditions in the 21st century, but other models suggest contrary results (Lapp et al., 2012). NPGO projections for 2100 suggest a significant positive trend favouring coupling between NPGO and PDO, indicating stronger and prolonged marine heatwaves (Joh & Di Lorenzo, 2017). El Niño events have also shifted over recent decades to become stronger and more frequent (Yeh et al., 2009). Based on relationships between El Niño events and salmon survival, we can assume these projected marine heatwaves and stronger El Niño events will negatively impact salmon survival (Rupp et al., 2012). Overall, evidence suggests climate change may shift these large-scale indices to negatively impacting salmon survival, but there is considerable uncertainty around whether past relationships will hold and in projections of indices.

1.2 Local physical indicators

Large-scale climate indices drive local physical conditions, which drive local biological conditions (Figure 1). The physical marine climate indicators relevant to salmon that we considered are temperature, salinity, and upwelling. Temperature and salinity define the density layers of the water column, determining the stratification or mixing of nutrients from deeper, cold, saline waters. Mixing promotes primary productivity, so if there are higher temperatures and lower salinities at the surface, there will be stronger stratification, less mixing, and decreased primary productivity (Mackas et al., 2007). Upwelling is the transportation of deeper, nutrient-rich water to the surface, driven by wind and current direction. Conversely, downwelling is the transportation of surface water to depth. The North Pacific Current bifurcates into the north-bound Alaskan Current and the south-bound California Current, and ranges in latitude from southern Alaska to Vancouver Island (Malick et al., 2017). Due to the Coriolis effect, the directionality of the California Current and Alaskan Current creates an upwelling and downwelling zone, respectively, in the spring and summer along their respective coasts. Temperature, salinity, and upwelling directly affect primary productivity, which influences food web dynamics through bottom-up effects. Additionally, temperature has been linked to zooplankton community composition and zooplankton bloom timing (Mackas et al., 2007). In particular, higher temperatures are linked to an increase in smaller zooplankton, gelatinous, and warmer-water species.

These local physical indicators have been linked to salmon survival, with contradictory relationships at different latitudes. Specifically in southern regions, positive anomalies in sea surface temperature (SST; temperature in the top 1 m of the water column) during the first year at sea have been associated with reduced pink and Chinook salmon growth and survival (Claiborne et al., 2021; Wells et al., 2007), possibly due to increased stratification impacting primary productivity or negative impacts on zooplankton communities (Mackas et al., 2007). Upwelling regions, however, have been positively associated with Chinook, sockeye, pink, and chum salmon growth and subsequent survival, likely due to resulting increases in productivity providing more prey for salmon (Wells et al., 2007). Conversely, in northern regions such as Alaska, positive anomalies in SST have been positively associated with pink, sockeye, and chum survival rates (Mueter et al., 2002). One potential explanation for these different results is that different mechanisms are driving salmon productivity and survival in upwelling or downwelling regions (Malick et al., 2017). Alternatively, given the differing temperatures in northern (colder) and southern (warmer) ecosystems, overall positive anomalies in SST could be shifting the ecosystem towards or away from the optimal temperature of salmon, respectively (Mueter et al., 2002).

In addition to identifying indicators that can be used to provide insights into salmon survival, it is important to predict how climate will be changing in the future, thus providing further insight into how salmon may become more vulnerable to climate change. Climate change projections from the Intergovernmental Panel on Climate Change suggest the average global temperature will likely increase by at least 1.5 ^{o}C by 2100 (IPCC, 2014). Based on the contradictory relationship between SST and salmon growth and survival dependent on latitude, these climate change effects may have negative and positive impacts on salmon populations in southern and northern regions, respectively. Climate projections also suggest delayed and shorter upwelling seasons off the west coast of Vancouver Island (Foreman et al., 2011), which would likely negatively impact salmon production due to decreased prey available. Alternatively, projections suggest an increase in the intensity of alongshore winds and therefore upwelling, which would positively impact salmon production. These SST and upwelling projections have direct impacts on primary productivity, food web dynamics, and therefore salmon populations.

1.3 Local biological indicators

Local biological indicators that we considered are primary productivity, spring bloom timing, prey quantity, prey quality, competition, and predation. A common proxy measure of the primary productivity in the marine environment is chlorophyll-a, a photosynthetic pigment used by marine phytoplankton. Due to bottom-up effects, chlorophyll-a provides an indirect metric of prey availability for salmon since zooplankton consume phytoplankton and are a primary source of prey for salmon. Therefore, chlorophyll-a and zooplankton biomass are potential metrics for these marine climate indicators that have demonstrated links to increased salmon growth and survival (Perry et al., 2021; Tomaro et al., 2012; Wells et al., 2007).

Additional biological indicators, such as prey quality, show strong relationships to juvenile salmon growth and survival. Prey quality represents the variation in zooplankton lipid and essential fatty acid content based on zooplankton community composition, representing the nutritional value of salmon prey (Costalago et al., 2020; Mackas et al., 2007). Zooplankton that are lipid-rich and contain higher essential fatty acid content promote salmon growth and physiological development, so zooplankton metrics that provide this information are critical for determining juvenile salmon growth and survival (Paulsen, Clemmensen, & Malzahn, 2014; Sargent et al., 1995; Sheridan, 1994). Some relevant metrics include the biomass of good- vs. poor-quality zooplankton species, such as northern vs. southern copepods, respectively. Northern vs. southern copepod species is an index that can be used in upwelling regions off the west coast of Vancouver Island (Galbraith & Young, 2019; Peterson et al., 2014). Southern copepods are smaller, lipid-poor, 'warm' water species transported northward from warmer waters, whereas northern copepods are larger, lipid-rich, 'cold' water species transported southward from cooler waters via the California Current, including the boreal and subarctic copepod communities. A distinction can also be made between lipid-poor gelatinous zooplankton, colloquially referred to as "squishies", and lipid-rich crustacean zooplankton, or "crunchies" (Galbraith & Young, 2019). A crunchie:squishie index (CSIndex) is the ratio of these two plankton types and may be a useful metric of changes in prey quality through time. However, a caveat of the CSIndex is it does not differentiate between lipid-rich and lipid-poor "crunchies", which is an important distinction. Therefore, northern vs. southern copepod biomass may be a more useful metric to consider, although CSIndex does provide more general prey quality information if detailed taxonomic data is unavailable.

Further, although salmon generally consume zooplankton, there are differences in each salmon species' preferred diet, with varying proportions of zooplankton and ichthyoplankton species, so creating species-specific diet groupings may be useful for defining prey quality metrics. Chinook and coho salmon are two species with a preference for small fish and fish larvae. Conversely, sockeye, pink, and chum salmon prefer larger zooplankton species such as euphausiids, calanoid copepods, amphipods, and fish larvae. Chum salmon are unique in that they also prey on gelatinous zooplankton species (James et al., 2019; Zahner et al., 2021). These species-specific prey quality metrics can provide more detailed information for individual species' potential growth and survival.

Spring bloom timing is another important indicator to determine the coincidence of juvenile salmon early marine residence with periods of peak prey abundance. Spring bloom timing and the biological spring transition (onset of the upwelling season) can be measured using chlorophyll-a and the presence of northern copepod species, respectively (Keister et al., 2011; Peterson et al., 2014). Bloom timing is driven by physical ocean conditions, which vary based on the marine environment. For example, in the Strait of Georgia (SOG) the spring bloom is driven by salinity, controlled by the freshet from the Fraser River, and mixing due to winds (Okey et al., 2014). Alternatively, the spring bloom in upwelling regions, such as the west coast of Vancouver Island, is driven by wind and current (Okey et al., 2014). The spring bloom provides food for zooplankton, so a match between spring bloom timing and zooplankton emergence is critical, as well as a match between zooplankton bloom timing and juvenile salmon outmigration and residence in coastal waters. This is evidenced by coho salmon smolt-to-adult survival being greater when salmon were released during a period of high productivity compared to a mismatch (Chittenden et al., 2010). However, further evidence suggests latitudinal differences exist between spring bloom timing and salmon productivity. An earlier spring bloom was associated with higher and lower productivity in northern and southern pink salmon populations, respectively (Malick et al., 2015). This once again suggests different biological mechanisms in northern and southern regions based on the type of region (i.e., upwelling, downwelling).

These biological indicators are shifting with climate change. Increasing temperatures have been hypothesized to influence zooplankton communities, reducing prey quality, including increasing the abundance of gelatinous zooplankton, and of smaller, lipid-poor, southern copepod species (Brodeur et al., 2008; Mackas et al., 2001). This will negatively impact nutritional composition of prey available to salmon, which can impair growth and physiological developmental (Paulsen, Clemmensen, & Malzahn, 2014; Sargent et al., 1995; Sheridan, 1994). Additionally, climate change has distinct impacts based on region. In the SOG, changes in climate can shift spring bloom timing earlier, due to increased precipitation, storms, and an earlier freshet (Johannessen & Macdonald, 2009). Conversely, upwelling projections off the British Columbia coast suggest the onset of upwelling is becoming delayed, and the season is becoming shorter, indicating a later and shorter spring bloom (Foreman et al., 2011). These shifts in spring bloom timing may cause a potential mismatch between salmon and their prey, negatively impacting salmon survival. Additionally, zooplankton bloom timing is predicted to occur earlier in the SOG, due to increasing temperatures (Johannessen & Macdonald, 2009), and juvenile salmon outmigration timing has been proposed to shift with climate change as well, which can potentially lead to a mismatch between outmigration timing and prey availability. Cumulatively, these changes could lead to reduced salmon productivity and survival during their early marine phase, depending on the latitudinal range of salmon populations, ultimately impacting marine survival.

2.0 Metrics and Datasets

2.1 SST point data

Time series SST point data have been downloaded from Department of the Fisheries and Oceans Canada (DFO). These are open data available from active, in-active, and archived light stations along the BC coast. Monthly SST is available for the sites, with data from active stations updated quarterly. If thermal thresholds are identified for juvenile salmon in the marine environment, these could be applied to the light station data to provide a benchmark for good or poor ocean conditions.

2.2 SST raster data

SST raster data is collected by satellites and available from several sources (Table 1). SST anomalies can be calculated using the historical average of data available, and averaged annually, monthly, or seasonally (e.g., for April – November, the months of juvenile salmon early marine residence). Sentinel-3 data have a high spatial resolution, allowing a clear picture of inlets and fjords, whereas other satellite data sources only have data available down to 4 km spatial resolution (Table 1). This allows for a clear picture of the BC coast, but it loses the data from inlets and fjords. However, there is the possibility of interpolating 4 km data to 1 km spatial resolution. On the other hand, Sentinel-3 is a shorter time series, whereas the other data sources have longer time series spanning greater than 10 and 20 years.

Table 1. Satellite data sources for sea surface temperature and chlorophyll-a.

Satellite Data	**Pros**	**Cons**
Sentinel-3	High spatial resolution (300 m)	Short time series (~6 years)
NASA Aqua-MODIS	Long time series (~20 years)	Mid spatial resolution (4 km)
NOAA	Long time series (~25 years)	Mid spatial resolution (4/5 km)
Copernicus	Various data sources Includes high spatial resolution options	Mid time series (2007-present)
ACRI Hermes	Compiles multiple satellite sources, including Sentinel-3 Good data quality for BC	Mid spatial resolution (4 km) Only includes chlorophyll-a data

2.3 Chlorophyll-a annual anomalies

Chlorophyll-a raster data are also collected by satellites, and available from various sources (Table 1). Annual anomalies can be calculated using the historical average of data available, for the months March – June, which captures the spring bloom duration. Similar to SST, the different data sources have pros and cons based on spatial and temporal resolution. However, another data source is listed as ACRI Hermes, which is a site that compiles multiple satellite sources, providing good data quality for BC.

2.4 Spring bloom timing

Spring bloom timing can be measured using chlorophyll-a satellite data to calculate the first week of the spring bloom (Table 1). Alternatively, zooplankton data can be used to identify the biological spring transition in upwelling regions using the arrival of northern copepod species. Their arrival marks the transition between copepod communities, which indicates the onset of upwelling (Table 3).

2.5 Zooplankton biomass annual anomalies

Zooplankton abundance, biomass, and species composition data are available as point data from DFO tows in the Strait of Georgia and the west and north coast of Vancouver Island (Figure 2). Summary data from tows, separated into broad taxonomic groups, are publicly available for download. DFO has conducted marine surveys since 1980 at various stations in the SOG, west coast Vancouver Island, Queen Charlotte Strait, Queen Charlotte Sound, and Hecate Strait, although data have not been collected from Hecate Strait since the early 2000s. Vertical zooplankton tows are conducted at each station with approximately 230 µm bongo nets. Zooplankton are identified to species, with designated biomass data. From these data, total biomass can be calculated, and zooplankton can be grouped together to form 'prey quality' or taxonomic groups as needed.

Total zooplankton biomass annual anomaly is a prey quantity metric for juvenile salmon (Table 2). Prey quality metrics include northern vs. southern copepod biomass annual anomalies, CSIndex biomass annual anomalies, and species-specific biomass annual anomalies. The breakdown for each prey quality metric is summarized in Tables 3-5. All annual zooplankton anomalies can be calculated using the historical average of data available for months April – November, during the early marine residence of juvenile salmon.

Table 2. Summary list of marine climate indicators, metrics, and impacts on salmon.

Category	Indicator	Metric	Projected impact of climate change	Impact on salmon	Data
Local biological indicators	Prey quality	Crunchie: Squishie Index (CSIndex)	Predicted to decrease with more gelatinous species dominate zooplankton communities	Crunchies are generally considered higher quality prey for most salmon species, so decreases in CSIndex may negatively impact salmon	DFO zooplankton tows (Figure 2) BC data SOG data
		Northern copepod biomass	Unknown	Northern copepod species are higher quality, so years with higher northern copepod biomass may be positively associated with salmon survival	

		Southern copepod biomass	Unknown	Southern copepod species are lower quality prey, so years with higher southern copepod biomass may be negatively associated with salmon survival	
		Species-specific diet biomass anomalies (sockeye, pink, chum, Chinook, coho)	Predicted increase in gelatinous zooplankton, so juvenile chum salmon diet biomass anomalies will increase Other salmon species' diet biomass anomalies will decrease	Gelatinous prey is generally lower quality prey, so growth and survival of salmon would generally be negatively impacted However, chum salmon growth will likely be positively impacted, as chum diets consist of more gelatinous zooplankton	
	Prey quantity	Total zooplankton biomass anomalies	Unknown	Total zooplankton biomass is positively associated with juvenile salmon survival	
	Primary productivity	Chlorophyll-a	Unknown	Chlorophyll-a is positively associated with juvenile salmon survival	Satellite data (Table 1)
	Spring bloom timing	First week of spring bloom/ First week northern copepod presence	Spring bloom timing will occur earlier in the SOG, but later on the west coast of Vancouver Island	Potential mismatch of juvenile salmon early marine residence and spring bloom timing, causing a mismatch between juvenile salmon and prey availability	Satellite data (Table 1); DFO zooplankton tows (Figure 2) BC data

Local physical indicators	Temperature	SST anomalies	More positive SST anomalies	Negative impacts on salmon growth and survival	Satellite data (Table 1)
		SST	SST temperatures will increase	Negative impacts on salmon growth and survival	DFO light station data

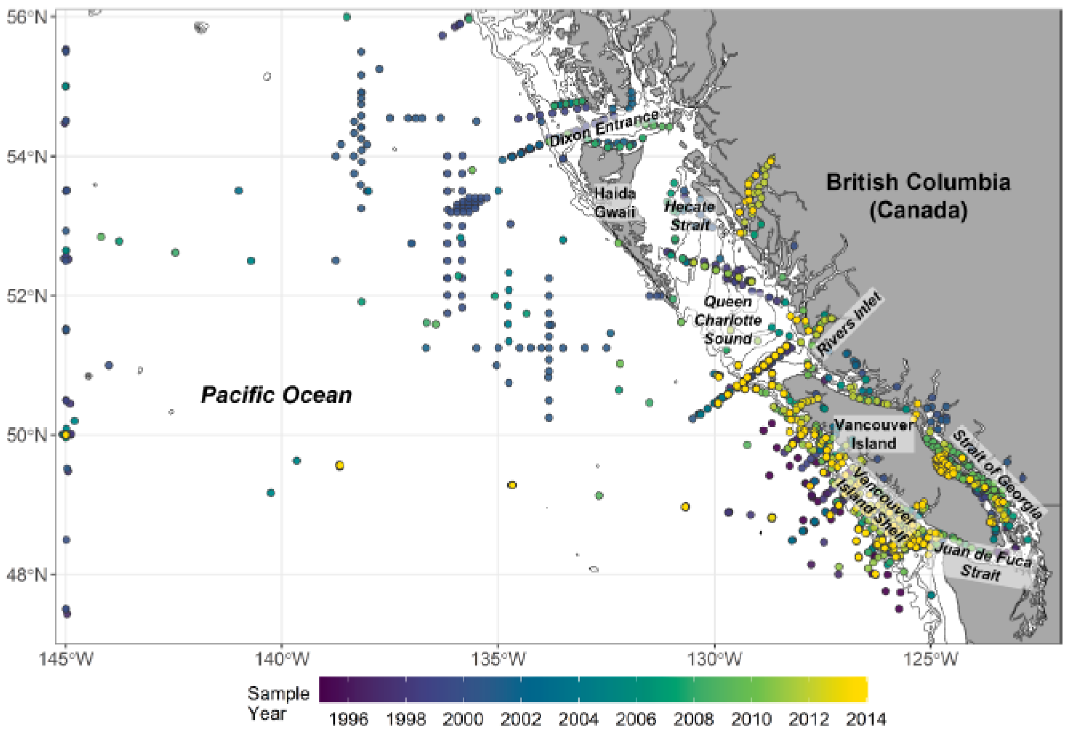

Figure 2. DFO zooplankton stations in British Columbia across years (adapted from Pata et al., 2022).

Table 2. Northern vs. southern copepod species classification (adapted from Boldt et al., 2019).

Zooplankton Group	Species
Northern copepods (boreal shelf copepods)	*Calanus marshallae, Pseudocalanus mimus, Acartia longiremis*
Southern copepods	*Acartia danae, A. tonsa, Clausocalanus spp., Calocalanus spp., Ctenocalanus vanus, Eucalanus californicus, Mesocalanus tenuicornis, Paracalanus spp.*

Table 3. CSIndex: Classification of "crunchie" and "squishie" broad taxonomic groups.

Zooplankton Group	Broad Taxonomic Groups
Crunchie	*Amphipoda, Copepoda, Cirripedia, Cladocera, Cumacea, Anomura, Brachyura, Caridea, Pleocyemata, Euphausiacea, Isopoda, Mysida, Ostracoda*
Squishie	*Bryozoa, Polychaeta, Chaetognatha, Anthozoa, Hydromedusa, Siphonophora, Scyphozoa, Ctenophora, Echinodermata, Cephalopoda, Nemertea, Phronida, Pisces, Platyhelminthes, Sipuncula, Appendicularia, Thaliacea*

Table 4. Salmon species-specific diet classification.

Salmon species	Diet composition
Chinook	Larval fish, euphausiids, amphipods, larval decapods
Coho	Larval fish, euphausiids, amphipods
Chum	Gelatinous spp., larval fish, calanoid copepods, euphausiids, chaetognaths
Pink	Larval fish, decapod larvae, calanoid copepods, euphausiids, chaetognaths
Sockeye	Larval fish, euphausiids, calanoid copepods, cladoceran, barnacles, decapods

3.0 Discussion

Marine conditions are important drivers of salmon survival that are shifting with climate change. Climate change projections suggest future marine conditions may generally be unfavourable for salmon survival, though there is considerable uncertainty both in how biological conditions will shift and how salmon will respond. In this report, we reviewed marine climate indicators that may be useful for tracking and assessing the status of marine conditions relevant to salmon. We outlined several marine climate indicators and metrics under three broad categories: large-scale indices, local physical indicators, and local biological indicators. Below we provide recommendations on these marine climate indicators and metrics that would be the most useful to include in the Pacific Salmon Explorer.

3.1 Recommendations

Section 4 provides a detailed list and description of quantifiable metrics and associated datasets for recommended marine climate indicators. These recommended indicators exclude large-scale climate indices due to contrasting evidence of their impact to salmon populations. It is also uncertain how these large-scale indices will change with climate, so it would be difficult to predict the response of salmon populations. Lastly, since local physical and biological indicators provide more direct evidence and links to salmon populations, we recommend these as preferable marine climate indicators to incorporate into the Pacific Salmon Explorer.

Regarding the local physical and biological indictors, there is some redundancy as multiple marine climate indicators represent the same biological mechanism. For example, upwelling and primary productivity (chlorophyll-a) are indicators and metrics for primary productivity. Since chlorophyll-a is a proxy of photosynthetic pigment representing the phytoplankton bloom, and therefore more directly represents primary productivity, this is suggested as a preferred marine climate indicator to incorporate into the Pacific Salmon Explorer.

Many prey quality metrics are also recommended including northern and southern copepod biomass anomalies, the CSIndex, and species-specific diet biomass anomalies. Although these provide information for the same marine climate indicator, they provide different levels of detail dependent on species and region, so it is recommended to incorporate them all. However, a caveat of the CSIndex is it incorporates lipid-rich and lipid-poor zooplankton species as "crunchies". This can potentially bias the results of the index to suggest prey quality is higher than what is available for salmon. For this reason, this index is not recommended to incorporate, unless data is unavailable describing detailed taxonomic groups and it is not possible to provide metrics for northern and southern copepod and species-specific diet biomass anomalies.

3.2 Next steps

The recommended marine climate indicators will be quantified using the datasets outlined in this report. Additional work is required to acquire remotely sensed datasets at the appropriate spatial and temporal scales, for SST and chlorophyll-a metrics. Zooplankton data has been compiled, but analysis is required to create the metrics listed above. Lastly, the recommended marine climate indicators will be incorporated and visualized in the Pacific Salmon Explorer.

3.3 Conclusion

We have provided an overview of potential marine climate indicators and described quantifiable metrics and associated datasets for each marine climate indicator (Table 2). We also provide recommendations and rationales for the incorporation of potential marine climate indicators into the Pacific Salmon Explorer (www.salmonexplorer.ca). These marine climate indicators are valuable to incorporate into this online tool as they will help provide a full suite of pressures salmon face during their life cycle, in the context of climate change.

References

Achuthavarier, D., Schubert, S.D., & Vikhliaev, Y.V. (2017). North Pacific decadal variability: insights from a biennial ENSO environment. *Clim. Dyn., 49,* 1379-1397.

Beamish, R.J., & Mahnken, C. (2001). A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. *Elsevier Science Ltd, 49,* 423-437.

Beamish, R.J., Mahnken, C., & Neville, C.M. (2004). Evidence That Reduced Early Marine Growth Is Associated with Lower Marine Survival of Coho Salmon. *Transactions of the American Fisheries Society, 133,* 26-33.

Boldt, J.L., Leonard, J., & Chandler, P.C. (Eds.). (2019). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2018. *Can. Tech. Rep. Fish. Aquat. Sci., 3314,* vii + 248 p.

Brodeur, R.D., Decker, M.B., Ciannelli, L., Purcell, J.E., Bond, N.A., Stabeno, P.J., Acuna, E., & Hunt Jr., G.L. (2008). Rise and fall of jellyfish in the eastern Bering Sea in relation to climate regime shifts. *Elsevier Ltd., 77,* 103-111.

Chittenden, C.M., Jensen, J.L.A., Ewart, D., Anderson, S., Balfry, S., Downey, E., Eaves, A., Saksida, S., Smith, B., Vincent, S., Welch, D., & McKinley, R.S. (2010). Recent Salmon Declines: A Result of Lost Feeding Opportunities Due to Bad Timing? *PLoS ONE, 5,* e12423.

Claiborne, A.M., Campbell, L., Stevick, B., Sandell, T., Losee, J.P., Litz, M., & Anderson, J.H. (2021). Correspondence between scale growth, feeding conditions, and survival of adult Chinook salmon returning to Puget Sound and coastal Washington: Implications for forecasting. *Elsevier Ltd, 198,* 102443.

Costalago, D., Forster, I., Nemcek, N., Neville, C., Perry, R.I., Young, K., & Hunt, B.P.V. (2020). Seasonal and spatial dynamics of the planktonic trophic biomarkers in the Strait of Georgia (northeast Pacific) and implications for fish. *Nature Scientific Reports, 10,* 8517.

Di Lorenzo, E., Scheider, N., Cobb, K.M., Franks, P.J.S., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchitser, E., Powell, T.M., & Riviere, P. (2008). North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophysical Research Letters, 35,* L08607.

Duffy, E.J., & Beauchamp, D.A. (2011). Rapid growth in the early marine period improves the marine survival of Chinook salmon (*Oncorhynchus tshawytscha*) in Puget Sound, Washington. *Can. J. Fish. Aquat. Sci., 68,* 232-240.

Farley, E.V., Murphy, J.M., Adkison, M.D., Eisner, L.B., Helle, J.H., Moss, J.H., & Nielsen, J. (2007). Early marine growth in relation to marine-stage survival rates for Alaska sockeye salmon (*Oncorhynchus nerka*). *Fishery Bulletin, 105,* 121-130.

Foreman, M.G.G., Pal, B., & Merryfield, W.J. (2011). Trends in upwelling and downwelling winds along the British Columbia shelf. *Journal of Geophysical Research, 116*, C10023.

Galbraith, M., & Young, K. (2019). West coast British Columbia zooplankton biomass anomalies 2018. In: Boldt, J.L., Leonard, J., & Chandler, P.C. (Eds.). (2019). State of the physical, biological and selected fishery resources of Pacific Canadian marine ecosystems in 2018. *Can. Tech. Rep. Fish. Aquat. Sci., 3314,* vii + 248 p.

Hertz, E., Trudel, M., Tucker, S., Beacham, T.D., Parken, C., Mackas, D., & Mazumder, A. (2016). Influences of ocean conditions and feeding ecology on the survival of juvenile Chinook Salmon (Oncorhynchus tshawytscha). *Fisheries Oceanography, 25,* 407-419.

IPCC (2014). Climate change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

James, S.E., Pakhomov, E.A., & Hunt, B.P.V. (2019). Spatial and temporal trends in juvenile sockeye salmon diets across oceanographic regimes on the coast of British Columbia. *North Pacific Anadromous Fish Commission Technical Report, 15,* 85-89.

Joh, Y., & Di Lorenzo, E. (2017). Increasing Coupling Between NPGO and PDO Leads to Prolonged Marine Heatwaves in the Northeast Pacific. *Geophysical Research Letters, 44*, 11,663-11,671.

Johannessen, S.C., & Macdonald, R.W. (2009). Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada. *Climate Research, 40*, 1-21.

Keister, J.E., Di Lorenzo, E., Morgan, C.A., Combes, V., & Peterson, W.T. (2011). Zooplankton species composition is linked to ocean transport in the Northern California Current. *Global Change Biology, 17,* 2498-2511.

Kilduff, D.P., Di Lorenzo, E., Botsford, L.W., & Teo, S.L.H. (2015). Changing central Pacific El Ninos reduce stability of North American salmon survival rates. *PNAS, 112,* 10962-10966.

Lapp, S.L., Jacques, J-M.St., Barrow, E.M., & Sauchyn, D.J. (2012). GCM projections for the Pacific Decadal Oscillation under greenhouse forcing for the early 21st century. *International Journal of Climatology, 32,* 1423-1442.

Litzow, M.A., Malick, M.J., Bond, N.A., Cunningham, C.J., Gosselin, J.L., & Ward, E.J. (2020). Quantifying a Novel Climate Through Changes in PDO-Climate and PDO-Salmon Relationships. *Geophysical Research Leters, 47,* e2020GL087972. https://doi.org/10.1029/2020GL087972

Mackas, D.L., Thomson, R.E., & Galbraith, M. (2001). Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. *Canadian Journal of Fisheries and Aquatic Sciences, 58,* 685-702.

Mackas, D.L., Batten, S., & Trudel, M. (2007). Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. *Elsevier Ltd., 75,* 223-252.

Malick, M.J., Cox, S.P., Mueter, F.J., & Peterman, R.M. (2015). Linking phytoplankton phenology to salmon productivity along a north-south gradient in the Northeast Pacific Ocean. *Can. J. Fish. Aquat. Sci., 72,* 697-708.

Malick, M.J., Cox, S.P., Mueter, F.J., Dorner, B., & Peterman, R.M. (2017). Effects of the North Pacific Current on the productivity of 163 Pacific salmon stocks. *Fisheries Oceanography, 26,* 268-281.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., & Francis, R.C. (1997). A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. *Bulletin of the American Meteorological Society, 78,* 1069-1080.

Moss, J.H., Beauchamp, D.A., Cross, A.D., Myers, K.W., Farley, E.V., Murphy, J.M., & Helle, J.H. (2005). Evidence for Size-Selective Mortality after the First Summer of Ocean Growth by Pink Salmon. *Transactions of the American Fisheries Society, 134,* 1313-1322.

Mueter, F.J., Peterman, R.M., & Pyper, B.J. (2002). Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (Oncorhynchus spp.) in northern and southern areas. *Canadian Journal of Fisheries and Aquatic Sciences, 59,* 456-463.

Newman, M., Alexander, M.A., Ault, T.R., Cobb, K.M., Deser, C., Di Lorenzo, E., Mantua, N.J., Miller, A.J., Minobe, S., Nakamura, H., Schneider, N., Vimont, D.J., Phillips, A.S., Scott, J.D., & Smith, C.A. (2016). The Pacific Decadal Oscillation, Revisited. *Journal of Climate, 29,* 4399-4427.

Okey, T.A., Alidina, H.M., Lo, V., & Jessen, S. (2014). Effects of climate change on Canada's Pacific marine ecosystems: a summary of scientific knowledge. *Rev. Fish. Biol. Fisheries, 24,* 519-559.

Pata, P.R., Galbraith, M., Young, K., Margolin, A.R., Perry, R.I., & Hunt, B.P.V. (2022). Persistent zooplankton bioregions reflect long-term consistency of community composition and oceanographic drivers in the NE Pacific. *Progress in Oceanography, 206,* 102849.

Paulsen, M., Clemmensen, C., & Malzahn, A.M. (2014). Essential fatty acid (docosahexaenoic acid, DHA) availability affects growth of larval herring in the field. *Marine Biology, 161,* 239-244.

Peterman, R.M., & Dorner, B. (2012). A widespread decrease in productivity of sockeye salmon (*Oncorhynchus nerka*) populations in western North America. *Can. J. Fish. Aquat. Sci., 69,* 1255-1260.

Peterson, W.T., Fisher, J.L., Peterson, J.O., Morgan, C.A., Burke, B.J., & Fresh, K.L. (2014). Applied fisheries oceanography: Ecosystem indicators of ocean conditions inform fisheries management in the California Current. *Oceanography, 27,* 80-89.

Rupp, D.E., Wainwright, T.C., Lawson, P.W., & Peterson, W.T. (2012). Marine environment-based forecasting of coho salmon (Oncorhynchus kisutch) adult recruitment. *Fisheries Oceanography, 21,* 1-19.

Sargent, J.R., Bell, J.G., Bell, M.V., Henderson, R.J., & Tocher, D.R. (1995). Requirement criteria for essential fatty acids. *J. Appl. Ichthyol., 11,* 183-198.

Sheridan, M.A. (1994). Regulation of lipid metabolism in poikilothermic vertebrates. *Comp. Biochem. Physiol. 107B,* 495-508.

Tomaro, L.M., Teel, D.J., Peterson, W.T., & Miller, J.A. (2012). When is bigger better? Early marine residence of middle and upper Columbia River spring Chinook salmon. *Marine Ecology Progress Series, 452,* 237-252.

Wells, B.K., Grimes, C.B., Waldvogel, J.B. (2007). Quantifying the effects of wind, upwelling, curl, sea surface temperature and sea level height on growth and maturation of a California Chinook salmon (Oncorhynchus tshawytscha) population. *Fisheries Oceanography, 16,* 363-382.

Yeh, S-W., Kug, J-S., Dewitte, B., Kwon, M-H., Kirtman, B.P., & Jin, F.F. (2009). El Nino in a changing climate. *Nature, 461*, 511-515.

Zahner, V.R. (2021). Strategies for coexisting: juvenile pink and chum salmon diets and interactions in a challenging section of coastal migration. M.Sc. Thesis, The University of British Columbia.