

**Investigating and Projecting the Impacts of the Temperature Size Rule and Heat Stress on
Chinook Salmon (*Oncorhynchus tshawytscha*) in the Gulf of Alaska**

BIOL*4110: Ecological Methods

Dr. Joey Bernhardt

Group 2

Hannah Bennett (1125667), Rose Brandt (1174398), Nora de Vos (1134440), Karleigh Fishback

(1128401)

2024.12.05

Introduction

Chinook salmon (*Oncorhynchus tshawytscha*) are a keystone species with significant cultural, economic, and ecological roles, with a wide habitat range spanning from California to Alaska (DFO, 2019; NOAA, 2024; State of Salmon, 2021). Salmon are commonly used as biological indicators for aquatic ecosystems due to their role in nutrient cycling between marine and freshwater systems, and their sensitivity to environmental conditions throughout their life stages (Hyatt & Godbout, 1999). The Alaskan chinook salmon's complex anadromous life cycle includes spawning in inland freshwater rivers before smolting to the juvenile stage and migrating to the Pacific Ocean through the Gulf of Alaska (NOAA, 2024; Bourret et al., 2016; IYS, 2019). Due to declining populations, they are now a candidate species under the Endangered Species Act, emphasizing the need to investigate possible harms to their populations and life histories (NOAA, 2024).

Annual average air temperatures from 1895 to 2011 rose 0.7°C in the Pacific Northwest, raising concerns about water temperatures and thus, the survivability and success of chinook salmon (Crozier et al., 2014). In particular, chinook salmon eggs are extremely vulnerable to heat stress because they are immobile, preventing them from seeking refuge in more favourable conditions (Del Rio et al., 2019). Consequently, rising water temperatures are expected to decrease the number of eggs per spawner that successfully develop into juveniles, threatening the overall chinook salmon population size (Onslow et al., 2013; WSDE, 2000).

The juvenile stage of a salmon's life cycle is the transitional period between freshwater and marine environments, during which it prepares for migration (Bourret et al., 2016). During migration, chinook salmon experience great stress, which is compounded by temperature stress as they are limited throughout various life stages by their narrow thermal tolerance ranges (Twardek et al., 2023; Richter & Kolmes, 2005; Keefer et al., 2018). Adult chinook salmon can

tolerate temperatures between 12.8°C and 17.8°C, with an optimal temperature of 15.6°C and significant population declines observed at temperatures exceeding 18°C (National Wildlife Federation, n.d.; Richter & Kolmes, 2005). Chinook salmon subjected to rising temperatures might experience a natural phenomenon called the Temperature-Size Rule (TSR), wherein ectothermic species, such as fish, develop and mature quickly in warmer conditions, resulting in smaller adults (Forester et al., 2011).

While there is a lot of information regarding how rising temperatures increase the mortality of chinook salmon, little is known about how rising temperatures impact body size and reproduction in specific populations in real time and in the near future. Generally, it is hypothesized that temperatures approaching or exceeding thermal tolerance limits will increase heat stress on chinook salmon, resulting in a reduced number of juveniles per spawner (J/S). It is predicted that increased temperatures associated with climate change will linearly reduce the number of eggs surviving to the juvenile stage. Additionally, it is hypothesized that rising temperatures will cause chinook salmon to develop and mature at an accelerated rate due to the TSR, resulting in predicted smaller body sizes over time. These hypotheses will be referred to as the Heat Stress Hypothesis and the TSR Hypothesis, respectively, named for their mechanisms. The results of this study will provide insight into the future of chinook salmon populations in Alaska and inform predictions of broader ecological consequences.

Methods

To analyze the effects of rising temperatures on Chinook salmon in Alaska, open-source datasets were cleaned to remove irrelevant information. Temperature data from the Alaska Center for Conservation Science (AKTEMP, n.d.) was filtered to include four stations (OSM_Neva, OSM_Buskin, OSM_Klag, and OSM_Afognak) overlapping the study's spatial and temporal scope. Data from 2009–2019 was averaged to seasonal means (May–September) to

reflect salmon's freshwater environment and exclude winter temperatures to avoid skewed results (Kambestad et al., 2024). A linear regression model in R was used to assess changes in freshwater temperatures over the study period.

Salmon length data was sourced from two datasets by the Alaska Department of Fish and Game: "ASL_formatted_SoutheastKodiak.csv" (Kodiak ASL) (DCFADFG, 2021: [KNB](#)) and "Unuk 1995 to 2017_Lewis.xlsx" (Unuk ASL) (DCFADFG, 2019: [KNB2](#)). The Kodiak ASL data, originally spanning from 1979-2017, was trimmed to 2010-2017 using WordPad due to its large size. Both datasets were then further processed in Rstudio and filtered to include only chinook salmon from May to September (2010–2017). These datasets were then merged with temperature data for analysis.

Using the cleaned and combined ASL and temperature datasets, linear regression models were used to analyze relationships between seasonal mean temperature, salmon length, and year. Two models were implemented: one examining the direct effect of seasonal mean temperature on salmon length and another incorporating both seasonal mean temperature and year to assess trends over time. Model fit was evaluated through Akaike's Information Criterion (AIC) to determine which model to use for further analysis. Predictive modelling, based on the linear model with date and temperature data, was then performed to estimate salmon length changes over the next 20 years (2018–2037). This model assumes consistently rising temperatures following the pattern of changes over 2010-2017 and does not account for salmon mortality or minimum size limits.

To evaluate the impact of heat stress on juvenile productivity, data from Howard and von Biela's (2023) Supplementary Table S1 was used, which detailed the number of eggs that survive to the juvenile life stage per spawning adult salmon. This dataset was converted to .csv format,

cleaned in R software to include "Total J/S" and "Year" columns, and merged with the cleaned temperature data.

Preliminary graphing revealed a parabolic pattern, prompting the use of a nonlinear least squares algorithm to test for correlation between temperature, year, and J/S. A Levenberg-Marquardt algorithm was used to modify the non-linear least squares problem, as the step progression for the year analysis became too small and produced errors. The fit of the non-linear least squares models for J/S by year and J/S by temperature were compared through AIC to ensure patterns were due to a change in temperature through time and not only a temperature-J/S relationship.

All R codes to conduct these methods can be found in the R Code folder on our GitHub and can be found at this link: [BIOL4110/Group2_Heat_Stress_Chinook_Salmon](https://github.com/BIOL4110/Group2_Heat_Stress_Chinook_Salmon).

Results

Temperatures in the rivers of the Kodiak and Unuk regions of Alaska showed a significant positive increase by approximately 2.5°C over the study period (2009-2019) with an adjusted R^2 of 0.36 (Figure 1, $p = 0.039$).

The length linear model analysis revealed a strong, significant negative correlation between seasonal mean water temperature and salmon body length (Figure 2, $p = 0.0015$). However, the relationship's explanatory power was modest, with an adjusted R^2 value of 0.18.

Temporal trends showed a decline in salmon length in both regions using date and temperature as predictors (Figure 3). Unuk salmon remained consistently longer than Kodiak salmon. Overall, salmon lengths declined annually by 8.64 mm/year ($p = 0.0005$). The adjusted R^2 for this model was 0.25, with approximately 25% of the variation in salmon length explained by temperature and year.

AIC revealed no statistical difference between linear models with a ΔAIC of 3.53. Predictive modelling for 2017–2037 (Figure 4) showed continued reductions in salmon length under consistently rising temperature scenarios. Future projections indicated that the average adult salmon size could fall below 500 mm by 2037.

The nonlinear least squares analysis for seasonal temperature (May–September) and J/S revealed a parabolic pattern resembling an optimal temperature curve with a peak at 13.5°C (Figure 5). A similar pattern was also observed in the nonlinear least squares analysis for J/S over time (Figure 6), showing an increase in J/S until 2014, followed by a decline. The ΔAIC between models was 2.06. Therefore, these models are not significantly different from each other.

Discussion

The relationship between rising water temperatures and J/S over the study period did not decline linearly as originally predicted. Instead, a pattern emerged resembling an optimal temperature curve response. Although a small sample size and low statistical power made it difficult to develop this pattern fully, it suggests that J/S will likely continue to decline as temperatures continue to rise. This supports the basic mechanism of the Heat Stress Hypothesis, which suggests that temperatures above a certain threshold will cause a decline in J/S. This decline is biologically important because the variability in adult salmon returns is largely attributed to juvenile abundance estimates due to fewer individuals entering the population (Howard & von Biela, 2023). Further research into reproductive capabilities and varying life-stage survival under varying temperatures would help to inform this relationship.

Previous literature suggests that heat stress of unfertilized eggs begins at around 13°C, and 12–15°C impacts fertilized egg survival to the juvenile stage (Richter & Kolmes, 2006). As such, it was predicted that J/S would exhibit a noticeable linear decline following these

temperatures. This differs from the findings of this study, which observed peak juvenile survivability at temperatures of 13.5°C. This discrepancy could be attributed to a time lag, different thermal tolerance ranges due to location or specific population attributes, or a long-term shift in tolerance resulting from exposure to rising temperatures under climate change. However, our sample size is too limited to conclusively point to an exact optimal temperature or reason for deviance from the literature.

Rising water temperatures are significantly associated with reductions in chinook salmon length, supporting the TSR hypothesis. Smaller body sizes negatively impact reproductive success by reducing egg viability and overall population resilience (Schindler et al., 2020; Ohleberger et al., 2020), which is concerning given that the results revealed an annual decline in salmon length of 8.64 mm in both the Unuk and Kodiak populations. Lindmark et al. (2022) found that optimal temperature in fish declines by 0.31°C per unit increase in body mass, making larger-bodied species, such as those found in the Unuk region (Figures 2-4), more susceptible to TSR-driven effects.

A decline in J/S and a reduction in body size has broad ecological and anthropogenic implications. As a keystone species, chinook salmon play a vital role in predator-prey dynamics and nutrient cycling. This nutrient cycling has widespread effects on aquatic ecosystems as returning salmon's waste, eggs, and carcasses replenishes nutrient-poor natal rivers with nitrogen, phosphorus, and carbon (Stockner & Ashley, 2003; Watkinson, 2000; Hilderbrand et al., 2004). As the second top predator of chinook salmon, grizzly bears benefit from this cycling, as the availability of salmon directly impacts their population dynamics (Deacy et al., 2023). Humans are the primary predators of chinook salmon and experience a dependence on chinook salmon as a food source, especially in northern communities such as those in Alaska (Deacy et

al., 2023; Whitney et al., 2020). As salmon body length decreases, the flesh recovery rate and caloric value per fish decreases since bone and organ proportions must be consistent for the fish to maintain bodily function (Oke et al., 2020). A decrease in caloric value per individual fish poses challenges to both human fisheries and animal predators (Oke et al., 2020). A decreased flesh recovery rate may result in overfishing to compensate for this caloric deficit, further exacerbating population declines. People who fish chinook salmon as a food source, either traditionally or recreationally, will be negatively impacted by decreasing body size as fish retention legislation states that only fish longer than 71cm may be retained (ADFG, 2024). The projected decline in length towards 50cm over the next 20 years suggests that fishing will become increasingly regulated and even prohibited. This, paired with a decline in population size, means less accessible and sustainable food sources for rural northern populations, including Indigenous communities, who already face food scarcity and extortionate pricing due to location (Whitney et al., 2020).

Future research should focus on long-term monitoring of chinook salmon populations and investigate regional variability in thermal tolerance and reproduction. Efforts to restore habitats and implement conservation strategies that mitigate the effects of climate change are crucial for maintaining salmon populations and the ecosystems they support. Future conservation initiatives will be essential to prevent the cascading effects of Chinook salmon declines, preserving not only their populations but also the broader ecological and socioeconomic systems that depend on their resilience.

Appendix

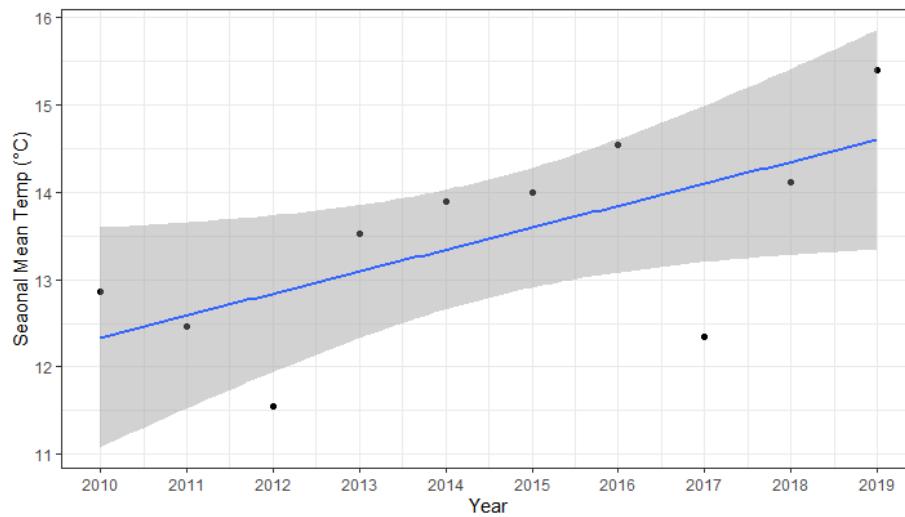


Figure 1: The change in temperature from 2009 to 2019 in the Gulf of Alaska. Measurements were taken from four stations across the Gulf of Alaska from the Alaska Center for Conservation Science (AKTEMP, n.d.). The blue line shows the results of a linear regression, with the grey shading indicating the standard error. Graph created using RStudio.

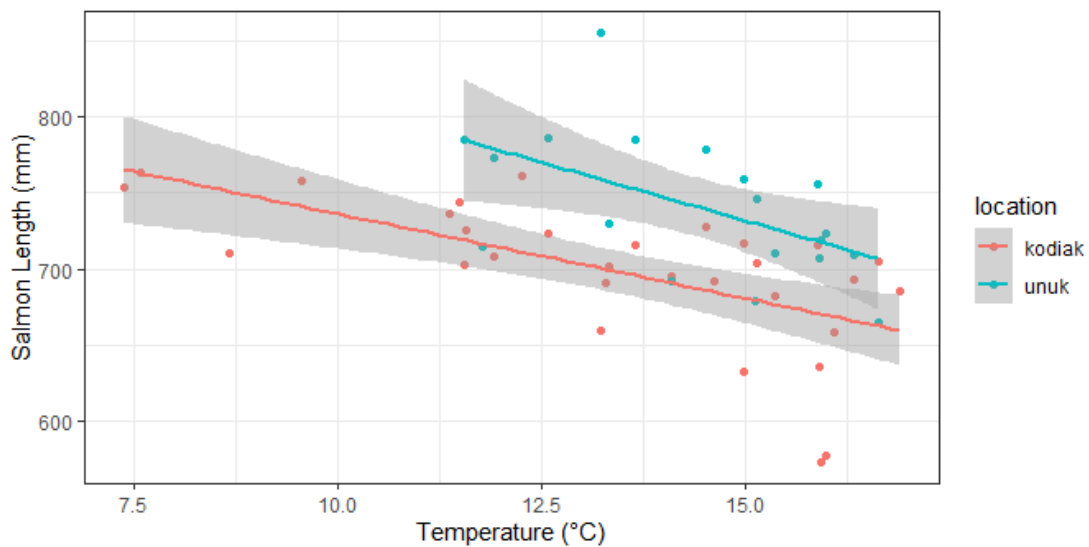


Figure 2: Relationship between seasonal mean temperature (°C) and chinook salmon length (mm) (2010–2017) in the Unuk region (blue line) and Kodiak region (red line) from the Gulf of Alaska. Salmon length was analyzed against spawning temperature data recorded from May to September. The grey shading indicates the standard error for each line. Graph created using RStudio.

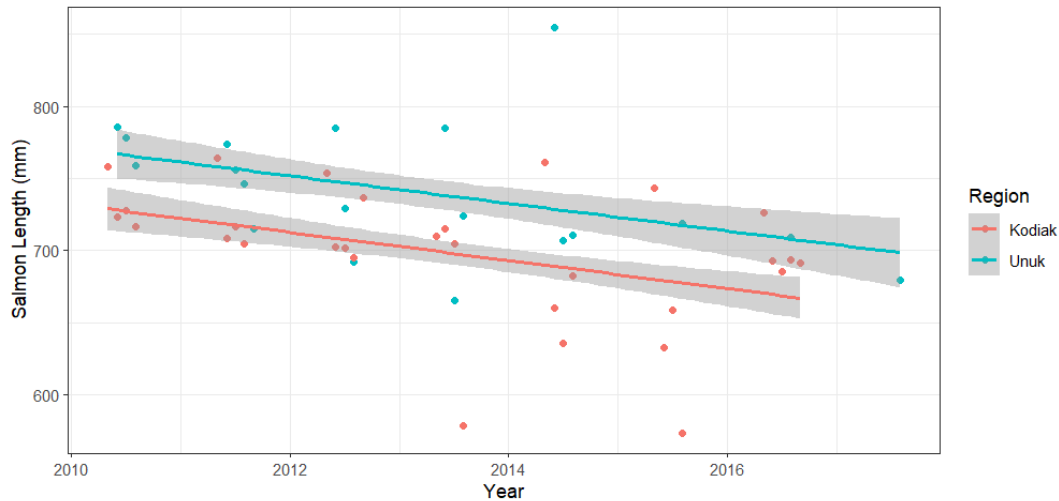


Figure 3: Relationship between seasonal mean temperature (May–September) and chinook salmon length (mm) for two regions, Unuk (blue) and Kodiak (red), from 2010 to 2017. The linear regression lines represent the best fit for each region. The grey shading indicates the standard error for each line. Graph created using RStudio.

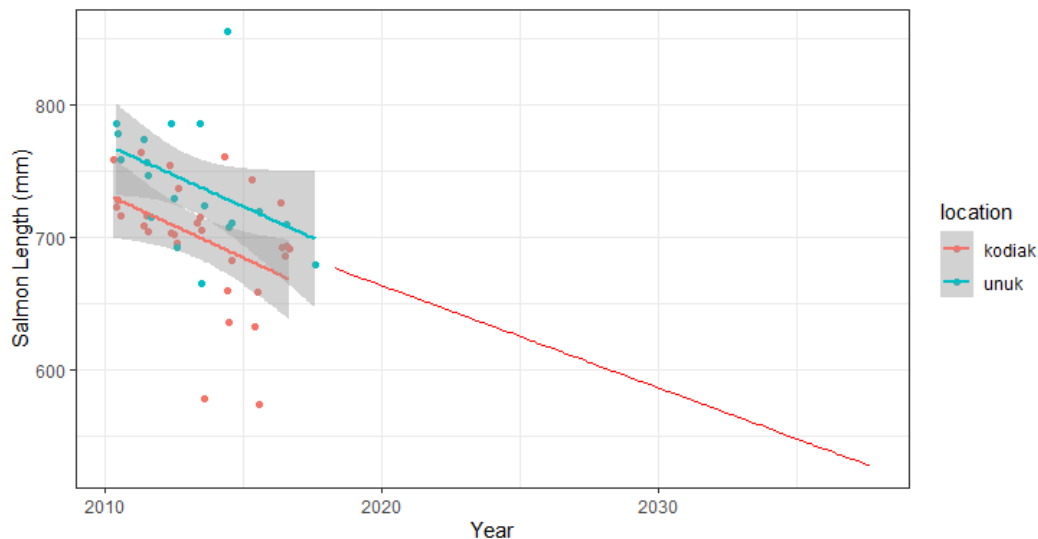


Figure 4: Predicted chinook salmon length (mm) (2017–2037) for two regions, Unuk (blue line) and Kodiak (red line), based on historical length data (2010–2017). Predictions are derived using linear regression models, incorporating historical seasonal mean temperatures (May–September) and salmon length trends. The solid red line represents projected values under continued rising temperature trends. The grey shading indicates the standard error for each line. Graph created using RStudio.

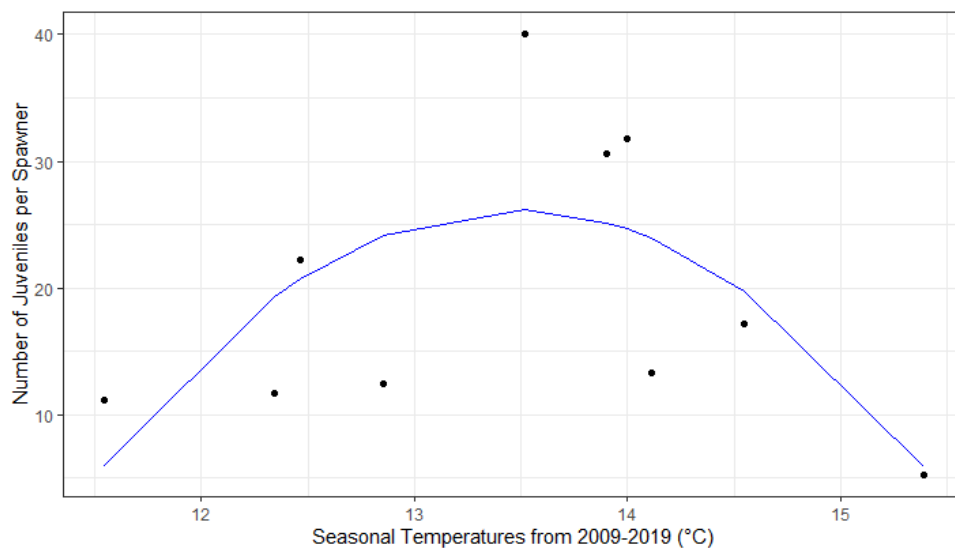


Figure 5: The results of a Levenberg-Marquardt nonlinear least squares model showing the relationship between the number of surviving juveniles per adult spawning chinook salmon and the seasonal mean temperature. These seasonal temperatures contain the average May-September temperatures from 2010-2017 in the Kodiak and Unuk regions of the Gulf of Alaska. Each data point is a specific observation, and the blue line is the model output. Graph created using RStudio.

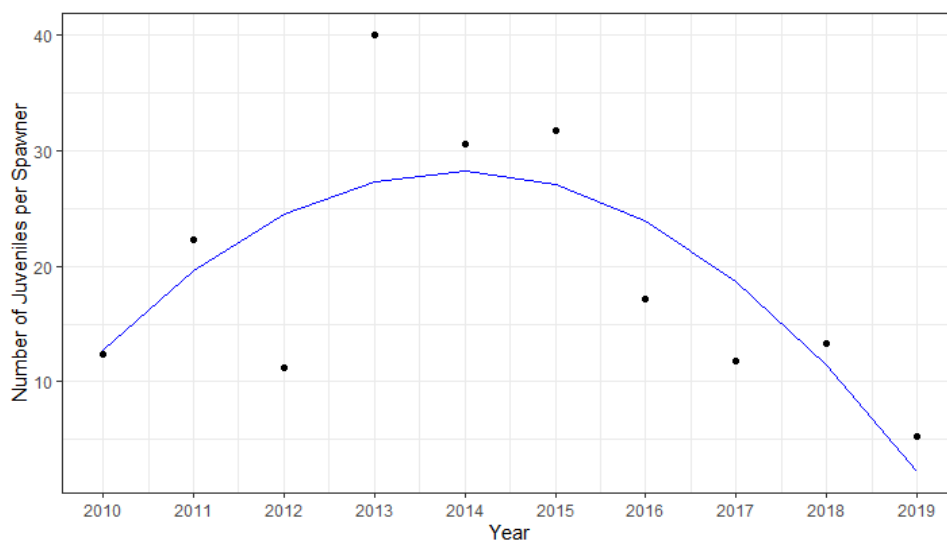


Figure 6: The results of a Levenberg-Marquardt nonlinear least squares model showing the relationship between the number of surviving juveniles per adult spawning chinook salmon and the year of observation. Each data point is a specific observation, and the black line is the model output. Graph created using RStudio.

References

- Alaska Center for Conservation Science (AKTEMP). (n.d.). *AKTEMP: Temperature Data Portal*. Retrieved from <https://aktemp.uaa.alaska.edu/#/>
- Alaska Department of Fish and Game (ADFG). (2024). 2024 Sports fishing regulations summary Southeast Alaska. https://www.adfg.alaska.gov/static/regulations/fishregulations/PDFs/southeast/2024se_sfr_egg_complete.pdf
- Barrett, T., Dowle, M., Srinivasan, A., Gorecki, J., Chirico, M., Hocking, T., & Schwendinger, B. (2024). `_data.table`: Extension of `'data.frame'`. R package version 1.16.2. <https://CRAN.R-project.org/package=data.table>.
- Bourret, S.L., Caudill, C.C. & Keefer, M.L. (2016). Diversity of juvenile Chinook salmon life history pathways. *Rev Fish Biol Fisheries* 26, 375–403. <https://doi.org/10.1007/s11160-016-9432-3>
- Crozier, L., Dechant, D., & Sullivan, K. (2014, August). *Impacts of climate change on Columbia River Salmon*. Welcome to the NOAA Institutional Repository. <https://repository.library.noaa.gov/view/noaa/25641>
- Deacy, W. W., Leacock, W. B., & Armstrong, J. B. (2023). Modeling the interaction between Salmon Management and consumption by Coastal Brown bears. *Ecosphere*, 14(5). <https://doi.org/10.1002/ecs2.4518>
- Del Rio, A. M., Davis, B. E. Fangue, N. A., & Todgham, A. E. (2019). Combined effects of warming and hypoxia on early life stage Chinook salmon physiology and development, *Conservation Physiology* 7. <https://doi.org/10.1093/conphys/coy078>
- Division Commercial Fisheries Alaska Department of Fish and Game (DCFADFG). (2019). *Chinook salmon age, sex, and length data from major rivers in Southeast Alaska, 1988-2017*. Knb.ecoinformatics.org. <https://knb.ecoinformatics.org/view/doi:10.5063/F11R6NSS>
- Division Commercial Fisheries Alaska Department of Fish and Game (DCFADFG). (2021). *Salmon age, sex, and length data from Westward and Southeast Alaska, 1979-2017*. Knb. <https://knb.ecoinformatics.org/view/doi%3A10.5063%2FJ38QX8>
- Elzhov, T.V., Mullen, K.M., Spiess, A., & Bolker, B. (2023). `_minpack.lm`: R Interface to the Levenberg-Marquardt Nonlinear Least-Squares Algorithm Found in MINPACK, Plus Support for Bounds. R package version 1.2-4. <https://CRAN.R-project.org/package=minpack.lm>.
- Fisheries and Oceans Canada (DFO). (2019, December 9). Information about pacific salmon. Pacific Region | Fisheries and Oceans Canada. <https://www.pac.dfo-mpo.gc.ca/fm-gp/salmon-saumon/facts-infos-eng.html#>

- Fisheries and Oceans Canada. (n.d.). *Region 1 - Vancouver Island, the Gulf Islands and the Mainland*. <https://www.pac.dfo-mpo.gc.ca/fm-gp/rec/fresh-douce/region1-eng.html>
- Forster, J., Hirst, A.G., & Atkinson, D. (2011). How do organisms change size with changing temperature? The importance of reproductive method and ontogenetic timing. *Functional Ecology*, 25, 1024-1031. <https://doi.org/10.1111/j.1365-2435.2011.01852.x>
- Grolemund, G., & Wickham, H. (2011). Dates and Times Made Easy with lubridate. *Journal of Statistical Software*, 40(3), 1-25. <https://www.jstatsoft.org/v40/i03/>.
- Hilderbrand, G. V., Farley, S. D., Schwartz, C. C., & Robbins, C. T. (2004). Importance of salmon to wildlife: Implications for integrated management. *BioOne*, 15, 1–9. [https://doi.org/https://doi.org/10.2192/1537-6176\(2004\)015%3C0001:IOSTWI%3E2.0.CO;2](https://doi.org/https://doi.org/10.2192/1537-6176(2004)015%3C0001:IOSTWI%3E2.0.CO;2)
- Howard, K. G., & von Biela, V. (2023). Adult spawners: a critical period for subarctic Chinook salmon in a changing climate. *Global Change Biology*, 29(7), 1759-1773. <https://doi.org/10.1111/gcb.16610>
- Hyatt, K. D., & Godbout, L. (1999). A Review of Salmon as Keystone Species and Their Utility as Critical Indicators of Regional Biodiversity and Ecosystem Integrity. <https://www.env.gov.bc.ca/wld/documents/fr02hyatt2.pdf>
- International Year of the Salmon. (IYS) (2019, March). Chinook migrations across the North Pacific Ocean. <https://yearofthesalmon.org/wp-content/uploads/2019/03/Mar-15-Chinook-in-the-Northeast-Pacific-Oceanv2.pdf>
- Kambestad, M., Hellen, B. A., Lennox, R. J., Velle, G., & Sægrov, H. (2024). Validity of winter sampling for estimation of salmonid abundance by electrofishing. *Fisheries Research*, 271, 106929. <https://doi.org/10.1016/j.fishres.2023.106929>
- Keefer, M. L., Clabough, T. S., Jepson, M. A., Johnson, E. L., Peery, C. A., & Caudill, C. C. (2018). Thermal exposure of adult chinook salmon and steelhead: Diverse behavioral strategies in a large and warming river system. *PLOS ONE*, 13(9). <https://doi.org/10.1371/journal.pone.0204274>
- Lindmark, M., Ohlberger, J., & Gårdmark, A. (2022). Optimum growth temperature declines with body size within fish species. *Global Change Biology*, 28(7), 2259-2271. <https://doi.org/10.1111/gcb.16067>
- National Wildlife Federation. (n.d.). Chinook salmon. National Wildlife Federation. <https://www.nwf.org/Educational-Resources/Wildlife-Guide/Fish/Chinook-Salmon>
- NOAA. (2022, October 6). *Salmon Life Cycle and seasonal fishery planning*. NOAA Fisheries. <https://www.fisheries.noaa.gov/west-coast/sustainable-fisheries/salmon-life-cycle-and-seasonal-fishery-planning>

- NOAA. (2024, July 24). *Candidate species under the Endangered Species Act*. Endangered Species Conservation.
<https://www.fisheries.noaa.gov/endangered-species-conservation/candidate-species-under-endangered-species-act>
- NOAA. (2024, September 9). *Chinook salmon*. NOAA Fisheries.
<https://www.fisheries.noaa.gov/species/chinook-salmon>
- Ohlberger, J., Schindler, D. E., Brown, R. J., Harding, J. M. S., Adkison, M. D., Munro, A. R., Horstmann, L., & Spaeder, J. (2020). The reproductive value of large females: Consequences of shifts in demographic structure for population reproductive potential in Chinook salmon. *Canadian Journal of Fisheries and Aquatic Sciences*, 77(8), 1292–1301. <https://doi.org/10.1139/cjfas-2020-0012>
- Oke, K. B., Cunningham, C. J., Westley, P. A. H., Baskett, M. L., Carlson, S. M., Clark, J., ... & Palkovacs, E. P. (2020). Recent declines in salmon body size impact ecosystems and fisheries. *Nature communications*, 11(1), 4155.
<https://doi.org/10.1038/s41467-020-17726-z>
- Onslow, J., Boutin, C., Bolog, S., Oliver, S., Bredthauer, E., & O’Harra, H. (2013). *Skein 3 - Eggs*. Alaska Salmon in the Classroom Curriculum.
<https://www.adfg.alaska.gov/index.cfm?adfg=curricula.salmon>
- R Core Team (2024). *_R: A Language and Environment for Statistical Computing_*. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.
- Richter, A., & Kolmes, S. A. (2005). Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. *Reviews in Fisheries Science*, 13(1), 23–49. <https://doi.org/10.1080/10641260590885861>
- Robinson, D., Hayes, A., & Couch, S. (2024). *_broom: Convert Statistical Objects into Tidy Tibbles_*. R package version 1.0.7. <https://CRAN.R-project.org/package=broom>.
- Schindler, D., Munro, A., Harding, J., Brown, R., Atkinson, M., & Ohlberger, J. (2020, April). *Changes in Quality of Chinook Salmon Escapement in the AYK Region*. Sustainable Salmon Initiative.
https://www.aykssi.org/wp-content/uploads/1615-AYK_SSI-EQ-Expert-Panel-Report-Illustrated-Summary-April-2020.pdf
- State of Salmon. (2021, January 13). Salmon recovery 101. State of Salmon.
<https://stateofsalmon.wa.gov/salmon-101/>
- Stockner, J. G., & Ashley, K. I. (2003). Salmon nutrients: Closing the circle. *American Fisheries Society*, 35, 3–15.
<https://commons.bcit.ca/riversinstitute/files/2013/06/Salmon-nutrients-Closing-the-circle.pdf>

- Twardek, W. M., Cooke, S. J., & Lapointe, N. W. R. (2023). Fishway performance of adult Chinook salmon completing one of the world's longest inland salmon migrations to the upper Yukon River. *Ecological Engineering*, 187, 106846. <https://doi.org/10.1016/j.ecoleng.2022.106846>
- Washington State Department of Ecology (WSDE). (2000, July). *Effects of elevated water temperatures on salmonids*. Focus Number 00-10-046. <https://apps.ecology.wa.gov/publications/publications/0010046.pdf>
- Watkinson, S. (2000). Life after death: The importance of salmon carcasses of British Columbia's Watersheds. *Arctic*, 53, 92–96. <https://www.jstor.org/stable/40511897>
- Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemond, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., & Yutani, H. (2019). "Welcome to the tidyverse." *Journal of Open Source Software*, 4(43), 1686. <https://doi.org/10.21105/joss.01686>.
- Wickham, H. & Bryan, J. (2023). *_readxl: Read Excel Files_*. R package version 1.4.3, <https://CRAN.R-project.org/package=readxl>.
- Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *_dplyr: A Grammar of Data Manipulation_*. R package version 1.1.4, <https://CRAN.R-project.org/package=dplyr>.
- Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York.
- Whitney, C. K., Frid, A., Edgar, B. K., Walkus, J., Siwallace, P., Siwallace, I. L., & Ban, N. C. (2020). "Like the plains people losing the buffalo": perceptions of climate change impacts, fisheries management, and adaptation actions by indigenous peoples in coastal British Columbia, Canada. *Ecology and Society*, 25(4). <https://doi.org/10.5751/es-12027-250433>